A Survey of Radio Propagation Modeling for Tunnels

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***Abstract*—Radio signal propagation modeling plays an important role in designing wireless communication systems. The propagation models are used to calculate the number and position of base stations and predict the radio coverage. Different models have been developed to predict radio propagation behavior for wireless communication systems in different operating environments. In this paper we shall limit our discussion to the latest achievements in radio propagation modeling related to tunnels. The main modeling approaches used for propagation in tunnels are reviewed, namely, numerical methods for solving Maxwell equations, waveguide or modal approach, ray tracing based methods and two-slope path loss modeling. They are discussed in terms of modeling complexity and required information on the environment including tunnel geometry and electric as well as magnetic properties of walls.**

***Index Terms*—Channel models, indoor radio communication, Maxwell equations, path loss measurements, propagation, ray tracing.**

I. Introduction

THE CHANGE of lifestyle in the last century with daily commuting within the city as well as frequent travelling between cities led to enormous growth of transport flows and increased use of underground traffic infrastructure, such as tunnels, corridors and underground passages. People use this infrastructure while commuting by metro, train, car or even walking. For safety reasons and also to meet the public demand to deliver services anytime and anywhere, mobile operators had to face the challenge to provide services in underground environments with the same level of experience for end users as in usual operating environments.

In order to estimate the number of required base stations and their positions, engineers usually calculate radio coverage using radio propagation models. There are many such models available for indoor and outdoor environments implemented in commercial radio planning tools [1], but only a few models refers to radio propagation in tunnels. There are several reasons for this, the most important being (i) the main objective of mobile operators has been to cover places where people live, (ii) a leaky feeder was seen as a viable technology for enabling radio communication in tunnels, which does not need complicated channel models for system design, and (iii) measurement campaigns in tunnels that are needed for channel characterization are difficult to organize and carry out, because they hinder normal traffic flow. Leaky feeders proved to be unreliable, because of possible cuts in the case of fire, which consequently causes breakdown of communication in the entire tunnel. This fact pushes mobile operators to install base stations in tunnels and motivates research on propagation modeling for tunnels.

Radio services in tunnels are of vital importance not only for mobile operators but also for audio and video broadcasters, public protection and disaster relief forces, mine companies and companies responsible for management and maintenance of road and railway tunnels [2], [3]. Particularly during car accidents and fires in tunnels the network infrastructure can be damaged and public safety users are forced to communicate directly with each other without using communication infrastructure. In such cases, it is important to know the wireless channel characteristics at distances, exceeding the range of typical base station in tunnel.

There have been several theoretical and experimental studies analyzing propagation of VHF and UHF radio signals in tunnels. Many of them have been carried out for shorter distances and at frequencies allocated to public wireless communication systems, such as GSM, UMTS, WiFi, LTE and WiMAX. In the tunnel, the attenuation in the far field has been shown in [4]–[11] to be generally smaller than in free space. Channel models describing these phenomena are divided into deterministic and empirical channel models. The deterministic channel models include waveguide models [11]–[13], models based on ray tracing approach [5], [14]–[19] and models based on numerical methods for solving Maxwell equations for tunnel environment. Typical representatives of empirical channel models are two-slope channel models [13], [20], [21].

The aim of this paper is to survey channel modeling approaches for frequency bands allocated for personal mobile communications in tunnels. The paper is organized as follows. In Section II, the main approaches in the radio propagation models for tunnels are described and their limitations, advantages and disadvantages are discussed. The tunnel parameters that affect the path loss and delay spread in the tunnel are presented in Section III. Finally, concluding remarks are given in Section IV.

II. Radio propagation models for tunnels

The knowledge of radio propagation environment is essential for specification and installation of wireless communication systems. The statistical properties of wireless channel, for example probability density function of received signal strength, fade durations, level-crossing rate, etc., taken into consideration by statistical channel models, are relevant for

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specifying transmitter and receiver characteristics and link budget calculation. For the installation of wireless communication systems the radio wave propagation models are applied, characterized by the radio environment as a function of frequency and distance between transmitter and receiver. These radio propagation models typically predict path loss, power delay profile or delay spread for specific transmitter and receiver location.

We distinguish between empirical and deterministic channel models [22]. The former comprise closed form mathematical expressions with a set of environmental and communication system dependent parameters. Parameters and mathematical expressions are obtained from measurements of received signal strength and delay spread so that the expressions follow the level of measured signal. The accuracy of empirical models depends on the degree of similarity between the environment in which model parameters are estimated and the environment to which the model is applied. Typical representatives of empirical channel models are two-slope channel models.

In deterministic channel models, radio wave propagation mechanisms such as reflection, absorption, diffraction and refraction, are applied to determine the received signal strength and the power delay profile. Large computational complexity and incomplete data describing the propagation environment are the main drawbacks of deterministic channel models. The deterministic channel models are further divided into numerical methods for solving Maxwell equations, waveguide based models and ray tracing channel models.

In general, radio wave propagation can be described by Maxwell equations. In a real environment consisting of countless number of elements and made of materials with various electromagnetic properties, precise consideration of Maxwell equations leads to extremely complex propagation models. However, straight and empty tunnels present rather simple propagation environments, similar to that in a waveguide, suitable for using the Maxwell equations to determine the value of time-dependent electric and magnetic fields.

The time dependent electric and magnetic fields in a tunnel can be calculated, applying the first and second Maxwell equations, also known as Faraday's Law of induction [23]. In the far field the antenna produces approximately plane waves that propagate in a direction perpendicular to the electric and magnetic fields so that electromagnetic propagation can be approximated by a radio wave. When a plane radio wave hits a facet, it partially reflects and partially penetrates the wall. The energy of radio wave reflected from the facet is calculated using reflection coefficient $\mathbf{\Gamma}_i$, while the energy transmitted through the wall is estimated using transmission coefficient $\mathbf{T}_i$. Assuming a typical radio propagation environment in tunnels, where one medium is air and the other is thick concrete wall, the reflection coefficient depends on the signal wavelength λ, angle of incidence Θ_i, relative permittivity ϵ_r, conductivity σ and relative permeability μ_r of the wall [24] and polarization of the radio wave. The effect of radio wave transmission through the tunnel walls on the radio signal level in the tunnel is typically negligible.

The described reflection mechanism and the assumption that the angle of incidence is equal to the reflection angle (Snell's law), provide the basis for the Geometrical Optics (GO) approach to path loss prediction. However, radio waves spreading behind obstacles cannot be described precisely just by reflection, therefore radio wave diffraction is introduced into the propagation model. Radio wave diffraction obeys Huygens's principle, which says that each point on a primary wave front can be considered as a new source of a secondary spherical wave. The details on diffraction modeling can be found in [23] and [24]. An alternative approach to diffraction, based on Geometrical Theory of Diffraction (GTD), is described in [25].

A. Numerical Methods for Solving Maxwell Equations

In general, the Maxwell equations in differential form can be solved by applying different numerical methods. The most often applied for tunnels are: the Finite Difference Time Domain method (FDTD), Vector Parabolic Equation method (VPE), Method of Moments (MoM) and Finite Element Method (FEM).

The FDTD, a well-known method for solving partial differential equations in discrete time and for discrete points [26], first divides space into a regular or irregular grid and then calculates time and space approximations of the electric and magnetic field strength in this grid. The method provides a solution in time domain suitable for software implementation. However, it is applicable only if the spatial grid is sufficiently fine to resolve both the smallest electromagnetic wavelength and the smallest geometrical feature in the model. Given the dimension of the road and railway tunnels and the operating frequencies of existing and emerging wireless communication systems, i.e. UHF radio frequencies and beyond, the FDTD method is memory demanding, which prevents its application on commonly available computers. In railway and road tunnels, a common approach to reduce the complexity of FDTD is to predict electric and magnetic field only in two instead of in standard three dimensional space [27], [28]. For further reduction of the calculation complexity a hybrid approach is proposed, where the FDTD method is applied to calculate electric and magnetic field close to antennas, and ray tracing method is used to estimate electromagnetic field in farther regions [29].

A computationally efficient method to calculate the electric and magnetic field in straight and curved tunnels is Vector Parabolic Equation (VEP) method [19], [30]–[33]. The Maxwell equations are approximated by parabolic equations assuming that the electromagnetic energy travels predominately along the tunnel and that the electric field variation along the tunnel is slow compared to the transverse electric and magnetic field variations. The scalar parabolic equations are valid when transverse electric and magnetic fields propagate independently of each other, i.e. in the tunnel with perfectly conducting walls. However, the realistic tunnel walls are not perfectly conducting and thus there exists a coupling between magnetic and electric fields. In such case the vector parabolic equations can be applied and consequently solved by Crank Nicolson method [34]. Measurements of the diffracted field were performed for various tunnel cross sections in straight or curved tunnels and found good agreement with analytical results obtained by vector parabolic method.

Another frequently used technique to solve scattering, electromagnetic boundary and volume integral equation problems is the Method of Moments (MoM) [35]. The MoM method converts the operator equations into a system of linear equations, which is written in a matrix form. The electric and magnetic fields are obtained by solving matrix equation numerically. The method is widely implemented in commercial antenna and electromagnetic simulation tools. In order to solve the problem with elements lager than the signal wavelength, which is the case for predicting electromagnetic field in tunnels, the MoM method is usually complemented by modules based on unified theory of diffraction [36].

The Finite Element Method (FEM), a numerical technique for finding approximate solutions to partial differential equations, finds its application also in electromagnetics [37], [38]. The FEM approach is very useful for the arbitrarily shaped tunnels but it requires a large computer memory and long computation time to solve the final matrix equation. The method is implemented in several electromagnetic software tools to calculate electromagnetic field within the tunnel. The method could be also applied for theoretical analysis of electromagnetic field distribution in railway tunnels with trains [39], [40]. The computational efficiency of the FEM method can be improved using the mode matching procedure in tunnels [41].

B. Waveguide Based Channel Models or the Modal Approach

The tunnel geometry and the conductivity of the construction materials lead to the idea that radio propagation in tunnels can be modeled in the same way as the propagation of radio waves in a waveguide. In fact, at frequencies of a few hundred MHz and above, the guiding wave phenomenon emerges [42], [43]. Early research showed, however, that the guided radio wave phenomenon appears only in tunnels with transverse dimensions that are several times larger than the wavelength of the signal [20], [21], [44]. Due to the waveguide effect, the radio signal attenuation in tunnels is usually much lower than in free space and decreases with increasing frequency. Therefore, in the UHF and upper VHF bands, the tunnel can be modeled as a waveguide with losses caused mainly by imperfections in the conducting walls.

In a waveguide with metallic walls, the electromagnetic field must comply with the boundary conditions, which allow transverse electric (TE) and transverse magnetic (TM) modes to propagate through the waveguide. The electric and magnetic fields can have several peaks in the transverse plane, denoted by indices m and n. The basic mode in a waveguide is TE_{10}, with one peak of electric field in the transverse plane and none in the magnetic field. The TE and TM waveguide modes propagate when the frequencies are higher than the cutoff frequency f_{mn}, where m and n denote the TE and TM waveguide modes. For frequencies below cutoff frequency, the waveguide effect is not present and the signal decays exponentially with distance [44].

Indeed, tunnel walls are not made of materials showing perfect conductivity, so the signal is attenuated along the tunnel. Hybrid modes (HE), in which the magnetic or electric field is not restricted to the transverse plane, are found to be the natural modes. In tunnels with the rectangular cross sections and walls made of lossy material the electric field can be expressed as the sum of modes [45]

TABLE I
THE ATTENUATION OF 21 MODES; $f = 1$ GHz, $r = 2$ m, $\epsilon_r = 12$, $\sigma = 0.02$ S/m [4]

Mode	**Attenuation [dB/m]**	**Mode**	**Attenuation [dB/m]**
TE_{01}	1.10	TE_{04}	13.9
HE_{11}	2.77	HE_{24}	16.9
TE_{02}	3.72	HE_{15}	18.2
HE_{21}	7.16	EH_{11}	20.2
HE_{13}	7.45	HE_{41}	20.7
TE_{03}	7.94	HE_{33}	21.1
HE_{12}	8.59	HE_{22}	21.8
HE_{14}	11.6	TE_{05}	21.9
HE_{31}	13.1	HE_{34}	23.2
TM_{01}	13.3	HE_{25}	23.7
HE_{23}	13.7		

$$E\left(x,y,z\right)=\sum_{m}\sum_{n}E_{0mn}e_{mn}\left(x,y\right)e^{-j\beta_{mn}z} \tag{1}$$

where E_{0mn} is the complex amplitude of the mn mode, $e_{mn}(x,y)$ is the modal eigenfunction and β_{mn} the complex propagation constant given by

$$\beta_{mn}=\frac{2\pi f}{c}\left[1-\frac{1}{2}\left(\frac{f_{mn}}{f}\right)^{2}\right]-j\alpha_{mn} \tag{2}$$

where

$$\begin{aligned}\alpha_{mn}=\frac{2}{a}\left(\frac{mc}{2af}\right)^{2}\mathrm{Re}\left[\frac{1}{\sqrt{\epsilon-1}}\right]+\\+\frac{2}{b}\left(\frac{nc}{2bf}\right)^{2}\mathrm{Re}\left[\frac{\epsilon}{\sqrt{\epsilon-1}}\right].\end{aligned} \tag{3}$$

Attenuation in a rectangular tunnel depends on the signal carrier frequency f, the width and height (a,b) of the tunnel, the permittivity of its walls ϵ, and their roughness and, in particular, on the propagation mode. The field magnitude in rectangular and circular tunnels as a function of axial distance can be divided into a near field region and a far field region. In the near field region, the electromagnetic field consists of many modes which interact and produce wide and rapid variations. In the far field region, low order modes determine the electromagnetic field. In addition, the measurements prove the trend of decreasing overall attenuation as a function of increasing frequency [4].

In [46] it is shown, that the TM type of mode presents good approximation for transmission of the low order modes in a rectangular tunnel model even when all four walls are imperfectly conducting.

The multimode waveguide model gives an analytical expression for a path loss and delay spread calculation at any position in the tunnel [47]. It confirms that the mode of attenuation depends mainly on tunnel dimension and operating frequency, while the power distribution among individual modes is governed by the transmitting antenna position. In the vicinity of the transmitter, signal attenuation is high and varies. Since the higher modes of attenuation decrease rapidly, their contribution to the received signal power level is negligible. Signal attenuation and its variation are reduced as the distance from the transmitter increases. In Table I, referred to in [4], the attenuation values for different modes are given for a tunnel of circular cross section with a radius of 2 meters and frequency of 1 GHz. The number of modes propagating in rectangular and circular multimode waveguides can be estimated as a function of excitation frequency and waveguide cross sectional dimensions [48].

In tunnels, radio signal propagation can be divided into near field and far field propagation regions. In the former, the propagation is affected by several modes. Attenuation in the far region depends only on the few lower order modes, typically only on one. The frequency of the propagation signal does not affect the power distribution among modes, but strongly influences the propagation constant [4], [47], [49]. Humidity, pressure, air temperature inside the tunnel, and the construction materials have negligible impact on signal propagation inside tunnels. Similar findings are noted in [50], where a radio signal propagation model for railway tunnels, combining the ray tracing model and mode analysis, is proposed. Two radio signal propagation regions are identified. The boundary between them is calculated using the ray tracing model, while mode analysis is applied to compute the propagation attenuation in both regions. The combination of the modal approach and ray tracing is introduced in [51] as a sort of mixed rays-modes approach. The propagation field description is based on the superposition of appropriate characteristic modes whose amplitudes are effectively evaluated by preliminary ray tracing procedure. In order to extend prediction capabilities to real tunnel environments including possible route curvatures, the possibility of associating each mode with proper optical bouncing on the tunnel walls is included.

In [49], the propagation of electromagnetic waves through different media is analyzed, and the channel model is described for underground mines and road and subway tunnels for GHz frequencies. Some of the experimental research on radio wave propagation in tunnels is focused on searching for the frequency band with the lowest attenuation rate. The results reveal that the optimal frequency window is between 1 and 2 GHz [11].

Imperfect waveguide models are proposed for empty curved tunnels in [52]. Modal analyses are applied to tunnels with rectangular and circular cross section and propagation constants are deduced in [53] for curved tunnels and different polarizations. An extensive analysis of attenuation using modal analysis in tunnels with circular cross section at frequencies between 1 GHz and 4 GHz is presented in [54]. The results confirm the existence of near and far regions. A mode based model is proposed for analysis of radio signal propagation in circular pipes up to 1.3 meters in diameter in [55]. The accuracy of the model depends on the distance between the transmitter and receiver and on the number of considered modes. The propagation characteristics show that the effect of higher order modes is strengthened with increased frequency [56]. Furthermore, the path loss due to wall roughness and tilt is also increased. Compared with traditional mode theory, that takes into account only fundamental modes, the theoretical results show good agreement with the published experimental results and with those, obtained using ray tracing model.

C. Ray Tracing Based Channel Models

Ray tracing approach, widely used in radars and recently in computer graphics, has also been applied to predict path loss in tunnels. Ray tracing models are based on a geometrical optics approach, where radio wave is approximated by ray. The facets where radio rays are reflected and diffracted are assumed to be much larger than the wavelength of the radio ray. The basic principle of ray modeling is given by the following equation [14]–[18], [21]

$$L_R\,[\text{dB}] = -10\log_{10}\left[\left(\frac{\lambda}{4\pi}\right)^2 \left|\left|\frac{G_t}{d} + \sum_{i=1}^{\infty}\frac{G_i R_i\left(j\frac{2\pi}{\lambda}(d_i - d)\right)}{d_i}\right|\right|^2\right] \quad (4)$$

where G_t and G_i are the gains of the transmitting and receiving antennas, which correspond to the path of direct and i-th reflected ray respectively, and d and d_i are the path lengths of the direct and i-th reflected rays. R_i is the product of the reflection coefficients of all walls from which the i-th ray is reflected [21]. The received signal is the sum of the direct ray and all reflected rays. The difference in the phases of the received rays results in the rays being added constructively or destructively. The constructive and destructive signal summation is presented as a variation of signal power with distance.

Two basic approaches for calculating ray paths are presented in [22], namely, (i) the Shooting and Bouncing Ray (SBR) method and (ii) the image method. In the former, rays or ray tubes are shot from the transmitter in all directions. The rays are then reflected from obstacles before they reach the receiver. The receiver is represented by a reception sphere whose radius depends on the path length of a particular ray and on the angle between neighboring shot rays. The method is illustrated in Fig. 1 for a straight tunnel. The computational complexity of the SBR method depends on the number of objects in the environment and the number of shot rays. The tunnels can be represented by a small number of facets, which makes this method efficient in tunnel propagation environments.

Image theory forms the basis of the image method. The reflected ray from the facet is represented as a ray radiated directly from the virtual source located symmetrically to the transmitter with respect to the plane that contains the facet. In tunnels, due to parallel facets, the number of images can be infinite. In order to keep the calculation complexity at a reasonable level, the number of images has to be limited.

A basic geometrical ray approach based on image method is proposed in [57] for a rectangular waveguide with imperfectly conducting walls. The method is validated by the comparison with modal approach. The ray tracing model can

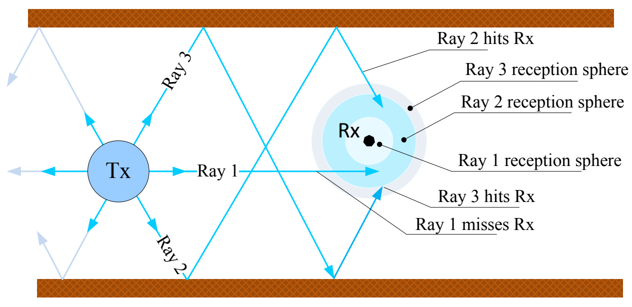

Fig. 1. Shooting and bouncing (SBR) method in a tunnel - presentation in two dimensions.

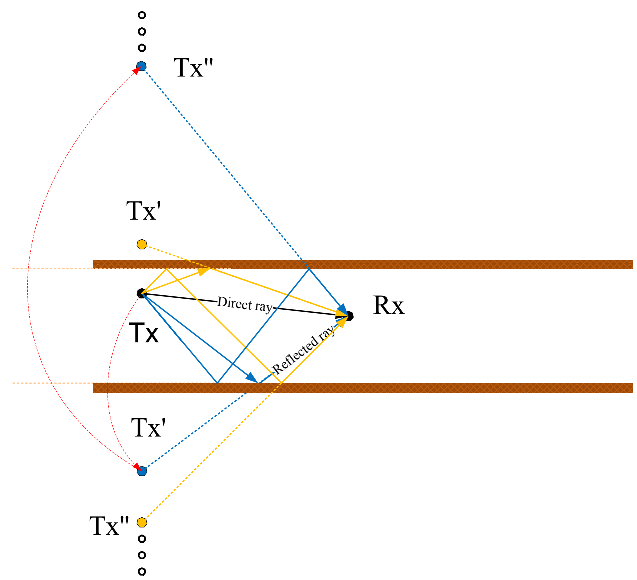

Fig. 2. Image ray tracing method in a tunnel - presentation in two dimensions.

be simplified for rectangular tunnels, by converting the three-dimensional radio signal propagation model into a simpler, two-dimensional model [17], [58], which is presented in Fig. 1 and Fig. 2. The approach significantly reduces the complexity and improves the efficiency. The two-dimensional ray model is presented in [58] for studying the entrance of a 2.1 GHz radio signal into a small tunnel. A ray-tracing method based on image algorithm is applied in [16] for predicting delay spread in tunnels. The approach takes into account all the rays that reach the destination after a random number of reflections, and incorporates the influence of incidence angle, material dielectric constant, antenna diagram and polarization, wall roughness and the tunnel cross section shape and size. The results indicate extremely low delay spread in a straight rectangular tunnel. The ray tracing method is also used to analyze signal propagation characteristics in tunnels and at the tunnel entrance at 900 MHz and 2.1 GHz bands [18].

The ray tracing model, focusing mainly on the reflected rays, is used in [59] for signal strength calculation in mine tunnels at a frequency band of 2.4 GHz. The simulation results obtained with the ray tracing model [60] were compared with those using a new Cascade Impedance Method (CIM) [61] and with measurements in an underground mine tunnel at 900 MHz. The analyses confirm that diffraction, reflection, and multiple paths are dominant phenomena in complex tunnels with rough surfaces. The ray tracing model using the image method was used to model radio wave propagation in an arched cross section tunnel at 1 GHz, 2.4 GHz and 5.8 GHz frequency bands [62]. The Ray-Density Normalization (RDN) based ray tracing approach, which allows radio signal path loss calculation for arbitrary shaped tunnels, can be used in UHF band with adequate precision as shown in [15]. Quasi-analytical ray tracing method in conjunction with analytical surface modeling is proposed for analyzing radio signal propagation inside underground mines and metro rail tunnels in [63]. The propagation model which involves the ray launching, ray bouncing and adaptive cube for ray reception is developed to obtain path details inside the tunnel.

A modified Shooting and Bouncing Ray (SBR) method [14] provides a relatively accurate calculation of the radio signal propagation, especially for tunnels where reflection is the dominant phenomenon. The authors observed a focusing effect that results in greater received power in arched tunnels than in rectangular tunnels. Modified ray launching technique is used to model the radio wave propagation in arched-shaped straight tunnels and rectangular curved tunnels using a reception sphere. Also minimization of the paths length is done according to the Fermat principle. In addition, an adaptive identification of multiple-ray technique has been developed based on the localization of reflection points [64].

A new three-dimensional model for wave propagation prediction in tunnels, an extension of motif model, is proposed in [65]. The model takes into account the imperfectly flat surfaces of obstacles considering diffuse scattering mechanism. The reflection, diffuse scattering and absorption of rays are determined on the basis of probabilistic parameters. The material parameters are replaced by probability radiation patterns, which are optimized empirically on the basis of the measured data. Since the waveguide model is appropriate for calculating accurate attenuation results only for straight rectangular tunnels, a simple geometrical optics extension to the standard hybrid waveguide solution is developed and proposed in [66], suitable for calculating attenuation in curved tunnels. Attenuation measurements, taken in curved road tunnel, and computer simulation results, based on GO approach, fit well, which indicates, that the model is reasonably good.

A method for predicting the radio propagation characteristics in round, semi-circular and oval-shaped tunnels is proposed in [67]. The approach is based on the transformation of the arbitrary tunnel shape to the rectangular shape, keeping the same cross section area. Geometric optics - uniform theory of diffraction (GO-UTD) method is used to predict the high frequency radio propagation characteristics. After finding the paths between transmitter and receiver using geometric optics, the received power is calculated by the uniform theory of diffraction method. Simulation results proved the accuracy and efficiency of the proposed method compared to general ray tracing approach.

The performance of the MIMO (Multiple Input, Multiple Output) systems in tunnels is analyzed in [68], applying ray tracing approach. The results reveal that the gain and capacity,

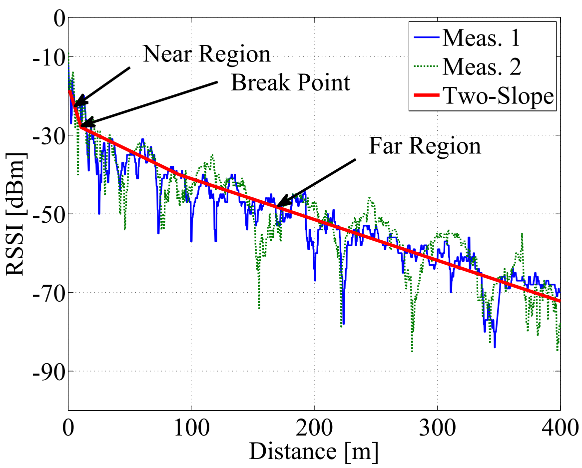

Fig. 3. Two-slope channel model.

compared to those obtained with the SISO (Single Input Single Output) systems, depend mostly on the tunnel dimension and communication range.

As discussed in previous subsection, the ray tracing approach can be combined with approaches using numerical methods for solving Maxwell equations, i.e. FDTD, MoM, VEP, and FEM, in order to provide detailed estimation of electromagnetic field near tunnel walls, obstacles in a tunnel, antennas and structures where antennas are mounted.

Common ray tracing tools represent a satisfactory solution in theory, but in practice their actual applicability strongly depends on the accuracy of the environment description and available computing capacity [51].

D. Two-Slope Path Loss Channel Models

The theory behind two-slope channel models for radio propagation in tunnels originates from the two-ray model proposed in [69]. This model is suitable for line of sight propagation conditions when the transmitter and receiver antennas are positioned several wavelengths above the tunnel floor and away from the wall. Two-slope channel models are typical representatives of empirical models based on measurements of the received signal strength [20], [21], [62], [70], [71]. In two-slope channel models, the path loss curve is divided into two regions, typically referred to as near and far region. Linear approximation of the path loss within the region is the most commonly used approach in two-slope channel models. In the near region, the path loss slope is steep. In many models it is modeled as free space path loss. In the far region, the waveguide effect appears with few lower order modes and the path loss slope is reduced significantly. The point of transition from near to far region is called the break point. An example of a two-slope channel model [70] is illustrated in Fig. 3. The signal path loss was measured in a 4 m wide, 5 m high and 500 m long abandoned railway tunnel, currently used as pedestrian and bicycle trail. The carrier frequency of the signal was 400 MHz. The two-slope model is illustrated by two solid lines, indicating far and near regions, interconnected by the break point.

The parameters of the two-slope path loss channel models, namely the break point location and region slopes, have been estimated for various tunnel shapes from field measurements at different frequencies, and for digital and analogue communication systems in empty and occupied tunnels. For example, measurements performed in a 16 m wide and 7 m high road tunnel at the carrier frequency of 2.1 GHz show that radio signal propagation in the empty tunnel follows the two-slope model described in [72]. The break point, determined by signal measurements, is in this case at a distance of about 300 m. For tunnels with smaller cross section, the break point moves towards the transmitter and the attenuation drops sharply, because of deep attenuation of higher order modes excited in the tunnel. In the presence of heavy traffic, the signal attenuation increases and the one-slope model fits better the experimental data.

Signal strength measurements at 900 MHz in mine tunnels are analyzed and a two-slope propagation model based on these measurements is proposed in [71] which consists of the free space propagation model and modified waveguide propagation model. Two-slope signal propagation model for ultra-wide band in coal mines is presented in [12]. UWB propagation model consists of multimode model in near region and waveguide model in far region. The location of the break point is determined by the distance at which the first Fresnel zone becomes obstructed. It can be estimated as the ratio of the square of the largest dimension of the tunnel cross section to the signal wavelength. Measurements made in a subway tunnel at 2.4 GHz are presented in [73]. The position of the transmitter installed on the tunnel wall and the receiver installed on the train strongly influence the signal propagation. Three different propagation regions are identified, namely, the line of sight (LOS), the non-line of sight (NLOS) and the far line of sight (FLOS). For all three propagation regions, the authors provided results for delay spread, channel impulse response, coherent bandwidth and power delay profile (PDP).

Procedures for determining path loss along tunnels using two-slope models are straightforward. Computation is time efficient, but rather inaccurate. Estimating break point is the key issue. The break point position depends mainly on signal frequency, tunnel dimensions, relative permittivity and on the antenna excitation and its position in the tunnel [47]. Break point estimation, using modal analysis, is time consuming. Typical modal analysis takes into consideration several modes before the break point and only the dominant mode after it. The break point is at $z_{bp} = a^2/\lambda$, where a is the maximum transverse dimension of the tunnel and λ is the signal wavelength in free space [13], [50], [74].

Analytical approach for the break point estimation in arched tunnels with an arbitrary cross section is presented in [75]. The approach is based on combination of the propagation theory and three-dimensional solid geometry. An analytical model for localization of the break point between the free space propagation mechanism and the multimode waveguide propagation mechanism is presented, where a specified distance is used to track the interaction of the first Fresnel zone and the walls of tunnel. The model is valid in different types of tunnels at different operating frequencies and can be applied in many realistic situations.

The break point position is estimated in [76] using the Plane Wave Spectrum (PWS) technique. The approach is based on the decomposition of total PWS area inside the tunnel into a direct PWS area and a dispersive PWS area. The influence of the dispersive PWS can be interpreted as power transference of the dispersive area to the direct area, resulting in two-slope behavior of the received power. The two-slope model [20] approximates wave propagation in the near region by double logarithmic regression and by reference power level at a given position, path length, tunnel cross section and frequency specific path loss factor in the far region. The break point, defined as a critical distance, depends on the largest cross section dimension of the tunnel and on the free space signal wavelength. This approach also defines the radio system coverage.

Zhang proposed in [21] a novel model for propagation loss prediction in tunnels consisting of two regions. In the near region, defined by the clearance of the first Fresnel zone, the propagation loss is calculated by the free space model. In the far region the constructive interference dominates, and propagation follows the waveguide model. The break point is defined as the point where propagation losses from both models are equal. The comparison of the model predictions with the measurements is done for various frequencies in UHF band and the location of the break point affected by changes in frequency, antenna parameters, and tunnel dimensions is analyzed and discussed.

Propagation model proposed in [77] combines three propagation mechanisms for two types of obstacles, namely relatively small obstacles such as pedestrians and cars and large size obstacles whose size is close to the tunnel size, e.g. trains in subway tunnels and large trucks in road tunnels. Along with the increase of the distance from transmitter to receiver, for small size obstacles, the free space propagation occurs first and the multimode waveguide effect follows. For large size obstacles the free space propagation can be partially or totally replaced by near shadowing effect, followed by multimode waveguide propagation model.

Radio propagation in long tunnel at the 400 MHz frequency band has been analyzed in [70], extending two-slope channel model to four-slope channel model. The path loss model consists of four regions, namely the free space region, near region, far region and extreme far region. Regions were proposed on the basis of extensive field measurements. The first region is characterized by free space propagation and is defined by the first Fresnel zone clearance and transmitter and receiver height. In the near region only a few reflected rays reach the receiver, resulting in high path loss. Constructive interference predominates in the far region and the waveguide phenomenon is apparent. In the extreme far region, the waveguide effect vanishes because of loosely reflecting media, and path loss again follows the free space path loss. The model is particularly suitable for coverage prediction in direct terminal to terminal communication in TETRA system.

Analytical methods for defining the radio wave propagation along various tunnels and underground passageways that do not follow a two-slope model are described in [78]. The System Identification Method (SIM) defines near and far region and break point by linear optimization. The Cascade Impedance Method (CIM) in combination with the Segmental Statistic Method (SSM) is appropriate for calculating radio wave propagation in straight and curved coal mines, buildings, roads, and railway tunnels with rough surfaces [61]. The basic idea of this approach comes from considering the radio channel in a tunnel as a transmission line. The method does not anticipate the two-slope radio signal attenuation approach and is evaluated with measurements at 900 MHz and 2.45 GHz [79], identifying two propagation regions.

E. Discussion

The choice of channel modeling approach depends mainly on the application of the channel model and on the time, required to calculate the level of electromagnetic field across the tunnel. The approach based on the numerical solution of Maxwell equations gives many detailed results of electromagnetic field propagation with the resolution smaller than the signal wavelength. However, the calculation of electromagnetic field in three dimensions with a resolution of few centimeters for the tunnel whose length exceeds several kilometers, may take several days. The hybrid approach, discussed in previous section, can significantly decrease the computational complexity while providing detailed results in transversal tunnel dimension as well as the path loss along the tunnel. Similarly, a detailed description of electromagnetic field in transversal dimension and path loss along the tunnel are obtained using modal approach. In the case when the tunnel dimensions are several times larger than the signal wavelength and the interest is mainly in the signal level several wavelengths away from the transmitter, the electromagnetic wave can be approximated by plane waves. The ray tracing approach, complemented by the general theory of diffraction, gives a good result in reasonable computation time frame.

Ray tracing channel model, modal approach based channel model and numerical methods for solving Maxwell equations are deterministic channel models. They were initially applied for modeling empty tunnels of different dimensions and cross sections and later on extended to model propagation in more realistic conditions, taking into consideration obstacles in tunnels, such as trains, cars, vans and trucks. However, close form expressions for the electromagnetic field along the tunnel, which take into account actual environment, are complex and cannot be calculated in acceptable time frame.

Moving obstacles in road and railway tunnels create rapidly changing propagation conditions resulting in the need for empirical path loss channel model, suitable for planning mobile communication system coverage in tunnels, which are mostly, due to difficult propagation conditions in road and railway tunnels, two-slope models.

Statistical models are considered to be empirical models. In our paper we have not looked closely at the statistical variation of the electromagnetic field. However, narrowband and wideband channel modeling for tunnel environment is discussed in numerous papers, which are trying to find probability density function of fading for narrowband [80] and broadband communication channel, assuming classical single input single output system (SISO) as well as multiple input multiple output (MIMO) systems [81].

III. PARAMETERS AFFECTING RADIO PROPAGATION IN TUNNELS

Radio wave propagation in tunnels depends on radio signal frequency, tunnel cross sectional dimensions and shape, curves in the tunnel, surface roughness, electromagnetic properties of walls, obstacles and their positions, polarization and radiation patterns of the transmitter and receiver antennas [82]. The impact of these parameters on radio wave propagation is discussed in the following subsections.

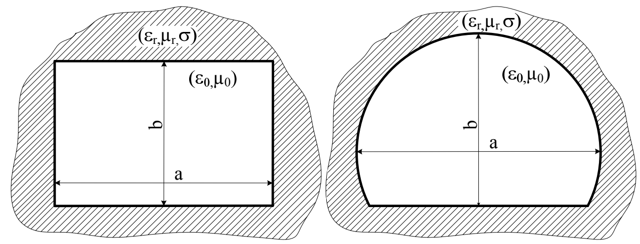

Fig. 4. Typical tunnel cross sections for road tunnels.

A. Tunnel Geometry

Tunnel cross section has an important impact on attenuation rate. Theoretical analyses typically apply the rectangular and circular cross sections, shown in Fig. 4. However, modern road tunnel cross sections differ slightly from these two ideal types. For various forms of tunnel cross section, a general equation for radio signal attenuation in dB/m is proposed in [83]:

$$\alpha = \kappa\lambda^2 \left[\frac{\epsilon_r}{a^3\sqrt{\epsilon_r - 1}} + \frac{1}{b^3\sqrt{\epsilon_r - 1}}\right] \quad (5)$$

where a is the maximum tunnel width, b the maximum height, and ϵ_r is the relative permittivity of the tunnel walls and floors. The value of coefficient κ varies with the shape of the tunnel: values $\kappa = 5.09, 4.343, 5.13$ and 4.45 are used for a circular, rectangular, arched and oval tunnels, respectively. It was demonstrated that the radio signal attenuation in rectangular and elliptical tunnels can be calculated using the attenuation coefficient for a circular tunnel, with the equivalent cross section area while for an arched tunnel, the attenuation coefficient for a circular tunnel can be used only at frequencies higher than 1.2 GHz [84].

The shape and the dimension of the tunnel cross section and curves in the tunnel have significant impact on radio signal propagation [85]–[87]. The influence of cross section on the attenuation is distinctive, particularly when signal frequency increases, where also the impact of curves, slopes and additional branches in tunnel is more emphasized. The influence of cross section dimensions in a rectangular tunnel has been studied in [88] and [89]. The simulation results show that the modification of tunnel height has greater effect on the vertical polarization mode, while the width impacts mostly the horizontal polarization mode. Tunnel curves may prevent direct visibility between the transmitter and receiver, thus affecting radio signal propagation, since reception of the direct wave is blocked. The radio signal delay spread is increased and the received power reduced by the decrease of the curve radius [87]. In straight tunnels, the radio signal attenuation decreases with increased frequency while in curved tunnels it increases. Under NLOS conditions only reflections and diffractions contribute to the received signal strength. For reliable communication it is preferable to install additional antennas and thus maintain the conditions of direct visibility (LOS) between adjacent antennas [87]. The comparison of measurements with the simulation results obtained by the ray tracing approach in a curved arched-shaped tunnels confirm that tunnel geometry, especially cross sectional shape and the course, have major impact on signal propagation, while the electromagnetic properties of materials are less important [80].

Chiba showed in [90] that the tunnel is a transmission channel of high-pass type. He proved that the radio signal attenuation in a straight tunnel decreases when the signal frequency and the transverse dimensions increase. If the tunnel is treated as a circular waveguide with the corresponding cross section, the experimental values of the attenuation constants correspond to the theoretical values of the TE01 and EH11 modes. When the largest tunnel cross section dimension is about fifteen times larger than the wavelength, the attenuation rate no longer depends on the shape and area of cross section [83]. In this case, the signal propagation is the same as free space propagation.

B. Electromagnetic Properties of Tunnel Walls

In most tunnels, the influence of conductivity can be neglected, since it is not sufficiently high [91]. As long as the dielectric constants of side walls, roof and floor are approximately equal, the attenuation rate of the vertically polarized mode is greater than that of the horizontally polarized mode as long as the tunnel width is larger than its height. In such tunnel, the horizontal polarized antenna is more appropriate than vertical polarized one [47]. The dominant mode attenuation, which is the result of the penetration into lossy tunnel dielectric walls, can be reduced by metallic strips placed on the wall surface. The solution is particularly suitable for the frequencies at which the signal wavelength is comparable with the tunnel cross section dimension [92]. The humidity of tunnel walls affects the conductivity and dielectric constant and consequently also the attenuation of electromagnetic wave propagation [93]. Measurements show negligible effect of humidity on the dielectric constant, while the effect of humidity on the conductivity cannot be ignored [47].

C. Antenna Radiation Pattern and Position

Radio wave propagation along the tunnel also depends on the position, polarization and radiation pattern of transmitting and receiving antennas [47], [68], [87], [88], [94]. The signal attenuation can be reduced by using antennas with suitable radiation pattern at appropriate locations. While the omni-directional antennas offer better signal coverage in NLOS tunnel regions, directional antennas perform better in LOS regions [95]. The optimal transmitter position is in the middle of the tunnel cross section, whereas the transmitter installed at the tunnel wall exhibits the worst propagation characteristic. These findings were confirmed by radio signal propagation simulations for rectangular mine tunnels [88], [96]. By moving the transmitter towards the wall of the tunnel, propagation becomes more complex, while the signal attenuation and delay spread increase. In an empty straight rectangular tunnel the delay spread is greater for horizontally polarized antennas than it is for vertically polarized antennas if the tunnel width is greater than the tunnel height [16]. In such tunnels the horizontal polarized wave attenuates less than the vertical one, because the attenuation of waveguide mode becomes lower with larger horizontal cross section dimension. In this case the number of modes becomes greater, which significantly contributes to the electromagnetic wave level in far field. Consequently, the electromagnetic wave attenuation is also lower for the horizontal polarization than it is for the vertical one [47]. In addition, the reflection coefficients on the horizontal ceiling and floor are larger than those on vertical walls, which additionally contribute to higher attenuation of vertical polarized electromagnetic waves [47]. Measurements show that this is also true for tunnels with arched cross section [68]. The propagation considering the transmitter outside the tunnel is analyzed in [97]. In this case the attenuation of radio signal at the entrance of the tunnel is significant and increases with the increasing incidence angle.

D. Obstacles

Obstacles and traffic in tunnels cause additional attenuation and increase the delay spread of the radio signal. Additional path loss, caused by traffic (about 150 trucks per hour) at the frequency around 900 MHz in road tunnels can reach up to 50 dB for the same transmitter and receiver position. Measurements of additional attenuation were taken into account to update the waveguide model and enable more accurate attenuation calculations in road tunnels in [98]. The impact of trains in tunnels is analyzed in [88]. Since reflections from train increase the delay spread, sufficient bandwidth is required in order to ensure communication quality. Due to the metal surface, the train has relatively small effect on the received signal level. When the train is passing the transmitter the near shadowing effect is created, which causes the attenuation that lasts up to several seconds. The attenuation value depends on the ratio between the train and the tunnel cross sectional dimensions and can reach up to 32 dB for passenger train in narrow one track tunnels [99].

Analysis of the impact of barriers on the propagation of a 900 MHz radio signal in a coal mine indicates that moving trolleys have significant effect on radio propagation, while the influence of small immobile objects is typically negligible [71]. Radio signal measurements in tunnels show that the radio signal propagation path losses caused by vehicles in tunnels depend mainly on their number and dimension, rather than on their relative position within the tunnel [86]. The wirelesss channel in road tunnels with traffic flow is described by theoretical mode-based analysis [100]. A proposed closed-form expression accurately predicts the signal propagation and field distribution at any point in a road tunnel filled with cars.

IV. Conclusion

Various empirical and deterministic models for cellular communication systems, such as GSM, UMTS, WiMAX and WLAN, are available for signal coverage calculation in urban, suburban and rural environments and inside buildings. They differ in calculation speed, accuracy, reliability and in the selection of model input data. Many contributions dealing with radio signal propagation models are published in the international scientific literature. A series of simulation packages for radio signal coverage calculation are also available. However, only a few contributions and software packages deal with calculation of radio signal coverage in tunnels. The main problem lies in performing measurements in the tunnel. A detailed literature review reveals that authors are predominantly interested in signal strength measurements and propagation properties up to a few hundred meters, which coincides with the range of base stations in cellular telecommunications systems. More recent research work also deals with radio signal propagation in longer tunnels at frequencies used in public safety and emergency communication systems where, in comparison to commercial cellular systems, the communication range is essential.

Available approaches to radio propagation modeling for tunnels, such as numerical methods for solving Maxwell equations, modal or wave guide approach, ray based and empirical approach, provide designers of wireless communication system with useful information about radio wave propagation in tunnels. However, the designers should be aware of respective model limitations and assumptions. The waveguide approach gives good analytical solution for empty road and train tunnels as well as for empty mine tunnels with smooth walls and ceiling. However, it is not appropriate for tunnels with obstacles and when tunnel walls contain various metallic structures, arches preventing collapse, or various kinds of objects mounted on the walls and ceiling. In this case the ray tracing approach is a suitable choice. Large number of obstacles in the tunnel can cause many reflected and diffracted rays which cannot be processed efficiently with available computing power in acceptable time frame. The required computing power is a serious problem, particularly if the description of the environment is too detailed. The problem can be partially solved by using a hybrid modeling approach.

The tunnels are usually filled with cars or trains, and the mine tunnels do not have smooth walls and contains various kinds of obstacles. Furthermore, the vehicles and people are moving inside the tunnel occupying the tunnel cross section, which causes the radio propagation environment in tunnels time-varying and unpredictable. In such cases empirical channel models, as for instance the two-slope model, provide generally adequate information about path loss in a tunnel. However, the difference between the environment for which the propagation model was developed and the environment for which the model will be used, have to be carefully evaluated.

In future, we believe that radio propagation modeling for tunnels will become even more important, because people, using contemporary and emerging means of transport, spend increasing amount of time in an underground transport system. Users expect the provision of mobile wireless services in tunnels. In addition, the provision of wireless services is a must for public protection and disaster relief forces in underground environments.

REFERENCES

[1] "Directory of wireless system planning tools," UBC Radio Science Lab. [Online]. Available: http://rsl.ece.ubc.ca/planning.html

[2] A. Forooshani, S. Bashir, D. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *IEEE Commun. Surveys Tutorials*, vol. PP, no. 99, pp. 1–22, 2013.

[3] S. Yarkan, S. Güzelgöz, H. Arslan, and R. Murphy, "Underground mine communications: A survey," *IEEE Commun. Surveys Tutorials*, vol. 11, no. 3, pp. 125–142, 2009.

[4] D. Dudley, M. Lienard, S. Mahmoud, and P. Degauque, "Wireless propagation in tunnels," *IEEE Antennas Propagat. Mag.*, vol. 49, no. 2, pp. 11–26, 2007.

[5] T.-S. Wang and C.-F. Yang, "Simulations and measurements of wave propagations in curved road tunnels for signals from GSM base stations," *IEEE Trans. Antennas Propagat.*, vol. 54, no. 9, pp. 2577–2584, 2006.

[6] J. Alonso, S. Capdevila, B. Izquierdo, and J. Romeu, "Propagation measurements and simulations in tunnel environment at 5.8 GHz," in *Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE*, 2008, pp. 1–4.

[7] M.-S. Choi, D.-Y. Kim, H.-S. Jo, J.-G. Yook, and H.-K. Park, "Path-loss characteristics in subway tunnels at 2.65 GHz," *Microwave and Optical Technology Letters*, vol. 48, no. 2, pp. 383–386, 2006. [Online]. Available: http://dx.doi.org/10.1002/mop.21357

[8] H. El-Sallabi and J. Tervonen, "Characterization of radio wave propagation in tunnels for microcellular communications," in *Antennas and Propagation for Wireless Communications, 2000 IEEE-APS Conference on*, 2000, pp. 91–94.

[9] M. Lienard and P. Degauque, "Natural wave propagation in mine environments," *IEEE Trans. Antennas Propagat.*, vol. 48, no. 9, pp. 1326–1339, 2000.

[10] Y. Zhang and Y. Hwang, "Measurements and statistical modeling of 900 MHz radio propagation channels for microcellular and personal communications in tunnels," *Wireless Personal Communications*, vol. 7, no. 1, pp. 25–39, 1998. [Online]. Available: http://dx.doi.org/10.1023/A%3A1008834724510

[11] Y.-P. Zhang and Y. Hwang, "Characterization of UHF radio propagation channels in tunnel environments for microcellular and personal communications," *IEEE Trans. Veh. Technol.*, vol. 47, no. 1, pp. 283–296, 1998.

[12] F. Li, P. Han, X. Wu, and W. Xu, "Research of UWB signal propagation attenuation model in coal mine," in *Proc. 4th international conference on Ubiquitous Intelligence and Computing*, ser. UIC'07. Berlin, Heidelberg: Springer-Verlag, 2007, pp. 819–828. [Online]. Available: http://dl.acm.org/citation.cfm?id=2391319.2391405

[13] Y.-P. Zhang and Y. Hwang, "Enhancement of rectangular tunnel waveguide model," in *Microwave Conference Proc., 1997. APMC '97, 1997 Asia-Pacific*, vol. 1, 1997, pp. 197–200.

[14] S.-H. Chen and S.-K. Jeng, "SBR image approach for radio wave propagation in tunnels with and without traffic," *Vehicular Technology, IEEE Transactions on*, vol. 45, no. 3, pp. 570–578, 1996.

[15] D. Didascalou, T. Schafer, F. Weinmann, and W. Wiesbeck, "Ray-density normalization for ray-optical wave propagation modeling in arbitrarily shaped tunnels," *IEEE Trans. Antennas Propagat.*, vol. 48, no. 9, pp. 1316–1325, 2000.

[16] M. Kermani and M. Kamarei, "A ray-tracing method for predicting delay spread in tunnel environments," in *Personal Wireless Communications, 2000 IEEE International Conference on*, 2000, pp. 538–542.

[17] J. Minghua, Z. Guoxin, and J. Wenli, "A new model for predicting the characteristic of RF propagation in rectangular tunnel," in *Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference on*, 2008, pp. 1–4.

[18] F. Pallares, F. Juan, and L. Juan-Llàcer, "Analysis of path loss and delay spread at 900 MHz and 2.1 GHz while entering tunnels," *IEEE Trans. Veh. Technol.*, vol. 50, no. 3, pp. 767–776, 2001.

[19] A. V. Popov and N. Y. Zhu, "Modeling radio wave propagation in tunnels with a vectorial parabolic equation," *IEEE Trans. Antennas Propagat.*, vol. 48, no. 9, pp. 1403–1412, 2000.

[20] T. Klemenschits and E. Bonek, "Radio coverage of road tunnels at 900 and 1800 MHz by discrete antennas," in *Personal, Indoor and Mobile Radio Communications, 1994. Wireless Networks - Catching the Mobile Future., 5th IEEE International Symposium on*, vol. 2, 1994, pp. 411–415.

[21] Y.-P. Zhang, "Novel model for propagation loss prediction in tunnels," *IEEE Trans. Veh. Technol.*, vol. 52, no. 5, pp. 1308–1314, 2003.

[22] M. F. Cétedra and J. Pérez-Arriaga, *Cell Planning for Wireless Communications*. London: Artech House Boston, 1999.

[23] Y. Huang and K. Boyle, *Antennas: from theory to practice*. Chichester: Wiley & Sons, Ltd, 2008.

[24] S. R. Saunders, *Antennas and propagation for wireless communication systems*. Chichester: John Wiley & Sons Ltd, 1999.

[25] J. B. Keller, "Geometrical theory of diffraction," *J. Opt. Soc. Am.*, vol. 52, no. 2, pp. 116–130, Feb 1962. [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=josa-52-2-116

[26] A. Taflove and S. C. Hagness, *Computational electrodynamics: the finite-difference time-domain method*, 3rd ed. Norwood, MA: Artech House, 2005.

[27] G. Kondylis, F. De Flaviis, G. Pottie, and Y. Rahmat-Samii, "Indoor channel characterization for wireless communications using reduced finite difference time domain (R-FDTD)," in *Vehicular Technology Conference, 1999. VTC 1999 - Fall. IEEE VTS 50th*, vol. 3, 1999, pp. 1402–1406.

[28] M. Rana and A. Mohan, "Segmented-locally-one-dimensional-FDTD method for EM propagation inside large complex tunnel environments," *IEEE Trans. Magn.*, vol. 48, no. 2, pp. 223–226, 2012.

[29] Y. Wang, S. Safavi-Naeini, and S. Chaudhuri, "A hybrid technique based on combining ray tracing and FDTD methods for site-specific modeling of indoor radio wave propagation," *IEEE Trans. Antennas Propagat.*, vol. 48, no. 5, pp. 743–754, 2000.

[30] A. Popov, V. Vinogradov, N. Zhu, and F. Landstorfer, "3d parabolic equation model of EM wave propagation in tunnels," *Electronics Letters*, vol. 35, no. 11, pp. 880–882, 1999.

[31] P. Bernardi, D. Caratelli, R. Cicchetti, V. Schena, and O. Testa, "A numerical scheme for the solution of the vector parabolic equation governing the radio wave propagation in straight and curved rectangular tunnels," *IEEE Trans. Antennas Propagat.*, vol. 57, no. 10, pp. 3249–3257, 2009.

[32] R. Martelly and R. Janaswamy, "An ADI-PE approach for modeling radio transmission loss in tunnels," *IEEE Trans. Antennas Propagat.*, vol. 57, no. 6, pp. 1759–1770, 2009.

[33] ——, "Modeling radio transmission loss in curved, branched and rough-walled tunnels with the ADI-PE method," *IEEE Trans. Antennas Propagat.*, vol. 58, no. 6, pp. 2037–2045, 2010.

[34] J. Crank, P. Nicolson, and D. R. Hartree, "A practical method for numerical evaluation of solutions of partial differential equations of the heat-conduction type," *Proc. Cambridge Philosophical Society*, vol. 43, p. 50, 1947.

[35] W. C. Gibson, *The Method of Moments in Electromagnetics*. Chapman & Hall/CRC, Taylor & Francis Group, 2008.

[36] A. Fourie and D. Nitch, "SuperNEC: antenna and indoor-propagation simulation program," *IEEE Antennas Propagat. Mag.*, vol. 42, no. 3, pp. 31–48, 2000.

[37] M. N. O. Sadiku, "A simple introduction to finite element analysis of electromagnetic problems," *IEEE Trans. Edu.*, vol. 32, no. 2, pp. 85–93, 1989.

[38] J.-M. Jin, *The finite element method in electromagnetics*, 2nd ed. John Wiley & Sons, 2002. [Online]. Available: http://www.worldcat.org/isbn/9780471438182

[39] J. Chiba and K. Sugiyama, "Effects of trains on cutoff frequency and field in rectangular tunnel as waveguide," *IEEE Trans. Microw. Theory Tech.*, vol. 30, no. 5, pp. 757–759, 1982.

[40] G. Poitau and A. Kouki, "Analysis of MIMO capacity in waveguide environments using practical antenna structures for selective mode excitation," in *Electrical and Computer Engineering, 2004. Canadian Conference on*, vol. 1, 2004, pp. 349–352.

[41] S. Jiping and Z. Chuanlei, "Transmission characteristics analysis for mine tunnel with metallic wind bridge using hybrid MM/FEM approach," in *Microwave Conference Proceedings, 2005. APMC 2005. Asia-Pacific Conference Proceedings*, vol. 4, 2005, p. 4.

[42] A. Emslie, R. Lagace, and P. Strong, "Theory of the propagation of UHF radio waves in coal mine tunnels," *IEEE Trans. Antennas Propagat.*, vol. 23, no. 2, pp. 192–205, 1975.

[43] D. Dudley, S. Mahmoud, M. Lienard, and P. Degauque, "On wireless communication in tunnels," in *Antennas and Propagation Society International Symposium, 2007 IEEE*, 2007, pp. 3305–3308.

[44] L. Deryck, "Natural propagation of electromagnetic waves in tunnels," *IEEE Trans. Veh. Technol.*, vol. 27, no. 3, pp. 145–150, 1978.

[45] S. Loyka, "Multiantenna capacities of waveguide and cavity channels," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 863–872, 2005.

[46] J. Wait, "Propagation in rectangular tunnel with imperfectly conducting walls," *Electronics Letters*, vol. 16, no. 13, pp. 521–522, 1980.

[47] Z. Sun and I. Akyildiz, "Channel modeling and analysis for wireless networks in underground mines and road tunnels," *IEEE Trans. Commun.*, vol. 58, no. 6, pp. 1758–1768, 2010.

[48] P. Nikitin, D. Stancil, and E. Erosheva, "Estimating the number of modes in multimode waveguide propagation environment," in *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*, 2011, pp. 1662–1665.

[49] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," *Physical Communication*, vol. 2, no. 3, pp. 167 – 183, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1874490709000408

[50] C. Briso-Rodriguez, J. Cruz, and J. Alonso, "Measurements and modeling of distributed antenna systems in railway tunnels," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2870–2879, 2007.

[51] F. Fuschini and G. Falciasecca, "A mixed rays-modes approach to the propagation in real road and railway tunnels," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 2, pp. 1095–1105, 2012.

[52] Y.-P. Zhang, Y. Hwang, and P. Ching, "Characterization of UHF radio propagation channel in curved tunnels," in *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, vol. 3, 1996, pp. 798–802.

[53] S. Mahmoud, "On modal propagation of high frequency electromagnetic waves in straight and curved tunnels," in *Antennas and Propagation Society International Symposium, 2004. IEEE*, vol. 3, 2004, pp. 2963–2966.

[54] D. Dudley and S. Mahmoud, "Linear source in a circular tunnel," *IEEE Trans. Antennas Propagat.*, vol. 54, no. 7, pp. 2034–2047, 2006.

[55] I. Howitt, S. Khan, and J. Khan, "A mode based model for radio wave propagation in storm drain pipes," *PIERS Online*, vol. 4, no. 6, 2008.

[56] Y. Huo, Z. Xu, and H.-D. Zheng, "Characteristics of multimode propagation in rectangular tunnels," *Chinese J. Radio Science*, vol. 25, no. 6, pp. 1225–1230, 2010.

[57] S. F. Mahmoud and J. R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels," *Radio Science*, vol. 9, no. 12, pp. 1147–1158, 1974. [Online]. Available: http://dx.doi.org/10.1029/RS009i012p01147

[58] J. Molina-Garcia-Pardo, J.-V. Rodriguez, and L. Juan-Llàcer, "Wideband measurements and characterization at 2.1 GHz while entering in a small tunnel," *IEEE Trans. Veh. Technol.*, vol. 53, no. 6, pp. 1794–1799, 2004.

[59] M. Moutairou, G.-Y. Delisle, and D. Grenier, "Experimentally assessed underground mines propagation model at high UHF frequencies," in *Antennas and Propagation (EuCAP), 2010 Proc. Fourth European Conference on*, 2010, pp. 1–4.

[60] M. Ndoh and G.-Y. Delisle, "Underground mines wireless propagation modeling," in *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, vol. 5, 2004, pp. 3584–3588.

[61] M. Ndoh, G. Y. Delisle, and R. Le, "A novel approach to propagation prediction in confined and diffracting rough surfaces," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 16, no. 6, pp. 535–555, 2003. [Online]. Available: http://dx.doi.org/10.1002/jnm.521

[62] E. Masson, P. Combeau, M. Berbineau, R. Vauzelle, and Y. Pousset, "Radio wave propagation in arched cross section tunnels simulations and measurements," *Journal of Communications*, vol. 4, no. 4, 2009.

[63] B. Choudhury and R. Jha, "A refined ray tracing approach for wireless communications inside underground mines and metrorail tunnels," in *Applied Electromagnetics Conference (AEMC), 2011 IEEE*, 2011, pp. 1–4.

[64] E. Masson, Y. Cocheril, P. Combeau, L. Aveneau, M. Berbineau, R. Vauzelle, and E. Fayt, "Radio wave propagation in curved rectangular tunnels at 5.8 GHz for metro applications," in *ITS Telecommunications (ITST), 2011 11th International Conference on*, 2011, pp. 81–85.

[65] L. Subrt and P. Pechac, "A 3D model for wideband propagation predictions in tunnels," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*, 2009, pp. 2253–2256.

[66] M. Nilsson, J. Slettenmark, and C. Beckman, "Wave propagation in curved road tunnels," in *Antennas and Propagation Society International Symposium, 1998. IEEE*, vol. 4, 1998, pp. 1876–1879.

[67] J. Minghua, "A modified method for predicting the radio propagation characteristics in tunnels," in *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*, 2011, pp. 1–4.

[68] J. M. M. G. Pardo, M. Lienard, P. Stefanut, and P. Degauque, "Modeling and understanding mimo propagation in tunnels," *J. Communications*, vol. 4, no. 4, pp. 241–247, 2009.

[69] H. Xia, H. L. Bertoni, L. Maciel, A. Lindsay-Stewart, and R. Rowe, "Radio propagation characteristics for line-of-sight microcellular and personal communications," *IEEE Trans. Antennas Propagat.*, vol. 41, no. 10, pp. 1439–1447, 1993.

[70] A. Hrovat, G. Kandus, and T. Javornik, "Four-slope channel model for path loss prediction in tunnels at 400 MHz," *Microwaves, Antennas Propagation, IET*, vol. 4, no. 5, pp. 571–582, 2010.

[71] Y.-P. Zhang, G. Zheng, and J. H. Sheng, "Radio propagation at 900 MHz in underground coal mines," *IEEE Trans. Antennas Propagat.*, vol. 49, no. 5, pp. 757–762, 2001.

[72] S. Betrencourt, M. Lienard, P. Degauque, and D. Degardin, "Mobile communication in road tunnels: influence of the traffic conditions on the channel characteristics," in *Electrotechnical Conference, 2000. MELECON 2000. 10th Mediterranean*, vol. 1, 2000, pp. 432–435.

[73] R. He, Z. Zhong, and C. Briso, "Broadband channel long delay cluster measurements and analysis at 2.4 GHz in subway tunnels," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, 2011, pp. 1–5.

[74] B. Taha-Ahmed, M. Calvo-Ramn, and L. Haro-Ariet, "WCDMA uplink capacity of a long tunnel cigar-shaped microcells for underground train service," *International Journal of Wireless Information Networks*, vol. 15, no. 2, pp. 90–97, 2008. [Online]. Available: http://dx.doi.org/10.1007/s10776-008-0075-8

[75] K. Guan, Z. Zhong, B. Ai, and C. Briso-Rodrguez, "Modeling of the division point of different propagation mechanisms in the near-region within arched tunnels," *Wireless Personal Communications*, vol. 68, no. 3, pp. 489–505, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11277-011-0464-7

[76] J. Alonso, B. Izquierdo, and J. Romeu, "Break point analysis and modelling in subway tunnels," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*, 2009, pp. 3254–3258.

[77] K. Guan, Z. Zhong, B. Ai, and C. Briso-Rodriguez, "Novel hybrid propagation model inside tunnels," in *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, 2012, pp. 1–5.

[78] D. Dudley and H.-Y. Pao, "System identification for wireless propagation channels in tunnels," *IEEE Trans. Antennas Propagat.*, vol. 53, no. 8, pp. 2400–2405, 2005.

[79] M. Ndoh, G.-Y. Delisle, and R. Le, "An approach to propagation prediction in a complex mine environment," in *Applied Electromagnetics and Communications, 2003. ICECom 2003. 17th International Conference on*, 2003, pp. 237–240.

[80] D. Didascalou, J. Maurer, and W. Wiesbeck, "Subway tunnel guided electromagnetic wave propagation at mobile communications frequencies," *IEEE Trans. Antennas Propagat.*, vol. 49, no. 11, pp. 1590–1596, 2001.

[81] J.-M. Molina-Garcia-Pardo, M. Lienard, and P. Degauque, "Propagation in tunnels: Experimental investigations and channel modeling in a wide frequency band for MIMO applications," *EURASIP J. Wireless Communications and Networking*, vol. 2009, no. 1, p. 560571, 2009. [Online]. Available: http://jwcn.eurasipjournals.com/content/2009/1/560571

[82] Y. Kim, M. Jung, and B. Lee, "Analysis of radio wave propagation characteristics in rectangular road tunnel at 800 MHz and 2.4 GHz," in *Antennas and Propagation Society International Symposium, 2003. IEEE*, vol. 3, 2003, pp. 1016–1019.

[83] Z. Changsen and M. Yan, "Effects of cross section of mine tunnel on the propagation characteristics of UHF radio wave," in *Antennas, Propagation EM Theory, 2006. ISAPE '06. 7th International Symposium on*, 2006, pp. 1–5.

[84] Z. Chang-sen and G. Li-fang, "Research on propagation characteristics of electromagnetic wave in tunnels with arbitrary cross sections," in *Future Computer and Communication (ICFCC), 2010 2nd International Conference on*, vol. 1, 2010, pp. V1–22–V1–25.

[85] D. Didascalou, J. Maurer, and W. Wiesbeck, "Natural wave propagation in subway tunnels at mobile communications frequencies," in *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, vol. 3, 2000, pp. 2009–2013.

[86] Y. Yamaguchi, T. Abe, and T. Sekiguchi, "Radio wave propagation loss in the VHF to microwave region due to vehicles in tunnels," *IEEE Trans. Electromagn. Compat.*, vol. 31, no. 1, pp. 87–91, 1989.

[87] X. Yang and Y. Lu, "Research on propagation characteristics of millimeter wave in tunnels," *International J. Infrared and Millimeter Waves*, vol. 28, no. 10, pp. 901–909, 2007. [Online]. Available: http://dx.doi.org/10.1007/s10762-007-9268-y

[88] S. Wang, "Radio wave attenuation character in the confined environments of rectangular mine tunnel," *Modern Applied Science*, vol. 4, no. 2, pp. 65–70, 2010.

[89] L. Cheng and P. Zhang, "Influence of dimension change on radio wave propagation in rectangular tunnels," in *Wireless Communications, Net-*

working and Mobile Computing, 2009. WiCom '09. 5th International Conference on, 2009, pp. 1–3.
[90] J. Chiba, T. Inaba, Y. Kuwamoto, O. Banno, and R. Sato, "Radio communication in tunnels," *IEEE Trans. Microw. Theory Tech.*, vol. 26, no. 6, pp. 439–443, 1978.
[91] J. Sun, L. Cheng, and X. Liu, "Influence of electrical parameters on UHF radio propagation in tunnels," in *Communications, 2004 and the 5th International Symposium on Multi-Dimensional Mobile Communications Proceedings. The 2004 Joint Conference of the 10th Asia-Pacific Conference on*, vol. 1, 2004, pp. 436–438.
[92] Y. Yamaguchi, T. Honda, M. Sengoku, S. Motooka, and T. Abe, "On the reduction of wave propagation loss in tunnels," *IEEE Trans. Electromagn. Compat.*, vol. 34, no. 2, pp. 78–85, 1992.
[93] L. Cheng, L. Zhang, and J. Li, "Influence of mine tunnel wall humidity on electromagnetic waves propagation," *International J. Antennas and Propagation*, vol. 2012, p. 5, 2012. [Online]. Available: http://dx.doi.org/10.1155/2012/734379
[94] Y. Huo, Z. Xu, H. dang Zheng, and X. Zhou, "Effect of antenna on propagation characteristics of electromagnetic waves in tunnel environments," in *Microelectronics Electronics, 2009. PrimeAsia 2009. Asia Pacific Conference on Postgraduate Research in*, 2009, pp. 268–271.
[95] Y. Rissafi, L. Talbi, and M. Ghaddar, "Experimental characterization of an UWB propagation channel in underground mines," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 1, pp. 240–246, 2012.
[96] X. Han, S. Wang, T. Fang, and Z. Guo, "Propagation character of electromagnetic wave of the different transmitter position in mine tunnel," in *Networks Security, Wireless Communications and Trusted Computing, 2009. NSWCTC '09. International Conference on*, vol. 1, 2009, pp. 530–533.
[97] P. Mariage, M. Lienard, and P. Degauque, "Theoretical and experimental approach of the propagation of high frequency waves in road tunnels," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 1, pp. 75–81, 1994.
[98] Y. P. Zhang, "Natural propagation of radio signals in confined spaces," *Microwave and Optical Technology Letters*, vol. 23, no. 1, pp. 38–42, 1999.
[99] K. Guan, Z. Zhong, J. Alonso, and C. Briso-Rodriguez, "Measurement of distributed antenna systems at 2.4 GHz in a realistic subway tunnel environment," *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 834–837, 2012.
[100] Z. Sun and I. Akyildiz, "A mode-based approach for channel modeling in underground tunnels under the impact of vehicular traffic flow," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3222–3231, 2011.

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