Hybrid Frequency Domain Methods: From Analysis to Design

J. L. Volakis
ElectroScience Laboratory, Dept. of Electrical Engineering
The Ohio State University
1320 Kinnear Rd, Columbus, OH 43212

Abstract: Frequency domains methods have been the workhorse of electromagnetic computations since the early 1980s. This presentation will provide a historical overview of frequency domain developments, with particular focus on hybrid formulations and fast methods and their integration with formal design methodologies for antenna applications.

INTRODUCTION
Over the past twenty years, we have witnessed an increasing reliance on computational methods for a variety of electromagnetic characterizations. By and large, frequency domain methods have been the workhorse for all sorts of electromagnetic applications. Although much of the early focus was on metallic structures, recent interest has been on large scale computations for practical problems which include volumetric materials as well as composite and coated or multilayered structures.

Formulations for treating volumetric structures date back to the 1960s [1] for 2D dimensional scattering, with later extensions to three dimensional implementations [2, 3]. However, although robust, these formulations, did not allow for practical utilizations. It is the need to model composite structures that brought to focus hybrid methods. Such methods combined partial differential equation (PDE) methods [4], integral equations [5, 6] and the traditional high frequency approaches [7]. PDE methods allow for a most efficient modeling of inhomogeneous, possibly anisotropic materials, whereas integral equation methods permit robust treatment of the outer domain [8]. For very large and detached structures, integration with high frequency methods continues to provide an attractive alternative [9-11]. The robustness of these formulations and growth in wireless applications resulted in an increased software reliance during the 1990s and the consequential development/availability of several commercial packages for antenna analysis, microwave circuits and scattering applications.

Nevertheless, although the various hybrid formulations provided a methodology for treating complex geometries, the $O(N^2)$ and often $O(N^3)$ computational requirements of traditional solvers were bottlenecks to most practical applications. Thus, much of our attention over the second half of the 1990s was on the development of fast methods such as the multilevel fast multiple method (MLFMM) and adaptive integral methods (AIM). These methods reduce the computational requirements down to $O(N\log N)$ and have truly provided for significant changes on our ability to carry out practical antenna and scattering computations [12-14]. As we move forward in this decade, these fast simulations are opening possibilities for true design in electromagnetic systems which may include any combination of material structures, multilayered and vertical integration, RF systems-on-a-chip, electromagnetic interference and compatibility studies and novel materials for new antennas and RF filters, to mention a few.

SUCCESSES
The decade of the nineties is highlighted with truly remarkable progress on our ability to carry out simulations, not only for large scale problems, but also in terms of hybridization and integration of passive and active RF circuits for a variety of applications. Figure 1 provides a glimpse at the many applications where frequency domain methods have played a significant role on our understanding. Among them is broadband antenna design, large multilayered and multifunctional antennas with embedded FSS and metamaterial substrates, MEMS analysis and design, large finite arrays and full scale aircraft scattering analysis using first principle methods, EMI/EMC coupling and interference of systems involving passive and active...
components, MRI simulations, indoor propagation and evaluation of wireless systems, etc. What is probably so remarkable is that a decade ago (early 90s), we had just started looking at three-dimensional applications and the development of practical simulation tools seemed far away considering that in the mid 80s a mere 1500 unknown problem might have required out-of-core memory along with much ‘suffering’ due to the ensuing $O(N^3)$ CPU requirements. Today, we have access to robust 3D $O(N \log N)$ algorithms for composite materials modeling [15] and we have also demonstrated that practical simulations of entire aircraft or large finite antenna arrays [16, 17] and possibly RF integrated systems can be carried out using a desktop PC. In addition, we have delved into topology optimization/design [18]. The latter holds promise for generating novel antenna and microwave circuits, RF filters and RFICs for mixed signal applications, and others. With the commercialization of wireless technologies and need

Figure 1. Several applications demonstrating capabilities of modern frequency domain methods.

Figure 2. (a) Left: RF material design for bandwidth enhancement using formal topology optimization methods[18]; (b) Right: Coupling studies and validations within a large finite array involving several million unknowns[16].

For broadband systems, our community has a bright future and so do students pursuing graduate studies in RF engineering. It goes without saying that to realize our potential, it will
be necessary to aggressively recruit excellent students that can pursue and realize the potential of wireless applications. The latter is probably the most challenging obstacle that must be overcome. Given that (over the past decade) the majority of research within the U.S.A has occurred at Universities, there is even a greater need to recruit and retain top students who will enable the potential of RF applications.

REFERENCES