Tucker-Enhanced VoxCap Simulator for Electrostatic Analysis of Voxelized Structures

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The electrostatic analysis tools are of paramount importance for the analysis and design of interconnects on chips, boards, packages, as well as microelectromechanical systems. During the iterative design explorations, the designers execute these tools many times to quickly analyze their designs and perform necessary changes. While developing their prototypes in modern voxel-based virtual fabrication environments, the designers are in need of electrostatic analysis tools developed for the structures discretized by voxels. To meet this demand, a fast Fourier transform (FFT)-accelerated VoxCap simulator for capacitance extraction of voxelized structures has been developed recently (Yucel et al., *USNC/URSI Nat. Radio Sci. Meeting*, 2018). The VoxCap simulator solves the surface integral equations after discretizing the charge density on conductor and dielectric surfaces via piecewise constant basis functions, applying Galerkin testing, and forming a linear system of equations. While iteratively solving the linear system of equations, VoxCap leverages FFTs to expedite the matrix-vector multiplications. Just like other integral equation simulators, the applicability of the VoxCap simulator to many practical problems is limited by its memory requirement, which primarily stems from the memory footprint of block circulant tensors. In order to boost the applicability of VoxCap simulator and to be able to execute it on a desktop computer for the real-world structures discretized with billions of voxels, the memory footprint of block circulant tensors should be reduced via special compression schemes.

In this study, Tucker decompositions are proposed to reduce the memory requirement of block circulant tensors that arise in VoxCap simulator. The proposed Tucker decompositions allow representing the circulant tensors in terms of low-rank core tensors and factor matrices during the setup stage of the simulator. During the iterative solution stage, each compressed tensor is restored to its original format and used in FFT operations to perform matrix-vector multiplications. The proposed Tucker enhancement achieves more than three/four orders of magnitude reduction in the memory requirement of circulant tensors for large-scale structures while requiring negligible restoration/decompression time (i.e., computational overhead). Preliminary results show that the memory requirement of circulant tensors in Tucker-enhanced VoxCap simulator scales with $O(N^{1/4}\log N)$, where N is the number of voxels used to discretize the structure. For an example structure discretized on a 320x320x320 voxel grid, it reduces the memory requirement of block circulant tensors by a factor of 4595 for a prescribed accuracy of 10^{-8} and required negligible decompression time, which is less than one fifth of the computational time needed to perform one FFT operation. The memory savings achieved by and (negligible) computational overhead imposed by the proposed Tucker enhancement in VoxCap simulator will be demonstrated through various numerical examples involving complicated and large scale structures discretized with billions of voxels, which are analyzed on a commodity desktop computer.