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Characterization of the Propagation Channel aboard Trains

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Abstract-The propagation channel aboard trains is investigated with reference to the attenuation law governing propagation within cars, to the frequency response and impulse response for both horizontal and vertical polarization, and to the delay spread. Results show that the path loss exponent is slighlty smaller than in free space, possibly due to reflections by metal walls, and that it does not depend significantly on the position of transmitter and receiver. Also, the average value of the delay spread changes with polarization, proving that the latter impacts the channel's statistical properties. The main application of the study is the investigation of the reliability features of telecommunication systems on board, for both infotainment and safety purposes.

I. Introduction

Use of telecommunication services aboard trains is becoming more and more common for providing information and entertainment (i.e., infotainment) services to passengers during trips. Access to GSM and UMTS systems is usually deployed by means of base transmitting stations (BTS) located along the train tracks, also providing service to nearby communities. However, more recently WiFi access points have started to be mounted on board with the aim of providing passengers with wide-band access to the Internet.

Trains are a possibly harsh environment to wireless propagation, given the presence of metal walls, large obstacles like seats, moving obstacles like passengers, not to mention the host of electric and electronic equipment whose emissions may interfere with the optimal operation of service, or the power quality phenomena that propagate through the power system and that may cause interference with electronic devices [1]–[3]. To determine the optimal strategies against performance degradation, a thorough investigation of the quality-of-service (QoS) parameters is therefore required. This in turn calls for actions in two different fields of research: first of all, the study of the propagation characteristics aboard trains (i.e., the propagation channel) is necessary to explore the propagation law that rules attenuation of the signal in the train environment along with the multi-path characteristics. Secondly, the effects of external disturbance onto the telecommunication signal must also be investigated. With reference to the latter topic, in [4]–[6] authors have performed an extensive measurement campaign to characterize the time and frequency behavior of the transient disturbance radiated by the electric arc generated at the gap between pantograph and overhead wire that may arise during the train trip, with a specific focus on: *i*) the transient amplitude, rise time and duration, whose empirical cumulative distribution functions (CDF) have been compared to some theoretical models; *ii*) the average power spectrum, to explore the frequency range bounding most of the disturbance power; *iii*) the time-frequency behavior, to determine the persistence over time of each frequency component. The effect of pulses onto some QoS parameters have been investigated in [7], [8], where the bit and frame error rates have been correlated to transient characteristics to assess reliability of the GSM-R system usually devoted to both ground-to-train voice and data communication. The results of the experimental investigation can return useful information for FMECA analysis of systems mounted on board [9].

With reference to the characterization of the propagation channel, it is required that the propagation law is determined and that the multi-path features are explored. It must be said that the environment inside the train has not been fully investigated yet. This is mostly because until recently transmission used to occur between a transmitter located outside the train (i.e., the BTS) and a client inside it (i.e., the passenger). Literature about this topic usually includes research papers about the propagation in different scenarios and at different frequencies. In [10], [11] the propagation of a signal at 5 GHz in free space between a BTS and an high-speed train has been simulated, showing that the use of a directive antenna reduce the Doppler spread and increase the received power when train runs towards the BTS; when train moves away from BTS the omni-directional antenna provides better results.

In [12]–[15] the effect of some particular structures like viaducts and terrain cuttings (canyons) onto a GSM-R telecommunications system has been take into account. Results show that the classical model for propagation loss (such as Hata model and two-ray model) are inadequate for attenuation prediction. Moreover, the presence of canyons, especially if topped by bridges, determines higher path losses than in the case of viaducts. Papers [16]–[19] study the propagation inside high-speed, medium-sized and subway tunnels by a narrow-band approach. Both fast fading and slow fading is present; however, path loss is lower than in the free space and is related to the tunnel cross section. With specific reference to propagation on board, in [20], [21] an experimental study has been performed with reference to the attenuation of the signal between and within train cars with a wide-band approach. A narrow-band approach has also shown that the transmitted signal can re-enter cars through windows and that its contribution to inter-car propagation is more relevant than the line-of-sight (LOS) signal, although the use of omni-directional antennas limits the study of multi-path characteristics. In [22] propagation on board has been analyzed with a 2.35 GHz continuous-wave signal and both a planar and an omnidirectional antenna, placed at different locations. The path loss and the Ricean K-factor are shown to be related to the antenna type, while the delay spread (its distribution, mean and variance) is independent on the measurement configuration. Studies performed aboard ships [23]–[28] only partially can be applied to trains due to the geometrical ad electromagnetic difference between the two propagation scenarios: trains can be modeled as cylindrical waveguides with apertures (windows), while ships can be modeled either as large horizontal areas (decks) between reflective planes (ceiling and floor) or as rectangular waveguides without apertures (corridors). The paper is organized as follows: in Section II the measurement setup and methodology for the experimental studies are described; in Section III the results are presented.

Fig. 1. Measurement setup

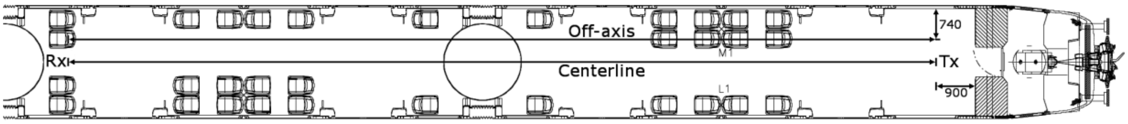


Fig. 2. Train layout

II. Measurement setup

Measurements were run on a 1500 Vdc electrified transportation system run by Circumvesuviana s.r.l., an Italian local transportation service whose network covers over 140 km with 6 lines and 96 passengers stations. The system’s maximum speed is 90 km/h, the average speed around 60 km/h, while the commercial speed (average speed including station stops) is 38 km/h.

Characterization of the propagation channel has been carried out with a narrow-band analysis. The two ports of a FieldFox N9918A Vector Network Analyzer by Agilent have been connected to a BBHA 9120D horn antenna manufactured by Schwarzbeck (at the transmitting end, port 1) and an EM6865 biconical antenna by Electrometrics (at the receiving end, port 2) through coaxial cables. The system has been preliminary calibrated according to an automated procedure to normalize the results with respect to the attenuation introduced by cables. Antenna factors have not been taken into account. This is not a limitation to the research because its main focus is on the propagation loss exponent, i.e. the steepness of the attenuation law, and not on the absolute value of the loss itself. Measurements have been executed in a steady train, without significant reflectors in close proximity on the outside of the car.

Path loss measurements were made both at the centerline of the car and away from it (off-axis measurements) at 120 cm height. Fig. 2 shows the layout of the train with distances from the wall for the two propagation configurations. In both configurations the distance between transmitter and receiver antenna was changes from 1 to 20 m in 10 cm steps. Fig. 1 shows the typical propagation environment for off-axis measurements. Beside reflection due to metallic walls, propagation is affected by the presence of seats and vertical handrails. Their presence has also reduced the number of measurements points from 190 to 171 and 151 for the centerline and

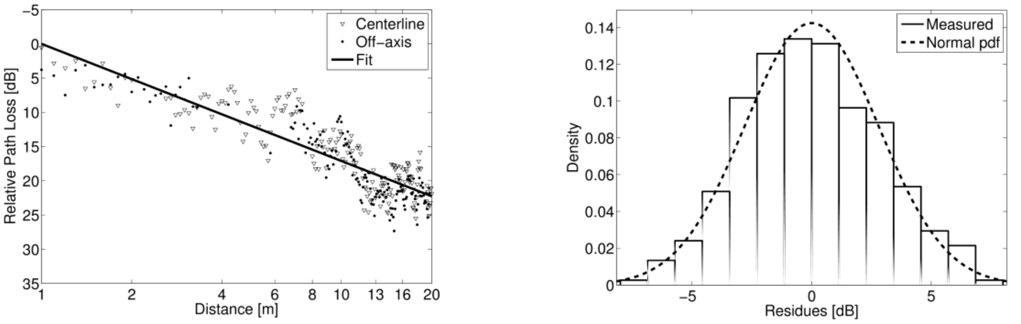
off-axis configuration, respectively.
Delay spread measurements were carried out at the centerline of the car, both in vertical and horizontal polarization, at 120 cm height. The distance between antennas was 10 m but the position of the entire system (transmitting and receiving antenna) was changes in 10 cm steps: the first measure was taken with the transmitter antenna at 90 cm from the wall (see Fig. 2); in the last measure the transmitter antenna was at 10.90 m from the wall. Due to the presence of the vertical handrails, the numbers of measured points was 77 for the vertical polarization and 76 for the horizontal polarization, instead of 100 theoretical points.

II. Results

In the following paragraphs we will present results about some typical propagation parameters, namely: the propagation loss, frequency and impulse response for both vertical and horizontal polarization and the associated delay spread.

A. Propagation loss

Characterization of channel propagation in the WiFi band has been carried out because it is expected that internet access is provided with a WiFi access point mounted at some location inside cars. Fig. 3a shows the relative path loss [29] for the investigated band, i.e. the path loss obtained by normalizing the received power to that measured at 1 m from the transmitting antennas. Measured data are shown for both centerline and off-line measurement, while regression is carried out without distinction between the two configurations.



(a) Path loss (b) Residues

Fig. 3. (a) Relative path loss for centerline and off-axis with regression; (b) distribution of residues

Variations about the regression line is caused by the expected uncertainty contribution [30] inherent to electromagnetic phenomena and electromagnetic measurement setups [31]–[33]. It must be said that, in principle, because of the inhomogeneity of the propagation environment (see Fig. 2), different exponents are expected to rule the power-decay law along the channel. This suggests to adopt the approach shown in [34]. However, the limited number of points assigned to each propagation layer would have resulted in a reduced significance of the regression analysis. For this reason, the exponent n can be thought of as being representative of the average behavior over the whole distance. The adopted propagation loss model is the following:

(1)

where d_0 = 1 m is the reference distance and X is a random variable describing the effect of multipath propagation onto received power, expected to be distributed according to a Normal r.v..

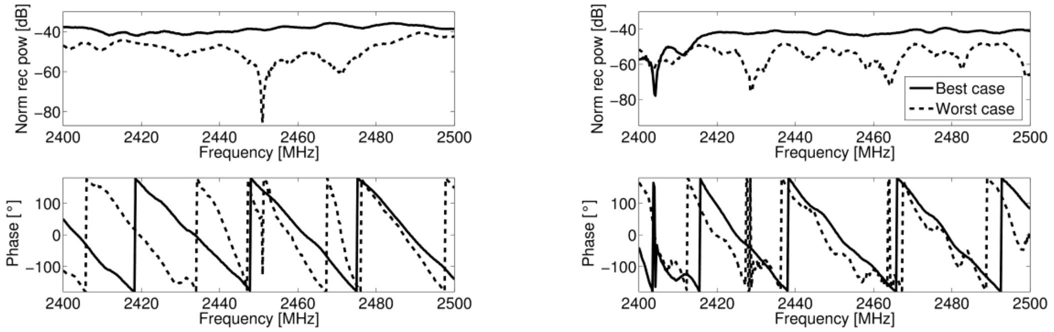
Table 1. 95% confidence interval for n

n, average	n_c, centerline	n_o, off-axis
[1.61;1.81]	[1.53; 1.81]	[1.60;1.86]

Based on the regression analysis, the exponent ruling the propagation loss is n = 1.71, smaller than that for free-space due to the contribution of reflection by metal walls. The exponent pertaining to the two different propagation, i.e. centerline and off-axis measurements, are n_c = 1.67 and n_o = 1.73 respectively. The strong overlap of the 95% confidence interval associated to n_c and n_o, shown in Table 1, proves however that propagation in the two configuration is very similar. Fig. 3b shows that the Gaussian model fits the experimental distribution of residues from the linear regression as expected by the model (1).

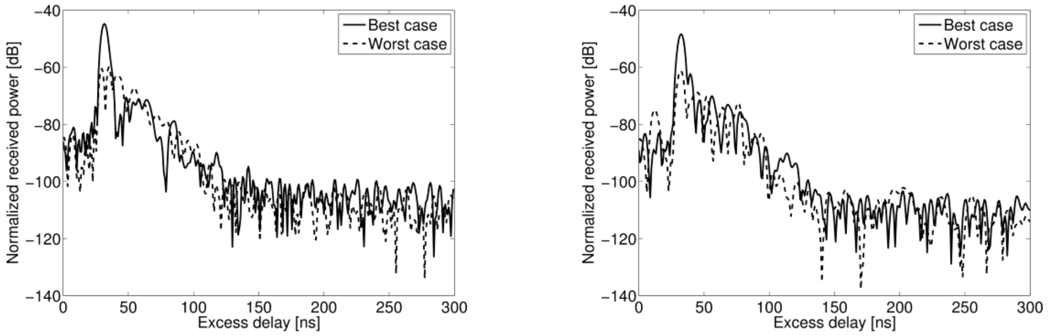
B. Frequency and impulse response

Fig. 4 show the frequency response (magnitude and phase) of the propagation channel for both horizontal and vertical polarization, with 10 m separation. In each figure the responses with the smallest and largest *rms* delay spread, calculated according to [35] and described in the next section, are plotted. The square magnitude of the associated impulse responses are plotted in Fig. 5.



(a) H polarization (b) V polarization

Fig. 4. Frequency response for (a) horizontal and (b) vertical polarization



(a) H polarization (b) V polarization

Fig. 5. Impulse response for (a) horizontal and (b) vertical polarization

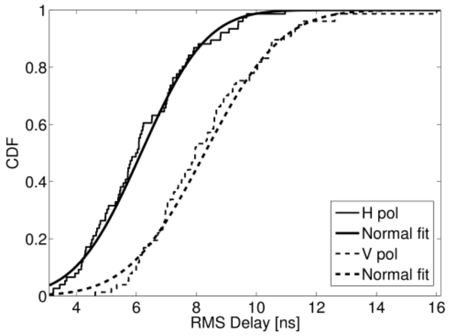


Fig. 6. Distribution of Delay Spread

B. Delay spread

The experimental distributions for the delay spread obtained from measurements in both horizontal and vertical polarization are shown in Fig. 6. In both cases, the Normal distribution provides the best fit as expected [36]. To exclude noise from the computation of the delay, we used the last 100 bins (about 90 ns) of the response to estimate the mean value and the standard deviation of the noise; then we set a threshold four times the standard deviation above the noise mean value. Delays spread's sample means and standard deviations are reported in Table 2. Hypothesis about equality of averages and variances between the two polarization have been tested, resulting in failing to reject the null hypothesis of equality of variances at ($P = 0.16$), while equality of means has been rejected ($P < 0.1\%$).

Table 2. Delay spread

pol	[ns]	s [ns]
H	6.2	1.7
V	8.3	2.0

II. Conclusions

The characterization of propagation aboard train with a narrow-band methodology has been presented. Results show that the propagation law is very close to the free-space one, without significant differences between the investigated propagation conditions, while the delays spread is strongly dependent on the polarization of the test signal, the horizontal polarization showing typically smaller spreads.

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