Application of the MREMC Algorithms for Performance-Based Circuit Board Design

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Abstract—**Meeting radiated electromagnetic emissions requirements can be a significant challenge for engineers designing today's electronic devices. Traditional approaches rely heavily on design rules. However, the optimum circuit board designs often violate well-known design rules, while successfully controlling radiated emissions. This paper describes the application of a design methodology that relates design decisions to the product's requirements. The methodology takes advantage of maximum radiated emissions calculations to identify the components and circuits capable of causing the system to fail to meet requirements.**

Keywords—*EMC; PCB; Electromagnetic Compatibility; Circuit Board; Design*

I. INTRODUCTION

The goal of performance-based EMC design of printed circuit boards is to ensure that no circuit on the board is capable of being the source of radiated or conducted emissions that are strong enough to cause the system to fail to meet requirements. A similar approach can be applied to ensure that no circuit or component in a given configuration is capable of being interfered with by external transients or fields resulting from system level immunity tests. A key tool in this design process is a set of algorithms that calculate the worst-case electromagnetic coupling in various situations.

Algorithms for calculating the maximum possible radiated emissions from circuit board structures have been developed over the past 19 years [1-17]. The first algorithms were developed by researchers at the University of Missouri-Rolla (now Missouri S&T) in collaboration with a number of electronics hardware and software companies participating in the *UMR EMI Expert System Consortium*. Over the years, these algorithms have been refined, replaced and expanded culminating a set of tools that can be used to identify most potential EMI problems in a circuit board layout before the board has been built or tested.

Four of these algorithms have been coded into a web-based tool called the Maximum Radiated Emissions Calculator (MREMC). This paper provides a brief overview of the performance-based EMC design approach and demonstrates how the MREMC tool can be used to identify potential EMI problems.

II. PERFORMANCE-BASED EMC DESIGN

The goal of performance-based EMC design is to ensure that each component and circuit on a printed circuit board is incapable of causing the device to fail to meet its EMC requirements [18]. An important step in this process is the calculation of the maximum possible system-level radiated emissions originating from each circuit. In general, there may be several ways that power coupled from a circuit can ultimately result in radiated emissions. Therefore, it is necessary to evaluate the worst-case coupling from each circuit to every possible structure that might serve as the "antenna" responsible for the radiated emissions. Various algorithms are applied to calculate the power coupled from each circuit to every possible antenna with all unknown variables (e.g. dielectric constants, cable lengths, etc.) set to their worst-case values. On a typical circuit board with hundreds of circuits and several potential antenna structures, thousands of calculations might be required. All of the calculations are closed-form, so they can be performed relatively quickly on a computer. Nevertheless, in order to have a reasonable chance of ensuring that thousands of source-antenna combinations are all incapable of creating an EMI problem, it is generally necessary to start with a very good design that controls digital transition times, routes signals intelligently, and pays attention to the relative positions of the strongest sources and the best antennas.

A. Identify the EMC Requirement

The first step in the process of performance-based EMC design is to identify the requirements. For example, CISPR 22 requires that the radiated field strength 10 meters from a Class A product be no greater than 47 dB(μV/m) or 224 μV/m between 230 MHz and 1 GHz. This means that the power radiated must be less than:

$$P_{RAD} < \frac{1}{2} \frac{|E|^2}{\eta_0} \frac{4\pi r^2}{D_{max}}$$
$$< \frac{1}{2} \frac{\left|224 \times 10^{-6} \text{ V/m}\right|^2}{377\,\Omega} \frac{4\pi(10\,m)^2}{1.6} \quad (1)$$
$$< 52\,\text{nW}$$

where $r = 10$ m is the distance from the source, $\eta_0 = 377$ Ω is the intrinsic impedance of free space and D_{max} is the maximum directivity of the radiating structure. (In this case, we'll assume the radiating structure is omnidirectional, so the directivity should not exceed 1.6.) Equation (1) indicates that a circuit that is incapable of supplying more than 52 nW of power will not be capable of being the sole source of a radiated emissions failure in this frequency range. Similarly, it can be shown that at least 10 nW of radiated power is required to exceed the CISPR Class A specification between 30 MHz and 230 MHz. Performance-based EMC design requires that the maximum power that these circuits are capable of generating is known and/or controlled. This will limit the number of possible source-antenna combinations that must be evaluated; and define the bandwidth of the calculations.

B. Control and Identify all Signal Bandwidths

One relatively easy way to limit the unnecessary power in a signal or circuit is to limit the bandwidth to those frequencies necessary for the proper operation of the device. For analog circuits, this is usually done by filtering. For baseband digital circuits, this is accomplished by controlling transition times.

Any digital circuit source that cannot deliver at least 52 nW of power at a frequency between 230 MHz and 1 GHz cannot be the sole source of radiated emissions that exceed the specification in this frequency range. This is true no matter how poorly the circuit is routed and no matter what other circuits or structures the signal may couple to. A primary objective in performance-based EMC design is to ensure that no source produces power capable of exceeding the specification unless that power is necessary for the circuit to serve its intended function.

By default, digital signals at 100 Mbps or slower often operate with transition times on the order of 1 ns or less depending on the source resistance and load capacitance (or parasitic inductance for a matched termination). This is faster than necessary to convey the signal and provides opportunities for unintentional coupling that could result in excessive radiated emissions. Slowing transition times to 20% of the bit width can significantly reduce the power in digital signals at frequencies above the fifth harmonic. For example, suppose our signal source is a clock output with a 2.5-volt signal amplitude and a 20-ohm source resistance (i.e. 125 mA max current). If the operating frequency is 32 MHz and the signal terminates in a 5-pF load, the bit width is 31 ns and the transition time is approximately 0.22 ns (2.2RC). The signal voltage at each odd n^{th} harmonic of the clock frequency (assuming a trapezoidal waveform) would be given by:

$$V_n = \left| \frac{2A}{n\pi} \right| \left| \frac{sin\left(\frac{n\pi t_r}{T} \right)}{\left(\frac{n\pi t_r}{T} \right)} \right| \leq \left| \frac{2A}{n\pi} \right| \times MIN \left\{ 1 \quad OR \quad \left| \frac{T}{n\pi t_r} \right| \right\}$$

(2)

where A is the peak-to-peak signal voltage, t_r is the signal transition time, and T is the signal period.

Now let's assume that all of the power produced by the source is radiated (i.e. the source directly drives a lossless matched antenna), then

$$E_{RAD} \leq \sqrt{\eta_0 \frac{|V_n|^2}{R} \frac{D_{max}}{4\pi r^2}} .$$

(3)

Fig. 1 shows a plot of the maximum possible radiated emissions compared to the CISPR Class A radiated emissions test limit. Note that this signal source is capable of producing radiated emissions about 25 dB above the limit at 1 GHz and 65 dB above the limit at 100 MHz.
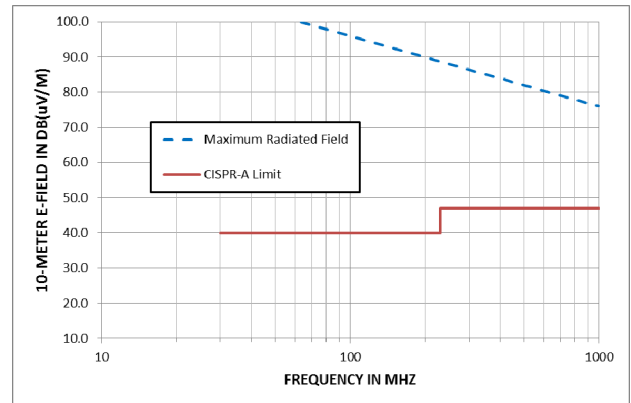

Fig. 1. Maximum radiated emissions from a 32-MHz, 2.5-volt, 125-mA source with a 0.22-ns transition time.

The 0.22-ns transition time for this circuit is much faster than necessary to convey the data. Adding a 520-Ω resistor in series with the driver slows the transition time to 6.0 ns (20% of the bit width). This reduces the amplitude of the upper harmonics and reduces the maximum current at all frequencies without adversely affecting the signal integrity. Fig. 2 shows a plot of the maximum possible radiated emissions from the same circuit with a 520-Ω series resistor. Note that now the component is not capable of producing radiated emissions above the limit at any frequency higher than 500 MHz. Thus, by controlling the transition time, any further analysis of this circuit can be limited to frequencies below 500 MHz.
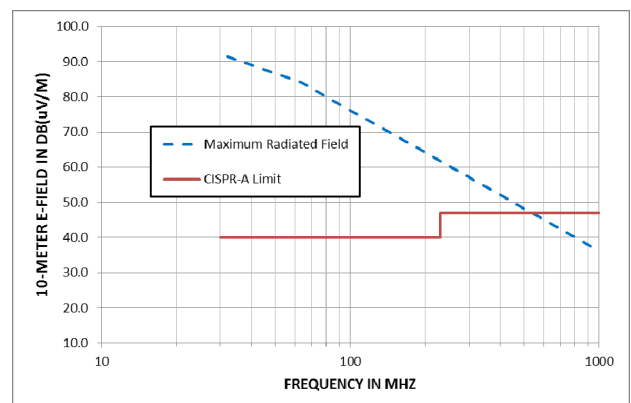

Fig. 2. Maximum radiated emissions from a 32-MHz, 2.5-volt source in series with a 520-Ω resistor (6.0-ns transition time).

C. Evaluate Radiation Mechanisms

After controlling all transition times, many of the circuits on a typical circuit board will be incapable of supplying enough power to exceed the specification at any frequency. These circuits do not need to be considered further. For the remaining circuits and frequencies all possible radiation mechanisms must be evaluated. A radiation mechanism is a means by which power in a signal can couple to a structure that serves as the antenna. Possible radiation mechanisms include:

- Differential-mode radiation where the signal path itself acts as an antenna and radiates some of the signal;

- Coupling from the signal path to other structures on the board that act as antennas (e.g. large heatsinks or power planes);

- Coupling of the signal that induces common-mode currents on attached cables or the enclosure.

These radiation mechanisms can be evaluated using the maximum radiated emissions algorithms that were developed for the EMC expert system. The algorithms implement closed-form radiated emission calculations that were developed and validated in a series of published papers [3-17]. Several of these are implemented in an open-source web-based calculator [19].

Maximum emissions calculations basically assume that everything not known about a particular source/antenna geometry is worst-case. For example, if a source drives a cable of unknown length, the calculator assumes that the cable is a lossless, resonant antenna at every frequency of interest. If a transition time is unknown, it is assumed to be zero. While these calculations will generally overestimate the actual measured radiated emissions, they provide an upper bound based on what is known about the system. For EMC work, an upper bound is generally preferable to an exact calculation of emissions from a specific configuration that may not maximize the radiation.

III. DESIGN EXAMPLE

To illustrate how the MREMC algorithms are applied, consider the 32-MHz clock circuit described in the previous section. Assume it is implemented on a printed circuit board and propagates down a 15-cm long, 1-mm wide microstrip trace that is 0.25 mm above a solid return plane. The transition time has been slowed to 6.0 ns using a 520-Ω series resistor. As indicated in Fig. 2, there is enough power in this signal to present a radiated emissions problem at harmonics up to 500 MHz, so the circuit can't be ignored. The maximum possible emissions from this circuit must be evaluated up to 500 MHz for each possible radiation mechanism.

A. Differential-Mode Radiation

Direct radiation of a signal by the conductors that form the signal path is known as differential-mode radiation. It basically occurs because the fields developed by currents flowing in one direction (e.g. source-to-load) are not exactly canceled by the fields developed by the return currents flowing in the opposite direction. A basic formula for the radiated field from two parallel wire segments carrying a differential-mode current is derived in [20]. This calculation can be performed using the MREMC calculator [21]. Differential-mode radiation is very inefficient for microstrip trace configurations and it is unlikely that any of the circuits on a well-designed board will be capable of radiating in this manner enough to exceed a radiated emissions specification. An evaluation of the example circuit using the Differential-Mode EMI calculator [19] indicates that the maximum differential-mode radiation is at least 35 dB below the CISPR-A specification at all frequencies below 500 MHz.

B. Common-mode Currents Induced on Cables

Another possible radiation mechanism is electric or magnetic field coupling from the example circuit that induces common-mode currents on attached cables. This is one of the most common reasons that some systems fail to meet radiated emissions requirements. Common-mode currents as low as 15 µA induced on a 1-meter cable can result in radiated fields that exceed the CISPR-A limit. The physics of this coupling was first described and quantified in [3, 4], and refinements to the original model have been developed over the years [8, 10, 11, 13, 15]. There are two forms of coupling to be evaluated. Electric-field (or voltage-driven) coupling results from a difference in the electric potential of the trace relative to the cable. Magnetic-field (or current-driven) coupling is the result of a mutual inductance between the signal current path and the effective antenna formed by the board and its attached cables. Equations for determining the amplitude of an equivalent common-mode voltage source that drives the cable are derived and validated in [8] and [13]. Equations for determining the maximum possible radiated emissions from a board-cable structure driven by a common-mode voltage source are derived and validated in [11] and [15].

The algorithms implementing the equations derived in [13] and [15] were incorporated in the MREMC calculator as documented in [22]. Fig. 3 shows the results of these algorithms applied to the 32-MHz clock trace when it is located on a board that is 40 cm x 20 cm. In this case the board has one attached cable. The position of the attached cable is indicated by the black square in the "Top View" section of the figure. The trace location is indicated by the red line. Note that the calculator plots the 3-meter field strength. Subtracting 10 dB from this value yields the 10-meter field strength. For this configuration, the electric-field coupling is stronger than the magnetic-field coupling, but the maximum possible radiation due to electric-field coupling is still below the CISPR-A limit (50 dBµV/m on this plot).

Although the calculated emissions are within a few dB of the limit at 32 MHz, this is a worst-case calculation and therefore the circuit need not be considered further. By modifying the parameters in the calculator, it is easy to show that increasing the trace height or moving the trace closer to the corner would cause the maximum radiated emissions enough to exceed the limit at 32 MHz, requiring the designer to take additional steps to ensure compliance. The online tool also includes a calculator for determining the maximum possible radiated emissions that can occur when there is crosstalk between a source circuit and an I/O circuit that carries the

coupled noise off the board [23]; as well as a calculator for determining the maximum possible radiation due to power bus noise [24].
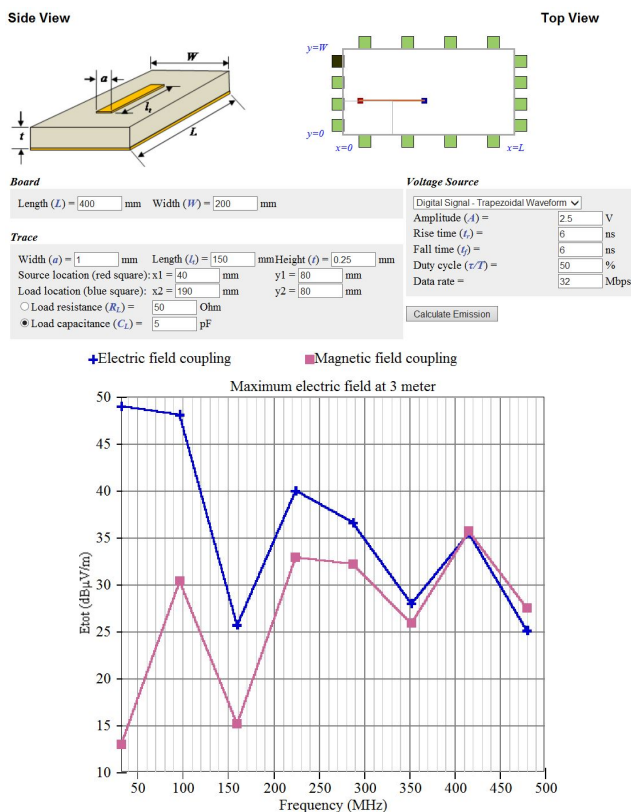

Fig. 3. Results of common-mode coupling calculation for the 32-MHz clock trace on a board with one attached cable.

IV. CONCLUSION

Although the performance-based EMC design approach requires more time and effort than a design-rule based approach, it is much more likely to result in a low-cost, compliant design on the first pass. The maximum radiated emissions algorithms play a key role in this approach. These algorithms are open-source and continue to be refined and expanded as more experience is gained applying them to real-world product designs.

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