Underground Mine Environmental Impact on RF Coupling to Electric Blasting Caps

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***Abstract*— The 2006 Mine Improvement and New Emergency Response Act (MINER Act) requires all U.S. underground coalmines to install wireless communications and electronic tracking equipment. An RF transmitter (Tx) may induce currents in nearby conductors and hence, may interact with the lead wires of a blasting cap generating sufficient current in the leads to cause an inadvertent firing of the cap. There are standards and guidelines that prescribe a minimum separation distance between transmitters to ensure that such induced currents or powers are below an assumed threshold. Generally these prescriptions account for the possible enhancement of the electric fields at the receiver (Rx) (cap) due to ground bounce. In underground mines, there may be additional reflections off the walls and roof that can further enhance the superposed fields indicating that the minimum separation distances recommended by the standards may not be adequately conservative in the underground mine environment. This paper presents analysis and corroborating measurement results to indicate that the presence of additional reflecting surfaces as in a mine environment can enhance the transmitted electric fields experienced by an Rx beyond the field levels predicted in the standards. Introduction**

I. Introduction

A portable radio, acting as a transmitter (Tx), emits radio frequency (RF) energy which may induce currents in nearby conductors and hence, interact with the lead wires of a nearby blasting cap possibly inducing sufficient current in the leads to cause an inadvertent firing of the cap. There are standards and guidelines, for example [1, 2], that provide recommendations as to the minimum required separation distance between a Tx and electric blasting caps to ensure that the coupled energy is less than that necessary to ignite a blasting cap.

The National Institute for Occupational Safety and Health (NIOSH) began to investigate the minimum separation distances between a Tx and blasting caps (receiver, Rx) given the recent influx of radio communications and electronic tracking equipment being installed in underground coal mines. The minimum separation distance between a Tx and Rx was calculated using equations from the IEEE standard [1]. We wondered whether multipath effects in a tunnel environment were adequately addressed. Multipath refers to the phenomenon that EM waves can reach an Rx via multiple paths. EM waves can travel directly (line-of-sight, LOS) between a Tx and Rx and also by reflecting off surfaces. For example, on the earth's surface, a wave can travel directly and reflect off the ground. A similar reflection can happen in a mine (see Fig. 1), but the signal from the Tx can also reflect off the roof, or either of the side walls. There are more opportunities for multipath underground than on the surface. The significance is that under certain conditions, these multiple signals can add constructively at the Rx, resulting in an electric field strength which could be stronger than would be predicted from a worst case analysis assuming LOS and a single reflection.

This paper does not represent an exhaustive study into RF coupling to blasting caps in an underground mine environment, but rather the identification of a potential hazard inadequately addressed by existing standards. In this paper, RF coupling to blasting caps is investigated using a combination of theoretical modeling and experimental measurements. The modeling [1] is based on the theory that the power coupled to the blasting cap leg wires results from the product of two terms: the EM power density in W/m^2, which is proportional to the value of the electric field at the cap squared, and the effective aperture in m^2 of the Rx leg wires. The focus, here, is on the enhancements to the EM power density, i.e., the first term, as a result of the additional multipath.

II. Three Ray Modeling

To simplify the analysis, we will consider only three rays that leave a source and reach the Rx (blasting cap leads): a direct line-of-sight (LOS); and two additional rays, one that has

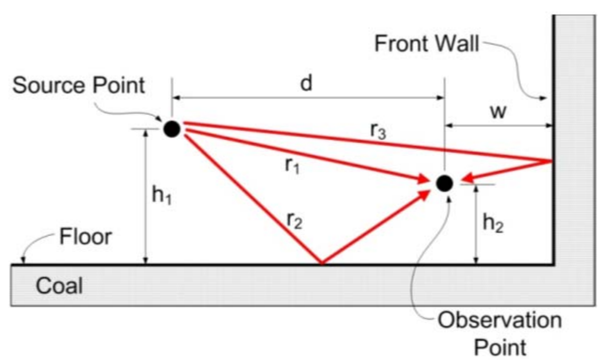

Figure 1. An illustration of multipath in a tunnel when there is an LOS ray, r_1 and rays reflecting off the floor, r_2, and the front wall, r_3.

a single reflection off the floor and one that has a single reflection off a side wall. Also, for simplicity, we assume the Tx and Rx are points equally distant (*h*) from the floor and side wall. The net electric field, if we add the contributions arithmetically, E_{3ray} at the Rx for a vertically polarized transmission is [2]

(1)

where *C* is the amplitude of the transmitted field, assumed to be 1; r_1 is the LOS distance; r_2 the distance traveled by the ray reflecting off the floor (see Fig. 1); and r_3 the distance traveled by the ray reflecting off the front wall. The sign accounts for the fact that we should add the three fields vectorially. $R(\theta)$ is reflection coefficient for parallel (transverse magnetic) polarizations given by [2]

(2)

The permittivity of the walls and roof/floor are assumed equal and $= \varepsilon/\varepsilon_o = \varepsilon_r\text{-}j\sigma/(2\pi f\, \varepsilon_o)$, where ε_o is the permittivity of free space, ε_r is relative to free space; σ is the conductivity; and f the frequency. Note that for the high symmetry case described here, the results are identical for horizontal polarization.

In contrast, for two ray modeling, which would be appropriate for surface blasting operations where rays reflect off the earth, only the second term of (1) would be used assuming a vertically polarized incident ray. For even greater simplicity and conservatism with two ray modeling, it is sometimes assumed that the reflector is a perfect electrical conductor (PEC). An even further conservative assumption is that the net electric field at the Rx cannot exceed twice the LOS electric field. This can be shown to be the case in [1] where, for example, in Table 4 the minimum separation distance for a 5 W 450 MHz UHF Tx from a blasting cap is given. The recommended distance is 5.3 m which is twice the value obtained from the LOS equation to account for the assumed doubling of the electric field by the reflected ray. However, it is possible to exceed twice the LOS when there are additional rays. Figure 2 shows a plot of Rx field for f = 905 MHz for the configuration of Fig. 1 with $h_1 = h_2 = 0.5$ m and w = 0.0829 m (¼ wavelength). The dashed line represents the two times LOS limit for the Rx field. The solid curve is the Rx field for the LOS plus ground plane plus front wall relative to twice the LOS field. The additional reflection from the front wall enhances the Rx field such that for the case modeled, there is a 2.6 dB increase in Rx power at a separation of 1.4 m. Thus, for the situation analyzed, the E field from three rays exceeds the E field value that would be estimated as two times E LOS (as in [1]) by 35% and the minimum separation distance would need to be increased (by 35% in this case).

The National Institute of Standards and Technology (NIST) measured the Rx power as a function of separation from a 905 MHz 30 dBm source. The Tx and Rx were ¼-wave vertically polarized monopole antennas. The Rx was placed ¼

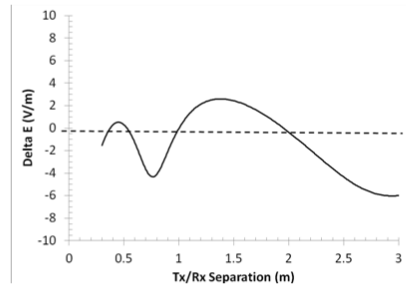

Figure 2. Rx power for two time LOS (dashed) and enhancement in field relative to two times LOS field (solid).

wavelength (8.29 cm) from a transverse conducting wall. The Tx and Rx heights were 1.5 m and 0.015 m, respectively, above a conducting ground plane. Figure 3 is the difference in measured Rx power for a ground plane with a conducting wall relative to just a ground plane. As seen, the additional reflection enhances the received power by as much as 15 dB at certain values of Tx/Rx separation.

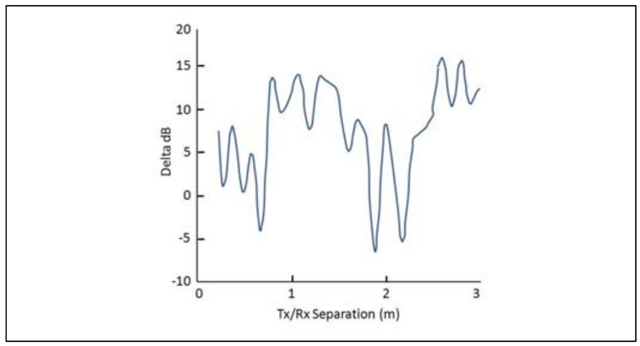

Figure 3. Rx power (dBm) for ground plane, conducting wall, and LOS relative to measurements for LOS plus ground plane.

III. Conclusion

Through modeling and measurements, we have shown that a single ground-reflection model, even one that conservatively assumes the reflected wave produces an additive field equal to the LOS, may be inadequate to account for the enhanced fields from multiple reflections in a tunnel.

Disclaimer: The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH).

References

[1] *IEEE Recommended Practice for Determining Safe Distances from Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations,* IEEE Standard C95.4, 2002.

[2] *Safety Guide for the Prevention of Radio Frequency Radiation Hazards in the use of Commercial Electric Detonators (Blasting Caps)*, SLP-20, Institue of the Makers of Explosives, Washington, DC, Dec 2011.

[3] C. A. Balanis, *Antenna Theory*, 3rd ed.,Wiley Interscience, 2005.