NOTE: This is an incomplete paper without citations, but I hope it will serve as a useful reference to some.
It has also not been revised or proofread, so I apologize in advance for errors.

“Designing for EMC” is a topic I researched for my own enjoyment while I was designing circuits for SPIRIT 3, a corporate/university-sponsored project to develop an experiments payload for an atmospheric rocket.

EMI Susceptibility of Electrical Systems

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By definition, a system is electromagnetically compatible (EMC) if it is not susceptible to interference from itself or other systems, and if it is not a source of interference to other systems.

Methods of EMI Transmission

1) **Common Impedance Coupling** can occur between any two electrical circuits that share a common impedance (conductor). The current from each circuit contributes to the voltage drop across this shared impedance, so a change in the current from one of the circuits would have a direct impact on the voltage drop seen by all the rest of the conductor. This problem is most often encountered in systems with shared ground busses.

2) **Magnetic Field Coupling** results from mutual inductance between two or more conductors. The current through each conductor creates a magnetic field that can induce currents in other neighboring conductors. This is a big factor of loop area and inductance.

3) **Electric Field Coupling** results from mutual capacitance between two or more neighboring conductors. Their interacting electric fields create a differential voltage between them causing crosstalk. Capacitance is proportional to the shared area between the conductors, and inversely proportional to the square of the distance between them. To reduce this effect, minimize the length and size of conductors, and do not place conductors too close.

4) **Far-Field Electromagnetic Radiation Coupling** describes the transfer of noise between a source and receiver separated by at least 1/6th the noise wavelength.

The physical placement of components and traces is a key factor in determining the board's electromagnetic compatibility, especially regarding its near-field coupling, its emissions and susceptibility. There are many conventions that can be followed to ensure a design is EMC. Not all can be implemented for one board. Weigh your options and prioritize according to your project needs.

Areas that affect EMC

1) Distance between source and victim
2) Effective pick-up loop area
3) Quality of transmission conductors
4) Quality of power distribution system
5) Shield between source and victim

The first factor to be considered is the distance between the EMI source and a victim. If a board is to support circuitry of extreme signal differences, the stages should be organized according to signal speeds and intensities. Avoid routing susceptible signals near excessive EMI fields.

Another important issue is the effective area enclosed by the current loops of the electrical system. EMI fields passing through this area cause a magnetic flux that induces current within the loop. Reducing this loop area will reduce the EMI fields passing through it, and thus weakening the induced EMI current. Loop area is often reduced by routing power and return conductors next to each other, or by using twisted pair.

The quality of electrical signals are only as good as the lines on which they are transmitted, so signal traces should be designed to minimize length, bends and turns, and overall impedance. Shorter conductors are less susceptible to field coupling and are less resistive than longer conductors. Minimal conductor bends reduce unnecessary inductance of the line and improve signal transmission (especially at high frequencies). In addition, high speed transmissions are also improved when the conductor surface area is maximized to reduce skin-effect.

Another important aspect of signal transmission is the power distribution system; EMI on the power or return conductors will likely be imprinted within the load circuitry. To reduce susceptibility, the power and return paths should be of minimal length and should be routed together, either alongside one another or in a twisted pair cabling. Susceptibility can be further reduced by dividing the power loop area with bypass capacitors.

Finally, when all areas have been considered, EMI transmission can be reduced by placing a shield between the source and the victim. The function of a shield is largely based on the behavior of a wave when it encounters a boundary between two medium. By enclosing a space in a seamless conductive layer, much of the electromagnetic wave's energy will be reflected, and the remaining energy will be transmitted to the new medium (shield).

1) Distance between Source and Victim

Conductors carrying dramatically different signals along with related circuitry should be separated as much as possible, and when considering signal types, they can be grouped according to relative amplitude, frequency and function.

- DC Power (mA to A)
- Low-Level Analog (µV to 2V typical)
- AC Power (50Hz to 60Hz)
- Digital (±5V to ±15V, DC to GHz)
- High-Level Analog (5V to 50V typical)

Now, considering their signal type, they can be grouped according to their emissions and susceptibility to emissions. Due to their dramatic differences, it is easy to see that the low-level analog signals are most susceptible to emissions, closely followed by the DC power. Signals in these two categories would likely fall victim to the radiation of other systems. AC power, on the other hand, is often a source of radiant energy, and is similar to high-level analog. Finally, the sharp transitions of a digital square wave make it a powerful source of high frequency noise in nearby components. If possible, signals that source emissions should kept at a distance from the susceptible signals to avoid cross-talk.

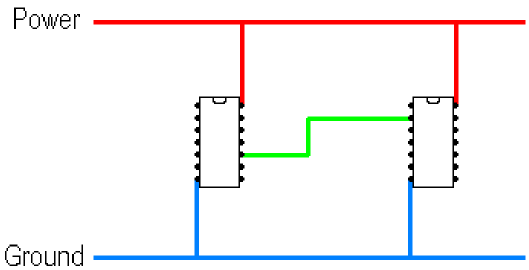
This concept is also applied to the processing circuitry for these signal types. They should be separated according to the above descriptions.

2) Effective pick-up loop area

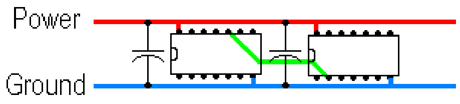
According to Faraday's Law of Induction, a changing magnetic field through a conductive loop induces a current in the loop. We also know that in a changing magnetic field, the magnitude of induced current in this loop is a factor of the loop area. This effect can occur within any circuit loop, and must be minimized to avoid EMI.

To minimize loop area of conductors, twisted pair reduces it to near zero. This technique has been employed by phone companies for decades without need for further noise reduction circuitry.

When routing a circuit over a distance, the loop area can be obviously minimized by keeping the two sides of the loop as close as possible. This can be employed with power cables and the power and ground conductors on a circuit board.



Large Pick-Up Loop Area



Small Pick-Up Loop Area

Decoupling capacitors can also be used to divide the effective loop area. Placed at the power terminals of components, they act as a low impedance return path for high frequency signals that could be induced on the power loop.

3) Quality of Transmission Lines

The purpose of an electrical transmission line (conductor) is to carry energy from one point to another with minimal losses and minimal signal degradation. The efficiency of transmission lines can be easily compared according to their impedance, as characterized the following equation:

$Z= \sqrt{(^{R+jwL}/_{G+jwC})}$ ohms

An ideal transmission line has zero resistance, zero impedance, zero inductance, and zero capacitance, so all signal energy is transmitted. These ideal conditions are unattainable in reality, but certain conventions can be followed to maximize signal transmission.

The undesired capacitance of a transmission line is usually not a concern unless a high potential difference exists between it and nearby conductors. The electric fields formed by these two conductors allow their voltage fluctuations to influence each other in a form of EMI known as cross-talk. This condition becomes increasingly destructive as the frequency of the higher voltage conductor increases.

The capacitance (and electric field) between two conductors is proportional to their shared area and inversely proportional to the distance between them. This means that the flat design of circuit board traces helps to reduce E-field coupling among conductors in a plane by minimizing their shared area. However, when conductors are in different planes of a multi-layered board, the shape of these traces can cause a large shared area. Fortunately, ground planes can be easy implemented into multi-layered boards to shield the interacting conductors from each other.

A conductor’s inductance is a strong factor of its length and its degree of curvature. This undesired inductance is negligible in most applications, but it adds to the already high impedance seen by high frequency signals. Another high-frequency concern is the internal inductance of the transmission line.

Within a solid conductor, inductance increases as you move toward the center axis causing the impedance to increase as well. This creates greater impedance at the center, forcing high frequency currents to travel near the conductor’s outer edge (skin effect), and thus degrading their transmission. To improve performance, use lines with a high ratio of surface area to volume, like braided copper or the flat traces of a circuit board, and avoid unnecessary bends and turns of traces. This is one of the reasons for coax cabling of TV signals and antenna connections.

Maximize the copper surface-area of the ground plain

Unused portions of the ground plane should be filled with copper to lower the return impedance and to spread out the return current. Spreading out the ground current reduces the current density and thus reduces the electric field coupling that causes cross-talk (since the large return currents often act as the source of noise coupled onto low-level signals in the circuit). This technique is known as “ground filling,” and is usually performed after all other traces have been mapped.

4) Quality of power distribution system

One of the most critical components of a system’s EMC is the quality of power distribution. This area is the leading cause of common impedance coupling because it’s the conductive loop that all subsystems share. There are a few conventions to consider when designing a stable power distribution:

Within a circuit board or subsystem

1) Provide multiple paths of varying lengths for return currents on a circuit board(ground plane, grounded grid, ground filling)
2) Provide multiple paths of varying lengths for power currents (power plane, power grid)
3) Use bypass capacitors to decouple high frequency noise at various points along the power loop

Provide each subsystem or circuit board with a single path from the power supply to the star ground reference.

1) Avoid ground loops
2) Use bulk capacitors at the power entry point of distant subsystems or circuit boards

A good DC power distribution layout has minimal impedance, minimal loop-area, minimal inductance, and maximum capacitance.

Providing circuit board components with multiple return paths is a good method of increasing EMC. Besides lowering the overall distribution impedance, it also minimizes current density through the conductors which intern minimizes their radiated field strength. Another benefit is that components have multiple distances to travel to ground, thus reducing effects of standing waves.

There are a few common layout techniques for circuit board power distributions. They depend mostly on the type of circuit board used.

To keep the impedance low, components should be provided with multiple return paths to distribute their current and to keep current density low.

layout provides components with multiple paths to ground so they can naturally lowest impedance

Within a Subsystem or Circuit Board

The Power supplies can be the source of much instability in poorly designed layouts. Stability of the power bus is essential to EMC since it’s the current loop that all components share. The power distribution can be stabilized with many different methods, but they all help to do two things: 1) reduce transmission line impedance, 2) reduce effective pick-up loop area.

The impedance of a transmission line is described as: $Z= \sqrt{({}^{R+jwL}/_{G+jwC})}$ ohms. This equation implies that impedance can be reduced by decreasing the inductance and increasing the capacitance of the power bus. The following are possible solutions. The inductance of a transmission line is a strong factor of its length. Minimizing wire/trace lengths and component lead stand-off is helpful in reducing the transmission loop. Another way to lower inductance is to provide multiple paths for return current.

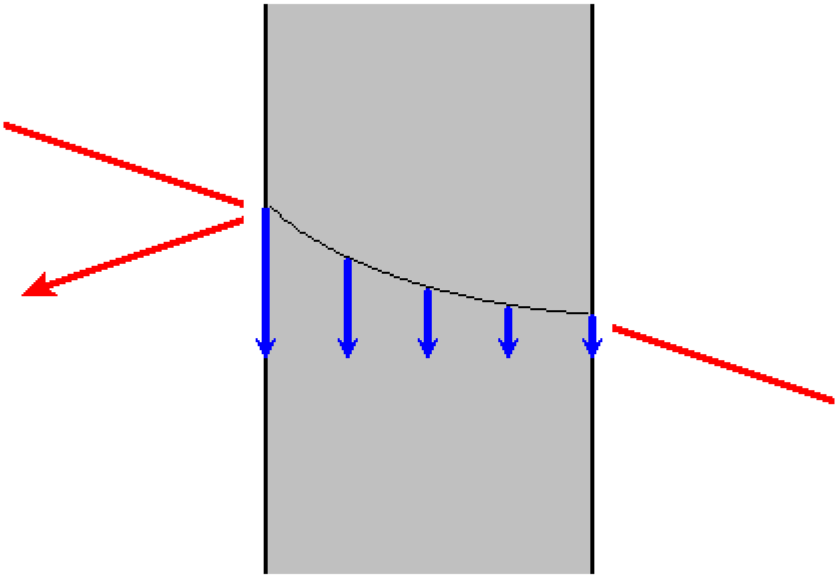
5) Shield between source and victim

The concept of shielding is best introduced with a description of the associated waves. Every electromagnetic wave is composed of two oscillating fields: electric and magnetic, located on perpendicular planes. Together, these two oscillating fields create the electromagnetic wave.

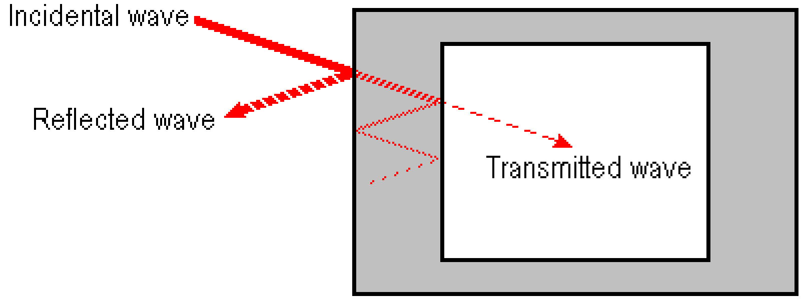
An important property associated with electromagnetic waves is the impedance they create in their environment. ZW, known as the wave impedance, is the ratio of the electric field intensity (V/m) to the magnetic field intensity (A/m) of a certain point in space. This value is typical a constant 377 ohms, but in the space near the source, ZW can be a range of values determined by the I-V properties and frequency of the source. The behavior of this property, as a function of source proximity, creates two spatial regions for analysis: The Near-Field and the Far-Field.

The Near-Field describes the area around an EM source, of which the wave impedance is determined by the properties of the source. For an EM source oscillating at a given frequency, the near field is the area enclosed within 1/6 of a wavelength from a source, beyond which ZW is constant. A low-impedance source (high I, low V) emits strong magnetic fields so its near-field ZW is low (less than 377). Similarly, a high-impedance source (low I, high V) emits strong electric fields so its near-field ZW is high (more than 377).

The Far-Field (or radiation field) includes all space beyond a source's near-field and is characterized by the constant wave impedance of 377 ohms. Here, waves are seldom analyzed by their electric and magnetic fields, and are often termed as radiation.



As stated previously, the function of a shield is largely based on the behavior of a wave when it encounters a boundary between two medium. Physical laws explain that the amount of energy reflected depends on the magnitude of difference between the two medium. With regards to electromagnetic waves, reflected energy is determined by the magnitude of difference between their impedances. By using a conductive shield, we are creating two impedance boundaries between the source and victim.



Electromagnetic Radiation Through A Shield

Provide multiple paths for return current

Traces and wires carrying dramatically different currents should be separated to reduce cross-talk. When considering signal placement, you can break them into two groups:

1) Signals susceptible to radiant emissions. (Low-level analog, DC power)
2) Signals that are a source of radiant emissions. (Digital clock, high-level analog, AC power)

The first and most destructive noise problem is that of common-impedance coupling. Ideally, the impedance Z of the power distribution system should be zero, so that all elements get the same supply voltage and no power is lost on the return. In reality, however, our real-world components prevent us from achieving such ideal conditions, so we must aim for minimal impedance to reduce the systems susceptibility to noise.

The characteristic impedance of a transmission line shows that a low impedance power distribution would imply minimal inductance and maximum capacitance. Inductance is a strong factor of wire length, so all traces should be as short as possible to provide the quickest return path. In addition, the power and return conductors should be mounted as close as possible to minimize the effective pick-up loop area. Bypass capacitors can also be used to minimize the effective loop.

The electrical properties of a capacitor work to prevent sudden changes in the voltage, by responding with either a depletion or accumulation of charge on the plates.

As discussed earlier, the goal of DC power distribution is to provide a consistent supply voltage to the necessary components on the board with a consistent supply voltage to the necessary components with

The noise problems mentioned above must be considered during the circuit layout design, so that stabilizing solutions can be implemented appropriately.

Perpendicular Capacitor/Inductor

Capacitors and inductors should be positioned perpendicular to each other to prevent mutual inductance between the inductor and the leads of the capacitor. If positioned along the same axis, the capacitor's leads would be immersed in the coils magnetic field, inducing a mutual response. To avoid this complication solder all components flush against the board