Shooting-Bouncing-Rays Technique to Model Mine Tunnels: Theory and Accuracy Validation

Stephen Kasdorf, Blake Troksa, Jake Harmon, Cam Key, and Branislav M. Notaroš
Colorado State University, Electrical & Computer Engineering Department, Fort Collins, CO
skasdorf@rams.colostate.edu, blake.troksa@gmail.com, J.Harmon@colostate.edu, camkey@rams.colostate.edu, notaros@colostate.edu

***Abstract*—We present a shooting-bouncing rays technique for electromagnetic modeling of wireless propagation in long tunnels focusing on the accuracy of ray-tracing computation. The examples demonstrate excellent agreement with the traditionally more accurate but less efficient alternative ray-tracing approach using path corrections based on image theory and with a commercial solver.**

Keywords—computational electromagnetics, frequency-domain analysis, high-frequency techniques, microwaves, ray tracing, signal propagation, waveguides, wireless communications.

I. INTRODUCTION

Electromagnetic (EM) modeling and simulation of wireless signal propagation in underground mines presents extraordinary challenges since the mine tunnels and galleries at wireless communication frequencies are electrically extremely large, with mine tunnels spanning thousands of wavelengths in length in typical applications. Using traditional full-wave computational electromagnetics (CEM) solvers for such applications may prove impractical in most cases due to computation run time required, as well as memory requirements, depending on the particular technique employed. Asymptotic methods for numerically approximate high-frequency modeling, such as ray-based techniques, are less accurate but much faster than the full-wave methods for numerically rigorous field computation, such as integral-equation techniques, and provide a good approach to modeling of wireless propagation and received signal strength simulation in underground mines.

This paper addresses application of the ray-tracing (RT) approach [1] to CEM analysis of long real tunnels. It presents and validates our RT method based on a shooting-bouncing rays (SBR) approach. Most importantly, it shows that when all the major components of the SBR RT methodology are properly developed and implemented, the accuracy of the new technique is sufficient for realistic wireless propagation modeling of tunnels and matches or outperforms the accuracy of computationally slower but traditionally more accurate alternative RT simulations.

II. SHOOTING-BOUNCING RAYS METHOD

There are two broad classes of ray tracing techniques common in CEM. The first is known as image theory (IT), or the method of images. This technique finds exact ray paths between a transmitter and receiver by employing images from the transmitter across reflecting surfaces in the environment being modeled. This is advantageous because the exact paths determination completely eliminates any phase error. However, the computational complexity of IT is O(N^R) [2], where N is the number of observation points, and R is the number of reflections. In situations where reflection is the dominant propagation phenomenon, the IT technique becomes impractical due to its complexity.

The SBR approach in RT involves launching a set of rays from a transmitter in every direction. Each ray represents an equiphase surface, which combine to cover the radiation pattern of an antenna. These rays are then geometrically traced through the scene according to Snell's law, and their complex amplitude is governed by Fresnel's coefficients [3]. Once the ray path has been determined, the paths are tested for intersections with receivers. If the ray is determined to intersect the receiver, its electric field is calculated and added to the total computed field at that point. These ray paths are not the exact paths from the source to the receiver, so phase error is introduced making it traditionally less accurate than IT. While SBR includes phase error, it offers much lower computational complexity than IT making it more flexible in different scenarios. For this reason, SBR is chosen as the technique for modeling mine structures and tunnels [4], [5] in the present study.

Within the SBR family, there are two common methods of tracing the rays. The phase fronts are represented either using a center ray approach, known as "cones", or rays are used to trace the edges of the phase front, i.e., "tubes." To accurately model the radiation pattern of a transmitting antenna, the cones approach necessitates the overlap of phase fronts on adjacent rays. This leads to the problem of double counting of this phase surface, leading to substantial error in the simulation. While these double counts can be identified and eliminated, this causes an increase in computational demand of the simulation [6]. The tubes approach uses rays along the edge of triangular or rectangular geometries, which can fill the radiation pattern without any overlap. This eliminates overlaps of the phase fronts but requires a minimum of 4 times the number of rays per tube. In complex environments, a high number of rays is necessary to accurately sample the environment, which puts this method at a disadvantage. The cones method is used in our approach for this reason.

This work was supported by the National Science Foundation under grant ECCS-1646562.

Submitted On: September 9, 2020
Accepted On: September 9, 2020

https://doi.org/10.47037/2020.ACES.J.351103

III. RESULTS AND DISCUSSION

Testing of the ray tracing method we developed was conducted on a real rectangular tunnel. This scene was chosen because the reflection phenomenon is extremely important in tunnel environments and represents a difficult simulation case for SBR. The tunnel cross section dimensions are chosen to be 5 m × 8 m, and the tunnel walls are characterized by relative permittivity ε_r = 5.5 and conductivity σ = 0.03 S/m. The waveguide is excited with a vertically polarized half-wave dipole transmitter at a frequency of 1 GHz. Electric field measurements (simulations) are taken along the length of the tunnel from 30 m to 150 m.

This tunnel embodies a very challenging case for ray-tracing as reflections become very important for the electric field, and rays must be traced to very long distances. The rays propagating long distances can have a very large number of reflections before reaching a receiver, and they can, in turn, accumulate a large path length error, leading to significant inaccuracies in the electric field solutions.

The results of the tunnel are compared to an SBR/IT hybrid method developed in [7], where an SBR algorithm was improved with IT path corrections. Fig. 1 shows the results of the two ray-tracing methods on this scene.

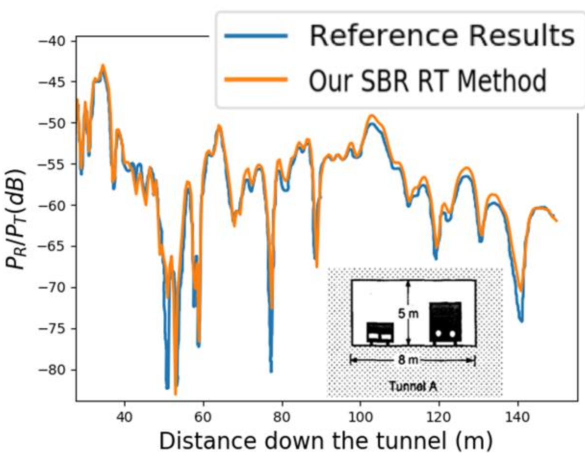

Fig. 1. Received/transmitted power along a rectangular tunnel (ε_r = 5.5, σ = 0.03 S/m) excited with a vertically polarized half-wave dipole transmitter at 1 GHz: comparison of our SBR RT method and an SBR algorithm with IT path corrections from [7].

We observe in Fig. 1 an excellent match of our SBR technique when compared to SBR/IT reference solution, at distances up to 150 m. This shows the accuracy of the SBR technique developed and its ability to very successfully eliminate the phase errors up to very long distances.

Additionally, we simulate a second real tunnel, now with a partly curved cross section to help verify the effectiveness of this model. Curved structures are traditionally difficult for ray-based techniques due to the images not being well defined.

We observe from Fig. 2 an excellent agreement of our SBR results with the hybrid SBR/IT solution from [7] for a tunnel with curved ceiling. Additionally, shown in Fig. 2 are the results obtained by the commercial software REMCOM Wireless InSite. We see that all three simulations agree very well.

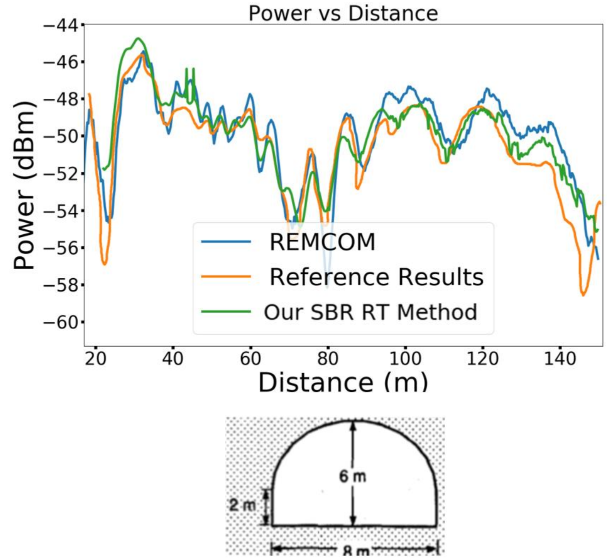

Fig. 2. Power [dBm] down the length of an arched tunnel (the tunnel cross section is shown; σ = 0.03 S/m, ε_r = 5.5; excitation: vertically polarized dipole antenna at 1 GHz): comparison of our SBR RT method with the results by the hybrid SBR/IT RT solution [7] and by the commercial REMCOM Wireless InSite solver.

IV. CONCLUSIONS

This paper has presented and validated the accuracy of our shooting-bouncing rays technique for ray-tracing modeling of long tunnels. The examples have demonstrated the excellent agreement of our method with the traditionally more accurate but less efficient hybrid SBR/IT ray-tracing approach, using image-theory path corrections, as well as with REMCOM Wireless InSite.

REFERENCES

[1] M. F. Cátedra and J. Perez, Cell Planning for Wireless Communications. Norwood, MA, USA: Artech House, 1999.

[2] D. Didascalou, "Ray Optical Wave Propagation Modelling in Arbitrarily Shaped Tunnels", Forschungsberichte aus dem Institut für Höchstfrequenztechnik und Elektronik der Universität Karlsruhe, vol. 24, Institut für Höchstfrequenztechnik und Elektronik, Universität Karlsruhe, 2000.

[3] B. M. Notaros, Electromagnetics, New Jersey: PEARSON Prentice Hall; 2010.

[4] B. Troksa, C. Key, F. Kunkel, S. V. Savic, M. M. Ilic, and B. M. Notaros, "Ray Tracing Using Shooting-Bouncing Technique to Model Mine Tunnels: Theory and Verification for a PEC Waveguide," Proceedings of the 2018 International Applied Computational Electromagnetics Society (ACES) Symposium – ACES2018, Mar. 25–29, 2018, Denver, Colorado, USA.

[5] C. Key, B. Troksa, F. Kunkel, S. V. Savić, M. M. Ilic and B. M. Notaroš, "Comparison of Three Sampling Methods for Shooting-Bouncing Ray Tracing Using a simple Waveguide Model," 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, MA, 2018, pp. 2273-2274.

[6] Z. Yun, M. F. Iskander and Z. Zhang, "Development of a new shooting-and-bouncing ray (SBR) tracing method that avoids ray double counting," IEEE Antennas and Propagation Society International Symposium. 2001 Digest. Boston, MA, USA, 2001, pp. 464-467.

[7] S.-H. Chen and S.-K. Jeng, "SBR image approach for radio wave propagation in tunnels with and without traffic," IEEE Transactions on Vehicular Technology, vol. 45, no. 3, Aug. 1996, pp. 570-578.