A Butterfly-Based Domain Decomposition SIE Simulator for EM Analysis of Wireless Communication Systems in Mine Environments

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The design, (re)configuration, and EMC certification of wireless communication systems in underground mines call for powerful simulators capable of analyzing electromagnetic (EM) wave propagation in electrically large and complex mine tunnels and galleries. Full-wave EM simulators are a perfect fit for this task were it not for the fact that they require enormous computational resources. To reduce their computational costs, we recently proposed a memory and CPU efficient, full-wave, domain decomposition-based surface integral equation (SIE) simulator (Sheng et. al., *Proc IEEE Int. Symp. Antennas Propagat.,* 2016). This simulator proceeds in three stages: (i) First, it subdivides mine tunnels and galleries into subdomains separated by equivalent surfaces. (ii) Next, it computes scattering matrices that characterize EM wave propagation between the equivalent surfaces bounding each subdomain. (iii) Finally, it constructs and solves a global inter-domain system that accounts for EM interactions between subdomains. This simulator oftentimes is many times faster than a single-domain simulator, especially when the structure contains many identical subdomains (Sheng et. al., *Proc IEEE Int. Symp. Antennas Propagat.,* 2016). That said, its cost remains prohibitively high, especially when applied to the analysis of high frequency communication systems for which the equivalent surfaces separating subdomains support thousands of basis functions. This high cost stems from the fact that the simulator computes scattering matrices one column at a time via the repeated iterative solution of a Poggio-Miller-Chang-Harrington-Wu-Tsai (PMCHWT) SIE for all possible excitations of the equivalent surfaces bounding subdomains.

This paper presents a new domain decomposition based simulator that uses a far more efficient solver for constructing scattering matrices characterizing subdomains. In contrast to its predecessor, the new simulator leverages a butterfly-based direct solver, as opposed to an iterative PMCHWT solver, for computing scattering matrices, realizing significant savings by avoiding the repeated restart of the iterative solver, and relying on efficient backsubstitution processes instead. Specifically, the solver LU factorizes discretized PMCHWT equations by recursively operating on butterfly-compressed blocks of partial LU factors to construct a complete hierarchical block LU factorization of the system matrix (Guo et. al., *USNC-URSI Radio Science Meeting*, 2015). In this process, new butterfly-compressed representations of sums and products of previously butterfly-compressed matrices are continuously updated via a low computational complexity scheme that extends randomized methods for constructing low-rank matrix approximations (Liberty et. al., *Proc. Natl. Acad. Sci.*, 104(51), 20167-20172, 2007). When integrated in the domain decomposition framework, the direct PMCHWT drastically reduces the cost of applying step (ii) when compared to the iterative PMCHWT solver, even when the latter is accelerated by a fast, say fast multipole–fast Fourier transform method (Taboada et. al., *IEEE Antennas Propag. Mag.*, 51(6), 20-28, 2009). The computational efficiency and accuracy of the proposed enhancement in the domain decomposition framework will be demonstrated through analysis of EM wave propagation inside various large-scale mine tunnels and galleries.