Modeling RF Propagation in Mines Using Wireless InSite

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Abstract: This paper presents results from modeling RF propagation in a mine using Wireless InSite®. The Edgar Mine in Idaho Springs, CO provided the realistic scenario for the model. The path loss exponent was evaluated for a 5m section of the modeled mine by considering three different materials (concrete, dry earth, and dry granite) and three different standard deviation of surface roughness values for dry granite (0cm, 0.5cm, and 1cm). When comparing this simulated data with data retrieved from the Edgar Mine it was determined that the Uniform Theory of Diffraction (UTD) ray tracing code, of Wireless InSite, is capable of portraying a communications system within a mine environment.

Keywords: RF Propagation, Mine, Tunnel, Shooting and Bouncing Rays, Diffraction

1. Introduction

Ray tracing has been used to analyze the propagation of wireless transmissions in mines and tunnels for many years [1]. Initial geometrical optics approaches were later replaced by uniform theory of diffraction (UTD) calculations since UTD provided an accurate way to calculate diffraction around curved and branched tunnels as well as diffraction from obstructions within the tunnels [2]. Results compared well with experimental measurements. An alternative method of study took a systems approach and evaluated multimodal propagation in tunnels using analytical approaches for various tunnel shapes [3]. These results were verified through experimental measurements. More recently, computer models have incorporated more detail, including rough walls [4].

This paper presents some initial results of modeling propagation in mines using commercial simulation software package Wireless InSite, which using ray tracing approaches with UTD to predict electromagnetic wave interaction with walls, and terrain.

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2. The Edgar Mine Model

The basic numerical model of a mine tunnel is taken from the Edgar Mine in Idaho Springs, CO. Fig. 1 shows a map of the mine tunnels with a blowup of an interesting area for computer modeling. Some experimental measurements of wireless propagation were done at 2.4 GHz and analytical propagation models were found from the measurements [5]. These measurements focused on the near-zone propagation discussed in [3], where multimodal excitation from the transmitting antenna creates a region of propagation that can be modeled with a path loss exponent. In this range, the power loss with range follows an inverse power law (loss in dB/dec is constant). At ranges far from the transmitting antenna, the dominant mode takes over, and power loss is then exponential, meaning that the loss in dB per m is a constant. In this paper, we evaluate the near-range power variation with range and show that it agrees well with the analytical results in [4] and the measured results in [5], where LOS propagation resulted in a path loss exponent less than 2 (attenuation<20dB/dec). This is consistent with the fact that the waveguiding effect in tunnels reduces the path loss compared to free space propagation, which ideally gives a path loss exponent of 2, or an attenuation of 20dB/dec.

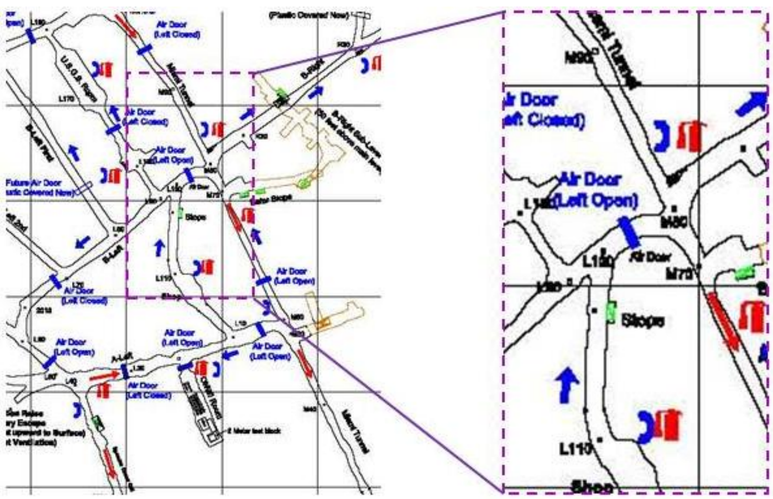

Fig. 1. Map of the Edgar Mine.

3. Wireless InSite Modeling of a Mine Tunnel

Wireless InSite is an electromagnetic modeling tool that uses propagation theory to compute the electric field for receiver points in space. These fields are evaluated for each path based on the Uniform Theory of Diffracton (UTD) [6-8]. It is ideal for most propagation situations and has recently been modified to model propagation inside a tunnel, or culvert structure. Wireless InSite provides accurate results for frequencies as great as 100GHz due to advanced high-frequency electromagnetic methods. The software models the complete scene by considering different antennas, different waveforms for transmitters and receivers, interactions within urban scenarios, interactions with terrain in both rural and urban scenarios, complex structures like buildings and mines, etc. It can also model the physical characteristics of a rough structure like a mine, urban building features, terrain variations, etc. Within the software there are two Shooting and Bouncing Raytracing (SBR) full 3D models.

The SBR calculations are made by casting rays throughout the scene. These rays originate from the transmitter as described in [9] and [10]. The allowed interactions can be chosen by the user to consider reflections off feature faces, diffractions around edges, transmissions through features, etc. For mine or tunnel propagation, the reflections from walls dominate the electric field calculation. Tunnel bends or obstructions require another time expensive diffraction calculation. Too many obstructions or bends result in significant signal loss. The work presented in this paper demonstrates Wireless InSite's capabilities of modeling a simple mine and its potential to handle much more complex mines with various materials and mean surface roughness values.

The mine model in Wireless InSite is an infinitely long shaft with a 2m by 2m square cross section. There are no bends, obstructions, or irregularities. The walls of the Edgar Mine are primarily granite. Material properties of dry granite along with concrete and dry earth appear in Table 1. In addition to modeling these three material properties of the mine wall, the standard deviation of the surface roughness for dry granite was 0cm, 0.5cm, or 1cm.

Table 1: Conductivity (σ) and Relative Permittivity ($\boldsymbol{\varepsilon_r}$) for modeled materials

Material	**σ (S/m)**	$\boldsymbol{\varepsilon_r}$
Concrete	0.015	7.0
Dry Earth	1.0e-003	4.0
Dry Granite	0.01	5.0

The 2.4 GHz transmitter transmits 30dBm through a half-wave, vertically polarized dipole. The propagation path starts 1m from the transmitter (out of the near field) and extends down the center of the tunnel for 5m. Receivers sample the signal along the path every 1 cm. The validity of Wireless InSite's results were reviewed by checking the received power at each receiver and visually inspecting the ray-traced paths.

Viewing propagation paths is an option available in Wireless InSite that allows the user to see each path and its power contribution. It is good practice to check the paths for a handful of receivers to ensure many different paths contribute to the overall power. More often than not, only the 10 strongest paths, with regard to power, are the most influential when calculating the electric field at each receiver. For this study, all transmitter/receiver pairs generated 25 ray-traced paths and almost all of them were unique. This vast amount of unique paths provides confidence that the fields from the UTD based ray-tracer were generated in a manner to provide accurate results.

4. Results

The simulation results of tunnel propagation along the chosen path are shown for concrete, dry earth and dry granite tunnels in Fig. 2. The peaks and valleys in each tunnel are due to multimodal propagation, and in the log-log plots, are shown to agree well with an inverse power law. The least-squares fit for the data is shown in equation form at the top right of each plot. Notice that the path loss exponent is always less than 2 (1.202, 1.387, and 1.518 for concrete, dry earth and dry granite respectively). Although the simulated tunnel is square and the tunnels in [4] and [5] are more rounded, this implies that the path loss exponent and the multimodal waveguiding that it represents, is to some degree independent of tunnel cross-sectional shape. It is interesting to note that the concrete tunnel, with the highest dielectric constant, has more fading (more frequent peaks and nulls) than the dry earth and dry granite tunnels. This could be due to higher reflections from the tunnels walls due to the higher impedance mismatch between air and concrete.

In addition to the straight line fit, we also present the deviations from the fit, as a histogram of amplitude gain with respect to the straight line fit. The histogram was compared with a Weibull distribution to evaluate the type of fading. The Weibull shape parameter is 2 for a Rayleigh distribution. The shape parameter for all three tunnels is larger than 2, and coupled with visual inspection of the distribution, indicates that the fading is not Rayleigh fading, but more Rician in character, since these are line-of-sight (LOS) propagation scenarios. This was also seen in the measured results of [5]. Since the concrete tunnel has more fading that the dry earth or dry granite, the histogram for concrete is well distributed around an amplitude gain of 1 (the straight line fit), whereas for the dry earth and dry granite tunnels, the absence of as many nulls skews the histograms in favor of the peaks and centers them above 1. In a real tunnel, the roughness and irregularity of the walls will give more fading than observed in these ideal tunnels of Fig. 2.

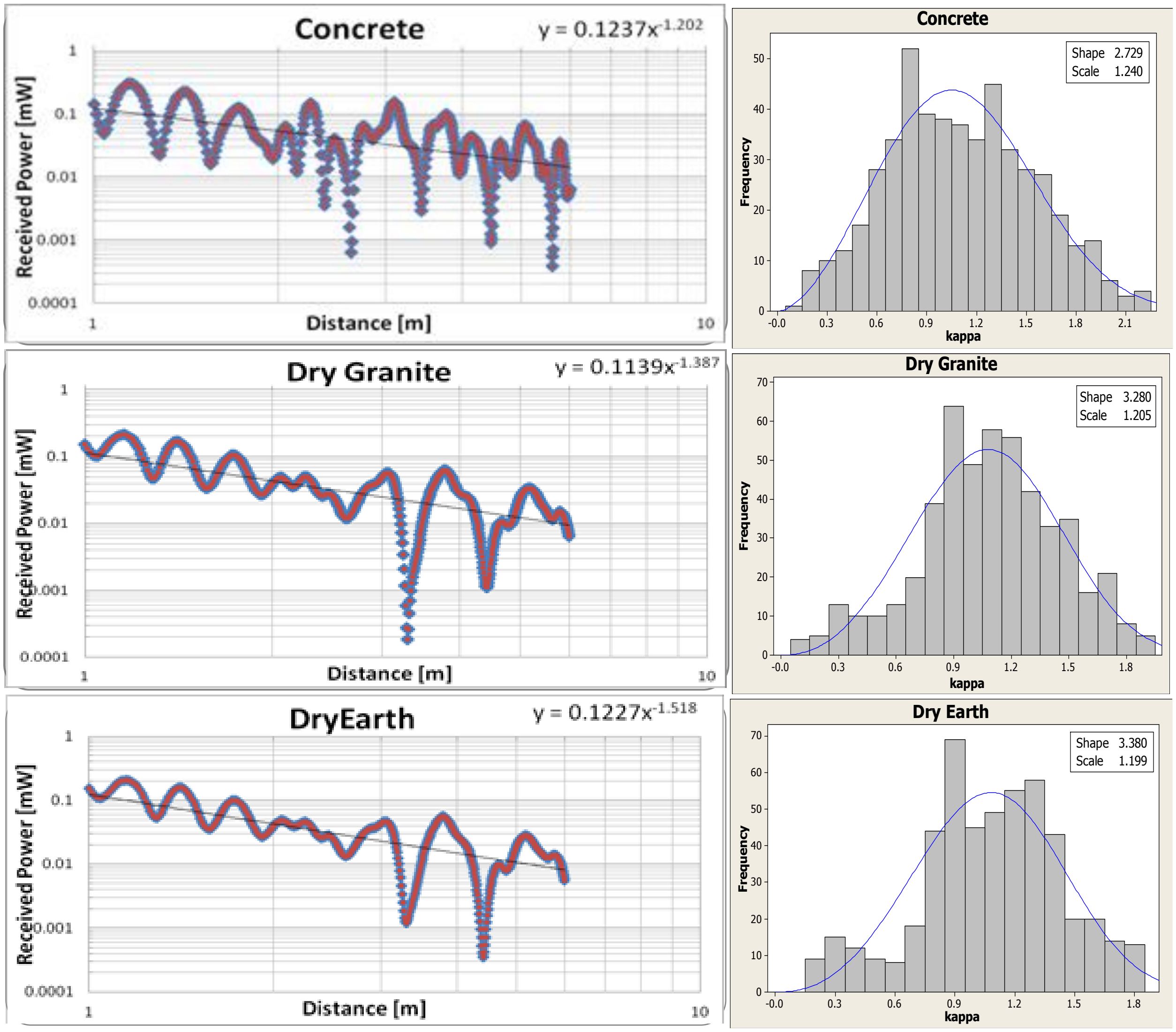

Fig. 2. Received Power vs. Distance for each material, also displaying n-value as exponent of power law fit (right). Histogram of field amplitude deviation from the straight line fit, compared to Weibull distribution.

In order to evaluate how the surface roughness feature of Wireless InSite captures the real nature of the tunnel walls, simulations for dry granite tunnels were repeated with a roughness parameter. Fig. 3 presents the results of these simulations for 3 different roughness parameters: 0cm (smooth tunnel), and 0.5cm and 1cm respectively. The path loss exponent increases for increasing roughness: 1.387, 1.416, and 1.501. This indicates there is more power loss vs. range for the rough tunnels – it is possible that this energy is being scattered into the rock walls and dissipated within them. The height of the peaks and the depth of the values were also diminished slightly due to the additional roughness scattering that introduces variations in amplitude and phase of the scattered rays. Other than this the fading characteristics were not significantly affected by the surface roughness. No new peaks or valleys were introduced. In a real tunnel, the diameter of the tunnel also varies irregularly, but this is not modeled here.

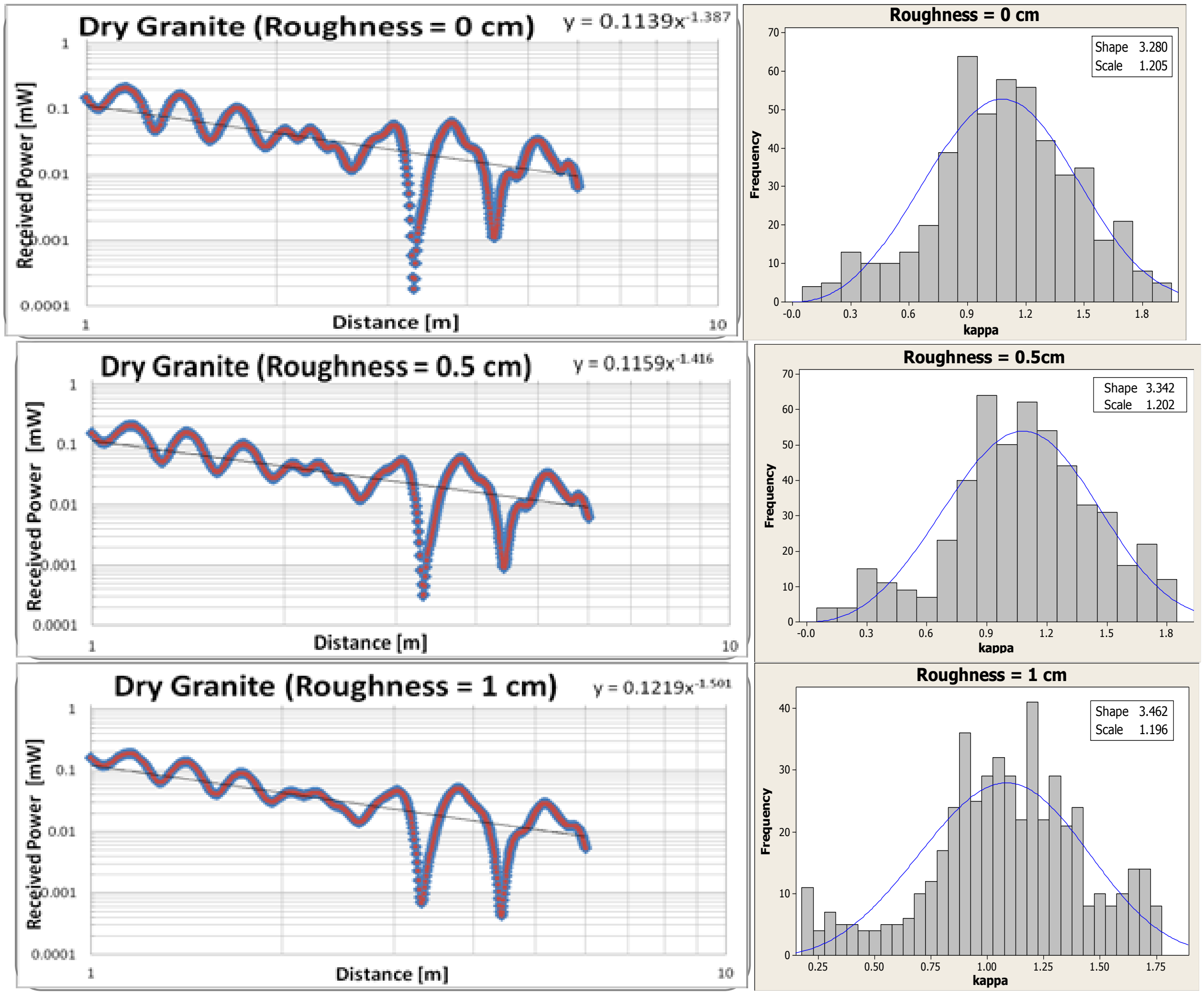

Fig. 3. Received Power vs. Distance for each surface roughness of the Dry Granite material, also displaying n-value as exponent of power law fit (right). Histogram of field amplitude deviation w.r.t. to the straight line, compared to a Weibull distribution.

5. Conclusions and Future Work

The work presented in this paper showcases the mine modeling capability within Wireless InSite. We have shown through simulations, the multimodal waveguiding effect that is seen in the near-field range of a tunnel and that gives rise to a path loss exponent less than the free space value. As aforementioned, the simulated results from Wireless InSite and the works from [4] and [5] are consistently below 20dB/dec which supports the theory of multimodal waveguiding effect. We have also shown that Wireless InSite can be used to model the effect of different wall materials, and that the different materials affect the fading characteristics (for example, concrete vs. dry earth and dry granite.)

Future work should include changing such variables as shape, size, roughness, thickness, materials, and frequencies. These variables will ultimately impact how the waves propagate through the enclosed space. Wireless InSite can accurately model different shapes and sizes of mines making it ideal for such applications. This paper presented uniform tunnel diameters and materials within the mine which may not be realistic in certain cases. Multiple materials included within the mine will produce a more realistic model as the electric properties change from material to material. It is also possible to model other common obstacles such as: metal rails along the floor, metal doors along the side of walls, and pool water along the floor. Introducing these additional obstacles will more accurately simulate a real world mine. In addition more validation work can be done. This paper includes simulation results that have been compared to measured data taken from one mine. A logical next step could include taking additional measurements from different mines, modeling the scenario in Wireless InSite, and then comparing the two.

References

[1] S.F. Mahmoud and J.R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels," *Radio Science*, Vol. 9, 1974, pp. 1147-1158.

[2] Y.P. Zhang, Y. Hwang, and R.G. Kouyoumjian, "Ray-optical prediction of radio-wave propagation characteristics in tunnel environments – part 2: analysis and measurements," *IEEE AP-S Trans.*, Vol. 46, No. 9, Sep 1998, pp. 1337-1345.

[3] D. G. Dudley , M. Lienard , S. F. Mahmoud and P. Degau-que "Wireless propagation in Tunnels", *IEEE AP-S Mag.*, Vol. 49, No. 2, 2007, pp.11 -26.

[4] R. Martelly and R. Janaswamy, "Modeling radio transmission loss in curved, branched and rough-walled tunnels with the ADI-PE method," *IEEE AP-S Trans*., Vol. 58, No. 6, Jun 2010, pp. 2037 – 2045.

[5] Weiss, M.D., Peak, J., Schwengler, T., "A Statistical Radio Range Model for a Robot MANET in a Subterranean Mine", *IEEE Trans. Vehicular Technology,* Vol. 57, No. 5, Sep 2008, pp. 2658 – 2666.

[6] Balanis, C.A., *Advanced Engineering Electromagnetics*, Wiley, New York, 1989, pp. 782-790.

[7] R. Luebbers, "Finite Conductivity Uniform GTD Versus Knife Edge Diffraction in Prediction of Propagation Path Loss," *IEEE AP-S Trans*., Vol. 32, No. 1, Jan 1984, pp. 70-76.

[8] R. Luebbers, "A Heuristic UTD Slope Diffraction Coefficient for Rough Lossy Wedges," *IEEE AP-S Trans*., Vol. 37, No. 2, Feb 1989, pp. 206-211.

[9] J. Schuster and R. Luebbers, "Hybrid sbr/gtd radio propagation model for site specific predictions in an urban environment," *12th Annual Rev. of Progress in Applied Computational Electromagnetics*, Vol. 1, 1996, pp. 84–92.

[10] J. Schuster and R. Luebbers, "Comparison of site-specific radio propagation path loss predictions to measurements in an urban area," *IEEE AP-S International Symposium and URSI Radio Science Meeting*, Vol. 1, Jul 1996, pp. 1210–1213.