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1 Ray Launching Modeling in Curved Tunnels 2 with Rectangular or Non Rectangular Section

3 Émilie Masson, Pierre Combeau, Yann Cocheril,
4 Lilian Aveneau, Marion Berbineau and Rodolphe Vauzelle

5 Additional information is available at the end of the chapter

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7 1. Introduction

8 Since several years, digital wireless transmissions are experiencing a significant increase
9 with the development of digital TV, satellite communications, mobile phones, internet,
10 wireless local area networks and automation in various domains. The transportation field as
11 a whole is a major actor of these changes. Technologies and systems for wireless
12 communications are increasingly used in the field of guided transport (underground,
13 conventional trains, high speed trains, tramways, *etc.*) to ensure communications between
14 trains and between a train and the infrastructure. These systems answer the key operational
15 needs for safety and comfort, such as control and command of the trains, traffic
16 management, maintenance, security and information for passengers and crew members. We
17 can distinguish two main families of systems: low-data rate reliable transmissions, for traffic
18 control and command, and robust high data rate transmissions, for video surveillance,
19 remote diagnostic or embedded multimedia applications. Consequently, the radio coverage
20 prediction of these wireless systems is mandatory to optimize the deployment of the radio
21 access points in order to ensure the robustness and reliability of radio links and to minimize
22 the antennas positioning phase duration. Indeed, minimum field strengths are generally
23 required to ensure Key Performance Indicators (KPI) related to the requirements of
24 dependability and Quality of Service (QoS).

25 For underground applications, these systems operate in complex environments, such as
26 tunnels, where the usual laws for predicting the propagation in free space are no longer
27 valid. Like the telecommunication operators, railway manufacturers or guided transport
28 operators should invest in planning tools to deploy their radio communication systems.
29 However, to our knowledge, no general model for predicting free propagation in tunnel
30 exists, as easy to use as well known existing models in the world of mobile phones, such as

1 statistical models derived from Okumura-Hata, Cost231, *etc.* The tunnel case is usually
 2 solved with heavy measurement campaigns that are time consuming and costly. Thus, the
 3 development of specific and efficient propagation models for tunnels is very relevant for
 4 railway industry to allow both fast responses to tenders, and quick deployments of their
 5 wireless communication systems in these specific environments. The tunnels can be
 6 rectangular, circular or arch-shaped. In addition, they may be straight or curved, with only
 7 one or two tracks.

8 Several methods to model radio wave propagation in tunnels have been published in the
 9 literature and will be presented in this chapter with their advantages and drawbacks.
 10 Among them, only few works are dedicated to non rectangular cross section and curved
 11 tunnels. Hence, we focus on a new method recently developed. The structure of the chapter
 12 is as follows. Section 2 presents the context of the works and why deployments of wireless
 13 telecommunication systems are needed for transport applications. Existing techniques to
 14 model radio wave propagation in tunnel are presented in section 3 with their respective
 15 advantages and drawbacks. The fourth and fifth sections are respectively devoted to the
 16 design and the evaluation of a propagation prediction model for curved tunnel with a
 17 rectangular or a circular cross section. Finally, section 6 concludes and presents some
 18 perspectives to these works.

19 **2. Wireless telecommunication systems needs for transport applications**

20 The growing of wireless networks including cellular (GSM, GPRS, EDGE, UMTS, *etc.*) saw
 21 the arrival on the market of a number of software tools dedicated to radio systems planning,
 22 for industrial and telecom operators. These tools allow the identification of sites to set up
 23 base stations from the definition of the characteristics of areas to cover, possibly by
 24 imposing the location of some sites (favorite sites). Most of these tools are very heavy to
 25 handle, dedicated to radio engineers, optimized and enriched by in-house phone operators
 26 to take into account the different propagation environments encountered.

27 Like the general public telecommunications world, the widespread use of wireless
 28 communication systems in the field of transport requires the use of software tools for
 29 planning and optimization for the efficient deployment of these systems. Some existing tools
 30 in the world of telecommunications are specifically adapted, for example for the
 31 deployment of GSM-R infrastructures in various European countries. But to our knowledge,
 32 no module specifically dedicated to the metro tunnels is currently sold.

33 Thus, in most cases, the industrials perform measurement campaigns that are time
 34 consuming and costly. These experimentations require free access to the operational sites,
 35 which is a difficult task to achieve:

- 36 • In the case of a line under construction, site access depends on the progress of the
 37 construction that may experiences significant delays. Indeed, the development of a
 38 wireless communication system is the final step of the overall transportation system;

- 1 • In the case of a line already in operation, access to the site has to be done outside the
2 hours of operation of the metro, which leads to very short ranges that occur most often
3 during night.

4 To limit the measurement campaigns, it is necessary that the railway industrials possess
5 planning tools to determine the field strength regardless of the environment encountered:
6 consideration of tunnels with different cross and longitudinal sections and building
7 materials for example. Propagation models must meet the best compromise between
8 accuracy and computation time and have to be simple to use.

9 For outdoor areas, predictive models of the radio coverage are the well-known statistical
10 models, such as free space attenuation, Okumura-Hata model or 2-rays model. These
11 models work well because the deployment is in Line-Of-Sight (LOS) and distances between
12 transmitter and receiver are weak. The measurement campaigns are easy to implement and
13 generally there are few constraints for the positioning of access points that are most often
14 located on existing poles (signaling, lighting, *etc.*).

15 In tunnel areas, the prediction of radio coverage is currently based on intensive use of
16 feedback on measurements and implementation of engineering rules.

17 Configurations of complex tunnels, such as curved tunnels of circular cross section are more
18 frequently encountered in the modern metro lines and it becomes necessary to refine the
19 prediction process of the radio coverage for deployment based on more sophisticated tools,
20 such as the method presented in this chapter.

21 **3. Existing techniques to model radio wave propagation in tunnel**

22 Methods based on simulation and measurement of radio wave propagation in tunnels were
23 presented in the literature. Analyses based on measurements at 900 MHz and 1800 MHz
24 represent the first approach (Hwang et al., 1998), (Zhang & Hwang, 1998a), (Zhang et. al,
25 1998), (Zhang & Hong, 2004), in order to characterize propagation in wide rectangular
26 tunnels. In (Zhang & Hwang, 1998b), (Lienard & Degauque, 1998), statistical characteristics
27 of propagation channel in tunnels are performed from measurement results. However,
28 analyses performed from the measurements presented in these papers are specific to a given
29 shape of tunnel. Radio wave propagation modeling in generic tunnels is thus a major
30 research field.

31 Some authors have proposed methods based on the modal theory to provide all the modes
32 propagating in tunnel. Approximate and exact solutions have been determined for straight
33 rectangular tunnels and straight circular tunnels respectively (Laakman & Steier, 1976),
34 (Emslie et al., 1975), (Mahmoud, 1974), (Dudley & Mahmoud, 2006), (Dudley et al., 2007).
35 The modal theory considers tunnels as oversized waveguides. It provides good results but it
36 is limited to canonical geometries, which are not the main cases according to the generally
37 encountered tunnels.

1 Several papers present results based on an exact resolution of Maxwell's equations using
2 numerical techniques such as integral methods or the resolution of the Vector Parabolic
3 Equation (Chang et al., 2009), (Reutskiy, 2008), (Popov, 2000), (Bernardi et al., 2009). One
4 more time, these kinds of techniques are limited, mostly due to the computational
5 complexity. Indeed, these methods are based on a volume discretization of the propagation
6 environment with a scale that should be smaller than the wavelength. Consequently, the
7 complexity is prohibitive for operational environments.

8 Finally, frequency asymptotic techniques based on the ray concept, being able to handle
9 complex tunnel geometries in a reasonable computation time, seem to be a good solution. A
10 first simple approach based on a 2-rays model was proposed in (Zhang, 2003), (Ahmed et
11 al., 2008). This method suffers from lack of accuracy due to approximations on the number
12 of rays considered in the model. In (Mahmoud, 1974), a model based on a Ray Tracing,
13 based on image method, takes into account multiple reflections, but only for the case of
14 straight rectangular tunnels. In (Mariage et al., 1994), the authors use this method and adds
15 diffraction phenomenon in order to analyze the coupling between indoor and outdoor. In
16 (Agunaou et al., 1998), works are purchased by considering changes of tunnel sections, but
17 still only in straight rectangular tunnels. However, tunnels in real environments, such as
18 metro ones, can have non rectangular cross section. Furthermore, they can be curved. Ray
19 Tracing is no longer valid with curved surfaces since the source image is no more unique.
20 Consequently, only a few studies deal with the case of non-rectangular cross sections and
21 curved tunnels.

22 The first intuitive approach for curved surfaces consists of a tessellation of the curved
23 geometry into multiple planar facets, as proposed in (Chen & Jeng, 1996), (Torres et al.,
24 1999), (Baranowski et al., 1998), (Masson et al., 2010). Unfortunately, the surface curvature is
25 not taken into account in this type of techniques. Furthermore, one of the major drawbacks
26 of this approach is the impossibility to identify an optimal number of facets for a given
27 tunnel cross section and a given frequency (Masson et al., 2010). In (Wang & Yang, 2006), a
28 ray-tube tracing method is used to simulate wave propagating in curved road tunnels. An
29 analytical representation of curved surfaces is proposed. Comparisons with measurement
30 results are performed in straight arch-shaped and curved tunnels. The paper lacks of
31 information. Consequently, we focused on the works presented in (Didascalou et al., 2000),
32 (Didascalou et al., 2001). A Ray Launching combined with a ray-density normalization is
33 presented. The surface curvature is taken into account. Comparisons with measurements are
34 performed respectively in a scaled tunnel (with 20 cm reduced diameter dimension, and
35 then higher frequency at 120 GHz for compensating the former), and in curved subway
36 tunnels at 900 MHz and 1800 MHz. The method provides good results but exhibits two
37 main defaults: the geometric shapes of the tunnels are not all flexible, and the computation
38 time is high due to the large number of rays launched at transmission. To overcome these
39 drawbacks, we developed a method to model the electromagnetic propagation in tunnels
40 with curved geometry, either for the cross section or the main direction. The main
41 advantage of this new method is its best compromise between accuracy and computation
42 time for applications at 5.8 GHz. It is presented in the next section.

1 **4. Design of a propagation prediction model for non rectangular cross** 2 **section and curved tunnels**

3 The aim of the developed method is to model radio wave propagation in non rectangular
4 cross section and curved tunnels. The problem to be solved consists in taking into account
5 the presence of curved surfaces which induces divergence of rays by reflection on surfaces.
6 An adaptation of the Ray Launching technique and a correction on paths trajectories have to
7 be performed.

8 The method consists of three main steps. First step consists of an adaptation of a classical Ray
9 Launching technique for the consideration of curved surfaces. Developments on emission,
10 reception and intersection between rays and curved surfaces are performed. Second step is to
11 correct the received paths trajectories after the Ray Launching step. It consists of a
12 minimization of the paths length, a choice of optimized paths and an adapted algorithm for
13 the Identification of Multiple Rays (IMR). Last step consists in taking into account the
14 divergence of rays for the Electric Field calculation in the presence of curved surfaces.

15 We consider four kinds of tunnel geometry encountered in operational cases, illustrated in
16 Figure 1:

- 17 • the straight rectangular tunnel;
- 18 • the straight circular tunnel;
- 19 • the curved rectangular tunnel;
- 20 • the curved circular tunnel.

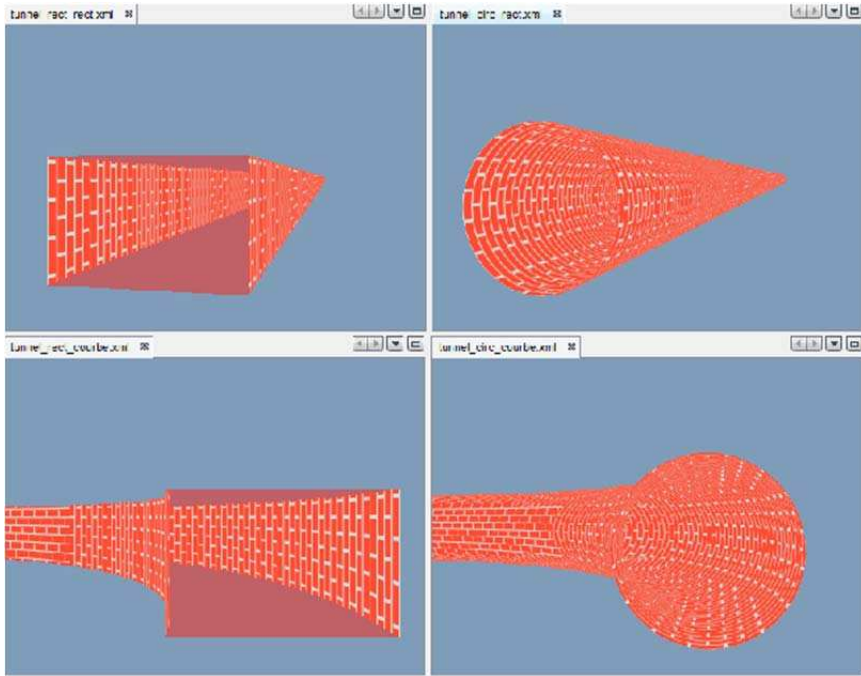
21 For tunnels with circular cross section, a floor and/or a roof can be added in the model of the
22 environment to take into account arch-shaped sections for example. All these configurations
23 lead us to consider three kinds of elementary geometry: The plane for the straight
24 rectangular tunnel and the additional floor/roof, the cylinder for the straight circular tunnel
25 and the walls of the curved rectangular one, and finally the torus according to the curved
26 circular tunnel. All these components are quadrics, which is important for the simplicity of
27 intersection computation with rays.

28 **4.1. Ray launching for curved surfaces**

29 *4.1.1. Emission*

30 Since *no a priori* information on privileged propagation direction is available, we chose to
31 implement a Ray Launching technique based on a uniform distribution of rays radiated
32 from the transmitter. There are different techniques to obtain a uniform distribution.

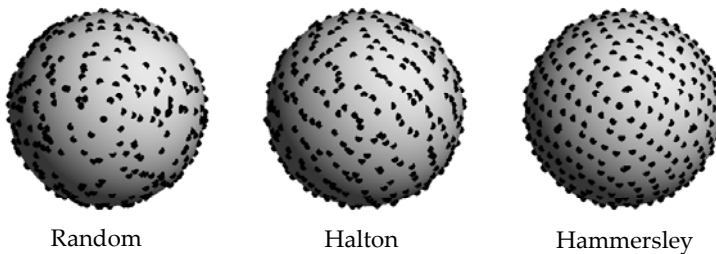
33 We consider a stochastic Monte Carlo method (Didascalou et al., 2000) in order not to skew the
34 results. Instead of using random sequences, the method consists in using quasi-random
35 sequences (Morokoff & Caflisch, 1995) to regularly cover all the space. Indeed, quasi-random
36 sequences allow minimizing the discrepancy, which corresponds to a measure of the gap
37 between a reference situation, generally perfect uniformity, and a given configuration.



1
2 **Figure 1.** Four kinds of treated tunnels

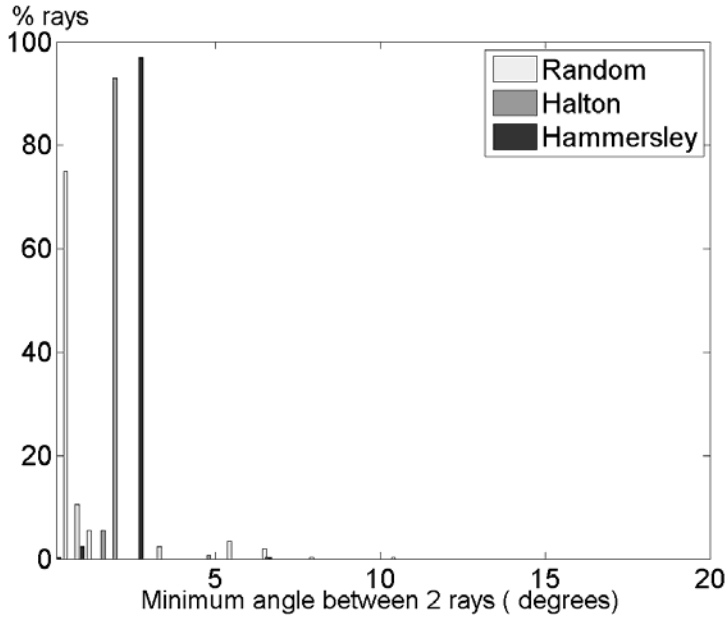
3 Figure 2 illustrates the distribution of 512 rays computed from a random sequence
4 compared to ones obtained from two quasi-random sequences, namely Halton (Halton,
5 1960) and Hammersley (Hammersley, 1964). The Hammersley sequence allows us to obtain
6 the best uniform distribution.

7 In order to prove it, we present in Figure 3 the histogram of the angles between each ray and
8 its nearest neighbor. So, the most uniform sequence is the one which provides the highest
9 peak for a given angle value in its histogram, it will then minimize the discrepancy. It
10 appears again that the best one is the Hammersley sequence. Therefore, we chose to use it to
11 trace the rays radiated from the transmitter.



12
13 **Figure 2.** Comparison of the distribution of 512 rays at transmission between the use of a random
14 sequence and 2 quasi-random sequences: Halton and Hammersley

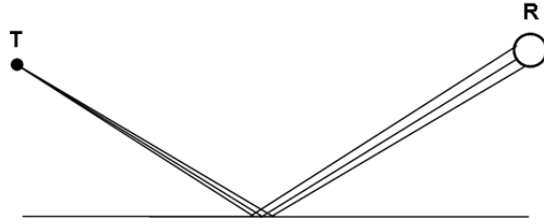
1

2
34 **Figure 3.** Histogram of minimum angles between two rays launched at transmission5 *4.1.2. Reception*

6 The Ray Launching technique requires a reception sphere to determine which rays
 7 contribute to the received power. Indeed, the probability that a given ray meets a receiver
 8 point is always zero. The reception sphere radius, denoted as r_R , depends on the path length
 9 r and the transmission angle γ (Seidl & Rappaport, 1994):

$$10 \quad r_R = \frac{\gamma r}{\sqrt{3}} \quad (1)$$

11 The main drawback of a reception sphere is that it should receive a collection of rays
 12 whereas an only one is predicted by Geometrical Optics. These rays are called multiple rays,
 13 as illustrated in Figure 4. If all of them are added together the result will be an
 14 overestimation of the received power. Thus, it is necessary to discriminate them. This can be
 15 performed with an Identification of Multiple Rays (IMR) algorithm (Iskander & Yun, 2002).
 16 Classical criteria include the number of reflections, the path length and the transmission
 17 angle. In case of curved surfaces, multiple rays are much more scattered and distant from
 18 each other. A specific treatment of the rays and an adapted IMR are so needed and proposed
 19 in section 4.2.



1
2

Figure 4. Illustration of multiple rays by using a reception sphere

3 *4.1.3. Intersection ray/curved surface*

4 We have shown that besides planar surfaces, both cylindrical and toroidal surfaces have to
5 be taken into account in the considered tunnel configurations. These geometrical objects
6 belong to the quadrics family and can thus be easily expressed in an analytical form.

7 In Cartesian coordinates, the equation of a cylinder with the axial direction along the y-axis
8 and centered at the origin is given by:

9
$$x^2 + z^2 = r_c^2 \tag{2}$$

10 with r_c the radius of the cylinder.

11 In a same way, the equation of a torus around the z-axis and centered at the origin is as
12 follows:

13
$$(x^2 + y^2 + z^2 + R_t^2 - r_t^2)^2 - 4R_t^2(x^2 + y^2) = 0 \tag{3}$$

14 with R_t and r_t the radiuses of the torus.

15 The definition of a ray being as follows:

16
$$x = d_x + t \cdot di_x,$$

17
$$y = d_y + t \cdot di_y, \tag{4}$$

18
$$z = d_z + t \cdot di_z$$

19 with (d_x, d_y, d_z) the origin of the ray and (di_x, di_y, di_z) the direction vector of the ray, the
20 intersection of a ray with a cylinder and a torus leads to the resolution of respectively, a
21 quadratic equation and an equation of degree 4.

22 **4.2. Optimized IMR and final choice of corrected rays**

23 The section 4.1.2 has shown that using a reception sphere leads to take multiple rays into
24 account. The multiple rays are determined by classical IMR algorithms based on similarity
25 criterion according to geometrical characteristics of the rays. Then, the choice of the retained

1 ray is randomly realized among the identified multiple rays, without any physical
 2 considerations. So, they lead to a bad approximation of the real ray. To enhance this
 3 approach, we propose here to add a correction algorithm of the trajectories of multiple rays
 4 that makes them converge to the correct geometrical one. The ambiguous choice of the ray
 5 for a correct field calculation is thus avoided.

6 4.2.1. Correction algorithm of the paths trajectories

7 The general principle is as follows. Once a ray is launched from the transmitter using the
 8 Hammersley quasi-random sequence, its propagation is recursively computed, by
 9 calculating its intersection with the curved surfaces, until it reaches the reception sphere.
 10 Either it undergoes the fixed maximum number of reflections, or it goes outside the tunnel.
 11 So, a contributive ray (a path), *i.e.* one that has reached the reception sphere, presents some
 12 geometrical approximations since it does not go through the exact receiver position, as it has
 13 been explained in section 4.1.2. Using the Fermat Principle, indicating that the path followed
 14 by a wave between two points is always the shortest one, we propose to reduce the
 15 geometrical approximation involved in each path: The correction algorithm consists, for a
 16 given path, in minimizing its length assuming that it reaches the center of the reception
 17 sphere.

18 While the path length function is not linear, we propose to use the well-known Levenberg-
 19 Marquardt algorithm (Marquardt, 1963). Nevertheless, the algorithm is efficient only if the
 20 starting point (*i.e.* the initial ray) is near the solution. By using the Ray Launching, it can be
 21 assumed that the paths caught by the reception sphere are close to the real paths existing
 22 with a Geometrical Optics meaning, *i.e.* the shortest. Thus the received rays represent a good
 23 initialization of the algorithm. The principle of the Levenberg-Marquardt algorithm consists
 24 in finding the best parameters of a function which minimize the mean square error between
 25 the curve to approximate and its estimation.

26 Applied to propagation in tunnels, the objective becomes a path length minimization. The
 27 criterion to minimize is then the total path length J given by:

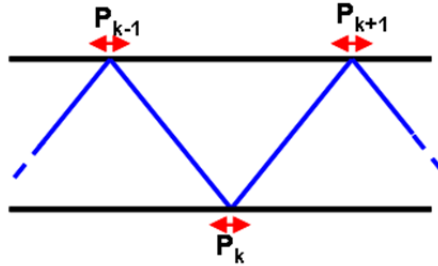
$$28 \quad J = \left\| \overline{EP_1} \right\| + \sum_{k=2}^N \left\| \overline{P_{k-1}P_k} \right\| + \left\| \overline{P_N R} \right\| \quad (5)$$

29 With E the transmitter position, R the receiver position and P_k the k^{th} interaction point
 30 position of the considered path, as illustrated in Figure 5.

31 The vectors defined in (5) depend on the coordinates of the interaction points along the
 32 path. The iterative algorithm requires the inversion of a Hessian matrix which contains the
 33 partial derivatives of the J criterion to minimize with respect to parameters. To keep
 34 computation time and numerical errors reasonable, the matrix dimensions and thus the
 35 number of parameters have to be minimized. Local parametric coordinates (u, v) from the
 36 given curved surface are used instead of global Cartesian coordinates (x, y, z) . The
 37 parameters vector θ can be written as:

1
$$\theta = [u_1 v_1 \dots u_N v_N]$$
 (6)

2 Where (u_k, v_k) correspond to coordinates of the reflection point P_k .

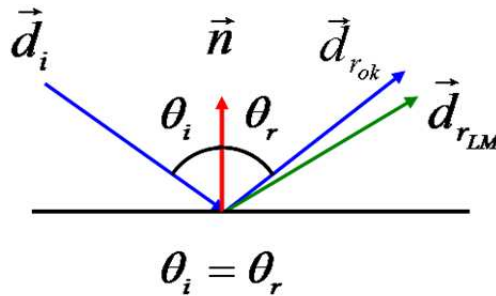


3
4 **Figure 5.** Principle of optimization of paths

5 *4.2.2. Validation of corrected trajectories*

6 Since the Levenberg-Marquardt algorithm is a numerical method, its convergence cannot be
7 guaranteed. So, we have to proceed to a validation test on the corrected paths, which can be
8 incoherent in the case of an algorithm divergence.

9 This test consists in checking if the Geometrical Optics laws are respected, specifically the
10 Snell-Descartes ones. For each reflection point, we verify if the angle of reflection θ equals
11 the angle of incidence θ_i , as illustrated in Figure 6. If not, the path is discarded. For instance
12 an unphysical path \vec{d}_{rLM} computed by the Levenberg-Marquardt algorithm different from
13 \vec{d}_{rok} (by considering $\theta = \theta_i$) is shown in figure 6. The path \vec{d}_{rLM} is thus eliminated.



14
15 **Figure 6.** Validation criterion of corrected paths

16 *4.2.3. Final choice of the correct ray*

17 Section 4.1.2 indicates that the Ray Launching algorithm leads to the existence of multiple
18 rays corresponding to the same contribution according to Geometrical Optics. They must be
19 identified and only one ray has to be kept. However, the correction technique previously

1 presented allows obtaining multiple rays very close to the real path, and consequently very
 2 close to each other. Nevertheless, due to numerical errors, they cannot be strictly equal to
 3 each other. Thus, the choice of the final ray can be done on the base of the reflection points
 4 localization: If the reflection points of two candidate paths are at a given maximal inter-
 5 distance, the paths are considered to be equal and one of the two is removed, it does not
 6 matter which.

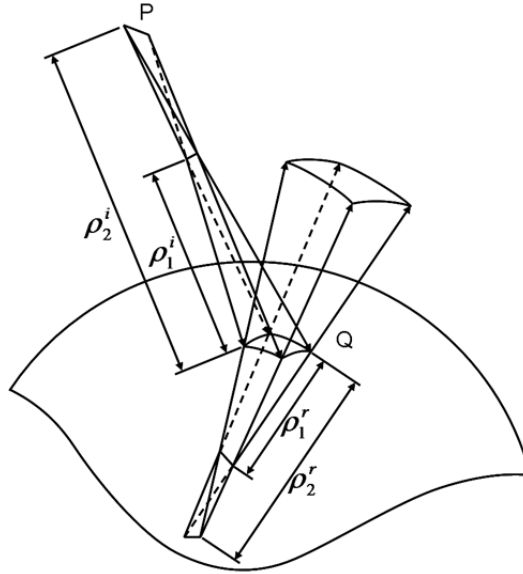
7 4.3. Electric field calculation

8 In the case of a curved surface, Electric Field can be computed after reflection by classical
 9 methods of Geometrical Optics as long as the curvature radiuses of surfaces are large
 10 compared to the wavelength (Balanis, 1989).

11 It can be expressed as follows (Figure 7):

$$12 \quad \overline{E}^r(P) = \sqrt{\frac{\rho_1^r \rho_2^r}{(\rho_1^r + r)(\rho_2^r + r)}} e^{-jk r} \overline{\overline{R E}}^i(Q) \quad (7)$$

13 With ρ_1^r and ρ_2^r the curvature radiuses of the reflected ray, r the distance between the
 14 considered point P and the reflection point Q , $k=2\pi/\lambda$ with λ the wavelength, and R the
 15 matrix of dyadic reflection coefficients.



16
 17 **Figure 7.** Reflection on a curved surface

18 Unlike the case of planar surfaces, the curvature radiuses of the reflected ray are different
 19 from those of the incident ray. Indeed, the following relation holds (Balanis, 1989):

$$\frac{1}{\rho_{1,2}^r} = \frac{1}{2} \left(\frac{1}{\rho_1^i} + \frac{1}{\rho_2^i} \right) + \frac{1}{f_{1,2}} \quad (8)$$

2 With ρ_1^i and ρ_2^i the curvature radiuses of the incident ray and $f_{1,2}$ a function depending on
3 ρ_1^i , ρ_2^i and the curvature radiuses $R_{1,2}$ of the curved surface (Balanis, 1989).

4 **5. Performance analysis in curved tunnels**

5 This section is dedicated to the performance analysis of the method presented in section 4 in
6 tunnels presenting non rectangular cross section and/or curved longitudinal section. This
7 evaluation is performed from measurement results obtained in real tunnel environments.
8 Performances are evaluated in narrow band by using a comparison of received narrow band
9 powers. First part of the section is dedicated to analyses in a straight arch-shaped tunnel.
10 Second and third parts of the section focus on rectangular and circular curved tunnels.

11 **5.1. Performance analysis in a straight arch-shaped tunnel**

12 *5.1.1. Configuration*

13 Measurements were first performed in a straight arch-shaped tunnel, the tunnel of Roux. It
14 consists of a two-way road tunnel located in Ardèche in France, and is illustrated in Figure
15 8. The straight section has a length of 3325 m. The arch-shaped cross section has a maximal
16 height and width of 5.8 m and 8.3 m respectively.



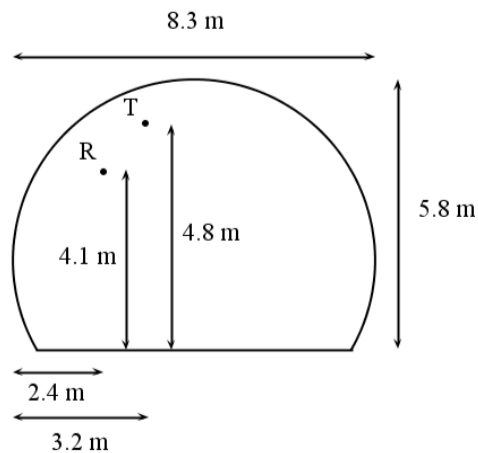
17
18 **Figure 8.** Illustration of the Tunnel of Roux

19 The measurements were performed at 5.8 GHz. The transmitter was located at a fixed
20 position at the center of the section, at a height of 4.8 m. It consists of a horn antenna (10.1
21 dBi gain at 5.8 GHz), vertically polarized. The receiver was moving along the longitudinal
22 axis of the tunnel thanks to a go-kart allowing a very small and regular velocity, compatible
23 with the acquisition rate. It is illustrated in Figure 9. The receiving antenna was vertically

1 polarized and had the same characteristics than the transmitting one. It was located in the
 2 middle of the two tracks, 2.4 m from the sidewall, at a height of 4.1 m. Figure 10 illustrates
 3 the antennas configuration of measurements.



4
 5 **Figure 9.** Go-kart used at reception

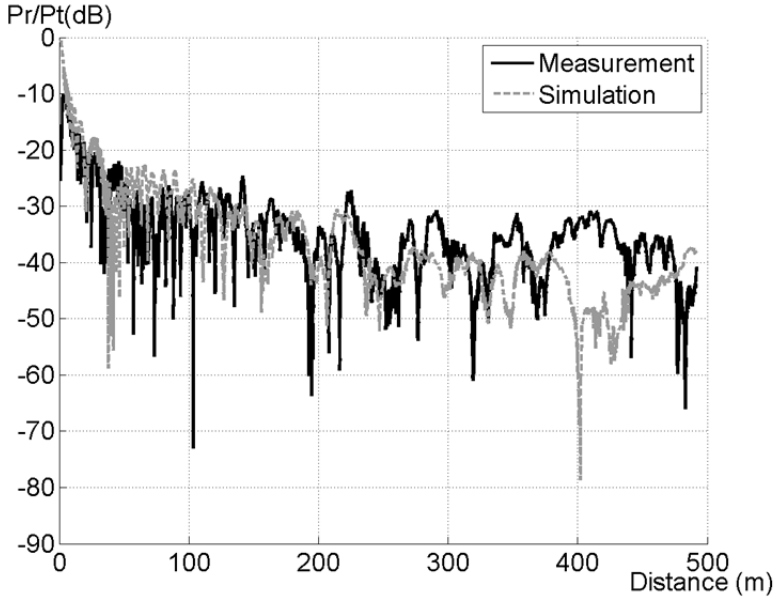


6
 7 **Figure 10.** Antennas configuration of measurements in the Tunnel of Roux

8 5.1.2. Comparison between simulation and measurement loss

9 Figure 11 presents the comparison between measurements and simulations in terms of
 10 normalized received power (P_r) with respect to the transmitted one (P_t), versus the distance
 11 between transmitter and receiver along the longitudinal tunnel axis in the Tunnel of Roux.

1 A quite good concordance between simulations and measurements is highlighted. A
 2 detailed analysis is performed in the following.



3
 4 **Figure 11.** Comparison between measurements and simulations loss in the Tunnel of Roux – 5.8 GHz

5 *5.1.3. Statistical analysis of results*

6 Statistical analysis of slow and fast fading is performed on simulation and measurement
 7 results. The procedure to extract these data is as follows. First step consists in smoothing
 8 signals by using a running mean. The window's length is 40λ on the first 50 m, and 100λ
 9 elsewhere, according to the literature (Lienard & Degauque, 1998).

10 Then, the analysis of slow fading can be performed by the computation of the mean and
 11 standard deviation of the error between measurements and simulations. Results are
 12 illustrated in Table 1. The slow fading analysis highlights a good agreement between results
 13 both for the mean and the standard deviation. Indeed, the values are in the range of 4/6 dB,
 14 which generally, from a practical point of view, illustrates good agreement.

15

	Mean (dB)	Standard deviation (dB)
5.8 GHz	5.35	6.86

16 **Table 1.** Mean and standard deviation (in dB) of the error between simulations and measurements in
 17 the Tunnel of Roux – 5.8 GHz

18 Second step consists of an analysis of fast fading. The data are extracted by the smoothing
 19 procedure as above. The Cumulative Density Functions (CDF) are computed from measured

1 and simulated data and the Kolmogorov-Smirnov (KS) criterion is applied. Comparisons
 2 with theoretical distributions of Rayleigh, Rice, Nakagami and Weibull are performed.
 3 Results are given in Table 2. It appears that the Weibull distribution better minimizes the
 4 KS criterion, for both measurements and simulations. This study is very useful to
 5 reproduce statistically fast fading variations in order to realize studies on system
 6 performance.

	Measurements	Simulations
Rayleigh	0.22	0.24
Rice	0.22	0.24
Nakagami	0.05	0.06
Weibull	0.03	0.02

7 **Table 2.** KS criteria of the simulations and measurements compared to theoretical distributions in the
 8 Tunnel of Roux – 5.8 GHz

9 All the analysis carried out according to measurement and simulation results leads us to a
 10 quite good matching between measurements and simulations in terms of slow and fast
 11 fading. The developed method provides good performances in a straight arch-shaped
 12 tunnel.

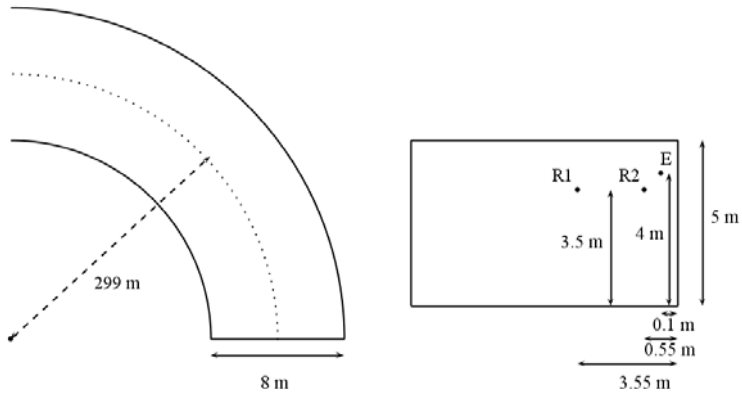
13 Furthermore, it has to be noticed that results presented in this part do not depend on the
 14 location in the tunnel, while the cross section is similar. This kind of results can be found in
 15 literature (Lienard et al., 2007). On the other hand, position of antennas in the cross section
 16 can have a big impact on the received power.

17 **5.2. Performance analysis in curved tunnels**

18 *5.2.1. Curved rectangular tunnel*

19 *5.2.1.1. Configuration*

20 Measurements were performed in a curved rectangular tunnel by an ALSTOM-TIS
 21 team. The measurement procedure is as follows. The transmitter is located on a side near
 22 the tunnel wall. It is connected to the radio modem delivering a signal at the
 23 required frequency. Two receivers, separated by almost 3 m, are placed on the train roof.
 24 They are connected to a radio modem placed in the train. Tools developed by ALSTOM-
 25 TIS allow us to carry out field measurements and to take into account a simple spatial
 26 diversity by keeping the maximum level of the two receivers. Measurements were
 27 performed at 5.8 GHz. The measurements configuration is depicted in Figure 12. The
 28 curved rectangular tunnel has a curvature radius equal to 299 m, a width of 8 m and a
 29 height of 5 m.



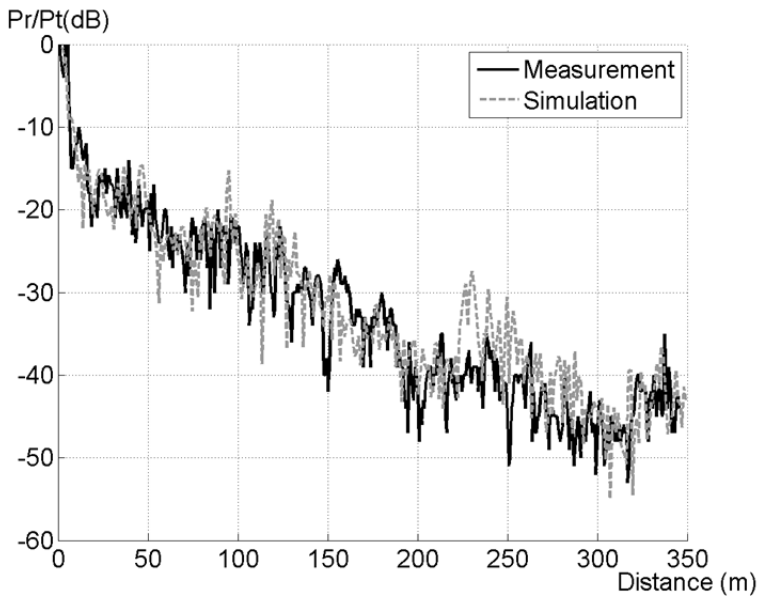
1

2 **Figure 12.** Antennas configuration of measurements in the curved rectangular tunnel

3 *5.2.1.2. Comparison between simulations and measurements*

4 Figure 13 presents the comparison between measurements and simulations in the
 5 configuration of Figure 12, in terms of normalized received power (P_r) with respect to the
 6 transmitted one (P_t), versus the distance between transmitter and receiver along the
 7 longitudinal tunnel axis in the curved rectangular tunnel.

8 One more time, a quite good concordance between simulations and measurements is
 9 highlighted. An analysis is presented below.



10

11 **Figure 13.** Comparison between measurements and simulations in the curved rectangular tunnel – 5.8
 12 GHz

1 5.2.1.3. Statistical analysis of results

2 For these measurements, analysis of fast fading was not possible because of the lake of
 3 measured data (spatial sampling greater than $\lambda/2$). We only present a slow fading analysis,
 4 as it was performed in the section 5.1.3. Mean and standard deviation values of the error
 5 between simulations and measurements are presented in Table 3. It can be observed values
 6 around 2 dB which represents a quite good concordance between measurements and
 7 simulations in the case of the curved rectangular tunnel.
 8

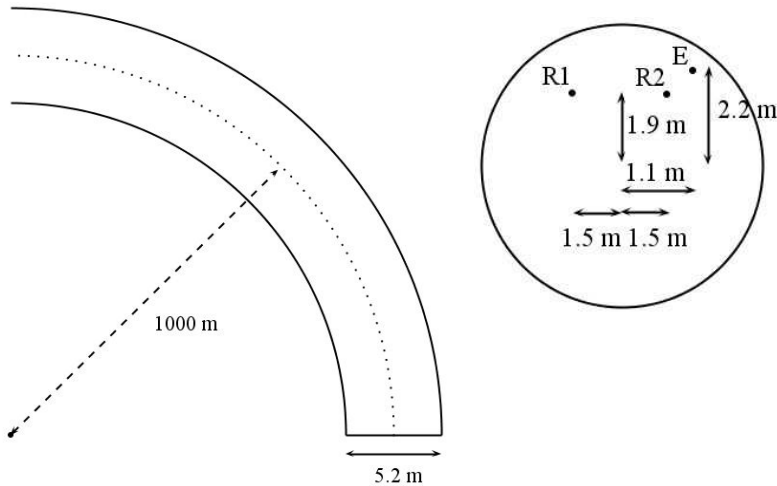
	Mean (dB)	Standard deviation (dB)
5.8 GHz	2.15	2.55

9 **Table 3.** Mean and standard deviation (in dB) of the error between simulations and measurements in
 10 the curved rectangular tunnel – 5.8 GHz

11 5.2.2. Curved circular tunnel

12 5.2.2.1. Configuration

13 Measurements were finally performed in a curved circular tunnel. As for the curved
 14 rectangular tunnel, the measurements were also realized by an ALSTOM-TIS team. The
 15 same measurement procedure was followed. Measurements were performed at 5.8 GHz.
 16 The measurements configuration is depicted in Figure 14. The curved circular tunnel has a
 17 curvature radius equal to 1000 m and a radius of 2.6 m.



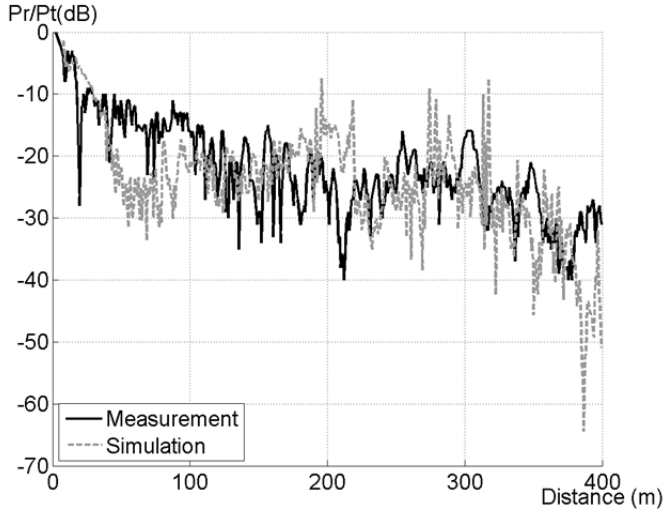
18
 19 **Figure 14.** Antennas configuration of measurements in the curved circular tunnel

20 5.2.2.2. Comparison between simulations and measurements

21 Figure 15 presents the comparison between measurements and simulations in terms of
 22 normalized received power (P_r) with respect to the transmitted one (P_t), versus the distance

1 between transmitter and receiver along the longitudinal tunnel axis in the curved circular
 2 tunnel.

3 It appears a relative good concordance between simulations and measurements. We analyze
 4 these results in the following section.



5
 6 **Figure 15.** Comparison between measurements and simulations in the curved circular tunnel – 5.8 GHz

7 *5.2.2.3. Statistical analysis of results*

8 As for the curved rectangular tunnel, analysis of fast fading was not performed in this case.
 9 Mean and standard deviation values of the error between simulations and measurements
 10 are presented in Table 4. It can be observed values around 6 dB which represents a relative
 11 good concordance between measurements and simulations in the case of the curved
 12 rectangular tunnel. However, some different behaviors can be observed on few areas, such
 13 as between 50 and 100 m or 150 and 200 m. These differences are due to problems that can
 14 remain in the correction algorithm and lead to a bad estimation of the received power.

15

	Mean (dB)	Standard deviation (dB)
5.8 GHz	5.35	6.80

16 **Table 4.** Mean and standard deviation (in dB) of the error between simulations and measurements in
 17 the curved circular tunnel – 5.8 GHz

18 A global remark can be added for the case of curved tunnels (with rectangular or circular
 19 cross section). As for the case of results presented in section 5.1, results are not dependent of
 20 the location in the tunnel while the cross section is similar and also while the curvature
 21 radius is the same. In this case also, position of antennas in the cross section can have a big
 22 impact on the received power.

1 **6. Analysis and discussion**

2 Modeling of radio wave propagation in non rectangular and/or curved tunnels was
3 presented. A first part is dedicated to the presentation of the requirements of wireless
4 telecommunication systems for transport applications. These systems lead to the need for
5 industrial of models to predict radio propagation in particular environments such as
6 tunnels. As presented in details in (Masson, 2010), no such tools are marketed in transport
7 domain and specific tools have to be developed for transport applications in tunnels.

8 Second part presents the methods to model radio wave propagation in tunnels. Three kinds
9 of models are presented. Methods based on the modal theory provide all the modes
10 propagating in tunnel. These methods provide good results but are limited to canonical
11 geometries, such as rectangular and circular straight tunnels. Some papers are based on the
12 exact resolution of Maxwell's equations. These kinds of techniques are also limited due to
13 the computational complexity. Finally, frequency asymptotic methods based on the ray
14 concept leads to the best compromise between accuracy and computation time. However,
15 tunnels in real environments can have non-rectangular cross section and can also be curved.
16 Only a few studies deal with these cases.

17 The developed method is presented in the third part where each step of the method is
18 detailed. This one is based on a Ray Launching technique combined with an optimized IMR
19 technique based on a correction of paths trajectories. It consists in a minimization of the total
20 distance of the considered path in order to make it converge to the real one, existing in
21 Geometrical Optics meaning. The technique is based on the well-known Levenberg-
22 Marquardt algorithm. A validation of computed paths after correction is realized by
23 verifying the angles of incidence and reflection. A new IMR algorithm is also developed
24 leading on comparison of reflection points.

25 Last part is devoted to the evaluation of the method in three different geometries of tunnels:
26 the straight arch-shaped tunnel, the curved rectangular tunnel and the curved circular
27 tunnel. This evaluation is performed from measurements realized in real environments, at
28 5.8 GHz. For the case of the straight arch-shaped tunnel, a slow fading study was realized
29 and lead to a mean and standard deviation between measurements and simulations of about
30 5-6 dB, which represents a quite good agreement between simulations and measurements. A
31 fast fading study was also performed. The data were extracted by a smoothing procedure.
32 The CDF were computed from measured and simulated data and the KS criterion was
33 applied. Comparisons with theoretical distributions of Rayleigh, Rice, Nakagami and
34 Weibull were performed. It appeared that the Weibull distribution better minimizes the KS
35 criterion, for both measurements and simulations. This kind of study is very useful to
36 reproduce statistically fast fading variations in order to realize studies on system
37 performance. For the case of curved rectangular and circular tunnels, similar studies on
38 slow fading were realized and lead to a mean and standard deviation between
39 measurements and simulations of about 3-6 dB, which represents a good agreement of
40 results, validating the method.

1 There exist many perspectives to this work. As it was seen in the previous section, in some
 2 areas, bad estimation of the received power is obtained in the case of a curved circular
 3 tunnel. These errors can be due to imperfection of correction algorithm that could be
 4 improved to obtain reliable results.

5 Right now, the method is able to treat empty tunnels. The following step will consist in
 6 taking into account the presence of trains in the tunnel. The phenomenon of masking train
 7 will also be investigated. In this case, diffraction has to be taken into account in the Ray
 8 Launching technique. The diffraction phenomenon would also allow taking into account
 9 complex geometries such as station, crossing, *etc.*

10 **7. Conclusion**

11 The chapter was dedicated to the radio wave propagation modeling in non rectangular
 12 and/or curved tunnels. It was shown that classical methods (modal theory, rigorous
 13 methods, asymptotic methods) to model propagation in these kinds of tunnels can not be
 14 used. Specific treatments on Ray Launching, based on a correction of paths trajectories, have
 15 to be implemented. They were presented, evaluated and discussed.

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