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Review article

Effect of tunnel geometry and antenna parameters on through-the-air communication systems in underground mines: Survey and open research areas

Intikhab Hussain[a,*], Frederick Cawood[a], Rex van Olst[b]

[a] *School of Mining Engineering, University of Witwatersrand, Johannesburg, South Africa*
[b] *School of Electrical and Information Engineering, University of Witwatersrand, Johannesburg, South Africa*

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A B S T R A C T

In the mining industry, communication systems are important for ensuring personnel safety and optimizing the mining processes underground. The need for through-the-air (TTA) in the underground mining industry has been evolved from man-to-man, man-to-machine and machine-to-machine real-time voice, video and data transmission. Reliable communication has always been a challenge in the underground environment due to harsh and dynamic conditions. This article surveys the effect of tunnel geometry and antenna parameters on TTA communication system performance in underground mines. It provides a comprehensive review of measurement campaigns that have been published to date by systematic organization of literature. The open research areas for future investigation are also discussed. Finally, digital system's findings in the University of Witwatersrand (WITS) mock-mine are presented.

Contents

* Corresponding author.
E-mail addresses: 1024894@students.wits.ac.za (I. Hussain), frederick.cawood@wits.ac.za (F. Cawood), rex.vanolst@wits.ac.za (R. van Olst).

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1. Introduction

Mineral resources play an important role in the global economy. In the past, many lives have been lost and significant financial losses incurred because of mining accidents, especially in underground mines [1]. Monitoring underground mines becomes important in order to avoid accidents and launching of rescue operations in case of an accident. Communication systems are important for ensuring personnel safety and optimizing the mining processes underground [2]. The task of reliably and quickly collecting and communicating information in underground mining is very important because losses (i.e. loss of lives, productivity, and deployed infrastructure) due to inefficient or incorrect information can be significant. The interest in wireless communication in underground mines started in the 1920's [3]. The first commercial development took place in 1970's using very-high-frequency (VHF) radios and leaky feeder distribution systems [4,5]. The modern era of underground mine communication systems began in the early 2000's leveraging on considerable advancement of ultra-high-frequency (UHF) (especially cellular phones), ultra-wideband (UWB), radio-frequency-identification (RFID) and wireless-local-area-networks (WLAN) technologies [2]. Although, the nature of the mining industry is inherently conservative and sceptical to invest on new unproven technologies, the health and safety issues invoke the mines and regulators to improve conditions by applying reliable underground communication systems [2].

The deployment of a wired communication system is a troublesome task in an underground mine. It requires expensive maintenance and has limited scalability [6]. Wireless communication systems on the other hand can benefit from its ease of deployment with an increased scalability, self-adaptive nature and low maintenance cost. Recent studies and applications of underground wireless communication systems have been stimulated by the potential advantages of next generation mobile communication systems. Underground mining is one of the few fields where the environment has a significant and direct impact on the communication performance [7]. Establishment of a reliable system in an underground mining environment is very difficult because of extreme working conditions [8–11]; e.g. poor line-of-sight (LOS), air quality and temperature, humidity, noise caused by different appliances/ cable lines/ electric motors/mining equipment, in-mine vehicle accidents, waveguide effect, toxic gases, floods, roof-fall and dust.

This work aims to survey the effect of tunnel geometry (cross-section dimension and shape) and antenna parameters on TTA communication system, identify research gaps and present open research areas. The remainder of this paper is organized as follows. Section 2 covers brief review of statistical radio propagation parameters. In Section 3, an overview of communication systems for underground mines is presented. Related work on the effect of tunnel geometry and antenna parameter on TTA communication system is covered in Section 4. Research gaps and open research areas are identified in Section 5. Section 6 discusses radio propagation characteristics of WITS mock-tunnel and the findings of tested communication systems in the mock-mine. Finally, the paper is concluded in Section 7.

2. Statistical characterization of radio channel

In this section, statistical radio propagation parameters that will be required in this paper are addressed and explained briefly. The material presented is primarily extracted from a survey of wireless communications and propagation modelling in underground mines [2], a performance study of line-of-sight millimetre-wave underground mine channel [12] and a book chapter [13].

The wireless signal from a transmitter to a receiver experiences different propagation phenomena, i.e. diffraction, refraction, reflection and scattering. This multipath fading effect needs to be taken into account when designing and developing a radio communication system. Modelling the channel has been the most difficult part of radio communication design. It is typically done using statistical approach where the signal characteristics are measured at different points and using a statistical models derived to match measurements of the intended spectrum [13]. The radio channel path-loss can be estimated from the measured channel transfer function [12], using Eq. (1). The relationship between path-loss and distance can be explained by Eq. (2) [13].

$$P_L(d) = -10 \log_{10} \left[\frac{1}{NM} \sum_{i=1}^{N} \sum_{j=1}^{M} |H_j(f_i, d)|^2 \right] \tag{1}$$

$$P_L(d) = P_L(d_o) + n10 \log_{10} \frac{d}{d_0} + X_\sigma \quad \text{[dB]} \tag{2}$$

where, $H_j(f_i, d)$ is the jth channel transfer function at frequency f_i and distance d. N is the number of sweep point in every transfer function and M is the number of measurements at each point. $P_L(d_o)$ is the path-loss at reference distance d_o, n is the path-loss exponent and X_σ is the zero-mean Gaussian distribution random variable with standard deviation σ.

Most path-loss models have several breakpoints that separate the areas where radio waves experience different path loss exponents [2], as shown in Fig. 1. The breakpoint location depends on tunnel cross-section dimensions, signal wavelength and antenna radiation pattern when antennas are placed inside the tunnel [14]. Assuming omni-directional antennas, the location mainly depends on dimensions of tunnel cross-section (w, h) and signal wavelength as shown in Eq. (3) [15].

$$r_{bp} = max \left(\frac{w^2}{\lambda}, \frac{h^2}{\lambda} \right) \tag{3}$$

The time dispersion parameters are used to quantify the multipath channel for designing a wireless channel [13]. These multipath parameters include mean excess delay, root-mean-square (RMS) delay spread and excess delay spread (X dB) can be obtained from power delay profile, $P(\tau)$, which is related to channel impulse response in Eq. (4) [13].

$$P(\tau) \approx \overline{k|h(t, \tau)|^2} \tag{4}$$

where, $h(t, \tau)$ is the channel impulse response, k is the gain which relates the transmitted power to the total received and the bar represents the spatial average over local area.

3. Communication systems for underground mines

In general, the underground mine communication systems are classified as through-the-earth (TTE), through-the-wire (TTW) and through-the-air (TTA) [2,16]. The need of underground mine safety, efficiency and productivity invokes man-to-man, man-to-machine and machine-to-machine communication.

3.1. Through-The-Earth (TTE) communication system

TTE communication systems use significant transmitting power and larger antennas to transfer ELF (Extremely Low Frequency), VLF (Very Low Frequency), LF (Low Frequency) signals through solid rocks from the earth's surface into underground mine [8,17–19]. It is used in case of disaster recovery to locate trapped miners (Fig. 2) [20]. There is a trade-off between system transmission rate and its range. In addition, the system performance is highly