Radio Wave Propagation in Arched Cross Section Tunnels – Simulations and Measurements

Emilie Masson[*1]
[*1] ALSTOM-Transport, Saint-Ouen, France
emilie.masson@inrets.fr

Pierre Combeau[*2], Marion Berbineau[*3], Rodolphe Vauzelle[*2], Yannis Pousset[*2]
[*2] Xlim UMR CNRS 6172, SIC department (Signal Image Communication), Chasseneuil-du-Poitou, France
[*3] INRETS French National Institute for Transport and Safety Research, Villeneuve d'Ascq, France
combeau@sic.sp2mi.univ-poitiers.fr, marion.berbineau@inrets.fr, {vauzelle, pousset}@sic.sp2mi.univ-poitiers.fr

***Abstract*—For several years, wireless communication systems have been developed for train to infrastructure communication needs related to railway or mass transit applications. The systems should be able to operate in specific environments, such as tunnels. In this context, specific radio planning tools have to be developed to optimize system deployment. Realistic tunnels geometries are generally of rectangular cross section or arch-shaped. Furthermore, they are mostly curved. In order to calculate electromagnetic wave propagation in such tunnels, specific models have to be developed. Several works have dealt with retransmission of GSM or UMTS [1], [2]. Few theoretical or experimental works have focused on 2.4 GHz or 5.8 GHz bands [3]. In this paper, we propose an approach to model radio wave propagation in these frequency bands in straight arch-shaped tunnels using tessellation in multi-facets. The model is based on a Ray Tracing tool using the image method. The work reported in this paper shows the propagation loss variations according to the shape of tunnels. A parametric study on the facets size to model the cross section is conducted. The influence of tunnel dimensions and signal frequency is examined. Finally, some measurement results in a straight arch-shaped tunnel are presented and analyzed in terms of slow and fast fading.**

***Index Terms*—Radio wave propagation, Arch-shaped tunnels, Ray tracing, tessellation, E-field measurements.**

I. Introduction

The need for wireless communication systems is increasing for train to ground or train-to-train communications in the railway or mass transit domains. These systems are developed to satisfy operational needs, such as traffic management, maintenance, information applications and security of passengers and staff. Among these applications we can mention control-command systems and also high data-rate transmissions for multi-media or other operational applications. Several systems are already deployed in the world using free propagation in tunnels in the 2.4 GHz or 5.8 GHz bands (*Urbalis* system for ALSTOM, *Airlink*® system used by SIEMENS). The prediction of radio coverage levels is required to optimize deployment phases and ensure availability and robustness of the links. Generally, minimal field levels are required to guarantee key performance indicators related to safety constraints or QoS requirements. In tunnels, the usual laws of free space propagation are no longer valid and the propagation phenomenon has to be specifically analyzed to develop statistical models which are easy to use to predict radio coverage [4]. Thus, up to now, the case of tunnel areas is generally treated via intensive measurement campaigns. The development of specific models is then very relevant.

In order to describe the radio wave propagation in tunnels, several modeling approaches can be set up. The numerical resolution of Maxwell's equations would be an ideal solution. However, this kind of techniques is not feasible due to the huge computational burden. A more conventional way to solve the problem is given by modal theory. The tunnel is here treated as a hollow waveguide with dielectric boundaries. Unfortunately, analytical expressions of the different constants, such as cut-off frequency and wave impedance, only exist for few canonical types of configuration, e.g. rectangular or circular cross section waveguides [5]. The prediction of radio wave propagation with an adequate accuracy in finite time is given by ray optics solutions. These solutions can be adopted in tunnels because dimensions in tunnels are generally large compared to the considered wavelength (frequency above 1 GHz). Several methods based on the ray-optical modeling approach have been proposed. They use Ray Launching [2], [6], Ray Tracing [7] or combination of each [1]. The classical approach of Ray Tracing techniques cannot be transposed to the case of curved surfaces. Indeed, the image method is not applicable because of the infinite line of images of one source compared to a single point for plane surfaces. For the Ray Launching, the concept of reception sphere is no longer valid for curved surfaces because of the non-conservation of reflection angles [8]. The first conceivable solution is the development of a completely novel model based on ray optics, as in [8], [9]. The second option is to consider the equivalent rectangular cross section tunnel with an equal area. The last solution is to tessellate geometries into multiple planar facets, as proposed in [1], [7], [10] and in this paper.

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The paper focuses on results obtained at 2.4 GHz and 5.8 GHz bands in straight arch-shaped tunnels. The model is based on a Ray Tracing tool using the image method. A method of tessellation in multi-facets of the cross section is used, and obtained results are compared to measurements. The first part of the paper presents the considered method of tessellation. Some results at 1 GHz are presented in order to compare with existing results in the literature. The influence of shape of tunnels is highlighted and a parametric study on the number of facets to model the cross section is realized. Then, a study of the influence of tunnel dimensions and signal frequency is realized, focusing on 2.4 GHz and 5.8 GHz bands. The last part of the paper is dedicated to measurement results obtained in an arch-shaped tunnel. Comparisons between simulations and measurements are realized in terms of slow and fast fading. Finally, conclusions and perspectives of the work are given.

II. Simulation Results

A. Modeling curved shape using facets – influence of numberof facets

A Ray Tracing method [11] combined to the tessellation of the curvature of the tunnel is used. First, the simulation tool is presented as well as the tessellation principle. Then, the simulation configurations are detailed. Finally, a parametric study on the facets size is realized to model the arched section.

Ray Tracing consists of a direct search of geometric paths followed by the waves. It allows us to determine exactly the set of paths from a transmitter to a receiver. This technique is based on the image theory and Snell-Descartes formulas. From these paths, the electric field is computed from Geometrical Optic (GO) laws and Fresnel coefficients. In the case of a curved surface, one source generates an infinite number of images. To solve this problem, we choose to approximate the curved surface by facets. Several problems appear, such as the position of the facets and the optimal size of facets. In [9], a first approach of tessellation of a curved surface is presented in the case of a 2D curvature. A method developed in [1] uses triangular facets to model the curved surface. A hybrid method based on a Ray Launching technique combined with the image theory is tested in some particular configurations of tunnels. Finally in [7], a tool developed for planning and design of wireless systems is presented. It is based on Ray Tracing techniques. Similar results to *Chen & Jeng* [1] are obtained. The use of the tessellation raises the problem of the size of facets to be used to represent a given curvature. A compromise has to be found on the number of facets retained. It has to be sufficient to represent the geometry of the arched section but not too large to stay in the limit of validity of the physical model based on a high frequency approach. None of the mentioned publications details the influence of facets sizes.

Three configurations of simulations of straight tunnels with equivalent cross section area from *Chen & Jeng* [1] are considered, illustrated in Figure 1: tunnel A is a rectangular cross section tunnel, tunnel B represents the intermediate tunnel, an arched cross section tunnel modeled with 3 facets, and tunnel C is an arch-shaped tunnel modeled with n facets. A 1 GHz frequency is considered. The transmitting and receiving antennas are dipoles vertically polarized and placed respectively in (4 , 0 , 4.5) m and (2.1 , y , 1.5) m, where y represents the longitudinal direction of the tunnel and varies from 10 m to 150 m with a step of 1 m. Results for tunnels A and B are rapidly obtained. For tunnel C, a study on the number of facets used to approximate the arched section has to be realized. To guarantee a valid physical model, the high frequency approach requires a size of facets $d >> \lambda$, where λ is the wavelength. We assume that these conditions are respected for $d > 2\lambda$. Given the tunnel dimensions, the conditions on the number of facets n, and the facets size d are as follows:

$$4 \leq n \leq 20 \tag{1a}$$

$$20\,\lambda \geq d \geq 2\,\lambda \tag{1b}$$

All the results presented are given in terms of received power (Pr) in comparison to transmitted power (Pt) depending on distance from transmitter to receiver along the longitudinal tunnel axis. Only the reflection phenomenon is considered in the simulations (10 reflections are considered in simulations). It represents the dominant effect in an empty tunnel: there is no transmission because of the tunnel walls properties (ε = 2.5 F.m^{-1}, σ = 0.05 S.m^{-1}) and no diffraction because of the lack of edge.

All the results presented in the paper are displayed with the same scale in order to facilitate the comparisons between the different curves.

Figure 2 presents the results obtained for tunnel C, depending on the facets size. An important signal level variation can be observed from one configuration to another. The influence of facets size is highlighted here by its impact on the received power. Figure 3 illustrates the results obtained for tunnels A, B and C, considering an arched section approximated by facets with a size of 3 λ, which gives the higher signal level. It is important to note that the higher signal level does not necessarily correspond to the real signal level. We will see later the comparison with measurement results in order to validate, or not, this observation. The results are very closed to those obtained in [1]. A « focusing » effect in terms of energy can be observed for the arched section compared to the rectangular one. This phenomenon is characterized by smaller depth fading and a higher global signal level. The signal level is also compared to the free space case, in Line Of Sight (LOS). This result highlights the guided effect in tunnels, compared to free space.

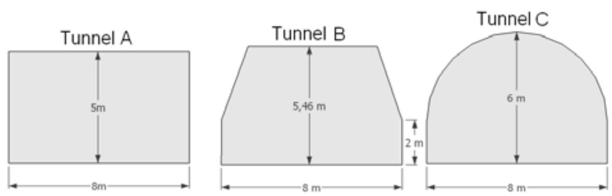


Figure 1: Geometry of tunnels

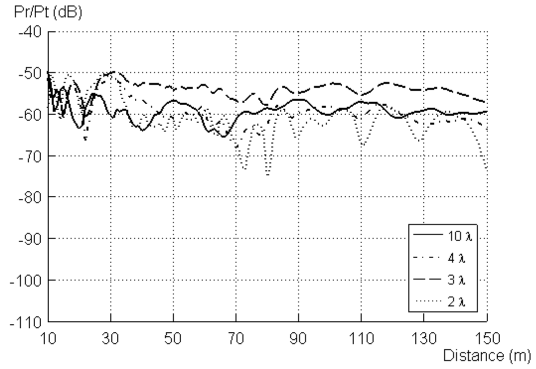


Figure 2: Simulated path loss as a function of the distance for different sizes of the tunnel facets - Tunnel C - 1 GHz

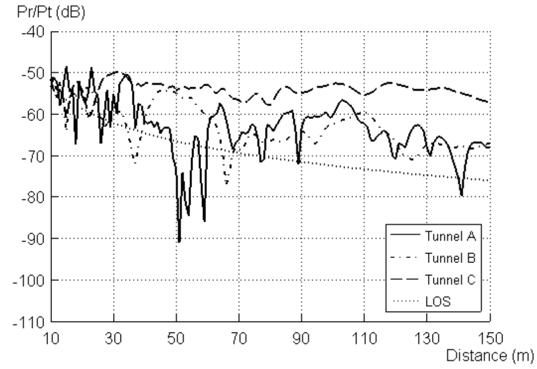
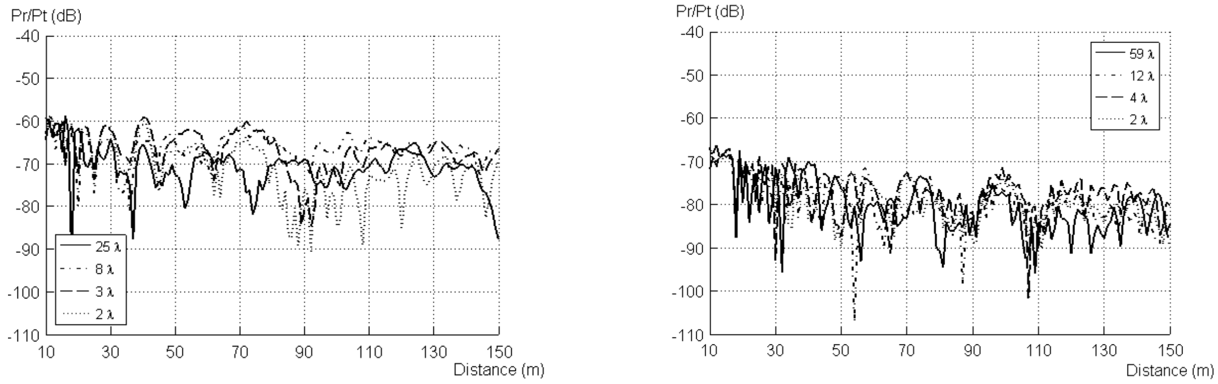
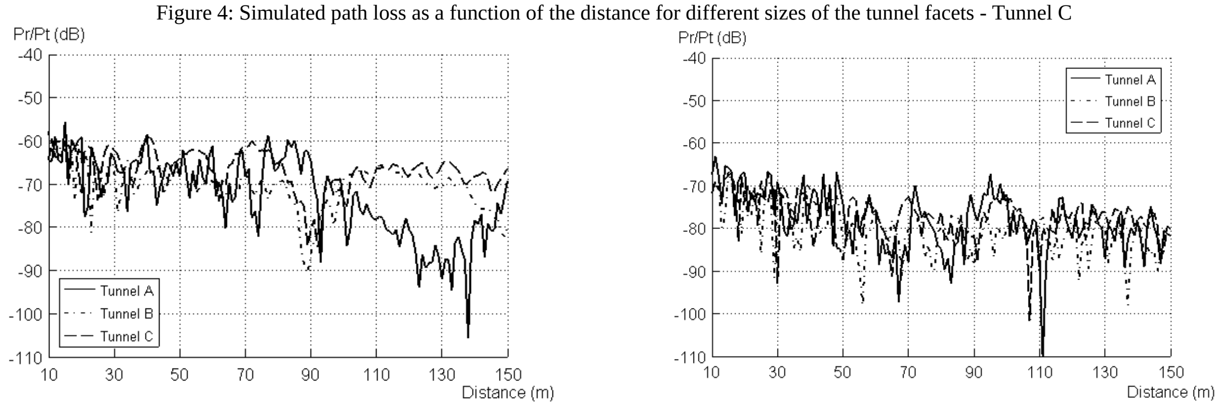


Figure 3: Simulated path loss as a function of the distance - Tunnels A, B C (facets size = 3 λ) - 1 GHz



(a) 2.4 GHz (b) 5.8 GHz

Figure 4: Simulated path loss as a function of the distance for different sizes of the tunnel facets - Tunnel C



(a) 2.4 GHz (facets size = 3 λ) (b) 5.8 GHz (facets size = 4 λ)

Figure 5: Simulated path loss as a function of the distance - Tunnels A, B, C

B. Influence of frequency and tunnel dimensions

1) Frequency influence

In this part, the frequency varies for similar tunnel geometry. High frequency conditions have to be respected. At 2.4 GHz, equation (1) becomes:

$$4 \le n \le 50 \tag{2a}$$

$$25\,\lambda \ge d \ge 2\,\lambda \tag{2b}$$

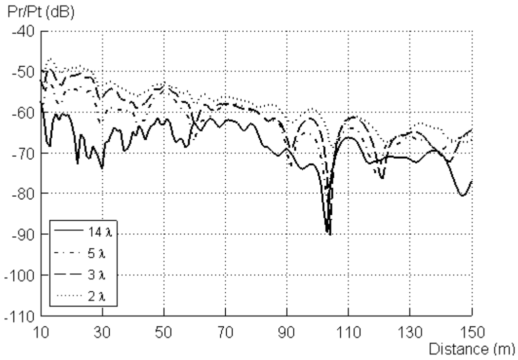
and at 5.8 GHz, this condition becomes:

$$4 \le n \le 120 \tag{3a}$$

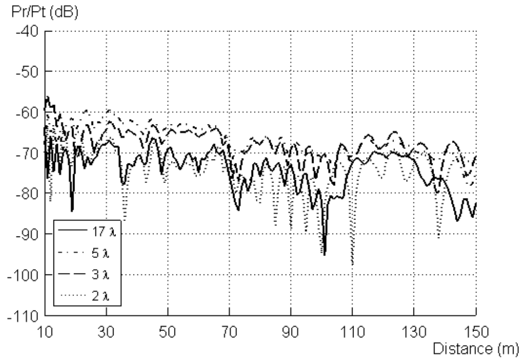
$$59\,\lambda \ge d \ge 2\,\lambda \tag{3b}$$

Figure 4 illustrates simulation results for tunnel C at the two frequencies. Some significant variations can be observed from one result to another. Figure 5 shows the results for the 3 tunnels A, B and C (considering facets size providing the higher signal level), respectively at 2.4 GHz and 5.8 GHz

The « focusing » effect observed at 1 GHz is greatly attenuated at 2.4 GHz and 5.8 GHz. The number of facets and the size of the facets have an important effect on the signal level. It has to be noticed that these conclusions concern tunnels of large dimensions (8 m x 5 m), such as TGV tunnels where GSM-R is deployed, or large motorway tunnels. We will then consider tunnels of smaller dimensions corresponding to mass transit tunnels.

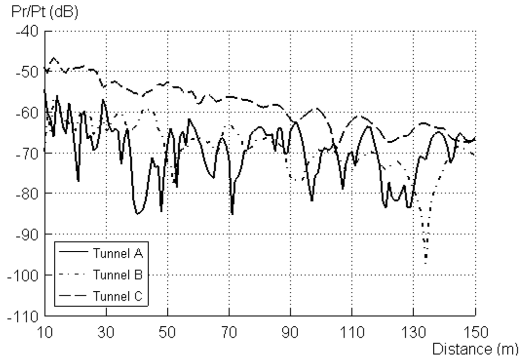


(a) 2.4 GHz

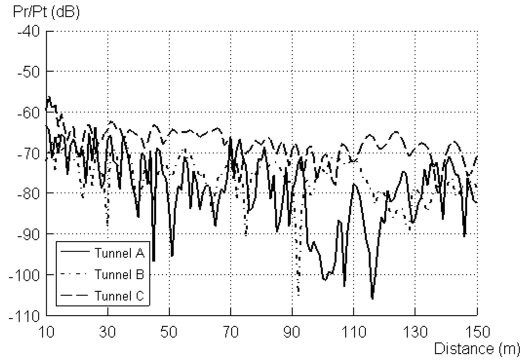


(b) 5.8 GHz

Figure 6: Simulated path loss as a function of the distance for different sizes of the tunnel facets - Tunnel C



(a) 2.4 GHz (facets size = 2 λ)



(b) 5.8 GHz (facets size = 3 λ)

Figure 7: Simulated path loss as a function of the distance - Tunnels A, B, C

2) Influence of Tunnel dimensions

Tunnels with small cross section, such as mass transit tunnels, are considered in this part. Tunnel A represents a square cross section tunnel with a size of 4.5 m, tunnel B is an arched cross section tunnel modeled by 3 facets, and tunnel C is an arch-shaped tunnel modeled by *n* facets.

Simulations are performed at 2.4 GHz and 5.8 GHz. The transmitting and receiving antennas are dipoles vertically polarized and placed respectively in (2.25 , 0 , 3.5) m and (1 , *y* , 1.5) m, *y* varying from 10 m to 150 m with a step of 1 m. High frequency conditions give the following constraints:

at 2.4 GHz:

$$4 \le n \le 28 \tag{4a}$$

$$14\,\lambda \ge d \ge 2\,\lambda \tag{4b}$$

at 5.8 GHz:

$$4 \le n \le 68 \tag{5a}$$

$$17\,\lambda \ge d \ge 2\,\lambda \tag{5b}$$

Figure 6 illustrates results obtained for tunnel C at the two frequencies depending on the facets size. Figure 7 shows the results for tunnels A, B and C (considering facets size providing the higher signal level) to illustrate the effect of section geometry.

Similar conclusions to the previous ones can be made in the case of small tunnels. An important variation is observed on the signal level for different facets sizes. A « focusing » effect for the arched section is also highlighted compared to the rectangular one.

III. Measurement results

A. Trial conditions

Measurements were conducted in the Tunnel of Roux, which is a two-way straight arch-shaped road tunnel located in Ardèche region of France. This tunnel is perfectly straight and has a length of 3.336 km (Figure 8). The transverse section of the tunnel is semicircular and has a diameter of 8.3 m. The maximum height is 5.8 m at the centre of the tunnel. The transmitting part is static. It is composed of a large bandwidth horn antenna (9.2 dBi gain at 2.4 GHz, 10.1 dBi gain at 5.8 GHz), vertically polarized, and connected by a low loss cable (63 dB/100 m at 2.4 GHz, 100 dB/100 m at 5.8 GHz) to a signal generator delivering a sinusoidal signal at the required frequency. The mobile reception system is composed of the same horn antenna, also vertically polarized, and connected by a low loss cable to a THALES VUH-TRC8025 receiver used in an analyzer mode and allowing an acquisition rate of 6 points/sec, which corresponds to one measurement every λ/2 at 2.4 GHz with a speed of 1.4 km/h. The system is installed on a go-kart allowing a very small and regular velocity.

The configuration of the measurements (Figure 9) is as follows. The transmitter is located almost at the center of the section, at a height of 4.8 m. The moving receiver is located in the middle of one of the two tracks, 2.4 m from the sidewall, at a height of 4.1 m. The measurements were conducted at 2.4 GHz and 5.8 GHz.

Figure 8: Tunnel of Roux

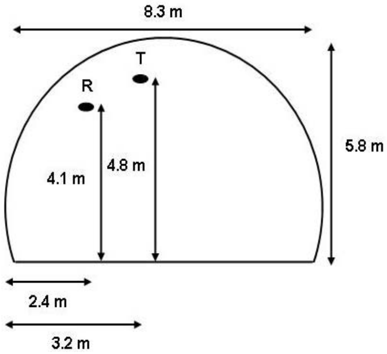
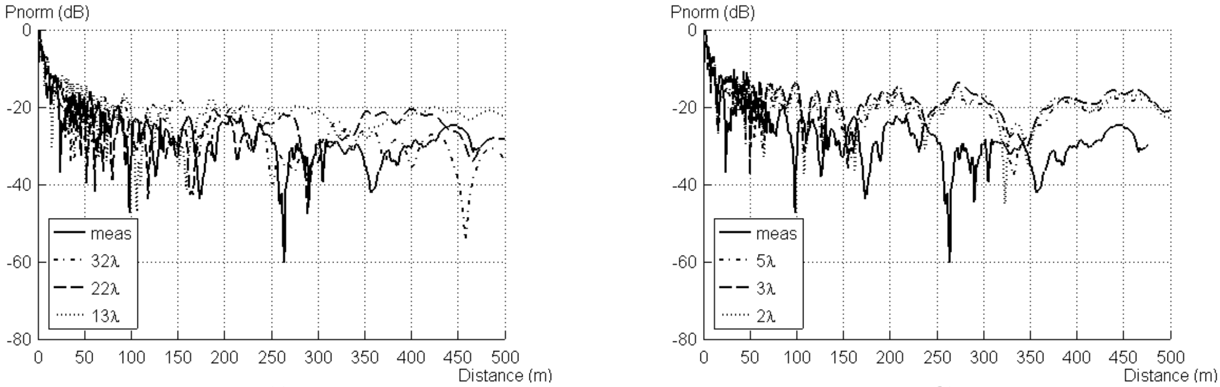
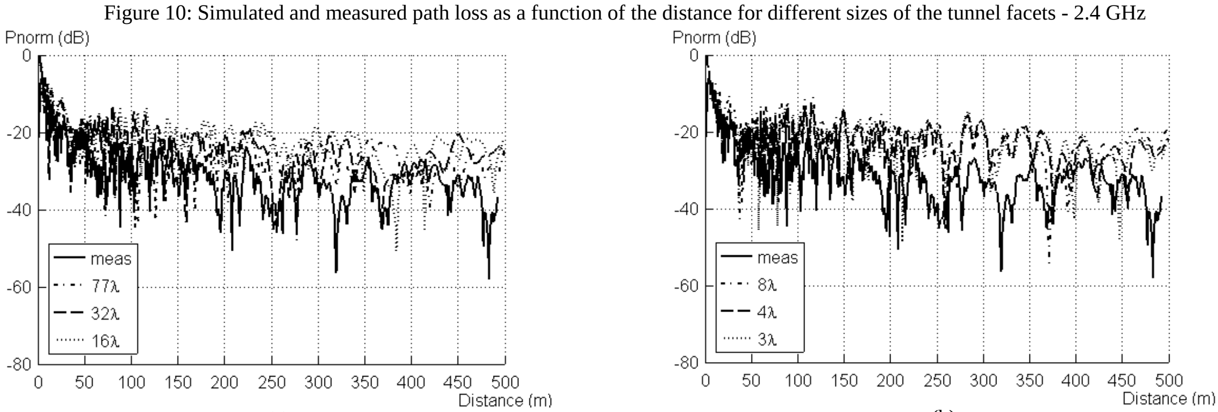


Figure 9: Measurement configurations



(a) (b)

Figure 10: Simulated and measured path loss as a function of the distance for different sizes of the tunnel facets - 2.4 GHz



(a) (b)

Figure 11: Simulated and measured path loss as a function of the distance for different sizes of the tunnel facets - 5.8 GHz

TABLE I.
STANDARD DEVIATION (IN DB) BETWEEN SIMULATIONS AND MEASUREMENTS

(a) 2.4 GHz

Facets size	Standard deviation
32 λ	21.85
22 λ	20.63
13 λ	17.10
5 λ	15.64
3 λ	13.65
2 λ	14.77

(b) 5.8 GHz

Facets size	Standard deviation
77 λ	18.43
32 λ	18.00
16 λ	15.41
8 λ	14.46
4 λ	15.71
3 λ	16.09

B. Statistical analysis of slow fading

All the results presented are normalized by the maximum of the received power along the tunnel in order to cancel the mistakes that could be made on antenna gain and cable loss.

The configurations of measurements were reproduced in simulation using our tessellation approach of the cross section. Once again, to guarantee the validity of the high frequency hypothesis, some conditions have to be satisfied according to the given tunnel dimensions:
at 2.4 GHz:

$$4 \le n \le 66 \tag{6a}$$

$$32\,\lambda \ge d \ge 2\,\lambda \tag{6b}$$

at 5.8 GHz:

$$4 \le n \le 160 \tag{7a}$$

$$77\,\lambda \ge d \ge 2\,\lambda \tag{7b}$$

Figures 10 and 11 illustrate the simulated received power for different facets sizes compared to the measured power at 2.4 GHz and 5.8 GHz.

To be free of fast fading variations, we smooth the received signal by using a running mean. The window's length is 40λ, on the first 50 meters, and 100λ for the rest [13]. Then for each simulation, i.e. for each tessellation, the standard deviation is calculated between the measured and simulated mean powers. Table I presents the standard deviation for each configuration (each facets size), respectively at 2.4 GHz and 5.8 GHz.

All the results presented lead to different conclusions. First, figures 10 and 11 highlight a convergence of the simulation results while increasing the number of facets. The received signal levels converge to a same level. This can be explained by the fact that for each facet added, additional path are considered in the estimation of the received power. Furthermore, for a large number of facets, multiple paths to the real path are added. This explains the presence of an offset between measurements and simulations. The Ray Tracing combined with the tessellation in multiple planar facets of the arched section overvalue the received signal level. All these analyses are confirmed by the results in Table I. In one hand, large standard deviations are obtained between simulations and measurements in general. In another hand, the standard deviations converge to a given value for a small size of facets (i.e. a large number of facets). At 2.4 GHz, this is observed from a facets size of 5 λ. At 5.8 GHz, we can notice a same behavior from a facets size of 8 λ.

In the following paragraph, we present a statistical analysis of the fast fading on the measured and simulated data in order to know if both measurements and simulations have a similar statistical behavior in terms of fast fading.

C. Statistical analysis of fast fading

The statistical analysis of fast fading is realized on the results obtained at 2.4 GHz. The two previous windows are considered to perform a running mean that is then subtracted from the signal in order to extract its fast variations. A comparison between measured and simulated data is realized. We examine the case of two different facets sizes: 32 λ and 5 λ.

The Cumulative Density Functions (CDF) of the measured and simulated data are calculated. They are both compared to the Rayleigh, Nakagami and Weibull distributions. We used the Kolmogorov-Smirnov test in order to decide which distribution best fits the results. Figures 12 and 13 show the CDF of the simulated data for a facets size of 32 λ and 5 λ respectively compared to the fitted models at 2.4 GHz. Figure 14 illustrates the CDF of the measurement results. The parameters of the theoretical distributions are determined by Maximum Likelihood estimators. Tables II and III contain the Kolmogorov-Smirnov (KS) criteria of the different distributions and the estimated values of the parameters of the statistics, respectively.

Figures 12 to 14 highlight a good matching with the Weibull distribution [14], [15], for simulation and measurement results. Table II confirms this observation. The distribution which minimizes the Kolmogorov-Smirnov (KS) criterion is the Weibull distribution.

The results highlight a similar behavior in terms of fast fading statistics for measurements and simulations.

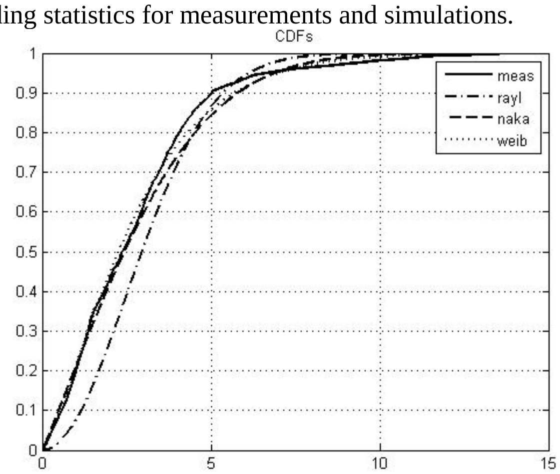


Figure 12: Simulated data (facets size = 32 λ) and fitted distributions

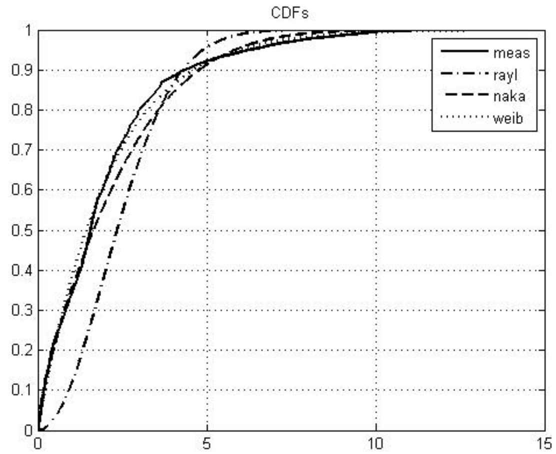


Figure 13: Simulated data (facets size = 5 λ) and fitted distributions

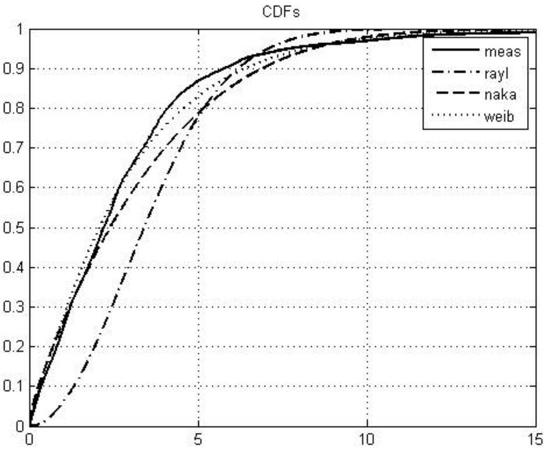


Figure 14: Measured data and fitted distributions

TABLE II.
KS CRITERIA BETWEEN SIGNAL AND FITTED DISTRIBUTIONS

Signal / KS criteria	Meas	Simu 32 λ	Simu 5 λ
Rayleigh	0.2558	0.1813	0.2515
Nakagami	0.0930	0.0599	0.0681
Weibull	0.0426	0.0445	0.0539

TABLE III.
VALUES OF FITTED STATISTIC DISTRIBUTIONS

Signal / Stat values	Meas	Simu 32 λ	Simu 5 λ
σ Rayleigh	2.8894	2.5046	2.0021
m Nakagami	0.3842	0.5189	0.3773
ω Nakagami	16.6976	12.5496	8.0187
k Weibull	2.9286	2.3939	2.0592
l Weibull	1.0661	1.2938	1.0332

IV. CONCLUSIONS

This paper illustrates a method to model the radio wave propagation in tunnels. The results obtained using a Ray Tracing process combined with a tessellation of a straight arch-shaped tunnel are presented. The influence of signal frequency and tunnel dimensions is analyzed. Finally, some measurements were performed in real conditions in a road tunnel.

We realized the study on three configurations of straight tunnels, at 1 GHz, 2.4 GHz and 5.8 GHz. A « focusing » effect is observed on the received signal for the arched section compared to the rectangular section, even if this phenomenon is less marked at higher frequencies. An important variation on signal level can be observed for different facets length, whatever the tunnel dimensions are.

The simulations with the tessellation approach were then compared to measurements performed in an arch-shaped straight road tunnel. An analysis on slow fading and fast fading is made on the results. We observed that the results obtained with the tessellation approach combined with Ray Tracing techniques overvalue the estimation of the received power. However, the behavior in terms of fast fading statistic is quite similar between measurements and simulations.

The tessellation of the cross section into multiple planar facets was a first approach to model the wave propagation in non-rectangular tunnels. We envisaged as the continuation of this work, to consider another solution, based on Ray Launching techniques associated to real curved surfaces. At the same time, we envisage to compare the presented simulation results with those obtained with exact methods, such as FDTD on small sections, for computation time reasons.

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Emilie Masson was born in Armentières, France, on October 21, 1982. She received the Engineer degree from the Institut Supérieur de l’Electronique et du Numérique, Lille, in 2005.

Currently, she works as a PhD student in ALSTOM-Transport (Saint-Ouen) and she is tutored by the LEOST (Transport Electronics and Signal Processing laboratory) of INRETS (French National Institute for research on Transport and Safety) and the Xlim UMR CNRS 6172 SIC Laboratory of the University of Poitiers. She is working in the field of electromagnetic wave propagation in non-rectangular and curved tunnels for railway and mass transit applications.

Pierre Combeau was born in Angoulême, France, on June 12, 1978. He received the M.S. degree in mobile radiocommunication and image processing and the Ph.D. degree in signal processing and telecommunications from the University of Poitiers, respectively in 2001 and 2004.

Since 2005, he is professor assistant at the University of Poitiers in the department SIC (Signal Image Communications) of the Xlim Laboratory. His fields of expertise include the study of the electromagnetic waves propagation for the SISO and MIMO wireless communication systems.

Marion Berbineau was born in Toulouse, France, on September 18, 1962. She received the Engineer degree in electronics, automatic and metrology from Polytech’Lille (France) and the PhD in electronics from the University of Lille respectively in 1986 and 1989.

She joined INRETS as a full time researcher in telecommunications in 1989. She is currently Research Director and Director of the LEOST laboratory.

Dr Berbineau field of expertise are EM propagation, channel characterization and modeling for transport environments, signal processing for wireless communication systems, MIMO systems. She is involved in several national and European projects. She is author and co-author of several publications and patents. Dr Berbineau is an IEEE member, affiliated to the VTS society.

Rodolphe Vauzelle was born in France, in 1968. He received the PhD degree in 1994 from the Poitiers University. Since 2005, he is a professor in the Electrical Engineering department of Poitiers University. He develops his research activities in the SIC –Signal Image Communication- group of the XLIM institute (UMR CNRS 6172).

Dr Vauzelle field of expertise is the optimization of radio links for wireless network in complex environment: multi-path wave propagation, MIMO channel modeling and characterization, digital communication, ad’hoc network. He coordinates a team on this thematic. He is the author and co-author of an hundred of publications and he contributes to several collaborative research projects

Yannis Pousset received the PhD degree in mobile radiocommunication from the University of Poitiers, in 1998.

Since 2000, he is professor assistant at the University of Poitiers in the department of electrical engineering. He develops its research activities in the SIC-XLIM (Signal Image and Communication) laboratory of the University of Poitiers. His research interests include the study of the electromagnetic waves propagation for the SISO and MIMO wireless communication systems.