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Electromagnetic interferences in electrical measurement systems demystified

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Abstract This paper is concerned with the practical aspects of protecting an electrical measurement system against different kinds of interfering cross-talk. We categorise different kinds of cross-talk, describe their origin and how to decouple them in order to protect the system. This presentation is a primer for students or application engineers concerned with the practical operation of an electrical measurement system. We explain cross-talk phenomena with a minimum of electromagnetic theory, focusing more on understanding the origin of cross-talk in terms of basic electric and magnetic circuits rather than advanced electromagnetic wave equations, and how to decouple them. Compared to a typical textbook presentation on the subject, this work categorises all kinds of electromagnetic interferences using a minimum of mathematical equations, clearly explaining their origin and illustrating how each one is decoupled.

Keywords coupling/decoupling; cross-talk; grounding; shielding

Most of us have had some kind of EMI experience; the most common is when you hear your mobile phone ring signal interfere with your radio set. While this problem is annoying at most, electromagnetic interference (EMI) can be a major problem elsewhere. It is of critical importance to prevent EMI in security systems like avionic flight control, automobile braking systems, hospital life-support equipment etc. All these systems have to have electromagnetic compatibility (EMC) with the surrounding environment in which they are intended to operate.

Despite the importance of the subject, it receives surprisingly little attention in electrical engineering programmes at universities in general. It is a subject that is rumoured to be complicated both among students and at the application engineer level. This is not their fault; they have all the components to understand it (electricity and basic electromagnetic field theory) but it is hard to connect all the dots on your own to see how this explains EMI phenomena. My own experience is also that when the subject is treated at universities it is too theoretical. This work aims to show that you do not need advanced electromagnetic wave equations to handle these problems; basic electricity and high school-level electromagnetic theory will get you far (far enough for most application engineers).

With the increasing amount of wireless communication devices around us, such as cell phones, routers, GPS navigators, digital TV/radio broadcasts, Ipads, etc., the need for EMI skills should be taken seriously and this work should be considered as a primer on the subject. Not only will I present and categorise EMIs; at the end of this work I will suggest some illustrative demonstrations that I have used in my university lectures for several years which have been highly appreciated. The work will focus on electrical measurement systems in particular, but the presented material

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is applicable to other similar situations too like electronic design, printed circuit board manufacturing, electronic system dimensioning etc.

Electrical measurement systems inherently suffer from external electrical/magnetic interferences. Unless the system is properly protected, externally coupled interferences will corrupt the measurement signal. In most systems, operating engineers protect their systems by utilising shielding and grounding tricks based on ‘rule-of-thumb’ rather than sound electromagnetic theory. This paper will describe these shielding and grounding tricks and explain them in terms of simple electromagnetic theory only. The purpose of this article is first of all to provide measurement engineers with a set of practical, hands-on tools to protect the system, and secondly to show that the shielding and grounding necessary, can be explained and motivated from basic electric and magnetic equations only. Among some application engineers, the shielding/grounding of systems is considered almost ‘magical’. This paper is intended to demystify the area of interference coupling/decoupling.

In this paper we will only consider external noise sources, i.e., the system’s inherent noise sources like Johnson noise, shot noise and quantisation noise are not considered.

In order for an interference to occur in a measurement system, three conditions must be fulfilled:

1 An external noise source must exist;
2 The noise source’s frequency must be within the measurement system’s bandwidth;
3 There must be a coupling between the noise source and the system.

By ‘coupling’ we mean a ‘way’ into the measurement signal path. Note in particular that all three conditions above must be fulfilled in order to cause a problem in a measurement system. For example, the characteristic disturbance in an FM radio or a TV set caused by a calling mobile phone will not be a problem in a measurement system operating at a bandwidth of only 1 MHz, since the phone disturbance signal is way out of that frequency range (whereas for the FM radio and the TV set, it is a problem).

Consequently, in order to get rid of a disturbance in a measurement system, you only have to eliminate *one* of the conditions above. Do not immediately start shielding/grounding arbitrary signal wires as soon as interferences appear. Start with the obvious: Try to identify the noise source and see if you can get rid of it. By simply realigning the signal wire further away from a coil or a high-voltage transformer you may solve the problem entirely. Another possibility is to relocate the system’s frequency range by modulation techniques in order to move it outside the noise frequency bandwidth.[1]

All these things should be considered first, before you indulge in desperate shielding and grounding. Don’t misunderstand this though, some basic shielding and grounding should always be incorporated at the design stage of a measurement system. From experience (or from this paper) you will learn what these basic precautions are, but you might still get into trouble and have externally coupled interferences corrupting your signal, and at that point, you need to address the problem in a structured way.

In most cases though, you will not be able to eliminate the noise source (how do you eliminate the 50/60 Hz power line interference in an electrical measurement lab?) or you may not even be able to identify the noise source at all. A frequency modulation may not be possible or may be considered too advanced or too expensive.

At this point, you only have one option left; you have to break the coupling between the noise source and the measurement system. In order to break a noise coupling, you must know how noise is coupled into the system. Only then can you decouple them. Noise may be coupled in the following ways:

1 By radiation;
2 By capacitive cross-talk;
3 By inductive cross-talk;
4 By common ground cross-talk;
5 By channel cross-talk.

The last two are really two sides of the same coin, but we will treat them separately here anyway.

The rest of this paper is organised as follows: In the next five sections we will describe how each one of the disturbances above is coupled and how to decouple them. Then I will suggest a few illustrative demonstrations and finally will summarise, draw some conclusions and state a few general recommendations.

Coupling by radiation

Electromagnetic (EM) waves are always present in any typical measurement environment and they emit electric and magnetic fields.[2] For example, any a.c. current-carrying wire emits EM waves.[2] From fundamental electromagnetic theory, we know that these EM waves may be picked up by antennas.[3] In a typical measurement environment, two kinds of antennas may pick up EM waves; electric dipole antennas may pick up **E** radiation and magnetic dipole antennas may pick up **B** radiation (see Fig. 1).

The disturbance picked up by the electric dipole antenna is proportional to the **E** vector component parallel to the antenna and proportional to the wire length. There are three ways to decouple this interference:

1 Try rearranging the system wires; only the **E** component parallel to the wire causes the interference.
2 Keep all wires as short as possible; the magnitude of the picked up interference is proportional to the length of the wire.
3 Shield the wire; According to Faraday,[4] there can be no electric fields within a closed metal casing (a 'Faraday cage') (Fig. 2).

In a typical situation, countermeasures 1 and 2 above will not be enough and you will have to apply a closed shield for your system. Note that this will have to be a

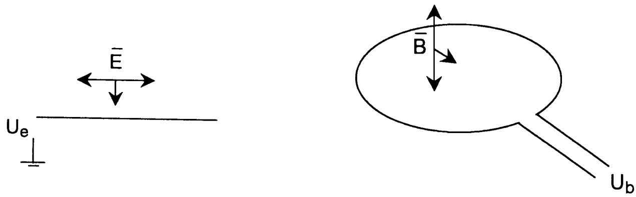

Fig. 1 *Electric and magnetic dipole antennas.*

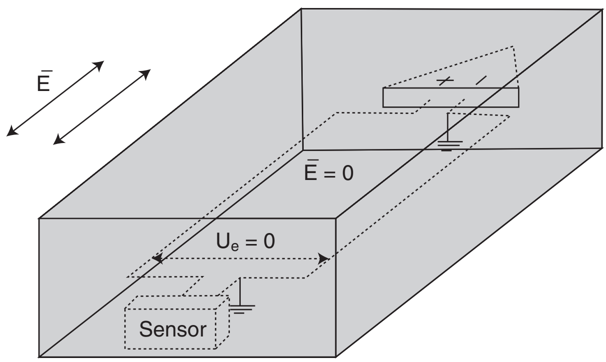

Fig. 2 *Enclose the system in a Faraday cage.*

closed shield. Lots of measurement engineers have enclosed their acquisition electronics in expensive metal casings, only to ruin the entire screening effect by penetrating the casing with an unshielded wire. The signal path must be shielded all the way, cables included.

Note also the following: A common misunderstanding is that the shield has to be connected to ground for this to work. This is not true! A Faraday cage only requires that the **E**-field is short-circuited by a closed metal casing.[4] No grounding is necessary. (Probably you will ground the shield anyway, but that is for other reasons and has nothing to do with the Faraday cage protecting you against electrical radiation; see section below about capacitive cross-talk.)

Metal instrument casings may be very expensive, and using plastic casings painted inside with a metal colour-coating has been suggested,[5] but it is normally not recommended as most metallic paints don't have the conductance necessary to short-circuit the cage.

Note that the Faraday cage only blocks electrical radiation, so magnetic radiation is still a problem. It could be blocked by a high-permeability material like μ-metal (a nickel-iron-copper-molybdenum alloy) but this is too expensive for most systems. As in the **E** radiation case, it is only the **B** component with the right angle of incidence (perpendicular to the antenna loop) that will induce a disturbance, so it might help to rearrange cables here too. The induced disturbance is also proportional to

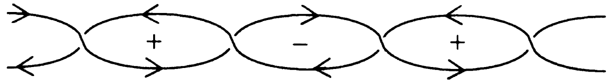

Fig. 3 *A TP cable is a series of magnetic dipoles that will cancel each other pair wise.*

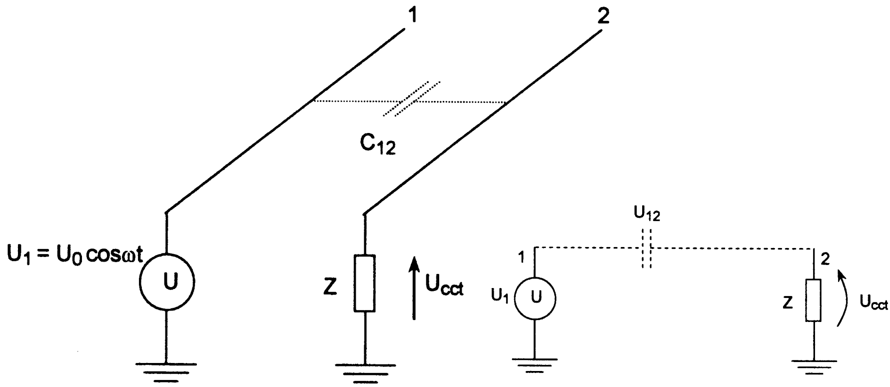

Fig. 4 *Capacitive cross-talk.*

the magnetic dipole antenna loop area. Keeping all loop areas to a minimum is absolutely vital. This is one of the reasons why *Twisted Pair* cables (TP cable) should be used. Not only is the loop area minimised, the interference induced in one small magnetic dipole will be cancelled by an equally large interference, but of opposite sign, in the adjacent dipole (Fig. 3), since the induced currents will have opposite direction in adjacent loops in a twisted cable.

Note that the TP cable itself only cancels the normal mode interference, however. Magnetic fields may very well induce common mode interferences and for that reason, the TP cable should also be close to the ground plane in order to make the common mode area zero. Note also that only time-varying **B** radiation induces cross-talk.[3] Static **B** radiation is not a problem.

Capacitive cross-talk

From fundamentals of electricity, we know that there is always a capacitance between two metal surfaces. This is true for the two plates in a capacitor as well as for two signal wires. Consider Fig. 4. Signal wire 2 is the measurement signal and in signal wire 1 is another, interfering signal. Since the wires are metallic, there is a capacitance C_{12} between them. How much of the current from signal wire 1 crosses over to wire 2 is determined by Kirchoff's law[4] and depends on the impedance of C_{12}. Since $Z_C = 1/j\omega C$, we can see that capacitive cross-talk is primarily a high-frequency problem.

How do we decouple this capacitive coupling? Remember that in order to protect the system against electrical radiation, we already have a metal shield around the

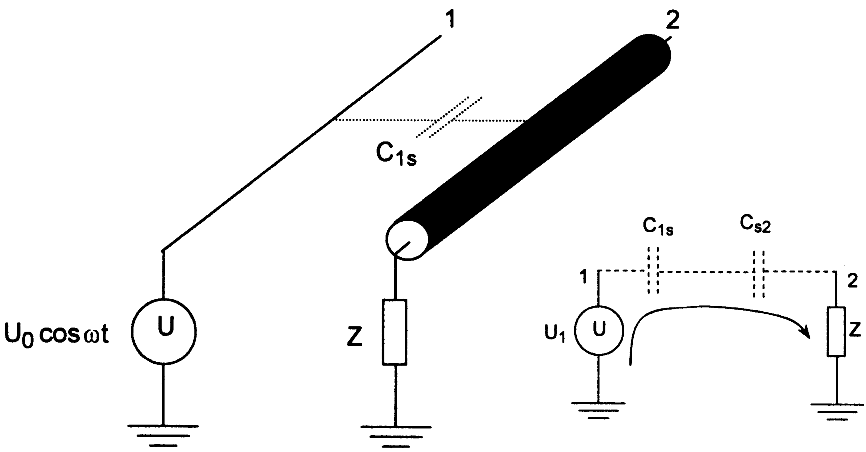

Fig. 5 *Shielding alone will not protect the system from capacitive cross-talk.*

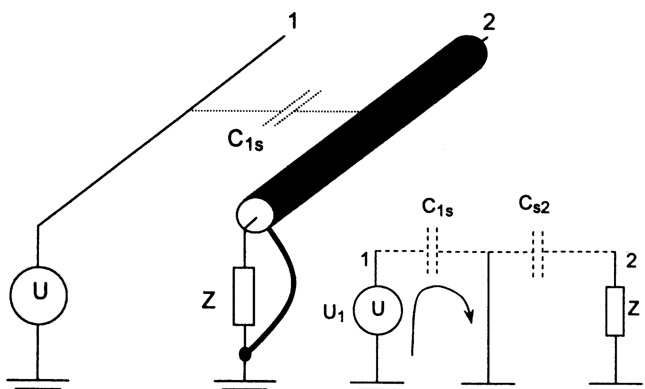

Fig. 6 *The shield needs to be grounded in order to cancel capacitive cross-talk.*

signal wire (Fig. 5). However, this shield does nothing to prevent capacitive cross-talk! There is still a capacitance C_{1s} between wire 1 and the shield, and another capacitance C_{s2} between the shield and signal wire 2. The only consequence of the shield (apart from blocking **E** radiation) is that the capacitance C_{12} is divided into two separate capacitances. The capacitive cross-talk is hardly affected at all.

However, from Fig. 5 it is obvious how the capacitive cross-talk can be decoupled; if we simply short-circuit the point between the capacitors in Fig. 5 to ground, any interfering signal crossing over from wire 1 will be short-circuited to ground.

This will efficiently block the capacitive cross-talk. The point between the capacitors in Fig. 5 corresponds to the shield itself; the shield should be grounded (Fig. 6).

Hence, a grounded shield blocks two interferences; **E** radiation and capacitive cross-talk.

Inductive cross-talk

Any signal cable has some characteristic inductance per unit length;[2] you may consider the signal wire to be a small coil. This means that if you place two wires close together, you really place two coils close together and that is a transformer. Between the coils in a transformer, there is always a mutual inductance M (Fig. 7).[4]

The primary coil (wire 1, Fig. 7) will induce a voltage U_{ict} in the secondary coil (wire 2) with a magnitude of:[6]

$$U_{\text{ict}} = M_{12}\frac{\mathrm{d}i_1}{\mathrm{d}t} \propto M_{12}\cdot\omega\cdot i_1 \tag{1}$$

where M_{12} is the mutual inductance between wires 1 and 2. This is inductive cross-talk and illustrated in Fig. 8. Note from eqn (1) that, just like in the capacitive case, inductive cross-talk is mainly a high frequency problem.

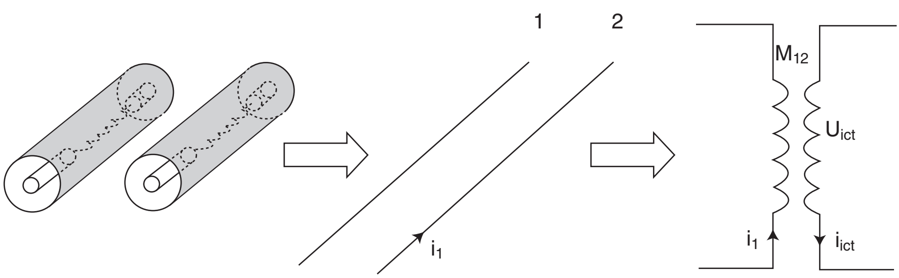

Fig. 7 *Adjacent signal wires will form a transformer.*

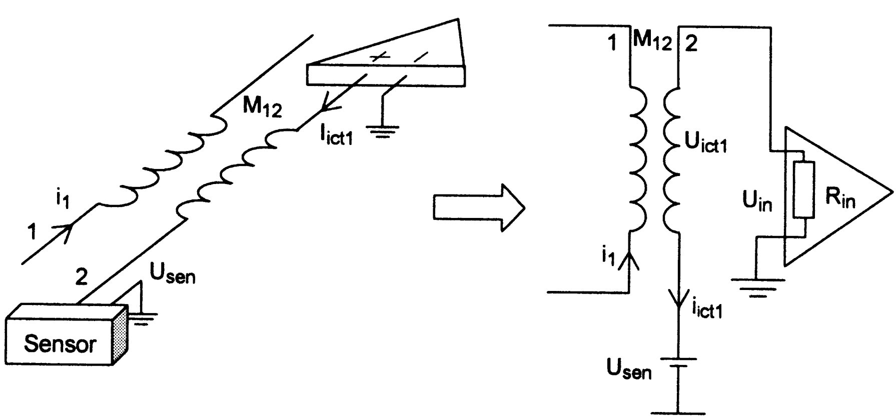

Fig. 8 *Inductive cross-talk.*

How do we decouple inductive cross-talk? Note in Fig. 8 that, according to Lenz's law,[4] the induced current in the secondary coil (signal wire 2) is in the opposite direction to the current that induced it (current in signal wire 1). Therein lies the solution. Let's temporarily separate the cables in Fig. 8 and introduce a third wire (a shield wire) (Fig. 9).

Signal wire 1 still induces a current i_{ict1} in wire 2, but it also induces a current i_S in the shield wire. Since there is also a mutual inductance between the shield and wire 2, M_{2S}, i_S will induce a current i_{ictS} in wire 2 and this will have opposite sign relative i_{ict1}. i_{ictS} and i_{ict1} will cancel each other (Fig. 10).

The total induced interference in wire 2 is

$$U_{ict,total} \propto \omega \cdot (M_{12} \cdot i_1 - M_{2S} \cdot i_S) \tag{2}$$

i_1 is larger than i_S, but on the other hand, $M_{2S} > M_{12}$. Properly arranged, $M_{12}i_1$ will equal $M_{2S}i_S$ and the total inductive cross-talk interference will cancel in eqn (2).

In practice, the shield wire in Fig. 9 is not a separate wire. Remember from Fig. 6 that we already have a 'wire shield' between wires 1 and 2; the shield we introduced to block **E** radiation and capacitive cross-talk will work fine for inductive

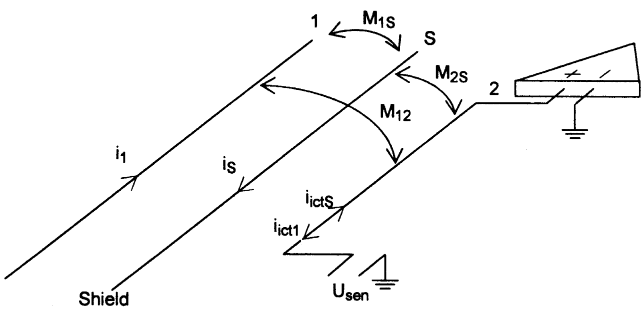

Fig. 9 *We introduce a shield wire.*

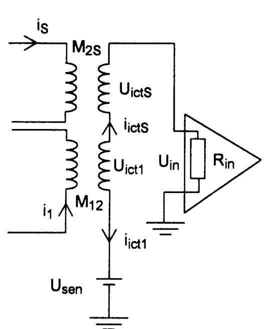

Fig. 10 i_{ictS} *and* i_{ict1} *will cancel each other.*

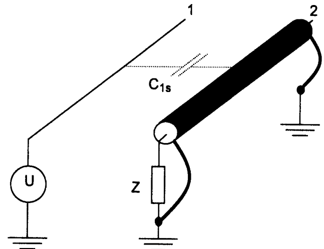

Fig. 11 *Now we block* **E** *radiation, capacitive and inductive cross-talk.*

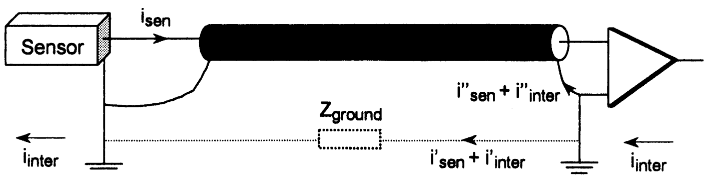

Fig. 12 *The return current from other current loops will induce an interference.*

cross-talk too, after some small adjustments. Figure 9 is not complete; in order for the shield wire in Fig. 9 to work as a shield, it has to be able to carry a current. This requires that it is a closed loop; it has to be grounded at both ends. Consequently, in order for the shield in Fig. 6 to also block inductive cross-talk, it has to be grounded at both ends (Fig. 11).

As we will see in the next section, if the shield is also the return line, grounding at both ends is not a good idea, so we will modify this later. (We have to do that anyway, since in Fig. 11, there is no protection against **B** radiation.)

Common ground cross-talk

The most common transmission cable in any measurement lab is the coax cable. Its outer copper shield inherently protects your system against **E** radiation and if grounded at both ends it will protect you from capacitive and inductive cross-talk. However, it is also the return line for the signal current loop, and grounding a closed current loop at more than one point is never a good idea.

The reason is that the impedance, Z_{ground}, between two ground points is never zero and neither is the impedance of the return cable, Z_{return} (Figs 12 and 13). Some of the interfering return currents from other sources will pass through the shield and some of the return current from the sensor, i_{sen}, will return via common ground. The impedance between the two ground points will be $Z_{ground} // Z_{return} \neq 0$, i.e. the two ground points will not have the same potential and the potentials will vary depending on the interfering current i_{inter}. This is common ground cross-talk.

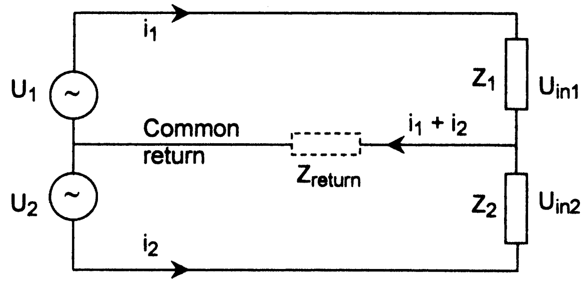

Fig. 13 *Common return line in multi-channel systems.*

The decoupling solution is simple: Sensor and input amplifier cannot both be single ended. At least one of them (preferably both) has to be differential ended so that there is no need for grounding at both ends. A coax cable should only be grounded at one end. On the other hand, it has to be grounded at both ends in order to block inductive cross-talk, so we have a contradictory situation where we cannot simultaneously protect our system against common ground cross-talk and inductive cross-talk. We will address this problem in detail when we summarise in a later section.

Channel cross-talk

Channel cross-talk is basically the same phenomenon as common ground cross-talk and appears in multi-channel systems that use common return lines for several channels. Even though the return line is not the overall system ground, there will still be cross-talk interferences due to the fact that the impedance of the common return line is not zero, see Fig. 13.

For example, the input to channel 1, U_{in1}, in the system in Fig. 13, is

$$U_{\text{in1}} = U_1 - Z_{\text{return}} \cdot i_1 - Z_{\text{return}} \cdot i_2 \tag{3}$$

The first term is the sensor signal and the second term is ‘cable loss’. The cable loss is a measurement disturbance, but it is not induced by cross-talk. The third term, however, is channel cross-talk, since it originates from channel 2.

The solution is simple here too; in a multi-channel system, all channels must have separate returns. That also has another advantage; all signal wires can be twisted pair-wise with their return wire.

Suggested classroom demonstrations

Most of these EMI phenomena are really easy to demonstrate (and I think they should be demonstrated). First of all, the power of a Faraday cage for blocking **E** radiation is easily illustrated. Turn on a small, battery powered FM radio. Make a Faraday cage of some aluminum foil and demonstrate what happens when you place the radio inside it (static only). Finally, make a small hole in the Faraday cage (simulating an external wire connection) and penetrate the Faraday shield with a wire (or metallic pointing stick) to demonstrate how easily the shield is ruined by careless cable connections.

Secondly, the EMIs caused by magnetic dipole antennas are also easily demonstrated with an oscilloscope. Make a small coil by just wrapping a few turns of a wire (a magnetic field 'sniffer') and connect its terminals to the oscilloscope probe. Move the coil over some area where you know there is an alternating magnetic field (in front of the oscilloscope's CRT screen, for example) and watch the oscilloscope screen to see the **B** field EMI.

Demonstrating capacitive cross-talk is equally easy. Connect an unshielded wire to the input of an oscilloscope. Connect a power cable to the wall power outlet and place it close to the unshielded wire connected to the scope. This will induce 50 Hz interferences of several 100 mV. To prove that this is capacitive cross-talk and not **E** field radiation cross-talk, cover the unshielded signal wire with aluminum foil (but don't ground it yet). You will see that this doesn't affect the EMI at all. Using a short separate wire, short-circuit the aluminum foil shield to the oscilloscope ground and see the EMI being cancelled.

Finally, channel ground cross-talk can also be demonstrated (with some effort). From a common signal generator (like Agilent's 33120) connect a small sinusoidal voltage (100 mV) to oscilloscope channel 1 and the signal generator's reference output (5 V digital) to oscilloscope channel 2 and make sure they share the same return line. Now, in order to see channel ground cross-talk, this has to be a digital oscilloscope where you can change the input impedance of each channel. By default they are set to 1 MΩ, but that will not allow enough current to see the cross-talk. However, if you change the input impedance to 50 Ω on channel 2, you will have no problem seeing a lot of channel cross-talk on channel 1.

Conclusions

We have obtained some contradictory conclusions above; I would like to summarise by proposing a 'perfect' solution. In order to have protection against **B** radiation, we need a TP cable. We also learned that we should have a shield, grounded at both ends (without introducing common ground cross-talk).

The solution that in theory solves all our problems is the use of shielded TP cable. Since the signal wire is twisted with the return wire, the shield is not carrying the return current and may be grounded at any points. In Fig. 14, the TP cable blocks

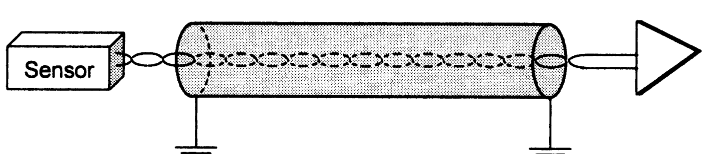

Fig. 14 *Complete noise decoupling.*

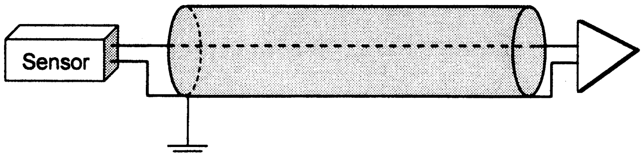

Fig. 15 *Sufficient noise decoupling.*

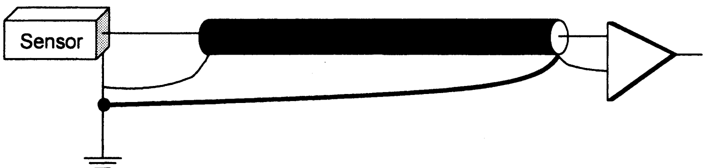

Fig. 16 *One grounding point only.*

B radiation. The shield itself blocks **E** radiation. The shield and the fact that it is grounded blocks capacitive cross-talk. The shield and the fact that it is grounded at both ends blocks inductive cross-talk and the fact that the return wire is not grounded anywhere prevents common ground cross-talk. The solution above assumes that both the sensor and amplifier ends are differential ended. This is the typical case. If this is not so, they can easily be differentiated using isolation transformers or opto couplers.[7]

Finally, a recommendation based on experience: when designing measurement systems, you have to prevent cross-talk interferences from **E** radiation, capacitive coupling and common grounds. These are always a problem and will corrupt your signal if not decoupled. However, **B** radiation and inductive cross-talk interferences are typically negligible and need not be considered at design stage and are only dealt with afterwards if necessary. Consequently, in a typical system, a coax cable, grounded at one end, will be sufficient for most environments. Figure 15 illustrates the 'sufficient system protection' situation.

If you insist on using coax cables and are exposed to inductive cross-talk, you can still try to ground the coax shield at both ends, but you have to ground them at the same point and use a very low-resistance cable (a thick copper wire) (Fig. 16).

No classroom demonstration was included in the previous section for inductive cross-talk. This is because I simply haven't been able to find a demonstration set-up for it. Even when I try my best to provoke it, I cannot see it. This should give you some indication of to what extent you need to worry about it; the 'sufficient protection system' should typically be all you need.

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