Measurement 110 (2017) 43–52

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

# Propagation modeling for outdoor-to-indoor and indoor-to-indoor wireless links in high-speed train

Lei Zhang [a,b,*], José Rodríguez-Piñeiro [c], Jean R.O. Fernández [b], José A. García-Naya [c], David W. Matolak [d], Cesar Briso [b], Luis Castedo [c]

[a] Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
[b] Department of Signal Theory and Communications, Technical University of Madrid, 28031 Madrid, Spain
[c] Department of Computer Engineering, University of A Coruña, 15071 A Coruña, Spain
[d] Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

ARTICLE INFO

*Article history:*
Received 19 July 2016
Received in revised form 26 May 2017
Accepted 12 June 2017
Available online 15 June 2017

*Keywords:*
Propagation measurements
Channel modeling
Railway
High speed train
Relay system
LTE

ABSTRACT

Nowadays telecommunication companies have shown a great interest in deploying broadband mobile wireless networks in high-speed trains (HSTs) with the aim of supporting both passenger services provisioning as well as automatic train control and signaling. The train carriage, as a confined steel structure, has specific propagation characteristics, which motivates the study of the indoor-to-indoor and outdoor-to-indoor radio propagation characteristics for broadband wireless communication systems in high-speed railways, constituting the main contribution of this work. This study has been performed by means of measurements considering an actual Long Term Evolution (LTE) network deployment, as well as a portable test transmitter and different configurations of antennas and receivers at 2.4, 2.6 and 5.7 GHz in a commercial high-speed rail line in Spain. The results show that radio waves incur obvious waveguiding effects inside the HST car. Moreover, for the propagation from the railway station to a mobile receiver inside the HST car, waves at higher frequencies experience less attenuation through the train carriage, by better propagating through windows. Although the railway station and train interior contain objects that induce a rich set of multipath components, the analysis of small-scale fading statistics shows that the channel still has a dominant path. Also, the LTE coverage tests for Base Transceiver Station (BTS)-Train and BTS-Mobile links were conducted and with internal and external antennas on board the train. We found that there was a strong signal penetration loss of approximately 26 dB caused by the train carriage structure. The final results constitute an initial model for the propagation incurred by a relay-based communications system for fourth generation (4G) network in railways.

## 1. Introduction

During the last few years, the increasing demand for the use of mobile phones, laptops and other wireless devices by high-speed-train passengers has attracted great interest from railway companies. Simultaneously, the Mobile-Relay technique has been proposed in [1] as a way to provide coverage to passengers based on a relaying scheme (from cellular base to an external antenna on the train, which is then relayed to a local base within the train carriage).

These factors motivate the increasing interest in the radio propagation characteristics for wireless communication systems in railways, with the aim of providing broadband communications in trains [2]. Propagation properties for different yet related scenarios involving outdoor-to-indoor transmission with movement have been studied, such as for elevator shafts [3], cars [4], aircraft [5], indoor environments [6], such as rooms, corridors, and tunnels [7,8]. In these settings, researchers concluded that path loss exponents are less than 2 in the confined scenarios, which indicate waveguiding effects. This effect also has been reported in [9–11] in the case of radio propagation aboard the train in the 2 GHz band. Reflected waves from car-body in railway tunnel at 2.4 GHz have been estimated by Finite-Difference Time-Domain (FDTD) analysis in [12], which states that a nearby train does not significantly affect the radio propagation. Experimental results in [13] have shown an extra 10.4 dB loss of the signal re-entering through the

---

* Corresponding author at: Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China.

*E-mail addresses:* lei.zhang@mail.sim.ac.cn (L. Zhang), j.rpineiro@udc.es (J. Rodríguez-Piñeiro), jean.raphael.olivier.fernandez@gmail.com (J.R.O. Fernández), jagarcia@udc.es (J.A. García-Naya), matolak@cec.sc.edu (D.W. Matolak), cbriso@diac.upm.es (C. Briso), luis@udc.es (L. Castedo).

http://dx.doi.org/10.1016/j.measurement.2017.06.014
0263-2241/

windows of the train in Inter-Car links at 5 GHz. The performance for fourth generation (4G) systems under high-speed conditions in a car by using both antennas placed outdoors and indoors was experimentally studied in [14], while in [15] a similar scheme was deployed for subway tunnel scenarios. Outdoor-to-indoor high speed channels were also evaluated by means of measurements and simulations in [16,17].

In general, a wireless network access system for the railway environment can be classified into five types:

1. Intra-Car link: the link between a mobile receiving device and an Access Point (AP), both located inside the same railway car.
2. Inter-Car link: the link between a mobile receiving device inside one railway car and the AP located inside another other railway car.
3. Station-Mobile link: the link between a mobile receiving device inside one railway car and the transmitter located in the railway station.
4. Base Transceiver Station (BTS)-Train link: the outdoor-to-outdoor link between a BTS and the external antennas of the train.
5. BTS-Mobile link: the outdoor-to-indoor link between a BTS and a mobile device inside the train.

The main contribution of this article is to present a propagation study for the five aforementioned wireless communication links by means of measurements in the real train environment at three frequencies: 2.4 GHz, 2.6 GHz and 5.7 GHz, which cover both the outdoor-to-indoor and indoor-to-indoor scenarios in railways. Different setups are considered to model both the large-scale and small-scale fading inside the train. On the other hand, the average SNR gain when using the outdoor antennas with respect to the indoor ones is about 26 dB for the whole path.

The rest of the paper is structured as follows: Section 2 describes the scenarios as well as the equipment used for the measurement campaign in the high-speed test line; Section 3 presents the empirical results, the path loss models for the wireless communication links and small scale fading evaluations, as well as the presentation and analysis of the results from broadband Long Term Evolution (LTE) signal measurements when the train is moving. Finally, Section 4 is devoted to the conclusions.

## 2. Experimental setup

We evaluated experimentally the five types of wireless network access systems for the railway environments that we have considered: intra-car, inter-car, station-mobile, BTS-train, and BTS-mobile. Our aim is to compare the classical approach of direct communication link between the BTS and the mobile receiver of each passenger inside the train with an alternative approach based on a relay architecture where the signal is distributed inside the train through repeaters or APs, whereas external (train-car mounted) antennas are used for the BTS-train link. It is worth noting that at least two different links are involved in a relay architecture, which are: (a) the BTS-train link, and (b) the Intra-Car link (or the Inter-Car link). In this work, these links are studied independently, e.g., no coordination or interference between these links is considered. In a practical deployment, several possibilities could be implemented, such as: (i) a simple amplify & forward scheme or (ii) each AP on the train acts as a femtocell to the LTE network [18]. Whereas the first approach is probably the simplest one, some interference management mechanism is required in case that the same frequency bands are used for both links in Frequency Division Duplex (FDD). Regarding the second approach, it may be more efficient in terms of resource sharing, although it would probably require the installation of a different femtocell per network operator. Alternatives involving non-LTE signals inside the train could be also considered, such as Wi-Fi APs.

The railway test environment described above is shown in Fig. 1, where the tower used for the BTS antenna deployment, the test train, and the interior of a train car are shown.

### 2.1. Measurement environment

The measurement campaign was conducted at the high-speed rail line between Córdoba and Málaga (Spain), where the commercial operation speed reaches up to 330 km/h. The test track is a segment in the vicinity of Antequera-Santa Ana railway station (Kilometric Point (KP) 96.800). This track section includes a BTS site located at KP 97.075[1] consisting of 2G/3G commercial equipment with a 40 m height tower with antennas for different wireless technologies and frequencies (see Fig. 1(a)). The train was parked at the railway station (not moving) for the measurements considering intra-car, inter-car, and station-mobile links; and moving in the open area during the tests of BTS-train and BTS-mobile links.

The test train was the *Séneca* laboratory train (Talgo A-330) provided by the Spanish railway operator ADIF. It is a 80.92 m long electric train that can reach a maximum speed of 363 km/h (see Figs. 1(b) and (c)). The cross section of the *Séneca* train is shown in Fig. 1(e), which also specifies the size of the narrow transition door between carriages.

### 2.2. Evaluated wireless network access systems

Two different testbeds were used to measure the five considered wireless network access systems. The first testbed is used for modeling the propagation conditions of a receiver inside the train carriages (intra-car, inter-car, and station-mobile link measurements), whereas the second one – the so-called GTEC Testbed [19] – is employed for measuring the propagation between the train and a commercial Evolved NodeB (eNodeB) when using external and internal antennas at the train (BTS-train and BTS-mobile link measurements, respectively).

#### 2.2.1. Intra-car, inter-car, and station-mobile link measurements

These measurements were performed with the train parked at the railway station. The propagation testbed transmitter was installed at a fixed position in the first car, whereas the testbed receiver was moved inside the train for the intra-car and inter-car links. For the station-mobile link, the transmitter was placed at the platform and the receiver was moved inside the train. The moving distance of the receiver is about 40 m, which is longer than the length of two train cars.

The propagation testbed transmitter consists of two continuous wave (CW) transmitters followed by power amplifiers and antennas for each considered carrier frequency (see Fig. 2(a), the corresponding configuration parameters of the testbed are listed in Table 1). At the receiver, the testbed consists of a portable spectrum analyzer with a pre-amplifier as shown in Fig. 2(b). The sensitivity is $-100$ dBm and the dynamic range is 100 dB, from 0 to $-100$ dBm. All these devices are controlled by a custom-developed software installed in a laptop computer. On the other hand, the two receive antennas for 2.4 GHz and 5.7 GHz are omnidirectional in azimuth, and they are connected to the receiver and attached on the shoulder of the operator at 1.6 m height, whereas the transmitter antenna height is 1.7 m. Note that measurements were carried out at both frequencies separately.

---

[1] The exact Global Positioning System (GPS) coordinates of the site are $37^\circ\ 4'\ 3.14''$N, $4^\circ\ 43'\ 12.52''$W.