Channel Model for Train to Train Communication using the 400 MHz Band

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***Abstract*—This paper presents a channel model for direct train-to-train communication appropriate for the 400 MHz band. Extrapolation of theoretical and experimental results obtained for the planning of other railway communication systems like GSM-R is not obvious due to the difference in frequencies, antenna height and absence of base stations. In this paper, the analysis of the channel model covers different radio phenomena including path loss, Doppler, fading, and delay spread. Concretely we consider three scenarios (train stations, shunting yards and regional networks), for which the propagation channel characteristics are discussed. Furthermore, influence of special railway environments like cuttings which can be found near cities and towns, tunnels and bridges are encountered.**

I. INTRODUCTION

The German Aerospace Center (DLR) is currently developing a Railway Collision Avoidance System (RCAS) [1] that will allow the train conductors to have an up-to-date accurate knowledge of the traffic situation in the vicinity, and act in consequence. The system is intended to not rely on components in the infrastructure, this way substantially reducing its rollout- and maintenance costs, as well as inherently providing a migration strategy. The basic idea of RCAS is to calculate the own position and movement vector and broadcast this information as well as additional data like vehicle dimensions to all other trains in the area. Thus, the train driver's cabin could be equipped with a display showing the position of the other vehicles in the region. Computer analysis of the received information, the own position and movement vector and an electronic track map allows to detect possible collisions, displaying an alert signal and advising the conductor of the most convenient strategy to avoid the danger.

In order to optimize the communication link, it is necessary to approach the design attending the specific characteristics of the channel. Since one of the most critical requirements of RCAS is the communication range [2], the path loss prediction model should be chosen carefully. A deterministic approach to establish the parameters of the propagation channel is not feasible due to the high dynamic railway channel characteristics that can change the instantaneous amplitude very rapidly.

Relatively little work has been undertaken on characterizing the propagation environment for railways. Most of the available work deals with GSM-R [3], which uses a proprietary frequency band (876-880 MHz uplink, 921-925 MHz downlink). GSM-R is a communication system for data and voice based on GSM for European high speed trains using base stations, while the direct train-to-train communication in RCAS is intended to be used in regional networks where the curves are less smooth and the lines are not so straight. Therefore in RCAS we cannot assume for instance LOS in contrast to GSM-R.

There have been as well some analysis of deterministic channel models undertaken in the 25 GHz band [4], and in the 5 GHz band [5]. In general, all this research is done for high speed lines. On the other hand, general propagation prediction models for different terrain profiles, like Hata-Okumura, Ibrahim and Parson are widely used when planning a terrestrial system [6].

Furthermore, there are a few more systems that can be found for frequencies close to RCAS target frequency band, i.e. 400 MHz [2]. For instance the Terrestrial Trunked Radio (TETRA) [7] standard for digital Private Mobile Radio (PMR) on the 400 MHz frequency band, Digital Video Broadcasting - Handheld (DVB-H) [8] on the 170-230 MHz and 470-862 MHz band, which is an internationally accepted open standard for digital television bringing broadcast services to handheld receivers, and finally the Global System for Mobile communications (GSM) [9].

As explained in [2], we consider three scenarios: train stations, shunting yards and regional networks. It should thus be noted that RCAS is not focused on high speed lines. Each scenario is not only characterized by the radio environment, but in particular by a different maximum train speed.

The paper is organized as follows: First, the path loss prediction models for each of the scenarios are discussed. Then the special constraints in train-to-train communication are identified. Section 3 examines the doppler shift present in the train-to-train channel and section 4 presents the fading characteristics of the chosen railway scenarios. Finally, section 5 introduces the delay spread features of the channel before section 6 provides a summary.

II. PATH LOSS

Accurate prediction methods are needed to determine the parameters of a radio system which has to provide efficient and reliable coverage of a specific service area. Factors that influence the signal strength are buildings and other man made obstacles, which produce multipath. On the other hand, trees and other vegetation cause shadowing, scattering and absorption.

In the ideal case of no obstacles the path loss would be the free space loss:

$$L_B(\text{dB}) = 32.44 + 20log_{10}f_{\text{MHz}} + 20log_{10}d_{\text{km}} \quad (1)$$

In order to obtain transmissions under free space conditions, the first Fresnel zone should be kept substantially free of obstructions [10]. The radius of a transversal section of the Fresnel ellipsoid is given by

$$r_n = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}}, \quad (2)$$

where, d_1 and d_2 are the longitudinal distances from the transversal section to the transmitter and receiver, respectively.

To have less obstacles within the first Fresnel zone, antennas are usually installed in elevated areas. For train-to-train communication the antennas will be installed on the top of the trains, which is around 4.8 m over the floor level. Since the floor is a fixed obstacle, the maximum propagation distance where free space conditions can be considered is $d_1 + d_2 = d$ in equation 2, being $d_1 = d_2$, where $r_n = 4.8\text{m}$ and $\lambda = \frac{c}{400\text{MHz}}$ as can be seen in Figure 1. This means, up to $d = 123$ m Free Space Loss conditions can be considered. Therefore, (1) is not applicable for large distances.

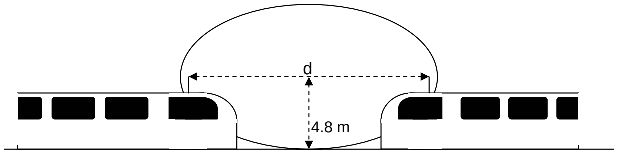

Fig. 1. Obstruction of the first Fresnel zone by the ground level.

1) Scenario Train Station: Train station structures mainly contain parallel "streets" separated by platforms. Due to its reduced dimensions a train station can be considered a microcell. Big main stations are covered by high roofs, that do not interfere in the propagation of the LOS signals. Small train stations are not covered at all and in middle size train stations each platform is covered separately by a roof situated at the same level as the train roof, therefore separating physically the visibility among train antennas placed in parallel streets.

Following those observations, small and big train stations can be modeled as wide avenues, while railways of medium sized stations are considered as parallel streets. As it has been analyzed the first 123 m can be modelled by (1). For larger distances we consider an empirical model suggested by Kaji and Akeyama for microcells with low antenna heights inside streets [11] as applicable, though it is only proposed for distances d between 200 m and 1 km:

$$L(dB\mu V) = -20log_{10}(d^a(1 + \frac{d^b}{g})) + c \quad (3)$$

In this formula a is the basic attenuation rate for short distances, i.e. 1.15 for 5 m antenna height, b is an additional attenuation rate for distances beyond the breakpoint g, i.e. the position where the first Fresnel zone just touches the ground surface, so $\frac{123}{2} = 61.5m$. For the train roof mounted antenna height, $b = -0.14$ and the offset factor $c = 94.5$. These values are in principle adjusted for the 900 MHz band except g that has been calculated above. However, measurements taken at different frequencies (see [10]) show, that there is high correlation between them for short distances.

2) Scenario Shunting Yard: Shunting Yard are open areas grouping parallel rails. They are usually close to a train station and therefore delimited by cuttings, that are often lower than the train heights and thus under the antenna level. Behind the cuttings, the shunting yards are surrounded by buildings.

Consequently, this structure allows for LOS. According to measurements taken in similar conditions [12], the signal variability can be well predicted by a two-ray model, where one ray is LOS and the second one is ground reflected.

$$\begin{aligned} L_B(dB) &= 40log_{10}d - 20log_{10}h_T - 20log_{10}h_R \\ &= 40log_{10}d - 27.24 \end{aligned} \quad (4)$$

where h_T and h_R are the antenna heights and as such equal to 4.8 m.

3) Scenario Regional Network: Regional networks cover relatively large areas. Therefore microcellular models are not applicable any more and due to the variety of radio propagation environment more general models are necessary. Currently, for macrocells, the Okumura-Hata Model is still the most used [13]. The model is valid for frequencies between 150 MHz and 1500 MHz and for distances up to 20 km. Consequently, the model is appropriate for train-to-train communication in terms of frequency. Since the maximum expected necessary range is 5 km, the model fits as well in terms of range. The most suitable version of the Okumura-Hata model would be the path loss model in open rural areas [13] given by:

$$\begin{aligned} L_B(\text{dB}) = L_B(\text{Urb}) &- 4.78(log_{10}f_c)^2 \\ &+ 18.33log_{10}f_c - 40.94 \end{aligned} \quad (5)$$

where $L_B(\text{Urb})$ is the path loss in urban area and is given by (6)

$$\begin{aligned} L_B(\text{Urb}) = 69.55 &+ 26.16log_{10}f_c - 13.82log_{10}h_t \\ &- a(h_r) + (44.9 - 6.55log_{10}h_t)log_{10}d \end{aligned} \quad (6)$$

In (5) and (6), f_c is the frequency in MHz, h_{te} and h_{re} are the effective antenna heights in meters, d is the distance in kilometers and $a(h_{re})$ is a correction factor that depends on the coverage range, in our case:

$$a(h_r) = (1.1log_{10}f_c - 0.7)h_r - (1.56log_{10}f_c - 0.8) \quad (7)$$

In regional networks the train travels through flat terrain in the best case, but it can as well travel through forest or, which would be worst, through mountainous areas. According to measurements [15] it corresponds to a suburban model. Therefore, in this case the Hata-Okumura Suburban model applies:

$$L_B(dB) = L_B(\text{Urb}) - 2(log_{10}\frac{f_c}{28})^2 - 5.4 \tag{8}$$

A well-known model for the attenuation due to foliage is the COST-235 model [14], which also includes an adjustment to account for seasonal variation in tree conditions, for vegetation out of leaf shown in (9) and in leaf given by (10). However, this models are only valid in order to calculate local path loss.

$$L_B(dB) = 26.6 f_c^{-0.2} d^{0.5} \tag{9}$$

$$L_B(dB) = 15.6 f_c^{-0.009} d^{0.26} \tag{10}$$

where f_c is in MHz and d in metres.

DVB-H [8], a system situated in a frequency band close to 400 MHz, uses the GSM COST-207 channel model [9]. Furthermore, GSM-R utilizes COST-207 as basic channel model. However, since GSM-R is high speed line oriented, LOS can be assumed due to the gently curved track and the continuous presence of base stations along the tracks. Therefore a LOS path has to be added to the GSM model. Nonetheless, unlike GSM-R, our train-to-train communication approach is regional network oriented and infrastructureless. Consequently, no base station can be used, the lines are not gently curved, usual curvatures lie around 250 m and curvatures down to 160 m can be found. The railway street width for train speed up to 200 km/h is 11.60 m, beyond this speed, the width is 13.30 m. Therefore the first obstacle the signal finds in its way is the ground.

According to measurements taken by Göller [15], the radio environment for railways is predominantly rural. When the railway runs through urban or mountainous areas, the hilly terrain or typically urban model would be more appropriate. The path loss models that GSM employs are Hata-Okumura versions and other COST models improved with topographical data bases. Since we require a general model, topographical data bases would be superfluous.

There is a path loss model in forest environment developed for TETRA [16]. However, although the frequency band is the same, this model is for short range applications of a few hundred meters only.

Therefore, the prediction path loss in regional networks in our approach will be calculated with a Hata-Okumura model. The drawback of this model is that it is valid for values of antenna heights h_{te} greater than 30 m. This is obviously not the case for trains. Nonetheless, a higher antenna implies a larger coverage, on the other hand, when the antennas are at the same level surrounded by structures on both sides, like in the case of a forest, a guiding effect exists. Consequently, and due to the heterogeneous landscape where the trains run, the suburban model will be employed. As it can be seen in Figure 2, this model is more optimistic than the Urban one, but worse than the open rural path loss prediction model.

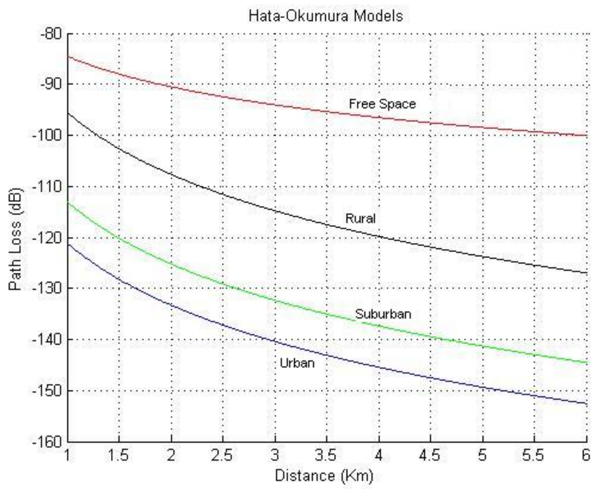

Fig. 2. Hata-Okumura path loss prediction models.

Shadowing due to structures like bridges is unlikely, since the bridges are situated above the antenna level. Similarly, cuttings do not constitute a shadowing source, their slopes of 20-30 degrees have even a guiding effect. However, mountains may cause severe shadowing.

Tunnels are large sections, constructed in concrete, with smooth curves that act like waveguides. Their cut-off frequency is a few MHz. Therefore train-to-train signals can be guided. The path loss is between 15-25 dB per kilometre [17]. Additionally, 15-20 dB should be added due to diffraction at the edges of the tunnel, from inside to outside, and from outside to inside the tunnel.

III. DOPPLER

It is well known that the relative motion of transmitter and receiver produces an apparent change in frequency. This is the Doppler shift that is described in (11).

$$f = \frac{v}{\lambda} cos\alpha \tag{11}$$

The maximum Doppler frequency shift f_m occurs when the communicating trains run in opposite direction ($\alpha = 0$) on a straight line. In this case $f_m = \pm\frac{v}{\lambda}$.

As a result of the existence of many scatters coming from different directions, the apparent frequency shift will be diverse for each scatter. Hence, a Doppler spectrum is shaped.

In the case of isotropic scattering radiation, the Doppler spectrum is the Jake's model given by

$$D(f) = \frac{1}{\sqrt{1-(\frac{f}{f_m})^2}}. \tag{12}$$

This approximation is not valid when there is LOS. For LOS a Doppler spectrum with an added δ-function [9] can be used:

$$D(f) = \frac{0.41}{2\pi f_m \sqrt{1-(\frac{f}{f_m})^2}} + 0.91\delta(f-0.7f_m). \qquad (13)$$

1) Scenario Train Station: The structure of train stations allows for LOS in train-to-train communication. The speed of the trains in this area is lower than 20 km/h. This low speed leads to a small maximum Doppler shift of few Hertz, and would cause a δ in the Doppler spectrum.

2) Scenario Shunting Yard: In shunting yards the speed of the trains is very low as well. The usual speed limit is 25 km/h, whereas an exceptionally permitted maximum speed in the area is 40 km/h. As in the case of train stations, the Doppler spectrum is given by (13).

3) Scenario Regional Network: Regional networks permit speeds up to 200 km/h, the apparent speed of two trains driving one to each other is 400 km/h. The resulting maximum doppler shift is 148 Hz at 400 MHz.

The Jakes Doppler spectrum applies in this case. This point is confirmed by the TETRA rural channel [7].

IV. FADING

The models analyzed in the previous section refer to the median signal strength value. Due to changes in the environment, fluctuations of various tens of decibels around this median value are feasible.

There is a variation in the median signal as the train moves from place to place caused by large-scale variations in the terrain profile along the path due to changes in the nature of the local topography. This is the slow fading, characterized by a log-normal distribution.

Fast fading are variations caused by multipath propagation in the immediate vicinity. When good visibility exists, LOS is possible and the channel is Ricean, in the other case the channel is Rayleigh. The Rayleigh fading is characterized by its standard deviation σ, while the Ricean fading is characterized by a parameter $K = \frac{A}{2\sigma^2}$ which can be interpreted as the ratio of the LOS signal A to that of the multipath components, i.e. the random components. The value of σ can be extracted from K.

Therefore, in order to determine the amplitude in a point, three models have to be taken into account, the path loss model, slow fading and fast fading.

Knowing the standard deviation value, it is possible for Jakes doppler spectrum channels to calculate the rate at which fades of any depth occur and the average duration of a fade below any given depth. This is of extreme importance when designing the system, because it provides a valuable aid in selecting coding schemes, word lengths and bit rates. The rate at which fades below a threshold R occur is given by the *level crossing rate* (LRC) parameter described in [10]:

$$LRC = \sqrt{\frac{\pi}{\sigma^2}} R \cdot f \cdot e^{(-\frac{R^2}{2\sigma^2})} \qquad (14)$$

The *average duration of a fade* (AFD) below a threshold R is given by [10]:

$$AFD = \sqrt{\frac{\sigma^2}{\pi}} \frac{e^{\frac{R^2}{2\sigma^2}} - 1}{R \cdot f} \qquad (15)$$

where f is the frequency.

1) Scenario Train Station: As it has already been discussed, train stations allow for LOS. Therefore the fast fading in train stations is Ricean. An average Rice parameter for ranges under 6 km, as it is the case for train stations and town environments, is $K = -1.2$ [10].

2) Scenario Shunting Yard: Similarly to train stations, shunting yards would have a Ricean channel. The Rice parameter should be in the same range as for train stations $K = -1.2$.

3) Scenario Regional Network: In contrast to the GSM-R high speed line channel, modelled by Ricean fading, the fading that can be found in regional network channels is typically Rayleigh, since no line of sight can be guaranteed. Some measurements have been conducted in areas with Rayleigh characteristics, which we consider representative also for train-to-train communication in regional networks. As a result, the standard deviation was 5.57 dB [15].

In section II, it has been explained that the worst scenario in regional networks is given in mountainous areas, where the channel has a suburban or even urban characteristic. For this case, measurements carried out by Okumura in Tokio show that in suburban areas or in hilly terrain typical values for the standard deviation were 7 dB in the 400 MHz band. Other measurements in the 400 MHz band showed 5.65 dB. Consequently a standard deviation of 6 dB seems to be reasonable.

There are as well some equations describing the standard deviation of the slow fading in terms of frequency [18] as shown in (16), which gives us $\sigma = 11.4$ dB at 400 MHz. Other models for standard deviation take into account the type of terrain by means of a parameter Δh [19] which depends on the terrain roughness. This model is described in (17). Δh lies between 80 and 150 for hilly terrains, 150 and 300 for mountainous terrain and 300 and 700 for rugged mountainous terrain. This leads to values of σ between 11.25 dB and 12.97 dB for hilly terrains, till 15.4 for mountainous terrain and till 19.6 dB for rugged mountainous terrain.

$$\sigma(dB) = 3log_{10}f_c + 3.6 \qquad (16)$$

$$\sigma(dB) = 6 + 0.55\sqrt{\frac{\Delta h}{\lambda}} - 0.004\frac{\Delta h}{\lambda} \qquad (17)$$

V. DELAY SPREAD

This section concentrates on describing the multipath effect over the bandwidth of the signals. If the transmitted signal bandwidth is sufficiently small, so that all the frequencies behave similarly, then the channel has flat fading. In this case, the delay of the paths is spread inside the transmitted symbol. When the delay spread is greater than the symbol period, the channel exhibits frequency-selective fading and yields *inter-symbol interference* (ISI) which produces severe distortion of the signal. For that reason, the delay spread delimits the coherence bandwidth, the spectral area were the transmitted signal is not severely distorted.

Typical values of multipath spreads range from 1 to 10 μs in urban and suburban areas, whereas in rural and mountainous areas they are in the range from 10 to 30 μs [13]. Higher frequencies show higher delay spreads. A deterministic analysis of two railway scenarios at 5 GHz, noise barrier and vegetation, provides 1 μs and 0.71 μs of delay spread respectively [5]. However, experimental models show higher delay spread in similar scenarios at lower frequencies. The exception is the model for the TETRA system considered a flat fading channel and where no delay spread is specified [7].

1) Scenario Train Station: A train station can be considered as an urban area. The GSM model for urban areas advises a minimum delay spread of 1.6 μs and a maximum of 5 μs [9].

2) Scenario Shunting Yard: A significant model that can be found in the literature similar to the shunting yard scenario is the motorway scenario in the DVB-T system [8]. This model provides a maximum delay of 9 μs.

3) Scenario Regional Network: The best scenario present in regional networks are open areas or areas with forest, where the number of paths is reduced due to the absence of obstacles or the absorbtion characteristics of foliage areas. In these cases, the GSM-R rural area model which presents a maximum delay between 0.4 and 0.6 μs can be used [3]. However, in the presence of mountains where the signals are much better reflected, the adequate model would be the hilly terrain one. This model presents a maximum delay spread around 20 μs.

VI. CONCLUSION

In this paper, we presented a comrehensive channel model for a train-to-train communication system in the 400 MHz frequency band. Concretely, this channel model will be used in the design of the RCAS system. The analysis is divided into three basic scenarios: train stations, shunting yards and regional networks. The presence of other structures, like bridges and tunnels has been studied as well. A microcell, two rays, and Hata-Okumura models have been considered as the basic path loss models for each scenario respectively. A relatively low maximum Doppler frequency shift of 148 Hz can be found. When a Ricean channel applies, the fast fading factor is $K = -1.2$, whereas in the case of Rayleigh fading the considered standard deviation is $\sigma = 6dB$. Finally, maximum delay spreads of 5, 9 and 20 μs for trains stations, shunting yards and regional networks are considered.

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