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High-Speed Simulation of PCB Emission and Immunity with Frequency-Domain IC/LSI Source Models

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Abstract

Some recent results from research conducted in the EMC group at Okayama University are reviewed. A scheme for power-bus modeling with an analytical method is introduced. A linear macro-model for ICs/LSIs, called the LECCS model, has been developed for EMI and EMS simulation. This model has a very simple structure and is sufficiently accurate. Combining the LECCS model with analytical simulation techniques for power-bus resonance simulation provides a method for high-speed EMI simulation and decoupling evaluation related to PCB and LSI design. A useful explanation of the common-mode excitation mechanism, which utilizes the imbalance factor of a transmission line, is also presented. Some of the results were investigated by implementing prototypes of a high-speed EMI simulator, HISES.

Keywords

printed circuit board, modeling, power-bus resonance, device model, LECCS model, common mode, imbalance, EMI simulator, HISES

INTRODUCTION

Total EMC design of a printed circuit board (PCB), which enables us to evaluate and control the emission and immunity characteristics before fabricating an electronic system, is one of the ultimate goals of circuit engineers. The target frequency range is increasing up to several gigahertz with the recent, remarkable progress in digital systems. However, a typical high-speed digital PCB contains a number of ICs/LSIs as noise sources and is densely mounted with components and traces, so it is difficult to characterize a full PCB with devices.

Another possible way to obtain the EMC characteristics of a PCB is to model it in terms of sub-components and simulate its operation numerically or analytically. Generally, full-wave simulation techniques, such as the FDTD method or the method of moments, or equivalent circuit simulation techniques, such as the PEEC method, have been applied to solve PCB EMC problems.

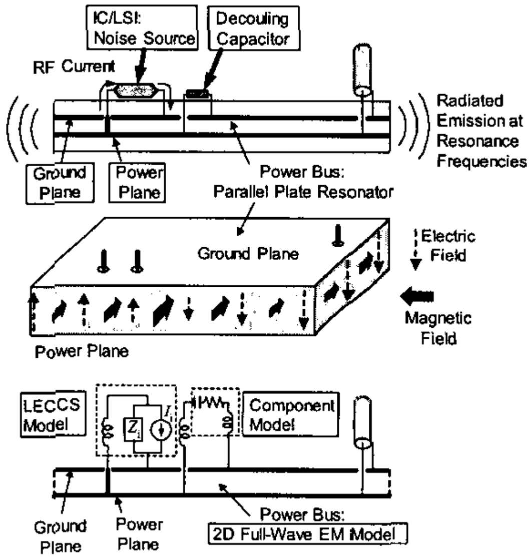

Figure 1. Modeling of EMI Caused by Power-Bus Resonance.

Figure 1 shows an example of "power-bus resonance", which causes electromagnetic emission at resonance frequencies. The pair consisting of a power plane and a ground plane, or a "power bus", is modeled as a parallel plate resonator, which acts as an emission antenna. The power bus is excited by active devices via the power and ground interconnections, or via holes. The RF current in a via is the excitation source. The device is usually a nonlinear switching device. For signal integrity (SI) problems, and sometimes for power integrity (PI) problems, device models such as SPICE, IBIS, or

IMIC are used; however, these models are nonlinear. They are suitable for time-domain simulation but require long calculation times. As for EMI (electromagnetic interference, or radiated emission) or EMS (electromagnetic susceptibility, or immunity) problems, frequency-domain simulation is much more suitable than time-domain simulation.

To achieve fast EMI/EMS simulation, we have investigated a linear macro-model for digital IC/LSIs, which was recently named the LECCS[1] model. The model was originally proposed for the core circuits of ICs/LSIs[1,2]. It was then extended to a model for devices that have output drivers [3].

We modeled the power bus of a PCB as an electromagnetic (EM) planar (2D) circuit by applying a full cavity-mode resonator model and the segmentation method [4]. Combining the LECCS model of a device as a noise source and the power bus model acting as a resonator and an antenna, we then analyzed the EM field distribution and radiated emission from the PCB, as shown in Fig. 1. The simulation was performed in the frequency domain, which requires a very short time for calculation. Some parts of the simulation was implemented as an EMI simulator with a GUI, which we call HISES.[2]

In this paper, we review our recent results on power-bus modeling[5], IC/LSI modeling[6], and EMI/EMS and decoupling simulations with the LECCS model[7,8]. We also model the common-mode excitation on a PCB with a narrow ground plane[9,10]. The common-mode model was implemented as another part of HISES and is also demonstrated here.

POWER-BUS MODELING: HISES

Power-bus resonance was modeled by using Green's functions to obtain a closed-form expression for the impedance Z-matrix of the power and ground planes, and a fast algorithm was developed. For a rectangular power bus, the expression of the Z-matrix is in the form of a singly infinite series [4]. A power bus is modeled as a network with multiple ports for mounting components. Once the EM characteristics are expressed by a Z-matrix, a simulation with components can be performed as an ordinary circuit simulation. The expression of the Z-matrix for a rectangular board is analytical, and the dimension of calculation is determined only by the number of actual ports, plus one additional observation port. We do not have to divide the planes in small elements for numerical calculation, which helps to reduce the order of the calculation. The calculation algorithm for this case was implemented as HISES Ver. 3.0.

For power-bus structures with more general shapes, the planes were segmented into sub-rectangles[5,11,12]. The more general approach was implemented as HISES Ver. 3.1. The sub-rectangles are connected by virtual ports between adjacent segments. Figure 2 shows a simulation example with HISES Ver. 3.1. The effect of modifying the shape of the power plane or the positioning of the decoupling capacitors can be evaluated in a very short time. This technique has been further extended with triangular segments.

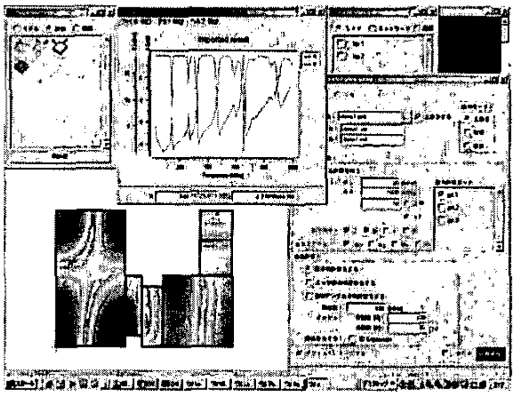

Figure 2. High-Speed EMI Simulator (HISES Ver.3.1).

In simulation, the power-bus model can be excited by a model of an active device with some decoupling components [7,8], as shown in Fig 1. For a rectangular PCB, EMI and power decoupling simulation were implemented in HISES Ver. 3.2 with the LECCS model, as described in the next section.

EMC MODELING OF IC/LSI

Linear noise source model: LECCS

The EM noise on a PCB is excited by the high-frequency (RF) currents generated by active devices. Noise-source currents are classified as either signal currents or power currents. A power current consists of a core current and an I/O power current, as shown in Fig. 3. For signal integrity (SI) simulation, the signal waveforms are the main concern of designers, and SPICE, IBIS, or other time-domain models are usually applied in this case. These models, however, are not suitable for EMI simulation because of their complexity and nonlinearity. Of course, most active devices have nonlinear characteristics, but the transient characteristics are not that important for EMI evaluation, and in most cases, the resonance characteristics in the frequency domain are more important.

Thus, we have proposed a frequency-domain model for LSIs and applied it to both decoupling simulation and EMI simulation [1-3,6-8]. This model, the LECCS model, was originally proposed for the core circuit of an LSI with no direct connection to the output. It is composed of a linear equivalent impedance, Z_i, and an internal equivalent current source,

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[1] LECCS: Linear Equivalent Circuit and Current Source.

[2] HISES: High-Speed EMI Simulator.

I_i, as shown in Fig. 4. Both of these values are derived from direct measurements of the device [1,2]. The device model provides the RF current in a power pin of an IC/LSI as a noise excitation source.

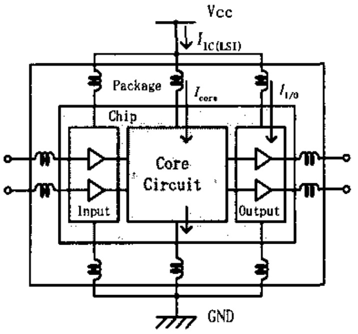


Figure 3. Power Current of an LSI.

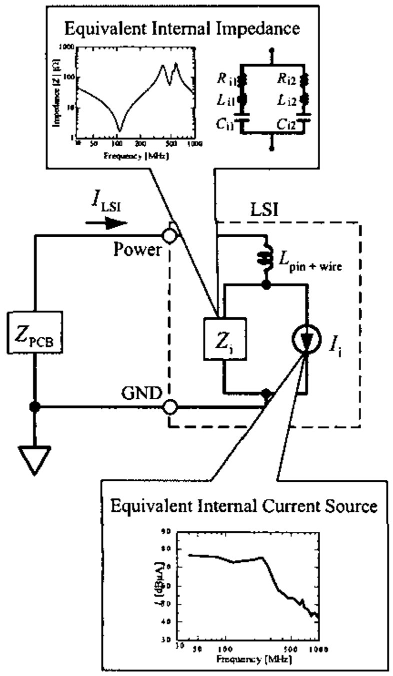


Figure 4. LECCS (Linear Equivalent Circuit and Current Source) Model for Core Circuit of an LSI.

The LECCS model for the core current has the following features: (1) All the model parameters can be determined by measurements, so there is no need to consider the internal design parameters. Of course, the parameters can also be derived from a SPICE model of the device. (2) The internal current source is determined from the measured current spectrum. The standard measurement method for an RF current spectrum is described in the international standard IEC 61967-6 [13]. (3) The model can express the noise characteristics of the power current of an IC/LSI. The effects of the decoupling capacitors on a PCB or of on-package and on-chip decoupling capacitors can be evaluated [7,8]. This was demonstrated during the design process of a microprocessor [14,15]. (4) Although the model is linear, its accuracy is sufficient for EMI/EMS simulation.

Recently, a device model for EMC simulation, called ICEM, was discussed at IEC TC93, and a technical report was published [16]. ICEM is also a macro-model for ICs/LSIs and is designed to provide EMI/EMS simulation as related to power currents [17]. The structure of ICEM is very similar to that of the LECCS model.

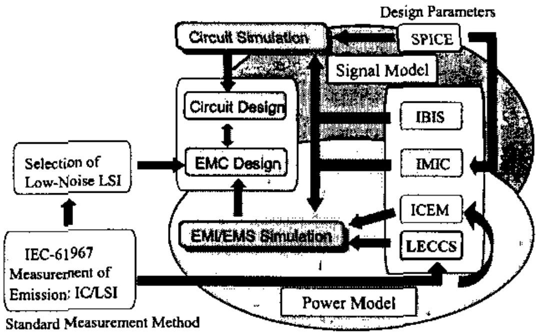


Figure 5. Device Models for Simulation.

Fig. 5 gives an overview of some device models for simulation. For SI circuit simulation, models that express the signal characteristics are used. SPICE and IBIS are very popular, and there are some other candidates as well. As for EMC simulation, including emission and immunity characteristics, the power current is essentially important, so the LECCS model and ICEM are both promising candidates. We are currently extending our LECCS model from the core to provide a multi-terminal model, including driver outputs[3,6]. Recent results have shown that our extended LECCS model can express not only the decoupling effect on power distribution, but also the dependency on the driving output.

To validate the LECCS model for core circuits, we designed an evaluation module, which we call the "IC module" here, as shown in Fig. 6. The IC module consists of a CMOS 6-inverter IC and a crystal oscillator on a 1-inch-square four-layer PCB with some passive components. It was designed for evaluating the internal power decoupling technique on a package. As shown in Fig. 4, the operation current, I_i, of the IC is supplied from either a DC power supply or a bypass capacitor mounted close to the IC. The high-frequency (RF) component of the power current, I_V, drives the power and ground planes in the PCB and causes EMI. If we bypass the RF current by introducing an internal decoupling capacitor, as shown in Fig. 7, the EMI can be reduced. Moreover, if we add some inductance, L_{DI}, in series with a power-pin connection, as shown in Fig. 7, this also suppresses the RF current. The IC module includes pads for the internal decoupling capacitor, C_{in}, and the internal decoupling inductor, L_{DI}.

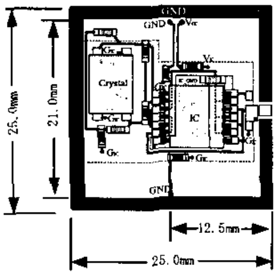


Figure 6. IC Module to Demonstrate Power Decoupling.

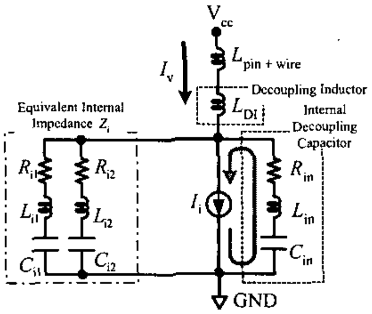


Figure 7. Power Decoupling with Internal Capacitance and Inductance.

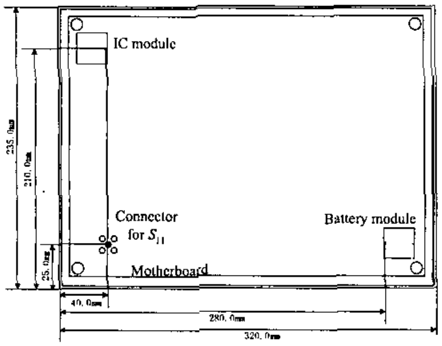


Figure 8. Evaluation board; two layer FR4, with rectangular power and ground planes.

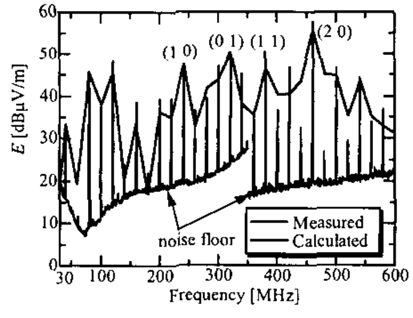
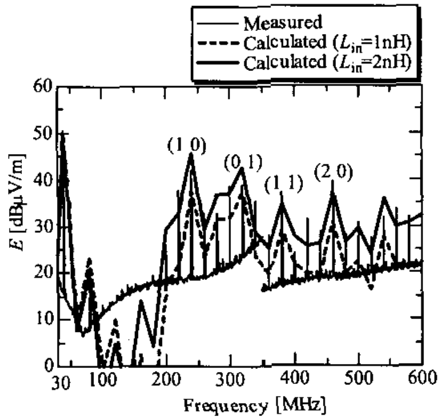
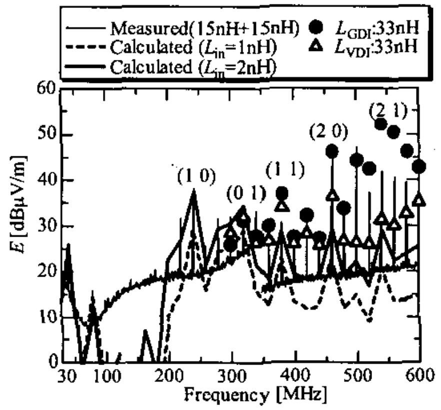


Figure 9. Simulated and Measured EMI without Power Decoupling.



(a) with 1000 pF Internal Decoupling Capacitor



(b) C_{in} = 1000 pF, L_{DI} = 30nH(33nH).

Figure 10. Simulated and Measured EMI with Power Decoupling Technique.

POWER-BUS EMI SIMULATION

The radiated emission from a power bus in a multi-layer PCB was simulated by applying the PCB power-bus model and the device model. The IC module and a battery module were mounted on the evaluation board shown in Fig. 8, and the radiated emission in a semi-anechoic chamber was measured and simulated. The horizontal distance between the board and the antenna was 3 m, the height of the antenna was 1.5 m, and the height of the board was 1 m. Peak values were recorded while the board rotated on a turntable through 360°. Figure 9 shows the simulation results with no internal decoupling[7,8].

The simulation was performed again with an internal bypass capacitance of 100 or 1000 pF and internal decoupling inductances, as shown in Fig. 10. In the low-frequency region up to about 350 MHz, the linear equivalent circuit model was quite accurate and effective. The simulated EMI spectra corresponded with the experimental results to within 6 dB. Even in this region, however, we also observed that a very small parasitic inductance, such as a trace inductance of 1 nH, could affect the results and make a few decibels of difference. In Fig. 10, the difference in the calculated results with two different values of the trace inductance, L_{in}, is plotted. In the higher frequency range above 350 MHz, the situation became more critical; even a few picofarads of stray capacitance could affect the results. Fig. 10(b) shows one example of the effect of stray capacitance[18].

IMMUNITY SIMULATION WITH LECCS MODEL

The power-bus noise on a PCB is regarded as one of the main factors causing faulty operation of CMOS LSIs. It is believed that power-bus noise generates a potential difference across the internal impedances of an LSI, interfering with its correct operation. Here as well, we applied the LECCS model to an LSI. The immunity characteristics of the LSI were also measured by the direct power injection method, which is now under discussion as an international standard, IEC 62132-4[19]. We applied a sinusoidal wave of constant frequency as noise. Our results showed a very close match between the internal voltage generated in the LSI, as simulated by the model, and the experimentally measured immunity characteristics of the LSI[20].

COMMON-MODE SIMULATION

Common-mode radiation from PCBs is of practical importance in reducing EMI. A high-speed device on a PCB drives a normal-mode signal, and it couples to a common-mode current, which causes significant EMI at a certain resonance of the structure. We have investigated the mechanisms of common-mode generation on PCBs, and many authors have presented papers on this topic. The fundamental EMI source mechanisms of common-mode radiation were discussed in ref. [21], and two schemes for common-mode generation were presented: one has been denoted a "current-driven" mechanism; the other, a "voltage-driven" mechanism. The common-mode effect on a PCB with a ground plane of finite width was explained by applying the current-driven mechanism in ref. [22].

Among practical PCBs, the structure shown in Fig. 11 is very common. A high-speed trace for a fast signal line either runs above a narrow ground plane or close to the edge of a ground plane. It is well known that the ground pattern under the signal trace plays an important role as a current return path. Thus, a microstrip structure requires a wide ground pattern for signal integrity and EMI. When signal traces are routed in the vicinity of a ground plane edge or run on a narrow ground plane, common-mode radiation is generated.

For a PCB with a narrow ground pattern, we developed another common-mode generation scheme [22] by using a parameter called the "current-division factor", which express the degree of imbalance of a transmission line. In this approach, we focused on the discontinuous point of the transmission-line structure. The current-division factor is derived from the cross section of a transmission line. In most cases, the factor is also different at the discontinuous point because of the imbalances of the transmission lines on both sides, and a common-mode driving voltage is induced in proportion to the difference between the imbalances.

Recently, we found that this "imbalance-driven" mechanism is essentially equivalent to the current-driven mechanism. In this special session, we explain this identity and present some examples of common-mode evaluation[9]. The estimations agreed well with the measurements. The current-division factor can be derived by two-dimensional electrostatic field analysis, so this calculation scheme is very useful for practical simulation[10].

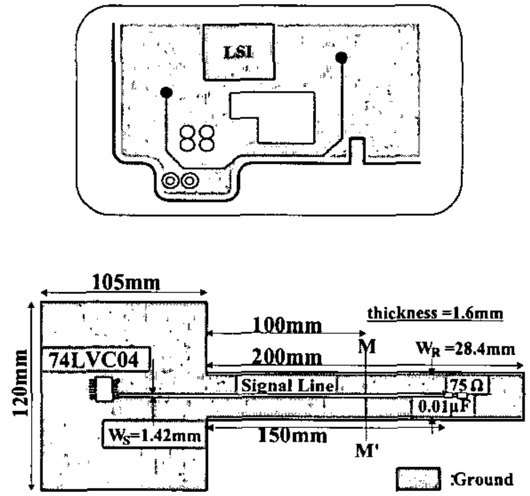


Figure 11. Evaluation of Common Mode Excited at Narrow Ground Plane.

CONCLUSIONS

We have reviewed some recent results from our research. More details are presented in separate papers in this special session. Our linear macro-model for devices, the LECCS model, has a very simple structure and is sufficiently accurate, even though it is a linear model. Combining the LECCS model with analytical simulation techniques for power-bus resonance simulation can enable high-speed EMI simulation and decoupling evaluation related to PCB and LSI design. We have also presented a useful explanation of the common-mode excitation mechanism. Some of these results have been investigated by implementing prototypes of a high-speed EMI simulator, HISES. We will continue to investigate EMC evaluation and control problems.

ACKNOWLEDGMENTS

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