Evaluation of Train Communications in Bridges and other Metallic Structures

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***Abstract*—The objective of this work was to develop a model in order to analyse the effect of a metallic bridge in different telecommunications systems, working in the 900 (GSM), 2600 (LTE) and 5900 MHz (WiFi/BBRS) frequency bands, for railway environments. The strategy adopted in this work evolved around two main directions. The first one was simply to implement propagation models in order to calculate path loss for the various environments under study. The novelty of this work comes with the second one, which consists of an electromagnetic model, based on CST software, for the analysis of penetration losses through a metallic bridge. The model was based on the schematics of a real bridge and different configurations were tested in order to reach a compromise between an accurate representation of the real problem and limited computational resources. It is then possible to estimate maximum communication distances for given configurations, as well as performance degradations that come with the inclusion of the metallic obstruction. In what concerns GSM, viaduct environments lead a range decrease roughly from 19% to 44% relative to their maximum communication distances, whereas other scenarios can see deteriorations from 45% to 56%. For BBRS, it is concluded that the currently used distances of around 300 m between BSs are conservative. This is also the scenario where the metallic bridge yields the biggest performance decrease, with communication distances reduced around 86%.**

Keywords-Railway Communications; Metallic Bridges; Path Loss; CST; Throughput

I. INTRODUCTION

Over the last years, High Speed Railways (HSRs) have been developed in order to improve the quality of life of train passengers. This method of transport can drastically reduce the cost and duration of passengers' trips, but it also comes with new needs in what concerns technology, infrastructures and safety.

This development emerges as an improvement in different areas, such as railway infrastructure deployment (railway tracks, overhead wires, tunnels, bridges and stations), the rolling stock, training facilities and all the required equipment to supply the tracks with telecommunication systems.

The constant need for communications inside trains and along stations (whether it comes from the trains' own communications systems or the passengers' devices) has led to increasing investments by many entities (railway infrastructure owners, managers and service providers) in order to supply the currently existing networks with not only voice and data transmission but also different passenger safety and cargo tracking systems.

Mobile communications are an essential part of this investment, which comes with special needs in what concerns signalling and safety compared to standard personal communications. Like these systems, railway telecommunications evolved from the analogue 1G system and currently operate using mostly a 2G system with special railway functionalities.

In 2000, European railway companies finalised the specifications for the Global System for Mobile Communications – Railway (GSM-R), an international communications standard for railway communications based on the second-generation GSM with specific railway functionalities, with the objective of replacing all analogue systems then in use. It is implemented with dedicated Base Stations (BSs) along the railways in the specific frequency bands: GSM-R and E-GSM-R. Nokia, Huawei and Kapsch are the main suppliers of GSM-R infrastructure. In most implementations, the BSs are usually located 7 to15 km apart from each other, however, countries such as China opt to use lower distances (3 to 5 km) in order to achieve higher levels of redundancy, which guarantee higher network availabilities. Countries such as Germany and Italy have GSM-R networks with between 3 000 and 4 000 BSs.

GSM-R is essentially the same system as the 2nd generation GSM, with additional railway functionalities, such as group calls, broadcast calls, emergency calls, shunting mode, functional and location-dependent addressing. Its specifications are defined by the European Integrated Railway Radio Enhanced Network (EIRENE) and approved by Mobile Radio for Railway Networks in Europe (MORANE). Nowadays it is mainly used in Europe, Asia, North Africa and Australia, replacing the majority of the older railway communications standards. It provides a secure platform for voice and data communication for trains, control centres, rail staff and user devices; however, it has the same limitations of the GSM standard, that is, the low maximum data rate (172 kbps), the high levels of interference from other users operating in the same bands and of course, disadvantages related to circuit switch techniques.

Terrestrial Trunked Radio (TETRA) is a private communications system of trunked mobile radio. Like GSM-R, it provides data and voice transmission, however, as a private network, its focus revolves around entities such as security forces, emergency services, military, transport companies and governments. Its specifications are defined by the European Telecommunications Standards Institute (ETSI) and it aims to provide a radio system for a closed group of users. It features voice encryption and emergency call reliability and its unique services include wide-area fast call set up and direct mode operation, mainly useful in emergency situations.

TETRA uses a low frequency band, which allows the coverage of large areas with a reduced number of BSs. In the absence of a network, radio terminals can use the direct mode, which allows the direct communication among different channels. It provides a point-to-point function, enabling users to have trunked radio links between each other without the direct involvement of an operator. Operation modes include transmission from one mobile terminal (MT) to another and one MT to many MTs (Broadcast or user groups), useful for railway communications. Some limitations of this technology are related to the limited available bandwidth. Interference from other services is expected and acceptable and the allowed transfer rates are low (up to 36 kbps). Besides data and voice, signalling is also transmitted, enabling the distinction of different MTs, which are identified by their phone numbers. This is important when the group of users using the service follows a hierarchy, which is the case of most, if not all, of the aforementioned entities. Overall, this system has low installation and maintenance costs and offers a reliable service to its users, albeit with low data rates.

Broad Band Radio System (BBRS) is a proprietary system, mainly used in metro and railway scenarios, which uses WiFi technology (802.11n) and allows the transmission of data between the rolling stock and the wayside, as well as eventual existing stations or any other physical infrastructure. It provides data rates close to the ones of 802.11n (theoretical maximum of 75 Mbps for a single 20 MHz channel data stream with no guard interval) and serves the need of systems asking for real time information, such as live video transmission, public addressing, passenger live information and help points, as well as train management and maintenance services.

Long Term Evolution – Railway (LTE-R) is the emerging platform for railway communications, featuring high data rates and the possibility of performing handovers with no data loss. The system operates using single sector cells and possible frequency bands to be used are the 450, 800, 900, 1400, 1800 and 2600 MHz ones. Since it is fully built on packet switch, it suits better data communications and offers reduced delays on signalling, useful for train specific operations and systems such as the European Train Control System (ETCS). More efficient spectrum usage and higher throughputs (peak rates of almost 100 Mbps) are consequences of upgrades in what concerns modulation and access techniques over 2G systems, making LTE-R the current stand-out winner in what concerns data rates in railway communications.

Even though 2G railway networks are present in most developed countries, implemented via GSM-R, the same is not true for newer generations. On the one hand, the standards for 4G LTE-R are being finalised and therefore operators may be waiting on their release in order to fully plan their networks, and on the other hand, perhaps there is currently no real demand for this technology in order to justify the investment needed to upgrade the existing railway networks to their successors.

The first LTE-R network launched in the world is located in the Korean city of Busan, providing communications to a 40 km long subway line, as a partnership between SK Telecom and Samsung. With the approach of the XXIII Olympic Games, held in Korea in the Winter of 2018, Samsung in partnership with Korea Telecom provided visitors of the games with safer train trips. As seen in [1], this LTE-R network went live in December 2017, in the Korean line of Wonju-Gangneung, which has an extension of 120 km and enables access to the LTE-R network onboard of its trains, operating at speeds of up to 250 km/h.

This work focuses on the impact of metallic structures, such as bridges and viaducts, on the different telecommunication systems already presented. EM simulations were performed in order to simulate the behaviour of a specific scenario, where a train is crossing a metallic bridge and different propagation models are implemented in order to properly estimate path loss and consequently obtainable throughputs for different systems and modulations. The main contribution of this work resides in the fact that the metallic bridge problem is modelled with CST software [2], which allows the development of an attenuation model for different work frequencies.

This paper is presented as follows: Section I – Introduction; Section II – State of the Art; Section III – Model Development; Section IV – Results; Section V – Conclusions.

II. State of the Art

This section provides a brief overview of the work that has been done so far in different types of structures one can find in the railway communications field.

In [3], a path loss model for HSR Viaducts is proposed based on empirical data at 930 MHz. It considers the influence of heights of the viaducts and BSs, which are not well predicted by large scale models, particularly the Hata model, versus which the proposed model is compared. The mean values of the errors between the predicted values and actual measurements are around 0 dB for the proposed model, whereas the Hata model reaches errors with means from 3 to 8 dB. Values of around 2.5 dB for the path loss exponent and 2.4 dB for the standard deviation error are achieved with this model. The work shows that the fading depth is between 14.38 and 15.96 dB for HSR environments and that the maximum fading depth is between 28.92 and 40.32 dB, values which are unaffected by the viaduct's height.

In [4], cutting scenarios are approached with the study of a slope measuring from 7 to 8 m and around 70º of inclination. Viaduct measurements are also obtained as a term of comparison. The data is collected using an antenna on top of a train (3.5 m high) operating on a GSM-R network, which moved at speeds from 240 to 320 km/h. The transmitter antenna was located at a height of 33 m and operated at a frequency of 932.8 MHz. The authors developed tuned path loss models for the cutting and viaduct scenarios, reaching values for path loss exponents of 4.3 for cuttings and 3.5 for viaducts. They found out that the shadow loss could be described by a log-normal distribution, with a standard deviation of 3.5 dB. Additionally, it is seen that bridges built on top of cuttings can yield propagation losses of around 5 dB and concluded that cuttings experience much more fading than viaducts.

In [5], the losses in train stations are analysed. Based on empirical data measured at 930 MHz in Chinese train stations, this work interprets train stations as a combination of a solid obstacle and a non-existent obstacle, providing two models for path loss in train stations. The conditions which are analysed here are the distance between the Tx and the station, the type of train station, the track on which the train operates and the different propagation mechanism zones. Errors lower than 2 dB for the mean and 5 dB Root Mean Square Errors (RMSEs) are achieved, which show the developed models adapt well to the studied scenario.

Following their previous works, R. He *et al*. developed a standardised path loss model for HSR in [6]. Based on a series of measurements at 930 MHz, the authors propose an empirical propagation model for the different scenarios that can be present in railway environments via the introduction of two new correction factors. The results obtained with the proposed model were compared against the Hata, Winner, 3GPP and ITU-R models and, based on the different RMSEs, it was concluded that the proposed model outperformed the previously mentioned models for two distinct HSR lines.

III. Model Development

This chapter presents the different models, methods and software used in this thesis, as well as the explanation of some assumptions and approximations.

A. *Model Overview*

Figure 1 states the methodology followed along this work, where the most important input parameters are the centre frequency, the type of modulation that is used, *M*, and the respective coding rate *R*, the average transmission powers, the heights of both the BS and the MT, as well as the different types of environment at hand.

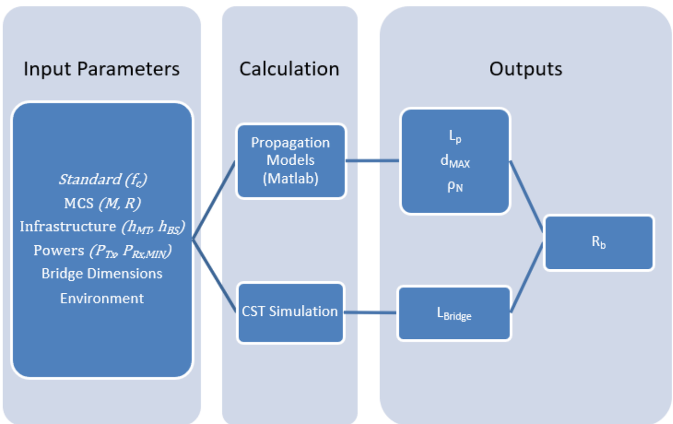


Figure 1. Work Methodology

After the input of all the parameters mentioned in the previous paragraph there are 2 steps that need to be performed in order to obtain the outputs. Firstly, the propagation models developed in this work yield parameters such as propagation losses, maximum communication distances and required signal to noise ratios for the different modulations. Along with this procedure, one also needs to account for the presence of a metallic bridge and therefore an EM simulation is performed in order to obtain an estimate of the additional losses due to the introduction of this metallic structure, which can be considered indoor propagation losses.

Finally, all these calculated parameters are taken into account and throughputs are estimated for the different systems and modulations.

B. *Winner II Model*

The Winner II model deals with the environments being studied in this work under section D2a (Moving Networks). According to [7], the model considers a rural LOS situation where the 2.5 m high trains move at speeds of 350 km/h. The frequencies to be considered are between 2 and 6 GHz. The model considers there are BSs every 1000 to 2000 m along the track and either:

1. 50 m away from the tracks with 30 m high antennas;
2. 2 m away from the tracks with 5 m high antennas (optimal for BBRS).

In a general way, the Winner II model for path loss can be written as seen bellow,

$$L_{p,WinnerII[\mathrm{dB}]} = A\log\left(d_{[\mathrm{m}]}\right) + B + C\log\left(\frac{f_{c[\mathrm{GHz}]}}{5.0}\right) + X \quad (1)$$

where:

A: Fitting Parameter;

B: Intercept Parameter;

f_c: Centre Frequency;

C: Path Loss Frequency Dependence;

X: Environment-Specific Parameter;

d: Tx-Rx Separation Distance.

For moving networks,

$$\begin{cases} A = 21.5; B = 44.2; C = 20; X = 0, \quad 10\ \mathrm{m} < d < d_{BP} \\ L_{p,WinnerII[dB]} = 40\log\left(d_{[\mathrm{m}]}\right) - 18.5\log\left(h_{BS[\mathrm{m}]}h_{MS[\mathrm{m}]}\right) \\ \quad +1.5\log\left(\frac{f_{c[\mathrm{GHz}]}}{5.0}\right) + 10.5, \quad d_{BP} < d < 10\ \mathrm{km} \end{cases} \quad (2)$$

where:

h_{BS}: Actual BS' antenna height;

h_{MS}: Actual MS' antenna height;

d_{BP}: Breakpoint distance, with:

$$d_{BP} = 4 \cdot h_{BS} \cdot h_{MS} \cdot \frac{f_c}{c} \quad (3)$$

C. *He et al. Model, 2011*

This model was developed for the 930 MHz band (intended to be applied to GSM-R), specifically for viaducts with heights ranging from 10 to 30 m above ground and cell radii from 2.5 to 4 km. The BS' antennas are positioned 20 to 30 m above the rail surface and 10 to 20 m away from the railway. The MT's antennas are placed on top of the train, 30 cm above its roof, on its middle. The train at study moves at speeds of 200 to 350 km/h and is 204 m long, 3.8 m high and 3.3 m wide.

The relevant dimensions mentioned in model are schematised in Figure 2, where:

- *H:* Viaduct's Height;
- w_t*:* Train's Width;
- h_t*:* Train's Height;
- h_{AR}*:* Antenna's distance to the roof of the train, with:

$$h_{MS} = h_{AR} + h_t \tag{4}$$

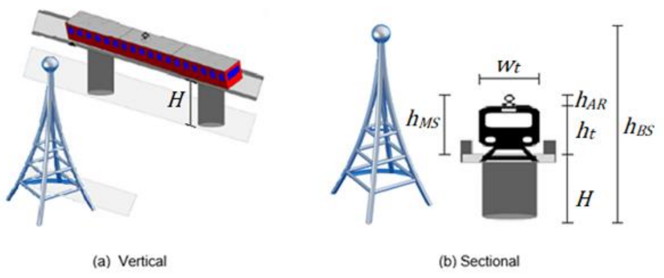


Figure 2 - Vertical and sectional viaduct views (adapted from [3]).

The authors conclude that when the viaduct is low, most obstacles are bellow it and therefore little to no phenomena such as diffraction, reflection and scattering occur, leading to quasi free space propagation and a path loss exponent close to 2.

In contrast, when the viaduct is high, these phenomena are present, however, the reflected and scattered components from the rail and the ground below the viaduct have little to no chance of reaching the MT's antenna, leading to a two-ray model with a path loss exponent close to 4.

The path loss exponent increases with the viaduct's height, ranging from 2 to 4 for the tested scenarios. Viaduct heights higher than 30 m lead to bad channel quality. The same happens for heights lower than 10 m, due to the scattering of multipath components.

Based on the effect of the different factors, the proposed model for the path loss has the following expression,

$$\begin{aligned} L_{p,HZAD11[\mathrm{dB}]} &= \Big[C_a H_{[\mathrm{m}]} + C_B\big(h_{BS[\mathrm{m}]} - h_{MS[\mathrm{m}]} - H_{[\mathrm{m}]}\big) \\ &+ \frac{C_C}{h_{BS[\mathrm{m}]} - h_{MS[\mathrm{m}]} - H_{[\mathrm{m}]}} + C_D\Big] \cdot 10\log\left(\frac{d_{[\mathrm{m}]}}{d_{0[\mathrm{m}]}}\right) + 20\log\left(\frac{4\pi d_{0[\mathrm{m}]}}{\lambda_{[m]}}\right) \\ &+ xy,\ \ h_{BS[\mathrm{m}]} - h_{MS[\mathrm{m}]} - H_{[\mathrm{m}]} > 0 \end{aligned} \tag{5}$$

where:

- C_A = 0.04798;
- C_B = 0.00194;
- C_C = 42.84;
- C_D ~ N(-0.266, 0.318), where *N* stands for the Normal Distribution Function;
- *x* ~ N(0,1);
- *y* ~ N(2.319 dB, 0.702 dB);
- *λ:* Wavelength;
- d_0*:* Reference distance (around 500 m for HSR viaducts).

D. He et al. Model, 2014

The present model introduces new correction factors to the Hata model. It was tested and validated for HSR scenarios at 930 MHz.

Starting with the Hata path loss model for urban areas, with the large cities correction factor:

$$\begin{aligned} L_{p,Hata[\mathrm{dB}]} &= 74.52 + 26.16\log\big(f_{c[\mathrm{MHz}]}\big) \\ &-13.82\log\big(h_{BS[\mathrm{m}]}\big) - 3.2\log^2\big(11.75 h_{MS[\mathrm{m}]}\big) \\ &+\big[44.9 - 6.55\log\big(h_{BS[\mathrm{m}]}\big)\big]\cdot\log\big(d_{[\mathrm{km}]}\big) \end{aligned} \tag{6}$$

R. He *et al*. introduce the correction factors Δ_1 and Δ_2 so that this model translates the propagation in commonly found HSR structures more accurately. This is shown in the following expression:

$$\begin{aligned} L_{p,HZAD14[\mathrm{dB}]} &= \Delta_1 + 74.52 + 26.16\log\big(f_{c[\mathrm{MHz}]}\big) \\ &-13.82\log\big(h_{BS[\mathrm{m}]}\big) - 3.2 log^2\big(11.75 h_{MS[\mathrm{m}]}\big) \\ &+\big[44.9 - 6.55\log\big(h_{BS[\mathrm{m}]}\big) + \Delta_2\big]\cdot\log\big(d_{[\mathrm{km}]}\big) \end{aligned} \tag{7}$$

The correction factors are derived from the difference between the optimal path loss curve (Least Squares (LS) fit curve of the measurements) and (6) and are shown in Table 1 for the different types of environments. Δ_1 is used to normalise the constant in the model in order for it to fit the data, while Δ_2 deals with the path loss exponent changes introduced by railway environments and buildings.

Table 1 - Correction Factors for the Path Loss Model (adapted from [6]).

HSR Environment	Correction Factors [dB]
Urban	Δ_1 = -20.47 Δ_2 = -1.82
Suburban	Δ_1 = 5.74log(h_{BS}) - 30.42 Δ_2 = -6.72
Rural	Δ_1 = 6.43log(h_{BS}) - 30.44 Δ_2 = -6.71
Viaduct	Δ_1 = -21.42 Δ_2 = -9.62
Cutting	Δ_1 = -18.78 Δ_2 = 51.34log(h_{BS}) - 78.99
Station	Δ_1 = 34.29log(h_{BS}) - 70.75 Δ_2 = -8.86
River	Δ_1 = 8.79log(h_{BS}) - 33.99 Δ_2 = -2.93

E. Throughput Models

In what concerns the achievable data rates, the model for LTE is adapted from [8]. The expressions for the different modulations are expressed bellow, with slight modifications from the original ones (introduction of constants) in order to account for single streams of data. These were obtained through experimental measurements of several manufacturers from [9].

Note that the presented expressions only consider a single data stream scenario with negligible interference and all 100 resource blocks in use.

For QPSK the throughput is given by,

$$R_{b[\mathrm{bps}]}^{QPSK,\frac{1}{3}} = \frac{2.34201 \cdot 10^6}{14.0051 + e^{-0.577897 \cdot \rho_{N[\mathrm{dB}]}}} \cdot 50 \quad (8)$$

where:

R: Coding Rate;

ρ_N: Signal to noise ratio at receiver.

Similarly, for 16QAM, one can obtain the throughput as:

$$R_{b[\mathrm{bps}]}^{16QAM,\frac{1}{2}} = \frac{47613.1}{0.0926275 + e^{-0.295838 \cdot \rho_{N[\mathrm{dB}]}}} \cdot 50 \quad (9)$$

And finally, for 64QAM, the expression is:

$$R_{b[\mathrm{bps}]}^{64QAM,\frac{3}{4}} = \frac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{N[\mathrm{dB}]}}} \cdot 50 \quad (10)$$

In what concerns WiFi data rates, the approach to acquire throughput expressions was quite different. Figure 3 shows air interface throughput curves obtained for a real 20 MHz system using 802.11n, for different MCSs.

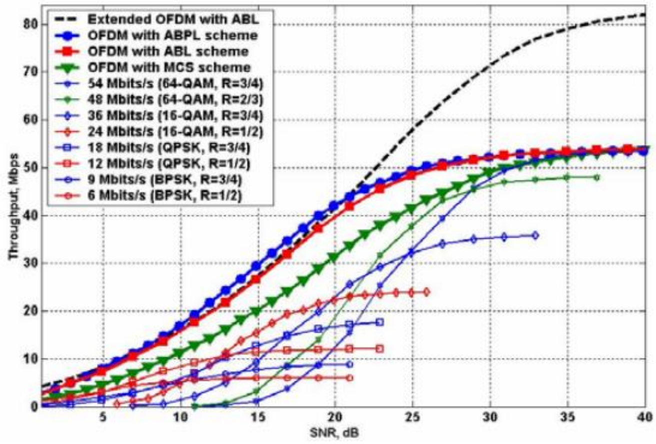


Figure 3 - 802.11n's Air Interface throughput (extracted from [10]).

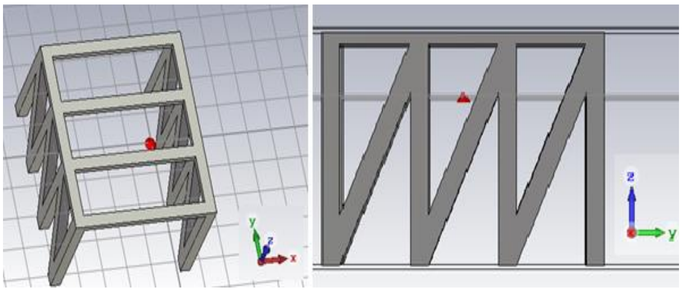
Considering that the hardware in use is capable of performing adaptative coding and modulation, the available throughput expression contemplates 5 different branches, corresponding to the best available MCS for the current ρ_N. This is done through the use of the MATLAB fitting tool, which is able to interpolate the points with a polynomial approximation. Using the modulation with the highest throughput for a given signal to noise ratio, one can set the modulation boundaries as seen in Table 2.

Table 2 - BBRS Modulation Boundaries (extracted from [10]).

Modulation	Condition
64-QAM, ¾	$\rho_N \geq 28.8$ dB
64-QAM, ⅔	$28.8 > \rho_N \geq 22$ dB
16-QAM, ¾	$22 > \rho_N \geq 19.5$ dB
16-QAM, ½	$19.5 > \rho_N \geq 12.3$ dB
QPSK, ½	$12.3 > \rho_N \geq 0$ dB

F. CST Modelling

The task at hand is to derive the attenuation caused by the bridge's metallic beams within the far field region of the antenna, which is a half-wavelength dipole, placed on top of a train, as seen in Figure 4.



(a) Top View (b) Lateral View

Figure 4 - Top and lateral views of the CST simulation schematic.

When one looks at a two-way railway, the first consideration when analysing the different angles of the problem is that there are some symmetries and therefore one does not need to analyse all range of angles φ ∈ [0, 360] º.

The range of φ ∈ [0, 90] º is symmetric to φ ∈ [270, 360] º and the scenario φ ∈ [90, 180] º is the same as φ ∈ [180, 270] º. For these reasons, the only zones that need to be looked at are the first and third quadrants of the problem, that is, φ ∈ [0, 90] º and φ ∈ [180, 270] º. This angle is shown in Figure 5.

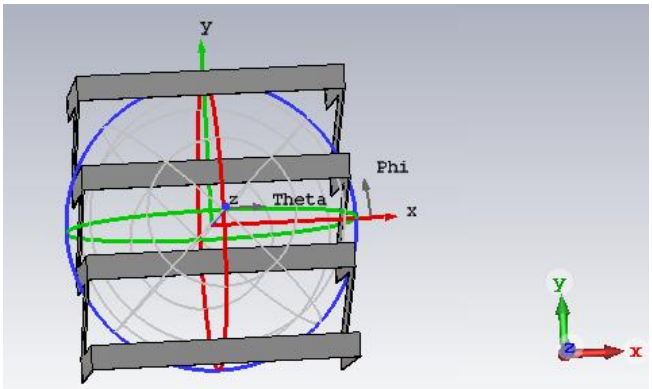


Figure 5 - Problem's Angle Definition.

Numerous simulation configurations led to the conclusion that the analysis of the current problem with the available computational resources is not feasible. A simulation with the actual bridge model in the 900 MHz band results in more than 2 days of simulation time and increasing the frequency of the problem to 2600 MHz leads to weeks of simulation time.

Due to these reasons, the solution to this complexity revolves around CST symmetry planes. These marginally reduce the number of mesh cells at hand, however the cost of this operation comes associated with the fact that the simulated environment does not represent the actual problem exactly as it exists.

IV. Results

The current chapter presents the results obtained when applying the developed models and simulating the previously defined scenarios, as well as their analysis. These are split into the developed bridge attenuation model and the analysis of the different networks' maximum communication distances and throughputs.

A. Bridge Attenuation Modelling

The first result has to deal with the materials that are used when simulating the EM behaviour of the bridge. Simulations were made, both for the PEC and a specific type of Steel (Steel-1010 in CST studio), in order to analyse the intensity of the electric field for the whole range of azimuth angles. Even though Steel-1010, which is actually a real material, is the one considered henceforth, the difference between the two distinct materials is marginal, and therefore it can be argued that the use of either type of material will produce similar results, since the high reflectivity of metallic structures resembles the behaviour of perfect electric conductors.

The simulation results from CST show that, at 925 MHz, the magnitude of the electric field follows the behaviour shown in Figure 6. The data presented is already corrected, meaning that, in a procedure similar to knife-edge and two-ray models, some points have been saturated, both for the maximum and minimum values. As previously stated, only data for $\varphi \in [0, 90]$ º is shown, since the CST model is symmetric and therefore no additional data is given by the remaining points.

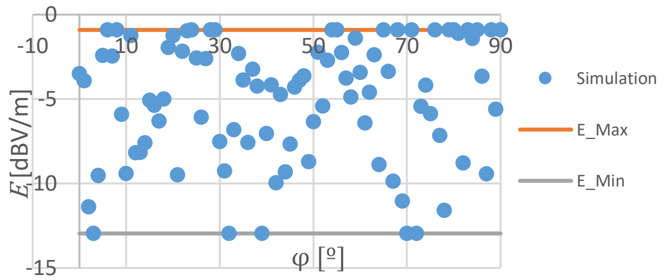


Figure 6 - Saturated field magnitudes at 925 MHz.

With the use of Excel, it is possible to analyse the data provided by CST and, through the calculation of averages and standard deviations, analyse the respective z-scores, seeing that the simulation results can be approximated by a normal, left-truncated (at zero), distribution curve with an average of 3.5 and a standard deviation of 4.1. Figure 7 shows the respective cumulative density function (CDF), both with the simulation results and the normal approximation curve.

The obtained CDF follows the expression:

$$P(X \le x) \approx \begin{cases} \frac{1}{2}\left[1+\operatorname{erf}\left(\frac{x-3.5}{4.1\sqrt{2}}\right)\right], x>0 \\ 0.2, x=0 \end{cases} \qquad (11)$$

where:

erf stands for the error function;

σ: Standard Deviation;

μ: Average.

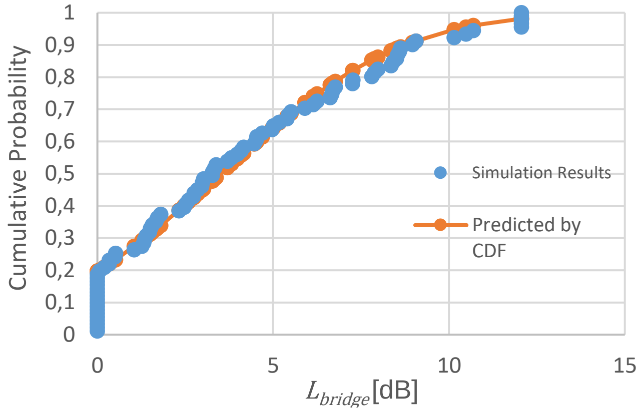


Figure 7 - Simulation results and normal CDF approximation at 925 MHz.

It is important to state that the accumulation of points corresponding to 0 dB losses is not caused by a lack of resolution from CST, as one would expect when looking at this kind of graph, but by the saturation of points made in the previous step. The normal curve approximation is used henceforth in order to reflect the average scenario in what concerns losses in a metallic bridge environment and not a specific bridge. The graph represented above provides L_{bridge} for the forthcoming calculations, allowing one to calculate a new system margin for a case where there is a metallic bridge present in the scenario. For instance, the maximum value of bridge propagation losses for 90% of the cases is defined as the standard value for the scenarios where a metallic bridge is present at 925 MHz and its value corresponds to 8.75 dB. One can write this as:

$$L_{bridge}^{GSM-R,90\%} = 8.75 \text{ dB} \qquad (12)$$

Repeating this procedure for the LTE-R case, one concludes the simulation results can be approximated by a left-truncated (at zero) normal CDF with an average of 2.7 and a standard deviation of 5.8. The obtained results are expressed in Figure 8 and the specific obtained CDF follows the expression:

$$P(X \le x) \approx \begin{cases} \frac{1}{2}\left[1+\operatorname{erf}\left(\frac{x-2.7}{5.8\sqrt{2}}\right)\right], x>0 \\ 0.3, x=0 \end{cases} \qquad (13)$$

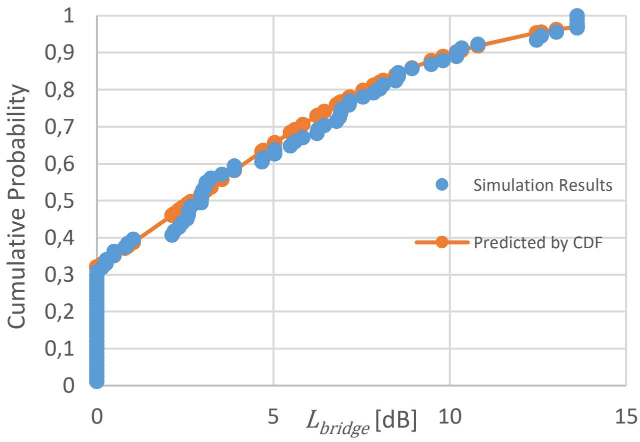


Figure 8 - Simulation results and normal CDF approximation at 2600 MHz.

Once more, now for LTE-R, one can write:

$$L_{bridge}^{LTE-R,90\%} = 10.13 \text{ dB} \quad (14)$$

Finally, the remainder parameter to obtain is related to the propagation losses in a metallic bridge scenario at 5.9 GHz, that is, for a BBRS system. Due to the high frequency at hand and the limited hardware available, CST simulation is not a viable strategy since it would result in weeks of simulation. For this reason, the procedure to obtain the losses for this last scenario is through the linear approximation involving the values obtained in the GSM-R and LTE-R simulations. Of course, the higher frequency can change the behaviour of the EM signals and one must be conscious that the best method to obtain these values would be through diffraction analyses such as ray-tracing techniques, which would introduce another degree of complexity in the current work. Nonetheless, works such as [11], [12], [13] and [14] show that both losses and reflection coefficients are somewhat linear and monotonous when operating with frequency selective structures up to 10 to 20 GHz, frequencies that are still quite above the one at hand. This is also the case when dealing with metallic walls.

With this is mind $L_{bridge}^{BBRS,90\%}$ is the parameter one is looking for in order to calculate the penetration losses in the BBRS metallic bridge scenario, which can be obtained with a simple linear approximation, resulting in:

$$L_{bridge}^{BBRS,90\%} \approx 18.55 \text{ dB} \quad (15)$$

B. *GSM-R*

In this section, a different set of environments is analysed. GSM-R is not capable of reaching data rates high enough to support video transmission and therefore the performed analysis regards the maximum distance one can support in order to guarantee voice transmission, that is, the maximum distance that guarantees the system sensitivity of -102 dBm.

With the intent of analysing different viaducts behaviour, the first result shows the effect of the height of the viaduct itself. Figure 9 shows the path losses for different heights of viaducts when the height of the base station is fixed at 30 m.

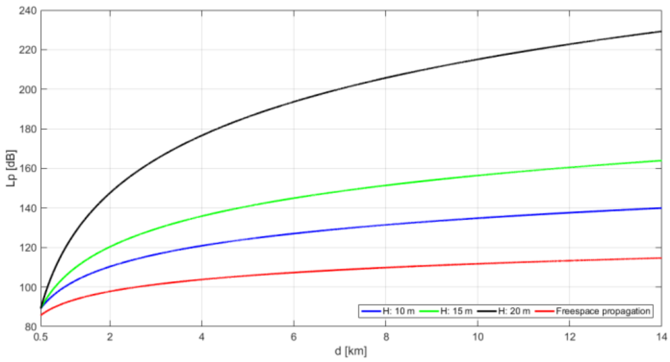


Figure 9 – Effects of the Viaduct's Height.

One can see that the losses increase with the height of the viaduct, which is explained by the fact that the reflected and diffracted components of the transmitted signals both on the ground and the surface of the have difficulty reaching the receiver's antenna.

One would expect that higher heights of the viaducts would lead to lower obstacles present in the signals' paths and therefore better performance, however, with a viaduct's height starting at 10 m, on top of the antenna being placed on top of the train, most obstacles are already below the rails and lower viaduct heights will actually provide the best clear LOS situations between the transmitter and the receiver.

Table 3 shows the maximum distances supported for some studied cases. It can be seen that one configuration (30 m high BS with a 10 m viaduct) vastly outperforms the others, which is a clear indicator that network planning is essential when dealing with viaducts.

Table 3 - Maximum BS distances for different viaduct configurations.

h_{BS} [m]	H [m]	d_{MAX}		
		w/o bridge [km]	**w/ bridge [km]**	**Relative Decrease [%]**
20	10	1.464	1.178	19.5
25		3.711	2.470	33.4
30		8.377	4.711	43.8
	15	3.381	2.298	32.0
	20	1.386	1.129	18.5

Apart from viaducts, other common HSR scenarios were studied, using the He *et al*., 2014 model. Figure 10 shows the propagation losses for the first set of environments analysed in this subsection when the height of the BS' antenna is set at 20 m.

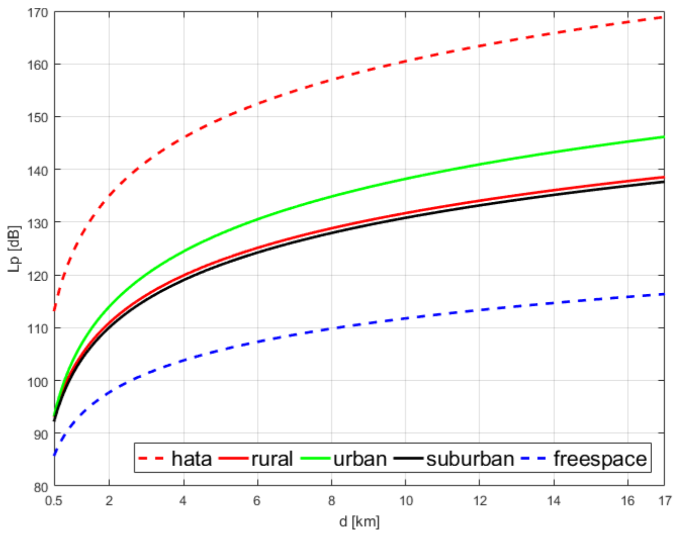


Figure 10 - Path Losses for Urban, Suburban and Rural Environments.

When comparing the Hata model with for urban scenarios with the large cities' correction factor against the urban HSR scenario, the immediate drawn conclusion is that the use of a standard path loss model instead of an HSR one can lead to differences in path loss higher than 20 dB. With system margins in the order of 10 dB, this is an exceptionally high value that most certainly impacts on the development of any telecommunications system.

Apart from the previous result, one can still see that the difference between Rural and Suburban scenarios is very small, leading to differences of, at most, 1 dB between each other, whereas the Urban scenario can incur losses up to 7 dB higher than the rural case. As mentioned in [6], this often occurs in most HSR models, with some of them not even distinguishing between these 2 environments since, as seen with these results, the differences are negligible.

Table 4 shows communication distances for the remaining studied scenarios.

Table 4 - Maximum communication distances for different scenarios.

Scenario	d_{MAX} w/o bridge [km]			d_{MAX} w/ bridge [km]		
	h_{BS} 20m	h_{BS} 30m	Change [%]	h_{BS} 20m	h_{BS} 30m	Change [%]
Urban	6.7	8.4	25.4	3.7	4.3	11.6
River	8.2	9.4	14.6	4.5	5.0	11.1
Rural	10.3	12.6	22.3	5.1	6.2	21.6
Cutting	12.8	8.1	**- 36.7**	5.6	4.4	**- 21.4**
Station	17.4	14.4	**- 17.2**	8.4	6.7	**- 20.2**

In what concerns stations, a higher BS height means that more components of the transmitted signals will be retained in the awnings on top of the station and other obstacles such as information panels, leading to signal scattering and consequent higher losses. In what concerns the Cutting, a possible explanation is that a higher number of multipath components that are reflected along its walls have trouble reaching the receiver antenna, often getting confined within the valley. The restructuration of the previous data shows that the insertion of a metallic bridge in GSM-R scenarios yields degradations in communication distances ranging from, roughly, 45 to 56%.

C. LTE-R

Unlike the previous system, the 4G LTE-R is capable of handling the required throughputs to transmit video. The analysis made in this section is not as linear as in the previous section, in the sense that the powers and throughputs depend on the modulations and coding rates that are used. Adaptative Coding and Modulating (ACM) is hard and expensive to implement in HSR scenarios due to the low coherence times that lead to channel instability, as previously explained. It is essential to know beforehand which options are available for each scenario in what concerns throughputs and available MCSs.

Table 5 states the minimum signal to noise ratios needed in order to use different LTE modulation and coding efficiently, that is, a value that enables an acceptable (near the saturation zone) throughput for QPSK, 16-QAM with a better performance than QPSK and 64-QAM with a throughput higher than 16-QAM's.

Table 5 - LTE's MCS' signal to noise ratios.

MCS	$\rho_{N,MIN}$ [dB]
QPSK, ⅓	- 8.0
16-QAM, ½	5.5
64-QAM, ¾	13.0

The results expressed here contemplate a viaduct height of 10 m, whereas the heights of the BS' and the MT's antennas are fixed at 30 m and 5 m, respectively. This is due to the fact that the effect of these parameters has already been analysed in the previous section.

Table 6 shows the maximum communication distances, with and without the presence of a metallic bridge, in order to obtain a throughput of 4 Mbps. The relative decrease in distance due to the insertion of the bridge is also stated in these results.

Table 6 - LTE-R's maximum communication @4 Mpbs.

Environment	d_{MAX}		Relative Decrease [%]
	w/o bridge [km]	w/ bridge [km]	
Viaduct	4.56	2.33	48.9
Urban	3.66	1.83	50.0
River	3.98	1.94	51.2
Rural	4.76	2.11	55.7
Cutting	3.42	1.66	51.5
Station	5.04	2.08	58.7

With the shown data, it can be concluded that the presence of a metallic bridge in LTE-R scenarios yields reductions from roughly 49 to 57% in what concerns maximum communication distances, which are in the same order of the ones observed in the GSM-R scenarios, albeit a bit more severe.

The distances reduce dramatically (reductions from around 67 to 77%) when enhancing the throughput from 4 Mbps to the 20 Mbps rate for different scenarios. Distances for the 30 Mbps rate result in values lower than the model's reference distance of 500 m, rendering it inaccurate. The same happens, to some extent, to the 20 Mbps rates metallic bridge scenario.

D. BBRS

Regardless of the modulation in use, WiFi is more demanding than LTE in what concerns the required signal to noise ratios. Even though the maximum path loss values are lower than the ones allowed by LTE, the distances between base stations in BBRS are also smaller in order to account for this requirement.

It is necessary to state that the used model for this system (Winner II) considers a rural LOS scenario, however, in this work, the model is used for any scenario with this work frequency, as stated in model implementation. This is due to the fact that the distances in use are so low (around 300 m) that the impact of the surrounding terrain is not going be noticeable in what concerns propagation losses.

Figure 11 shows path loss for BBRS when both the MT's and the BS' antennas are located at a height of 5 m. This BS height is different from the previous ones since, in a BBRS setting, the APs are to be located alongside the railway, at approximately the same height as the receivers. One can clearly see the breakpoint distance, which is located at 1968 m.

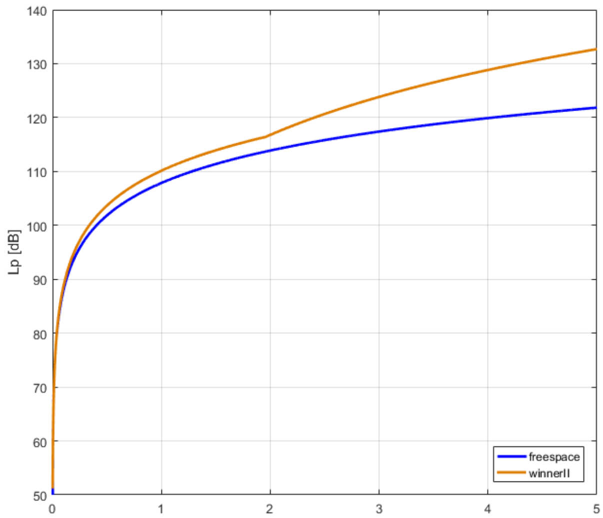


Figure 11 - BBRS path loss for BS and MT heights of 5 m.

The maximum communication distances for the different throughputs are shown in Table 7.

Table 7 - Maximum BBRS Communication Distances.

Throughput [Mbps]	d_{MAX}		Relative Decrease [%]
	w/o bridge [m]	w/ bridge [m]	
4	2207.3	333.7	84.9
6	1893.7	261.1	86.2
10	1220.7	168.3	86.2
12	1028.5	141.8	86.2
20	648.9	89.5	86.2
30	379.9	52.4	86.2
40	252.9	34.1	86.5
54	55.3	7.6	86.3

Placing the APs 300 m apart from each other guarantees a 4 Mbps rate, even with a metallic bridge obstruction between the Tx and the Rx, however, for higher rates, the system notices a severe degradation. This performance decrease is somewhat constant through all of the rates and yields a communication distance decrease around 86% in order to maintain the same throughput. One can also see that the distance of 300 m is conservative when providing rates of 20 Mbps, however this study does not account for interference providing from other nearby communication systems. The maximum rate of 54 Mbps for a single data stream is especially difficult to provide, needing distances of 55.3 m between the AP and the train in a scenario without a metallic bridge and becoming impossible to provide should the bridge exist.

V. Conclusions

This work addresses a specific problem, which has to do with the presence of an obstruction in the form of a metallic bridge between the transmitter and the receiver of a telecommunications system. Its objective was to develop and implement a model capable of analysing the problem in the form of maximum allowed communication distances and obtainable throughputs. The model itself was developed with EM simulation via CST software and all the numerical analysis and propagation model implementation was done with MATLAB.

The developed work is therefore separated into two main modules. The first is a block of code that enables the user to input the scenario's characteristics, such as the location of the antennas and the frequency of work and extract propagation losses as a function of distance, whereas the second one is a software model of the problem with the objective of providing the losses due to the metallic bridge obstruction in a railway scenario. In conjunction, these allow one to translate the bridge into an additional propagation loss, which is combined with the standard path loss to analyse the problem in terms of obtainable throughputs.

The first set of propagation results has to deal with the 925 MHz frequency, where one can see that the presence of a metallic bridge in viaduct environments yields communication distance decreases from 18.5% to 43.8%, depending on the viaduct configuration. Still working in the same band, another set of scenarios, consisting of Urban, River, Rural, Cutting and Stations, is approached, where one can see the impact of changing the heights of the BS's antenna and, once more, the performance decrease caused by the presence of the metallic obstruction. It is seen that Cuttings and Stations do not behave as expected compared to other scenarios, that is, an increase in this parameter from 20 to 30 m does not yield a better system performance, but instead diminishes the obtainable communication distances from roughly 17% to 37%. The presence of the metallic bridge has a rougher impact, decreasing the maximum allowed distances from around 45% to 56%, depending on the environment at hand. One concludes the commonly used Hata model results in overestimations in what concerns path loss in railway scenarios, a factor which is also stated in [6] and that there exists room for improvement when planning the location of BSs in HSRs.

Unlike the GSM-R scenarios, the 2600 MHz LTE-R results contain an approach regarding MCS, which affect the obtainable throughputs, the main focus in both LTE-R and BBRS results. It is suspected that the 30 Mbps distance is only reachable in a scenario where a metallic bridge is not present, however, due to model limitations, however, actual signal measurements can lead to a different conclusion. It is seen that raising the required throughput from 4 to 20 Mbps comes with reductions from 67% to 77% in what concerns communication distances and that the introduction of a metallic bridge in this frequency deteriorates the achievable communication distances from roughly 49% to 57%, which are in the same order of the ones observed in the previous case. Finally, it is shown that sudden drops in signal to noise ratios can have quite different effects in the resulting throughputs. On the one hand the reduced signal to noise ratio can allow the modulator to work with the same MCS, resulting in a low performance decrease, of around 2.7% for the analysed case. On the other hand, should the drop be high enough to force the system to work in a lower MCS, one can see performance degradations of around 55% to 64%.

Finally, the 5900 MHz BBRS scenario is studied. The same statements regarding system signal to noise ratios are made, however different throughput levels are defined. This is due to the fact that the used model (Winner II) does not have a reference distance limitation and the APs in BBRS are placed at low distances from each other, resulting in less demanding cases in what concerns path loss. It is seen that this scenario contains the cases where the metallic bridge obstruction has the highest impact, with decreases around 86% for all analysed throughputs. This study shows that the theoretical maximum rate of 54 Mbps is very hard to provide, even without a metallic bridge obstruction, and becomes impossible should it be present since this case would result in distances between the train and the APs of around 8 m. It can be concluded that the commonly used distance of 300 m for the BBRS' AP placement in order to guarantee rates below 20 Mbps is somewhat conservative, however one has to remember this study does not account for interference providing from other communication systems. Similarly to LTE-R, throughput performance is analysed as a function of decreases in signal to noise ratio caused by the introduction of the metallic bridge. Performance deterioration is more severe in this system due to the high frequencies in play and consequent higher attenuation caused by the metallic bridge. Unlike the LTE-R examples, all situations that are analysed here see a significant performance drop, ranging from around 14.8% where the same MCS is available after the inclusion of the obstruction, to a high 93.4% decrease in a situation where the used MCS is forced to a less complex one.

In what concerns future work, several aspects can be explored. The first has to deal with the simplifications made during the CST modelling of the metallic bridge. Due to computational and time constraints, the studied case contemplates a totally symmetric bridge, which is not the real case. Of course the objective of this work is not to study the penetration losses of a specific bridge, but instead to provide a general model that can be followed for other scenarios, however, this can be useful in order to model different types of bridges and see if their shapes and symmetries have a significative impact on the obtained results. One can argue that an important point was missed with this work, which is the impact that a two-way railway and the presence of another train have on telecommunications systems, which is a point that could be enhanced.

Signal to noise requirements can greatly vary between different providers and therefore a more specifically target analysis towards BBRS could be studied, with data prevenient from actual hardware measurements. The same can be said for LTE, however a factor which would probably produce better results is the use of another model, specifically developed for the 2600 MHz band, which may render the data inaccurate.

Instead of CST EM modelling one could use an analytical model in order to solve the problem recurring to reflection factors. This is certainly a more complex way of approaching the current problem, however it could yield interesting results.

Finally, the most interesting and originally planned idea revolves around the use of FSSs in order to analyse the problem, as stated previously in this work. The limitation here is that the currently existing and publicly available FSS models are designed to work with very small structures compared to metallic bridges such as arrays of dipoles or resonators. Even though some of the work developed in these models can be used, such as the general behaviour of metallic structures with frequency, using these types of models will certainly provide meaningless results.

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