An FMM-FFT Accelerated Integral Equation Solver for Characterizing Electromagnetic Wave Propagation in Mine Tunnels and Galleries Loaded with Conductors

Abdulkadir C. Yücel*[(1)], Yang Liu[(1)], Hakan Bağcı[(2)], and Eric Michielssen[(1)]
(1) Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA
(2) Division of Computer, Electrical, and Mathematical Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal 23955-6900, KSA

Reliable wireless communication and tracking systems in underground mines are of paramount importance to increase miners' productivity while monitoring the environmental conditions and increasing the effectiveness of rescue operations. Key to the design and optimization of such systems are electromagnetic (EM) simulation tools capable of analyzing wave propagation in electromagnetically large mine tunnels and galleries loaded with conducting cables (power, telephone) and mining equipment (trolleys, rails, carts), and potentially partially obstructed by debris from a cave-in. Current tools for simulating EM propagation in mine environments leverage (multi-) modal decompositions (Emslie et. al., *IEEE Trans. Antennas Propag.*, 23, 192-205, 1975; Sun and Akyildiz, *IEEE Trans. Commun.*, 58, 1758-1768, 2010), ray-tracing techniques (Zhang, *IEEE Tran. Vehic. Tech.*, 5, 1308-1314, 2003), or full wave methods. Modal approaches and ray-tracing techniques cannot accurately account for the presence of conductors, intricate details of transmitters/receivers, wall roughness, or unstructured debris from a cave-in. Classical full-wave methods do not suffer from such restrictions. However, they require prohibitively large computational resources when applied to the analysis of electromagnetically large tunnels loaded with conductors. Recently, an efficient hybrid method of moment and transmission line solver has been developed to analyze the EM wave propagation inside tunnels loaded with conductors (Brocker et. al., in *Proc IEEE AP-S Symp*, pp.1,2, 2012). However, the applicability of the solver is limited to the characterization of EM wave propagation at medium frequency band.

In this work, a fast and memory efficient 3D surface integral equation (SIE)-based full wave simulator is proposed for analyzing very large-scale mine environments loaded with conductors in the medium and UHF bands. The simulator solves Poggio-Miller-Chang-Harrrington-Wu-Tsai and electric field SIEs to account for the scattering from mine walls and conductors, respectively. During the iterative solution of such SIEs, the simulator employs a parallel fast Fourier transform and fast multipole method (FMM-FFT) acceleration scheme to reduce the memory requirement and accelerate the matrix-vector multiplication (Taboada et. al., *IEEE Antennas Propag. Mag.*, 51(6), 20-28, 2009). The method's efficiency and applicability are demonstrated through the simulations of communication links inside very large-scale mine environments loaded with conductors.