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DOMAIN DECOMPOSITION METHODS FOR SOLVING EMC/EMI PROBLEMS: ELECTRICALLY LARGE (ANTENNAS ON PLATFORMS) AND SMALL (SIGNAL INTEGRITY IN ICS AND PACKAGES)

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Introduction: Modern antenna engineering often involves the use of metamaterials, complex feed structures, and conformally mounted on large composite platforms. However, such antenna systems do impose significant challenges for numerical simulations. Not only do they usually in need of large-scale electromagnetic field computations, but also they tend to have many very small features in the presence of electrically large structures. For example, consider the multiple antenna "farms" installed on a mock-up fighter jet as shown in Fig. 1. There are total of 23 antenna systems, including a X-band radar antenna array resides in the nose region and protected by dielectric radome shells. In order to cover various channels and mission critical communications, the operating frequencies range from 75MHz to Ku band. In the design of the antenna systems as well as placing these antenna farms appropriately, it is of paramount importance to reduce unwanted in-band and out-of-band electromagnetic couplings and interferences [1]. Such multi-scale electromagnetic problems tax heavily on numerical methods (finite elements, finite difference, integral equation methods etc.) in terms of desired accuracy and stability of the corresponding mathematical formulations.

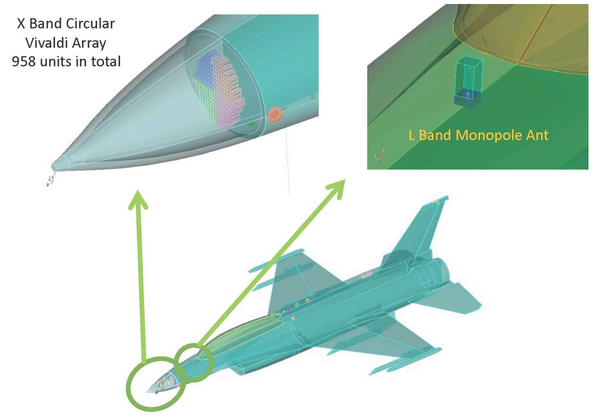

Figure 1: Multiple antenna farms placed conformally on a large air platform.

Another important electromagnetic application is the full wave analysis of signal integrity in ICs and full packages. Recent advances in VLSI interconnect and packaging technologies, such as the increasing number of metal layers and the 3D integration, have paved the way for higher functionality and superior performances. During the reduction of the size, power, and cost in today's advanced IC interconnect and packages, the signal integrity (SI) has become more crucial for system designers. Empirical or curve-fitted equivalent circuits used by conventional circuit simulation tools, such as SPICE and IBIS, are not suitable for higher and wider operating frequencies in terms of accuracy, flexibility, and reliability. The previous common practice adopted by industries, such as using only static parasitic RC or RLC equivalent networks for physical designs, are gradually abandoned. It has come to use full-wave computational electromagnetic (CEM) methods for the ultimate accuracy check [3].

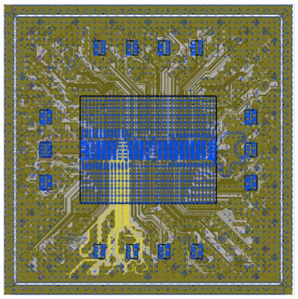

Figure 2: A complex IC package model.

However, even with today's state-of-the-art, full wave numerical approaches, it remains extremely challenging to conduct 3-D real-life package signal integrity analysis satisfactorily. To understand the nature of the problem, we may take a product-level package model as an example. The first challenge arises from its geometrical complexity, which contains tens of thousands of small entities, such as signal traces, 3-D interconnects (through-hole vias and berried vias, solder bumps and bump wires) and metallic power/ground layers. As shown in Fig. 2, it contains about 40,000 geometrical entities. It will be extremely challenging to generate a mesh of the entire package with all fine features, let alone solving them efficiently. Secondly, even if such a mesh can be constructed, the resulting degrees of freedom (DOF) will be astronomical. It requires excessive computation time and memory to simulate this real-life 3-D package model. In addition, we should also mention the extremely small electrical size of this package. For the example shown in Fig. 2, when the simulation frequency changes from 1 MHz to 30 GHz, the electrical size of the package model varies from $\lambda / 20{,}000$ to $3\lambda / 2$, with λ the wavelength in free space. This will cause an extremely ill-conditioned matrix equation, which will be difficult to solve using iterative matrix solution techniques. Thirdly, the real-life package is a multi-port system with a wide-band frequency of interest. The efficient solution of such multi-input/multi-output (MIMO) responses over a wide frequency band adds another computational complexity. In this regard, it is essential to develop a reliable algorithm that is capable of producing fast and accurate computation of multi-port wideband spectral responses.

Proposed Non-conformal Domain Decomposition Methods: In this talk, I will present our on-going efforts in combating the multi-scale electromagnetic problems, both electrically large (antennas on platform) and electrically small but complex (SI in ICs and packages) through the use of non-conventional PDE methods that are non-conformal. The non-conformal numerical methods relax the constraint of needing conformal meshes throughout the entire problem domains. Consequently, the entire system can be broken into many sub-problems, each has its own characteristics length and will be meshed independently from others. Particularly, our discussions will include the following topics:

- **Efficient Direct Solver for Solving Dense IE Matrix Equations**

A novel direct solver is developed herein for solving dense matrix equations resulted from the application of surface integral equation methods, such as electric field integral equation (EFIE), magnetic field integral equation (MFIE), and combined field integral equation (CFIE). The proposed algorithm exploits the smoothness of the far field and computes a low rank decomposition of the off-diagonal coupling blocks of the matrices through a set of skeletonalization processes. Moreover, a recursive multi-level version of the algorithm has also been implemented. Although asymptotically the algorithm would not alter the bleak complexity, $O\left(N^3\right)$, with N denotes the number of unknowns, for electrically large EM problems; through numerical examples, we found that the proposed multi-level direct solver scales as good as $O\left(N^{1.3}\right)$ for moderate large EM problems. Furthermore, due to the low rank feature of the so-called h-refinements, the algorithm exhibits $O\left(N\right)$ complexity with the decreases of the discretization size.

- **Integral Equation Domain Decomposition Method (IE-DDM)**

A very significant breakthrough that has been accomplished in our group recently is the IE-DDM formulation. For example, we show an electromagnetic plane wave scattering from the F-16 aircraft at 5 GHz by dividing the platform into 4 closed objects, and noting that they will be touching each other through common interfaces. Instead of applying the CFIE to one large problem as is traditionally done, we have employed MLFMM CFIE for each of the four regions separately, and iterated the numerical solutions until they converge.

- **Non-Conformal DDM with Higher Order Transmission Conditions and Corner Edge Penalty**

By introducing two second-order transverse derivatives, one for TE and one for TM, the derived 2nd order TC provides convergence for both the propagating and evanescent modes. Moreover, on the corner edges sharing by more than two domains, an additional corner edge penalty term needs to be added in the variational formulation. Consequently, the robustness of the non-conformal DDMs is now greatly improved.

- **Multi-region/Multi-Solver DDM with Touching Regions**

Many multi-scale physical problems are very difficult, if not impossible, to solve using just one of the existing CEM solvers. We have been pursuing a multi-region multi-solver domain decomposition method to effectively tackle such problems. Various CEM solvers are now integrated into our MS-DDM code and collectively, it emerges as the only alternative for solving many real-life applications that are thought to be un-solvable today.

- **Discontinuous Galerkin Time Domain (DGTD) Method with GPU Implementation**

In this talk, I will also discuss our approach on the MPI/GPU implementation of an Interior Penalty Discontinuous Galerkin Time-Domain (IPDGTD) method to solve the time dependent Maxwell's equations. In our approach, we exploit the inherent DGTD parallelism and describe a combined MPI/GPU and local time-stepping implementation. This combination is aimed to increase efficiency and reduce the computational time, especially for multi-scale applications.

The CUDA programming model together with non-blocking MPI calls to overlap communications across the network were used. Finally, a good scalability with a parallelization efficiency of 85% up to 40 GPUs and 80% up to 160 CPU cores was achieved at the Ohio Supercomputer Center, Glenn cluster.

References

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