

A Survey of Wireless Communications and Propagation Modeling in Underground Mines

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Abstract—Mining and mineral exploration play important roles in the global economy. In mining operations, communication systems play vital roles in ensuring personnel safety, enhancing operational efficiency and process optimization. Over the period 1920-2012, this article surveys the evolution of wireless communications in underground mines, the developments of the underlying technology, and progress in understanding and modeling the underground wireless propagation channel. Current and future trends in technology, applications and propagation modeling are also identified. About ninety relevant references have been reviewed that consider: 1) the emergence of technology and applications, 2) analytical, numerical and measurement-based propagation modeling techniques, and 3) implications of the physical environment, antenna placement and radiation characteristics on wireless communication system design. Affected systems include narrowband, wideband/ultra-wideband (UWB) and multiple-antenna systems. The paper concludes by identifying open areas of research.

Index Terms—Underground communications, wireless propagation modeling, underground mines, tunnels, waveguide models, geometrical optical models.

I. INTRODUCTION

THE MINING industry plays a vital role in the global economy. The current estimated market capitalization of global mining companies is about \$962 billion [1], [2]. A large portion of these operations are underground and involve specialized equipment and processes. Communication systems play an increasingly important role in ensuring personnel safety and optimizing the mining process. The estimated size of underground mining equipment market alone is currently about \$45 billion [3], a small but important portion of which is allocated communications systems.

Although interest in deploying wireless communication systems in underground mines dates back to the 1920's [4], [5], the first wide deployment didn't take place until the early 1970's when the mining industry began to deploy very-high-frequency (VHF) radios and leaky feeder distribution systems [6]-[10]. The modern era of underground communications began in the early 2000's as the mining industry sought to take advantage of considerable advances in ultra-high-frequency (UHF) technology, especially cellular phones, wireless-local-area-network (WLAN), UWB and

radio-frequency-identification (RFID). Although the mining industry is inherently conservative and reluctant to invest in costly new technologies, high profile accidents often prompted regulators to require that the mining (and mining communications) industry devote increasing attention to safety and safety communications [11]. Recent interest in deploying next generation wireless communications technology in underground mines has stemmed from: (1) recent advances in short-range wireless communications technology and commercial-off-the-shelf WLAN, wireless-personal-area-network (WPAN), UWB, RFID, radar devices, and (2) the potential to increase mine efficiency and productivity through more effective voice communications, better access to management information systems and automated dispatch [12], [13].

In an underground mine, there are three possible mechanisms for communication signaling: through-the-earth (TTE) at extremely-low-frequency (ELF)/very-low-frequency (VLF)/low-frequency (LF) bands, through-the-wire (TTW) at medium-frequency (MF)/VHF/lower-UHF (*e.g.*, leaky feeders) and through-the-air (TTA) at upper-UHF/super-high-frequency (SHF) [14]. Each has been developed for different applications and each requires specified propagation channel modeling and design. Most of the recent wireless systems fall under the TTA category and also seem to be promising wireless technology for future applications. The main focus of this survey is on methods for characterization of the TTA wireless channels at UHF-band; TTE and TTW are briefly considered.

The need to understand and characterize wireless channels has been recognized since the earliest days of wireless communications. The objective of channel characterization or modeling is to capture our understanding of the manner in which the propagation environment impairs and distorts wireless signals in a form useful in the design, test and simulation of wireless systems. This is particularly important for underground environments, which are much different from surface environments. Subway tunnels lack the rough and tilted walls that characterize underground mines. However, because their propagation characteristics show some similarities to those of underground mines, they have been considered here as well.

For decades, researchers have recognized and studied the differences between wireless propagation in tunnels and underground mines and surface environments. Valuable theoretical and experimental contributions have been made by several individuals and groups including J. Wait *et al.*, S. F. Mahmoud, A. E. Goddard *et al.*, A. G. Emslie *et al.*, P. Delogne, Y. Zhang *et al.*, M. Lienard *et al.*, and C. Despins *et al.* Two non-

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recent reviews, one from 1978 [7] and one from 1991 [10] are about early stage wired/wireless communication technologies such as different types of phones, pagers, leaky feeders and TTE communications. In 2009, the Canada Center for Mineral and Energy Technology (CANMET) reviewed the current state of wireless communications technology for underground mines including products manufactured by key suppliers, their specifications, limitations and advantages [15]. Products by key companies, such as Becker Mining Systems, Mine Radio Systems, MineSite Technology, MineCom, Tunnel Radio of America and Varis, are evaluated in this study. In addition, for documents involving safety and permissible designs for electronic communications systems, the National Institute for Occupational Safety and Health (NIOSH) has provided on-line resources such as collections of past and current mine communications publications, tutorials and workshops [16]. In another recent survey [17], both past and current communication systems in wired/wireless forms are introduced and the significance of each is briefly discussed.

Despite of all of this past effort, there is no comprehensive survey to date of underground communications that not only introduces the technologies and their significance but also reviews the propagation channel models developed for underground tunnels and mines. This can be a barrier for those who want to enter into this field or would like to know more about the subject matter.

In this work, we aim to present a comprehensive survey of wireless propagation in tunnels and underground mines with a focus on current wireless channel modeling, technologies and applications. Our objective is to put previous work in perspective, identify trends and gaps, and summarize accomplishments and opportunities. In Sec. II, we begin the survey with a brief review of the basic wireless propagation terminology. In Sec. III we present a brief history of wireless communications in underground environments. In Sec. IV, we show how the related numerical and analytical models have evolved over time. In Sec. V, we consider measurement-based models. In Sec. VI, we summarize the practical implications for wireless system design based on significant contributions of several researchers. Finally, in Sec. VII, we present the conclusions of this study.

II. WIRELESS PROPAGATION TERMINOLOGY

In this section, some technical terms that will be required throughout the paper are addressed and briefly explained. These terms will be described by explaining how a transmit signal undergoes pathloss and fading before reaching a receiver. Most of material presented here has been extracted from a comprehensive survey on propagation models for mobile communications in [18] as well as a book chapter [19].

As a wireless signal traverses the path from a transmitter to a receiver, it experiences different propagation phenomena such as reflection, diffraction, scattering and refraction as suggested by Fig. 1. As a result of interaction of the signal with its surroundings, replicas of the signal may take multiple paths from the transmitter (Tx) to the receiver (Rx). Because the replicas reach the receiver after different delays, the signal experiences time dispersion (quantified by delay spread).

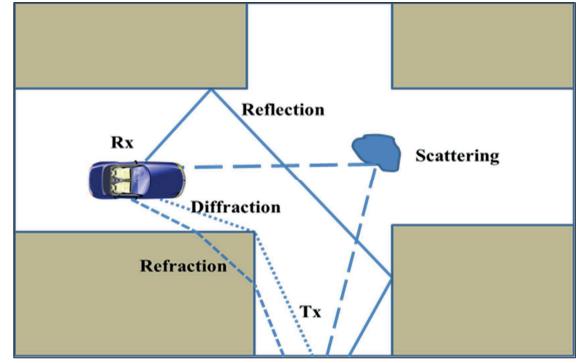


Fig. 1. Wireless propagation phenomena.

Because they also arrive from different directions, the signal experiences angular dispersion (quantified by angular spread) [19]. If either the scatterers or one of the terminals (Tx or Rx) moves, rapid changes in the phase relationship between multipath components can cause the signal to fade randomly, *i.e.*, fading. Such variation in received signal strength over time is equivalent to frequency dispersion (quantified by Doppler spread). Fading can be categorized into two main types: small-scale fading and large-scale fading, which are shown in Fig. 2.

Small-scale fading models characterize the rapid fluctuations of the received signal strength over very short travel distances (few wavelengths), whereas large-scale fading characterizes signal fadings over a large area. Pathloss and pathloss exponent (or distance exponent, power-distance-factor) are terms used in large-scale models for indoor and outdoor environment. In decibels, pathloss, PL is defined as

$$PL = P_{Tx} + G_{Tx} + G_{Rx} - P_{Rx} \quad (1)$$

where P_{Tx} and P_{Rx} are the time-averaged power levels (in dBm) at the output of the transmitter and the input of the receiver, respectively, and G_{Tx} and G_{Rx} are the gains (in dBi) of the transmitter and receiver antennas. The relationship between pathloss and the distance, d , between the transmitter and receiver follows a power-law relation and can be described by [19]:

$$PL(d) = PL_0 + n 10 \log_{10} \frac{d}{d_0} + X_\sigma \quad (2)$$

where PL_0 is the value of pathloss (in dB) at the reference distance d_0 , n is the distance exponent and X_σ is a zero-mean Gaussian random variable with standard deviation σ . The pathloss exponent is 2 for free space and 4 for the case of specular reflection from the ground surface. In some environments, such as buildings and other indoor environments, the pathloss exponent can reach values in the range of 4 to 6. On the other hand, a hallway or a tunnel may act as a waveguide, resulting in a pathloss exponent less than 2.

Most pathloss models have one or several breakpoints that distinguish areas where radio waves experience different pathloss exponents (Fig. 3). The Tunnel dual-slope pathloss model has a breakpoint that separates far-field (or far zone) and near-field (or near zone) regions. The breakpoint location in a

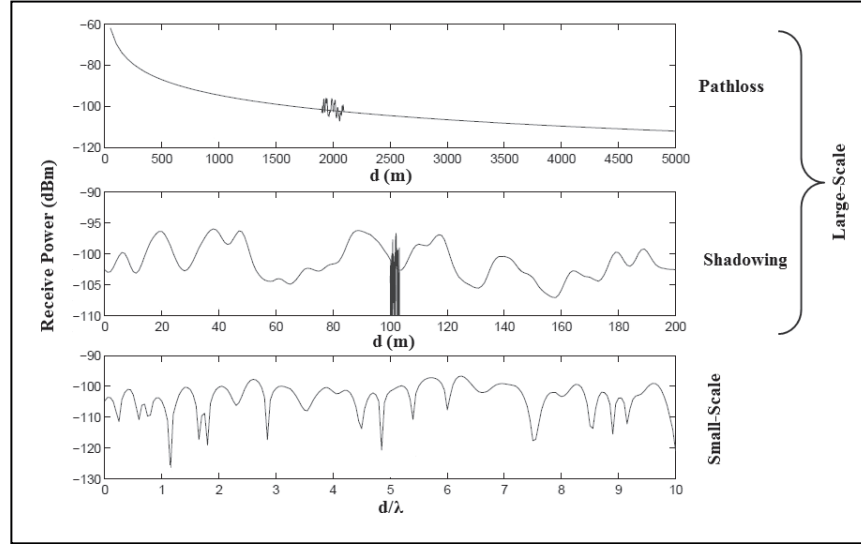


Fig. 2. Large-scale and small-scale fading.

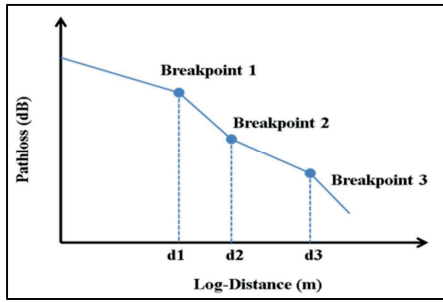


Fig. 3. A pathloss model with three breakpoints.

tunnel depends on the largest cross-sectional dimension (width or height) of the tunnel relative to the signal wavelength.

The near-field region of a straight tunnel is the region before the breakpoint where signal fluctuation is significant because of the reflections and multipath components coming from different directions, which are comparable to the line-of-sight path. In this region, the pathloss exponent is closer to that of an indoor environment ($n \geq 2$). On the other hand, the far-field region of a straight tunnel is the region after the breakpoint where the received signal is well established, and there is little signal fluctuation because all the paths received at the receiver are from almost the same angle as the direct path. In this region, pathloss exponent is less than that of free space pathloss, (*i.e.*, $n = 2$), and so-called waveguide propagation occurs.

The attenuation constant describes the attenuation of an electro-magnetic (EM) wave propagating through a dielectric medium per unit distance from the source. It is the real part of the propagation constant, measured in Nepers per meter (Np/m) and accounts for attenuation due to propagation in a lossy environment. The attenuation constant of a vacuum is equal to zero because it is a lossless medium. Assuming a transverse-EM (TEM, *i.e.*, E and H are both perpendicular

to direction of propagation) plane wave propagating in the z direction can be represented using the phasor expression:

$$E(z, \omega) = E_0 e^{-\gamma z} \quad (3)$$

where ω is the radian frequency and γ is the complex propagation constant given as:

$$\gamma(\omega) = \alpha(\omega) + j\beta(\omega) \quad (4)$$

where α (Np/m) is the attenuation constant and β (rad/m) denotes the phase constant.

III. THE EVOLUTION OF WIRELESS COMMUNICATIONS IN TUNNELS AND UNDERGROUND MINES

In this section, the evolution of wireless communications in underground mines is discussed in terms of technologies and applications. Both reveal that the initial motivation for underground mine communications was to increase the safety of miners by implementing man-to-man communications. As underground mine communications have evolved, man-to-machine and machine-to-machine communications have been implemented to meet efficiency and productivity objectives.

A. Through-The-Earth Communications

Interest in wireless communications for underground mine dates back to the 1920's when the earliest pioneers of radio were interested in the possibilities of TTE wireless transmission. N. Tesla suggested to use ELF signals, and the earth as a transmitting medium to send messages across the world in 1899 [20]. This continued until the late 1940's when techniques such as carrier-current radios and TTE signaling were commercially offered by the U.S. Bureau of Mines for ordinary communications and for emergency operations in mines [4], [5], [10]. TTE communications in mines use huge antennas to transfer ELF or VLF signals through solid rock from the surface into the underground mine. In late 1940's, due to limitations such as low data rate and bulky

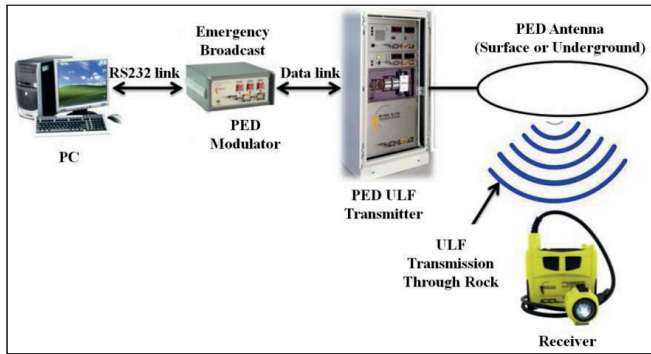


Fig. 4. Through-the-earth communications.

mobile equipment, early studies of wireless communications in tunnels were terminated [21], [22].

Recent mine regulations have renewed interest in TTE communications since it offers a wider coverage inside the mine compared to modern wireless systems. There are apparent advantages to modern wireless systems in underground tunnels and mines, but they could be quite vulnerable when a major disaster occurs. Disasters such as explosion, flooding, rock burst, or severe roof fall, may damage the relay system or block airways. TTE communications has been proven to be suitable for emergency communications because it accesses every part of the mine by propagating through the rock and requires no cabling between the surface and underground [23]. Two-way communication systems are preferred over one-way systems because in most emergency cases, it is essential for escaping or trapped miners to relay valuable information to the surface.

Until several fatal incidents occurred in 2006, the number of mining disasters had been following a decreasing trend. The Mine Improvement and New Emergency Response (MINER) Act of 2006 requires that mine operators install wireless two-way communications and tracking systems that will connect surface rescuers to the underground workers [24]. Two commonly used wireless solutions for emergency cases are text messaging based on TTE and tracker tagging.

Personal-emergency-device (PED) is an emergency warning system based on TTE technology [25], which uses VLF/ULF signals to transmit text messages (Fig. 4). Initially, this product had one-way communication capability, but recent versions are capable of two-way communication via text messaging [25].

B. Through-The-Wire Communications

In the early history of through-the-wire communications in tunnels and underground mines, implementation of communication systems was based on experimental observations without any theoretical insights or empirical modeling attempts. People working in underground mines found that low frequencies on the order of 10 MHz (cutoff frequency of fundamental modes of most tunnels) could cover distances of less than 30 m in an empty mine [26]. However, they also observed that conductors such as electrical cables, pipes and *etc.*, running in most mines, enhance EM propagation with

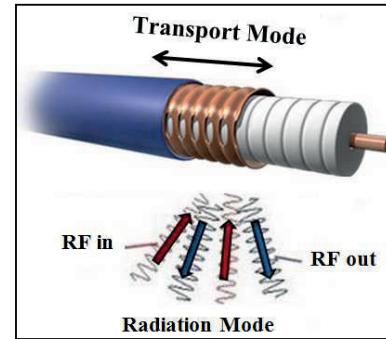


Fig. 5. Leaky feeder cable.

low attenuation, and therefore increase the range [20]. This fact was not immediately understood by experimenters, but it resulted in development of the monofilar technique at the end of the 1960's. Monofilar system became an introduction for leaky feeder systems that were widely used thereafter.

In general, TTW signals can travel over coaxial, twisted pair, trolley, leaky feeder and fiber optics from the surface or inside the mine and reach the mobile equipment. Since one side of the system is wired and the other is wireless, it is also called a hybrid or semi-wireless system. During the 1950's and 1960's, leaky feeder systems and other distributed antenna systems were developed in order to extend the coverage of VHF wireless communication systems to the relatively short underground transportation tunnels found in major urban centres for public safety [9]. In the late 1960's when the safety concerns prompted government regulators and safety boards in Europe and North America to encourage the mining industry to improve communications with underground workers by deploying wireless systems based upon VHF-FM portable radios and leaky feeder distribution systems [10]. Leaky feeder is the most well-known TTW-based communication system in underground mines. The cable is called 'leaky' as it has gaps or slots in its outer sheath, allowing signal to leak into or out of the cable along its entire length (Fig. 5). Because of this leakage of signal, line amplifiers must be inserted at regular intervals, typically every 350 to 500 meters. Key disadvantages of leaky feeder system are difficult maintenance, fixed infrastructure, limited capacity and low coverage near the face, *i.e.*, the region of the mine where ore is extracted [10].

C. Through-The-Air Communications

TTA is another wireless system for communications in underground mines. It is capable of offering various applications such as two-way voice and data communications, tracking miners and equipment, remote control and sensing, video surveillance and *etc.*

In the early 2000's, advances in short-range digital communications to cover 100's of meters motivated the mining industry to consider WLAN off-the-shelf products to support short-range applications in underground. In the late 2000's, the mining industry was attracted to low data rate technologies such as ZigBee, active-RFID (10's of meters), passive-RFID (about 1 meter) and high data rate systems, such as UWB systems, because they offer short-range, low power

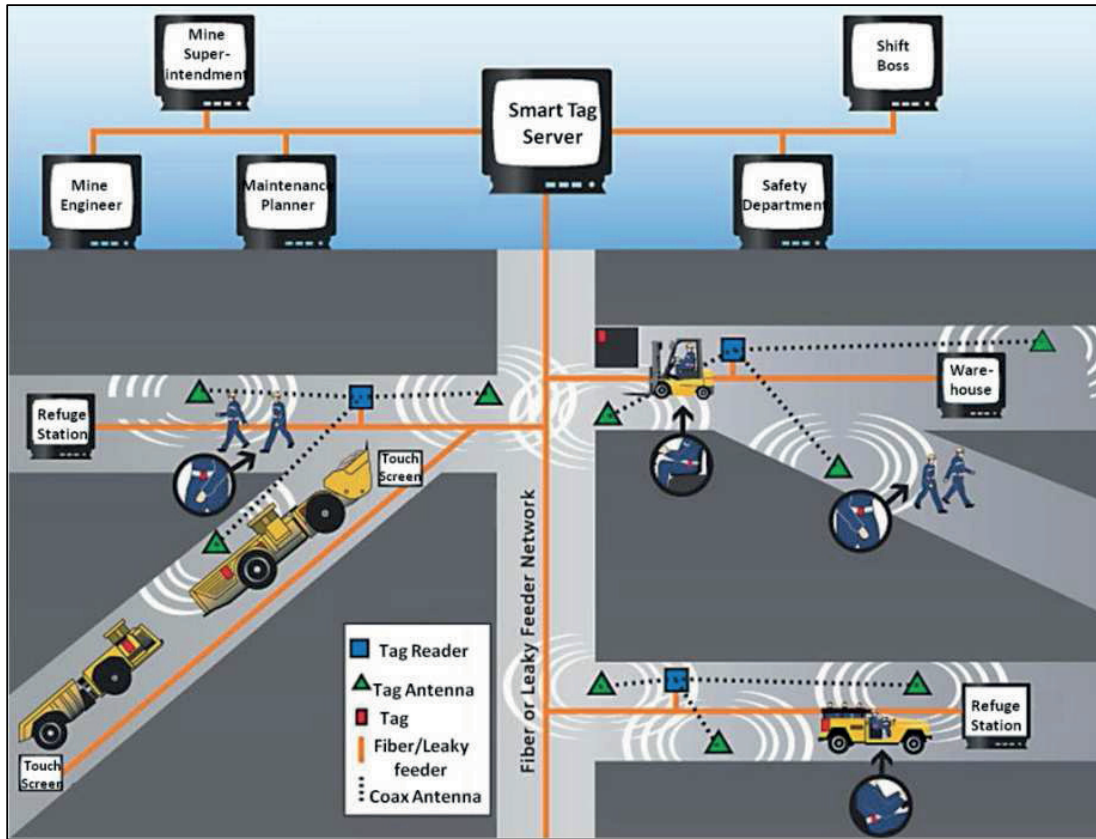


Fig. 6. Tracking system in an underground mine [29].

and positioning capabilities. These technologies can support various applications such as dispatch and sensor networks. These applications can be implemented based on WLAN backbone. So far, WLAN mesh networks that are redundant, self-learning and self-healing seems to be the most reliable wireless systems. If any part of the network is destroyed, the remainder continues to function, and therefore it is especially desirable in a dynamic environment where link failures are frequent as in the mine galleries [13], [25]. One of the attractive wireless applications is tracking, which can be implemented based on RFID technology using WLAN, fiber optics or leaky feeder backbone (Fig. 6). This tracking system provides the ability of real-time monitoring the location of personnel, vehicles and equipment underground. Mining equipment such as vehicles, containers, drills and other valuable mobile ore production equipment are constantly moving through large underground areas. Because the equipment does not necessarily follow a pre-defined track and is spread throughout the mine, it is difficult to locate particular assets that are needed in real-time [27], [28].

A typical RFID-based tracker system is shown in Fig. 6. This system consists of: (1) active tags to identify personnel/vehicles/assets or store data and histories, (2) tag readers to exchange information with the server and tags, (3) antennas to connect tags and tag readers and provide triangulation information for location finding, (4) a server computer system for control and monitoring, and (5) backbone system that can

be fiber optics or leaky feeder to connect tag readers to the server [29].

Another important application of short-range wireless is remote control and sensing. Some of commonly deployed control applications of wireless communication are real-time remote equipment diagnostics, remote monitoring, remote programmable-logic-controller (PLC) programming, *etc.* As an example, a PLC in local control station can wirelessly communicate with the remote automation and sensor devices (such as pull cords, belt misalignments and tilt switches or motion sensors) along a conveyor in a mine site.

Before employing the aforementioned wireless technologies in tunnels and underground mines, careful characterization of the wireless propagation in terms of parameters such as pathloss, delay spread and angular spread, *etc.* is required. This is because wireless propagation in tunnels and underground mines is significantly different from conventional indoor and outdoor environments, and therefore existing channel models developed for conventional surface environments are not applicable. Consequently, it will be necessary to develop new channel models that capture the nature of the relevant impairments and their dependence on the new environment.

A good channel model is abstract, simple, and focuses on those aspects of the channel that affect the performance of a system of interest and ignore the rest. Over-engineering the communications links is needlessly expensive and under-engineering them leads to either insufficient reliability or ca-

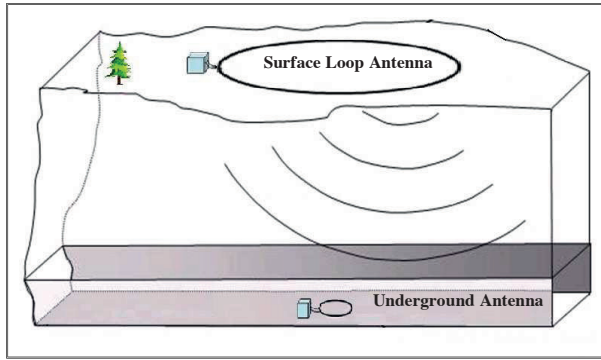


Fig. 7. Surface antenna for through-the-earth communications.

capacity. Propagation and channel modeling facilitates efficient design and system deployment by answering questions such as What channel impairments do we need to mitigate? or What is the optimum frequency, antenna placement/configuration and range?

IV. PROPAGATION ANALYSIS MODELING

In this section, we focus on the different mechanisms by which wireless signals propagate in underground environments. First, TTE (through the earth) and TTW (through the wire) propagation will be briefly explained. Then, as the main focus of this survey is TTA (through the air) communications, we will elaborate more on analytical modeling for this method. As it will be seen, TTE method is similar to geophysical probing, TTW method can be analyzed similar to transmission lines and TTA in underground tunnels can be considered as waveguide propagation.

A. Propagation Through-The-Earth

In TTE underground communications, the antenna and propagation mechanism are similar to subsurface communications and geophysical probing of the Earth. Both applications require transmission of electromagnetic waves through the earth, and both face the problem of high attenuation. To penetrate the earth to depths of 100 m or more, it is necessary to employ low frequencies (ELF, VLF) [30]. For TTE communications, an extensive loop antenna or a ferrite rod antenna on the order of few kilometers is often used to send/receive the magnetic waves through the rocks (Fig. 7). The choice of magnetic fields for TTE communications might be due to the fact that the earth attenuates and changes the magnetic fields less than the electric fields. The antenna is deployed either on the surface or underground to communicate with miners under the ground [14]. Broader coverage is achievable by increasing the size of the antenna. Power for the underground transmitter is limited due to permissibility requirements. Frequency, geology, noise and depth will influence the probability of successfully communicating with the surface using TTE communications [14].

Based on initial studies, conductivity of the earth's layers was found to be important in VLF ranges. Studies showed the presence of any metallic conductor such as pipes, power

cables, rails, *etc.* greatly enhances the transmission of radio waves TTE. Conductivity proved to be a function of the types of rock or soil through which a signal passed as well as a function of the signal frequency [20]. The effect of rock layers on the EM propagation was extensively studied by J. Wait *et al.* [31]. Their work underlies later studies on TTE EM probing or signaling. They have addressed continuous-wave and transient problems over a range of conductivity and dielectric values.

Numerous studies of EM noise were also carried out after it was realized that at VLF or ELF ambient noise is a major problem. The source of the background noise was determined to come from the interaction of particles of solar origin with the earth's electric and magnetic fields and from worldwide lightning [19]. References concerned with the problem of EM propagation through-the-earth and other significant accomplishments by J. Wait *et al.* are listed in [31]. Currently, TTE signaling is used for emergency communications in underground mines. Portable, person-worn wireless TTE systems exist and are often used instead of hard-wired systems to establish contact with miners because they offer better resistance to damage from roof falls, fires and explosions.

B. Propagation Through-The-Wire

For propagation through-the-wire, frequency bands higher than ELF are used by stretching a longitudinal conductor along the tunnel. Such a conductor can support a quasi-TEM mode spread between the conductor and the tunnel sidewall (Fig. 8-a), referred to as the monofilar mode and characterized by a zero cutoff frequency. The fields of such a mode are accessible in the whole cross-section of the tunnel at the expense of power loss due to high power absorption by the tunnel wall. In order to reduce such loss, a two (or more) wire transmission-line (TL) system should be used, whereby a new mode that has anti-phased currents in the two wires is created (Fig. 8-b). This mode that is usually referred to as the bifilar mode, has fields that are concentrated in the vicinity of the TL and hence has lower cross-sectional coverage but relatively low loss [32].

Under some simplifying assumptions, a modal equation for the monofilar mode of a single wire in a rectangular tunnel was obtained by Wait *et al.* [33]. They extended their analysis in [33] to derive the modal equations for the monofilar and bifilar modes of a two open wire TL inside the rectangular tunnel and found the attenuation constants of these modes over a wide range of frequencies. They also considered the excitation of monofilar and bifilar modes in a TL in a circular tunnel using a short dipole antenna. Based on their results, the monofilar mode showed stronger excitation from an antenna placed in the tunnel, but the bifilar mode showed lower attenuation. The excessive losses in the monofilar or coaxial mode are attributed to the return current flow along the tunnel walls

In the bifilar or TL mode, the fields are more confined to the region between the wire conductors [32]. Monofilar and bifilar techniques ultimately led to the radiating cables and leaky coaxial feeders that have been widely used for underground mine communications since the 1970's. Leaky feeder systems can be obtained by introducing periodic discontinuities into the

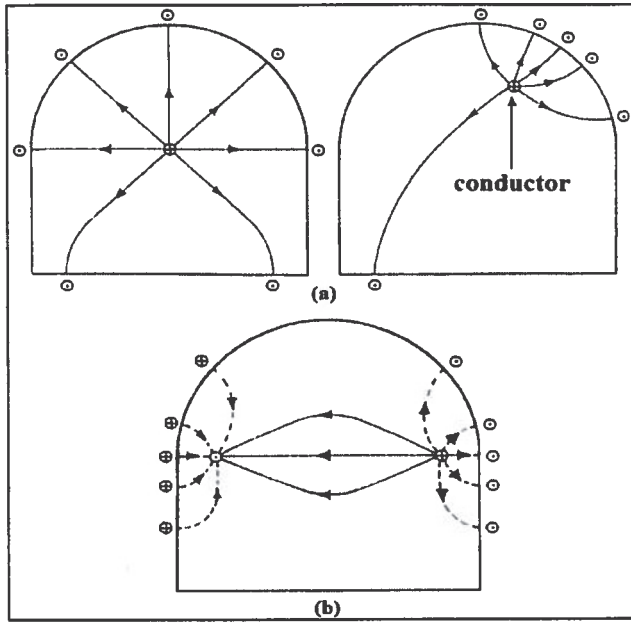


Fig. 8. a) Current distribution and electric field lines of the monofilar mode (between each wire and the tunnel wall) and b) monofilar mode and bifilar mode (between the wires) [6]

coaxial cable that convert radio frequency energy from a non-radiating bifilar mode to a monofilar mode. The discontinuities are created by the insertion of specially designed mode converters, or radiating devices in the cable at the desired intervals [34].

C. Propagation Through-The-Air

In this section, various analytical and numerical models for characterizing TTA propagation in mine tunnels are discussed. As it will be seen, developing analytical models for extreme environments such as underground mines can be very elaborate unless simplifying approximations regarding the tunnel geometry are made. These approximations have been modified over the years according to applications at higher frequencies, and availability of faster processors. For instance, in several models, underground tunnels were treated as tunnels with smooth walls. However, as technology has migrated toward higher frequencies, analytical modeling has become more sophisticated. As an example, a single-mode waveguide model [35] proposed about forty years ago could model the propagation loss of lower-UHF band signals in mine tunnels. Today's version has been modified and enhanced into the multimode model which is capable of more precisely modeling propagation loss and delay spread in the upper-UHF band.

1) *Modeling Tunnels as Hollow Dielectric Waveguides:* In the UHF-band, a tunnel structure may guide the EM wave through the tunnel, and therefore can be modeled as a waveguide. Inside the waveguides, EM fields can be resolved into the sum of propagation modes given by the solutions of Maxwell's equations subject to the boundary conditions. These solutions include a dominant mode of propagation with the lowest loss

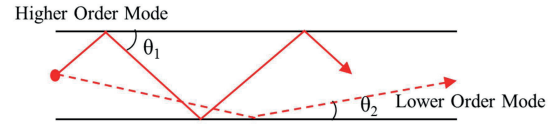


Fig. 9. Comparison of reflection angles of lower and higher order modes in a waveguide.

and higher order modes with higher loss. Higher order modes travel at larger reflection angles relative to the waveguide axis (Fig. 9), and therefore experience more reflections per unit distance and higher losses. Propagation modes of a hollow waveguide, in the case of perfectly conducting walls are pure transverse-electric (TE, *i.e.*, $E_z = 0$, $H_z \neq 0$) and transverse-magnetic (TM, *i.e.*, $E_z \neq 0$, $H_z = 0$) modes. Different modes of $TE_{m,n}$ or $TM_{m,n}$ may propagate in the waveguide depending on the frequency and cross-sectional dimension of the waveguide. In the case of dielectric walls, propagating waves may be represented by hybrid modes of index mn , with all three Cartesian components of the electric and magnetic field present [36]. These modes are lossy modes because any portion of the wave that radiated on a tunnel wall is partially refracted into the surrounding dielectric and partially reflected back into the waveguide. The refracted part propagates away from the waveguide and represents a power loss. By knowing tunnel dimensions and material, Maxwell's equations subject to boundary conditions created by the interfaces between the interior of the tunnels and the wall materials, determine the cutoff frequency, propagation constant and propagation loss for each mode. These are important environmental parameters for wireless designs in tunnels and underground mines.

Early theoretical work on hollow dielectric waveguides with circular and parallel-plate geometries in a medium of uniform dielectric constant had been established by authors such as Marcatili and Schmeltzer [36] and Glaser [37]. Their work became the fundamental basis for later waveguide-based modeling of tunnels and underground mines [35]. Emslie *et al.* extended the previous work on waveguides to tunnels by assuming them to be oversized lossy dielectric waveguides with rectangular cross-sections and found approximate mode equations based on the simple assumption of uniform dielectric constant for the tunnel [38]. Mahmoud and Wait in [33] and Emslie *et al.* in [35] assumed the dielectric constant of the sidewalls was different from that of the floor and ceiling, which provides more accuracy. In [35], Emslie *et al.* applied the waveguide model to tunnels with approximately rectangular cross-sections, such as coal mines with a considerable degree of roughness, and tunnels with tilted walls. Fig. 10 shows a map and digital photograph of an underground mine gallery [39].

They formulated the overall loss for the dominant mode of ($m = 1$, $n = 1$). Overall loss consists of refraction loss (proportional to f^{-2}), roughness loss (proportional to f^{-1}), sidewalls' tilt loss (proportional to f), and antenna insertion loss, or equivalently, antenna coupling loss to the dominant mode (proportional to f^{-2}). Antenna coupling loss occurs due to inefficient coupling of dipole antennas to the waveguide mode and decreases rapidly with increasing wavelength

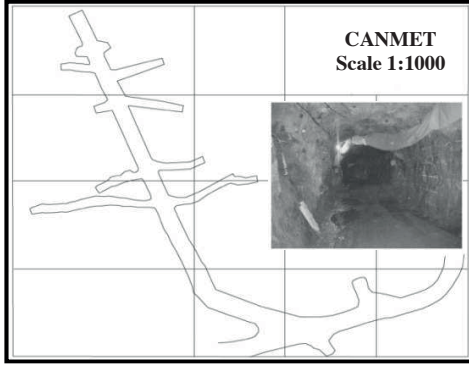


Fig. 10. Map and digital photograph of an underground gallery [39].

[35]. At frequencies of interest (UHF), ohmic loss due to the small conductivity of the surrounding material is found to be negligible compared to loss from refraction through the walls [35]. Refraction loss has been calculated for both horizontal and vertical polarizations of electric field, E_h , E_v , respectively. Depending on whether width or height of the tunnel is larger, either the horizontal or vertical polarization will dominantly propagate and only the loss of the dominant polarization can be considered. Different losses assuming half-wavelength dipole antennas at both sides in a straight tunnel are given as follows [35]:

Refraction loss for $E_{(1,1)}^{\text{horizontal}}$ mode ($m = n = 1$):

$$L_1 = 4.343 \lambda^2 \left(\frac{\epsilon_{r1}}{w^3 \sqrt{\epsilon_{r1} - 1}} + \frac{1}{h^3 \sqrt{\epsilon_{r2} - 1}} \right) d \quad (5)$$

Refraction loss for $E_{(1,1)}^{\text{vertical}}$ mode ($m = n = 1$):

$$L_2 = 4.343 \lambda^2 \left(\frac{1}{w^3 \sqrt{(\epsilon_{r1} - 1)}} + \frac{\epsilon_{r2}}{h^3 \sqrt{\epsilon_{r2} - 1}} \right) d \quad (6)$$

Roughness loss:

$$L_3 = 4.343 \pi^2 r^2 \lambda \left(\frac{1}{w^4} + \frac{1}{h^4} \right) d \quad (7)$$

Tilt loss:

$$L_4 = \frac{4.343 \pi^2 \theta^2}{\lambda} d \quad (8)$$

Half-wavelength dipole insertion loss for $\lambda \leq$ the transversal dimensions of the tunnel:

$$L_5 = \left[0.5233 \frac{\lambda^2}{wh} \cos^2 \left(\frac{\pi x_0}{w} \right) \cos^2 \left(\frac{\pi y_0}{h} \right) \right] \quad (9)$$

In each case, λ , w , h , ϵ_{r1} , ϵ_{r2} , r , d , θ , x_0 and y_0 are wavelength, tunnel width, tunnel height, relative permittivity of the rectangular tunnel sidewalls, relative permittivity of the rectangular tunnel floor and ceiling, root-mean-square (RMS) roughness, distance, sidewalls' RMS tilt angle (in radians) about a vertical axis, and transversal positions of the antenna (assuming the origin of the rectangular coordinate system is on the middle point of the tunnel cross-section), respectively. As can be seen from the formulae, some losses increase with frequency, and others decrease, and therefore an optimum frequency can be found in the range of 500-1000 MHz (Fig.

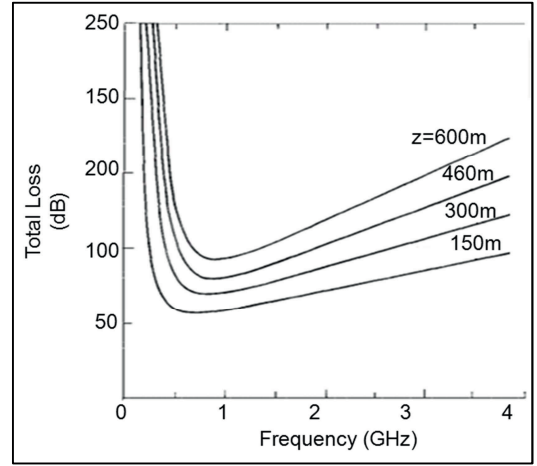


Fig. 11. Overall loss for various distances along a straight tunnel for half-wave antennas with horizontal polarizations (z is the Tx-Rx distance) [35].

11) for minimum overall loss, depending on the desired Tx-Rx distance.

Tables I and II present losses for different Tx-Rx distances and at several UHF frequencies for a straight tunnel and a tunnel with a corner, respectively [35]. $L_{\text{propagation}}$ is total loss from refraction, roughness and tilt of the walls, and also $L_{\text{insertion}}$ is the half-wave dipole coupling loss that is noticeably high. In the case of using an antenna with high directivity, coupling loss (insertion loss), which considerably contributes in the overall loss will be reduced. Overall loss is the summation of propagation loss and insertion loss. As it can be seen in Table II, a corner adds an extra loss directly proportional to the frequency. If the transmitter is outside the tunnel, additional loss due to EM coupling from outside to inside should also be considered, which is not shown in these tables [40]. This loss is dependent on the distance of the transmitter to the mouth of the tunnel, angle-of-arrival of the wave into tunnel relative to the tunnel axis, cross-sectional dimension of the tunnel and operation frequency. It should be noted that the results discussed in this part and rest of the paper are valid under the assumption of omni-directional antennas at transmitter and receiver. When using antennas with high directivity propagation is more similar to free space propagation rather than waveguide and is predicted to be less sensitive to tunnel's dimensions and frequency because waves have fewer interactions with tunnels' walls.

For the sake of simplicity, Emslie and other authors neglected the continuity of the boundaries of the corner regions by considering different materials for ceiling/floor, and side-walls [35]. One of the advantages of such an approach is that the modeling of tunnels whose walls have different electrical characteristics is viable [10]. In this model, underground mines were assumed to be rectangular waveguides with perfect geometrical shape, but with lossy dielectric characterization. Although this leads to a separable Helmholtz wave equation in Cartesian coordinates, the boundary conditions on the walls necessitate the intrinsic coupling of the basic modes and hence propagation constants are not easy to obtain. As shown by

TABLE I
OVERALL LOSS ALONG A STRAIGHT PATH (E_h MODE WITH HALF-WAVE ANTENNAS) [35].

f	$L_{\text{refraction}}$	$L_{\text{roughness}}$	L_{tilt}	$L_{\text{propagation}}$	$L_{\text{insertion}}$	$L_{\text{overall}}(\text{dB})$				
MHz	dB/30m	dB/30m	dB/30m	dB/30m	dB	30m	150m	300m	460m	600m
4,000	0.06	0.05	5.33	5.44	69.90	75	97	124	152	179
3,000	0.10	0.07	3.99	4.16	64.88	69	86	107	127	148
2,000	0.23	0.10	2.66	2.99	57.86	61	73	88	103	118
1,000	0.91	0.21	1.33	2.45	45.82	48	58	70	81	93
415	5.34	0.50	0.55	6.39	30.48	37	62	94	126	158
200	23.00	1.04	0.27	24.31	17.80	42	139	261	383	504
100	92.00	2.08	0.14	94.20	5.80	100	477	948	1419	1890

TABLE II
OVERALL LOSS ALONG A PATH INCLUDING ONE CORNER (E_h MODE WITH HALF-WAVE ANTENNAS) [35]

f	E_h Loss per corner	Overall Loss (dB) at different Tx-Rx distances			
MHz	dB	150m	300m	460m	600m
4,000	80.2	177	205	232	259
3,000	77.6	163	184	205	226
2,000	74.1	147	162	177	192
1,000	67.6	126	138	148	161
415	57.7	120	152	184	216
200	47.3	187	308	430	551

Wait [41], this causes fundamental difficulty in finding the modal eigenvalues and eigenfunctions of rectangular waveguides or any other form than circular. While most previous work on modeling tunnels use rectangular waveguide models, circular waveguide models have been considered for modeling arched road tunnels [42]-[46].

The single-mode waveguide model by Emslie *et al.* became the basis for later waveguide modeling of tunnels. Over time, several researchers have tried to enhance the model and make it more accurate. Since this model only considers the dominant mode to predict the propagation loss at lower-UHF frequencies, it is only valid for the far-field region where higher order modes are greatly attenuated and only the dominant mode exists. Therefore, it fails to predict propagation loss in the near-field accurately. As such, for tunnel microcell designs Zhang *et al.* modified the tilt and roughness loss formula of Emslie's model so that it became applicable to near-field [47].

The far-field (far-zone) and near-field (near-zone) inside straight tunnels are separated by a breakpoint [48]. The breakpoint will be explained in more details in the next subsection. Near-field, waveguide propagation has not been well established but suffers larger loss than far-field propagation. This is because the higher order modes are significant in the near-field and should be included in calculations. After the breakpoint (in far-field), higher order modes are greatly attenuated and become negligible, while the dominant mode remains significant. Far-field waveguide propagation is stabilized and undergoes smaller loss than near-field propagation [47]. The attenuation rate of the field in the far-zone is linear in dB, with a slope

determined by the attenuation constant of the lowest order mode (dominant mode) [49]. At higher frequencies (above-UHF) that are much higher than the cutoff frequency of the tunnels, breakpoint is extended further from the transmitter; in other words, the near-field is prolonged. Therefore, to achieve a model that characterizes the near-zone as well, higher order modes should also be included [49], [50]. For example, in [49], more than 20 waveguide modes have been considered for accurate modeling at 1 GHz in a railroad tunnel. In [50], Sun *et al.* proposed the multimode-waveguide model, which is capable of accurately characterizing fast fluctuations of the channel, and gives analytical expression for the received power and the power-delay-profile (PDP) at any locations in a tunnel. Based on this model, authors studied the effects of various factors, such as size of the tunnel, frequency of operation, electrical properties of the walls, antenna position and polarization.

2) *Two-Slope Pathloss Model*: Based on the single-mode waveguide model, pathloss (in dB) increases nearly linearly with increasing distance in a mine tunnel. However, as shown in Fig. 12, experimental and theoretical studies confirm that pathloss has two distinct sections that can be separated by a breakpoint for straight tunnels at UHF-band frequencies. Not having taken this breakpoint into consideration, the waveguide model has overestimated the coverage distance [51]. Before this breakpoint, the pathloss shows free space behavior (with free space pathloss exponent, *i.e.*, $n = 2$) and after it shows waveguide behavior (with lower pathloss exponent than free space, *i.e.*, $n \leq 2$) [51]-[53]. Accordingly, in [48], [51] Zhang

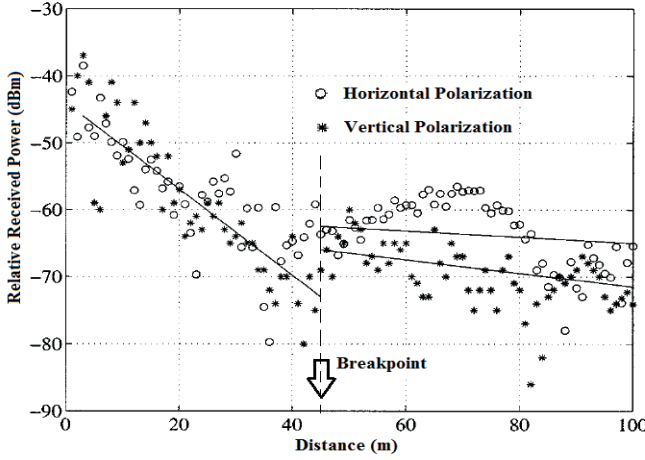


Fig. 12. Measured data for two polarizations at 900 MHz together with the two-slope regression fits in a coal mine [54].

proposed a ray-optical based hybrid model for tunnels and mines. This model consists of two types of propagation: (1) free-space model for the region close to the transmitter and (2) waveguide model in the region far from the transmitter. This was experimentally validated in [51], [54]. The location of the breakpoint can be obtained by intersecting two pathloss models as suggested in [48]. Breakpoint location depends on the tunnel excitation conditions (transmitter inside or outside the tunnel). In the case of an external base station, it depends on the angular position of the antenna with respect to the tunnel axis [52]. If the base station is inside the tunnel, the breakpoint location depends on the antenna radiation pattern, signal wavelength and size of tunnel cross-section.

Assuming an omni-directional antenna such as a dipole at both transmitter and receiver inside the tunnel r_{bp} , the breakpoint location (or critical distance) mainly depends on the tunnel cross-sectional dimensions (w , h) and the wavelength (λ) [53]:

$$r_{bp} = \max\left(\frac{w^2}{\lambda}, \frac{h^2}{\lambda}\right). \quad (10)$$

It should be noted that this simple model is only for pathloss modeling and cannot characterize the small-scale signal fluctuations of the multimode channel, in particular in the near-field zone. Moreover, this model may not be applied to some short mine tunnels at high frequencies. For instance, in CANMET mine at a 40 m depth for two frequencies of 2.45 and 18 GHz, the value of (w^2/λ) is 200 m and 1800 m, respectively. Therefore, the tunnel is too short to form a breakpoint and hence no waveguide effect is likely present [55]. Consequently, multimode-waveguide modeling [50] may be considered for propagation modeling of higher frequencies in short mine tunnels.

3) *Ray-Optical Models*: Ongoing interest in higher frequency (smaller wavelength) applications have motivated researchers in this field to use the ray-optical theory for their modeling. Ray-optical models are accurate when the environment dimensions are much larger than the wavelength and this is a condition that is satisfied in underground tunnels

at UHF-band frequencies. In these models, EM waves are considered as optical rays, and EM fields are calculated by summing the reflected rays from the tunnel walls. Unlike modal analysis in the waveguide model, which is restricted to simple geometries, ray-optical methods can be applied to more complicated scenarios such as occupied tunnels, tunnels with curvature, coupling between outside and inside of the tunnel, etc.

Ray-optical methods based on the classical geometrical-optics (GO) only take into account reflections and not diffractions. Those based on geometrical-theory-of-diffraction (GTD) [56] include both reflections and diffractions, however, the predicted fields at shadow boundaries become infinite, which is impossible in nature and produces a non-uniform solution. On the other hand, in uniform-theory-of-diffraction (UTD) [57], an extension of GTD, diffracted fields remain bounded across the shadow boundaries because of the addition of a transition function into the diffraction coefficient.

In [58], Mahmoud and Wait proposed a GO model for rectangular mine tunnels and compared it with their previous waveguide model for a case of an idealized waveguide with two perfectly reflecting sidewalls. Two models showed a satisfactory agreement. This was a theoretical foundation for further analysis. Thereafter, they included the influence of the wall roughness in their model by using theoretical and experimental results obtained by Beckmann and Spizzichino [59] and Beard [60], respectively. In this simple model, the rough surface is assumed to have a Gaussian distribution and modified Fresnel reflection coefficients are considered for the rough surface. The classical Fresnel reflection coefficient is used for smooth surfaces. In [61] a ray-optical model based on GO was developed to include curved boundaries. Contrary to classical ray-optical methods where one ray representing a local plane wave front is searched and can only treat reflections at the plane of boundaries, this ray-optical method is based on ray-density normalization and requires multiple representatives of each physical EM wave at a time. Therefore, curved boundaries can also be treated.

In [62], authors applied the UTD method to accurately model the coupling between inside and outside of the tunnel. This is a critical issue for short road tunnels, where the transmitter is outside the tunnel and the mobile station is inside with no repeaters between them. This is a case that cannot be easily modeled with waveguide or simple GO based model. A model based on the UTD was also proposed in [63] that allows one to find the effect of tunnel branches and obstructions such as vehicles and trains in a tunnel.

4) *Full-Wave Models*: Full-wave models may also be considered as an alternative method capable of solving Maxwell's equations with arbitrary boundary conditions using numerical methods, such as finite-difference-time-domain (FDTD). The FDTD method is an accurate model that fully accounts for the effects of reflection, refraction and diffraction, and provides a complete solution for the signal coverage information throughout a defined problem space. Therefore, it is well suited for accurate study of the EM propagation in complex environments. However, the FDTD requires memory to store the basic unit elements of the model and also demands iterations in time in order to update the fields along the

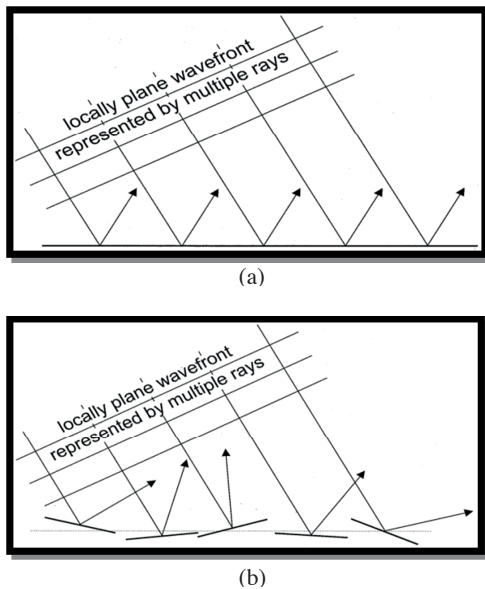


Fig. 13. Stochastic scattering approach: reflection at randomly oriented tangential planes for each discrete ray (a) same plane for all the rays and (b) randomly oriented planes [67].

propagation direction. Given the large size of tunnels and the high operating frequency (above-UHF), the computational burden of conventional FDTD exceeds well beyond the capacity of existing computers. Consequently, it has recently been attempted to enhance the efficiency of this method for wireless applications in tunnels by employing different approaches to reduce the runtime or computational cost.

In [64], excessive computing times were shown to be alleviated via the compute-unified-device-architecture (CUDA) parallel programming route. Whereas in [65], a cost-effective FDTD method for modeling tunnels with realistic construction profiles is proposed, which is based on the compact-FDTD concept and requires minimal computing resources. In [66], the authors have proposed the modified 2D FDTD method that converts a 3D tunnel model into a realistic 2D FDTD simulation. This removes the computational burden while at the same time preserving the factors that form the wireless propagation characteristics. This method has been used to determine a pathloss model that enables effective wireless-sensor-network (WSN) planning and deployment for monitoring and assessing deformation in curved arched-shaped tunnels for Tx-Rx distances of up to several hundred meters. For such applications, the FDTD method facilitates accurate modeling of near distance pathloss and close-to-wall antenna deployments. For most wireless propagation models of tunnels, the antennas are assumed to be along the central axis of the tunnel. Since this is not representative of most WSN applications where the wireless sensor nodes are mounted on the walls, it is important to accurately capture the performance degradation resulting from the antenna position using accurate full-wave models.

5) *Stochastic and Numerical Models*: In recent studies on modeling EM propagation in underground mines, more details of the environment such as wall roughness are included

in order to improve the accuracy. In most theoretical models concerning roughness, statistical solutions based on the Gaussian distribution for random roughness are employed. In [67], stochastic scattering approach is presented to treat rough surface scattering based on a combination of ray-optical and Kirchhoff formulations. Similar to the Kirchhoff modeling, this method is based on a tangential plane approximation of the rough surface, *i.e.*, it is applicable to surfaces with gentle undulation whose horizontal dimensions are large compared to the wavelength of incident waves. However, in contrast to Kirchhoff methods that are only valid for either slightly rough or very rough surfaces, this approach simultaneously includes both.

In this method as shown in Fig. 13, each local plane wave front is represented by multiple discrete rays instead of one ray, in order to model wall roughness. All of these discrete rays are reflected back from randomly oriented planes (Fig. 13-b) and not from the same boundary plane (Fig. 13-a). In this model, random roughness is characterized by standard deviation of surface height and correlation length, assuming they follow a Gaussian distribution. By applying this stochastic scattering approach, the inclusion of random surface scattering into ray-optical modeling becomes possible.

In [68], a numerical analysis has been used to accurately model roughness and bending in underground mines. In this analysis, the cascade-impedance-method (CIM) and segmental-statistical-method (SSM) are combined. The CIM method assumes the mining tunnel is a transmission line with diffracting and rough walls (Fig. 14-a). Therefore, its behavior can be considered analogous to a cascade of dielectric impedances with its associated losses (Fig. 14-b). In Fig. 14-a, Z 's are the dielectric impedances of the tunnel sidewalls, ceiling and floor. CIM is combined with SSM by dividing the mining tunnel into segments, each segment into sections and each section into multiple cells in the transversal and vertical directions. Variation distribution of the rough surface of each segment is then simulated by a 3D Gaussian function. From the dielectric impedances of the rough walls, equivalent reflection and transmission coefficients of each section in the form of matrix can be obtained. This allows the electric field, magnetic field, cutoff frequency and propagation constant to be determined for each segment of the tunnel.

The limitation of this method is in treating the borders of the grid. If the sections are chosen to be infinitely small, the problems of memory space and runtime arise. Therefore, to simplify the method and overcome these problems, the authors chose to substitute parameters of each section with their average values. As stated by the authors, these types of methods are preferred over modal analysis (waveguide models) for tunnel mines with rough sidewalls. However, for the case of smooth sidewalls, simple modal theory would be more effective.

Comparison of Analytical Models

As it was seen in this section, different theoretical models have been developed for characterizing propagation in underground mine tunnels. In Table III, the main advantages and disadvantages of each are presented which helps to compare them based on several criteria such as complexity, range of validity and modeling capabilities.

TABLE III
COMPARISON OF DIFFERENT ANALYTICAL MODELS.

	Single-mode waveguide model	Multimode waveguide model	Two-slope model	Ray-optical models	Stochastic & Numerical models	Full-Wave
Advantages	(1) Simple (2) Provides physical insight (3) Basis for most of theoretical modelings	(1) Accurate for different frequencies (2) Accurate for near-zone as well as far-zone (3) Provides physical insight (4) Capable to predict channel parameters such as RMS delay spread	(1) Simple (2) Same accuracy for near-zone and far-zone (3) Provides physical insight	(1) Simple (2) Capable of modeling tunnel branches (3) Provides physical insight	(1) Similar for different frequencies (2) Same accuracy for near-zone and far-zone (3) Capable of modeling tunnel roughness and branches	(1) Accurate (2) Provides physical insight (3) Capable of modeling tunnel roughness and branches
Disadvantages	(1) Less-accurate for higher frequencies (2) Only for pathloss predictions (3) Only valid for far-zone of the tunnel (4) Incapable to model tunnel roughness and branches	(1) Complex (2) Incapable to model tunnel roughness and branches	(1) Fails to model cases in which breakpoint does not exist (<i>e.g.</i> , when mine tunnel is too short to form breakpoint) (2) Incapable of modeling tunnel roughness and branches	(1) Less-accurate for lower frequencies (2) Computational load increases dramatically as the signal path is prolonged	(1) Complex (2) Provides no physical insight (3) Computationally extensive	(1) Complex (2) Computationally extensive

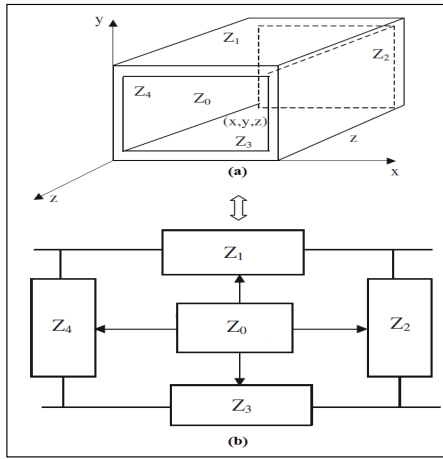


Fig. 14. (a) A rectangular waveguide and (b) CIM model for the waveguide in Fig. (a) [68].

As shown in Table III, theoretical models provide valuable physical insights about the EM propagation. However, since most of them are based on non-realistic assumptions, they need to be evaluated experimentally. Although the expense and level of effort for conducting RF measurements increases in complicated environments, the measurement based approach has proven to be useful and productive. It will likely remain the principal method for characterizing wireless channels in most environments for many years to come. As a result of its relevance, the next section is devoted to experimental modeling for underground environments.

V. MEASUREMENT-BASED MODELING

While theoretical models offer physical insights, empirical models are widely used to characterize wireless channels because they: (1) are more realistic, (2) provide results that are of immediate use to designers and developers, and (3) are useful in the validation of results obtained from simulation-based and theoretical methods. Despite the mentioned advantages, due to the difficulties of access to underground mines, safety issues, measurement complexity and expenses, they are not as common in the literature as theoretical studies.

Measurement studies for TTA communications at lower-UHF frequencies began in narrowband form with the motivation of characterizing propagation loss. They have been evolved over time into wideband and ultra-wideband signals with the motivation of characterizing channel-impulse-response (CIR) and delay spread. As shown in this section, while narrowband pathloss characterization is used to determine coverage area and transmit power, wideband measurements capture the effects of multipath components by characterizing the CIR.

A. Narrowband Measurements

Narrowband measurements mostly focus on modeling fading statistics and propagation loss. In this section, we present key findings on characterizing propagation in underground mines and compare them with their counterparts in conventional above ground environments as well as long tunnels.

1) *Fading Statistics*: The distributions, namely, Rayleigh, Rice, Nakagami, Weibull and Lognormal are among the most commonly used in wireless communications. Rice and

Rayleigh are used for modeling LOS and NLOS small-scale fading, respectively, while Lognormal is used for large-scale fading above ground. The fading distribution is Ricean (or Rice) when a dominant stationary (non-fading) signal component such as the LOS path is present. As the dominant signal becomes weaker, the fading distribution will follow a Rayleigh distribution. Components of small-scale and large-scale fading can be separated by applying different methods on the narrowband measured data. For instance, the small-scale fading envelope can be extracted from the measured data by normalizing the received signal to its local mean value.

Some experimental studies of straight sections in underground mines have shown they are similar to above ground environments; the large-scale fading follows Lognormal distributions [69], the small-scale fading follows Ricean distribution for LOS scenarios and Rayleigh distribution for NLOS scenarios, regardless of frequency [55], [70]. However, some studies such as the recent one in [69], have reported small-scale fading to follow Rayleigh distribution for some LOS cases in underground mines. This can be attributed to the rich multipath environment formed by the high density of scatterers in the mine.

2) *Pathloss Exponent*: Several experimental studies have characterized the pathloss exponent for different LOS and NLOS scenarios in underground mines and compared the findings with other environments. The study reported in [71] shows that at upper-UHF, pathloss exponents in underground mines are larger than their counterparts in indoor environments [71]. This can be explained by the fact that in indoor environments, such as in a corridor or a hallway with smooth walls and clear of obstacles, the pathloss exponent is lower than that of free space due to the constructive contribution of multipath signals. In mines, however, the walls irregularities and roughness are significant, and hence destructively contribute to the signal power resulting in a pathloss exponent similar to that of free space ($n = 2$) [71].

In another study, LOS and NLOS scenarios for two frequencies (2.4 GHz and 5.8 GHz) have been compared. 2.4 GHz showed a lower pathloss exponent than 5.8 GHz for the LOS scenarios, while 5.8 GHz showed a lower pathloss exponent than 2.4 GHz for the NLOS scenarios [55]. This result shows the difference between propagation in mines and in long straight tunnels (e.g., transportation tunnels) where increase in frequency decreases the pathloss exponent [72]. This confirms that there are substantial differences between underground mines and transportation tunnels, and therefore may not be treated under same category for accurate modeling. Table IV compares and contrasts UHF-band propagation based on theoretical and experimental studies, in underground mines and two similar environments; (1) long straight tunnels and (2) conventional indoor environments.

B. Wideband/UWB Measurements

Assuming the wireless channel acts as a linear filter, wideband measurements help in characterizing it accurately in the time and frequency domain by determining the CIR [18], [73], [74]. From the CIR, the PDP can be obtained, which determines RMS delay spread, received power, time-of-arrival

(TOA) of the first path, *etc.* Providing accurate temporal information, the CIR can also be used for location finding applications in underground mines.

1) *Delay Spread*: In low data rate wireless systems (i.e., when the symbol rate is lower than the coherence bandwidth of the wireless channel), delay spread can be neglected, and hence Gaussian noise is the dominant factor that causes bit errors. In high data rate systems on the other hand, delay spread, which causes inter-symbol-interference (ISI), is the main reason for bit errors [18]. As a result, it is necessary to model degrading effects of multipath delay as well as fading in modern wireless communication systems with high data rates. By characterizing RMS delay spread, coherence bandwidth that is necessary for optimization of modulation schemes and data rate, can be determined. Accordingly, wideband measurements have been conducted in underground mines and tunnels to characterize the CIR. Similar to above ground measurements, many factors such as frequency, wave polarization, height and transversal (i.e., cross-sectional or bi-dimensional) locations of the transmitter and receiver, scatterers and obstacles between transmitter and receiver affect the CIR [51], [55].

For long straight tunnels, the RMS delay spread is found to be: (1) a function of Tx-Rx distance, (2) larger for horizontally polarized waves in tunnels with horizontal aspect-ratio (i.e., width is larger than height) and (3) larger for occupied tunnels [50], [72]. However, some of these results have not been achieved for mine tunnels. For instance, no correlation between the Tx-Rx distance and the RMS delay spread has been found in mines [55], but has been found to be a function of Tx-Rx distance in both tunnels and indoor environments. The function is an increasing function at first and a decreasing function after a certain point (dual-slope relation) [50]. Some of these similarities and differences between mines and tunnels and conventional indoor environments are listed in Table IV.

RMS delay spread in mines has been found to be highly dependent on bidimensional position of the antennas [39] and larger in a mine with more rough walls, branches and obstacles [39], [72]. It has also been compared for different frequencies. In [55], two WLAN frequencies of 2.4 and 5.8 GHz have been compared. This study found the RMS delay spread to be larger for 2.4 GHz and they concluded that the maximum usable data rate with a relatively simple transceiver would be higher at 5.8 GHz in the mine they conducted their measurements.

In Table V, typical values for the pathloss exponent and RMS delay spread of different environments are presented. This allows the reader to compare underground mines with other environments more conveniently. It can be seen that for underground mines, the pathloss exponent and RMS delay spread have been found in the range of 1.8-5.49 and 1.7-60 nsec, respectively. The range of values varies according to the measurement scenario, size of the tunnel and frequency. A more detailed comparison of experimentally determined UWB and fading statistics experimental between mines and different indoor scenarios can be found in [69].

2) *Location Finding*: CIR characterization achieved through WB measurement can also be used to accurately (to within 2 m) locate mobile stations in mines and other confined environments for location tracking applications.

TABLE IV

SOME SIMILARITIES AND DIFFERENCES BETWEEN UNDERGROUND MINES, STRAIGHT LONG TUNNELS AND CONVENTIONAL INDOOR ENVIRONMENT FOR PROPAGATION AT UHF-BAND (f : FREQUENCY, n : PATHLOSS EXPONENT, τ_{rms} : RMS DELAY SPREAD, d_{Tx-Rx} : TX AND RX DISTANCE, \uparrow : INCREASE, \downarrow : DECREASE).

		Straight long tunnel [50],[72]	Conventional indoor [55],[68]
Underground mine (experimental study) [55]	Similarities	Large-scale fading: Lognormal Small-scale fading: Rice, Rayleigh $f \uparrow \rightarrow \tau_{rms} \text{ (near-region)} \downarrow$ Scatterers and obstacles increase τ_{rms}	Large-scale fading: Lognormal Small-scale fading for LOS: Rice (Rayleigh has been also reported for some studies in mines) Small-scale fading for NLOS: Rayleigh Scatterers and obstacles increase τ_{rms}
	Differences	<u>In underground mines:</u> $f \uparrow \rightarrow n \text{ (near-region)} \uparrow$ $f \uparrow \rightarrow \tau_{rms} \text{ (far-region)} \downarrow$ No correlation between d_{Tx-Rx} and τ_{rms}	<u>In underground mines:</u> No impulse response path arrival clustering effect Relatively larger pathloss exponent No correlation between d_{Tx-Rx} and τ_{rms}

TABLE V

PATHLOSS EXPONENT AND DELAY SPREAD ASSUMING OMNI-DIRECTIONAL ANTENNAS FOR SEVERAL FREQUENCIES IN DIFFERENT ENVIRONMENTS.

Type of Environment		Measurement frequency (GHz)	Size (width × height × length)	Mean τ_{rms} (RMS-delay spread) in nsec	Pathloss exponent (n)	Reference
Free Space		-----	-----	-----	2	[18],[73]
Urban Area Cellular Radio		UHF-band	Hundred meters (an outdoor site)- Several kilometers (San Francisco)	40-25500	2.7-3.5	
Shadowed Urban Area Cellular Radio					3-5	
In-Building (LOS)			Typical office-Open plan factory	4-130	1.6-1.8	
Obstructed In-Building				4-6		
Several Straight Long Tunnels	Empty	0.9	Tunnel1: 3.34×2.6×259 Tunnel2: 7.5×4×2000 Tunnel3: 4.2×3×10,000 Tunnel4: 2.4×2×200 Tunnel5: 7×3.7×120	Less than 25	1.87-5.49	[72]
	Occupied			Less than 103		
Straight Long Tunnel	Empty	0.9	3.34×2.6×259	4.12	4.2-4.49	
	Occupied			21.7		
Straight Long Tunnel	Empty	1.8	3.34×2.6×259	6.03	2.12-2.46	
	Occupied			58.65		
Underground Mine (Level 70m)	LOS (1-10m)	UWB (3-10)	(2.5-3)×3×70	1.72	1.8	[74]
	NLOS (1-10m)			3.76	4.01	
Underground Mine (Level 40) NLOS & LOS		2.4	5×5×75	Less than 60	2.13-2.33	[39]
Underground Mine (Level 70)	LOS (d=1m)	2.4	(2.5-3)×3×70	6.34	2.03	[55]
	NLOS (d=23m)				4.62	
Underground Mine (Level 70)	LOS (d=1m)	5.8		5.11	2.22	
	NLOS (d=23m)				3.51	
Underground Mine	LOS (d=40-44m)	0.4-0.5	5×6×500	19	-----	[26]
	NLOS			25-42	-----	[26]

As an example, the CIR provides the required information for using the fingerprinting technique, which in conjunction with a neural network can accurately locate the mobile [75]. Each user's information, such as CIR and PDP, is a function of user's location and can be obtained by several offline wideband measurements. These are recorded in a user fingerprint database and subsequently compared to real-time measured fingerprints corresponding to the user's new location [75].

The database, however, should be updated due to the fact that mines are dynamic environments [27], [76]. Heavy machinery or moving objects may considerably change the properties of the channel, requiring an update of the database's information (*e.g.*, a new training of the neural network). This channel variation issue can be resolved by using a master neural network [27], [76].

C. Multiple-Antenna Measurements

In addition to experimental studies of single-antenna systems in underground tunnels, multiple-antenna systems such as multiple-input-multiple-output (MIMO) systems have also been studied. Since there have been no MIMO studies in mines to date, results presented here are from experimental studies in transportation tunnels that are relatively similar to mine tunnels. MIMO measurements for underground tunnels were originally motivated by interest in supplying GSM-Rail service at 900 MHz [77], and most recently for advanced WLAN, worldwide-interoperability-for-microwave-access (WiMAX) and long-term-evolution (LTE) service at 2 GHz, in transportation tunnels. It is a well-known fact that performance of a MIMO system is mostly affected by the correlation between fading observed on adjacent antenna elements. This correlation depends on the type and configuration of the antennas and the range of angles over which the signals arrive or depart (quantified by angular spread of transmitter and receiver).

Despite the small angular spread of the direction-of-arrival (DOA) and direction-of-departure (DOD) of the rays in the tunnels, preliminary experimental results have shown that multiplexing gain (or capacity gain) is achievable by employing multi-antenna techniques [77]-[79]. However, the channel capacity is strongly dependent on the Tx-Rx distance, tunnel size and geometry. In a MIMO study in [79], correlation distance of antenna elements is found to be an increasing function of the axial distance of transmitter and receiver, and is larger for receiver elements in tunnels of smaller sizes. Correlation distance is the average spacing between two neighboring antenna elements at one end that produces a correlation coefficient smaller or equal to a certain value, typically 0.7. Antenna spacing in a MIMO system should not be less than the correlation distance to achieve acceptable performance. Despite the valuable contributions of MIMO studies in underground tunnels, MIMO performance is still uncertain in underground mines because of physical differences. This gap in the research, along with the promising results from MIMO in transportation tunnel studies, may encourage researchers to consider MIMO in underground mines for their research.

D. Techniques to Overcome Channel Impairments

In this section, we will discuss required baseband modeling considerations, which should be taken into account while designing underground mine radio receivers. In this regard, the main focus is on combating key channel impairments such as multipath fading (causing fading), delay spread (causing ISI) and Doppler spectrum (causing inter-carrier-interference: ICI). Experimental characterization of channel impairments can be very useful in radio receiver designs.

To eliminate ISI in underground environments, the orthogonal-frequency-division-multiplexing (OFDM) technique that is well-known for high data-rate wireless transmissions and robustness to multipath delays is used [80], [81]. OFDM is intrinsically capable of combating common distortions in the wireless channels without requiring complex receiver algorithms. Compared to conventional single carrier techniques, OFDM-based systems have a low complexity implementation in which instead of a complex equalizer, channel estimation based on the CIR is used to recover the received signal. The vector CIR can be represented by the following formula [82]:

$$h(t) = \sum_{i=1}^K A_i(t) e^{j\phi_i(t)} \delta(t - \tau_i(t)) \quad (11)$$

where i is the number of multipath components, $A_i(t)$ is the amplitude of the i^{th} path, $\tau_i(t)$ is the time delay of the i^{th} path and $\phi_i(t)$ is the phase shift of the i^{th} path. A wideband experimental characterization in CANMET mine [55] reveals that TOA of paths follow a modified Poisson distribution and their amplitudes undergo Rayleigh or Rice fading with uniformly distributed phase over $[0, 2\pi]$. Based on this statistical information and using the above formula, an OFDM channel estimation method is studied for wireless-LAN communications in underground mines [81], which employs the pilot-symbol-assisted (PSA) method. Performance of different estimation algorithms and modulation schemes such as 16 quadrature-amplitude-modulation (16QAM) for a 24 Mbps link, quadrature-phase-shift-keying (QPSK) for a 12 Mbps link, and binary-phase-shift-keying (BPSK) for 6 Mbps link, derived from the IEEE-802.11 wireless-LAN standard, are assessed and compared in terms of the bit-error-rate (BER).

To combat multipath fading for WSN applications in underground mines, the chirp-spread-spectrum (CSS) method is proposed [83]. The CSS uses wideband linear frequency modulated chirp pulses to encode information. It is resistant to channel noise, multipath fading even when operating at very low power and Doppler shift for mobile applications. The CSS method is suitable for wireless personal and sensor network communications, which require low power usage and need relatively low data-rates (1 Mbit/s or less).

Rather than combating, multipath components can also be exploited effectively in underground mines for increasing SNR based on diversity combining methods. This can be achieved by combining the energy in various multipath components using a rake receiver. A Rake receiver is not considered feasible in other industrial environments due to the large number of fingers required to combine the many resolved multipath components [84], [85]. In underground mines, however, the

energy is concentrated in fewer multipath components, and hence the number of fingers required is far less [86]. Study in [81] shows that the OFDM channel estimation that performs well at low Doppler frequency can efficiently reduce the effect of Doppler shift in underground mines. Nevertheless, due to low vehicle speeds, *i.e.*, typical in underground mines, system performance is less affected by ICI, and therefore ICI can be neglected [81]. Unlike underground mines where Doppler spectrum is negligible, it is one of the key channel impairments for vehicular-to-vehicular (V2V) applications in subway tunnels. This should be considered while designing vehicular wireless communication systems such as intelligent-transportation-systems (ITS). In [87], a V2V wireless channel inside a large subway tunnel has been experimentally characterized. It is shown that the V2V fading process is inherently non-stationary, and based on the estimations, RMS delay and Doppler spreads are log-normally distributed. Their study reveals that the spreads, excess delay, and maximum Doppler dispersion are larger on average when both vehicles are inside the tunnel compared to the "open-air" situation. Satisfying the institute-of-electrical-electronics-engineers 802.11p (IEEE-802.11p) standard requirements, they concluded that this standard will be robust towards inter-symbol-interference (ISI) and ICI inside a tunnel.

As was seen in this section, measurement-based characterization of underground mines provides realistic results that are of immediate use to designers and developers, and therefore has attracted more attention in the last decade. However, before applying the results, one must ensure that measured data is sufficient for any statistical inference about the propagation environment. This can particularly be a concern for underground mines because mine galleries differ from mine to mine, and even from level to level within the same mine [74]. Inconsistent experimental results from different UWB measurements in mines confirm this fact [74]. As a result, more measurement campaigns are required to achieve more general and non-site-specific conclusions about propagation in underground mines and their galleries.

VI. IMPLICATIONS FOR WIRELESS COMMUNICATION SYSTEM DESIGN

Designers and developers use channel models to predict and compare the performance of wireless communication systems under realistic conditions and to devise and evaluate methods for mitigating the impairments and distortions that degrade wireless signals. In this section, general conclusions achieved from characterization of wireless propagation in underground environments are presented. We will see how tunnel dimension and geometry, wall material and obstructions affect parameters such as optimum frequency, attenuation, RMS delay spread and angular information that are required in effective design of wireless systems. Additionally, we will see how antenna properties may be affected by underground geometry. This information is particularly valuable when configuring designs for multiple antenna systems.

A. Frequency of Operation

The optimum frequency for TTA communications in underground mines depends on several factors, including tunnel size, tunnel geometry and infrastructure inside the tunnel.

At the frequencies below UHF-band (MF-VHF), signal propagation is enhanced via coupling to conductors that may be in the mine entries, and antenna efficiency is not necessarily compatible with sizes that are portable [7]. At UHF frequencies on the other hand, theoretical studies show that mine tunnels act as relatively low-loss dielectrics with dielectric constants in the range 5-10, and therefore transmission takes the form of waveguide propagation in the tunnel [35]. As it has been shown by Emslie *et al.* in the 500-1000 MHz range, attenuation is relatively low in straight mine entries [35].

In contrast, practical tests have revealed that the MF-band (300 kHz-3 MHz) has more desirable coverage with less severe attenuation compared to UHF-band in both coal and metal/non-metal mines [14]. The MF-band has a proven coverage area of 300-460 m in conductor-free areas, and as much as 3200 m in conductor-filled areas where parasitic propagation help the signal travel longer distances [14]. Higher frequencies such as VHF, UHF and SHF propagate in LOS and 300 m down a mine entry. However, it is unlikely that an unaided (*i.e.*, no leaky feeder) VHF or UHF signal would be able to travel around more than about two crosscuts [14].

This contradiction can be explained by noting that attenuation rate of UHF frequencies is lower than MF frequencies assuming that the tunnel has smooth walls, is straight and empty. This is an unlikely situation for most underground mines and as it has been shown that attenuation of UHF frequencies is significantly higher when the signal propagates around a corner or when obstacles such as massive piece of machinery is in the path of propagation [7].

As a result, considering practical tests, and theoretical and experimental results, although high frequencies (UHF and higher) may offer a larger coverage area in straight and unobstructed tunnels, better coverage may be achievable by frequencies lower than UHF (MF-VHF) [6], [14] when corners, crossings and obstacles exist. Regardless, UHF-based technologies are more appealing to the mining industry because low cost, small form factor, scalable and easy to use applications are available off-the-shelf. In addition, their coverage and other propagation issues (*e.g.*, requiring line-of-sight between Tx and Rx) can be resolved by appropriate antenna and wireless network designs.

B. Tunnel Geometry

In this subsection, we discuss how tunnel structure impacts wireless communications in underground mines. In addition to pathloss, extra losses in tunnels are introduced due to tunnels' curvatures, sidewalls' tilt and changes of the cross-sections.

1) *Cross-Sectional Dimension*: Since each tunnel behaves like a waveguide, its cross-sectional dimension determines the cutoff frequency. For tunnels of arbitrary shape, a very rough approximation of the cutoff frequency is determined by the frequency whose free-space wavelength is about or equal to the tunnel perimeter. Well above this cutoff frequency, the number of propagating modes grows by the square of frequency. The cross-section of most tunnels that can accommodate vehicles, has dimensions of a few meters and the cutoff frequencies are consequently of a few tens of megahertz [88].

In addition to cutoff frequency, cross-sectional size also impacts the attenuation constant and small-scale fading statistics,

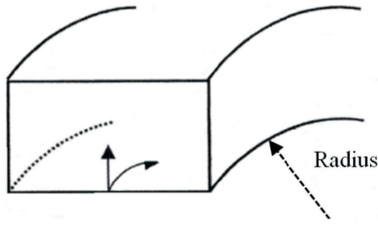


Fig. 15. Radius of a curvature in a rectangular curved tunnel [49].

owing to the fact that change in tunnel cross-sectional size is equivalent to change in frequency for TTA propagation. As such, an increase in a tunnel's width and height increases small-scale fading, which is similar to the impact of increasing frequency. For tunnels with larger cross-sectional dimensions compared to the wavelength, multipath becomes more significant, leading to more severe fluctuations and greater fading [7], [35], [51], [89], [90]. In addition, in larger dimension tunnels the attenuation constant is smaller, and therefore the near-field zone with small-scale and deep fluctuations is prolonged [50]. Severe small-scale fading for larger size tunnels (or higher frequencies) implies to either include fading mitigating techniques for SISO systems or consider MIMO systems to benefit from rich multipaths.

Cross-sectional size also impacts EM polarization loss. Propagation losses for horizontal and vertical polarizations are relatively the same in tunnels with a square cross-section with aspect-ratio of 1 (aspect-ratio: ratio of longer dimension to the shorter one) [72]. However, in rectangular tunnels with larger width than height (horizontal aspect-ratio), horizontal polarization has less attenuation in the region far from the transmitter.

2) *Curvature, Junctions and Tilt*: At the UHF-band, curvature in tunnels introduces additional loss. This loss is dependent on frequency of operation, width of the tunnel, radius of curvature (Fig. 15) and wave polarization. This loss is inversely proportional to the radius of curvature, and in contrast to straight tunnels, it is linearly proportional to frequency and width of the tunnel [91]. In curved tunnels, since the horizontal electric field is perpendicular to the curved walls, horizontally polarized waves are much more affected by the tunnel curvature than vertically polarized waves [49].

Junctions and bends change wave polarization. Therefore, unlike straight sections, inside the junctions/bends (or around the corners) waves are depolarized, and therefore received power around corners is usually independent of the receiver antenna's orientation [7]. The loss associated with one single corner is given in Table II. As it can be seen, corner loss is smaller for lower frequencies. Additional corners add extra loss and increase the overall loss. Attenuation caused by corners in mine tunnels can be compensated for by adding 90° reflectors to extend wireless propagation beyond the junctions and corners [92]. In most mine tunnels, walls are tilted about a vertical axis (tilt angle), which adds extra loss. Tilt loss becomes more significant as frequency increases [35], and therefore demands more precise analytical modeling at higher frequencies [93]. To precisely model pathloss and large scale

fading, this loss should be included in total loss for tunnels with considerable tilt on sidewalls, floor or ceiling.

3) *Surface Roughness*: Underground mine tunnels have wide variations in wall roughness, often on the order of 20 cm [49]. However, unlike tilt and curvature loss in a straight empty tunnel, roughness loss becomes more significant at lower frequencies in tunnels owing to the larger grazing angle and higher number of bounces per unit length [35], [93]. Therefore, this loss is insignificant at high frequencies (UHF and above) compared to tilt, curvature, corner and obstacle losses as Table I indicates.

C. Material and Infrastructure

Since infrastructure inside the tunnel changes EM properties of the tunnel, it is treated in the same section as the material from which the tunnel is dug.

1) *Material*: Electromagnetic properties of different materials are characterized by parameters such as relative permeability μ_r , dielectric constant ϵ_r and conductivity σ [88]. As shown in [35], Emslie *et al.* formulated the overall loss for UHF frequencies by assuming that the effect of ohmic loss is negligible due to the low conductivity of the surrounding material (coal) in coal mines. Conductivity of the coal at MF-band frequencies is 3×10^{-5} – 4×10^{-5} (S/m) and at 9 GHz is 0.12–0.73 (S/m) [88]. Dielectric constant of the coal at MF-band frequencies is 10–34, and at 9 GHz is 3.4–3.9, respectively [88].

Unlike permeability that for most rocks (except for rocks with a high concentration of metals of the ferromagnetic group) is very close to that of vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m, the dielectric constant and conductivity of rocks, are highly variable. Dielectric constants range from 2 to 70, but more frequently from 4 to 10 and conductivities range from 10^{-6} to 1 S/m. In general, both σ and ϵ_r increase with the water content and, as a general rule, σ increases and ϵ_r decreases with frequency [88].

In spite of the high variability of dielectric constant and conductivity of rocks, most recent studies such as [49], [50] show that walls' material does not significantly impact wireless propagation inside the mines, and as frequency increases (UHF and above), the material shows weaker impact. For WSN applications [66], however, material has been found to be an important element to consider in tunnel wireless propagation. This can be due to the small spacing of sensors and tunnel walls. In practical deployments, wireless sensors are often attached to walls with an antenna to wall spacing of less than 10 cm. Nevertheless, compared to antenna position and frequency of operation, this study concludes that material has less impact on wireless propagation in tunnels. Unlike insignificant impact of material at UHF-band for TTA communications, at medium frequency (MF) for TTW and TTE communications, material has significant impact on wireless propagation. In TTE communications, earth is the medium for propagation, and in TTW communications, the skin depth in the mine's wall for the return current of the monofilar mode is the degrading factor. That explains why there are many theoretical and experimental studies on the effect of mine's material on early underground communications.

2) *Infrastructure*: Conductors such as power cables, water pipes, rails, *etc.* inside the tunnels, considerably change the electromagnetic properties of the tunnel, in particular for TTE and TTA communication [88]. Metallic air ducts or heating-ventilating-and-air-conditioning (HVAC) systems that are used to circulate air within the underground mining complex may enhance the wireless propagation. Additionally, ground support infrastructure, such as wire mesh screens, used to prevent rock from falling and the tunnel from caving-in can also affect wireless propagation. At corresponding frequencies, where the mesh netting interval is on the order of 0.1 free-space wavelengths, the attenuation for the dominant propagation mode can be reduced [94].

D. Vehicles and Other Obstructions

Heavy machinery, trucks, miners and other obstacles increase propagation loss and RMS delay spread in tunnels. This loss is dependent on the dimension of obstacles. Larger dimension vehicles cause additional shadowing loss [90]. In this case, propagation rays may only find their way behind the vehicle through multiple diffractions. This degrades signal power significantly [63]. In addition to power loss, obstacles increase RMS delay spread, and therefore a decrease in data rate can be seen in occupied tunnels. As shown in Table III, in an experimental study, RMS delay spread was found to be less than 25 ns for a vacant tunnel and 103 ns for the same tunnel when occupied [72]. This demonstrates the influence obstructions have on delay spread. These results should be taken into account when deciding on transmit power, symbol rate, *etc.* for wireless transmission inside mines.

E. Antenna Placement, Gain and Polarization

The pattern and polarization of transmitter and receiver antennas greatly impacts wireless propagation in confined environment such as mines. As can be seen in Table I, antenna insertion loss contributes significantly to the overall propagation loss for all of the studied frequencies. The importance of antenna parameters becomes more evident if multiple-antenna systems are being used. In this case, not only the received power but also the decorrelation (or orthogonality) of antenna elements should be considered. Since there are no MIMO experimental studies in underground mines to date, some of the materials presented in this section are extracted from experimental studies of multiple-antennas in underground subway tunnels, which can help in predictions for employing MIMO systems in underground mines.

1) *Antenna Placement*: While the attenuation rate is mostly determined by the tunnel size and operation frequency (and not the location of the antennas), the power distribution among propagation modes is governed by the position of the transmitter antenna [50]. This can be valuable information for determining transmitter antenna position for different wireless systems with different objectives. For instance, in single-input-single-output (SISO) systems, higher power can be achieved by positioning the transmitter antenna at the centre of the tunnel, while for MIMO systems, studies have shown that positioning the transmitter off-center of the tunnel cross-section would offer higher capacity [79].

Cross-sectional location of the antenna also impacts the radiation pattern by introducing additional loss [72]. Antennas designed for free-space may not perform well in underground mines because of the large number of strong reflections from the walls, this has been regarded as insertion loss (or coupling loss) that was priorly discussed. This effect is more noticeable for omni-directional antennas, such as dipoles, when they are located off-centered of the tunnel cross-section. In fact, omni-directional antennas perform better (more similar to their behavior in free-space) when they are in the middle of the tunnel.

It is also shown in [77] that alignment of the antenna array in MIMO systems plays a critical role. MIMO configurations perpendicular to the tunnel centerline or along a diagonal line, are found to be better than parallel to the tunnel centerline.

Locating the transmitter outside or inside of the tunnel affects the radiation pattern of the Tx antenna. When the transmitter antenna is inside the tunnel, its radiation pattern becomes sharper than its free-space radiation pattern (*i.e.*, radiation pattern that an antenna would have if it were in free space where there is no reflection, scattering and diffraction). This change does not depend significantly on the transmitter position along the tunnel. Conversely, when the transmitter is outside, the coupling loss between free-space and inside of the tunnel is dependent on the transmitter position. The coupling loss is considerably dependent on the angle of incidence too, if it is greater than 10° with respect to the tunnel axis [62].

2) *Antenna Gain and Polarization*: When an omni-directional antenna is located inside the tunnel, its effective radiation pattern becomes sharper than its free-space radiation pattern. Results in [92] show that a directional antenna located in the middle of the cross-section of the tunnel is a desirable choice for effectively transmitting power along the tunnel. However, locating the antenna in the middle of the tunnel may not be practical for most cases.

For SISO systems in tunnels, signal-to-noise-ratio (SNR) may be improved by employing a directional antenna and directing the antenna beam parallel to the centerline of the tunnel because it prevents signal scattering in LOS scenarios. However, in NLOS cases where propagation into the branches is dependent on multipath components, directional antenna may not be a good option.

For MIMO systems in which a rich scattering environment is beneficial (due to offering larger angular spread), directional antennas may not be a good alternative unless, as shown in [77], its beam-width is equal to the angular spread. Preliminary measurements in [77] have shown that the average value of the angular spread in a subway tunnel is around 60° , which can be different in underground mines due to their smaller size, roughed walls and infrastructure.

For horizontally polarized antennas, the tunnel width plays a more significant role as the reflection coefficients on the horizontal ceiling/floor are larger than those on the vertical walls. Likewise, the tunnel height is more significant for vertically polarized antennas [50]. In rectangular tunnels with larger width than height (horizontal aspect-ratio), horizontal polarization has less attenuation in the region far from the transmitter. This can be interpreted from Emslie's refraction loss formula for both polarizations, and its experimental ver-

TABLE VI
KEY IMPLICATIONS FOR WIRELESS SYSTEM DESIGN AT UHF-BAND IN UNDERGROUND MINES

		Loss / Attenuation	RMS delay spread	Reference
Tunnel Geometry	Cross-sectional size (similar impact as frequency)	Larger size at a fixed frequency (or higher frequency in a fixed cross-sectional size) shows higher pathloss exponent in LOS scenario	Larger size at a fixed frequency (or higher frequency in a fixed cross-sectional size) shows smaller RMS delay spread	[55]
	Curvature/ corner/ branch	Increase (more significant at higher frequencies)	Increase	[51],[55]
	Wall tilt	Increase (more significant at higher frequencies)	NA	[35],[55]
Wall roughness		Increase (more significant at lower frequencies)	Increase	
Wall material		No significant impact	No significant impact	[49],[50]
Obstructions		Presence of obstruction results in higher loss	Presence of obstruction results in larger RMS delay spread	[51]
Antenna properties	Cross-sectional placement	Centre of the tunnel shows lower loss compared to off-centre	Centre of the tunnel shows larger RMS delay spread compared to off-centre	[50]
	Radiation pattern (gain)	Directional antenna shows lower coupling loss compared to omni-directional one in LOS	Directional antenna shows smaller RMS delay spread compared to omni-directional one	[35],[74]
	Polarization	Mine tunnel with horizontal aspect-ratio shows lower loss for horizontally polarized waves	Mine tunnels with horizontal aspect-ratio show larger RMS delay spread for horizontally polarized waves	[50],[51]

ification in [89]. As a result, horizontally polarized antennas are more appropriate in wide but short tunnels, and vertically polarized antennas are more appropriate for tall tunnels [50]. In addition, for a tunnel with horizontal aspect-ratio (width: 4.2 m, height: 3 m) the RMS delay spread is larger for horizontal polarization (13.5 nsec) compared to vertical polarization (5.49 nsec) [51]. Different RMS delay spreads are caused by different attenuation constants for the two polarizations. The lower attenuation of the horizontally polarized signals makes the power-delay-profile spread wider [51].

As it was seen in this subsection, optimizing antenna performance in tunnels remains an open topic for future studies. Better performance can be accomplished through careful design of customized antennas that are matched to the tunnel environment. In Table VI, significant results and implications useful for wireless system design have been presented. This table demonstrates how operation frequency, physical parameters of tunnels and antenna properties affect two main channel impairments; power loss and RMS delay spread.

(parts left with "NA" (not-available) representing cases that have not studied to date, or no information was available).

VII. CONCLUSIONS

The need for wireless communication in the underground mining industry has evolved from basic emergency signaling, to person-to-person voice communication and to high speed real-time data transmission. Accordingly, the supporting technologies have emerged from through-the-earth transmission, to radiating cables, to point-to-point and multi-point radios. Applications utilizing these technologies include voice communication, video surveillance, tele-operation of mining equipment

(tele-mining), wireless sensors networks, geo-location and tracking of personnel and assets. To develop and evaluate these technologies appropriately, wireless propagation and channel models are essential. Measurement and theoretical approaches to channel modeling are increasingly seen as complementary; many channel modeling studies employ both methods.

Analytical and numerical models based on waveguide theory, geometrical optical ray-tracing and other methods have been developed by many researchers. While the single-mode waveguide model is simpler and requires fewer inputs about the physical environment, it is not very effective in predicting propagation for near-field and too short tunnels with complex geometries at higher frequencies. Ray-optical models on the other hand, provide more detailed prediction for higher frequencies and complex geometries at the price of requiring detailed information about the physical environment, and computational burden which increases significantly if the area under study is prolonged. A recent theoretical model, multimode-waveguide, offers more accurate and realistic model with reasonable runtime, which can also characterize small-scale fading statistics. The main advantage of this model is the ability to accurately characterize both the near-zone and far-zone of the tunnel.

Experimental studies on the other hand, provide readily usable parametric values but are site specific and their statistical generalization requires extensive measurement campaigns in the underground mines. Measurement results in different frequency bands (*e.g.*, VHF, UHF and SHF) have been presented by several researchers, mostly covering narrowband transmission. Some limited wideband and UWB studies in UHF and SHF bands have been conducted. With the increasing interest in low-power sensor networks and battery-

powered access points, the availability of UWB transmission technologies and the transition towards even higher, millimeter wave frequencies for indoor applications, the need for further theoretical and experimental studies in underground mines is imminent.

Some implications of wireless communication design have been discussed in this article, which are interpreted from the previous studies. Open research areas for future investigation include characterization of frequencies above 10 GHz, incorporation of more complicated mine geometries in existing waveguide and ray-optical models, antenna configuration design and development of channel models for MIMO systems, design of optimum wireless mesh networks, channel modeling for body-area-networks, and *etc.* The results of these studies facilitate the employment of new technologies by the mining industry that ultimately improves work safety, productivity and efficiency in mines.

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