Characterization of a 5G Wireless Train Backbone via Ray-Tracing

Jorge Elizalde[1], Aitor Arriola[1], Manuel Alfageme[2], Jérôme Härri[3], Igor López[4]
[1]HW and Communication Systems, IKERLAN Technology Research Centre, Basque Research and Technology Alliance (BRTA), Arrasate, Spain, {jelizalde, aarriola}@ikerlan.es
[2]Systems Innovation, COMSA Corporación, Madrid, Spain, manuel.alfageme@comsa.com
[3]Communications Systems Department, EURECOM, Sophia-Antipolis, France, jerome.haerri@eurecom.fr
[4]Technology Division, CAF R&D, Beasain, Spain, igor.lopez@caf.net

***Abstract*—In this work the antenna propagation has been characterized for a 5G Wireless Train Backbone (WLTB). For this purpose, a train model has been generated and ray tracing simulations have been performed with antennas installed on the roof of the train. In order to obtain the most optimal antenna locations, the position of the antennas has been modified in vertical and horizontal directions. Tunnels have also been simulated, changing their material properties to study their effect on the signal propagation. Obtained results have allowed to identify potential locations for the antennas of the WLTB.**

***Index Terms*—antennas, propagation, simulation, 5G, railway**

I. Introduction

Shift2Rail initiative of Horizon 2020 aims at providing novel capabilities for railway industry through research and innovation [1]. One of these capabilities is the use of wireless communications in the Train Control and Monitoring System (TCMS), which has been one of the goals of CONNECTA-2 and Safe4RAIL-2 projects. In these projects, wireless devices based on LTE-V2X technology were developed for a Wireless Train Backbone (WLTB) at 5.9 GHz [2], and the applicability of 5G technology for the WLTB was also studied [3]. Regarding antenna installations for the WLTB, field tests done in CONNECTA-1 project indicated that the location of antennas and their close environment have a huge influence on the performance of the WLTB, as they can increase the multipath or even block the line-of-sight between antennas [4]. Therefore, antenna installation studies are considered of great importance for the correct deployment of the WLTB and are currently being carried out in Safe4RAIL-3 project via ray-tracing simulations [5].

Several works have been done related to ray tracing for either GSM-R Train-to-Ground (T2G) links [6, 7] or Train-to-Train links [8]. However, the wireless link between two antennas installed on the same train has not been simulated so far. The present paper presents these simulation results for antennas of the WLTB located on the roof of the train car. Usually, the roof of the train car has several metallic boxes accommodating multiple auxiliary items that generate a complex propagation environment.

The paper is structured as follows. The simulation model is detailed in Section II, which is a simplified version of a real train. In Section III the simulation results are presented for different antenna positions and tunnel environments with different material properties. Finally, conclusions and future work are presented in Section IV.

II. Simulation Model

To simulate the train, the SBR+ solver of ANSYS HFSS has been used. The model has been built based on the actual CAD file of a train. After importing the model, it has been simplified using surfaces to emulate the external contour of the real train. The model is shown in Fig. 1; it is composed of a train tractor unit with a pantograph, and a train car. On the roof of the train cars there are several metallic boxes to accommodate different items, as the power converters, or the air conditioning system. The model of the train is composed of metallic surfaces. A Perfect Electric Conductor (PEC) boundary has been established for these metallic surfaces.

An arched tunnel model [9] has also been included in the simulation in order to evaluate its effect in the signal transmission. The tunnel section is detailed also in Fig. 1. A Finite Conductivity boundary has been chosen for the tunnel, varying its permittivity and conductivity to study the effect of the material of the tunnel.

In large models, precise electromagnetic simulations can take a long time and lots of computer resources. To overcome this limitation, Shooting and Bouncing Ray tracing techniques (SBR) are used for such electrically large models (>10λ). This method is based on the optical properties of the

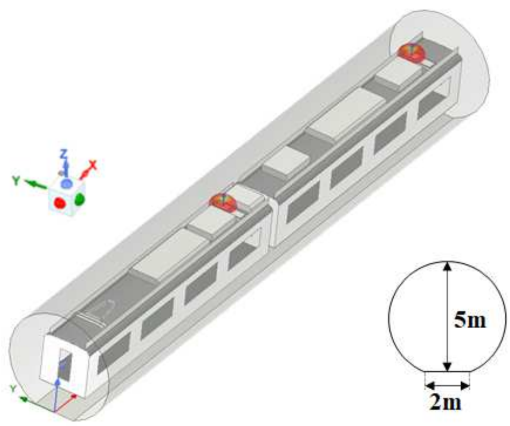

Fig. 1. Train model

high frequency electromagnetic waves. Numerous rays are launched from the selected source, and these rays propagate through the model according to the Geometrical Optics (GO) method, so that they bounce between the model surfaces.

In our model, the selected frequency has been 5.9 GHz, and the model has the following sizes, which are larger than 10λ:

- Length: 30.5 m
- Width: 5.2 m
- Height: 5 m

Quarter-wave monopole antennas at 5.9 GHz have been used in the model. As initial positions for the antennas the locations used for the T2G antennas have been taken, as they will allow a future combination of the T2G and WLTB links using the same antenna. Simulations have been done extending the SBR method, based on the Physical Optics (PO), using Physical Theory of Diffraction (PTD), Uniform Theory of Diffraction (UTD), and enabling Creeping Wave (CW) physics. First, to limit the processing time, the ray density and number of bounces have been optimized for this model. The final parameters used for the simulations have been the following ones:

- Ray density: 4 rays/λ
- Number of allowable bounces: 5

After that, the Z position of the antennas (height over the roof) has been changed, to study the effect of the model in the propagation of the wave. The Y position of the antenna with regards to the width of the train car has been also simulated, to obtain the best position on the roof.

It must be noted that ray-tracing techniques ignore the near-field effects caused by the proximity of metallic objects from the antennas. In the case of this work the reactive near field at 5.9 GHz extends to a distance of 8 mm (λ/2π), and in the different antenna locations that have been evaluated no object has been placed below that distance. Therefore, the near-field effect is not relevant in this case.

III. Simulation Results

In the following subsections the simulation results are shown. S_{21} parameter has been obtained between the two antennas for a bandwidth of 100 MHz centered at 5.9 GHz.

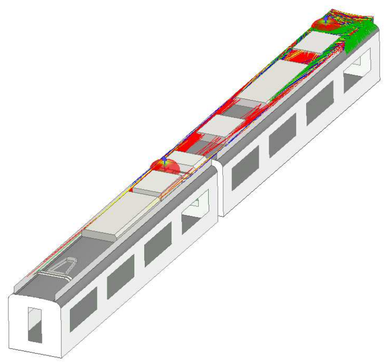

Fig. 3. Ray tracing for Z = 0 m, without tunnel

A. Height variation (Z position)

The effect of the Z position of the antennas on S_{21} parameter is shown in Fig. 2. In order to illustrate the ray tracing solution a graphical example is shown in Fig. 3 for the antenna position at Z = 0 m with no tunnel. The S_{21} peak to peak variation over the bandwidth is also represented in Fig. 4 to obtain a clearer picture to decide the best height to install the antennas. The height for the line-of-sight is indicated in this figure, showing that the variation of S_{21} is minimum for this configuration. In fact, once the antennas are over the boxes (Z > 0.257 m) and there is a direct line-of-sight between them, the obtained result is the expected one according to the free space theory. When the Z position of the antennas is lower than the height of the boxes, there are multiple reflections that affect the performance of the transmission. An optimal position is Z = 0.20m, which provides a low ripple in S_{21} (below 5 dB) and does not require the antennas to stand on top of the rest of the elements in the train roof.

It can also be observed that S_{21} values indicate a maximum path loss value for the wireless link in the range of 65 dB - 75 dB. Considering that the Effective Isotropic

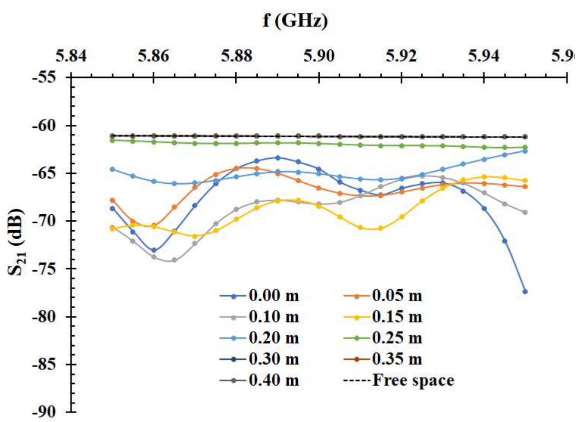

Fig. 2. Impact of Z position on S_{21} over the bandwidth

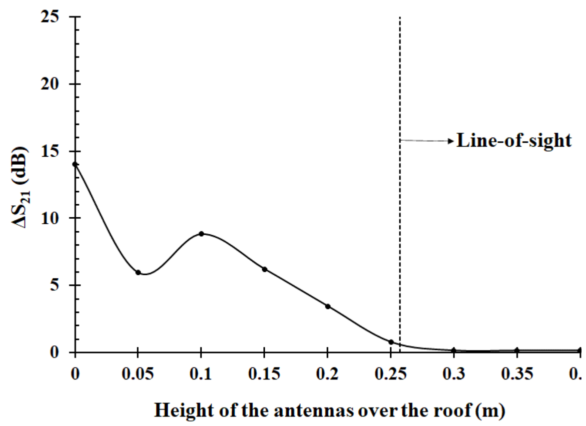

Fig. 4. Impact of Z position on S_{21} variation over the bandwidth

Radiated Power (EIRP) at the 5.9 GHz Intelligent Transportation System (ITS) band is limited to +23 dBm as specified in EN 302 663, and quarter-wave monopoles with a gain of 5.2 dBi are used in simulations, this means that the WLTB radio devices will be able to transmit a maximum power of 17.8 dBm. On the other hand, as detailed in [2] the WLTB radio devices have a sensitivity of -82 dBm. Therefore, the maximum path loss between two radio devices will be 99.8 dB, which is 20 dB higher than the values observed in simulations, indicating that the radio link is correctly covered at the simulated distance.

B. *Width variation (Y position)*

The variation of S_{21} between the actual position of the antenna and the side of the train car is shown in Fig. 5. The S_{21} peak to peak ripple over the bandwidth is also represented in Fig. 6, where the Y position for the line-of-sight is indicated. It can be observed that the position at 0.1m provides the lowest ripple in S_{21}, also providing a path loss value close to free space. It can also be observed that there is a peak in the ripple when antennas get close to the protective metallic fairing located on the train roof, even though there is line of sight between the antennas.

C. *Tunnel*

In this subsection, the effect of the tunnel on the WLTB has been studied. To do that, different tunnel materials have been simulated with different permittivity and conductivity values, as detailed in Table 1. The tunnel configuration has been studied varying the Z position of the antennas at Y = 0 m, and the Y position of the antennas at Z = 0 m. The data related to Z and Y variations are represented in Fig. 7 and Fig. 8, respectively. To summarize all the data, the S_{21} peak to peak ripple over the bandwidth has been represented in these figures.

The effect of the tunnel in the propagation losses changes depending on its material properties. The effect of the tunnel is also different in terms of Z or Y variation. Focusing on Z variation, it can be seen in Fig. 7 that Tunnel #2 and Tunnel #3 affect most to the propagation of the signal, mainly in the

TABLE I. SIMULATED TUNNEL PROPERTIES

Tunnel	Properties	
	Relative permittivity	*Conductivity (S/m)*
#1	1	$1{\cdot}10^{-3}$
#2 [10]	10	$1{\cdot}10^{-9}$
#3	1	1

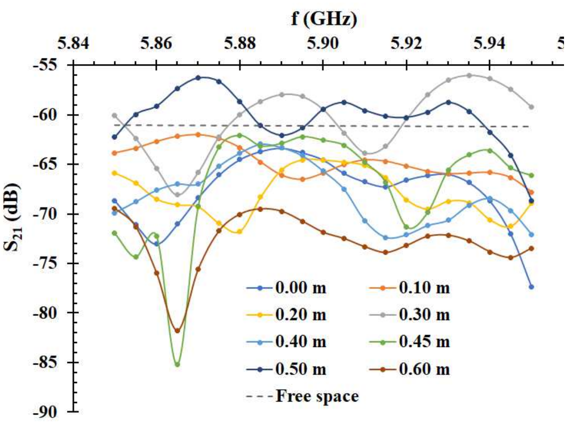

Fig. 5. Impact of Y position on S_{21} over the bandwidth

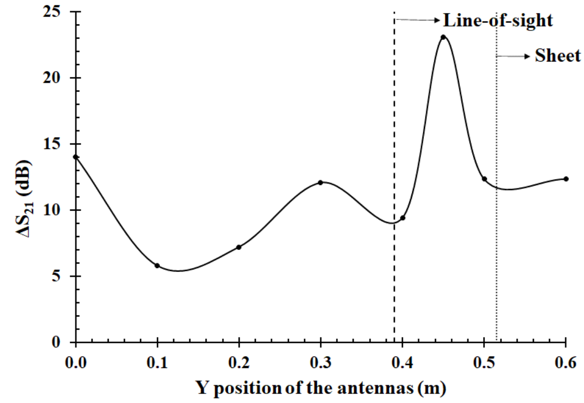

Fig. 6. Impact of Y position on S_{21} variation over the bandwidth

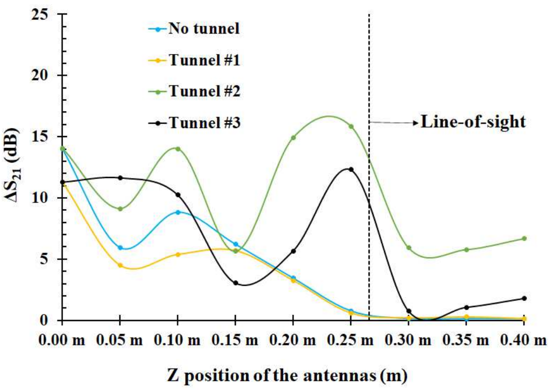

Fig. 7. Impact of Z position on S_{21} variation over the bandwidth for different tunnel properties

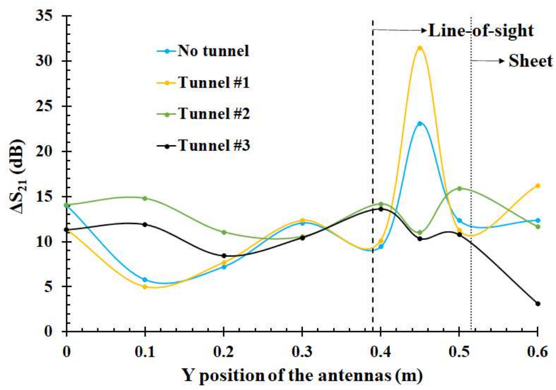

Fig. 8. Impact of Y position on S_{21} variation over the bandwidth for different tunnel properties

line-of-sight height and close to it. Therefore, heights of Z=0.00m and Z=0.15m are the ones showing the lowest variation for the different tunnel configurations. Regarding Y variation, it can be observed in Fig. 8 that no tunnel and Tunnel #1 scenarios affect the most in the line-of-sight area between boxes and the lateral metallic sheet or fairing. In this case, positions Y=0.00 and Y=0.30m are the ones showing the lowest variation between the different configurations. These conclusions apply to the specific train configuration showed in Fig.1.

IV. Conclusions and Future Work

The results obtained via ray-tracing simulations indicate that when using omnidirectional antennas, the wireless link of the WLTB is affected by the metallic surroundings on the roof, as well as the tunnels and their different properties. There are antenna locations that seem to be less sensitive to the effects of the tunnels, but these needs to be analyzed in more detail and for broader tunnel configurations. In the next phase, measurements are going to be made in a real train, and these results will be compared with the simulation results presented in this work.

The next steps will involve the study of directional antennas for line-of-sight situations outside the lateral fairing and between lateral fairing and auxiliary equipment boxes, as well as the use of mm-wave antennas (70 GHz) and the effect of track curvature.

Acknowledgment

This work has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No: 101015405, Safe4RAIL-3 (https://safe4rail-3.eu/).

Disclaimer

References

[1] Shift2Rail. https://shift2rail.org/ (accessed 13th October, 2021).

[2] Safe4RAIL-2. "D2.2 – LTE Equipment: Design, implementation and impact analysis on ETBNs." https://safe4rail.eu/downloads/deliverables/S4R2-D2.2-LTE-Equipment-PU-interim-M15.pdf (accessed 13th October, 2021).

[3] P. Aljama, A. Arriola, I. Martínez, I. Val, I. López, J. Manco, and J. Härri, "Applicability of 5G Technology for a Wireless Train Backbone," in *2021 15th European Conference on Antennas and Propagation (EuCAP)*, 22-26 March 2021, pp. 1-5.

[4] I. Lopez, J. Goikoetxea, A. Arriola, I. Zabala, and R. Priego, "Field Tests of an LTE-based Wireless Train Backbone in Metro Environments," in *2018 16th International Conference on Intelligent Transportation Systems Telecommunications (ITST)*, 15-17 Oct. 2018, pp. 1-6.

[5] Safe4RAIL-3. https://safe4rail-3.eu/ (accessed 13th October, 2021).

[6] D. He *et al.*, "Ray-tracing simulation and analysis of propagation for 3GPP high speed scenarios," in *2017 11th European Conference on Antennas and Propagation (EuCAP)*, 19-24 March 2017, pp. 2890-2894.

[7] N. Kumar, O. Chukwuka, and D. Seetharamdoo, "Integration of Antennas for Communication System on Complex Platforms," Cham, 2020: Springer International Publishing, in Communication Technologies for Vehicles, pp. 125-136.

[8] K. Guan *et al.*, "Channel Sounding and Ray Tracing for Train-to-Train Communications at the THz Band," in *2019 13th European Conference on Antennas and Propagation (EuCAP)*, 31 March-5 April 2019, pp. 1-5.

[9] J. M. García-Loygorri, "Estudio sobre un sistema de radiocomunicaciones ferroviarias de acuerdo al paradigma 4G," PhD, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Madrid, 2015.

[10] Z. Chang-sen and G. Li-fang, "Research on propagation characteristics of electromagnetic wave in tunnels with arbitrary cross sections," in *2010 2nd International Conference on Future Computer and Communication*, 21-24 May 2010 2010, vol. 1, pp. V1-22-V1-25.