

Compression of Scattering Matrices in Domain Decomposition Based Surface Integral Equation Simulator via Randomized Hierarchically Off-Diagonal Butterfly Factorization

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The design and (re)configuration of wireless communication systems in underground mines call for powerful simulators capable of analyzing electromagnetic (EM) wave propagation in tunnels and galleries. Full-wave EM simulators in principle are cut out for this task as they permit high-fidelity modeling of realistic mine environments. Unfortunately, they require enormous computational resources when deployed in scenarios involving multiple physical or synthetic excitations; such situations arise in uncertainty quantification and network optimizations. To address this concern, a memory- and CPU-efficient, full-wave, domain decomposition (DD) surface integral equation (SIE) simulator was proposed by Sheng et al (Sheng et. al., *Proc IEEE Int. Symp. Antennas Propagat.*, 2016). This simulator first divides mine tunnels and galleries into subdomains separated by equivalent surfaces. Next, it proceeds with an offline computation stage that computes scattering matrices to characterize EM wave propagation in each subdomain separately. Finally, it executes an online stage that constructs and solves a global inter-domain system; the latter accounts for EM interactions between subdomains and involves significantly fewer degrees of freedom than conventional fast simulators. When used for EM analyses with multiple excitations, the DD-based SIE simulator is significantly faster than conventional full-wave simulators since it only needs to solve the reduced system for each different excitation during its online stage.

Unfortunately, the above simulator remains slow when applied to tunnels and galleries with electrically large cross sections, a situation that often arises when analyzing high frequency communication systems. The principal culprit is the high computational complexity of operations involving full scattering matrices. Indeed, the naïve solution of inter-domain systems requires $O(N_p^2 N_{sur})$ and $O(N_p^2)$ computational and memory resources, respectively; here N_p is the number of basis functions used to discretize one equivalent surface and N_{sur} is the number of equivalent surfaces. To reduce the computational burden, the hierarchically off-diagonal butterfly factorization (HODBF) technique (Liu et. al., *IEEE Antennas Wireless Propag. Lett.*, 2016) is used to compress scattering matrices and reduce the computational and memory requirements of iteratively solving inter-domain system to quasi-linear (as opposed to quadratic) in the number of unknowns. This technique represents hierarchically decomposed off-diagonal blocks of a scattering matrix by factorizations that exploit the butterfly compressibility of high-frequency operators. The compressed scattering matrices are constructed via a randomized scheme (Liu et. al., *SIAM J. Sci. Comput.*, *submitted*) requiring only “black box” matrix-vector multiplications of scattering matrices with structured random vectors. The accuracy, efficiency, and applicability of the HODBF-enhanced DD SIE simulator are demonstrated via characterization of EM wave propagation in various electrically large mine tunnels and galleries.