Crosstalk, EMI, and Differential Z

Good, Bad, or Ugly?

Douglas Brooks

This month, let's take a look at these four things: crosstalk, differential impedance, EMI, and television transmission. Now, my question to you is, what is the relationship between them? Choose from one of the following: (a) They all depend on the same fundamental phenomenon. (b) They are totally independent phenomenon. (c) Two of them are exactly the opposite of the other two.

We don't often think of these four things at the same time. But before we consider the question, perhaps we should review our understanding about what "electromagnetic" radiation is. The two parts of the word give us a clue.

The "electro" half of the word relates to "electric" or "electron," or, more fundamentally, "charge." We all should remember that "like charges repel" each other and opposite charges attract. Those statements are generally known as Coulomb's Law and are accredited to Charles Augustin de Coulomb in 1785.

Now current is the flow of electrons. Electrons have a negative charge. If (negative) electrons flow, for example, onto one plate of a capacitor, electrons will be repelled from the other plate, leaving a "positive" charge (really just the absence of electrons.) If there is a stationary charge on the capacitor, we call the force that results "electrostatic," "electro" related to electron, or charge, and "static" because it doesn't change. This force manifests itself as a voltage across the plates of the capacitor.

There is a similar force that occurs as current (electrons) flows along a wire or trace (except that it is no longer static.) The electrons, which are part of the current flow, create an electric field along the wire that tends to repel other nearby electrons. The strength of the field is related to the number of electrons, or the magnitude of the current.

The "magnetic" half of "electromagnetic" refers to the magnetic field that surrounds a wire or trace when current flows along it. Boaters know this well. Flowing current can create a magnetic field that can cause a boat's compass to change its direction, a safety issue that is covered in every basic safe-boating course. Faraday's Law of Magnetic Induction (1831) states that if current flow is ***changing*** (as in an AC waveform), the magnetic field around the wire or trace changes. This changing magnetic field can cause or induce a current in a nearby trace or wire.

Thus, when current (electrons) flows along a wire or trace, there are two force fields around the trace – an electric field and a magnetic one – hence the term electromagnetic field. If the current is changing, both of these can induce changing currents in nearby traces or wires.

Crosstalk: When two traces are placed close together, the current flowing down one (in this context we call it the "aggressor" trace) induces a current in the other (victim) trace. The electric field causes a current in the victim trace that flows both ways, backwards and forwards. Think of the case of a single electron at a point along the aggressor trace. It will tend to repel electrons in the victim trace in both directions away from that point. We often call this type of coupling "capacitive" coupling.

The aggressor trace also generates a magnetic field, which in turn generates a current in the reverse, or backward direction in the victim trace. We often call this type of coupling "inductive" coupling. These two types of coupling tend to reinforce each other in the backwards direction, but they tend to cancel each other in the forward direction (they exactly cancel in stripline environments.) Hence, reverse coupling, or backwards crosstalk, tends to be the problem in this situation.

In summary, crosstalk is a direct result of the electromagnetic field radiated from the aggressor trace.

Differential Impedance: Differential signals are typically those where the signals on the two traces are exactly equal and opposite, and the traces are routed closely together. If we are designing impedance controlled differential traces, many references point out that that the net differential impedance is given by the relationship

$$Zdiff=2Zo(1-k)$$

where Zo is the single-ended impedance of each individual trace and k is the coupling coefficient between them.

This coupling, represented by k, is ***exactly*** the same coupling that occurs with crosstalk! Except that this is a very special case where (a) both traces are victim and aggressor at the same time, and (b) the coupling is symmetrical (since the signals are equal and opposite.) So while crosstalk is normally a bad thing, in the particular special case of differential signals it turns out to be a good thing!

EMI: The same electromagnetic force that can create a noise signal on an adjacent trace

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(crosstalk) can also create a noise signal on a trace further away. As the victim moves further away, we begin to stop calling the noise “crosstalk” and to start calling it “EMI”. And this radiated noise can be a very bad thing if the victim trace (or receiving antenna) happens to be at an FCC compliance testing range! So now the electromagnetic radiation is causing EMI problems.

Television Transmission: But what if the electromagnetic field is so well controlled that it only radiates at a single specific frequency? Then any victim trace (receiving antenna) receiving it can be “tuned” to that frequency. And if the electromagnetic field is modulated somehow to contain information, then the tuned receiver can demodulate and process that information. This is the basic principle behind all radio/television/signal transmissions.

Summary: So any wire or trace carrying an AC signal radiates a changing electromagnetic field. This can be a bad thing when the field causes crosstalk in an adjacent wire or trace, but a good thing when it couples to its differential pair. It can be a bad thing when it couples (radiates) to a trace or an antenna further away (e.g. at an FCC compliance testing range), but a good thing when we are electronically transmitting a radio or television signal. Our jobs as engineers and designers is to understand how to control these fields and how to minimize those we don’t want and how, perhaps, to maximize the ones we do want.