



A Beginner's guide to EMC in a Vehicle

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Agenda

- What is EMC?
 - Definition
- Understanding EMI
 - Source → Path → Victim
 - EMI Org Chart
- Radiated
 - Electric Field
 - Magnetic field
 - Loop Area
 - Unintentional Antennas
- Conducted
 - Common Mode
 - Differential Mode
- Edge Rates
- How do we deal with EMC?
 - Interrupt the path
 - Edge Rates
 - Radiated
 - Distance
 - Twisting
 - Shielding
 - Eliminate Unintentional Antennas
 - Conducted
 - Chokes / Ferrites / Filters
 - Return path
 - Defend the Victim
 - Attack the Source

What Is EMC?

What Is EMC?

EMC Definition

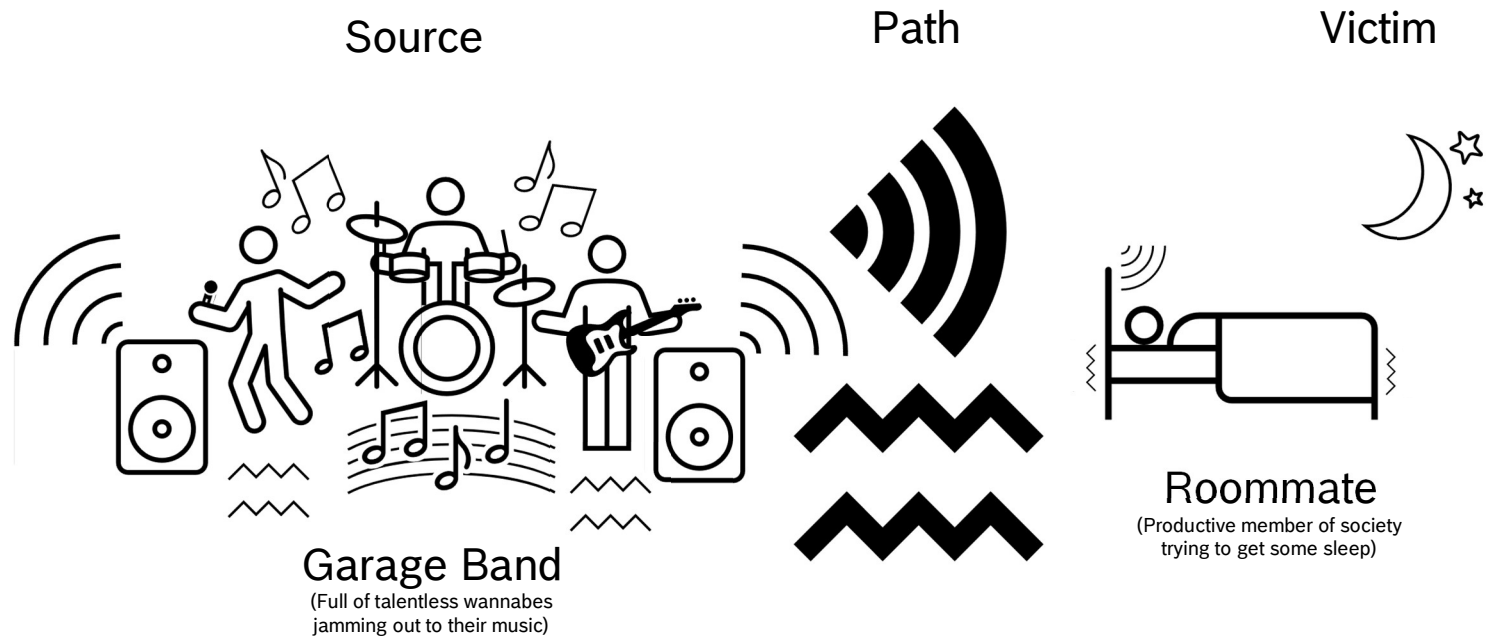
▪ ElectroMagnetic Compatibly

- “...the ability of electrical equipment and systems to function acceptably in their electromagnetic environment, by limiting the unintentional generation, propagation and reception of electromagnetic energy...” –[Wikipedia](#)
- EMC is a field of engineering that tries to understand and limit the effects of EMI (electromagnetic interference)
- EMI causes malfunctions in our electronics and systems
 - Noisy signals, communication errors/failure, unintended device resets, misbehaving devices resets and potential permanent damage to devices

Understanding EMI

Understanding EMI

Source → Path → Victim

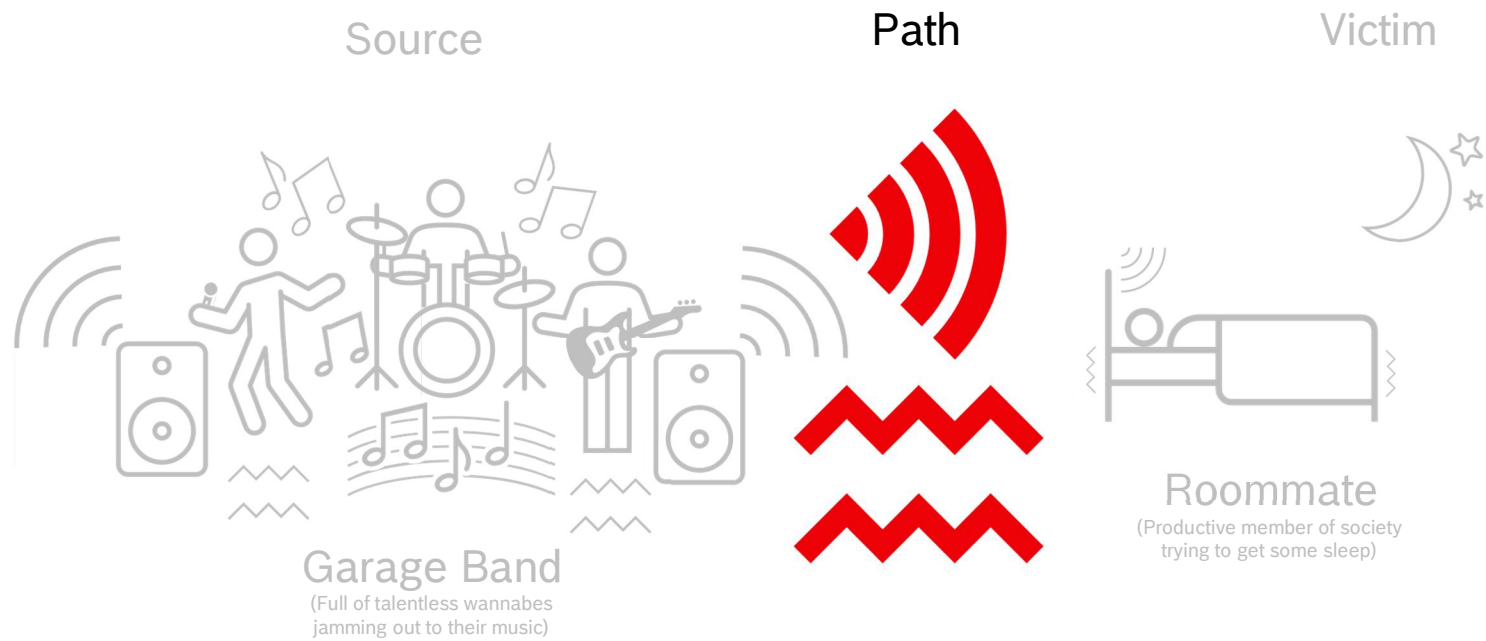


Understanding EMI Emissions



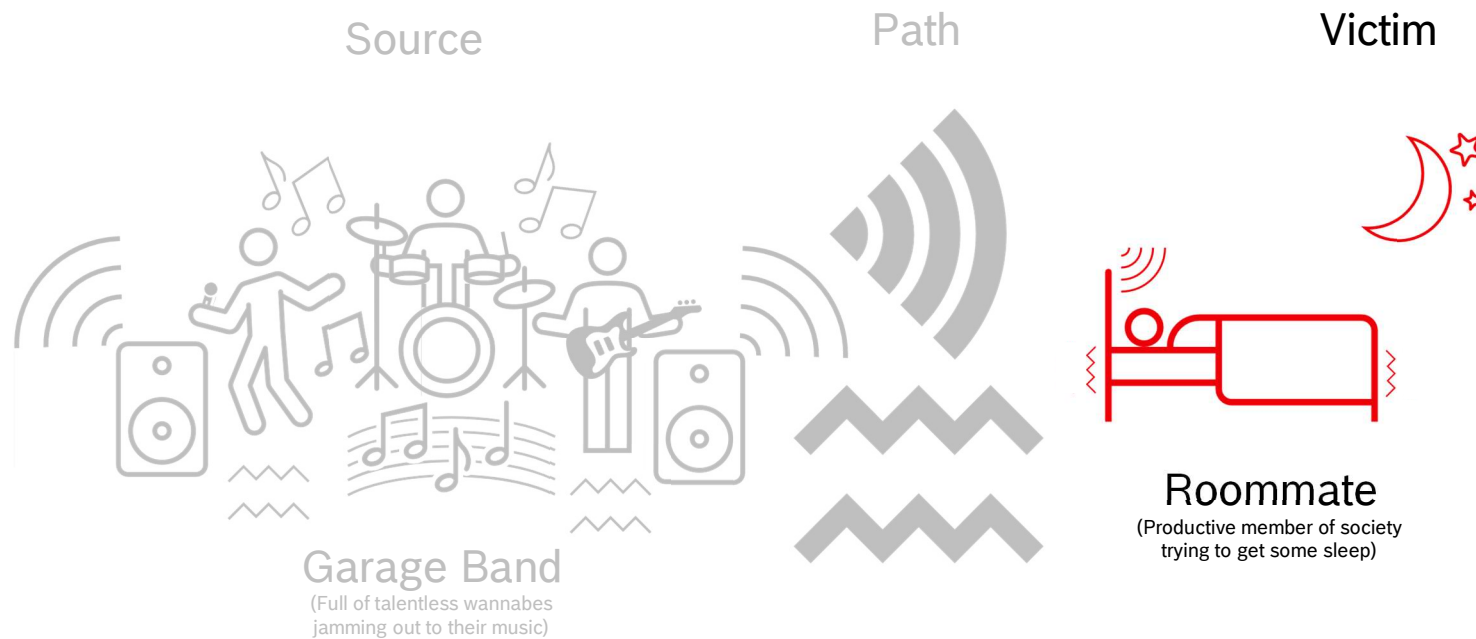
How much electromagnetic energy is unintentionally leaked into the surrounding environment?

Understanding EMI Path



How does the noise travel from the source to the victim?

Understanding EMI Immunity

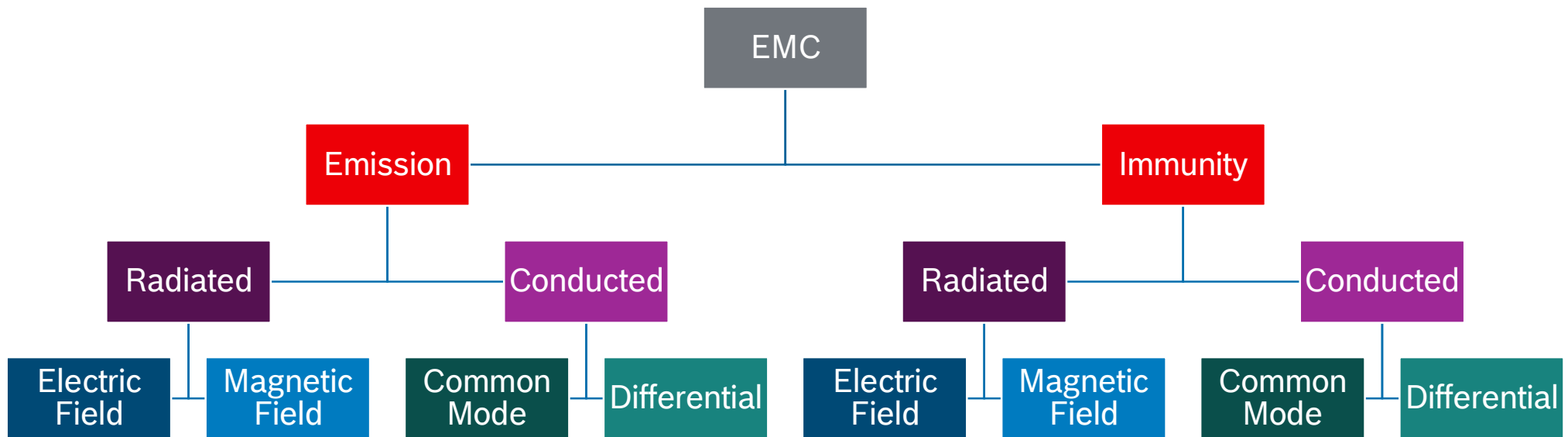


How resistant is the device to interference from electromagnetic energy present in the environment?

NOTE: Immunity is also referred to as Susceptibility

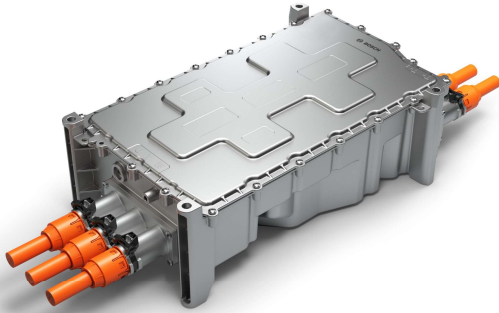
Understanding EMI

Org Chart



Understanding EMI Emissions: Notable Noise Sources

- Inverters / Motor Controllers

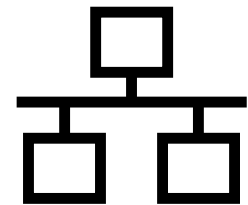


- Brushed Motors

- Electric Actuators
- Starters
- Pumps
- Valves



- Communication Busses



- Ignition Circuits



- Switching DC/DC Converters



- Solenoids & Relays



Generic automotive relay by Dark sabre is licensed under CC BY-SA 3.0

Understanding EMI

Immunity (Notable Victims)

▪ Electronic Control Units

– Communication Busses

- CAN
- Ethernet
- Serial

– Analog Signals

– Digital Signals

- Speed Sensors
- PWM Signals

– Power Supplies



▪ Wireless Interfaces

– Telemetry

- RF
- LTE

– GPS

– Radio

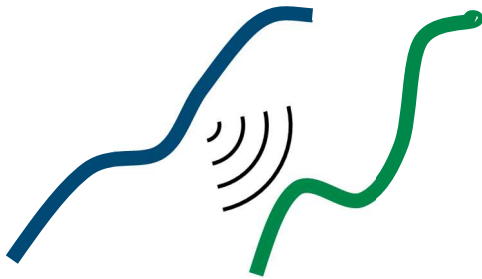


Understanding EMI

Path: Notable Paths (Coupling Modes)

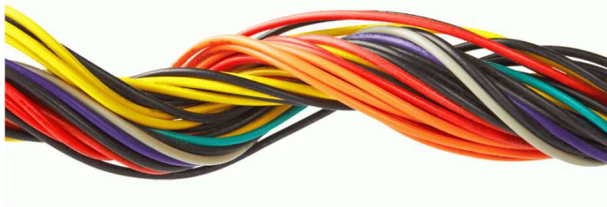
- Crosstalk

- Wires, Cables and Conductors to each other



- Conducted

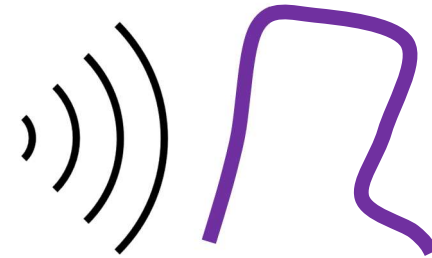
- Directly through Wires, Cables and Conductors



[cables.gif](#) by Ernesto Tolockais licensed under [CC BY-SA](#)

- Antenna

- Field to Wires, Cables and Conductors

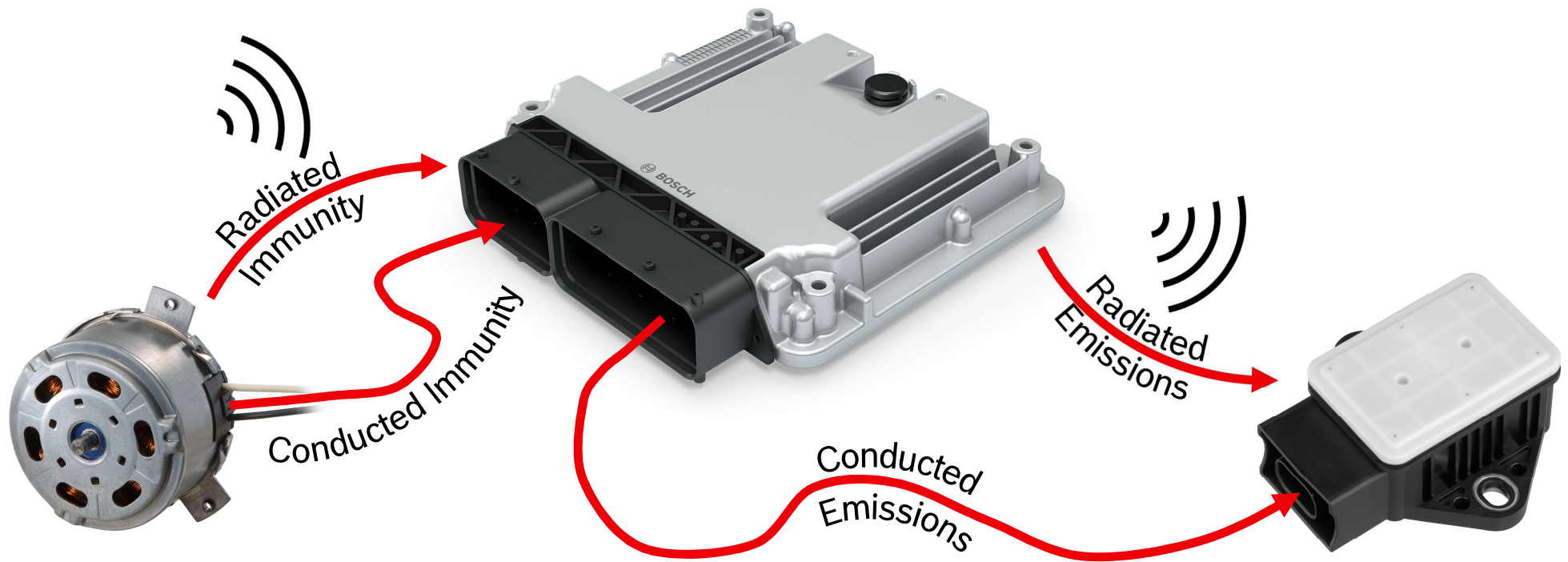


- Field to device (or device enclosure)



Understanding EMI

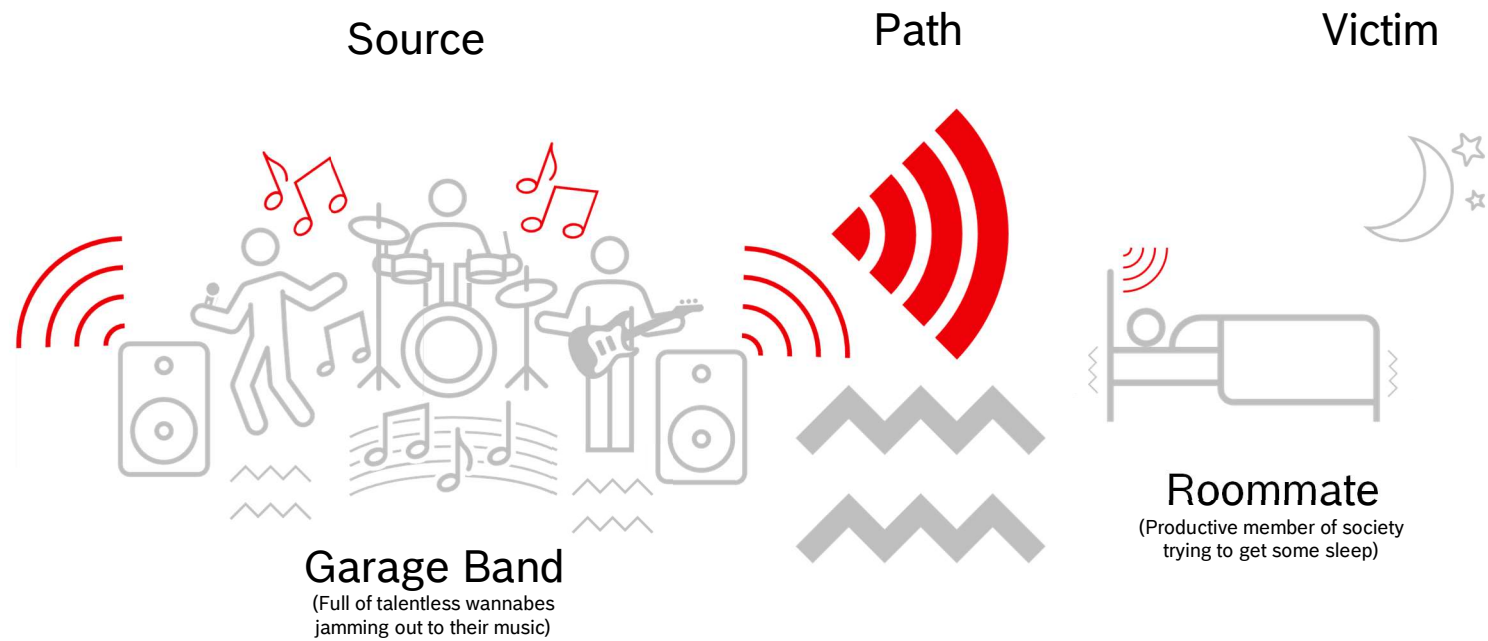
Combining it Together



Radiated

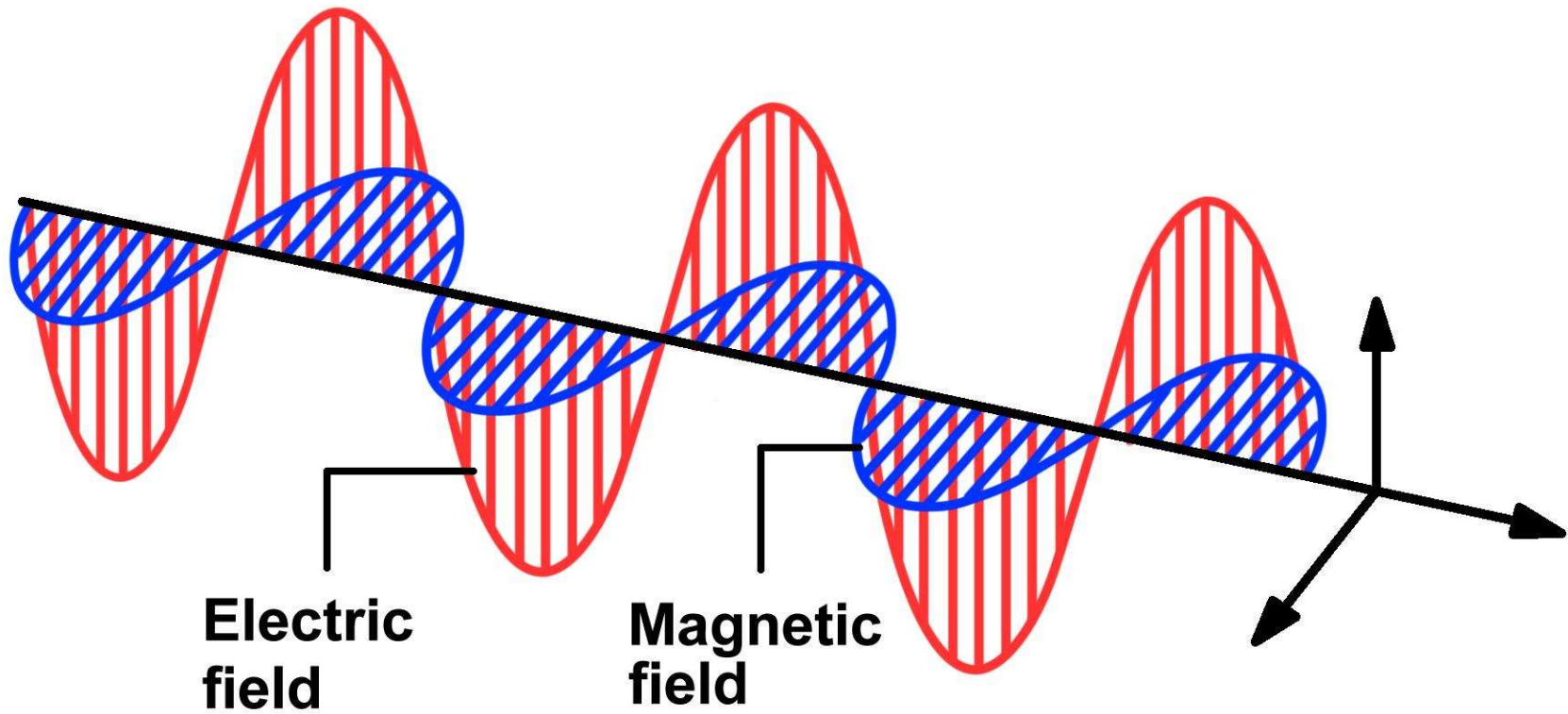
Radiated

Radiated Path

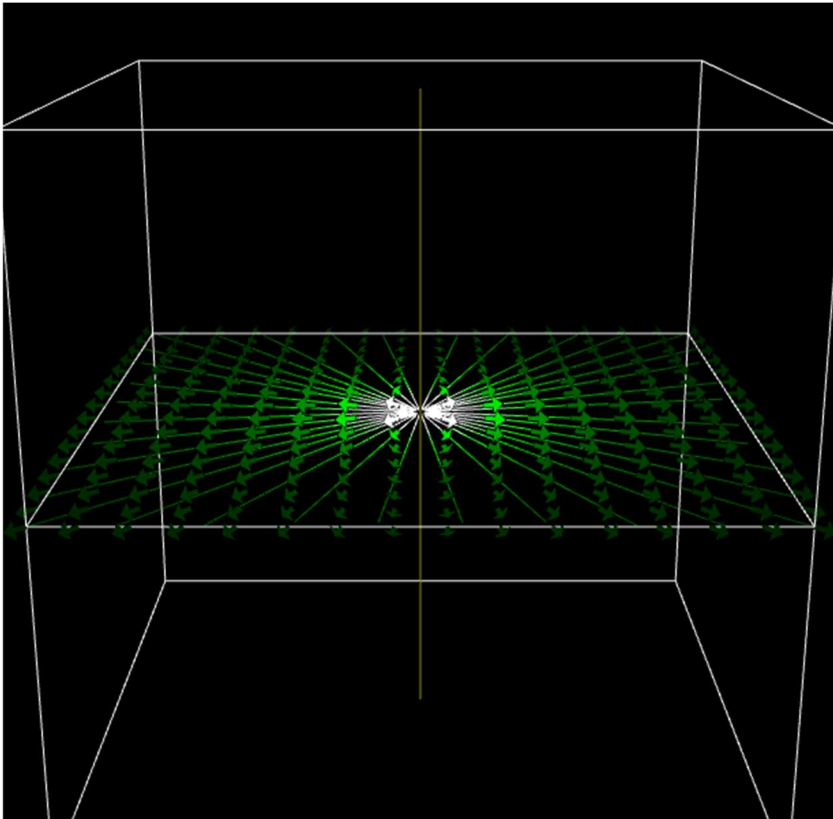


Radiated emissions takes a path through the propagation of electromagnetic fields.

Radiated Electromagnetic Waves



Radiated Electric Field



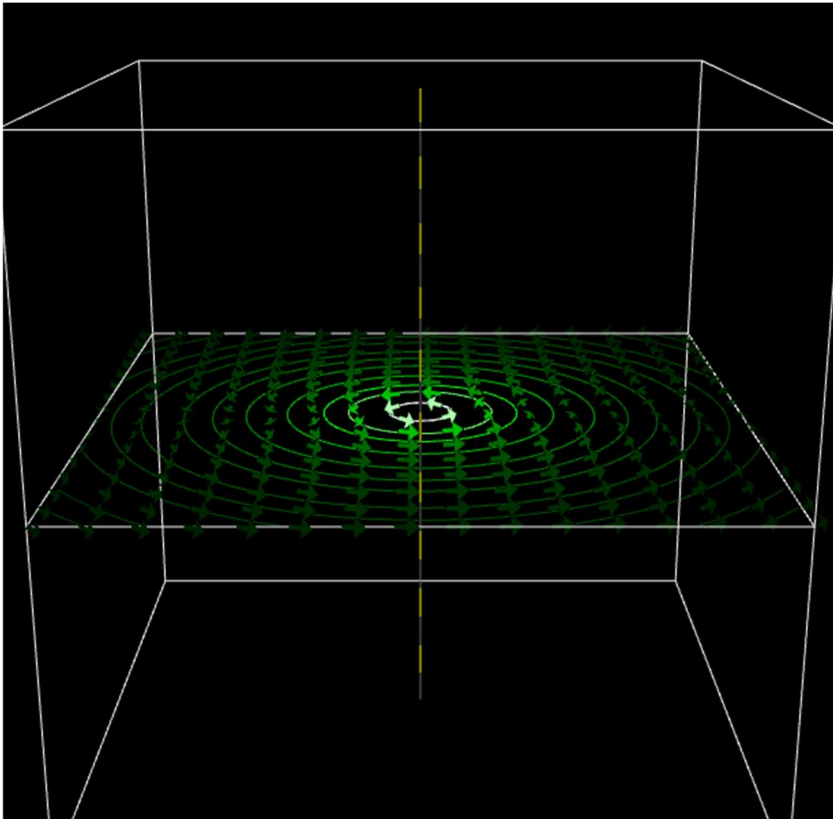
- Electric Field of a wire

$$E = \frac{\lambda}{2\pi r \epsilon_0}$$

- E is the electric field
- λ is charge per unit length
- r is the radius from the wire
- ϵ_0 is the permittivity of free space ($\approx 8.85 * 10^{-12} \frac{F}{m}$)

- Obtained using Gauss' law
- Electric field radiation → Created with fast voltage transients

Radiated Magnetic Field

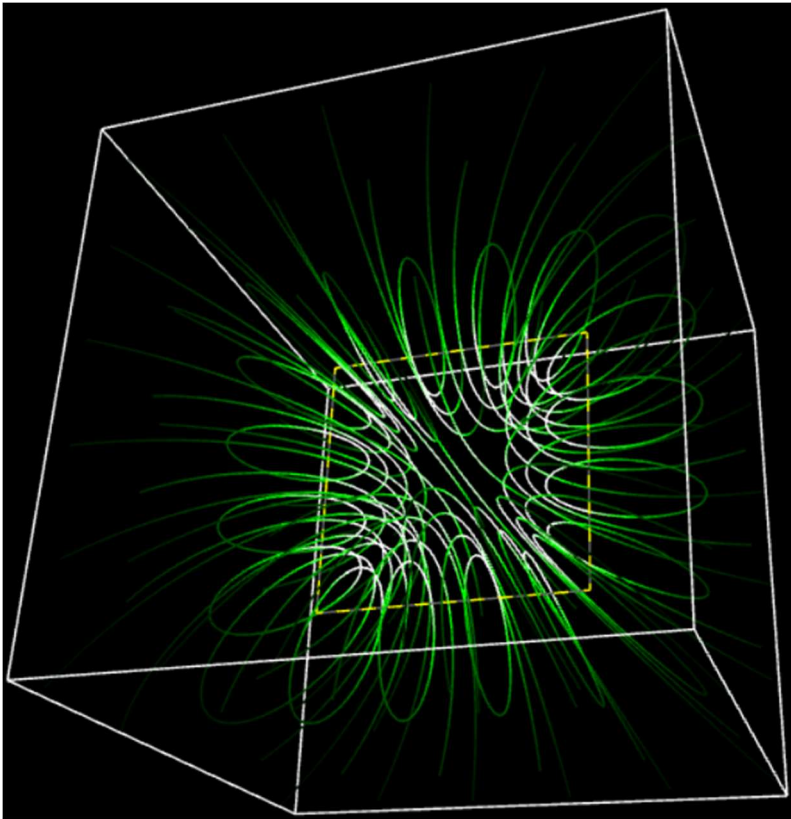


- Magnetic Field of a wire

$$B = \frac{\mu_0 I}{2\pi r}$$

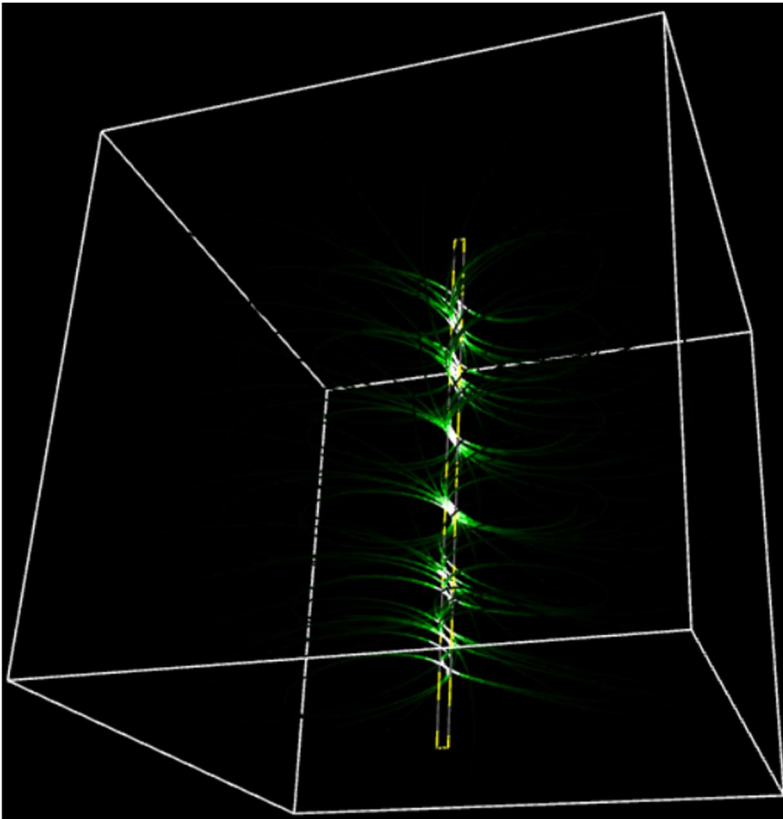
- B is the magnetic field
- μ_0 is the permeability of free space ($4\pi * 10^{-7} T \frac{m}{A}$)
- I is the current through the wire
- r is the radius from the wire
- Obtained using Ampere's Law
- Right Hand Rule
- Magnetic field radiation → Created with fast current transients

Radiated Loop Area



- Directly proportional to inductance of loop area
- Larger loop has larger inductance (Bad)
- More field lines fit for a given field strength

Radiated Loop Area

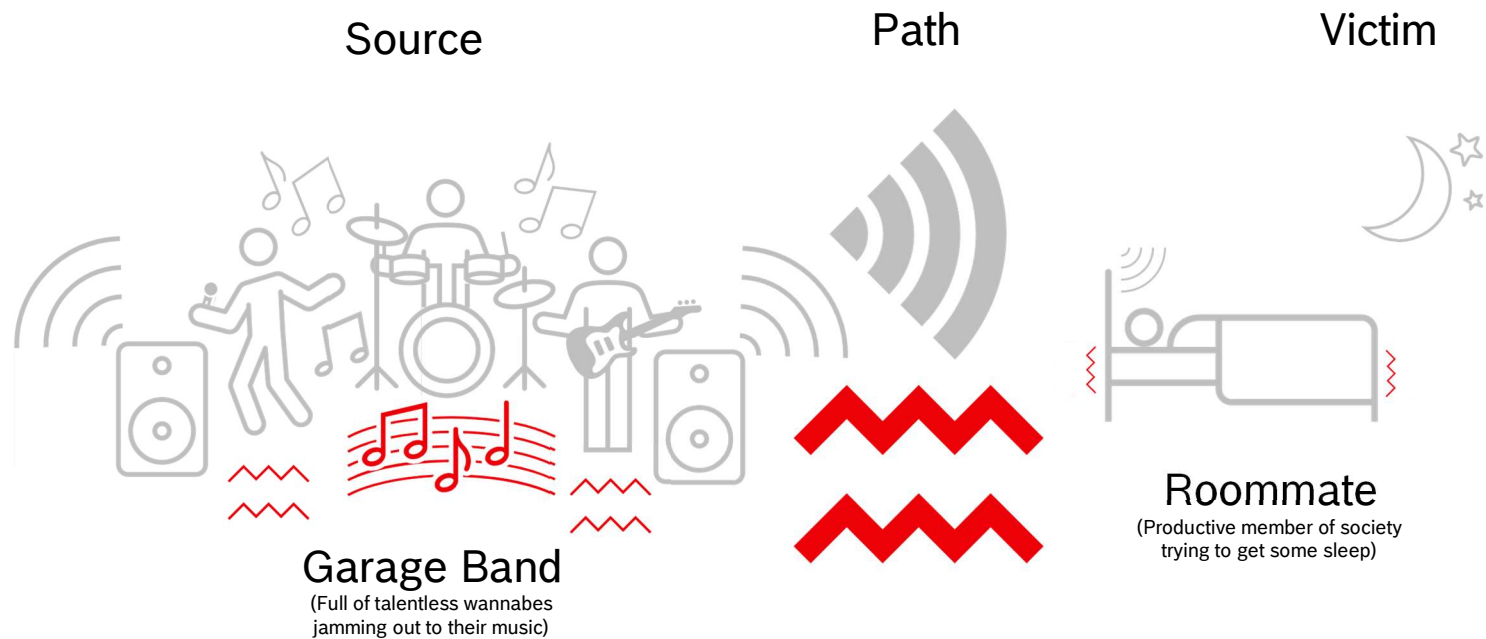


- Directly proportional to inductance of loop area
- Smaller loop has smaller inductance (Good)
- Fewer field lines fit for a given field strength

Conducted

Conducted

Conducted Path



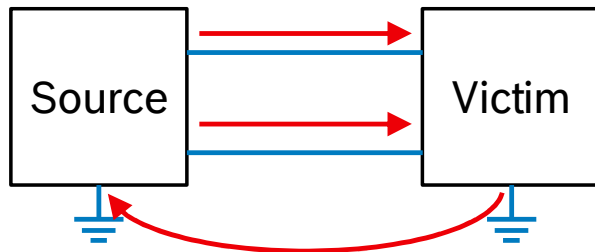
Conducted emissions take a path through cabling, traces, power planes, or parasitic capacitances.

Conducted

Common Mode vs. Differential

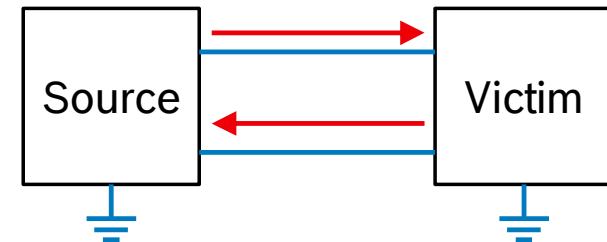
■ Common Mode:

- Voltage or current is in the same direction and magnitude
- Return Path is through Ground



■ Differential

- Voltage or current is in opposite direction and magnitude
- Return path is not through Ground



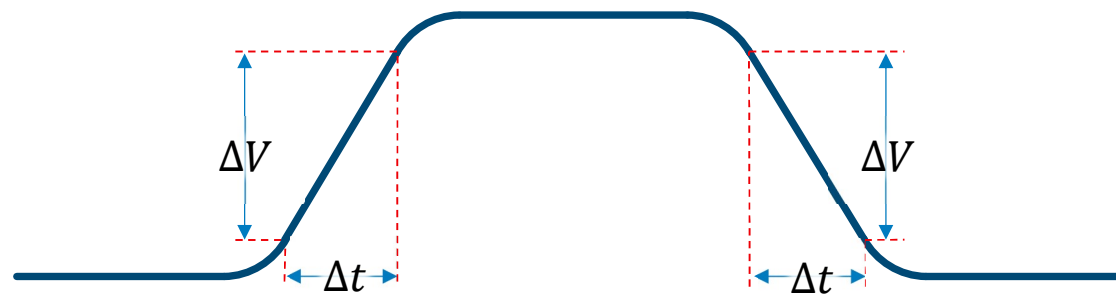
Edge Rates

Edge Rates

Definition

- Edge rate is how fast a voltage or current changes.
- Directly proportional to the voltage/current and inversely proportional to the rise/fall times
 - This can be a switching logic signal, communication bus bit edge,
- This is not the frequency or baud rate of a signal

$$\frac{\Delta V}{\Delta t} \quad \text{or} \quad \frac{\Delta I}{\Delta t}$$



Edge Rates

Good and Bad

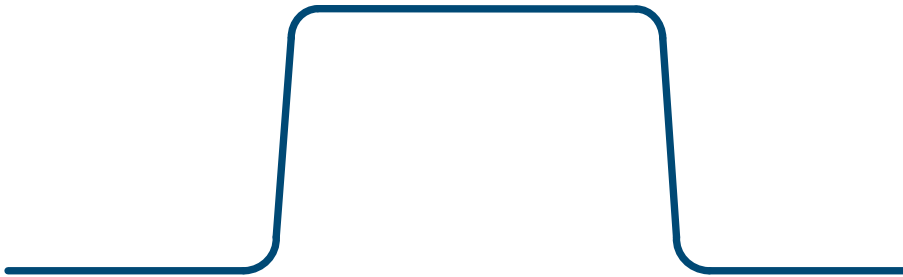
- Larger edge rates radiate more
- If possible, reduce edge rates
 - Balance with voltage tolerances, current needs and switching losses

- Example:

- HV Inverter $\rightarrow \frac{400V}{1\mu s} = 0.4 \frac{V}{ns}$

- 74LVC series logic gate $\rightarrow \frac{5V}{2.5ns} = 2 \frac{V}{ns}$

BAD



BETTER



Mitigation Techniques

Mitigation Techniques

Where to attack the EMI problem?

- Reduce noise at the source
 - Only a viable option if you make or can modify the noise source
 - Best option to reduce problems the device may cause
 - Device designers should be doing this from the outset of their project
- Interrupt the noise path
 - Often the only option the system integrator has
 - Techniques to “fix” problems at system integration stage are expensive and/or labor intensive
 - Many techniques are available, but most are only suitable to certain types of noise or coupling methods
 - Not easy to tell what the exact path(s) of noise is, and which technique should be used
- Increase immunity to noise at victim
 - Only a viable option if you make or can modify the victim
 - Best option to increase device compatibility with varied systems
 - Device designers should be doing this from the outset of their project

Mitigation Techniques

Hidden Antennas: Wire Antenna

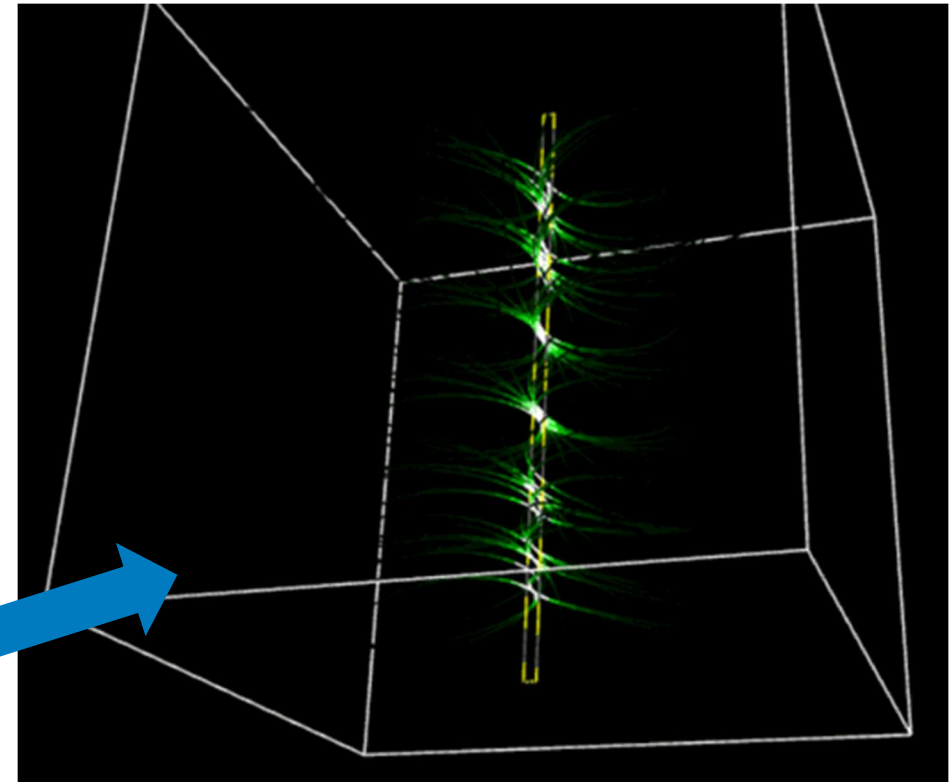
- Wire antenna:
 - Can act as a radiating antenna or a receiving antenna
 - Function of frequency (edge rate), length, impedance, geometry, current and distance
 - Wire with length $> 1/10^{\text{th}}$ of the wavelength (λ)
 - The higher the frequency (or rise/fall times) the shorter the wire necessary to be an antenna
 - Wavelength (in meters): $\lambda = \frac{c}{f} \cong \frac{3 \cdot 10^8 \text{ m/s}}{f} \cong \frac{300}{f_{\text{MHz}}}$
 - All wires are suspect
 - Can be mitigated with shielding and proper return paths

Mitigation Techniques

Hidden Antennas: Loop Antenna

■ Loop Antenna

- Very sensitive to magnetic fields
- Very good at radiating magnetic fields
- Does not necessarily have to be a single wire that forms a loop
- Can be formed with a device or load “in circuit” with the loop
- Loop area is important. The larger the loop, the more sensitive it is to a given field strength
- Minimize Loop Area
- Loop of constant perimeter length and loop current. Note the number and strength of field lines as loop area increases and decreases.

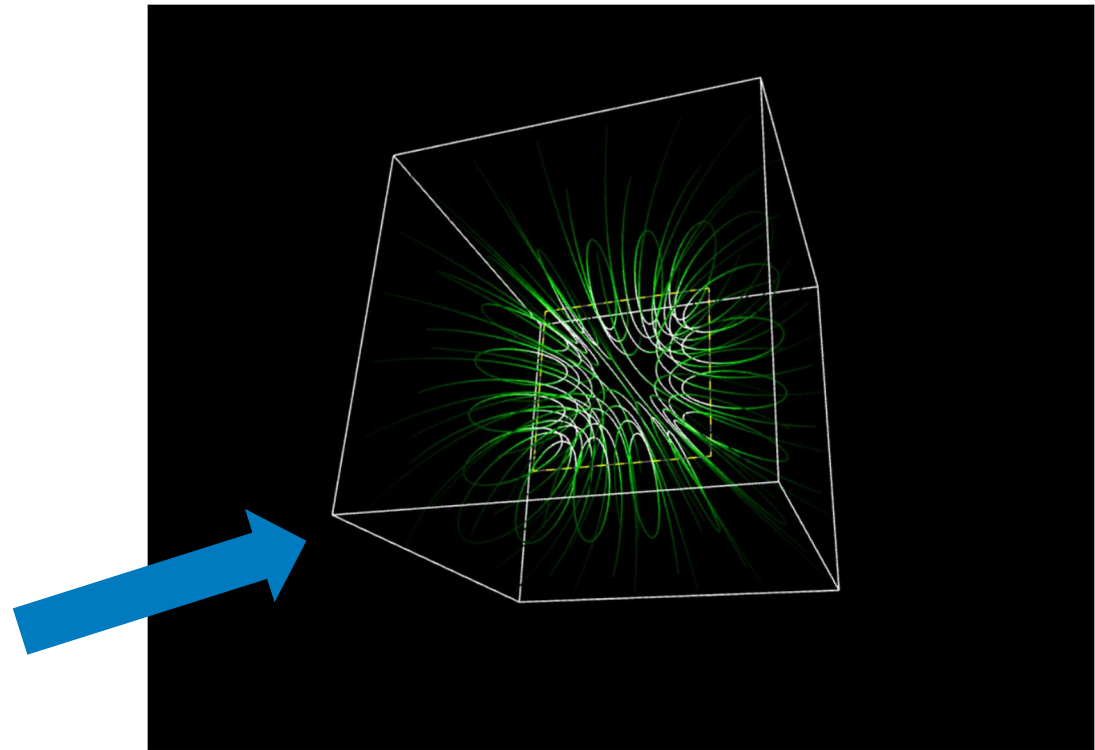


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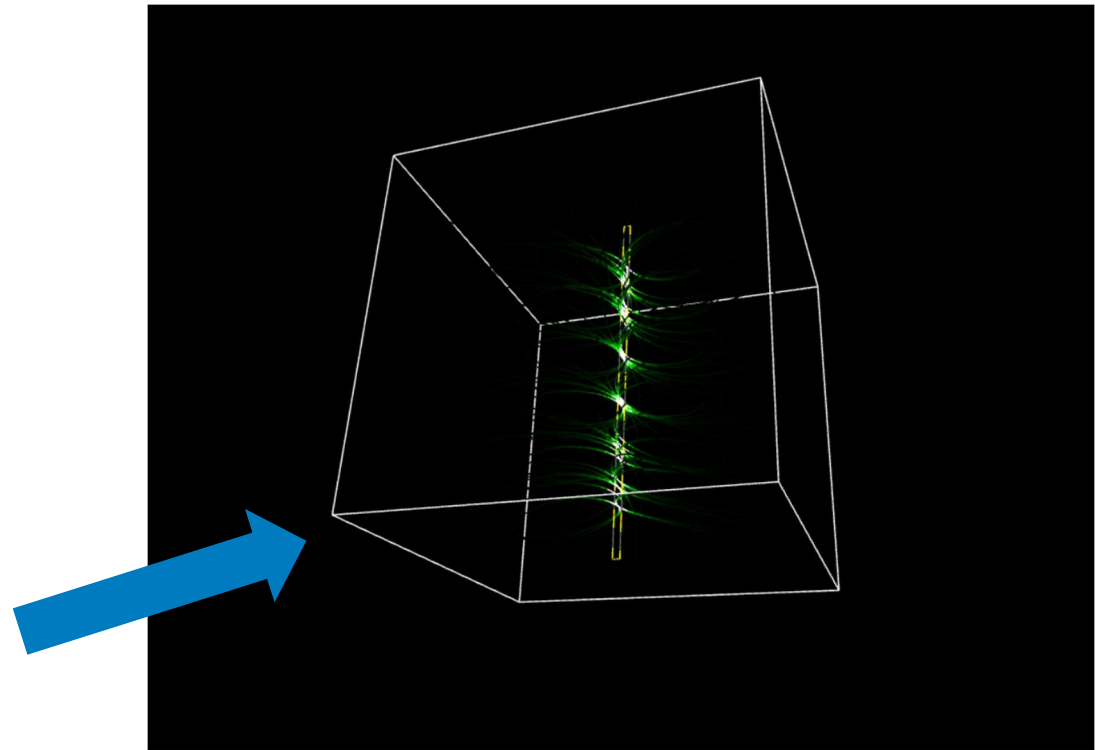


Mitigation Techniques

Hidden Antennas: Loop Antenna

■ Loop Antenna

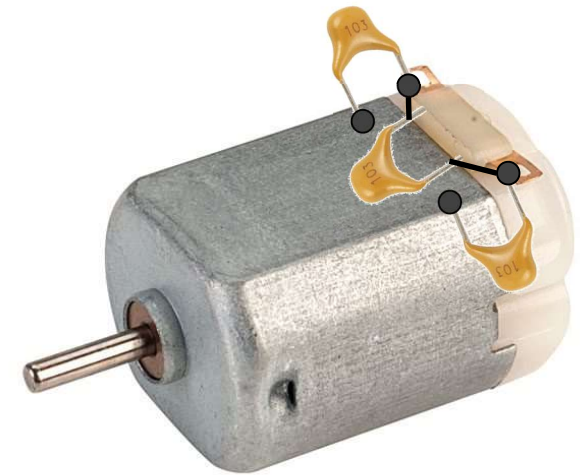
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Mitigation Techniques

Hidden Antennas: Spark Gap Transmitter

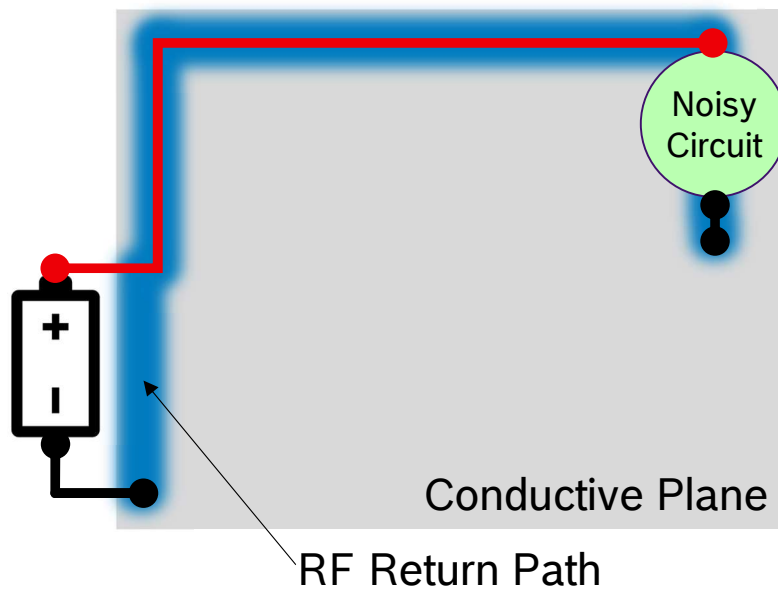
- Spark Gap Transmitter
 - Very first radio transmitter technology
 - Spark allows for very fast transients in Voltage and Current
 - Spark is not necessarily the “source” of the transmission. True source is wires and conductors leading to and from spark location.
- Common Spark Gap Transmitters
 - Ignition Circuits
 - Brushed Motors brush to commutator spark
 - Relays/contactors
 - Coils without Flyback or snubbing circuitry
- How to deal with these sparks:
 - Filtering
 - Snubbing
 - Provide short return path



Mitigation Techniques

Return Paths

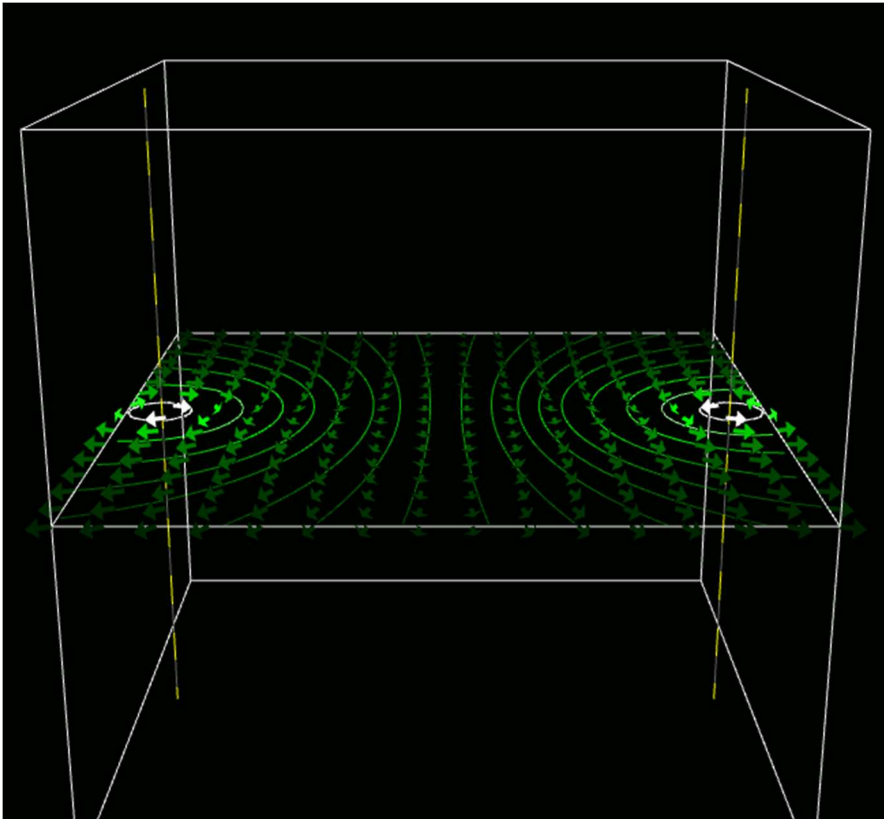
- RF current takes the path of Least Inductance
 - NOTE: this is not the same as the path of least resistance



- For **every** wire and circuit:
 - Identify or provide the return path
 - Twist return path with source path
 - Separate unrelated circuits
 - Don't rely on the frame/chassis as your return path
 - Don't separate power and ground of a device
 - Don't twist noise sources and sensitive signals together
 - Don't break return path
- Example:
 - Twist fuel pump motor wires together
 - Twist fuel pressure sensor wire together
 - Don't twist fuel pump motor and fuel pressure sensor wires together

Mitigation Techniques

Return Paths



- RF current takes the path of Least Inductance
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 - Don't twist fuel pump motor and fuel pressure sensor wires together
- Don't rely on the frame/chassis as your return path
- Don't separate power and ground of a device
 - Twist noise sources and sensitive signals together

Mitigation Techniques

Distance and Separation

- Keep unrelated circuits far away from each other.
 - Example: noisy circuits on left side of car, sensitive signals on right side.
- If they need to get close, route perpendicular to each other
- Place high conductivity and high permeability materials between noisy and sensitive circuits (Shield)

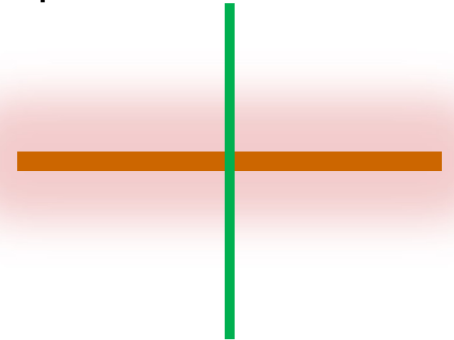
- Parallel → Bad



- Far Parallel → Ok



- Perpendicular → Good



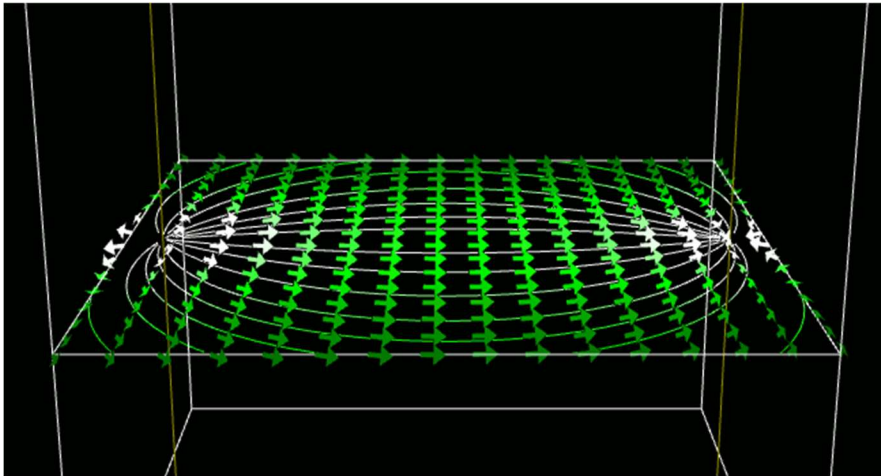
- Grounded Conductive material between wires → Good



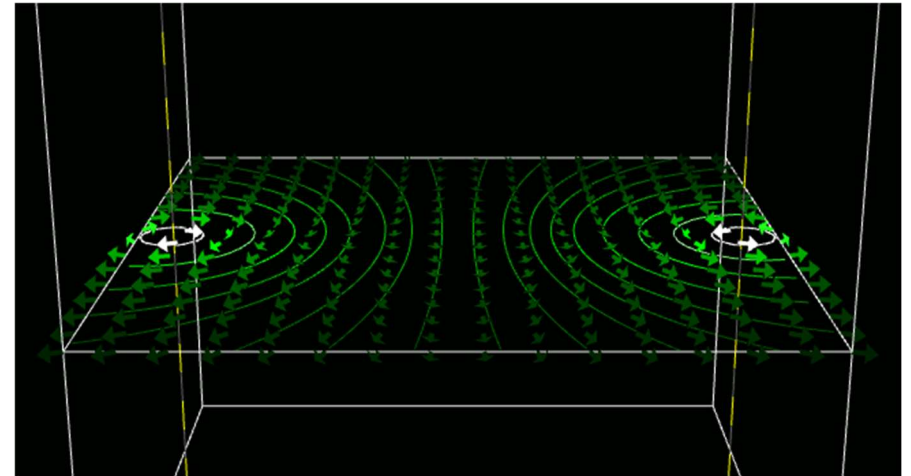
Mitigation Techniques

Reduce The Fields: Proximity

- Reduce fields with an opposing field in close proximity. The closer the better.
 - Twist wires of differential communication busses (e.x. CAN, Ethernet)
 - Twist Supply (e.x. Vbat) and Return (e.x. Ground) wires of devices together (e.x. Motors, ECUs, Loads)
 - Keep HV lines in close proximity to each other



E-Field lines and vectors with opposing voltages at various distances

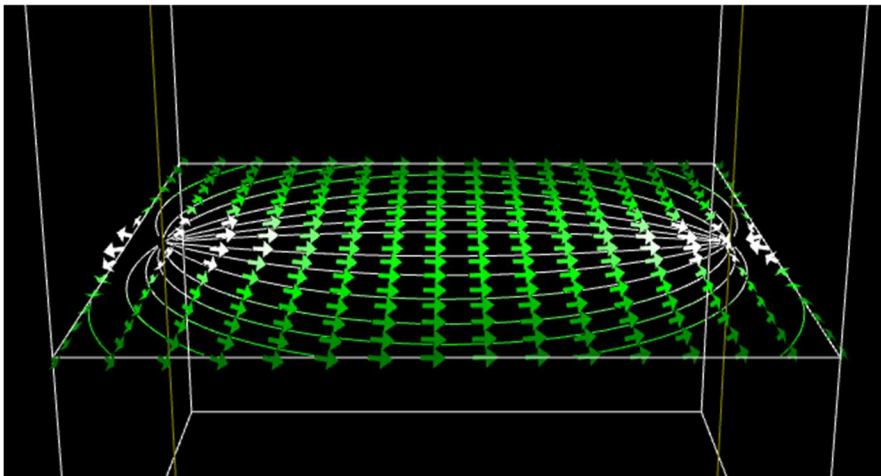


B-Field lines and vectors with opposing currents at various distances

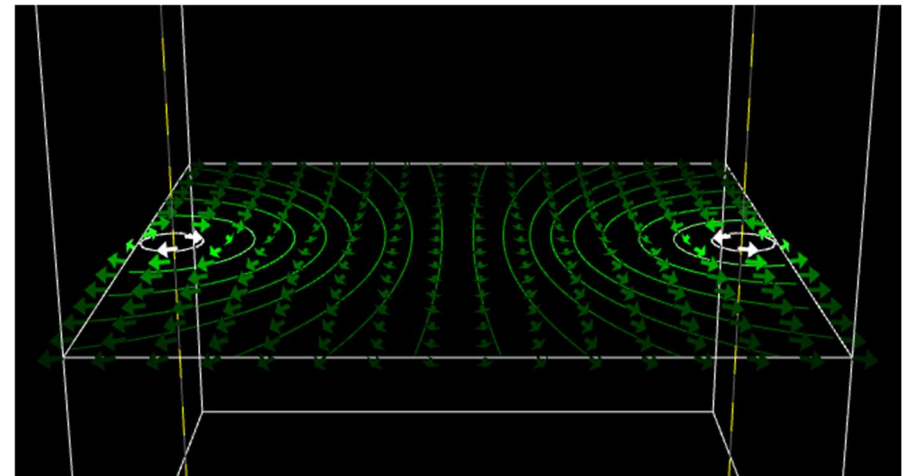
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E-Field lines and vectors with opposing voltages at far distance

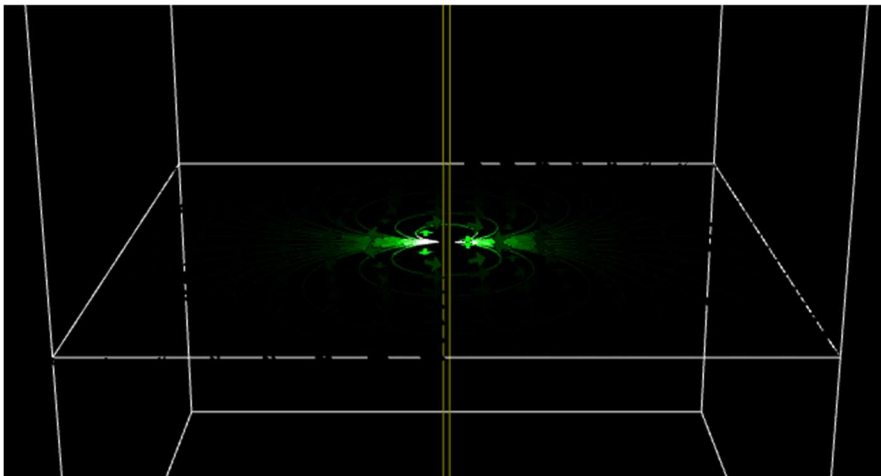


B-Field lines and vectors with opposing currents at far distance

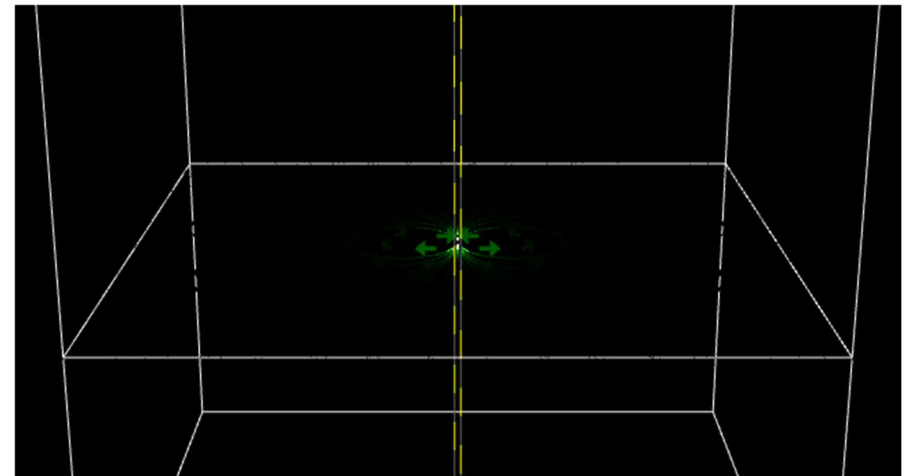
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E-Field lines and vectors with opposing voltages at near distance

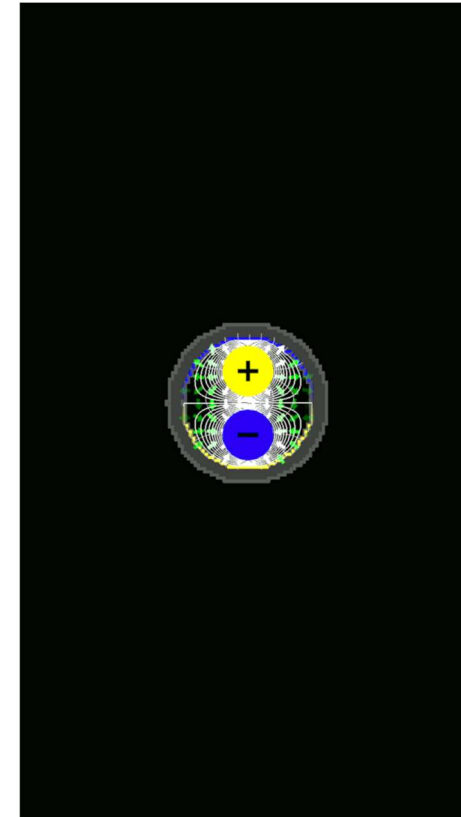
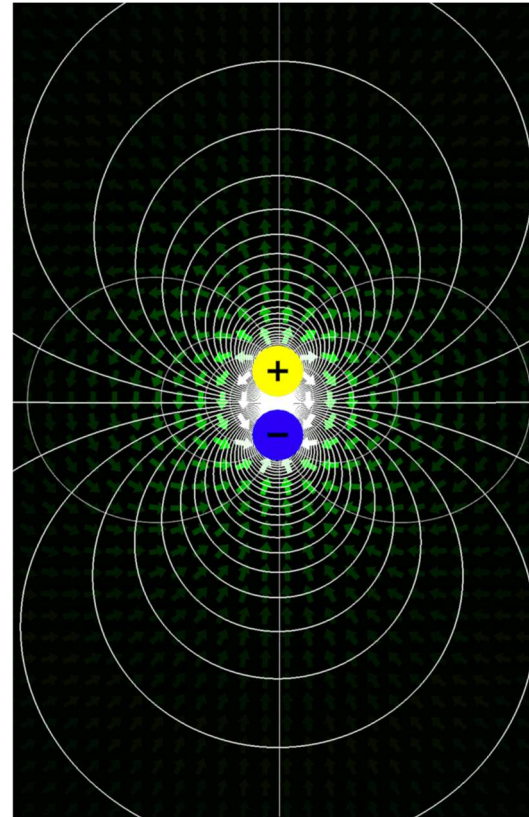


B-Field lines and vectors with opposing currents at near distance

Mitigation Techniques

Reduce the Fields: Shielding

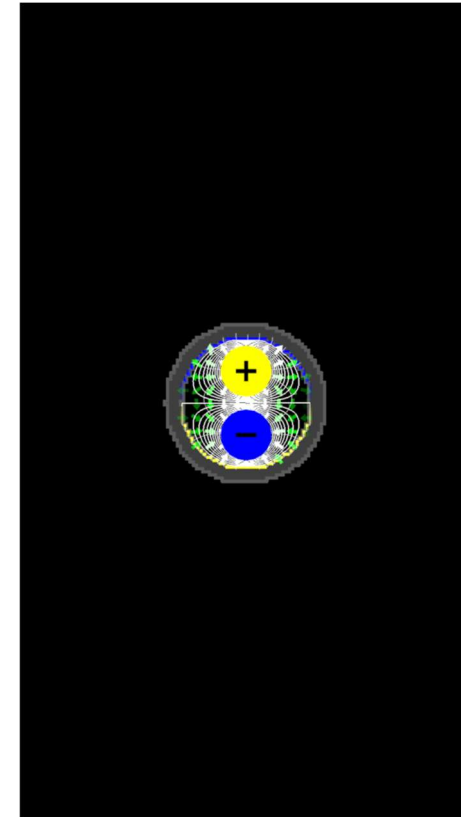
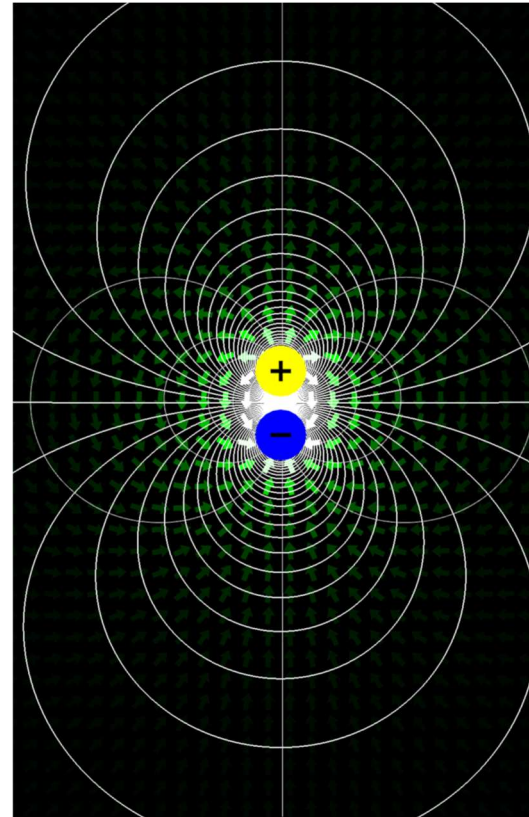
- Shields provide a preferred path for fields to terminate
- High Conductivity shields reduce E-Field
 - Copper ($5.8 \cdot 10^7$ S/m)
 - Aluminum ($3.77 \cdot 10^7$ S/m)
 - Steel ($6.99 \cdot 10^6$ S/m)
 - Stainless ($1.45 \cdot 10^6$ S/m)
- High Permeability shields reduce B-Field
 - Mu-Metal ($2.5 \cdot 10^{-2}$ H/m)
 - Stainless (Varies, only some grades work)
 - Steel ($1.26 \cdot 10^{-4}$ H/m)



Mitigation Techniques

Reduce the Fields: Shielding

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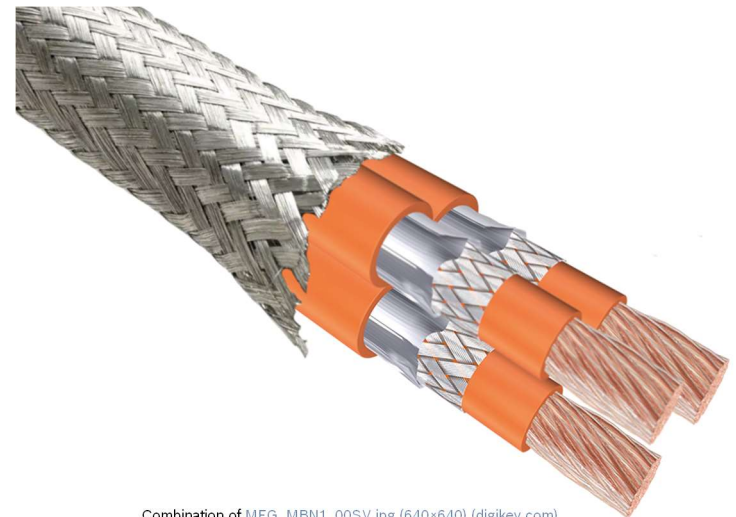


Mitigation Techniques

Reduce the Fields: Shielding

- Conductive shields commonly made from braided copper, aluminum, or aluminized mylar (or some combination)
- Terminate with low impedance to Ground
 - HV Shield terminations should be $\ll 10\text{m}\Omega$!
- Do not create openings in shields.
 - Openings create slot antennas
 - Beware of the back of connectors
 - Beware of poorly fitting lids and cable exits
- Shields are not perfect:
 - Shields will carry currents induced by E-field.
 - Currents will create a voltage across shield impedance.
 - Voltage on shield radiates

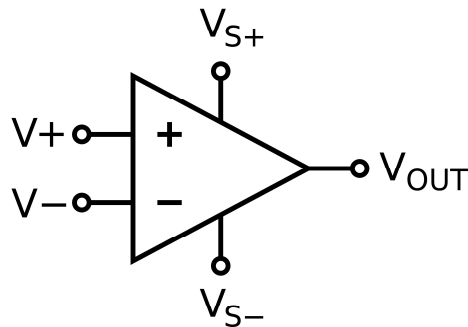
- HV EV and HEV vehicles:
 - Use Shielded HV cables.
 - Place additional Sum Shield over all 3 phases of HV Motor leads to capture shield leakage
 - Might also consider Sum Shield over HVDC wires



Mitigation Techniques

Twist sensitive wires

- Averages noise induced by external field into both signal and return path
- Makes noise “Common Mode” on signal and return. Noise mitigated with differential amplifiers, common mode chokes and cable ferrites



[Op-amp symbol](#) By Omegatron - Own work, CC BY-SA 3.0

- Untwisted
 - Noise couples into Green more than Yellow. Differential signaling amplifies noise with signal



- Twisted
 - Noise couples evenly (same magnitude and direction) into both Green and Yellow. Differential Signaling ignores the noise (within limits. Might need additional mitigation)



Mitigation Techniques

Clamp on Ferrites

- Can work on Common Mode Currents
 - Adds inductance to common mode currents



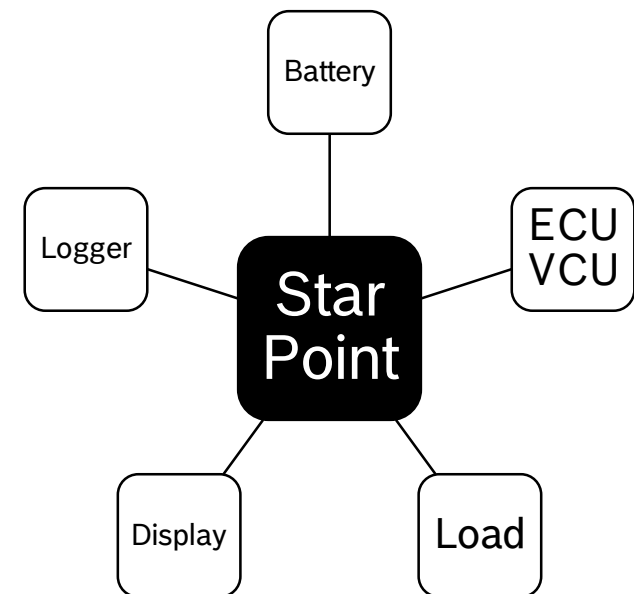
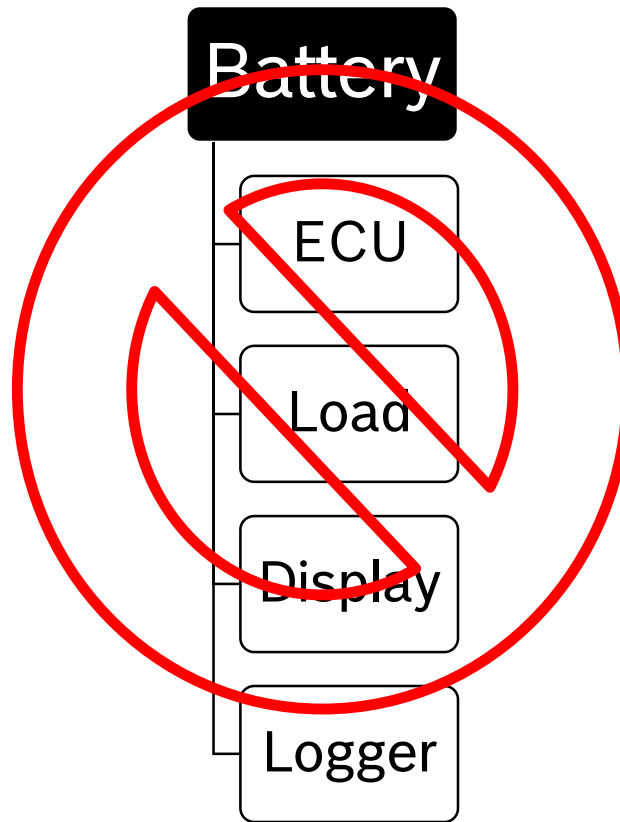
Ferrite clamp-on by Karl-Martin Skontorp is licensed under [CC BY](#)

- Some Considerations:
 - Must be matched to the frequency of the noise
 - Materials
 - Geometry
 - Can be saturated (ineffective) if current is too high
 - Often bulky and heavy
 - Does not work on differential currents
 - This property can be useful in troubleshooting if noise is differential or common mode

Mitigation Techniques

Star Point Ground

- Do not Connect signal and power grounds together
 - These should be connected inside your ECU/VCU if they are connected at all
- Connect Grounds for different devices at one location, that Star point



Summary

Summary

EMC

- Source → Path → Victim
- Radiated → through Fields
 - E-Field → Related to Voltage
 - B-Field → Related to Current
- Conducted → through Wires
 - Common Mode
 - Differential
- Edge Rates
 - dV/dt or dI/dt
 - Lower is better
- Beware of unintentional antennas
- Mitigation techniques
 - Reduce loop area
 - Identify source and return paths
 - Twist source and return together
 - Separate non-related circuits
 - Twist sensitive circuits
 - Shield Noisy circuits from sensitive circuits
 - Bond shields well to Ground
 - Beware of slot antennas (gaps in shielding)
 - Use clamp on ferrite for common mode noise

Summary

What not to do:



[image5.jpg](#) by Pat Clark of FSAE vehicle wiring from article "[Pat's Column - Relay Racing](#)", circa 2009.04.14 used under Fair Use for educational purposes