Measurement of the Influence of Antenna Pattern on Radio Frequency Propagation in a Concrete Tunnel[*]

Ronald Jacksha[1], Chenming Zhou[2], and Carl Sunderman[1]

[1]CDC NIOSH, Spokane, WA 99207, USA
[2]CDC NIOSH, Pittsburgh, PA 15236, USA

Abstract — **This paper investigates the influence of antenna pattern on radio frequency (RF) propagation in tunnel/mining environments. Propagation measurement results in a concrete tunnel using different antennas, i.e., omni-directional, Yagi, patch, and circular, are reported. Extensive measurements are carried out in various scenarios which include vertical, horizontal, and circular polarization for line-of-sight propagation (LoS) at four frequencies (455, 915, 2450, and 5800 MHz) that are common to many voice and data transport radio systems used in underground mines. The results show that antenna pattern has a strong influence on the uniformity of RF propagation gain in the near zone and does not significantly affect propagation behavior in the far zone except for a constant gain offset.**

Index Terms — **Tunnel Propagation, ray tracing, antenna pattern, waveguide.**

I. INTRODUCTION

Wireless systems operating in the Ultra-High-Frequency (UHF) and Super-High-Frequency (SHF) radio frequency (RF) bands are becoming commonplace in underground mining. These wireless systems provide communications, data backhaul, miner tracking, proximity detection, and environmental monitoring and control. Understanding RF propagation in underground mines is critical to the optimal performance and reliability of these wireless systems and, as a result, will contribute to enhancing overall miner safety and health.

While RF signal propagation in underground mines and tunnels has been studied for decades [1] - [3], most of the prior studies assume omni-directional antennas for both the transmitter and the receiver and the influence of antenna pattern on tunnel propagation has not been investigated. Particularly, RF propagation measurements in underground mines and tunnels have primarily been performed using omni-directional antennas. In practice, however, wireless systems installed in underground mines often use other types of antennas which could have distinctly different propagation characteristics. In this paper, RF propagation measurement results are reported using omni-directional, Yagi, patch, and circular antennas at 455, 915, 2450, and 5800 MHz for both horizontal and vertical polarizations.

II. MODELING RADIO PROPAGATION IN TUNNELS WITH ANTENNA PATTERNS INCLUDED

We consider a tunnel with a width of 2a and a height of 2b. Let T(x_0, y_0, 0) and R(x, y, z) represent the location of the transmitter and receiver. $f_t\left(\hat{\theta}_t,\hat{\varphi}_t\right)$, $f_r\left(\hat{\theta}_r,\hat{\varphi}_r\right)$ are the pattern functions for the transmitter and receiver antennas, respectively. Without loss of generality, we also assume the source is vertically polarized. Horizontal polarization results can be derived in a similar manner.

Based on the ray tracing theory, the received electric field can be obtained by summing the scalar electric fields of the rays from all the images of the source as [4]:

$$E_r(x,y,z)=E_t\sum_{m=-\infty}^{+\infty}\sum_{n=-\infty}^{+\infty}\frac{e^{-jkr_{m,n}}}{r_{m,n}}f_t\left(\hat{\theta}_{m,n},\hat{\varphi}_{m,n}\right)f_r\left(\hat{\theta}_{m,n},\hat{\varphi}_{m,n}\right)\rho_{\perp}^{|m|}\rho_{//}^{|n|} \tag{1}$$

where E_t is the magnitude of the transmitted electric field, k is the wave number in the waveguide (free space), and $r_{m,n}$ is the distance between the receiver and the image $I_{m,n}$, and is given by:

$$r_{m,n}=\sqrt{(2ma+(-1)^m x_0-x)^2+(2nb+(-1)^n y_0-y)^2+z^2} \tag{2}$$

$\rho_{\perp,//}$ represent the perpendicular and parallel reflection coefficients, respectively, and can be readily calculated as:

$$\rho_{\perp}=\frac{\cos\theta_{m,n}-\sqrt{\overline{\varepsilon}_a-1+\cos^2\theta_{m,n}}}{\cos\theta_{m,n}+\sqrt{\overline{\varepsilon}_a-1+\cos^2\theta_{m,n}}}$$
$$\rho_{//}=\frac{\cos\varphi_{m,n}-\sqrt{\overline{\varepsilon}_b-1+\cos^2\varphi_{m,n}}\Big/\overline{\varepsilon}_b}{\cos\varphi_{m,n}+\sqrt{\overline{\varepsilon}_b-1+\cos^2\varphi_{m,n}}\Big/\overline{\varepsilon}_b} \tag{3}$$

where $\overline{\varepsilon}_{a,b}=\left[\varepsilon_{a,b}-j\sigma_{a,b}/(2\pi f)\right]/\varepsilon_0$ denote the complex relative permittivities of the vertical and horizontal reflection surfaces. $\theta_{\perp,//}$ are the corresponding

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angles of incidence relative to the normal to the reflecting surface and are given by:

$$\cos\theta_{m,n} = \frac{|2ma + (-1)^m x_0 - x|}{r_{m,n}} \qquad (4)$$
$$\cos\varphi_{m,n} = \frac{|2nb + (-1)^n y_0 - y|}{r_{m,n}}$$

It has been shown in [4] that in the far region both $\theta_{m,n}$ and $\varphi_{m,n}$ are very small so that

$$f_t\left(\hat{\theta}_{m,n}, \hat{\varphi}_{m,n}\right) \approx G_t \qquad (5)$$
$$f_r\left(\hat{\theta}_{m,n}, \hat{\varphi}_{m,n}\right) \approx G_r$$

Substituting (5) into (1) yields

$$E_r(x,y,z) \approx G_t G_r E_t \sum_{m=-\infty}^{+\infty}\sum_{n=-\infty}^{+\infty} \frac{e^{-jkr_{m,n}}}{r_{m,n}} \rho_\perp^{|m|} \rho_{//}^{|n|} \quad \text{for large z} \qquad (6)$$

For omni-directional antennas where $G_t = G_r = 1$, (6) reduces to

$$E_r(x,y,z) = E_t \sum_{m=-\infty}^{+\infty}\sum_{n=-\infty}^{+\infty} \frac{e^{-jkr_{m,n}}}{r_{m,n}} \rho_\perp^{|m|} \rho_{//}^{|n|} \qquad (7)$$

A comparison of (7) and (6) show that in the far zone where z is sufficiently large, the received power is not significantly affected by the antenna patterns, except for a difference of a constant gain (i.e, $G_t G_r$) which is determined by the antenna patterns (shown in (5)) and the alignment of the two antennas. In the near zone where z is small, the contribution from the transmitter and receiver antenna patterns is highly dependent on angles of each ray and thus has a significant influence on the received power.

III. MEASUREMENT LOCATION AND METHOD

RF propagation measurements were performed in the 900 Gallery (tunnel) of the United States Bureau of Reclamation's Grand Coulee Dam. The concrete tunnel is 1.8-m wide, 2.4-m high, and has an arched ceiling beginning 1.5 m up the side of the wall. Detailed information on the RF propagation test apparatus and measurement method can be found in [5]. The concrete tunnel and test apparatus are shown in Fig 1.

At each frequency of interest, reference measurements were first completed using omni-directional antennas for both transmit (Tx) and receive (Rx). For subsequent measurements, the Rx antenna remained omni-directional while the Tx antenna was changed to a directional antenna. A representative sample of the test antennas is shown in Fig. 2.

Figure 1 – Measuring the influence of antenna pattern in concrete tunnel

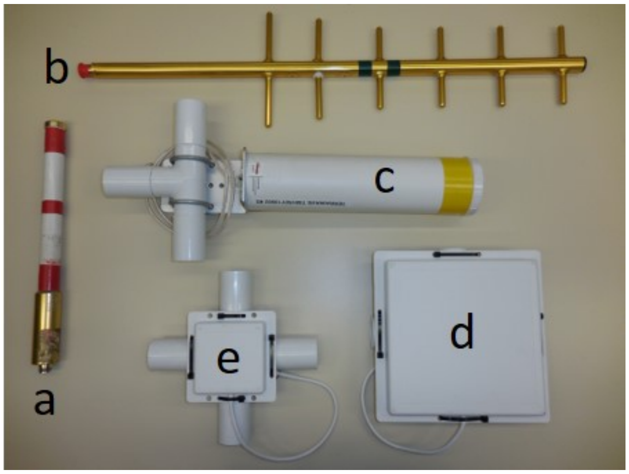

Figure 2 – Antennas: (a) 2450 MHz omni-directional, (b) 915 MHz Yagi, (c) 2450 MHz Yagi, (d) 915 MHz patch, (e) 5800 MHz circular

IV. MEASUREMENT RESULTS

As predicted by the ray tracing theory in Section II, antenna pattern has a strong influence on propagation when the Tx and Rx antennas are in relatively close proximity. A sample of measurement data showing the influence of antenna pattern on the near zone of propagation at 2450 MHz vertical polarization is shown in Fig. 3.

Fig. 4 shows propagation measurement results with different antennas at two frequencies of interest. It can be found that at great Tx/Rx antenna separation distances, the resultant increased signal strengths of the directional antennas are approximately uniform in comparison with the omni-directional antennas. This uniform gain is predictable as illustrated in Section II and measurement data confirm the accuracy of the predictive model.

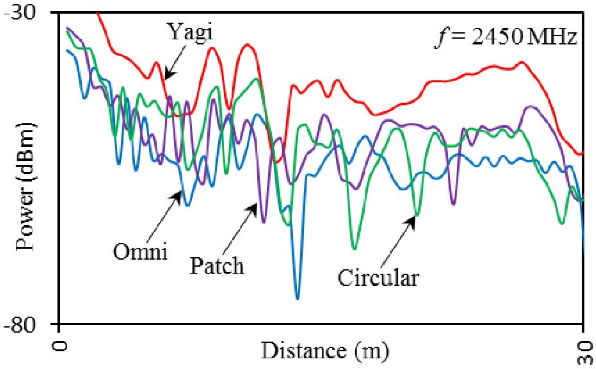

Figure 3 – Influence of antenna pattern on the near zone of RF propagation, 2450 MHz vertical polarization

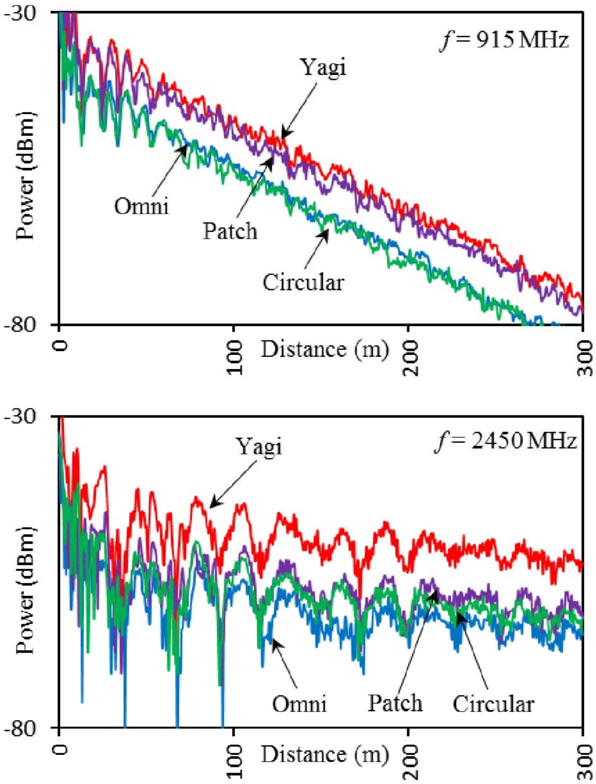

Figure 4 – Influence of antenna on the far zone of RF propagation, 915 MHz and 2450 MHz vertical polarization

VI. CONCLUSION

This paper presents measurement results of the influence of antenna pattern on RF propagation in a concrete tunnel. The measurement data show that in the near zone of propagation change in signal strength is not uniform as a function of antenna pattern. However, in the far zone of propagation signal strength uniformly increases or decreases as a function of antenna pattern and corresponds with the gain specified by the manufacturer.

Understanding the influence of antenna pattern on RF signal propagation is a key element in designing reliable wireless systems which are critical to production and miner safety and health in underground mines.

ACKNOWLEDGEMENT

The authors wish to acknowledge the management and staff of the United States Bureau of Reclamation’s Grand Coulee Dam for their cooperation and assistance in this work. The authors would also like to thank Nilo Tayag, Engineering Technician, NIOSH Spokane Mining Research Division (SMRD), for his assistance in taking the measurements.

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