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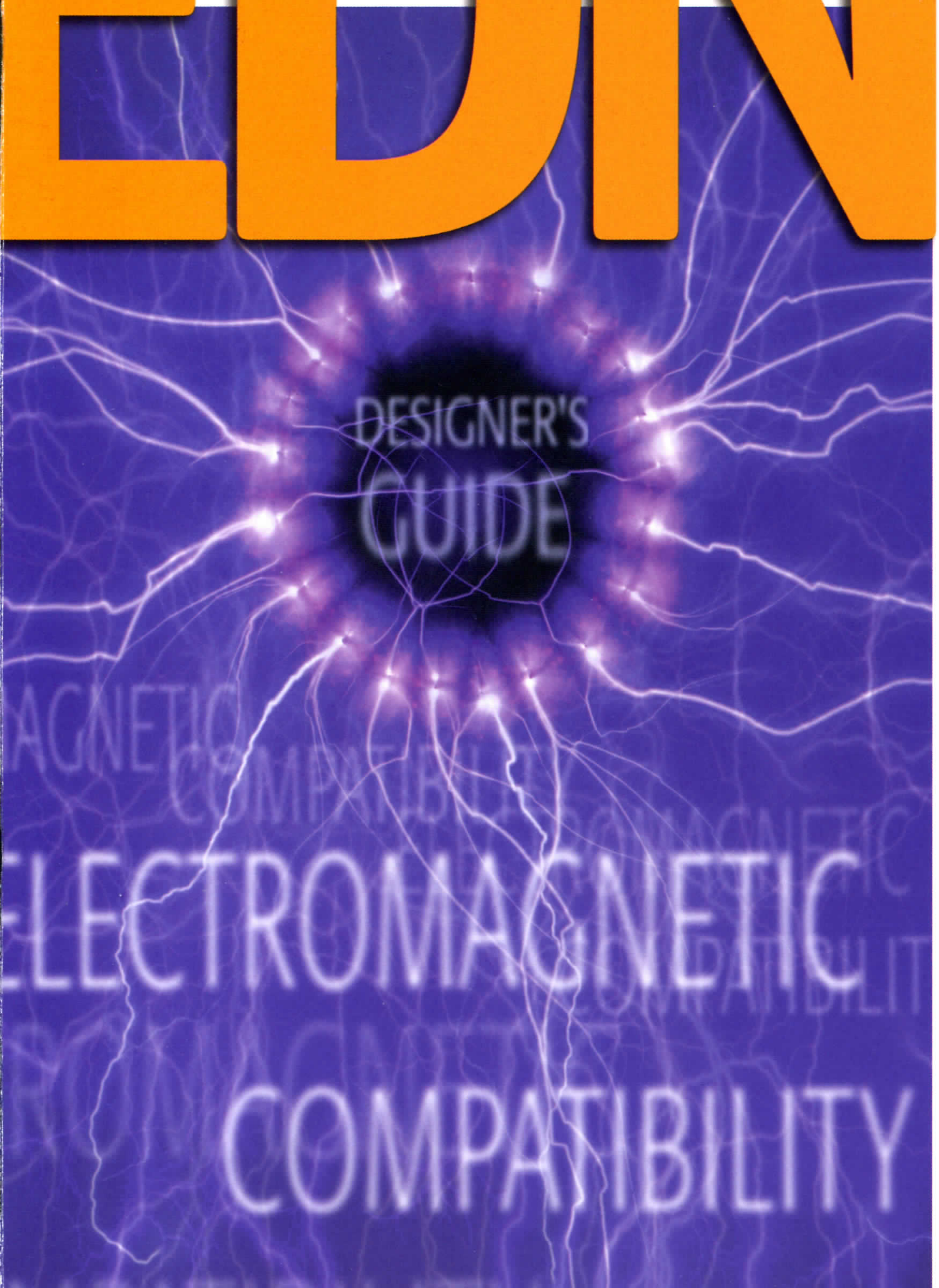

EDN

The Designer's Guide to Electromagnetic Compatibility

— Daryl Gerke, PE and Bill Kimmel, PE,
Kimmel Gerke Associates Ltd

DESIGNER'S GUIDE

Why did we update this series?

IN 1994, WHEN THE FIRST EDITION of the *EDN Designer's Guide to Electromagnetic Compatibility* appeared, enforcement of the mandatory European Union (EU) EMI/EMC (electromagnetic interference and compatibility) rules was still two years away. As such, many designers were just beginning to worry about EMI problems. Now, seven years later, the same old EMI problems are still with us, and some new ones have emerged as well.

Thus, when EDN asked us to update this popular guide, we readily agreed. As consulting engineers specializing in EMI/EMC issues, we continue to see a lot of misunderstanding and misconceptions about EMI. Between us, we share almost 70 years of collective EMI experience; for the past 14 years, we have dealt with nothing else but EMI. In spite of all our efforts (consulting, training, and publishing), we still see a lot of the same problems over and over again. Many of these problems could be avoided at little or no cost with simple design techniques.

If you have one of the original copies of the guide (they must be collectors' items by now), you'll recognize some of the same material. After all, the underlying principles and physics of EMC haven't changed. We have, however, updated time-sensitive information (such as regulations) and incorporated a number of new EMC concepts and ideas. The biggest improvements are the totally new chapter on components, the completely revised chapter on pc boards, and a dedicated chapter on emissions (previously covered in the chapter on RF interference).

We hope you enjoy our efforts and find them useful. Updating this guide has been a lot of work, but we saw it as our chance to give something back to our profession. As with the original, we've taken a nontraditional approach to EMC. You'll see very few equations (no integrals or partial differential equations) or arcane theories, and you'll find no excruciating details on EMC rules and regulations. Rather, we share our practical nuts-and-bolts ideas and insights, aimed at helping you identify, prevent, and fix EMI problems as you design your equipment and systems.

When we wrote the original guide, we were inspired by Bob Pease and his classic *EDN* series, *Troubleshooting Analog Circuits*. Reading his articles was almost like having a conversation with a friend. We've tried to capture that same feeling again. In fact, as we sit down at the keyboard, we often imagine that we're talking with a young, frustrated engineer that has just encountered his or her first big EMI problem. But we hope our insights also help those older duffers (like us) who are also often tormented by EMI.

We thank those who have graciously shared their time and EMI wisdom with us. It's impossible to name them all, but you know who you are. To our colleagues in the IEEE EMC Society, we owe you a special debt of gratitude. (If you are at all interested in EMI/EMC issues, this is the professional organization to join.) A special word of thanks to the editorial staff at EDN, who once again patiently supported this project. We have enjoyed reading EDN for years, and we have certainly benefited from the shared knowledge of the magazine's many contributors.

Finally, we owe special thanks to our families for supporting our dream of having our own consulting practice, as crazy and interesting as it has been. Once again, we dedicate this series to our wives, Mary Lou Gerke and Sharon Kimmel.

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DESIGNER'S GUIDE

EMI, noise, and interference—a different game

WELCOME TO THE UPDATED VERSION of the *EDN Designer's Guide to Electromagnetic Compatibility*. Since the original issue was published in 1994, there have been a lot of changes in the world of electronics, and many of those affect the EMI/EMC (electromagnetic interference and compatibility) of your equipment and designs. At the same time, underlying principles remain the same. This update attempts to combine the best of the old and the new regarding design tips and techniques for EMC. Welcome aboard!

There are two types of design engineers: those who have had EMI problems, and those who will. Regardless of which category you're in, you probably feel that EMI is a black art that defies logic, science, and perhaps even reason.

But like most technical problems, there is an underlying sense of order. There are rules and strategies— even regulations, thanks to government intervention. It's really just a game, and with some fundamental knowledge and insight, you can learn the EMI game. With enough time and practice, you can even become a pretty good player.

That's what this guide is all about: how to play the EMI game. It's a game we've played collectively for over 70 years as full-time consulting engineers that specialize in solving EMI problems. No, we're not EMI test engineers—we're design engineers like you, and our focus is on identifying, preventing, and fixing EMI problems at the equipment and systems levels. Because of that focus, we've seen some patterns emerge that can help you understand and solve EMI design problems. We've also encountered some myths and misunderstandings that only confuse the issues. We now hope to share some of that hard-earned knowledge with you, our colleagues in design.

This guide is a tutorial, not an in-depth treatise on EMI. It's aimed at the designer (not the EMI expert), and it's about EMI design issues (not testing or exotic theories.) It covers the EMI game in 14 articles. Each chapter is written to stand alone, so if you have a specific problem, you can just read the appropriate chapter. The first six chapters deal with the most common EMI problems and their impact on designs; the second six focus on EMI design solutions at the board, box, and systems levels; and the last two deal with testing and troubleshooting EMI problems.

One caution: We can't make you a 20-year EMI expert in 14 easy lessons, but we hope we can help you better understand the EMI game and how to play to win.

WHAT IS THIS THING CALLED EMI, ANYWAY?

If you're going to play any game, you need to know the rules. And you need to know the underlying philosophy of the game.

Let's start at the beginning with a few simple definitions. Although some of these terms may be used differently by others, we'll present how they're used in the EMI business.

EMI, or electromagnetic interference, is a problem. Simply stated, a piece of electronic equipment isn't working like it should, due to unwanted electrical energy in the wrong place at the wrong time doing the wrong things. EMI is a kind of electronic juvenile delinquent.

EMC, or electromagnetic compatibility, is the solution. Simply stated, a piece of electronic equipment works like it should in its intended electromagnetic

Source-Path-Receptor Model

ANY INTERFERENCE PROBLEM CAN BE BROKEN DOWN INTO
- THE SOURCE OF INTERFERENCE
- THE RECEPTOR OF INTERFERENCE
- THE PATH COUPLING THE SOURCE TO THE RECEPTOR

SOURCES	PATHS	RECEPTORS
MICROPROCESSORS	RADIATED	DIGITAL
VIDEO DRIVERS	EM FIELDS	RESET
SMPS	CROSSTALK	OTHER LOGIC
ESD	INDUCTIVE	LOW-LEVEL ANALOG
TRANSMITTERS	CAPACITIVE	RECEIVERS
RF GENERATORS	CONDUCTED	
POWER DISTURBANCES	SIGNAL	
LIGHTNING	POWER	
	GROUND	

ALL THREE ELEMENTS MUST BE PRESENT FOR AN EMI PROBLEM TO OCCUR

Figure 1

environment. At the same time, it doesn't cause problems for its electronic neighbors. EMC is a kind of electronic nirvana.

RFI, or radio-frequency interference, is a rather dated term for EMI. It harkens back to when most electronics used vacuum tubes and when most interference problems were related to radios. Later, there was TVI, or television interference, and then finally the more general term, EMI. RFI refers to interference from nearby radio transmitters, which is consistent with how the term is used in the EMC community.

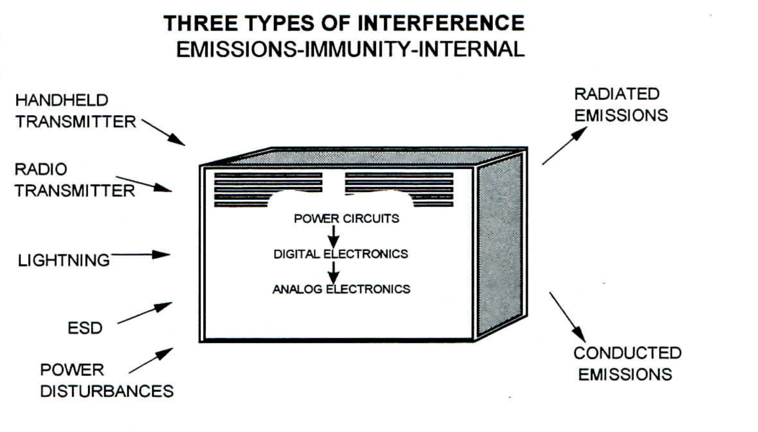
The terms, EMI, EMC, and RFI are often interchanged. It's not a big deal, but we'll try to be precise here. You should be careful with these terms, too. We've had several instances where part of the problem was in the communication; someone said one thing, and we heard another. We need to be sure we're all using the same language.

Signal integrity (SI) is a fairly new EMC-related term. While the primary emphasis is on maintaining clean signals on circuit boards, many of the same techniques apply to EMI/EMC issues as well. A key difference is that SI deals with millivolts and milliamps, and EMC often deals with microamps and microvolts for emissions, or often kilovolts or kiloamps for immunity. The chapter on EMC and circuit boards will look at SI in more detail.

Power quality (PQ) is another term that has become popular at the systems level. The term usually refers to power-related problems, such as surges, sags, transients, outages, etc. PQ is a special subset of the wider world of EMI/EMC, covered in more detail in the chapters on power disturbances and power-supply design.

Several more terms need a quick introduction. *Emissions* refers to energy originating from your equipment, which can be either radiated or conducted. *Susceptibility* refers to energy in the environment that can affect your equipment; *immunity* is another term for susceptibility, which can also be either radiated or conducted. This gives us four general categories for EMI radiated emissions (RE), radiated susceptibility (RS), conducted emissions (CE), and conducted susceptibility (CS). You often see these categories used in military and commercial standards for EMI.

Figure 2



SOME EMI PHILOSOPHY

One or our favorite discourses on philosophy in electronics was written by Bob Pease and appeared in *EDN*. In his article "Philosophy of troubleshooting," Bob states that "...a significant part of effective troubleshooting lies in the way that you think about the problem." So it is with EMI problems — it has much to do with how you think, not what you think. Here are four philosophical points about EMI for your consideration.

POINT 1—COMPLEX BUT NOT COMPLICATED

Many designers see EMI issues as a dark art, or worse. But in reality, all EMI problems can be explained by the basic laws of physics. Furthermore, once you understand the underlying principles, most EMI issues are really quite simple. Throughout this guide, simple models explain many common EMI problems.

EMI problems can become complex, however, because there are many variables, often with subtle and unexpected interactions. These variables can add up quickly, resulting in hundreds or thousands of possibilities for even simple situations.

For example, look at something as basic as a shielded cable. That's not too complicated, but even so, EMI questions quickly arise. Should you ground at one end, both, or neither? If you ground, where should it be? What about ground loops? Should you use braid or foil? What about double braid? Can you use plastic connectors, or should you use metal? Can you connect the signal ground to the shield ground? Should the wires be twisted? Should they have individual shields? Will a ferrite help? Several thousand combinations are possible with these questions alone.

The real challenge, then, is not in the physics, but in narrowing the possibilities to a reasonable number. Often, it's simply a matter of choosing the right tool for the job at hand.

POINT 2—EXCEPTIONS TO THE RULES

It's very common in the design world to develop design rules. Just follow these rules and you won't have any problems, right? If only real life were so simple.

Design rules are a sound concept, and most of the time they work. Unfortunately, EMI problems often occur when all of the design rules have been followed. The designer cries "foul," but to no avail. EMI problems are often the result of *exceptions* to the normal rules.

For example, when is a bypass capacitor not a bypass capacitor? When it's an inductor (due to lead length) at high frequencies. When is an inductor not an inductor? When it's a capacitor at high frequencies. When is a ground not a ground? When it's a sneak path for unwanted noise, often at low frequencies. When is a cable not a cable? When it's an antenna, particularly at multiple self-resonant frequencies.

Modifying the design rules can help some of the time, but even then, you can miss that one exception. The safest course with EMI problems is to assume that all the normal rules can be broken. There is, however, a silver lining. If you can find the exception, it's often very easy to fix the problem.

You can refer to these exceptions as *the hidden schematic*. Too often, you assume the components will be perfect at all frequencies, but they're not. Too often, you assume that the ground will have no impedance, but it will always have a finite impedance. Many times, EMI exceptions are about rules that were bent or broken.

Two other hidden concepts need discussion. The first is the combination of the hidden transmitter/receiver, and the second is the combination of the hidden antennas. These simple concepts can help you when dealing with radiated emissions or radiated immunity issues. The first identifies critical circuits, and the second identifies structures (traces, cables, boards) that support electromagnetic radiation. Since hidden antennas are highly dependent on physical dimensions, you may need to think more like a mechanical designer than a pure electronics designer.

POINT 3—EMI IS A MESSY NECESSITY

Many designers take great pride in the elegance of their creations, and rightfully so. In spite of what the nontechnical world may think of us techies, we often see real beauty and art in our scientific accomplishments.

And then along come those dirty little EMI problems. They force you to put in extra components, such as filters, that don't seem to contribute anything to the design function. They force you to route cables or wires in complex ways. They force you to add shielding, which complicates other issues like ventilation, and which adds cost and weight. Worst of all, they force you to think about all the dire possibilities and consequences of how your designs might ultimately be used.

But this messiness is often necessary if creations are to work in the real world. Furthermore, isn't that what engineering is all about: using technology to provide real-world solutions to real-world problems? If those problems include EMI, so be it—you need to prevent and solve them. You can't afford to ignore EMI problems, messy or not.

POINT 4—EMI REQUIRES A DIFFERENT VIEW

EMI often calls for a different way of looking at things. By now it should be apparent that the EMI game is different from the design game. It has a different set of rules and objectives.

We're very fond of analogies, and the simpler and cornier, the better, and we'll sprinkle some throughout this book. Some are borrowed and many are our own demented creations, probably the result of too many late nights agonizing over weird EMI problems.

This analogy is borrowed from a good friend and colleague, Dr Tom Chesworth of Seven Mountains Scientific Inc. Tom uses the games of chess and poker to compare the games of design and EMI. Chess (design) is a game of strategy played in a sedate environment; poker (EMI) is a game of tactics and odds played under pressure in a smoke-filled room. Each game has its own rules, and it takes a shift in thinking to switch from one game to another.

Tom stresses that in poker (like EMI), it's possible to lose with a good hand, yet win with a poor hand. Furthermore, the real problem is not in the cards you can see but in those you can't. You may need to hedge your bets (such as designing for threats that may or may not be there), and you may need to take some chances (such as experimenting when troubleshooting). Every game is different, but if you win more than you lose, you can play again tomorrow.

So it is with EMI problems. You need to shift your thinking if you want to stay in the game. You'll have a lot more success with a lot less frustration. Who knows? You might even start to enjoy an occasional game of EMI.

AN OVERVIEW OF PROBLEMS AND SOLUTIONS

That's enough philosophy for now. It's time to move from the abstract to the concrete. It's time to identify EMI problems and look at how to attack them.

EMI problems can vary widely, and you've probably faced several yourself. Last month, the production line was down because of power glitches; this month, your new product is failing an FCC test; and next month, you'll get a call about flaky field problems with a product that's several years old. All of the problems are different, but all of them are caused by this thing called EMI.

So how do you organize the information about these diverse problems? What do they have in common? How do they differ? What additional information do you need? How can you start to make some sense out of all this chaos?

One way is to approach EMI problems the same way a doctor approaches medical problems. You need to diagnose the problem before you can prescribe a solution. (If this is starting to sound like another analogy, well, it is.) But you can't ask just any old question, and furthermore, you need to organize the information you obtain. You need a diagnostic framework, a skeleton on which to hang all that information.

A simple model that's popular in the EMI engineering community is the source-path-receptor model. Simply stated, you need three elements for an EMI problem.

- a source of energy
- a receptor that is upset by the energy; and
- a coupling path between the source and receptor for the unwanted energy.

All three must exist at the same time. Sometimes you can identify all three elements, and other times you can only guess. It may be simple, but it does help you to organize your information.

Figures 1 and **2** illustrate these concepts, giving typical sources, paths, and receptors. As you can see, there are plenty of possibilities, but keep in mind that not all combinations end up as a problem.

The second part of this diagnostic phase is to flesh out the information. Several parameters can affect the diagnosis. For example, how sensitive is your circuitry? What is the frequency content of the threat? How long are the cables?

We try to gather information on at least five key parameters, which we dub *FAT-ID*, which stands for *frequency, amplitude, time, impedance,* and *dimensions*. Later on, you'll hear more about "fatness" and EMI, so this makes a good EMI mnemonic (or maybe a bad pun).

Frequency—This is a key parameter for any EMI problem. If you have an EMI problem with a communications system (or an FCC emissions test failure), you may know the exact frequency. At other times, you may need to guess or make an estimate. Usually, the higher the frequency, the more likely the coupling path is radiated; the lower the frequency, the more likely the coupling path is conducted.

Amplitude—You need to assess both the source and the receptor together on this one. The most severe combination is a strong source (such as a high-powered radio transmitter) near a very sensitive receptor (such as microvolt-level instrumentation). On the other hand, a weak source near an insensitive receptor may not even cause an EMI problem.

FIVE KEY THREATS (WITH TYPICAL LEVELS)

Figure 3

1. USA, IEC, EU	RADIATED: 30 - 300 µV/M, 30 MHz TO 1 GHz CONDUCTED: 250 µV - 3 MV, 150 kHz TO 30 MHz
2. IEC 61000-4-2	2 TO 15 kV, AIR 2 TO 8 kV CONTACT
3. IEC 61000-4-3	1 TO 10 V/M
4. IEC 61000-4-4 (EFT)	1- TO 4-kV BURST
IEC 61000-4-5 (SURGE)	1- TO 4-kV TRANSIENT
IEEE C62.41	6 kV/3000A CM, 500A DM
IEC 61000-4-6 (INJECTED RF)	10V RMS, 0.15 TO 80 MHz
5. ANALOG	µV - mV TYPICAL OPERATIONAL LEVELS
DIGITAL	100- TO 500-mV TYPICAL NOISE MARGIN

Time—This parameter has two dimensions: long term and short term. For the long term, determine if there is a cause-and-effect relationship. Do the lights dim only when a motor is turned on? (Suspect a power disturbance.) Do upsets occur only when someone touches the unit? (Suspect ESD.)

For the short term, look at rise times and clock rates, which can be converted to equivalent frequencies. Generally, you work in the frequency domain rather than the time domain for EMI problems. A good rule is to use an equivalent EMI frequency of $1/(\pi \times \text{rise time})$ for digital signals and transients. For 1-nsec logic, this means an equivalent EMI frequency of over 300 MHz; at 300 psec, it increases to over 1 GHz. No wonder we have EMI problems with high-speed systems.

Impedance—You need to determine the circuit impedance level of both the source and receptors. Similar source-receptor impedance levels are more likely to result in problems than different source-receptor impedance levels. Conversely, high-impedance sources have minimal impact on low-impedance receptors, and vice versa. This can be also be related to radiated, or field, coupling. High impedances are associated with electric fields, and low impedances are associated with magnetic fields. Note that impedances change rapidly near resonance, whether an LC resonance or a cable resonance, creating either very high or very low impedance states.

Dimensions—Finally, you must gather the physical dimensions, particularly cable lengths (which act as antennas) and enclosure openings and seams (which also act as slot antennas). Take a critical look at parallel cable or wiring runs (possible crosstalk) and even short wires on ground paths or cable pigtails. What you're looking for are lengths that represent significant fractions of a wavelength (the higher the frequency, the shorter the wavelength) or significant fractions of a rise-time distance (the shorter the rise time, the shorter the distance). For the former, a good rule of thumb is $^1/_{20}$ of a wavelength (about 6 in. at 100 MHz); for the latter, it helps to remember that 1 nsec translates to about 1 ft in free space and about 6 in. on a board.

A compounding factor in dimensions is resonance, which can amplify radiated emissions or immunity problems. For example, at multiples of ¼, wavelength cables can act like resonant antennas — very efficient at radiating and absorbing RF energy. And it's not just cables that can act this way. The same problems can occur due to circuit boards (hidden dipole or patch antenna), enclosure seams (hidden slot antenna), and even enclosures themselves (hidden cavity resonators.) Note that ¼ of a wavelength at 300 MHz is 25 cm, or about 10 in. Is your 10-in. circuit board an efficient antenna to your 300-MHz clock? You bet it is.

So there you have it: a quick and dirty way to organize data on an EMI problem. Source, path, and receptor and the FAT-ID parameters. Don't forget resonances, either. You may not have all the answers right away, but it helps to know which questions to ask in the first place. Remember, at this point, you're like a doctor trying to make a preliminary diagnosis or to prevent disease through good EMI hygiene. (This step is important. You wouldn't want a doctor to prescribe a drug without even considering your symptoms or situation.)

DEFINE OBJECTIVES BEFORE YOU BEGIN

As the old saying goes, "If I don't know where I'm going, any road will take me there." Before starting on this little journey into EMI-land, you need to know where you're going and why you're going there. What are the objectives and the constraints? Here are five key questions we ask our clients when we begin working with them on EMI design issues.

1. What are you designing? Is it a supercomputer or a control system? What type of technology are you using (analog, high-speed digital, motors and relays, etc)? Who will use it? At this point, detailed information is not needed—just the big picture.

2. What are your EMI requirements? Are there EMI-specific regulations to meet? If so, do you know your equipment category (Class A or B for commercial regulations, intended environment for military regulations)? Are there voluntary requirements that might apply (industrial standards, company guidelines)? Are you specifically exempt from certain regulations? At this point, you need to determine what you *must* meet.

3. What is your intended environment? Is it electromagnetically harsh? Is the power noisy? Are there lots of radio transmitters in use? What do you anticipate over the next five or ten years?

Even if you're exempt from mandatory EMI requirements, you may want to apply your own internal voluntary standards. For example, industrial controls are generally exempt from both emission and immunity standards in the United States, but many industrial manufacturers apply their own stringent EMI standards to their products. As a conscientious designer, you need to determine what you *should* meet, not just what you must meet.

4. What are your nontechnical constraints? What are your typical products costs? What are your anticipated volumes? What is your market window? Although nontechnical, these are valid engineering concerns. If you have a high-volume, price-sensitive product, then shaving the last few pennies out of your EMI fixes makes sense. On the other hand, if you're only building a hundred units and each one costs $100,000, it's probably cheaper to overdesign than to optimize the design. Look at the total life-cycle costs, not just the individual component cost.

5. What is the cost of failure? What happens if your equipment fails in the field? (A single field failure can easily cost thousands.) How much will it cost to re-test and requalify your equipment? (Typical costs range from $25,000 to $50,000 when you factor in engineering time.) How much will it cost if your equipment is named in a lawsuit? (Probably $100,000 and up. We've seen several cases where EMI was blamed in a lawsuit. Right or wrong, it happens.) Look at your risk and consider it as you make your EMI decisions.

After you've defined your objectives, you're ready to begin. By the way, don't be afraid to make tradeoffs, and when you do, be sure to have a back-up plan.

FIVE KEY THREATS FACING DESIGNERS

The final part of this introductory chapter identifies five key problem areas (**Figure 3**). There may be a few more, but these should cover 95% of the EMI problems you'll encounter.

THREAT 1—REGULATIONS

Anyone who has ever failed an EMI test appreciates this threat. And while it may be a pain to meet requirements, it's chilling to think what our electromagnetic environment might look like without these requirements (**Figure 4**).

Thanks to international treaties, some form of EMI regulations has actually existed for years. In the most general form, regulations protect the radio spectrum and limit spurious radiation from both intended radiators (such as transmitters) and unintended radiators (any electronic system). In the good old days (pre-computer), most unintended radiators were not much of a problem. Because of computer clocks (oscillators) and lots of cables (antennas), the game has changed drastically in the past few years. The microprocessor explosion in the mid-1970s led to a corresponding explosion in complaints of EMI problems with licensed communications systems. Most were television-related, although there are horror stories of aircraft or police communications being jammed by a nearby computer.

EMI REGULATIONS

COMMERCIAL REGULATIONS
MANDATORY
FOCUS IN USA - EMISSIONS
FOCUS IN EUROPE - EMISSIONS AND IMMUNITY
MILITARY REGULATIONS
CONTRACTUAL
CONTROL EMISSIONS AND IMMUNITY
AVIONICS REGULATIONS
CONTRACTUAL
CONTROL EMISSIONS AND IMMUNITY
AUTOMOTIVE
VOLUNTARY IN US, MANDATORY IN EUROPE
CONTROL EMISSIONS AND IMMUNITY
MEDICAL REGULATIONS
VOLUNTARY IN US (DE FACTO MANDATORY)
MANDATORY IN EUROPE
CONTROL EMISSIONS AND IMMUNITY

Figure 4

These problems soon resulted in very specific regulations that limit the emissions from computer or microprocessor- based equipment. The United States has the infamous FCC Part 15 regulations. Japan has the VCCI (Voluntary Control Council for Interference) limits, which are no longer "voluntary." In Europe, the VDE (Verband Deutscher Electrotechniker) of West Germany was a driving force, although those regulations were replaced in 1996 by the EU (European Union) regulations, which affect almost all of Europe.

Originally, commercial EMI regulations were based on controlling emissions and were aimed at protecting a nearby television or broadcast radio receiver. The Europeans changed that in 1996 with the addition of mandatory immunity requirements as well. The United States and Japan, however, still only require compliance to emissions requirements.

The military has had mandatory EMI regulations for years (both emissions and immunity), and most military designers are well versed in meeting these requirements.

For years, medical devices and industrial controls were exempt from EMI regulations in the United States. In recent years, however, the medical industry has come under scrutiny from the FDA (Food and Drug Administration) in the United States and overseas from the EU through a special medical-device standard. Furthermore, industrial controls are not exempt in Europe. Industrial and medical designers have had to scramble to come up to speed on EMI design issues.

The vehicular industry has had strict "voluntary" standards (emissions and immunity) for many years, based on real-world constraints faced by its equipment. Special EMI requirements exist for the automotive, avionics, railroad, and even farm-machinery electronics.

A common thread in all EMI standards is the attempt to simulate the intended environment in which the equipment will be placed. Thus, if you pass the required tests, you have high probability for success in the real world. EMI regulations are here to stay, and they will probably get tougher in the years ahead. The good news is that meeting these requirements usually results in a more robust and more reliable product.

THREAT 2—RFI

In this book, we'll use the term RFI, or radio-frequency interference, to describe the problem of interference to a system from a nearby transmitter. In terms of our diagnostic model, the source is a radio transmitter, the path is electromagnetic radiation, and the receptor is a system that is upset by the RF energy.

RFI is a serious threat to all modern electronic systems, due in large part to the proliferation of radio transmitters, including both large, high-power systems (television, radar, telemetry) as well as small, low-power systems (handheld radios and cellular telephones). The threat is particularly acute with sensitive analog circuitry, which can be overwhelmed by a nearby source of RF energy.

The problem is not always with high power and big antennas. In fact, most of the problems we see today are caused by low-power handheld radios operated close to equipment. The important parameter is field strength, which is a function of both the transmitter power and the distance from the antenna. Typical failure levels are at electric field strengths of 1 to 10V/m. As a rule of thumb, a 1W radio at 1m has a field strength of about 5V/m, so problems with small handheld radios can and do occur.

The European immunity limits are in the 1 to 10V/m range. Meeting these realistic levels can be difficult, however, and require careful attention to EMI design details. The simple emission approaches alone are usually inadequate.

THREAT 3—ELECTROSTATIC DISCHARGE

ESD is also a serious threat to modern electronic systems. Incidentally, in this guide, the term "ESD" describes the actual discharge to a system, not to individual components.

It no longer takes a direct discharge to cause problems; the intense electromagnetic field from a nearby indirect discharge can easily upset a system. We've seen this effect up to 20 ft away.

Typically, the indirect discharge causes upsets, and the direct discharge causes upset or damage. The damage may be immediate or latent.

The source of indirect discharges can be insidious. Most of today's requirements are based on human discharge. For example, a person touches a file cabinet and a nearby computer hangs. But recent research suggests that there are many sources of indirect discharge. One of the most interesting is the "micro-discharge" that occurs when someone sits down or gets up from a common desk chair. We once saw our EMC colleague Doug Smith demonstrate this effect with a simple AM radio next to a chair. When someone got out of the chair, the radio would crackle for a minute or more. Doug has been able to correlate these micro-discharges to actual computer failures. What will we need to worry about next?

A human ESD event is very rapid, typically with 1- to 3-nsec rise times and peak currents in the tens of amperes. The high currents and high rates of change cause EMI problems. ESD is considered a high-frequency problem; at 1 nsec, the equivalent EMI frequency is greater than 300 MHz. This may not be fast enough for all cases, though, as recent ESD tests have measured ESD spikes in the 100-psec range, which would push the equivalent EMI frequency well into the gigahertz range.

You need to consider ESD in any new design, regardless of whether it is required by regulations. The laws of physics dictate that it will be an EMI problem.

THREAT 4—POWER DISTURBANCES

Power disturbances are emerging as a serious EMI problem for all electronic systems. It's not that the environment is getting worse, but rather that modern electronic systems are becoming more vulnerable to power-line disturbances. The problem is compounded by the lack of definitions and guidelines, although this situation is beginning to change.

Power guidelines range from simple high/low-voltage limits to more sophisticated requirements such as the EFT (electrically fast transient) or the lightning surge transient. EFT simulates arcing and other high-speed noise that can play havoc with microprocessor-based systems. The high speed is usually ignored by older, slower electronics. The lightning transient test can be destructive, but then so can an actual lightning hit to the system power lines. Recent power guidelines also call for injecting RF into the power lines, which simulates having a nearby radio transmitter spraying the power wiring with RF.

Analog and digital circuits respond differently to power disturbances and that can confuse things. Digital circuits are easily fooled by spikes, and analog circuits can be fooled by sags, surges, and RF energy. Both types of circuits can be affected by severe long-term sags, which can starve the power supply of needed energy.

There is a new concern over power-line harmonics, caused by nonlinear loads such as switched-mode power supplies or other electronic loads. These loads typically consume power at the peak of the cycle, rather than over the entire sine wave. This can cause harmonic generation and waveform distortions that stress the power-distribution system. As a result, new regulations and guidelines have emerged for power-line harmonics and its first cousin, flicker.

THREAT 5—SELF COMPATIBILITY

The final threat is incompatibility internal to the system and includes problems with mixed technologies, such as analog/digital or motors/relay/digital. In the first case, the digital circuits typically jam the analog circuits; in the second case, the motors and relays jam the digital circuits. There is a third case, high-speed digital, where the digital circuits jam themselves. (This important special case is often referred to as signal integrity.)

Although most designers are well aware of these problems, they may not consider them EMI problems. Nevertheless, many of the same design techniques can be applied equally well to problems entirely inside the system. Remember, the laws of physics don't care where you draw the boundaries.

Finally, you can prevent many EMI problems by paying attention at the internal levels. You can save money, too. A few cents in decoupling capacitors on critical circuits is much cheaper than several dollars in shielding or filtering, and it probably results in a more solid design as well. Remember, every EMI problem ultimately begins or ends at the circuit level.□

DESIGNER'S GUIDE

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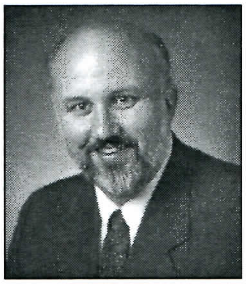

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