APPLICATION NOTE:

# EMC BEST PRACTICES - PART I

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# EXECUTIVE SUMMARY

This article is intended to allow the reader to assimilate and apply some useful design concepts associated with EMI for hardware-based project development.

As such, this treatment is divided into two parts. Part I describes the physical processes associated with electromagnetic interference generation. This leads to outlining recommended practices in part II of this series of application notes based on these processes.

# INTRODUCTION

We learned a lot about the art of electrical engineering through the medium of circuit schematics. Zero-volt earth returns, equipotential surfaces, and single-point grounding were concepts explained to us early on. These things came from various sources that I got introduced to as a student and later followed as an electronics engineering graduate. Fortunately, as I got to learn more, the blinders came off: I realized after quite some time, particularly as one became acquainted with RF and microwave electronics, that you must build systems that acknowledge the real physical properties of the components and assemblies that they are composed of.

The discussion starts from this viewpoint. The novel treatment here should allow the audience to readily associate what happens at very high frequencies with the consequences of adopting certain components, board layouts, module connections, and installation choices.

We look at specific themes that allow you to make designs that are EMC-oriented, irrespective of what part of the process you are concerned with. It is impossible to describe all the best possible ways of introducing EMC control measures, so a few examples of best practices are shared in the second part of this treatment - ranging from the circuit-board level to the integration of a complete system of “modules” within some kind of enclosure.

# BACKGROUND

Nobody (that I know of) likes environmental pollution. We try to avoid it if possible and mitigate its adverse effects on the quality of life using measures that sometimes involve high economic costs. Although we are generally unable to gauge its effects directly, the electromagnetic signal “space” that is manifested in the electromagnetic frequency spectrum is congested, with all kinds of signals and noise produced and propagated in the space that surrounds us. The message here is that the RF spectrum is already heavily polluted. The possibility of this energy affecting or being augmented by electronic products is now receiving ever more attention from the government and authorized international and regional bodies concerned with its regulation.

Many decades have passed after the coining of Moore’s Law, which focused on predicting the doubling of the number of devices that might be integrated into a single semiconductor die every two years. Along with the miniaturization of electronic functions has come the ability to speed things up. It is possible to establish reliable electrical digital data transmission rates of 10 Gb/sec over 100 meters, a benchmark that will no doubt be surpassed in short order.

EMI efforts were spearheaded in the industrial-military complex in the United States in the 1960s due to the need for various C3 (command, control, and communications) systems to operate successfully in the presence of radar transmitters delivering high levels of RF energy within the local environment: A common issue shared in land, sea, air and space warfare settings. Although the impetus to develop control measures against EMI came from this rather specialized application space, it is now the commonplace control regimen of industrial, commercial, and domestic settings. Standards now apply to these scenarios as well: They are well-established, legally binding norms that all designers need to be aware of.  The challenge of reducing a product’s ability to produce or to become affected by electrical noise is called EMC (electromagnetic compatibility). EMC is the ability of electronic systems to work in a noisy environment, in the presence of other appliances, without causing excessive EMI (electromagnetic interference) or becoming a victim (i.e., susceptible) of electronic noise emissions, irrespective of their nature.

The management of high-energy transients comes under the EMC remit. These transient upsets are induced by naturally occurring events, such as lightning, from normal operations, such as switching or relay activation within a power network or appliances, and from disturbances on the AC mains or other affected cabling used to channel power and data for an appliance.

# EFFECTS AND OBSERVATIONS

A typical design will be described at its highest level of hierarchy with specifications that contain block diagrams. Using these, engineers draw up component-level schematics for the physical electric networks.

Circuit schematics are an abstraction of the real networks of components and their connections: essential, they are pictures of circuits that spare overloading a reader with what might turn out to be important details because of the need to keep things simple. To raise awareness of this dichotomy between the concept and its physicality, several themes are raised in this first article to remind readers of the issues that relate to mitigating EMI and promoting EMC.

***Theme #1 – Real components, including wires and circuit board traces, are not ideal in practice. There are other electrical characteristics besides the desired property that are an integral part of those elements.***

# DC ELECTROMAGNETICS

To fill out the understanding behind theme #1, let's examine a piece of wire. Besides a vanishingly small amount of DC resistance, it has the capability of storing energy in what is called an electromagnetic field. As the name suggests, this is a combination of electric and magnetic fields that are linked to the conductor: When you pass an electric current through a wire, a magnetic field made up of closed, concentric loops of 'magnetic flux' results. It surrounds the entire length of the wire and moves out into the space around it. Creating this field involves the flow of electric charge: The physical work of moving the charge is translated into this magnetic field that "grows" around the conductor as current is established within the wire. The presence of the magnetic (H) field is demonstrated with the use of iron filings (which act like miniature magnets), as shown in Figure 1. If the DC current direction in the wire is changed, the direction of the imaginary magnetic flux lines changes, as shown in Figure 2. A magnetic field always exists in partnership with an electric (E) field when the charge is moving. The electric field geometry depends on the position of the conductor in relation to other objects - see Figure 3. Even when there is no current, a conductor can retain charge at a certain voltage. The electric field retains energy as work has been done to move charges into certain positions in this system. The property linking current in a conductor to its magnetic field is quantified by its inductance. Capacitance is the property of storing electric charge. Bear in mind that the E (electric field) and H (magnetic field) are always present together when current is present in a system.

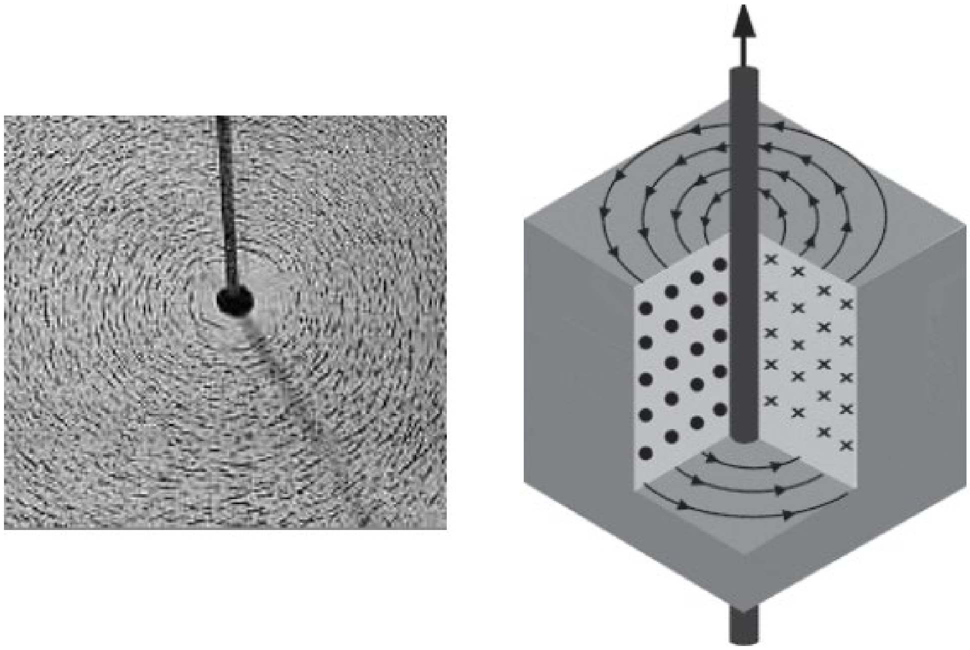


**Figure 1 - Left-hand view shows a vertical non-magnetic wire transporting DC current. The wire passes through a flat piece of card onto which small iron filings have been sprinkled. These iron particles are seen to 'react' to a static magnetic field present around the conductor. They align with magnetic 'flux' – note that the loops are concentric. In the right-hand view, dots (arrow points) are used to show magnetic flux emanating out of the surface, whilst the crosses (the tail end of the arrows) show flux penetrating into the exposed surface of the volume around the conductor. If current does not flow in a conductor held at a given potential, then the magnetic field disappears, leaving only an electric field. {accr: Researchgate.net}**

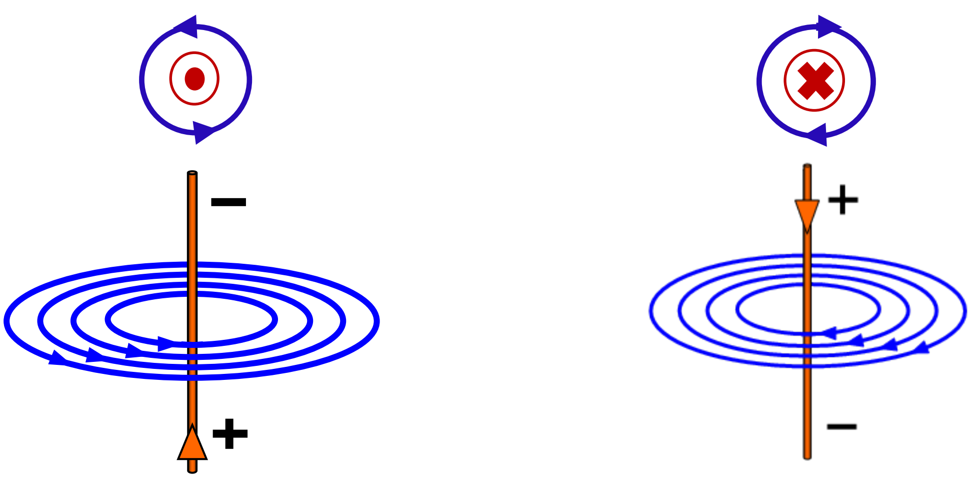


**Figure 2 – Closed loops of DC magnetic flux (in blue) produced by steady current moving from high (+) to low (-) voltage nodes in a wire (red). Currents move in opposite directions in each wire, giving rise to the opposite magnetic flux directions. A standard convention for current and flux direction is shown.**

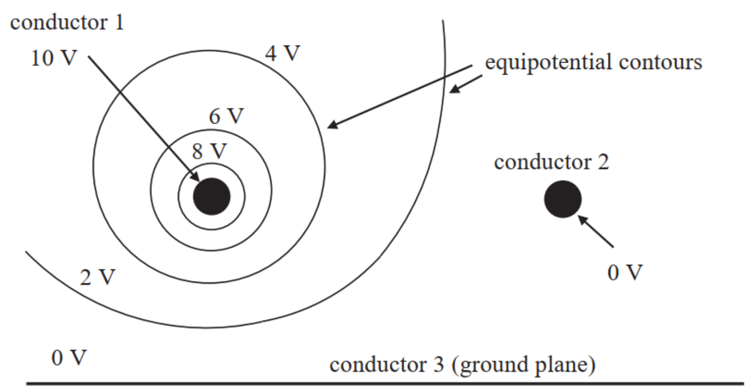



**Figure 3 – DC voltage contours formed in a system of 3 conductors: Conductor 1 has a potential difference with respect to conductors 2 and 3. Conductor 3 is a flat plate in cross-section. Conductors 2 and 3, being at zero volts, are on the same potential contour – there are no contours between these.**

To briefly recap, we have some simple models for fields around a DC-carrying conductor. With DC, electric and magnetic fields are static. When the amplitudes of voltage and current are varied, it is possible to carry all kinds of information in the form of analog (amplitude, frequency modulation) signaling as well as with digital bitstream formats. Changing electrical conditions in and across conductors results in changes in the electromagnetic field – this effect is called *electromagnetic induction*. The central part of this article describes processes associated with conductors that might be carrying signals, irrespective of the origin of these signals.

The reader should be careful to note that the view of fields and the dynamic effects (that are about to be described) associated with power and signal flows within the circuits *do not feature in circuit schematics.*

***Theme #2 - Without a mapping of a schematic to the circuit's physical arrangement, EMI mitigation cannot be achieved.***

# AC ELECTROMAGNETICS

Phenomena associated with changing E and H fields within a wire make themselves evident in a few ways. They become more pronounced with increasing speed of variation, expressed in terms of rates of change of current dI or change of voltage dV within a small-time increment dt as dV/dt or dI/dt.

# SKIN EFFECT

When current varies within a conductor, this results in the appearance of *eddy currents.* These form in conductors with the result that they end up acting against the original change in current. This is a consequence of Lenz's law, which states that *the induced current in a circuit due to electromagnetic induction always opposes the change in magnetic flux.*

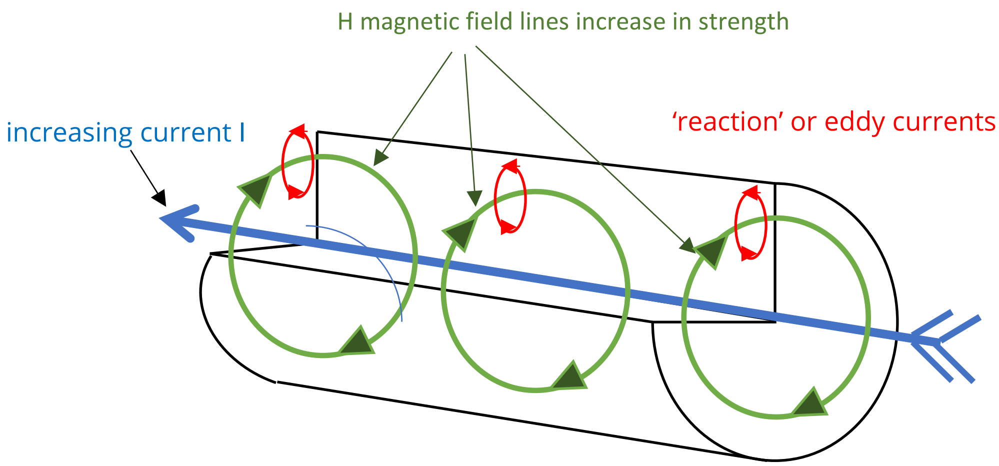



**Figure 4 – development of skin effect in a 'transparent' conductor (an inner face of the conductor is shown, exposed with a top quarter cut out of the conductor)**

Figure 4 crudely shows what is happening in a single wire. A steady current produces H magnetic field loops. A few field loops within the conductor are shown for the sake of simplicity. With I varying (in this case, increasing), the H field increases. Eddy currents appear. They are in loops that are spinning around the H field loops. These eddies orient themselves to *oppose the change* in the H field. The eddy currents - as seen on the exposed section of the conductor – spin anticlockwise. Notice how the eddy and original currents oppose each other inside the conductor's central area but not at its outer edge. The blue arrow for the conductor current clashes with those little eddy current spinners with the red arrows. Overall, the current appears to be diverted out of the central volume, being forced more toward the conductor's surface. Note that the red spinner arrows are running in the same direction as the DC current in the wire away from the conductor's central zone. At very high frequencies, the current runs within a thinning cylindrical annulus, as shown in Figure 5. This crowding of current just underneath the outer surface of the conductor is called *skin effect*.

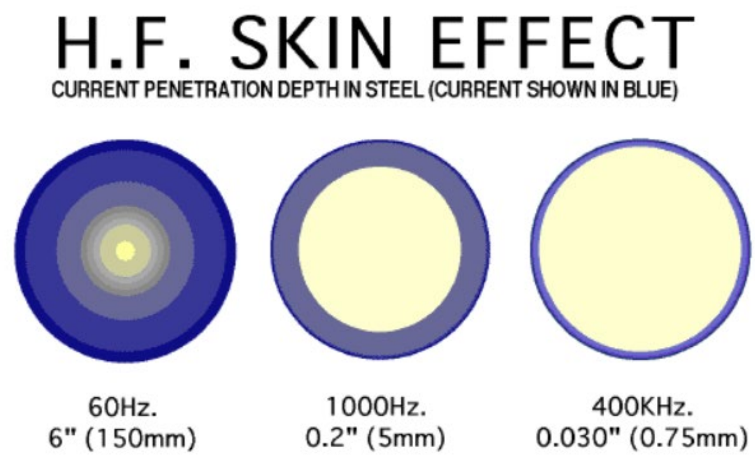



**Figure 5 – Increasing skin effect with frequency in a steel wire's cross section (accrd: Electrical Live *Skin Effect In Transmission Line | Electrical engineering interview questions*). See how the annulus for the current gets thinner and more concentrated at the outer surface of the conductor with increasing frequency of current.**

In what follows, the reader will note that skin effect is complementary in its impact to a phenomenon which occurs when at least 2 conductors are close together. In this case, the conductors are part of a loop carrying equal and opposite currents.

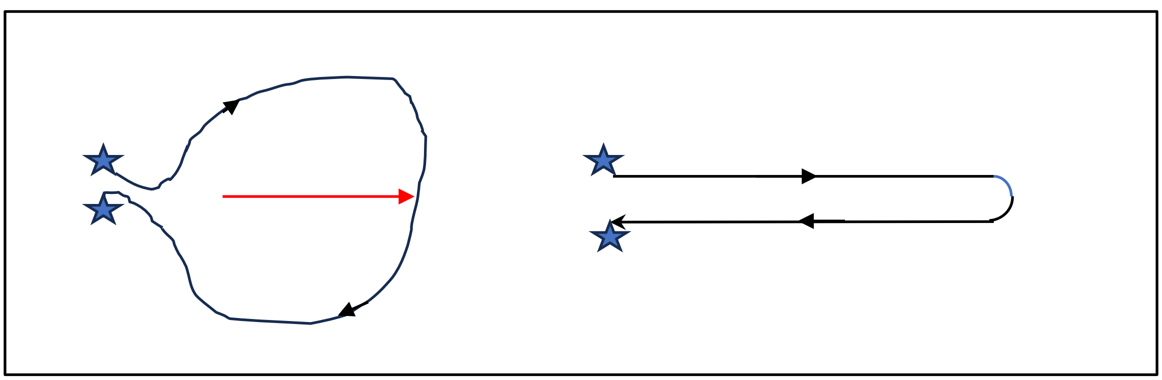


**Figure 6 – A loose partial loop of wire carrying current is pulled against the anchor points (stars) to form a tighter loop with less area within it than before**

# REVERSE PROXIMITY EFFECT

We will investigate this effect in the system of outbound and return conductors that look like the right-hand part of Figure 6. We effectively have not one but two wires, carrying the same current but in clearly defined directions relative to each other. The 'tight' loop has a very small area compared with the 'loose' one.

In the tight loop, the conductors in the pair interact, imposing their H fields on their neighbor. Eddy currents flow in the adjacent conductor in such a way as to counteract changes by the imposed field. Skin effect already acts on each conductor due to its own changing current. Reverse proximity modifies this current channeling effect, moving currents from the far sides of each current annulus normally associated with a single infinitely long current-carrying wire, forcing these currents to run across the inner surfaces of each conductor, as shown in Figure 7.

Figure 8 shows the symmetrical formations of current-carrying areas coming close together within the opposite faces of the pair of wires. The resulting EM field adopts a minimum volume consistent with the conductor geometry, the material surrounding the conductors, and the amount of current being carried in the loop. This is a manifestation of the *reverse proximity effect* as the currents in each conductor are flowing in opposite directions. The *proximity effect* applies to adjacent wires that carry current in the same direction. This effect, just like the skin effect, becomes more pronounced with increasing frequency.

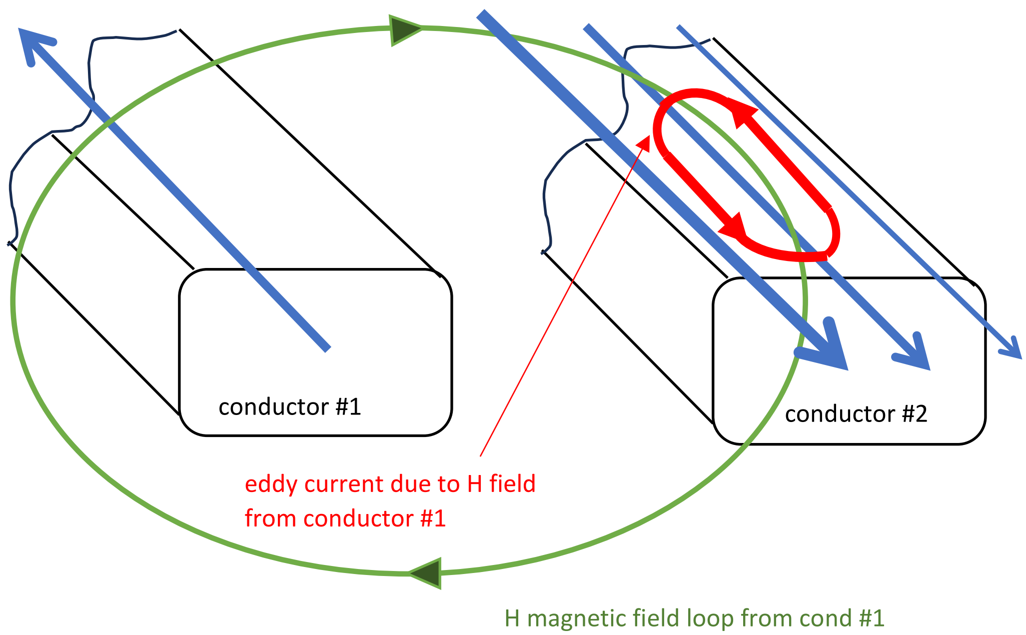



**Figure 7 - Eddy current formation associated with inbound current in conductor #1 in a closed loop conductor pair. Eddy current spin 'strengthens' the inner current component in conductor #2, weakening**

**the outermost current components in that same conductor. This is a simplified view to show the broad effect of reverse proximity.**

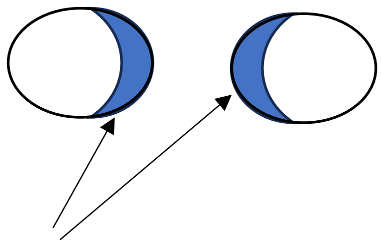


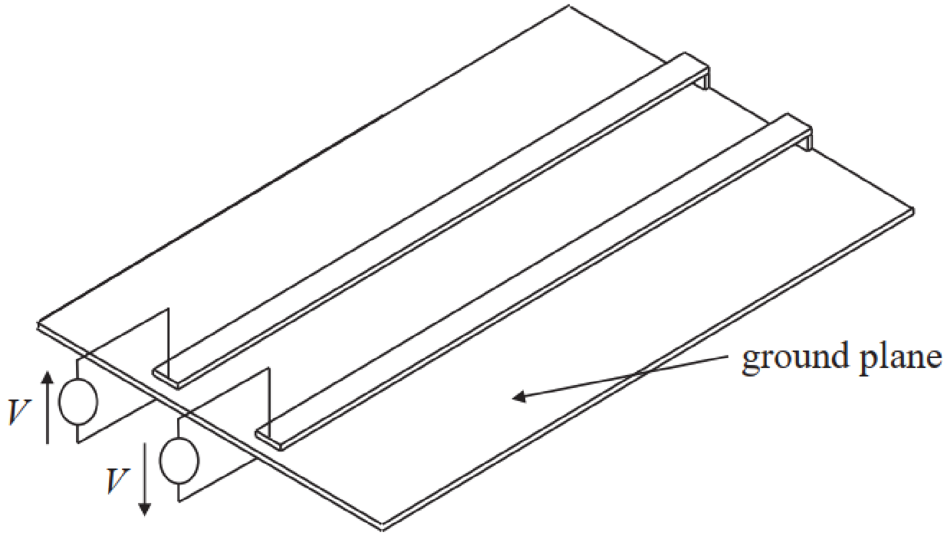

**Figure 8 - reverse proximity effect: the darker areas within the inbound and outbound current conductors represent areas of pronounced current density in the regions closest to the inner surfaces of the wires**

A change of signal in each conductor results in effects experienced in the adjacent conductor. The two wires are, in effect, *coupled* electrically, even though they are not physically connected. Changing currents flowing in the individual wires act on those in their neighbor. The two adjacent conductors are said to have a shared or *mutual* inductance.

***Theme #3 – The frequency of signals determines the way in which current is transported within a host conductor as well as conductors forming tight loops.***

***Theme #4 – By their very presence, conductors in different circuits have the propensity to couple with other conductors that are not physically connected to them due to mutual inductance. The efficiency of this coupling increases with frequency, orientation, and the size of the active and victim conductor loops.***

Besides cylindrical conductors, this effect will be seen in different conducting geometries. A common arrangement seen being used on printed circuit assemblies is shown in Figure 9. Figure 9(a) shows two conductor traces set over a conductive plate or foil, often dubbed the ground plane. Each trace is fed with AC currents that have opposing phases. The traces and ground plane are separated by insulation, called the substrate, which forms the foundation for setting the traces in place. The density of the moving charges is once again seen to be increasingly *localized* within clearly defined areas of the traces, as shown in figure 9(b). Outbound and inbound currents concentrate immediately within the underside of each outbound trace as well as on the top surface of the ground plane.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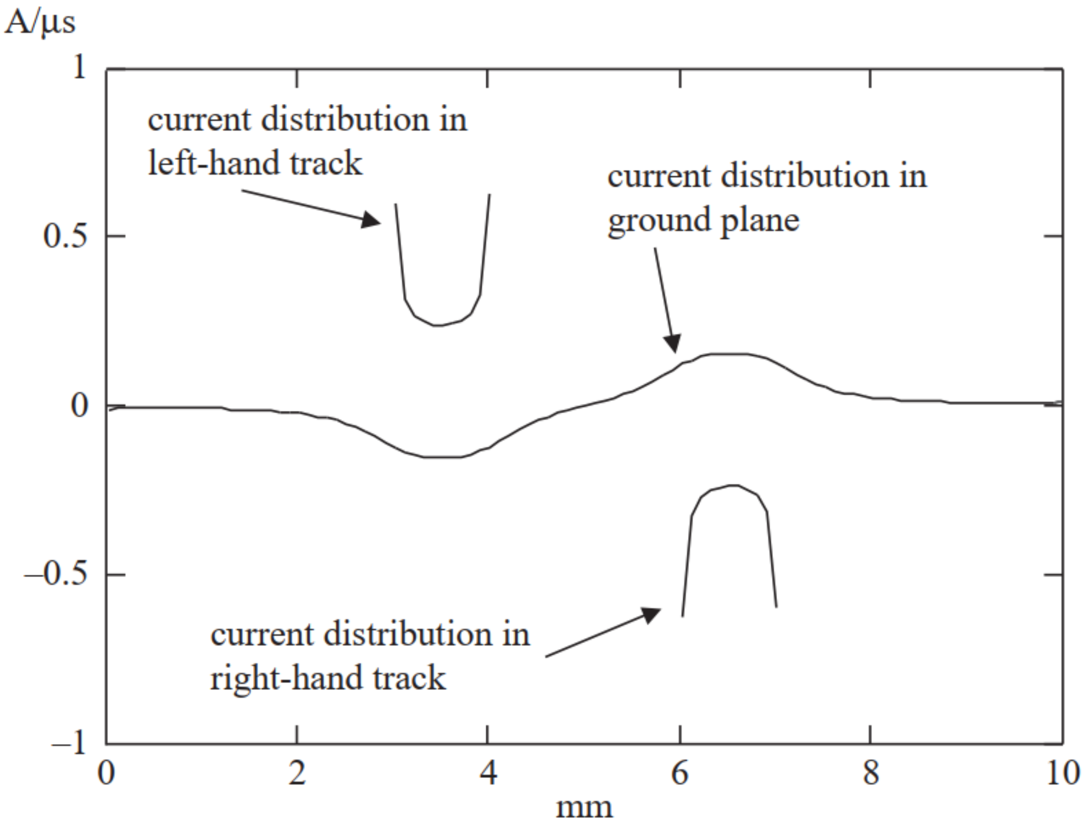
*(a)*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*(b)*

**Figure 9: (a) two printed circuit traces arranged over an insulated ground plane (b) distribution of current within the printed circuit board's cross section [ref 1]**

At high frequencies, return signal current pathways mirror those of the outbound traces when a conductive plane is installed close to the trace. This is the minimum conductive path length for the AC current.

In a complex circuit in which several different traces are co-located to such a ground plane, the ground plane accommodates many ground loops of minimal cross-section.

If there is a break in the return conductive ground path, this effectively opens up the 'tight' loop. This larger loop is able to propagate its AC magnetic field through a larger space. This excess energy propagating into the surrounding space will couple into any other conductive loops. Being able to radiate energy, this large loop is an efficient RF antenna, allowing it to both send and receive EM field-borne noise.

***Theme #5 – Every power or signal trace should have a continuous ground plane return or an adjacent return conductor situated close to it, thereby forming tight loops***

It is vital to maintain the continuity of conducting power and signal pairs. The effect of opening the space between the inbound and return conductors is that this system can propagate signals due to the expanded loop or "window" that the EM field is allowed to penetrate. It is as if a sail that had been rolled up against a mast on a boat has been unfurled to catch the wind - The bigger the sail is, the stronger its effect is on the boat's motion.

# CONCLUDING REMARKS

Outlined here were fundamental aspects of the physics of transporting electrical energy both in DC and AC forms in conductors. These mechanisms have an impact on notions of real circuit action that go beyond a schematic view of circuit function, and these need to be carefully considered.

To help simplify the process of developing remedial measures against EMI, several themes have been declared. In part II, the reader will see the problems of traditional circuit implementation arrangements highlighted by the application of these themes.

Part II will describe certain critical areas of a system that need consideration. There, the reader will also find illustrated some useful strategies at circuit board, system integration, and enclosure design levels of oversight that will promote EMC and mitigate EMI.

# REFERENCES

[1] Circuit Modeling for Electromagnetic Compatibility, Ian B Darney 2013 pub Scitech ISBN 978-1-61353-028-3

[2] Circuit Designer's Companion, Peter Wilson 4th Edition 2017 pub Newnes ISBN 978-0-08-101764-7

[3] Electromagnetic Compatibility Engineering, Henry W Ott 2009 pub Wiley ISBN 978-0-470-18930-6

[4] Grounds for Grounding, Elya B Joffe & Kai-Sang Lock 2010 pub Wiley ISBN 978-0471-66008-8