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Fusion of First-Principles and Statistical Analyses in Complex Electronics Systems

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Abstract

In this paper, we present recent progress in the first-principles modeling and quantitative statistical analysis of complex electronics systems. The scientific contributions are twofold: (i) high-performance and scalable algorithms to conquer the computational complexity of extreme-scale simulations on massively parallel computing platforms; (ii) hybrid deterministic and stochastic formulations for the statistical characterization of the in-situ performance and system behavior. The work overcomes some key challenges in the in-situ verification of complex electronic systems in realistic circumstances, and establishes a surrogate modeling capability which generates the statistical in-situ performance rapidly while retaining the underlying first-principles analysis.

1 Introduction

Ever-increasing complexity in high-speed electronic devices and systems presents significant mathematical and computational challenges in the electromagnetic (EM) field-based analysis. The major difficulties arise from the geometrical complexity of the underlying structures, and from the computational complexity in extreme multi-scale computations accounting for mutual interactions of interconnects, packages, boards and systems. Furthermore, even though we have been seeking for the highest possible fidelity, the computer representation of electronic systems will not be exactly the same compared to the real world. These uncertainties may arise from the imprecise knowledge of the system, small differences in the manufacturing, or numerical errors in the simulations. In most cases, those small differences can be considered as local perturbations of the entire system. Hence, the numerical solution is still a very good approximation to the exact solution of the physical problem. However, the situation can be completely different in complicated EM systems exhibiting wave chaos.

The work presented in this paper is divided into two parts. Part 1 involves first-principles computational algorithms for high-definition electronic systems ranging from circuit, package, board to system levels. The extreme-scale deterministic full-wave modeling is enabled by the ultra-parallel and data-sparse algorithms on the emerging high-performance computing (HPC) platforms. Part 2 discusses a hybrid deterministic and stochastic formulation for the quantitative statistical analysis of in-situ IC and electronics in complicated enclosures exhibiting wave chaos. The formulation seamlessly integrates the universal statistical properties of the systems and the site-specific features within a comprehensive statistical analysis framework. The combination of these research thrusts improves our ability to develop and predict the behavior of modern complex electronic systems, while maintaining a high level of confidence on the in-situ performance.

2 First-Principles-based Modeling

We first review recent progresses on first-principles-based EM modeling and analysis for complex electronic systems, since they serve as a basis for the proposed hybrid formulation. The emphasis is placed on advancing parallel algorithms that are provably scalable, and facilitating a design-through-analysis paradigm for emerging and future electronic systems.

A scalable geometry-aware domain decomposition (DD) method is developed to conquer the geometric complexity of physical domain. It breaks the entire electronic system into many small sub-systems (or sub-domains), and applies the suitable solution strategy to solve for each sub-system. The continuities of the physical quantities across the sub-domain interfaces and boundaries are enforced through a volume-based optimized Schwarz transmission condition [1] and a surface-based interior penalty boundary integral equation [2]. The results lead to quasi-optimal convergence in DD iterations as well as parallel and scalable algorithms to reduce the time complexity via high performance computing facilities.

Shown in Fig. 1 is the application of the method for the intra-system EM interference (EMI) analysis of a complex electronic system. There are two monopole antennas located at the back case of the computer. These two antennas are connected to the Intel Galileo board inside the computer box through two coaxial cables. The electronic system is firstly divided into the computer box, antennas, coaxial cables and board sub-systems. Each sub-system is further decomposed into sub-domains based on the number of processors available and the local memory each processor can access. The simulation requires 66 million DOFs with a total number of 92 sub-domains. Each sub-domain is assigned to one MPI process with 32 computing cores. The simulation takes 4 minutes for one DD iteration and 18 iterations are required to converge.

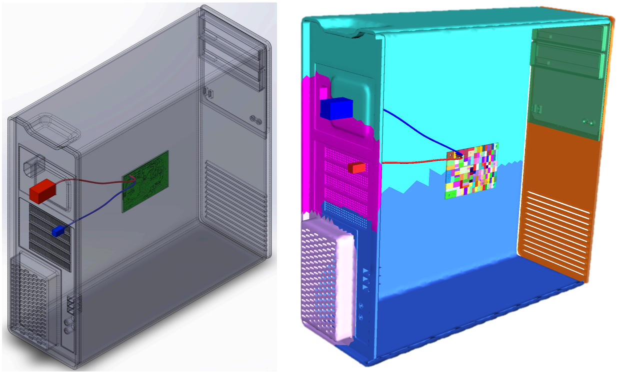

Figure 1. A complex electronic system and the computational partitioning.

The EM field distributions with respect to the monopole antenna radiation at 10 GHz are given in Fig. 2. The results show that the method is promising to simultaneously simulate heterogeneous sub-systems exhibiting vast differences in the aspect ratios, and provides concurrent resolution of multiple scales in the computational domain. Moreover, an electrical CAD (ECAD) to EM analysis framework will be presented in the conference. It aims to directly perform 3D EM modeling and simulation using ECAD layout files, and lead to a robust, cost-effective, fast turn-around electrical design automation.

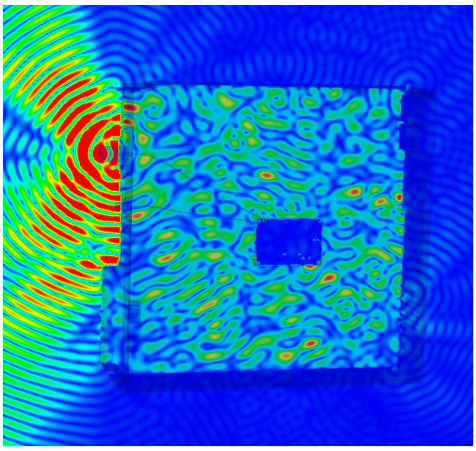

Figure 2. The calculated electric field distributions for the computer system.

3 Physics-based Surrogate Modeling

We remark that the first-principles-based EM analysis provide the ultimate accuracy and fidelity with all physical wave phenomena in electronics systems. On the other side, as depicted in Fig. 2, the high frequency wave solutions inside the computer box show significant fluctuations. They are extremely sensitive to the exact geometry of the enclosure, the location of internal electronics and the operating frequency. This phenomenon, known as wave or quantum chaos, has been discussed in [3–6]. In wave-chaotic systems, minor changes in the shape of the enclosure, or the reorientation of internal IC or electronics, can result in significantly different EM environments within the enclosure. The response of one configuration of the system may not be useful in predicting that of a nearly identical system. Further, imprecise knowledge of system parameters is another obstacle to predictability. Therefore, It necessitates a statistical characterization of the in-situ performance and EM propagation behavior.

3.1 Hybrid Formulation

This work presents a physics-based statistical surrogate modeling methodology. The philosophy is inspired by the fundamental physics principles. Wave-chaotic systems possess certain universal statistical properties despite their distinct complexity. Namely, the dynamics of the system are governed, in a qualitative way, by the symmetry of the system and not by the details of the interactions within the system [7]. Therefore, it is possible to use some minimum information of the system to obtain a trustworthy statistical characterization.

A hybrid deterministic and stochastic formulation is proposed, in which small components (electronics, antennas, etc.) in the computational domain are modeled using first-principles and large portions (cavity enclosures, scattering environments, etc.) are modeled statistically. The key ingredients are a non-overlapping multi-trace DD formulation, and a stochastic Green's function (SGF) method that quantitatively describes the universal statistical property of chaotic systems through the random matrix theory (RMT) [8, 9]. The work seamlessly integrates the universal statistical properties of the chaotic environments and the site-specific features within a comprehensive statistical analysis framework. Furthermore, it establishes a surrogate modeling capability, which generates the statistical EM interference rapidly while retaining the underlying first-principles analysis.

We have employed two theoretical tools to derive the SGF: (**i**) eigenfunctions of the wave-chaotic media have statistical properties similar to those of a random superposition of many plane waves, known as the random plane wave hypothesis; (**ii**) eigenvalue spectra are statistically similar to the spectra of Gaussian Orthogonal ensembles of random matrices, derived from Wigner's work on nuclear spectra [8]. The expression of SGF in wave-chaotic media can be written as:

$$G(\mathbf{r},\mathbf{r}') = \mathrm{Re}[G_0(\mathbf{r},\mathbf{r}')] + i\mathrm{Im}[G_0(\mathbf{r},\mathbf{r}')] \cdot g \qquad (1)$$

A few remarks on (1): g is a complex, random variable that describes the universal statistics of the system. For wave chaos in large cavities, the statistics of g is obtained by a dimensionless cavity loss-parameter [5] and the Gaussian

Orthogonal ensemble of random matrices. It is interesting to observe that this universal random variable only acts on the imaginary part of the free space Green's function, $\mathrm{Im}[G_0(\mathbf{r},\mathbf{r}')]$. It can be proved that the $\mathrm{Im}[G_0(\mathbf{r},\mathbf{r}')]$ indeed describes the correlations in Gaussian random fields correctly. Lastly, in cases where the free space Green's function is not applicable, we can also first calculate the numerical Green's function and substitute the result to (1), in analogy to the random coupling model [5].

The introduction of the SGF leads to a seamless integration of deterministic and stochastic formulations. Shown in Fig. 3 is the conceptual drawing of the application of the work. In the computational setup, we only need the knowledge of the site-specific features, namely, the electronics, apertures, and antennas, as illustrated in Fig. 3. The interaction with other parts of the 3D computer box is categorized statistically with the numerical SGF on the exterior surface of the antennas. As a results, the solution of this surrogate model can be obtained at the same cost as if the intra-system EMI is analyzed in free space.

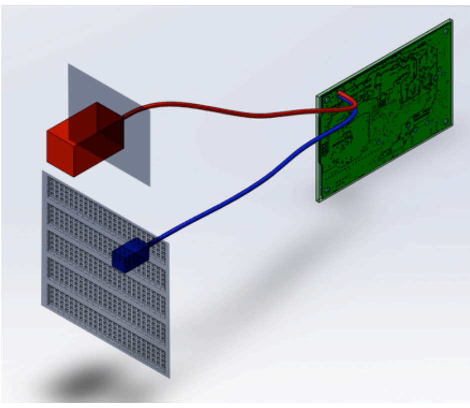

Figure 3. The surrogate model of the computer system.

3.2 Experimental Validation

We consider a complicated 3D aluminum box to validate the proposed work. The geometry and photograph of the experimental setup are illustrated in Fig. 4. The paddle-wheel mode stirrer is used to generate an ensemble of cavity measurements. Two X-band waveguide (WG) adapter mounted on the opposite walls are used as the transmitter and receiver. The cavity is significantly overmoded and EM fields exhibit wave chaotic fluctuations. In the experiment, 47620 frequency sample points are chosen. At each frequency point, the internal mode stirrer is rotated through 200 positions over 360 degrees. The resulting S_{11}, S_{12} and their ensemble average are shown in Fig. 5.

In the computational setup, we only need to model the site-specific features, namely, the WG antenna and its surrounding aluminum plate, as illustrated in Fig. 6. The probability density function (PDF) of the S-parameter of the antennas are given in Fig. 7. We observe a very good agreement comparing the computational results and measurements.

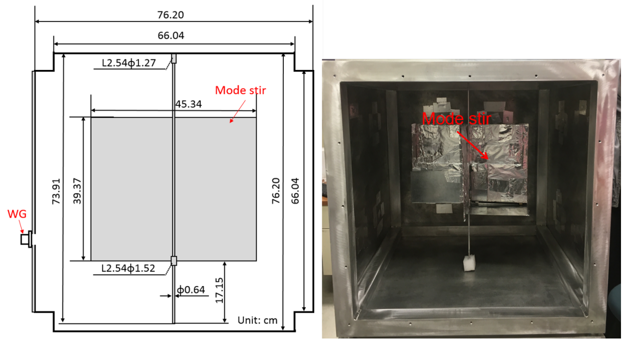

Figure 4. Configuration of 3D box, mode stir and WG antenna (unit: cm).

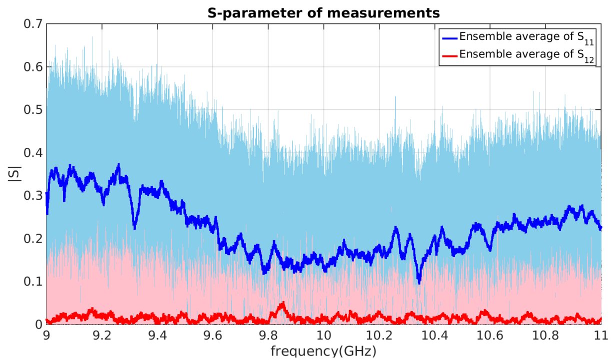

Figure 5. Measured S-parameter as a function of frequency.

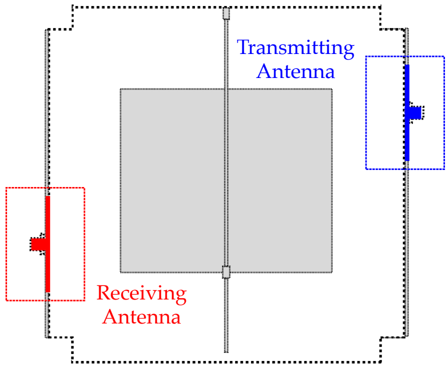

Figure 6. Configuration of the computational setup.

4 Conclusion

This paper present the recent progress in the first-principles and quantitative statistical analysis of complex electronics systems. The advancements in first-principles, high-performance algorithms will enable electronics designers to quickly create and analyze virtual prototypes of products. By simultaneously consider mutual interactions of circuits, 3D interconnects, packages and boards, it will serve as a powerful verification tool in the design stage. A hybrid deterministic and stochastic formulation integrating the order (first-principles) and the chaos (statistically) is proposed afterwards, and a physical-based surrogate modeling capability is established. The work is validated through rep-

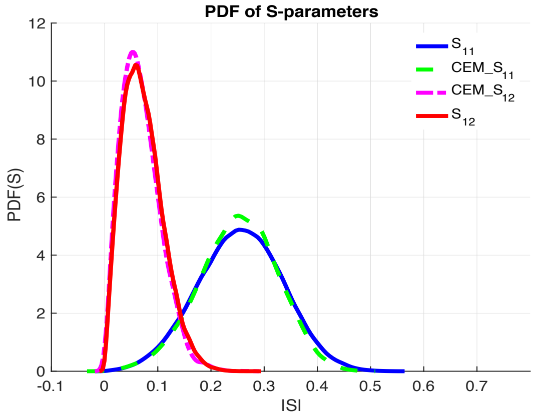

Figure 7. PDF of the S-parameter by measurement and computational results.

resentative experiments, and can be applied directly to the design, vulnerability and statistical analyses of microwave and electronic systems.

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