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 
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-Harrington-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.