Path Loss Analyses in Tunnels and Underground Corridors

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***Abstract*—**This paper presents the applicability of commercial and license free simulation tools for path loss calculations in tunnels and underground corridors. WinProp simulation tool has been selected for path loss calculation based on deep study of simulation tools performance, implemented radio propagation algorithms, results representation and representation and modeling of the propagation environment. A set of simulations at various frequencies were performed for tunnels with standard cross-sectional shapes, dimensions, material properties and in addition with presence of the obstacles preventing radio wave propagation along tunnel. The signal frequency and dimension of the tunnel cross section have considerable impact on path loss, while the tunnel cross shape and the transmitter/receiver position does not have it. The results were evaluated by four-slope empirical path loss model and measurement results performed in two different tunnels. The comparison confirmed the adequacy of the simulation tool for performing the path loss calculation and communication range determination in different tunnels and corridors.

***Keywords*—**GRASS-RaPlaT, measurements, multi-slope model, path loss, radio signal propagation, simulation tools, tunnel environment

I. Introduction

THE customers of mobile and broadcast operators and public protection and disaster relief forces require and expect to have access to services also when they are in underground corridors or tunnels. Particularly in emergency situations, where fast and reliable communication is crucial, using communication services become problematic. Commercial wireless communication systems do not provide the required reliability in emergency situations. Therefore, a reliable autonomous system operating completely independently from the telecommunication infrastructure in tunnel and it is specifically aimed for professional users must be established [1], [2].

In order to provide required services the radio propagation models and tools to place base stations and repeaters at the optimal positions are needed. Radio propagation models comprise a set of mathematical equations and algorithms that are used for radio signal propagation prediction in chosen environment. They can be classified into empirical, semi-deterministic and deterministic propagation models [3]. Empirical models are described by mathematical equations derived from statistical analyses of large number of measurements, while the deterministic models apply basic propagation mechanisms such as reflection, diffraction and absorption on the precisely descripted environment including its geometry and electrical parameters. The deterministic channel model output includes the receive signal strength as well as delay spread at the receiver position.

Unfortunately, there exist a few empirical models for underground corridors and tunnels. The main reason is the lack of propagation measurement data, since the measurement campaign in underground corridors and tunnels often causes stopping or slowing down normal traffic in tunnels. In addition the measurement campaigns nearly always require huge effort to obtain permission for measurement. The tunnel dimensions, their cross sections and the load with the traffic vary significantly, and developing universal empirical channel model with the tunnel shape and its dimensions as parameters is nearly impossible. However, computer simulations help to predict radio propagation in different tunnel cross sections and tunnel dimensions.

The aim of this paper is to study radio signal propagation in tunnels and underground corridors of different geometries and dimensions. The paper is organized as follows. In the following section an overview of existing simulation tools are given. The description of the simulation and measurement scenarios follows after that. The simulation results are described and discussed in the Section 4. Simulation tool verification using the four-slope model and data from measurement campaigns in two tunnels with the different cross sections and dimensions is performed in the next section. And finally, the concluding remarks are drawn in conclusion.

II. Simulation Tools

Various commercial simulation tools are available for radio coverage calculation. Usually their price is high while their accessibility and spread of usage are low [4]-[8]. Therefore, some cheaper yet functionally limited tools have appeared on market [9]-[11]. There are also some custom built technology-specific tools developed by hardware development companies [12] and also an open-source tools [13]. The majority of tools includes only modules for outdoor rural and

Manuscript received January 11, 2012.
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urban environments [4], [5], [7], [9], [11], [13] while the enlistment of the software tools for indoor propagation calculations is considerably lower [8], [10], [14], [15]. Indoor environment complexity causes strong multipath propagation, reflections, diffractions, penetration and shadowing effects which have significant influence on received power. Therefore, the software tools employ advanced deterministic approaches based on ray tracing techniques for the accurate indoor path loss calculation and this requires detailed environment database. Thus, the indoor modules usually comprises environment editing tool which enables detail constructing of the buildings and importing them from different well known CAD formats (DXF, DWG, shapefile).

Tunnels are special case of the indoor environment. The tunnel cross section varies, as well as the longitudinal profile. Unsophisticated tunnels can be built in environment editing tools of the software's indoor modules. More complex geometries can be imported from other CAD programs (Wireless InSite, CINDOOR, EDX) or built in special tunnel dedicated modules (WinProp). The WinProp and Wireless InSite are the two most suitable tools for propagation modeling in tunnels and underground corridors, while the GRASS RaPlaT [13] which also comprises ray tracing technique is under development. The WinProp simulation tool has dedicated tunnel module which enables detailed construction of complex tunnel environment, while in Wireless InSite the detailed tunnel environment has to be imported from CAD program.

A. WinProp

WinProp simulation tool is the main product of the AWE Communications [10]. Tool runs on standard computers under 32 or 64-bit MS Windows operating systems. It is suited for propagation modeling in different scenarios (rural, urban and indoor) and for network planning of different air interfaces. In addition also several modules for traffic simulation and converting building database and antenna diagrams in proper format. WinProp software tool is composed of four basic modules, namely:

- PropMan – propagation modeling and radio network planning,
- WallMan - graphical editor for urban and indoor databases,
- TuMan – graphical tunnel editor;
- AMan – graphical antenna editor.

The PropMan module is designed to predict path loss between transmitter and receiver including all important parameters of the radio channel. Various deterministic (ray-optical), semi-deterministic and empirical models are included to calculate path loss in rural, urban, indoor and tunnel environments. The basic tool is upgraded with network planning tool which supports different wireless radio interfaces such as 2G, 3G, LTE, WLAN, WiMAX, DVB-H/DVB-SH, TETRA, MESH, Sensors and UWB.

The software toll includes functionality for two- and three-dimensional graphical presentation of results and databases, plotting different graphs, statistical estimations (probability density function, cumulative density function, histograms ...), etc.

The WallMan module is destined to generate and edit urban and indoor building databases. Several filters are available for importing standard GIS (MapInfo, Arcview,...) CAD (DWG, DXF, Shapefile,...) and pixel formats (Bitmaps,...). Frequency depended electrical material properties stored in the database can be assign to each individual object. Since the preprocessing of the environment database, the path loss model should be chosen in WallMan module. In WinProp the indoor propagation is not restricted to the interior of buildings. It includes more or less any scenario which can be described with a 3D vector database (campus scenarios, tunnels, vehicles,…).

A special module for generating tunnel scenarios TuMan allows the definition of different cross sections within one tunnel. Additionally multiple curves with different radii can be defined to model the tunnel and its curved profile accurately. The tunnels can be exported in WinProp's indoor data format to process them further with WallMan. Because inside the tunnels besides fixed object also time-variant objects (e.g. cars, trucks, trains,...) have a significant impact on the wave propagation, further objects can be added to the tunnel database with WallMan. Shielding and wave guiding are depended on the obstacles inside the tunnels. If the obstacles are moving, the propagation environment changes significantly. Therefore WinProp includes a time-variant propagation option to consider these time variant effects even in tunnels. Since the tunnel scenarios are saved in WinProp's planar object database format, all indoor propagation models can be used. Due to the multiple reflections and wave guiding effects, ray-optical propagation models are recommended.

B. Wireless InSite

Wireless InSite is a radio planning tool for calculating the radio signal propagation and network planning in rural, urban, indoor and mixed environments [15]. The analyzed environment is either constructed using Wireless InSite's editing tools or imported from a number of known CAD formats. It also enables importing city data in raster format and geo-referenced foliage information from data in the Global Land Coverage Characteristics (GLCC) while the terrain can be read from DTED files and USGS DEM files. Separate calculations using different propagation models may be specified for portions of the overall area by defining study areas. This organizational tool keeps predictions made with different parameters separate from each other.

The transmitters and receivers with appropriate antennas must be placed on analyzed area to perform propagation calculations. In addition carrier frequency, wireless air interface and for the urban and indoor scenarios electromagnetic material properties must be defined. A different material or reflection and transmission coefficients can be assigned to each building or each building face.

Wireless InSite provides several different environment specific ray-based propagation models. These models all combine ray-tracing algorithms with the Uniform Theory of

Diffraction (UTD). In addition to the ray-based methods empirical models are applied (Free Space model, Hata model and COST-Hata model) and models based on the Finite-Difference Time-Domain (FDTD) are also available.

Wireless InSite performs analyses such as point-to-multipoint analyses (received power, path loss, time of arrival, direction of arrival, impulse response, SNR, and delay spread), point-to-point analyses (direction-of-arrival and impulse response), communication analysis (the output from the calculation can be further analyzed to produce bit-error rate information), interference analysis (C/I, C/I+N, and strongest base to receiver). Results are stored in standard ASCII files and can be presented in software's graphical user interface (GUI).

This software tool also enables radio signal propagation calculations in complex indoor environments. Built in editing tool is a bit clumsy and doesn't include tunnel dedicated module. Therefore, it is advisable to import the indoor simulation environment, including complex geometries of tunnels, from other CAD programs and use built in tool only for minor adaptations and material type assignment. For indoor and tunnel propagation calculations the full 3D ray tracing model is reasonable choice as it has no restrictions on object shape and considers all ray-optical phenomena.

C. GRASS-RaPlaT

GRASS-RaPlaT [13] is an open-source modular planning tool developed for GRASS, one of the most widespread open source GIS systems with a wide spectrum of already implemented supporting modules [16]. The core modules and libraries are written in the C programming language. For large projects, processing may be automated by using scripting languages. Individual tasks in GRASS are performed by calling separate modules which are grouped according to their functionality. GRASS can be used to analyze imported radio coverage data. By implementing radio coverage models in the form of additional modules radio coverage calculations can also be performed in GRASS.

GRASS-RaPlaT is composed of two basic groups of modules, namely modules for radio coverage calculations and modules for data comparison and for adapting input data to the GRASS data structure. Radio coverage calculation modules are based on statistical and combinatorial models and methods based on ray tracing techniques, which are linked together with a script written in the Python programming language.

Radio coverage calculation, which is the core of the radio coverage software, for the whole cellular network is divided into three steps:

- path loss calculation for isotropic source,
- calculation of radio coverage for a particular type and installation of antenna taking into account its radiation pattern, tilt and azimuth,
- generation of complete coverage data for the whole radio cell network.

The whole procedure is automated by a Python script, which reads the radio network configuration data in tabular form from an input file, and calls individual radio coverage computation modules as necessary. The modularity enables simple upgrade or substitution of existing mathematical modules, module independency from specific network and quick and simple recalculation for an individual segment or chosen geographical region.

III. Simulations and Measurements

In order to analyze path loss along tunnels and corridors of different dimensions and shapes numerous simulations at different frequencies were performed. Simulation results were validated by measurements performed in two different tunnels.

The WinProp simulation tool has been applied for simulation of the path loss propagation in tunnels and underground corridors mainly due to it module dedicated for modeling the tunnel architecture. This important functionality is not included in any of simulation tool.

A. Simulation Setup

The WinProp tool was used for the radio signal attenuation calculation along the tunnel. The procedure consists of three steps:

- building the propagation environment (tunnel),
- insertion of additional objects and database preprocessing and
- radio signal attenuation calculation.

Tunnels are very specific environments from the modeling perspective. Their cross sections, which have significant effect on radio signal propagation along the tunnel, are usually not of regular shape. WinProp simulation tool includes dedicated module for designing the tunnels, corridors and underground stations of arbitrary shapes, dimensions and longitudinal courses called TuMan.

In TuMan module the cross section shape and size for different standard tunnels were designed. Appropriate materials with corresponding electromagnetic parameters were chosen for individual wall. Afterwards the adequate tunnel longitudinal coursers were estimated. For further processing the tunnels with predefined longitudinal and transverse resolution were exported in the format corresponding to the WallMan module.

Exported files containing the main tunnel parameters were opened in the WallMan module as in building database where the number of individual facets and material electromagnetic properties were checked. In addition the tunnels were extended to the appropriate length and additional object according to the simulation scenarios were added. In addition the parameters specific for selected propagation model are set. The latest parameters affect the accuracy of the model as well as duration of simulations. Results of pre-processing were written in a file which was used to calculate the coverage in the PropMan module.

The prepared propagation environment database was imported into PropMan module. In PropMan the computational area was limited, output data folder was set, propagation parameters were chosen (path loss, signal strength, delay spread), transmitter position, antenna type, carrier frequency and transmit power were determined. The selected radio signal propagation prediction model was confirmed and the model parameters were found out.

Path loss calculations along the tunnel were performed by the advance deterministic ray tracing technique integrated in WinProp software. The approach allows detailed study of the environmental influences on the propagation characteristics and variation of several propagation parameters.

The intelligent ray tracing (IRT) simulation approach differs from standard ray tracing approach in finding out all possible ray paths. Approach accelerates standard ray approach by retaining its strengths and eliminating main weaknesses. It starts by single pre-processing of the simulation environment database. Building walls are dividend in the tilts and the junctions in the segments. All the visible connections between tilts, segments and receiver points in the database which are required for ray propagation path discovering, are independent of the transmitter position and are pre-calculated by WallMan module. The accuracy and complexity of calculations dependent on: the segment and tilt size, receiver mesh resolution, the size of the calculated area and on calculating area resolution reduction parameter. Pre-prepared database containing all information about the simulation environment and visibility between individual elements is the input to the PropMan module when using IRT approach. Since only visibility of the first level needs to be computed (transmitter - obstacle), it reduces computation time significantly compared to the standard ray tracing model. Selection of the propagation path does not distinguish from the standard ray tracing, so the accuracy of the models is completely comparable. The number of individual ray interactions with obstacles, the maximum number of considered ray paths at each pixel, maximum ray attenuation and the method for considering the influence of the individual tunnel and obstacle facets must be determined before radio running simulations on predefined area.

WinProp tool has some limitations associated with the environment database accuracy and implemented ray tracing models. The WallMan module uses up to 2 GB of RAM which together with computational time determine the resolution of receiver mesh and the number of the propagation environment elements between which the visibility tests must be performed. The number of elements defines the size of the analyzed environment and the size of the tilts and segments. Because of complexity of the tunnel cross sections and their length the receiver resolution was set to 1 m while the size of tilts and segments was set to 5 m. The influence of the elements size was tested in 300 m long tunnel with size of tilts and segments equal to 2 m and 5 m, respectively. The calculations confirmed negligible differences in computational results.

The accuracy of the radio signal attenuation calculations is affected also by limited number of ray interactions with obstacles. Number of reflections of each ray is limited to six, transmissions to four and diffractions to two. Despite the limited number of interactions the accuracy of built-in ray model at shorter distances is satisfying while at longer distances the accuracy is questionable. In such cases the adequate number of considered ray paths per pixel (20), maximum ray attenuation (200 dB) and the difference between the strongest and weakest ray at each pixel (100 dB) must be set.

Simulation tool with some simplifications of the environment database and limited ray model with properly configured model parameters is sufficiently accurate for radio signal propagation prediction in tunnels and underground corridors.

B. Simulation Scenarios

Radio signal propagation simulations were performed for straight tunnels with different cross sectional shapes and dimensions. First group of simulations contains analyses of the radio signal propagation in the tunnels with small cross sections. The second set of simulations was carried out in tunnels with the cross sections corresponding to the typical two lane road tunnels.

1) Tunnels with Small Cross Sections

The impact of the cross section shapes at the small tunnels on radio signal propagation was checked in three tunnels with different cross sections. The basic oval shaped tunnel is shown on Fig. 1 b. Its height and roadway width corresponds to the transverse dimensions of the old railway tunnel where reference signal strength measurements were taken [17]. In Fig. 1 a and 1 c the tunnel with square cross section and real cross section of old railway tunnel are shown, respectively. The tunnel lengths were set to 2000 m in order to analyze radio signal propagation in long tunnels and to verify the four-slope path loss model.

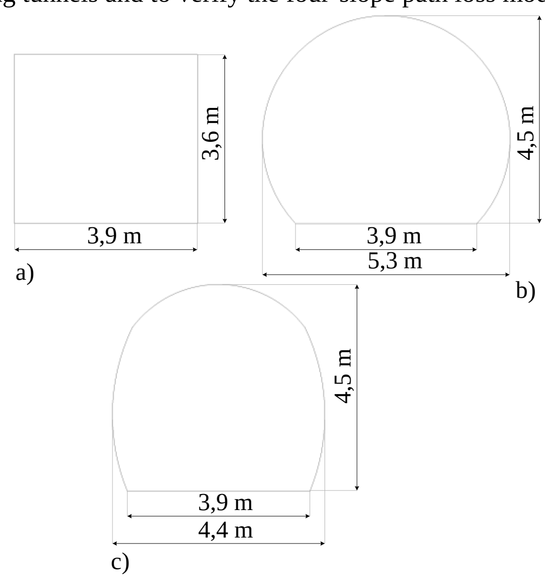

Fig. 1: Cross sections for small tunnels: a) rectangular, b) oval, c) old railway cross section

The results accuracy also depends on the electrical properties of materials. The tunnel walls and ceiling are of stone while the floor is asphalted. Newer tunnels are made of concrete. Therefore, the conductivity was set to σ=0.016 S/m and the relative permittivity to ε_r=7.

Transmitter with the 30 dBm transmit power and isotropic antenna was placed in the middle of the tunnel (1.95 m from the edge of the floor tunnel) 10 m from the tunnel entrance at 1.5 m height. Radio signal strength was calculated over the entire surface of the tunnel, 1.5 m above the ground with 1 m resolution. Since the small width of tunnel the radio signal attenuation was analyzed only along tunnel center line. The signal path loss was calculated for a set of carrier frequencies applied in mobile communication systems, namely 400 MHz, 900 MHz, 2400 MHz and 3500 MHz and for tunnel cross sections illustrated in Fig. 1.

The tunnels and corridors are usually occupied by vehicles, especially in emergency communications. The obstacles greatly influence the radio signal propagation and the communication range. The 250 m long, 2.5 m width and 2.8 m height metal obstacle (indicating train) at the distance of 240 m from the transmitter was placed in the tunnel shown on Fig. 1 c to model such a real situation. Relative permittivity of metal obstacle was set to ε_r=1 and the conductivity to σ=2222 S/m. The impact of the obstacle was analyzed for 400 MHz frequency band.

2) Tunnels with Large Cross Sections

Radio wave propagation was analyzed also for tunnels whose cross section shapes and sizes correspond to the typical road tunnels with two traffic lanes. Three different cross sectional tunnel shapes were modeled (Fig. 2). Tunnel lengths were set to 2000 m.

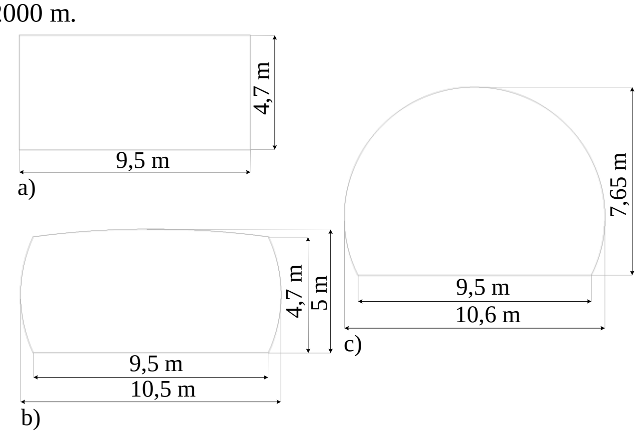

Fig. 2: Cross sections for large tunnels: a) rectangular, b) Karavanke cross section, c) oval

Traffic lanes and tunnel walls are usually constructed of reinforced concrete. Thus, the conductivity and relative permittivity were set to σ=0.016 S/m and ε_r=7, respectively.

Simulations were carried out for four frequencies (400 MHz, 900 MHz, 2400 MHz and 3500 MHz). Transmitter with isotropic antenna and transmit power of 30 dBm was placed 1.5 m above the ground and 10 m from the tunnel entrance. Signal strength calculations over the whole tunnel surface at 1.5 m height and 1 m resolution. Tunnel width enabled analyzing scenarios with different transmitter and receiver positions (next to the wall or in the middle of the tunnel).

Radio signal propagation in the road tunnel is affected by different vehicles. To analyze influence of vehicles the emergency situation illustrating traffic accident is simulated for tunnel depicted in Fig. 2 b. Two obstacles illustrating traffic accident were placed at the distance of 600 m from the tunnel entrance. Stopped vehicles on both traffic lanes were demonstrated by 16 m long, 2.5 m width and 3 m height blocks separated by 15 m. The first row of stopped vehicles extends from the tunnel entrance to 560 m and the second on the opposite lane from 610 m to 1500 m from the tunnel entrance. Relative permittivity and conductivity of the obstacle were set to ε_r=1 to σ=2222 S/m, respectively. Transmitter and receivers were installed at the center of the tunnel cross section. Calculations were performed for 400 MHz carrier frequency.

C. *Measurement Scenarios*

The simulations were compared with measurements taken in two different tunnels at different frequencies.

The first set of signal strength measurements was taken in the tunnel originally engineered for railway. The tunnel, which length is 520 m was closed and now it is used by pedestrians and cyclists. The shape and the dimensions of the tunnel are similar to Fig. 1 c. The tunnel, which width is 4.7 m and height is 4.5 m, has an arched cross section. The tunnel walls and ceiling are of stone while the floor is asphalted. It is slightly curved at the entrance and exit and straight in the middle. Small niches are located every 100 m and the illumination is provided by lighting along the topmost line of the ceiling arch.

The second set of measurements was taken in a dual-carriageway road tunnel linking Austria and Slovenia. The tunnel was closed in one direction at that time, while the second lane operated normally. The tube-shaped tunnel cross section is shown in Fig 2 b. It consists of two lanes, each measuring 3.75 m in width, and flanked by a pair of 1 m-wide pavements located at either side. The central part of the tunnel is designated for vehicular traffic. The height of the central part of the tunnel is 4.7 m, and the walls are made of reinforced concrete. The overall length of the tunnel is 7864 m, and consists of bends at the entrance and exit and a straight central part. The emergency breakdown bays for vehicles are located 1060 m apart. Each bay is approximately 25 m long and 3 m wide. On the ceiling large ventilators are mounted at approximately every 1060 m; these may also influence the propagation conditions.

Distance measurements were performed using especially developed device which is designed for counting the turns of a wheel and calculates the distance driven on the basis of radius. Measured distances are periodically relayed over a serial interface, or acquired on demand, and collected with the software for automatic signal strength measurement.

Transmitter was mounted on the tripod placed in the middle of the tunnel at a height of approximately 1.5 m. Receiver was placed on a specially designed handcart equipped with the distance measurement device. It was located 1.5 m above the ground. The measurements were triggered by the distance measurement device.

In tunnel with small cross section measurements at different frequencies were performed (400 MHz, 868 MHz, 2.4 GHz and 3.5 GHz) with three different technologies, namely TETRA, wireless sensors and WiMAX.

IV. Simulation Results and Analyses

The simulation results were processed and graphically presented by Matlab for the purpose of the analyses. Path loss curves were approximated by sectional linear curves. Break points defining individual sections and slopes of distinctive sections were estimated. Results for different frequencies and tunnel shapes were compared to the empirical four-slope path loss model and measurements. In addition, the influences of the tunnel cross section shape and size, carrier frequency, and transmitter and receiver positions were investigated.

The impact of the tunnel cross section shape on radio signal propagation was investigated for smaller and larger road tunnels for 400 MHz frequency band. Fig. 4 shows path loss in three different road tunnels. Black linear approximation curve in Fig. 3 clearly shows four different propagation regions separated by three break points. Break point positions and curve slopes of individual linear section coincident quite well with the calculated values by four-slope path loss model. While the attenuation curves are very similar for all three tunnels in the adjacent, near and extreme far region, the attenuation is higher for up to 5 dB in the central part of the rectangular tunnel. High attenuation in central tunnel part is the result of the smaller cross sectional area compared to oval and Karavanke tunnel.

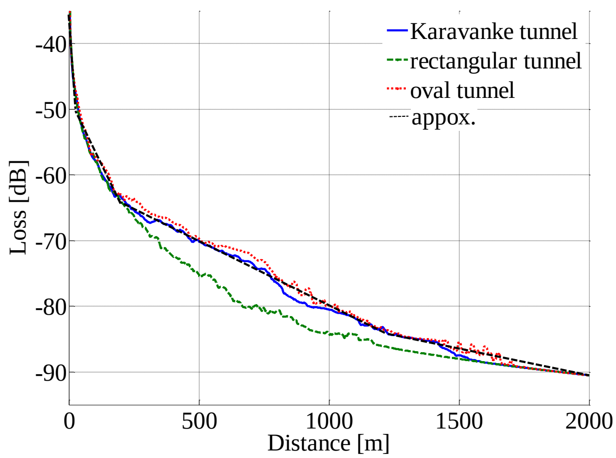

Fig. 3: Radio signal attenuation in different cross sectional shaped road tunnels; f=400 MHz

Tunnel shape has similar impact on radio signal propagation also in tunnels with small cross section dimension. Simulation results showed that the signal is the least attenuated in tunnel shown on Fig. 1 c while the strongest signal attenuation is observed in rectangular tunnel. Reason is again in smaller cross sectional area of rectangular tunnel compared to oval one.

The impact of the tunnel cross section size on radio signal propagation was studied by comparing the path loss calculated in large road tunnels and small cross sectional tunnels. The results are depicted on Fig. 1 at 400 MHz. Fig. 4 shows signal attenuation in oval shaped large and small tunnel. In the adjacent region the curves correspond to free space propagation. In the near region the attenuation in the small tunnel slightly increases. Difference in waveguide region is further increased. Waveguide attenuation curve slope in small tunnel is higher by 100 dB/km. In the last region the difference between curves is reduced, since the signal strength depends mainly on direct ray. Simulation results confirm strongest waveguide effect in tunnels with large cross sections compared to signal wavelength.

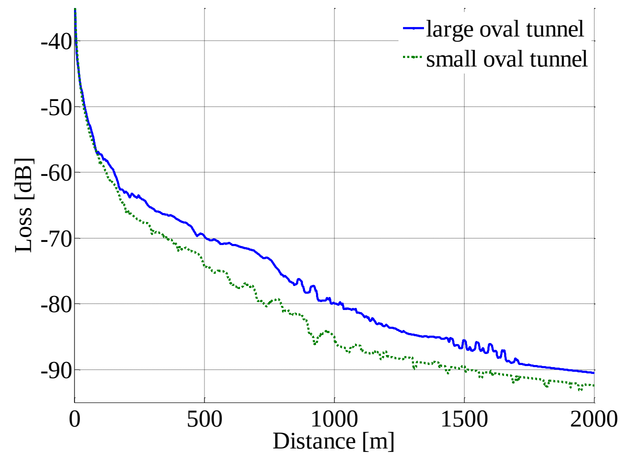

Fig. 4: The impact of cross sectional dimension on radio signal attenuation; f=400 MHz

In previous simulations the transmitter and receiver were placed in the center of the tunnel cross sections. Especially in wider road tunnels the transmitter and receiver transverse position can affect the received signal strength considerably. Simulation results for three different scenarios in tunnel Karavanke are shown in Fig. 5. Path loss curves for different transmitter and receiver positions are very similar. Individual linear sections of the curves differ up to 5.0 dB/km and the positions of the break points are moved only for few meters. The results are also applicable to other analyzed cross section tunnel shapes. Transverse positions of the transmitter and receiver inside the tunnel have negligible influence on radio signal attenuation along the tunnel and on position of the break points.

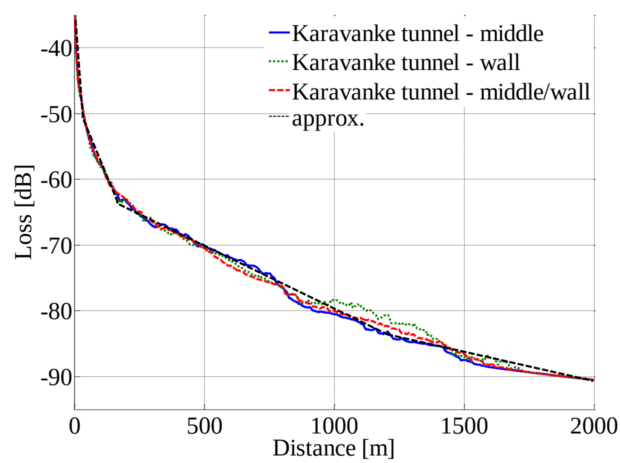

Fig. 5: The transmitter and receiver position influence on radio signal propagation in tunnel; f=400MHz

The slope of the curve in the tunnel waveguide region depends also on signal carrier frequency. The waveguide effect is more expressive with the signal frequency increasing and consecutively, the signal attenuation is decreasing. The statement was verified through simulations. Four series of simulations were performed in large rectangular tunnel. It was found that the strongest attenuation in the waveguide part of the tunnel is at 400 MHz which is approximately 20 dB/km. At higher frequencies the attenuation of the central part of the tunnel is expected to decrease. At 900 MHz is approximately 17.0 dB/km, at 2.4 GHz 13.0 dB/km and at 3.5 GHz only 10.0 dB/km.

Similar waveguide attenuation trend is noticeable also in small tunnel, where the attenuation values are slightly higher (about 10 dB/km). The reason for increased attenuation in waveguide region of the small tunnel is in previously stated influence of the cross section size on waveguide effect. The signal frequency affects also the radio signal propagation in tunnel adjacent and near region. While in the adjacent region the signal attenuation follows free space attenuation which increases with the frequency increasing, higher frequency causes smaller signal attenuation in near region.

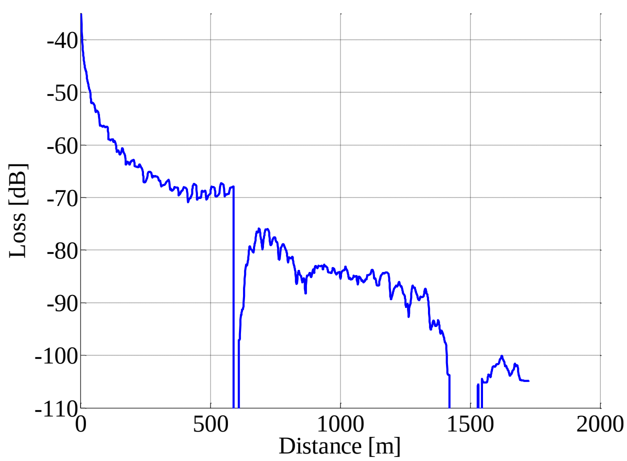

Fig. 6: The obstacle influence on the radio signal propagation in a large tunnel at 400 MHz

Obstacles in the tunnels significantly influence the radio signal propagation. Fig. 6 shows an impact of the obstacles on signal attenuation along the tunnel with large cross section. In the first part the attenuation is similar to the attenuation in empty tunnel. The signal strength slightly increases 200 m before the transverse obstacle. The phenomenon is the result of the constructive interference of the rays reflected from the obstacles. The communication at the place of the transverse obstacle and directly behind it is not possible as the diffracted ray do not reach the receivers. Complete absence of the signal behind the barrier is caused by simulation tools deficient that takes diffraction phenomenon into account very limited. Perpendicular obstacle blocks the propagation of the direct ray. Therefore, the radio signal strength in this part of the tunnel is rather smaller compared to empty tunnel. The absence of the direct ray reduces range of the wireless connection markedly.

The impact of the obstacle illustrating a train in tunnel with small cross section shown on Fig. 1 c was also investigated. Since the obstacle is placed in the middle of the tunnel the signal attenuation is analyzed along the tunnel 1.55 m from the wall. Signal attenuation along the tunnel is depicted in Fig. 7. Path loss attenuation course before the obstacle is similar to the attenuation in empty tunnel. Extremely high attenuation along 250 m long obstacle installed at the distance of 240 m from the transmitter is caused by small distance between tunnel wall and obstacle (about 0.7 m) and the absence of the direct ray. Behind the obstacle the signal attenuation is decreased as the reflected and diffracted rays over the obstacle and rays propagating along both sides of the obstacle constructively contribute to the received signal strength. The absent of the direct ray behind the obstacle affect the attenuation curve slope, which is significantly higher than in the equivalent empty tunnel, and consequently reduce communication range noticeably.

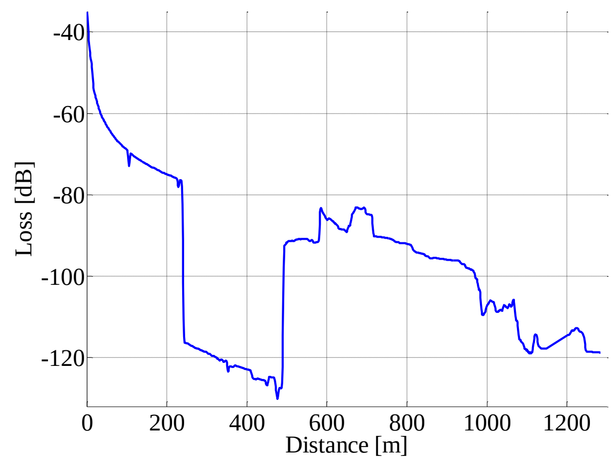

Fig. 7: The obstacle influence on radio signal propagation in small tunnel at 400 MHz

The signal attenuation along the tunnel for different electrical properties of materials was calculated. Relative permittivity ε_r and conductivity σ of the reinforced concrete were varied within reasonable limits (ε_r between 3.5 and 8, σ between 0.015 and 0.2). Results showed that by modifying electrical properties of materials changes the course of the path loss curve only for a few decibels per kilometer (up to 5 dB/km) and cause a much smaller impact than the barriers and traffic in the tunnel.

Based on extensive radio signal propagation simulations in tunnels with various cross sections the influence of different parameters on signal path loss along tunnels were investigated. The individual parameters together with the estimated impact are summarized in Table I.

TABLE I: PARAMETERS INFLUENCE ON RADIO SIGNAL PROPAGATION IN TUNNELS

	The impact on path loss		
Parameters	negligible	noticeable	strong
Tunnel shape	●		
Cross sectional dimension			●
Transmitter/ receiver position	●		
Signal frequency			●
Material properties		●	

Selecting category “negligible” means that the parameter has no evident effect on signal propagation along the tunnel. In the group “noticeable” are placed parameters which can be changed within reasonable limits without the significant impact on signal propagation. Parameters which have to be considered in the analyses of the radio signal propagation in the tunnels are classified in group “strong” and include signal frequency and dimension of the tunnel cross section.

V. Simulation Tool Verification s

In order to test simulation tool, we compare the simulation results, with the results of empirical multi slope channel model and path loss measurements in two different tunnels [17].

Multi-slope models are typical empirical models for radio signal propagation prediction in tunnels [17]-[21]. While standard multi-slope models consist only of two propagation regions with one break point and they are inappropriate for estimation of the communication range [18]-[21], authors in [17] propose a four-slope model with three break points appropriate for long range communications in tunnels.

The four-slope channel model was originally developed for 400 MHz frequency band [17] and its validity for frequencies above 1 GHz must be verified. The model consists of four regions separated by three break points. In the first region propagation follows free space channel model (FSL) [22] which can be applied if the first Fresnel zone is free of obstacles. Thus, first break point is defined as

$$d_0 = \frac{4h_R h_T}{\lambda} \tag{1}$$

where h_R and h_T represent receiver and transmitter height above the road (in meters) and λ is the signal wavelength. In the next region the received signal is composed of several reflected rays. Because of high reflection losses the path loss is modeled as [18]

$$L[\mathrm{dB}] = L_0[\mathrm{dB}] + \alpha(d - d_0) \tag{2}$$

whereat L_0 is attenuation at d_1 and α is the slope of the curve and d is the distance between transmitter and receiver. The second break point representing the end of the near region is calculated from the size of antenna array seen from the receiver point $N(d_1)$ and tunnel width a

$$d_1 = aN(d_1). \tag{3}$$

Second break point denotes the beginning of the far region where waveguide phenomenon is apparent. Waveguide propagation model is given by

$$L[\mathrm{dB}] = L_1[\mathrm{dB}] + 4.343\lambda^2 \left(\frac{\mathrm{Re}\left\{\frac{\varepsilon_r}{\sqrt{\varepsilon_r - 1}}\right\}}{a^3} + \frac{\mathrm{Re}\left\{\frac{1}{\sqrt{\varepsilon_r - 1}}\right\}}{b^3} \right)(d - d_1) \tag{4}$$

where $L_1[dB]$ is the attenuation at distance d_1, a and b are width and height of the tunnel and ε_r is the relative permittivity. In the furthest region, the effect of waveguide vanishes out, due to attenuation at each reflection and the path loss obeys the free space model. The end of the waveguide region specifies the last break point at 1200 m defined from measurements.

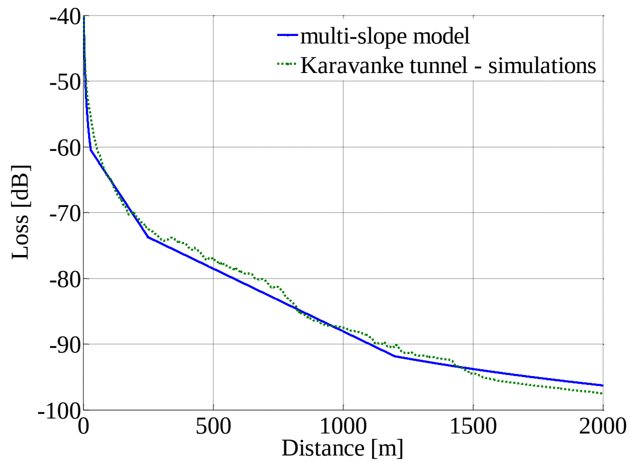

Fig. 8: Comparison of the simulated and multi-slope channel model

In Fig. 8 we compare the simulation results and modeled path loss in the road tunnel using multi-slope model. The complete match is observed, thus we can conclude the simulation tool, provide us with path loss curve, which is close to these obtained by multi-slope model.

Parameters denoted in Table I as “strong” and “noticeable” are considered in mathematical equations defining the multi-slope propagation model which also confirms accordance of the simulation results with the model for radio signal propagation predictions in long arbitrary shaped tunnels.

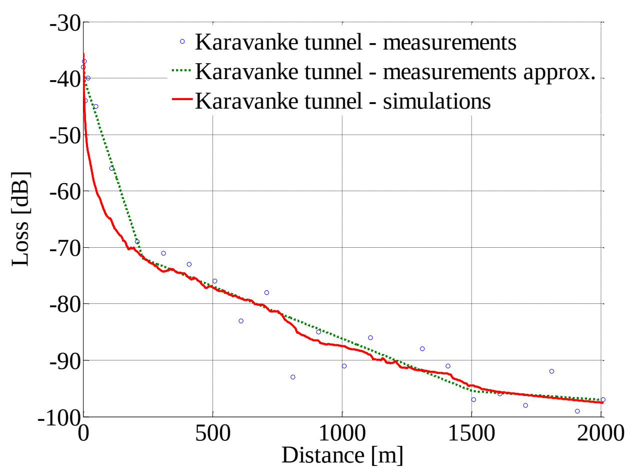

Fig. 9: Comparison of the simulation and measurements; f=400 MHz

Simulation results were compared also to measurements taken in two different tunnels. Fig. 9 shows simulations and measurements taken in Karavanke tunnel at 400 MHz. Certain differences are observed in the near region while in the waveguide part and very far region simulation curve coincidence rather well with measurements. Therefore, measurement results confirm that the simulations are suitable for predicting the path loss in tunnels and determining the communication range.

VI. Conclusion

Path loss analyses play an important role in designing wireless communication systems. Different simulation tools are used to estimate the number of the transmitters and their position, and to calculate the coverage of the radio signal. Several of simulation tools for radio signal propagation calculations and network planning are at disposal. However, only a few are dealing with radio signal propagation in tunnels and underground corridors.

This paper overviews simulation tools for radio signal propagation in tunnels and presents simulation results applying WinProp program. The influence of the cross-section shapes and dimensions of the tunnels, signal carrier frequency, transmitter/receiver positions, material properties and obstacles on path loss along the tunnels were analyzed. Results were evaluated using field measurements in two different tunnels and empirical multi-slope model.

It was shown that simulation tool adequately predict radio signal propagation along different tunnels and underground corridors. Some minor disagreements occur in the transmitter vicinity where simulations do not follow measurement results entirely. Nevertheless, the simulated path loss coincidences with the measurements and the model in the waveguide part and in far region. Therefore, the simulations are accurate enough for radio signal propagation prediction in tunnel and for determining the communication range of the wireless system. Their main drawback sticks in the cost of the simulation tool and in long computational times caused by ray-tracing approach and detailed environment database required for precise calculations.

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