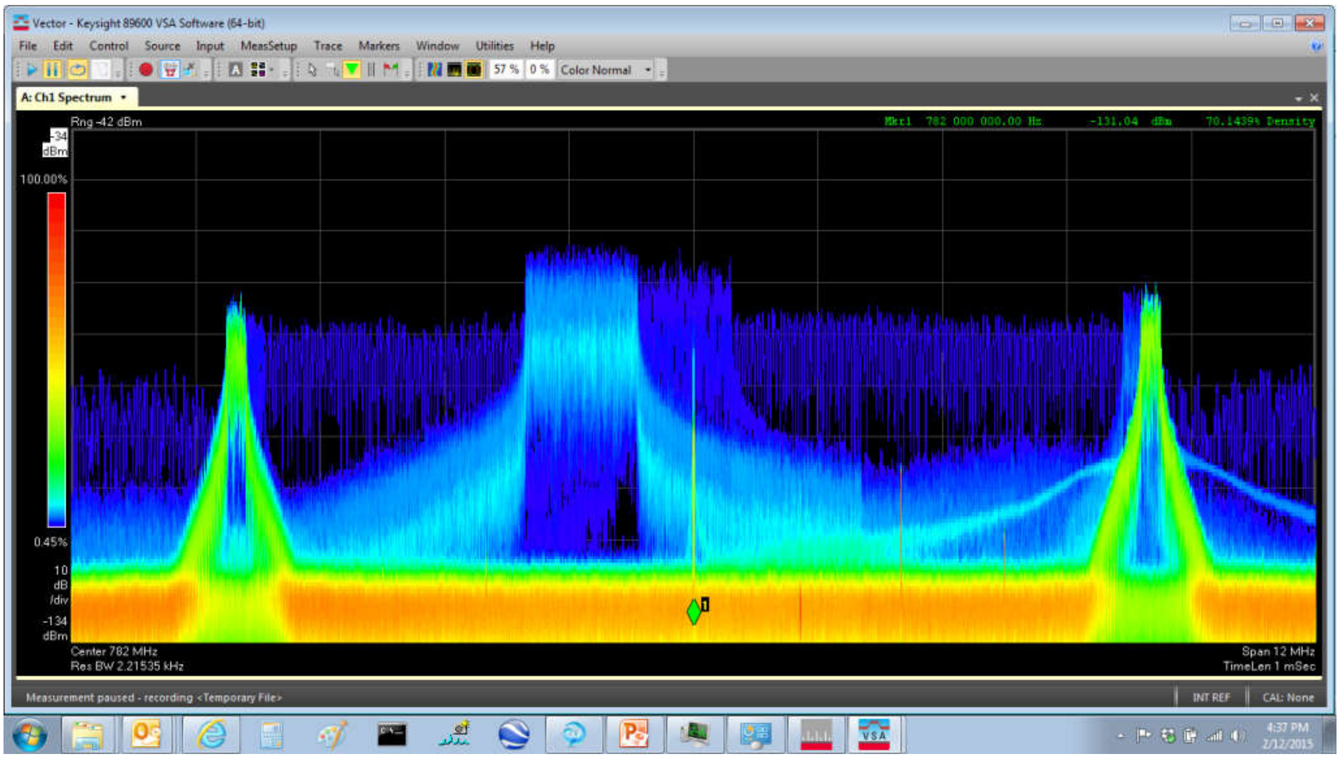
Rako Studios

Rako Studios » Media » Tech » Electronics » RF immunity, keeping noise out

RF immunity, keeping noise out

What you can do to increase the immunity of your system to RF interference.



Your electronic designs are being assailed by RF noise from cell phones, digital oscillators and even fluorescent lights. We are constantly bathed in steady streams of RF energy. Some of this energy is an accidental byproduct of a system; other RF sources are purposefully radiating, such as with radios and radar. Any of these RF sources can seep into your electronic system.

Indeed, some RF sources are so strong and so insidious they will create noise in simple wires, such as the magnet wire that forms the voice coil of a speaker. When users can hear noise in an audio system it is certainly undesirable. But if the RF noise causes a machine to go haywire or an airplane's

AT A GLANCE

- RF sources can transmit energy into cables, PC traces and ICs.
- Symptoms of RF susceptibility can be tricky to diagnose.
- The best option technique is to kill noise at its source.
- Shielding is a high cost Band-Aid.
- Careful layout and good system design can provide the best protection from RF.

instruments to malfunction then human life may be at stake.

This is one reason the European Community instituted RF immunity testing for products sold in the EU. When these standards were instituted over a decade ago engineers soon learned that passing CE immunity compliance tests were a lot harder than passing FCC noise radiation tests. When customers call Steve Bible, Microchip Technology technical staff engineer, he notes "Engineers don't think it is a problem until it is a problem for them. They are in a real time crunch. They have made a bad design and it's hard to convince them that it's bad. They want to find that one silver bullet, the one thing they can do so they can pass. Except there is no silver bullet."

In order to provide your systems with robust RF immunity you have to understand just how many RF sources your system will be subject to. The electric power industry is broadcasting 50 or 60 hertz radio waves as it sends power to your house. Your watch has a 32 kHz crystal emitting energy. Electronic ballasts for fluorescent lights operate at 40kHz. Traffic lights use loop sensors energized at 50 to 100 kilohertz.

At higher frequencies, you will soon run into what the FCC describes as intentional radiators, things like radio stations, TV stations and various private, public and military radios. Some of the most troublesome of these radios are cell phones. Out beyond cell phone frequencies are radar systems and exotic military systems.

A previous article described the problems caused by cosmic rays when measuring femtoampere current levels [Reference 1]. Steve Sockolov, the product line director for Analog Devices precision linear products group notes: "Every customer looks at it differently". He explains that it is hard to know how to help a customer that has an RF susceptibility problem since there are hundreds of ways to hook up and amplifier in a signal path. In addition there are a continuum of source frequencies to worry about. To help customers with precision measurement circuits, ADI has developed the AD8556, a functional equivalent of the AD8555, except that the part has EMI filters on the input pins, the reference pin and the clamp pin. This helps suppress RF interference across a broad band of frequencies.

Not all RF sources need concern you. The watch crystal operates at a relatively low frequency and transmits minuscule power levels. Other sources may look problematic but may not be. The package case of a FET used as a low side-switch in a synchronous buck regulator will swing the entire power supply voltage since it is connected to the switch node [**Figure 1**].

This node operates at the power supply frequency. So you would think that it would radiate RF energy. It is for these reasons that some engineers are loathe to layout the circuit with a large copper heatsink plane. What is not apparent is these nodes need not radiate much RF. In order to radiate RF there has to be current flowing. By using the package pin to carry the current and making the package tab the only a way to take heat of the circuit, a cleaver designer can cool the FET or transistor while minimizing the RF radiation.

One of the ways to solve an immunity problem is to stop the RF source. Decades ago automotive engineers learned this when they added radios to automobiles. It soon became evident that keeping noise out of the radio was very difficult, whereas killing the noise at the

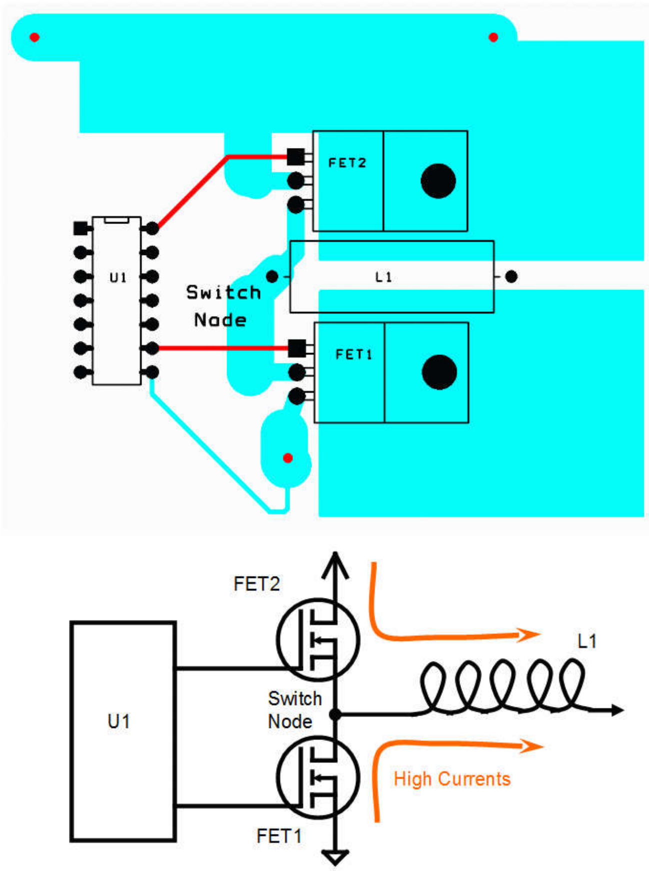


Figure 1; *The large heat sink formed by a copper pour may look problematical form an EMI perspective but since it carries no current it will not radiate large amounts of RF energy.*

source was very effective. This is why auto engineers added capacitors at the alternator. It was easier to suppress the diode switching spikes than it was to try and keep the noise out of the radio. Designing your power supply circuits with sensible, tight layouts that minimize circulating currents [Reference 2] will help you pass FCC radiation tests. It will also provide one less source of RF interference that may cause you immunity problems.

The hardest problem in RF interference arises because so often you do not have any control over the RF source that is polluting your system. This is often the case with radios, a class of device the FCC calls "intentional radiators". One of the worst intentional radiators we have to deal with is a cell phone. Unlike that watch crystal, cell phones put out a significant amount of power. Worse yet, the high frequencies cell phones operate at are able to get into many parts of your design: the cables, the circuit board traces and even the ICs themselves. And worst of all, cell phones are everywhere, often set near your product.

Indeed, Bob Thomas, an engineer with Cisco systems, reports that when he sets his cell phone in the package tray of his 2006 Honda, the noise radiated into the radio is louder than the station the radio is playing. Another Cisco engineer, Steve Abe, has noted that when he sethis cell phone on top of his Palm Zire, the Zire would reboot when he received a call. Many of us share the experience of Francis Lau, an engineer with FM transmitter manufacturer Aerielle. He says his home stereo buzzes when he is going to get a call on his phone.

In order to understand why cell phones can be a source of RF interference at audio frequencies we have to look at the RF transmission protocols. The North American Digital Cellular (NADC) phone system is associated with the TDMA protocol. In this protocol digital traffic channels (voice data) are multiplexed into time slots. A sequence of six time slots makes up a 40-millisecond frame. In a full-rate traffic channel the user transmits twice in each frame. This means a user assigned to time slot 1 will transmit again in time slot 4. By transmitting twice in each frame the EMI picked up by your system will look like a dirty square wave with a 20-millisecond (50 Hz) period [**Figure 2**].

The global GSM system protocols specifies a transmission once every 4.6 milliseconds [**Figure 3**]. This type of interference is far more audible. Since the GSM phone transmits

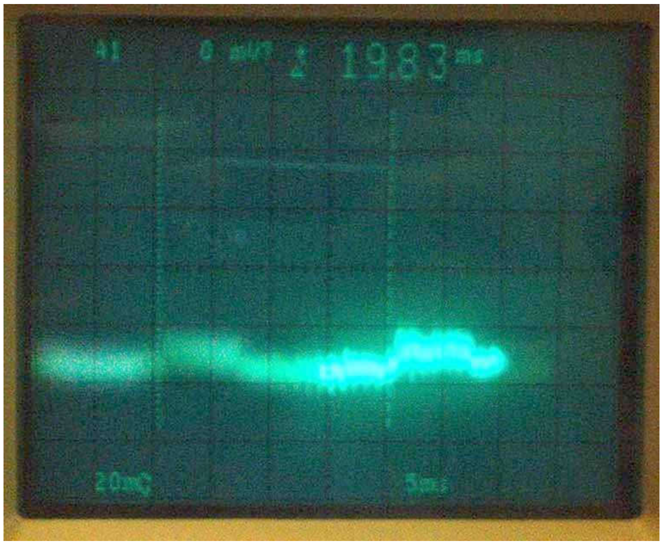


Figure 2; *The TDMA phone standard uses radio protocols that result in bursts of RF at 50 Hz. It is the demodulation of the signal envelope that you hear in your stereo and clock radios.*

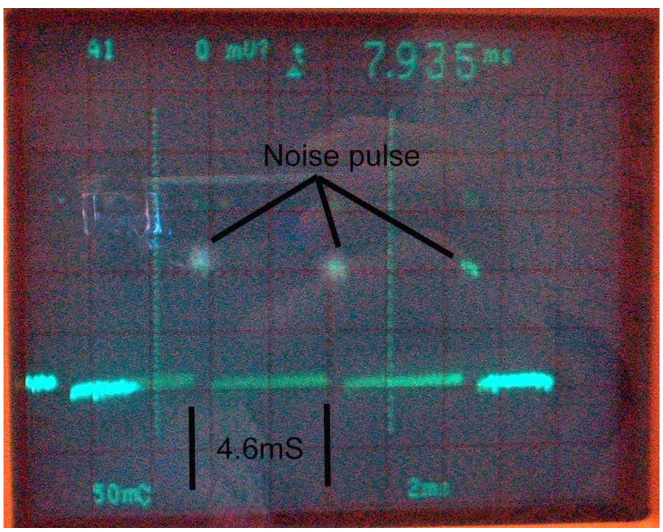


Figure 3; *The GSM standard has a signal envelop with a 217 Hz frequency. Since power levels are higher and the human ear is more sensitive at 217 Hz these phones can produce horrific interference problems.*

at 33dBm versus 20dBm for a TDMA phone, the interfering signal level is far higher. The figures 2 and 3 represent interference in a real-world system and in this case the GSM interference was 100 millivolts as opposed to the 5 millivolts caused by the TDMA phone.

The interference you hear in your car stereo and clock radios is not the 900 MHz burst, but rather, the repetitive envelop of those bursts that are detected in ICs and even wire due to the non-linearity in the system.

James Long, RF consultant advises: "All electronic devices have a transfer function that is a power series of the input signal(s). Vout = Vin x k1 + Vin^2 x k2 + Vin^3 x k3 and on in an infinite series. The result of this is that there are many extra frequencies produced including the demodulated base-band of the interfering signal." Long says that a notorious example of nonlinear circuits are those that depend on feedback to reduce distortion. At higher frequencies the feedback effect is zero and RF interference is not suppressed.

Long recommends two books for those interested in RF susceptibility [Reference 3,4]. Also recommended is EDN's own book on EM compatibility [Reference 5].

In general RF susceptibility is due to circuit traces and planes picking up radio frequencies. These frequencies are demodulated by input protection diodes and other junctions in the analog ICs and this demodulated signal is what appears as audio frequency noise. At 1 GHz the IC itself is not an effective antenna for typical RF emissions. The tiny bond wires and capacitances are more susceptible to frequencies in the 10s of Gigahertz, far above the excitation frequencies caused by cell phones.

It must also be stressed that the RF comes to the IC by way of the circuit board planes and traces. Different ICs of the same type or from different manufacturers will act differently depending on variations in input capacitance or lead frame inductance, but the susceptibility is still there. National Semiconductor has developed the LMV851, an op amp specifically designed to reject RF. They have devised a figure of merit called EMIRR that quantifies how well various pins of the IC provide RF immunity. The procedure for this evaluation is described in an application note [Reference 6].

FET and CMOS op-amp input structures are less prone to demodulation effects then bipolar amplifiers. Still, Kumen Blake, principal applications engineer from Microchip Technology points out that CMOS parts can detect RF if you drive the inputs hard enough. He states that under RF radiation "Even CMOS will reverse bias and create a transistor junction. Any op amp can covert RF or microwave energy into a DC signal."

He points out "Many customers don't understand what symptoms they will see if they have an EMI problem. A dc shift can be a symptom. A change in power level means there's a good chance there are some oscillations caused by RF interference. Another symptom is distortion of the signal, whether the frequency changes or the appearance of harmonic distortion. The worst symptom is erratic behavior, where the circuit just does not work right all the time".

Some ICs use resistance of the input structure to decouple the RF from inside the amplifier. Even a small input resistance can work in conjunction with the stray capacitance of the amplifier's ESD (Electro-static Discharge) protection diodes and other structures to effectively bypass the RF to ground.

Maxim's use of this technique to provide ESD protection on their LMX324 also provides RF immunity [**Figure 4**]. The downside is that the resistors limit bandwidth and reduce phase margin slightly.

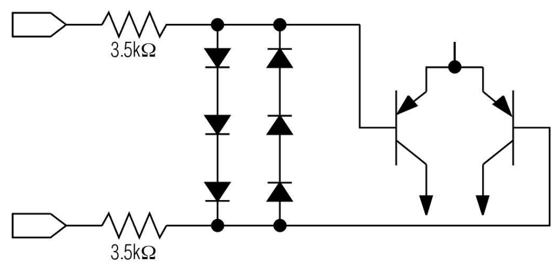


Figure 4; *The input pins of this op amp have series resistors and large capacitive clamp diodes to protect it from ESD (electrostatic discharge). An added benefit is that the part is more immune to RF interference. (Courtesy Maxim Integrated Products.*

A ground or power plane has more then enough impedance to cause RF reception or transmission via the wires that are attached to the plane. If you have a 20 by 20 cm circuit board with a ring style ground plane you cannot assume that the plane is equipotential [Reference 7].

Indeed Glen Dash, the author of the cited reference, soldered two antennas to different sides of a copper-clad circuit board and he could produce significant EMI interference by having digital chips on the board mis-routed so there were large fast-changing currents [**Figure 5**]. Even experienced engineers would look at the telescopic antenna soldered to a common plane and think that there would be no radiation from the system, but this was not the case.

RF susceptibility design rules.

Understanding the theory behind RF susceptibility you should be able to remember the design rules to minimize it. There are three general principles.

1. Low impedance is better then high impedance.

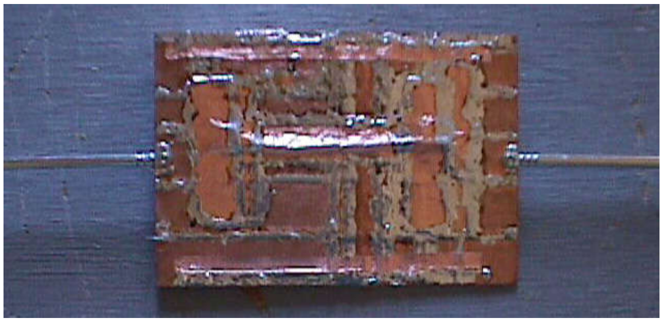


Figure 5; *This copper clad board has two antennas soldered to opposite sides of the same ground plane. When circuits with fast edges are operated on the board the antennas will radiate significant amounts of RF, even though they are galvanically connected. (Courtesy Glen Dash)*

2. Small loop areas are better then large ones.
3. Short wires are better then long ones.

The unstated principle is that when everything fails to solve the problem you will have to put the system in a shielded enclosure, a costly and often impractical option.

Microchip's Steve Bible comments that shielding is expensive "But if designers what to avoid that expense they have to do a good circuit board layout". Realize that a wire in space is an antenna. If the wire is connected to ground with a megaohm resistor that wire's voltage will wiggle around a lot more than if it's connected to ground with a 5 ohm resistor.

Gauss's law dictates that if you have a signal on two wires its better to route those wires closer together then in a big loop. The bigger the area in the loop, the greater the voltage that the wire will pick up for a given RF field strength. Finally, an antenna works best when it is the same length as the wavelength of the RF field. A 1 cm wire that has one side attached to earth ground will have pretty much zero volts all along it's length for frequencies under a Gigahertz. At 900 MHz, a wire 3 inches long is a quarter-wave antenna. Even an eight-wave antenna can bring significant RF energy into your systems. This highlights the importance of short traces and tight layouts. Some layout rules to minimize both susceptibility and RF emissions are detailed below.

1. All the product's cables should attach to the ground and/or power plane at the same point.
2. The sensor wires should not have one side connected to ground at the connector and the other run 3 or 4 inches to the input circuitry.
3. Sensor wires should run right next to each other as a pair, even if one side of the sensor is ground or power. Running them together insures common-mode interference stays that way instead of becoming single ended noise that you cannot reject from a real signal.
4. The sensor wires should be routed between the ground and power planes if possible and these planes should have decoupling caps arranged in a uniform pattern across the planes.
5. The impedances of the circuit should be as low as possible within the limits of power dissipation of the components and the power consumption of the product.
6. The circuit should be laid out as small as possible using the smallest possible components within the limits of manufacturability and power dissipation.
7. Rather than cutting the ground plane into sections it is preferable to keep a uniform ground plane and use placement and routing discipline to insure digital noise is not injected into analog circuits. Power supply circuits that have large AC circulating currents can be referenced to a top-side pour and then tied to the ground plane at the output cap common [Ref 2].

8. If a filtered power supply is needed for ICs, it should be created individually at those ICs as opposed to routing it with traces to those places that are several inches apart. Even a plane is susceptible once it goes beyond an inch in size.
9. If a long run has to be made over to a chip it should be the low impedance signal that is sent there, e.g. run the op-amp output a few inches and then keep delicate input circuitry close to the source.
10. Always try to run signals in a stripline, between two planes as opposed to using microstrip that runs the trace on the outer layers of the board.
11. Use differential signals that don't depend on ground or power if at all possible.
12. Small value (100pF) capacitors can be much more effective then large value capacitors to filter out RF. The self-inductance of a 0.1uF cap makes it useless at RF frequencies. You can look at the impedance charts provided by manufacturers to insure the capacitor selected is low impedance at the frequencies you are trying to suppress [Reference 8]. The layout can have footprints placed for small caps between op amp input pins, on signal path power pins and other sensitive nodes.

Some of these rules are mutually exclusive like low impedance and small parts, but the art of analog design is knowing how to make those trade-offs to achieve the desired result. Many designers do a basic debugging if their circuit boards with the signal layers on the outside.

After the fundamentals are met they next have the prototype board made with the power and ground planes on the outside. This puts all the long traces that might radiate or be susceptible to EMI in a gaussian cage formed by the outer layers. Via stitching can be used along the edges and to separate different areas. The vias can connect two outer ground planes on a 6-layer board and can feed to decoupling capacitors on a 4-layer board where power is one of the outside planes.

A tight, low-impedance layout with careful thought as to how the signals tie into the digital system takes considerable work, but this work is essential to insure the system has good EMI immunity.

If there is nothing you can do to eliminate the source of the RF, you must insure that as little of the RF is coupled into your circuits as possible. After that, judicious choice and diligent characterization of the ICs you pick for the design can improve the RF immunity.

Insidious RF

A broken wafer story

A large semiconductor machinery company routinely experienced severe EMI susceptibility issues. The machines were so sensitive to EMI that Intel banned the use of radios by maintenance workers on the fab floor. It was said that the provocation for this ban was an episode where a worker keyed his radio while standing next to a machine. The machine rebooted and this caused the loss of an entire wafer lot of expensive microprocessors.
While consulting to this semiconductor machinery company I noticed that the mechanical engineers had connected the power supply return, what is commonly called "ground" to the frame of the machine at several points. I tried to explain that this was bad practice. What should have been tied to the frame of the machine was the braided shield of the power supply cabling, not the return circuit. Even though these two lines are galvanically connected, much like the ground and neutral

wires in house wiring, the functions were very different. By letting the shield float and tying the power supply return to the chassis the engineers had created a set of horrible ground loops. Try as I might, I could not convince the department head, who was a mechanical engineer, that the shield should connect to chassis and that the power supply return should only connect to the frame of the machine at one point, perhaps with an inductor to isolate the common from noise on the chassis and to keep the noise on the common from being injected into the chassis. This would make the machine grounding a known system that could be evaluated and controlled and thus would work properly wherever the machine was installed.

The reason that the department head gave for not wanting to correct the grounding of the cables and power supply return was that it would not only require the cable drawings all be changed, but would also require him to move or add tapped holes in the machine frame to accommodate the cable shield ring terminals. This lack of understanding coupled with typical big-company bureaucratic inertia assured that they would have RF susceptibility problems for many years. Indeed, I was not the only consultant that was called to fix RF immunity problems.

Another broken wafer story

While consulting at a different semiconductor machinery manufacturer, I ran into another RF immunity problem. This time we were trying to get TUV to certify the machine for a CE mark.

As with most immunity and EMI compliance problems, the machine was on the loading dock, waiting to be shipped to Europe. The first problem during the immunity testing was static and snow on the control screen. We managed to convince the examiner that this was not a failure. We agreed that it was undesirable, but the operator could still read the screen. After getting a concession on the screen, we continued operating the machine under RF radiation. We were horrified when the wafer elevator crashed through a wafer, shattering it in a hundred pieces. Then the machine rebooted and it would return to normal. The TUV inspector would not allow such an egregious susceptibility.

The failure dealt with a motorized component and that could be a safely hazard. We experimented with this immunity problem and soon found out that the Banner sensor used to locate the wafer position was either misreading the position or not reading back at all. We put ferrite beads (called "prayer beads" by some EMI wags) and at least the computer would not reboot, but we still got wafer breakage. We were about to blame Banner for this problem with their part. Fortunately we mentioned the situation to the examiner and he asked how we connected the sensor to our computer.

I explained that it was cabled in with a shielded cable all the way back to the shielded computer enclosure. The TUV examiner asked if there were any connecters in the cable run. I said there was one, where the Banner pigtail ended, and our cable began. I showed the cable to the examiner and he smiled. The mechanical engineers that designed the cable had used red brick 4-pin Amp MR connectors. Two pins were for power and ground, and the third was for the sensor signal.

Dutifully, they had taken the shielding and connected that through the fourth pin. The problem was that the shielding was stripped back a good 2 inches on either side of the cable and bunched up to get crimped into the pin. The red brick Amp connectors are a simple plastic shell with no intrinsic shielding at all. The TUV inspector pointed at the 4 inches of shield pulled away from the cable and said: "At RF, this is an open circuit". Not only that, but the 4 inches of unshielded wires next to the shield were plenty long enough to admit high frequency RF. We switched to 9-pin D-subminiature connectors with metal housings and the machine passed RF immunity compliance with no problem.

An automobile story

Thirty years ago I worked as an automotive engineer in Detroit. Several things conspired to give us RF emissions headaches. First the ignition systems were going to high-energy systems for pollution control. Next the inner fenders of the cars were now plastic rather than metal. Next, Canada had instituted strict RF emissions laws. Finally there was more and more electronics on the car itself that was having problems with EMI/RFI. In order to try and reduce radiation we would "ground" the hoods of the car with a little ground strap that connected the hood to the body of the car. Many were baffled when we still experienced high frequency RF noise. Ed Winstead, who had been in the Army Radio Corps, explained the problem. Grounding one corner of a big metal car hood would only keep out radiation that had a longer wavelength then the size of the hood. At 100s of megahertz and beyond, the hood of the car may as well not have been there-- it made no contribution to the shielding. That's why when it comes to emissions, an important principle is to kill the noise at it's source rather then trying to put patches all over trying to keep the noise out.

References

1. Rako, Paul, "Measuring nanoamperes," EDN, April 26, 2007,
2. Rako, Paul, "Circulating currents: The warnings are out," EDN, Sept 28,2007,
3. The EMC Desk Reference Encyclopedia, by Don White ISBN 0-932263-49-6.
4. The ARRL RFI Handbook; Practical Cures for Radio Frequency Interference, ISBN-13: 978-0872596832
5. EDN Designers Guide to Electromagnetic Compatibility, ISBN-13: 978-0750676540
6. de Wagt , Gerrit; van Staveren, Arie, "A Specification for EMI Hardened Operational Amplifiers," Application Note 1698, September 2007,
7. Dash, Glen, "EMI: Why Digital Devices Radiate,"
8. "APPLICATION NOTES FOR MULTILAYER CERAMIC CAPACITORS" Kemet, page 46,

For more information

Analog Devices
www.analog.com

Aerielle
www.aerielle.com

Glen Dash
http://glendash.com/

James Long
www.analog-rf.com

National Semiconductor
www.national.com

Maxim Integrated Products
www.maxim-ic.com

Microchip Technology
www.microchip.com

Files