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Channel Models for Performance Evaluation of Wireless Systems in Railway Environments

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ABSTRACT In the automotive and rail domains, vehicles are entering the era of full automation thanks to wireless sensors and communication systems, shifting control functions from a human driver to computers. High data rate, robustness, high reliability and ultra-low latency wireless communications are required in the context of autonomous train and safety critical applications. Today, the Future Railway Mobile Communication System (FRMCS) is under development at European level within the International Union of Railways (UIC). This system will answer all the current and future needs of rail. It will be IP based, multi-bearer and resilient to technology evolution. In the context of the development of different FRMCS prototypes by industry, it is crucial to be able to test them in representative Railway radio environments thanks to laboratory tools. Characterization of radio channels in railway environments, by measurements or simulations, is a very active field. In this article, based on broad literature survey, we show that not all the published models are suitable for performance evaluation. Then, we propose a selection of typical Tapped-Delay-Line channel models to be implemented in an original hardware and software testing platform capable to reproduce the effect of representative Railway environments in laboratory, with real time emulation at RF (Radio Frequency) level. Preliminary results in Hilly 3 taps and Cutting 5 taps channel models are presented as a proof of concept of a *"zero on site testing"* approach, allowing for time and cost savings in the validation of railway communication systems.

INDEX TERMS Radio channel modelling, railway communications, tapped-delay-line models, channel emulator, open air interface, LTE.

I. INTRODUCTION

The deployment of various wireless communication devices is increasing in the railway domain, both for passenger applications and train operation, to increase safety and efficiency [1]. Particularly the need for safe and reliable radio links is becoming huge with the development of autonomous and driverless trains [2]. Today, Global System for Mobile communications-Railway (GSM-R) is obsolete [2] and a new Adaptable Communication System (ACS) for all railways, based on Future Railway Mobile Communication System [3], is under development. It is based on the concept of bearer independence [4] to ensure dynamic selection and combination of radio bearers. This will improve service availability, increase reliability and guarantee higher throughput, as well as resilience to technology evolution.

Testing these new systems along the tracks is time consuming and very expensive. Real trials should be replaced by appropriate emulation and test facilities in laboratory, able to reproduce representative railway environments for a large

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set of radio access technologies (RAT). This approach, called *"zero-on-site testing"*, consists of developing software and hardware tools allowing validation and verification activities in the laboratory, to avoid complex and expensive trials on real sites. It exists since several years in the automotive domain [5]. It should also permit the investigation of exceptional situations, such as security attacks, or severe failure, which cannot be accessed through real test runs along railway lines. As a consequence, a virtual test set-up requires the emulation of realistic and representative radio environments that rely on properly modelled radio channels. The European project Emulradio4Rail [6], within the Shift2Rail initiative [7], has developed an original testing and evaluation platform based on radio access emulation at RF level and network behaviour emulation at IP level. This platform can act as a flexible, configurable and programmable laboratory tool, to support the end-to-end validation in laboratory. The platform supports multiple RATs such as LTE, Wi-Fi, 5G and Satcoms. Therefore, it is crucial to emulate representative and accurate radio channel models to mimic Railway environments at the physical-layer.

The technical contributions of this article are twofold. First, it details a literature survey on railway radio channel models based on measurements and simulation and a methodology for the selection of representative models for railway environments, which are suitable for implementation in RF channel emulators for performance evaluation of wireless communication systems. Second, the paper describes the hardware and software components of the Emulradio4Rail platform and gives results of the proof of concept of the LTE emulation using the Open Air Interface (OAI) tool [8].

The paper is organised as follows. Section II gives generalities on mobile radio channel models. Mathematical representation and Tapped Delay Line (TDL) models are recalled. In section III, we describe the main railway radio environments such as open air, viaduct, cutting, hilly terrain and tunnel. In section IV, TDL models from the literature derived mainly from high-speed lines (HSL) measurements are detailed. Each environment is considered. Section V presents the selection of a set of railway TDL channel models that have been considered for implementation in the Emulradio4Rail platform. In section VI, the Emulradio4Rail platform developed for experimental assessment of the railway communication prototypes is described with the tests methodology. Then, end-to-end transmission results obtained with the platform while emulating LTE are given with two representative railway TDL models, namely a *Hilly* 3 *taps* and a *Cutting* 5 *taps* presented in Section V. Finally, some perspectives and conclusions are proposed.

II. MOBILE RADIO CHANNEL MODELS

A. MATHEMATICAL REPRESENTATION OF WIRELESS CHANNELS

The performance evaluation of wireless systems requires to model or to emulate the physical radio channel. The models are generally based on mathematical representation of the Channel Impulse Response (CIR) or the channel frequency response. This topic is widely treated in the literature and the channel models are constantly evolving, as the complexity of the communication systems increases. More and more parameters are taken into account in order to model radio channels as closer as possible to real channels. These radio channel models are generally obtained from measurements or simulations with ray tracing tools for example.

The CIR is a broadband characterization of the channel that contains all the necessary information to analyze any type of radio transmission across it. This results from the fact that, under certain conditions, the mobile radio channel can be modeled as a linear filter. It consists of the sum of the amplitudes and delays of several waves arriving at different moments of time. The base-band time-variant impulse response of the multipath channel can be expressed as (1) [9]:

$$h(t,\tau) = \sum_{i=0}^{N-1} c_i \cdot e^{j2\pi \cdot f_{di} \cdot t} \cdot \delta(\tau - \tau_i). \tag{1}$$

where c_i is the amplitude of the tap, f_{di} is the Doppler shift of the ith path and τ_i is the delay related to the ith path.

The Doppler shift refers to the shift of the radio signal frequency due to the mobility of the mobile station and variations in the environment. It is proportional to the mobile speed and the carrier frequency. The frequency spread corresponds to the difference between the largest and the smallest frequency shift due to multipath. Each individual path i arriving with an angle θ_i experiences a Doppler shift f_{di}. Then depending on the statistical distribution for the angle of arrival, a Doppler spectrum may be observed. When the distribution of the angles of arrival is uniform between $[-\pi, +\pi]$ the Doppler spectrum is the Jakes or Classical Doppler spectrum. This will considerably impact wireless communication, thus it is very important to have it into consideration in the chosen channel models.

The CIR can be expressed as simple TDL or Cluster-Delay-Line (CDL) models [10]. More complex models are available today, namely the WINNER II model proposed for 4G [9]. A survey focusing on general multiple-input, multiple-output (MIMO) models can be found in [11]. Trends on channel models for 5G are presented in [12], and [13] gives the 3GPP channel model in its latest version.

B. TAPPED-DELAY-LINE (TDL) CHANNEL MODEL

1) DEFINITION

The TDL model describes the paths between the transmitter and the receiver by statistical parameters, without taking into account the geometry of the environment. The time-domain CIR is represented by a discrete number of taps, each one with their own time-varying coefficients, amplitude and delay, as represented by the equation (2):

$$h(t,\tau) = \sum_{i=1}^{N} c_i(t) \cdot \delta(\tau - \tau_i). \tag{2}$$

TABLE 1. ITU channel model for vehicular-A (30 km/h) and vehicular-B (120 km/h) scenarios [15], [16].

Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0.0	0	-2.5	Classic
2	310	-1.0	300	0	Classic
3	710	-9.0	8 900	-12.8	Classic
4	1090	-10.0	12 900	-10.0	Classic
5	1730	-15.0	17 100	-25.2	Classic
6	2510	-20.0	20 000	-16.0	Classic

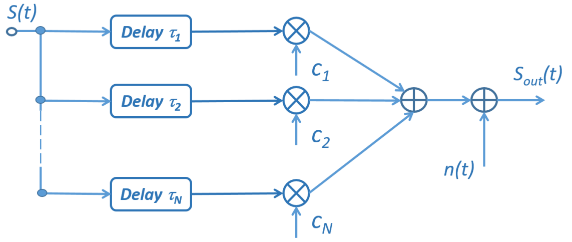


FIGURE 1. Simplified block diagram representation of a general tapped-delay channel model of multipath fading [14].

The tap is represented by a Dirac delta function. The impulse response $h(t, \tau)$ varies in time and is represented by the sum of all delayed taps. N represents the total number of paths, $c_i(t)$ is a time dependant complex amplitude coefficient, δ is a Dirac delta function and τ_i is the delay of the ith path. A Doppler spectrum is associated to each tap. It determines the change of the coefficients with time.

This type of model assumes that the channel impulse response is a finite representation of the channel, by the maximal number of paths N. The resolution between two paths is limited by the bandwidth of the system as follows: $\delta\tau = \frac{1}{W}$ where $\delta\tau$ is the maximal time resolution and W the bandwidth. For example, with a bandwidth equal to 20 MHz, the maximal time resolution is 50 ns. It is then possible to define a TDL model with tap delays corresponding to the sampling times. The associated weight is then a sum of the complex path amplitudes contributing to the considered delay. If the coefficients c_i are constant, the output signal of the channel can be written as (3). Figure 1 gives a simplified block diagram representation of a general tapped-delay channel model of multipath fading [14].

$$s_{out}(t) = \sum_{i=1}^{N} c_i \cdot s(t - \tau_i) + n(t). \tag{3}$$

where n(t) is additive white Gaussian noise (AWGN).

2) ITU MODELS

The well known ITU models were developed to evaluate the IMT-2000 and IMT-Advanced technologies like UMTS, LTE (3G) [15], [16]. The first one is used to model the time dispersion of the time variant wireless propagation channel as a TDL model. A set of four channel models is defined: Indoor office, Outdoor to indoor pedestrian, Vehicular, Mixed-cell pedestrian/vehicular. The models are constructed to simulate the multi-path fading of a SISO channel with a 5 MHz bandwidth at 2 GHz.

The multipath fading is modeled as a TDL system with six taps with non-uniform delay distribution. Each tap associates an amplitude characterized by a distribution (Rician with a K-factor $>$ 0, or Rayleigh with K-factor= 0) and the maximal Doppler frequency. The recommendation specifies two different delay spreads for each test environment: low delay spread represented by 'A', and medium delay spread represented by 'B'. The scenario called *Vehicular B* is defined for a speed up to 120 km/h with a six-tap TDL channel model. It is characterized by the number of taps, time delay relative to the first tap, average power relative to the strongest tap and Doppler spectrum, as presented in the table 1. The key parameters to describe each propagation scenario have to include: time delay spread, path loss and exceed path loss, shadow fading, multipath fading characteristics (Doppler spectrum) and operating radio frequency. More complex MIMO channel models based on CDL are proposed in [16]. These models can also take into account the antenna characteristics. The MIMO case is not considered in the Emulradio4Rail project.

3) SALEH-VALENZUELA CHANNEL MODEL

The Saleh-Valenzuela (SV) is a statistical model originally developed for a SISO wideband channel [17] and was further extended to MIMO systems by including angle of arrival (AoA) of the waves [18]. Nevertheless, the SV channel model is similar to the TDL model in terms of using path representation with delay and magnitude identification. The SV channel model uses a definition of the so-called *cluster* representation. A cluster is a group of paths that comes from a group of scatters. The magnitude of a path into a cluster is assumed to decrease following an exponential function. The same principle is assumed between two clusters.

III. RAILWAY ENVIRONMENTS

Railway environments are different than others generally considered for cellular systems or in other transport modes (automotive, maritime and aeronautical). Besides, they are also quite different from each other depending on the train category. In general, four main categories are considered: urban, regional, intercity and high speed.

For High Speed Lines (HSL) the profile of the line is generally linear or almost linear (large curvature radius). Classical HSL environments are open spaces, cuttings, viaducts, tunnels and stations. The authors in [19] described the geometry

TABLE 2. Classification of channel model for HSL from literature.

Scenario	Description of statistical propagation parameters (PL, K-factor, ...)	TDL models	CDL models	Incomplete models
Rural	[20], [21], [22], [23], [24] [25]	[26], [27]	[28], [29]	[21] [30] [31]
Viaduct	[32], [33], [34], [35]	[36], [37], [38]		[39]
Cutting	[40], [41], [33], [35]	[26], [42], [38]		[39]
Hilly terrain		[26], [43], [44]		
Station	[45]	[26]		[39]

TABLE 3. Classification of channel model for tunnel from literature.

Scenario	Description of statistical propagation parameters (PL, K-factor, AoA, AoD, ...)	Incomplete Saleh-Valenzuela model	Kronecker Weichselberger model	CDL model
Tunnel	[46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [64], [65]	[66]	[67]	[68]

of all these environments. The speed is generally between 300 and 320 km/h, thus from a radio point of view, channel models should take into account non-wide-sense-stationarity, rapid time-variability and large Doppler shifts caused by the high speed of the train.

Intercity lines or regional lines are mainly deployed in rural environment that can be open area, where it is possible to cross open field, forest, mountains, suburban areas, medium size tunnels, *etc*. The highest train speed is generally around 180 km/h. Areas with a lot of pylons and catenaries can be encountered near big cities or marshaling yards.

Metro are generally deployed in underground environments. The type and size of tunnels will vary depending on the line (old or new). The highest speed is generally around 60-80 km/h, but it can be up to 110-120 km/h for some lines.

The scenarios for train communications vary between Train-to-Ground (T2G), Train-to-Train (T2T) and intra-train communications. The development of channel models for railways is a very active research field in recent years, particularly for HSL and metro. A literature analysis shows that most of the scientific papers on the topic are dealing with radio propagation models. They mainly present narrow-band parameters such as path-loss, fading characterization, angle distribution statistics and, sometimes, the delay distribution. We have also identified papers that present TDL and CDL models in different railway environments.

We will detail in the next section the different TDL and CDL models identified in each type of railway environment for T2G. A specific subsection is devoted to HSL. In another subsection, we will focus on the tunnel case. Table 2 presents a classification of the different papers found, related to high speed lines, and Table 3 presents an equivalent classification for the tunnel scenarios. We will detail in the following subsections the main results extracted from the papers.

IV. CHANNEL MODELS OBTAINED WITH MEASUREMENTS AND SIMULATIONS ALONG HIGH SPEED LINES

HSL allows trains to run generally up to 350 km/h. Such a speed involves a lot of constraints for the measurements, such as large Doppler spread and fast variations of the channels parameters. A high speed train (HST) can, on the same line, pass over several scenarios. In [19], the high speed train geographical environment is divided in sub environments namely: open space, viaduct, cutting, hilly terrain, tunnel and station. We will follow this classification for the channel models.

In [20]–[24], [26] and [25], authors present results for various rural railway scenarios. A description of the radio propagation characteristics is given in [32]–[34] and [35] for viaduct scenario. The radio propagation characteristics in different cutting scenarios are described in [33], [40], [41] and [35]. An analysis of path loss and K-factor is performed in [45] for a station scenario.

Several TDL channel models are considered in [27] for rural scenario and also two CDL channel models in [28] and [29]. [36], [37] and [38] treated the case of viaduct scenario. [26], [42] and [38] deal with cutting scenario. References [26], [43] and [44] present results for hilly terrain scenario and [26] for station scenario. We will present all these channel models starting with the TDL models then we will describe the CDL models.

A. OPEN SPACE SCENARIO

This scenario is the most common HSL environment. If we consider T2G communications, the base stations are generally distributed along the tracks. Consequently, the Line of Sight (LoS) component is generally dominant between the transmitter and the receiver. As the distance between the transmitter and the receiver increases, the impact of the scatters becomes important and causes many multi-paths. In [27], the authors present a measurement campaign in China between Beijing South Railway Station and Wuqing Station over 30 km. They considered public LTE Frequency Division Duplex (FDD) transmission. The speed of train is equal to 300 km/h. They use a NI-USRP 2952 (National Instrument-Universal Software Radio Peripheral) board as receiver to get channel information from the LTE standard signal. The measurements are performed with SISO antenna configuration at 1.85 GHz with 20 MHz bandwidth and

30.72 MS/s sampling rate. Due to the bandwidth, the maximal delay resolution is equal to 0.06 μs. The maximal time delay, which can be calculated is 11 μs, because of the 90 kHz between two successive cell-specific reference signals (CRS) [69]. The receiving antenna is located inside the train. The authors are able to define a two taps channel model for this open area scenario but the characteristics of the antennas are not given.

We can mention two CDL channel models found for rural scenario: the WINNER II channel model D2a [28] and the IMT-A MRa channel model [29]. This model composed by a rural macro (RMa) cell scenario is referred as the typical open rural railway scenario. The frequency range, only for this RMa scenario, is from 450 MHz to 6 GHz, with a bandwidth up to 100 MHz. A HSL scenario is defined, as B3 scenario, for a train speed up to 350 km/h. This scenario covers a wide span, which can be up to 10 km. The base station (BS) antenna height is generally in the range from 20 to 70 m. Two CDL channel models are given for the RMa channel model, the LoS and Non-Line-Of-Sight (NLOS) ones. This article also defines all the path-loss parameters for the RMa scenario.

B. VIADUCT SCENARIO

In viaduct scenarios the LoS component is dominant and the scatters have a minor impact on the receiver. In [36] a measurement campaign is performed in a viaduct scenario in China on Beijing-Tianjin HSL. The transmitter antenna is 3 m above the rail, on the top of the train and the receiver is located on the road at 83 m away from the viaduct. The antennas configuration is SISO with a wide band vertical-polarized Sencity Rail Antenna HUBER+SUHNER [70] transmitting antenna and a dipole for the receiver antenna. The train speed is equal to 240 km/h and the receiver is an Elektrobit Propsound TM Channel Sounder working at 2.35 GHz with 10 MHz bandwidth. A direct sequence spread spectrum signal is used to extract the CIR with a length of 127 bits. Two Rubidium clocks are used to synchronize the transmitter and receiver.

Authors divide the environment into five sub-regions related to the intersection point (IP) between the transmitting pylon and the track. The sub regions are defined depending on the average number of taps obtained in each sub region. They set up five corresponding TDL channel models for the viaduct scenario. The five areas are Remote Area (RA) with two paths, Toward Area (TA) with four paths, Close Area (CA) with eight paths, Closer Area (CEA) with three paths and Arrival Area (AA) with one tap. The number of paths depends on resolvable multipath components over the distance between the transmitter and the receiver. Each sub-region is defined by different number of paths and relative time delay. The Doppler information is also presented. Variation in Doppler frequency becomes more severe when the track is close to Base Station (BS), and the rate of change is inversely proportional to the minimum separation between the track and the BS.

In [38], a measurement campaign is performed for a special scenario which is composed of four parts: a viaduct scenario situated between two cutting scenarios, followed by a tunnel. Here we focus only on the viaduct results. The measurements are performed for a SISO configuration where the transmitter is 20 m away from the tunnel entrance and 35 m high. The transmitting antenna is a directional L-Com HG72714P-090 panel with vertical polarization with 17° vertical and 90° horizontal beam width. The receiving antenna is a L-Com HG72107U vertically polarized. The omnidirectional receiving antenna moves along the track. The channel sounder uses a narrow pulse technology with a pulse period of 1 μs. Pulse width is equal to 30 ns, 45 ns and 60 ns. Two frequencies are investigated: 950 MHz and 2150 MHz. The sampling interval is 50 ns. Authors are able to provide a TDL channel model for two regions, near cutting 1 and near cutting 2. This channel model is validated by a Ray-tracing method which considers the same geometrical parameters as the measurement campaign performed at 310 km/h. The authors investigate the correlation coefficients between delay and Doppler. For the viaduct scenario the correlation coefficient equals 0.0308 and 0.0143 for 950 MHz and 2150 MHz, respectively.

In [37], another measurement campaign is performed for a viaduct scenario in the Chinese Harbin-Dalian HSL. The measurements are performed for a 2×2 MIMO configuration, where the transmitter is 15 m away from the viaduct at 40 m height. The transmitting antenna is omnidirectional with 45 ° of vertical polarization, with 65 ° and 7 ° vertical beamwidth. The receiving antennas are positioned on the roof of the train with a distance between them of 0.5 λ. The sounding signal is a M-sequence with a length of 1023, using Binary Phase Shift Keying (BPSK) modulation. The measurement campaign is performed at 2.6 GHz with a 20 MHz bandwidth. The train speed is equal to 370 km/h. Two Agilent N9020 spectrum analyzers are used with a sampling rate of 19.53 ns. Contrary to the TDL models for viaduct presented before, this model does not define sub-regions and provides a four-tap model. The mean root-mean-square (RMS) delay equals to 203 ns which is higher than the one obtained with WINNER II channel model for LOS rural environment.

C. CUTTING SCENARIO

In cutting scenario, a measurement campaign was performed in the Chinese Beijing-Tianjin HSL [26]. The authors use R&S TSMQ Radio Network Analyzer to extract the resolvable multipath component with a maximal resolvable time delay of 20 μs. A SISO antenna configuration is used to sound the channel signal using both Wide band Code Division Multiple Access (WCDMA) signal at 2.4 GHz with 5 MHz bandwidth at 240 km/h. The transmitter antenna is 30 m away from the track on the top of one slope wall. The receiving antenna is on the roof of the train. The antenna characteristics are not given. The authors provide a four taps TDL channel model of this cutting scenario, with a Classical/Rice Doppler spectrum distribution for the first tap and a classical Doppler spectrum distribution for the others. Another model for cutting is proposed in [38].

D. HILLY TERRAIN SCENARIO

This environment is densely scattered, with objects distributed irregularly and non uniformly. With high altitude transmitting antennas and low-altitude obstacles, the LOS component is observable and it can be detected along the entire railway line. However, multi path components scattered/reflected from the surrounding obstacles cause serious, constructive or destructive, effects on the received signal and therefore they influence the channel's fading characteristics [71].

In [44], a TDL model is proposed for hilly scenario, with a train speed equal to 295 km/h at 2.4 GHz with 40 MHz bandwidth on Guangzhou-Shenzhen HSL using Tsinghua University (THU) channel sounder [72]. The transmitted signal is a linear frequency modulated sequence (LFM) of length 12.8 μs. The transmitter antenna is a directional antenna and is located 10 m far from the railway track and 30 m high. The receiver antenna is omnidirectional and is placed on the roof of the train. Subspace Alternating Generalized Expectation (SAGE) algorithm is used to extract the multi path component. Authors divide into four sub-regions, the hilly terrain scenario depending on the number of predominant paths in each area: Remote Area (RA) with three paths, Distant area (DA) with five paths, Close Area (CA) with thirteen and Adjacent Area (AA) with three paths. Four TDL channel models are set up.

In [43], a SISO measurement campaign, in hilly terrain at 2.6 GHz, with 20 MHz of bandwidth, along the Harbin-Dalian HSL, at 370 km/h is studied. A 1023 bit length pseudo noise (PN) sequence is used, modulated by a BPSK generated by Agilent E4438C VSG. The transmitter antenna is fixed on the Base Station. This antenna is a cross-polarization directional antenna with 65° horizontal and 6.8° vertical beam width. The receiver antenna is omnidirectional placed on the roof of the train. The authors defined two sub-regions with 3 predominant paths in the near region and 5 in the far one. The maximal Doppler shift f_{max} is equal to 875 Hz.

In [26], a measurement campaign is performed in hilly terrain scenario on Beijing-Tianjin HSL. The scenario is composed by a plain environment on one side and a mountain at a distance of 800 m on the other side. The environments studied are plain, hilly terrain, U-shape cutting and station scenario. Here we focus only on the hilly terrain scenario. The authors use R&S TSMQ Radio Network Analyzer to extract the resolvable multipath component, with a maximum resolvable time delay of 20 μs. A SISO antenna configuration is used to sound the channel signal, using a WCDMA signal at 2.4 GHz with 5 MHz bandwidth at 240 km/h. The transmitter antenna is 30 m away from the track on the top of one slope wall. The receiving antenna is on the roof of the train. The authors provide a three tap TDL channel model of this hilly terrain scenario, with a Classical/Rice Doppler spectrum distribution for the first tap and a classical Doppler spectrum distribution for the others.

E. STATION SCENARIO

In [26] already mentioned, authors defined a three taps TDL channel model for the station scenario. The Doppler spectrum distribution for the first tap is Rice Doppler and a classical Doppler for the others.

F. THE SPECIFIC CASE OF TUNNELS

1) PROPAGATION IN TUNNELS

From a general point of view, the traditional free space radio wave propagation laws are not valid in tunnels. When the tunnel length can be considered as infinite, without curves, if the tunnel is not metallic and if the dimensions of the transverse section of the tunnel are large compared to the wavelength of the operating radio signal, the tunnel can be considered as an oversized dielectric wave guide [73]. The modal theory is often considered to permit physical interpretation of some phenomenona. For example, the propagation of an electromagnetic wave inside an infinite tunnel, with a rectangular cross section and with dielectric walls, is the consequence of the existence of an infinity of electromagnetic modes called hybrid modes EH_{mn}. All these modes are lossy modes, because the reflections on the walls imply that a part of the signal is refracted inside the wall and another part is reflected on the wall. The consequence is an additional power decrease with propagation inside tunnel.

Most results in the literature present the statistical properties of narrow band channel characteristics, such as Path Loss and K-factor, and distributions of angle of arrival or departure for the paths [46]–[65]. As for the HSL part, we decided to focus on channel models that can be used for system evaluation, i.e. models that provide a description of the complex impulse response of the channel. The literature in this part is not abundant. In [66], a Saleh-Valenzuela channel model is identified with two main clusters. However, these papers do not provide enough information about them to use it as a reference channel model. In [67], the authors focused on the Kronecker and Weichselberger channel models. Finally, [68] provides a CDL channel model based on the WINNER procedure, using a ray tracing method.

Recent papers present results obtained thanks to narrow band measurements or ray tracing simulations. Table 3 presents a classification of the different papers that we will detail in the following paragraphs. We recall that in this study we focus on papers that present channel models that can be considered to evaluate performances (expression of the complex impulse response of the channel).

Most of the measurement campaigns in tunnel are performed at 900 MHz, 2.4 GHz and 5.8 GHz, which correspond to the frequency bands considered for railway communications systems nowadays. [48], [62], [64], [66], [74]–[76], [60] and [56] highlight only on large scale fading parameters. In [60] a MIMO configuration is used to define also the path-loss (PL), power delay profile (PDP), K-factor and delay spread channel characteristics at 2.1376 GHz.

2) SOME GENERAL REMARKS FOR MIMO CASE IN TUNNELS

It is important to note the particularity of the case of MIMO systems in tunnels that can be explained with modal theory. In [74], the authors highlighted the decorrelation observed due to interference between the various hybrid modes. In [77], the hypothesis of the authors is that modal diversity can be compared to spatial diversity for MIMO techniques. Depending on the transverse or longitudinal position of the receiver in the tunnel, different hybrid electromagnetic modes EH_{mn} can be excited. This hypothesis was confirmed in [78]. In [67], the authors have illustrated very clearly the influence of the hybrid modes excitation on a MIMO system performance. Using ray tracing simulations in a straight tunnel with rectangular cross section, they highlighted that when the antennas are perpendicular to the tunnel longitudinal axis, the MIMO channel capacity is maximal. In contrary, when the antennas are parallel to the longitudinal axis, the MIMO channel capacity is minimal. These results have been also confirmed in underground mines by [79]–[81] and in railway tunnels by [76].

The keyholes phenomenon was highlighted by [82]. This phenomenon occurs when the distance between the transmitters and the receivers is large compared to the radius of the circle in which the scatters at transmission and receptions sides are situated [83]. This phenomenon exists when the signals propagate in a corridor or a tunnel or when the transmitter and receiver are very far to each other in outdoor. These channels are degenerated and can be represented by a channel matrix of rank 1 despite a total decorrelation.

The existence of a keyhole highlights the fact that at a certain position in the channel, all the paths are correlated. In this case, the channel matrix is degenerated with only one degree of freedom (only one non zero eigenvalue). This is very negative for MIMO performance. In [84], the authors analyze the probability of presence of keyholes [85], [86] in various tunnel types (old and new ones). They showed the influence of tunnel dimensions and changes in the cross section dimension as well as the fact that the tunnel is new or not.

In [87] the authors analyze the influence of the variations of dimension of the tunnel transverse section on the probability of presence of keyhole. References to keyhole effects are analyzed in [84], [88], [89]. Generally, the higher the correlation between the signals is, the lower the channel capacity becomes. Nevertheless, when the correlation between antennas is low, the channel matrix $\mathbf{H}$ presents a low rank (equal to 1) and a keyhole phenomenon can occur. The example generally chosen is a scenario with a small hole in a wall that separates the environment between transmitter and receiver. The mathematical description of the phenomenon is given in [86].

3) TDL CHANNEL MODELS FOR TUNNEL SCENARIO

As illustrated in table 3, only two papers give all the parameters of the models for T2G transmissions. At the moment of writing this article, we identified a Saleh-Valenzuela representation in [66], where authors define two clusters but do not provide information on the various parameters to use it. The Kronecker and Weichselberger models based on correlation can also be considered for performance evaluations as presented in [67] but it is difficult to consider them for channel emulation. Finally, a WINNER CDL channel model is defined in [68].

G. CONCLUSION REGARDING STATE OF THE ART RELATED TO CHANNEL MODELS FOR RAILWAY ENVIRONMENTS

The characterization of the channel models for railway environments is a large topic due to the diversity of common environments that a train can encounter during a ride. It appears also that the influence of other trains is not analysed. We have considered channel models obtained with measurements and simulations along high speed lines and tunnels, which can be considered to be implemented in the Emulradio4Rail platform to represent railway environments. The analysis conducted shows that there are a lot of papers dealing with a representation of some statistical channel parameters as path loss, K-factor, angle of arrival, *etc*. We do not find a lot of complete channel models that give a representation of the complex impulse response of the channel with the associated Doppler spectrum. A quite general and straightforward methodology to implement channel models is the TDL model. For the same scenario, different channel models can be defined depending of the number of representative paths. We found also two CDL channel models. The first one is presented in the WINNER II model created by the 3GPP. The second on is presented in the IMT-A model created by ITU. Both of them describe a CDL model for rural scenario. The set of choices remains limited, because the number of works dealing with such models is limited. In addition, we did not find a suitable model for the tunnel case. Further measurement campaigns or simulations, and data analysis are needed to derive such models. The development of new TDL channel models is needed to cover the large set of railway environments and frequency range for the communication systems. In the next section, we will consider two of the chosen models to prove the feasibility of a real-time evaluation of the radio link inside the complete Emulradio4Rail platform.

V. APPLICABILITY ANALYSIS OF THE CHANNEL MODELS FOR THE EMULATION PLATFORM

A. METHODOLOGY

The previous sections have highlighted that there are different railway channel models in the literature. Not all of them seem to be suitable to be implemented in a channel emulator for real time physical emulation at signal level, because they do not provide a complete description of the channel. In particular, a description of the Doppler spectrum is often missing.

TABLE 4. The selected models for the Emulradio4Rail project.

Scenario	Model	Comments
Hilly	[90], [43]	Typical GSM ETSI 6 taps model at 900 MHz, Model for LTE at 2.6 GHz and 370km/h
Rural	[90], [26]	Typical GSM ETSI 6 taps model at 900 MHz and Model for LTE at 2.1 - 2.6 GHz
Viaduct	[36], [38]	Model at 950 MHz, 2.15 GHz and 2.35 GHz
Cutting	[38], [26]	Model at 950 MHz and 2.15 GHz at high speed, Model for LTE like system at 2.6 GHz
Tunnel	[68]	Winner like model

The real time channel emulation, at physical level with real signals, needs to be performed under specific conditions, in order to efficiently address railway scenarios (urban, rural, hight speed, tunnel…), perturbations and technologies that have been requested. In addition, the industrial prototypes that will be tested with the Emulradio4Rail platform are based on SISO technique. For this reason, in order to achieve the proof of concept of the platform operation, we decided to select only a set of SISO TDL-based channel models, with a limited number of paths.

Regarding the completeness of the channel information, models should include the following information of the channel:

- Number of taps.
- Delay associated to each tap.
- Relative power associated to each tap (relative to the 1st one).
- Speed range considered.
- Doppler spectrum (i.e. distribution of the frequency shift in the Doppler domain).
- Frequency range.
- Bandwidth considered.
- Diversity (i.e. SISO, MIMO, *etc.*).

Consequently, the approach was to choose the TDL-based model that provides a more detailed description of the channel in each scenario. In case several models fulfilled this condition, the one with frequency bands close to those related to the telecommunication system to test was selected. In this work we have considered LTE and IEEE 802.11, with similar bandwidth and vehicular speed. For IEEE 802.11 (Wi-Fi) we focus on 2.4 GHz. For LTE we focus on Band 7 (2.66 and 2.54 GHz). Finally, channel models based on measurements are preferable to models based on simulations only.

B. SUMMARY OF THE CHANNEL MODELS MOST SUITABLE FOR EMULATION

In this subsection we summarize the channels we have found more suitable to be emulated. In table 4 a summary is provided.

1) HILLY TERRAIN SCENARIO

In this scenario two models are identified. First, we consider the SISO model described in the ETSI document [90]. This model is based on measurements in the 900 MHz band at a speed of 100 km/h. MIMO setups were not considered and information on Doppler spectrum is available (Jakes Spectrum). The considered bandwidth is up to 5 MHz. Both the time reference and the associated power for each tap are shown in table 5. The ETSI document presents also several models with 12 taps and a reduced version with 6 taps. For each model, two equivalent alternative tap settings, indicated respectively by (1) and (2) in the appropriate columns, are given. We have chosen the 6 taps model as a first proof of concept but, depending on the emulator capabilities, an extension to 12 taps is feasible.

TABLE 5. Selected model for Hilly terrain extracted from ETSI report in the 900 MHz band [90].

Tap number	Relative time (μs)		Relative power (dB)	
1	(1) 0.0	(2) 0.0	(1) 0.0	(2) 0.0
2	0.1	0.2	-1.5	-2.0
3	0.3	0.4	-4.5	-4.0
4	0.5	0.6	-7.5	-7.0
5	15.0	15.0	-8.0	-6.0
6	17.2	17.2	-17.7	-12.0

TABLE 6. TDL characteristics for Hilly terrain and HSL measurements at 2.6 GHz extracted from [43].

Parameter	Value			
Center frequency	2.6 GHz			
Bandwidth	20 MHz			
Speed	370 km/h			
Antenna configuration	SISO			
Scenario	Tap	Delay (ns)	Relative Power (dB)	Doppler
Hilly Near Region	1	0	0	f_{max}
	2	97.65	-6.77	$0.5f_{max}$
	3	216.79	-15.04	$0.5f_{max}$
Hilly Far Region	1	0	0	f_{max}
	2	78.12	-3.23	$0.5f_{max}$
	3	175.77	-7.79	$0.5f_{max}$
	4	234.36	-16.55	$0.5f_{max}$

Second, two other potential TDL-based models for hilly terrain can be considered [43] for SISO configuration at 2.6 GHz, which made it an interesting option for emulation of 5G. A 3 taps and a 5 taps channel models are proposed in table 6. Measurements were performed at 370 km/h. The Doppler spectrum is the Jakes one.

2) RURAL SCENARIO

The model is extracted from [26]. It was obtained thanks to measurements in the 2.4 GHz band. The TDL parameters are given in table 7. The Doppler spectrum considered for each tap follows the Jakes model. The other TDL model that could be considered is the GSM rural standard model from [90] given in table 8. Another model extracted from [27] has been selected.

3) VIADUCT SCENARIO

For viaduct environment, one TDL channel model was found in [36] and another one in [38]. This model is based on measurements taken at 2.35 GHz. The Doppler spectrum

TABLE 7. TDL characteristics of rural HSL model obtained in [90].

Parameter	Value		
Center frequency	2.1 - 2.6 GHz		
Bandwidth	5 MHz		
Speed	240 km/h		
Antenna configuration	SISO		
Scenario	Tap	Delay (μs)	Relative power (dB)
Rural	1	0	0
	2	0.3	-12.9
	3	0.6	-22.9

TABLE 8. GSM rural model with 6 taps in [90].

Tap number	Relative time (μ s)		Relative power (dB)		Doppler spectrum
	(1)	(2)	(1)	(2)	
1	0.0	0.0	0.0	0.0	RICE
2	0.1	0.2	-4.0	-2.0	CLASS
3	0.2	0.4	-8.0	-10.0	CLASS
4	0.3	0.6	-12.0	-20.0	CLASS
5	0.4		-16.0		CLASS
6	0.5		-20.0		CLASS

TABLE 9. TDL model for cutting from [42].

Parameter	Value		
Center frequency	2.35 GHz		
Bandwidth	50 MHz		
Speed	200 km/h		
Antenna configuration	SISO		
Scenario	Tap	Delay (μs)	Relative power (dB)
Cutting	1	0	0
	2	0.24	-8.6
	3	0.36	-12.12
	4	0.46	-8.5
	5	1.18	-12.83

follows a discrete distribution, with three possible values for the Doppler shift depending on the region (far or not from the transmitting point) and also on the tap. The other parameters for this model are a bandwidth of 10 MHz, SISO-only and measurements were taken at 240 km/h.

4) CUTTING SCENARIO

In the cutting scenario we found three different models: [26], [38], [42]. The three of them are measured at high speeds, neither of them consider MIMO schemes and all of them provide information about the Doppler spectrum. Regarding the frequency band they differ, because [38] covers both 950 MHz and 2.15 GHz; [42] covers 2.35 GHz and [26] 2.4 GHz. The TDL parameters for the model presented in [42] are shown in table 9.

5) TUNNEL SCENARIO

As mentioned previously, in the scientific literature there is no TDL-based model for tunnels. This could be due to many different reasons, one of them the high temporal resolution that is needed in order to solve the multipath components that may exist on a tunnel. Considering existing ray-tracing tools, the development of several TDL models based on realistic tunnel description, using simulations, is an open topic.

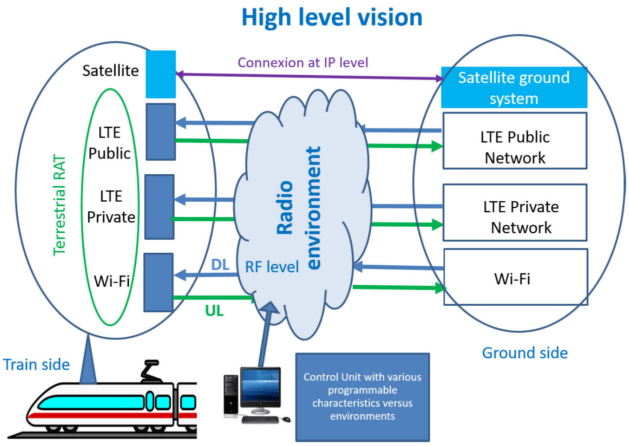


FIGURE 2. High level vision of the Emulradio4Rail platform.

As a consequence of this observation, a new model has been proposed by [91].

VI. IMPLEMENTATION IN THE Emulradio4Rail PLATFORM

A. GENERAL ARCHITECTURE OF THE PLATFORM

The Emulradio4Rail platform is a H&S platform built specifically to offer a laboratory equipment able to evaluate, in real time with real signals, the end-to-end performances of the prototypes of the new communication system for railway, developed within the X2RAIL-3 project [92] in the framework of the Shift2rail Join Undertaking.

These prototypes operate in SISO mode at the moment with several bearers in parallel: two LTE (one public and one private), one Wi-Fi and one satellite. The satellite link is considered only for one of the prototypes. The platform can emulate various representative radio channel environments and various radio access technologies, namely Wi-Fi, LTE and Satellite [93]. Wi-Fi and LTE are emulated at RF level using RF channel emulators, while the Satellite system is emulated directly at IP level. A high level vision of the Emulradio4Rail platform is given Figure 2.

To emulate the Wi-Fi radio access technology (RAT), we considered classical Wi-Fi modems/Access Points (APs) (IEEE 802.11b/g/n modems have been considered, but any other Wi-Fi standard can be used), which convert IP frames into RF signals and vice versa so that a RF channel emulator can be used. The two LTE networks are built using the Open Air Interface H&S open source platform [8]. A schematic view of the platform as developed in the project is given in Figure 3. The platform is built using an USRP 2901 board from National Instruments [94] for the eNodeB and a LTE dongle Huawei E8372h-153 [95] for the UE (user Equipment). OAI is configured to emulate in real time with real RF signals, a LTE FDD (Frequency Division Duplex) network 3GPP compliant, operating in Band 7 (2.54 GHz for Uplink (UL) and 2.66 GHz for Downlink (DL)) in SISO mode with 50 PRB (Physical Resource Block) [69] and 20 MHz bandwidth in Uplink and Downlink. The characteristics of the

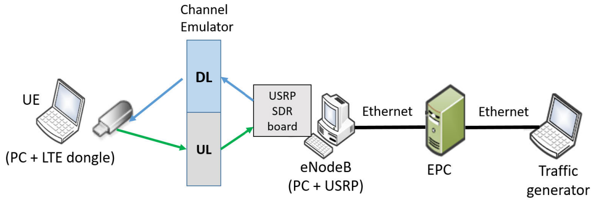


FIGURE 3. Schematic view of the OAI platform.

FIGURE 4. The Emulradio4Rail platform with one LTE bearer emulated by OAI and FPGA based channel emulator in the IKERLAN laboratory.

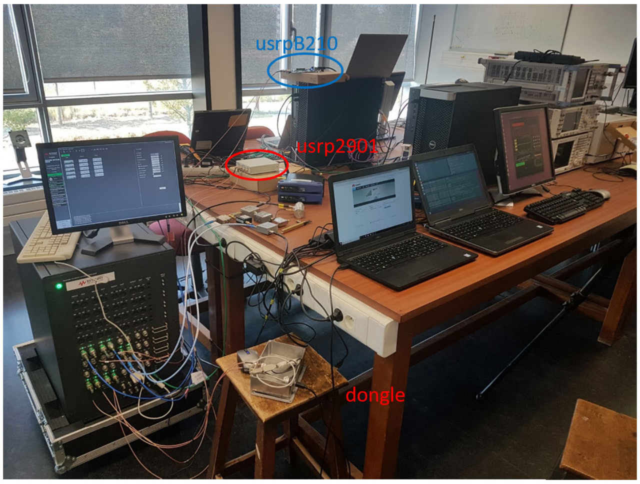


FIGURE 5. The Emulradio4Rail platforms with one Wi-Fi and two LTE bearers emulated by OAI.

LTE cell can be modified thanks to different configuration files available for OAI set ups. Details of the OAI platform can be found in [93].

Two channel emulators have been considered in the project. First a FPGA-based equipment developed for the project by IKERLAN [96]. Later, in a second step, the Propsim F32 equipment [97] from Keysight, offering more input and output (I/O) ports (Figure 5), was used to emulate in parallel all the required RF channels, in UL and DL, with all the RATs working at the same time. This means a total of 10 I/O ports (4 ports for each LTE system and 2 ports for the Wi-Fi). Figure 4 illustrates one of the set-ups at Ikerlan Laboratory, in Spain. Figure 5 shows the final set-up with a Wi-Fi and two OAI LTE bearers, installed in the laboratory at IRCICA in France, ready for future integration with an industrial prototype.

B. METHODOLOGY

As illustrated in Figure 2, industrial communication prototypes will be evaluated at RF level, by directly connecting the equipment at both ends of the platform. One of the industrial requirements for *zero on site testing* is to evaluate the different prototypes at IP level, considering different types of IP traffic. Consequently, to perform this type of evaluation in different railway environments, we need to develop IP impairment models of the different end-to-end IP metrics, in the different railway environments. To do so, we have performed "experimental assessment" of LTE and Wi-Fi bearers respectively, using the Emulradio4Rail platform with different railway channel models. We have used the classical IPERF3 tool [98] in order to send different types of traffic at both ends of the platform (from UE to the host PC and vice versa) and to obtain the different IP metrics behavior versus time and railway environments. The chosen IP metrics are the followings:

- UDP throughput in UL and DL,
- Packet error rate,
- End-to-end delay,
- Jitter.

By performing very long tests (more than 30 minutes), we can obtain different behavior of the IP metrics in different railways environments and different speeds. With that it is possible to deduce corresponding models of the IP impairments. This article presents preliminary results obtained on short test-runs (100 s), to serve as a proof of concept of the chosen methodology and to validate the overall platform.

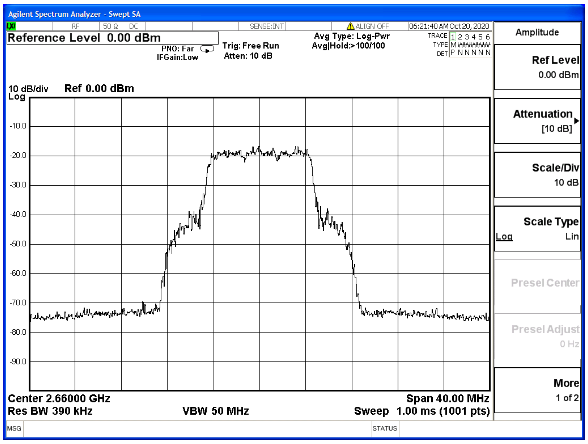
C. RESULTS USING TWO OF THE SELECTED RAILWAY RADIO CHANNELS: HILLY 3 TAPS AND CUTTING 5 TAPS

1) PRELIMINARY TESTS WITH FLAT CHANNEL

Preliminary results with Wi-Fi were presented in [99]. In the next section, we will focus on some results obtained with one of the OAI platforms and the Propsim channel emulator from Keysight, with two different selected railway channels.

The OAI platform is connected to the Propsim channel emulator as illustrated in Figures 3 and 5. First, the channel emulator is introduced simply with a flat channel to verify that the fixed delay introduced by the device is supported by the platform. The channel emulator introduced 30 dB in DL and 19 dB in UL and a fixed delay of 4.5 μs. Figures 6 and 7 show the signal observed with a spectrum analyzer in the respective bands during transmission.

The tests were performed in both directions UL and DL with IPERF3 and UDP protocol with a packet length equal to 1450 bytes. Tables 10 and 11 present the results obtained for the different IP metrics with a 1, 10 and 20 Mbits/s traffic respectively for DL and UL. In table 10 we also give the values of RTT (Round Trip Time) in ms obtained with a "ping" command between UE and Evolved Packet Core (EPC) and a packet length of 1450 bytes.


Agilent Spectrum Analyzer - Swept SA

Reference Level 0.00 dBm

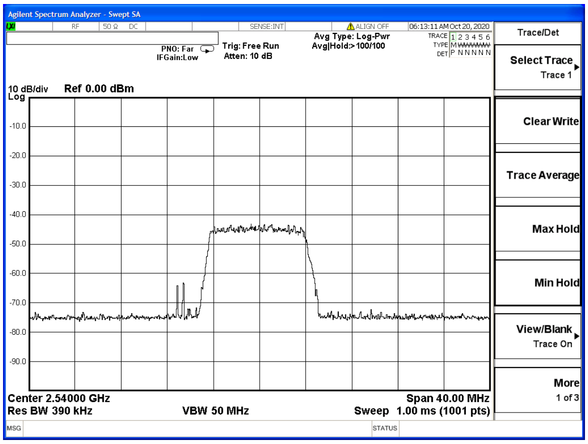
PNO: Far
IFGain:Low
Trig: Free Run
Atten: 10 dB
Avg Type: Log-Pwr
Avg|Hold:>100/100

06:21:40 AM Oct 20, 2020

10 dB/div Ref 0.00 dBm

Center 2.66000 GHz
Res BW 390 kHz
VBW 50 MHz
Span 40.00 MHz
Sweep 1.00 ms (1001 pts)

FIGURE 6. Transmitted signal at 2.66 GHz from the USRP2901 (DL).


Agilent Spectrum Analyzer - Swept SA

PNO: Far
IFGain:Low
Trig: Free Run
Atten: 10 dB
Avg Type: Log-Pwr
Avg|Hold:>100/100

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10 dB/div Ref 0.00 dBm

Center 2.54000 GHz
Res BW 390 kHz
VBW 50 MHz
Span 40.00 MHz
Sweep 1.00 ms (1001 pts)

FIGURE 7. Transmitted signal at 2.54 GHz from the LTE dongle (UL).

TABLE 10. Results OAI+LTE in DL Flat channel.

DL	Iperf traffic	Min	Max	Average	Standard deviation
Jitter(ms)	1 Mbits/s	34.75	38.52	35.81	1
PER (%)		0	1.3	0.1	0.35
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	10 Mbits/s	0.2	1.42	0.67	0.49
PER (%)		0	0.13	0.02	0.04
Throughput (Mbits/s)		0.901	0.901	0.901	0
Jitter(ms)	20 Mbits/s	0.12	1.82	0.72	0.42
PER (%)		0	0.06	0.01	0.02
Throughput (Mbits/s)		18	18	18	0

The results in the UL direction present higher jitter and PER values. This behaviour is not normal and was also observed in the simple wired connection. We analysed that this was due to the performance of the USRP2901 considered to emulate the eNodeB, in terms of Automatic Gain Control and signal processing capabilities. This is not observed in the DL direction, because the dongle used for UE is a commercial device specifically designed to receive and transmit LTE signals.

Despite this drawbacks, we introduced successively the Hilly Near Region TDL channel model with 3 taps given in table 6, and the Cutting 5 taps channel model given in table 9. We considered 1 Mbps UDP traffic. We varied the speed in the channel emulator successively from 0 to 280 km/h. Each speed value requires a specific emulation stage in the Propsim F32 emulator, but the number of taps and the delays in the model do not change. The Doppler spectrum for each tap is the "classical" one. For each configuration presented, the test duration is 60 s, with 1 s average.

TABLE 11. Results OAI+LTE in UL Flat channel.

UL	Iperf traffic	Min	Max	Average	Standard deviation
Jitter(ms)	1 Mbits/s	35.19	37.35	35.40	0.27
PER (%)		0	0	0	0
Throughput (Mbits/s)		0.904	0.905	0.90425	0.044
Jitter(ms)	10 Mbits/s	0.59	1.17	0.70	0.15
PER (%)		0	0.38	0.85	5.16
Throughput (Mbits/s)		9.04	9.27	9.06	0.04
Jitter(ms)	20 Mbits/s	0.56	0.63	0.6	0.01
PER (%)		0	0	0	0
Throughput (Mbits/s)		18.20	18.6	18.21	0.06
RTT (ms)		64.65	138.94	91.77	10.03

TABLE 12. Results OAI+LTE in DL Hilly 3 taps channel model.

DL 1 Mbits/s	Speed (km/h)	Min	Max	Average	Standard deviation
Jitter(ms)	0	34.60	37.56	35.57	0.70
PER (%)		0	0	0	0
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	100	34.78	48.06	37.09	2.06
PER (%)		0	0	0	0
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	200	51.56	437.75	155.3	90.48
PER (%)		6.40	50.00	24.92	10.90
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	250	70.88	822.03	333.5	214.78
PER (%)		2	63	35	14.23
Throughput (Mbits/s)		0.905	0.905	0.905	0

2) HILLY 3 TAPS

Table 12 and table 13 display the obtained results. Using simple "ping" command, we obtained also the variation of the RTT (Round Trip Time) in ms, also given in table 13. One can observe the expected behavior, with performance degradation (jitter and PER increase) when speed increases. In UL direction, the jitter increases drastically even at very low speed.

3) CUTTING 5 TAPS

For this 5 taps channel model, the highest delay is 1180 ns, with a relative power of -12.83 dB from the first tap. The experiment configuration is similar to the one described before. Tables 14 to 15 summarize the results obtained. The Jitter and PER increase with the number of taps and the delay associated. For DL and UL it was not possible to reach 250 km/h. At that speed, the UE is disconnected due to OAI configuration limitation.

TABLE 13. Results OAI+LTE in UL Hilly 3 taps channel model.

UL 1 Mbits/s	Speed (km/h)	Min	Max	Average	Standard deviation
Jitter(ms)	0	22.58	3147.74	387.94	822.77
PER (%)		0	90	13.98	22.86
Throughput (Mbits/s)		0.904	0.905	0.90437	0.049
Jitter(ms)	100	1320.28	2665.70	2004.96	348.96
PER (%)		75	97	89.58	5.34
Throughput (Mbits/s)		0.904	0.905	0.90439	0.05
Jitter(ms)	200	2010.41	3146.16	2818.03	297.40
PER (%)		75	99	93.98	4.75
Throughput (Mbits/s)		0.904	0.905	0.90426	0.044
Jitter(ms)	250	2539.29	3146.31	3034.52	171.52
PER (%)		83	99	95.71	3.76
Throughput (Mbits/s)		0.904	0.905	0.90442	0.05
RTT (ms)	10	25.93	151.83	47.78	11.00
RTT (ms)	100	25.93	194.81	55.63	17.25

TABLE 14. Results OAI+LTE in DL Cutting 5 taps channel model.

DL 1 Mbits/s	Speed (km/h)	Min	Max	Average	Standard deviation
Jitter(ms)	0	18.84	21.72	19.37	0.61
PER (%)		0	0	0	0
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	100	19.28	22.82	20.89	0.92
PER (%)		0	0	0	0
Throughput (Mbits/s)		0.905	0.905	0.905	0
Jitter(ms)	200	21.63	343.32	91.10	78.99
PER (%)		0	54	23.56	14.75
Throughput (Mbits/s)		0.905	0.905	0.905	0

TABLE 15. Results OAI+LTE in UL Cutting 5 taps channel model.

UL 1 Mbits/s	Speed (km/h)	Min	Max	Average	Standard deviation
Jitter(ms)	0	19.38	2668.22	805.61	924.38
PER (%)		0	97	35.94	33.31
Throughput (Mbits/s)		0.904	0.905	0.90426	0.044
Jitter(ms)	100	1156.37	2666.14	1927.99	371.49
PER (%)		77	97	89.94	4.76
Throughput (Mbits/s)		0.904	0.905	0.90431	0.047
Jitter(ms)	200	4090.64	4965.21	4845.65	218.85
PER (%)		80	99	95.19	3.92
Throughput (Mbits/s)		0.904	0.905	0.9044	0.049
RTT (ms)	10	24.56	157.82	46.97	11.10
RTT (ms)	100	30.55	185.79	63.18	20.12

The evolution of the measured IP parameters, in relation with the different channel models, is as expected. Taps, delays and speed degrade the performance. The two configurations are working, but we experienced poor results compared to well known LTE performance. In addition, with high speed and high throughput we lost connection. After analysis we can report several problems/limitations with the performance of OAI.

First, the USRP 2901 is very sensitive to power changes and it needs to be calibrated properly. This behavior makes the system more vulnerable to power changes, such as the ones emulated during the tests (fadings and Doppler), as we observed in the UL.

Second, the Open Air Interface implementation version chosen was selected at the very beginning of the project. It does not seem to be prepared for high performance testing like the one carried out with IPERF. LTE processing (from baseband signal, up to network layer) is a high demanding task, which requires a soft-real-time behavior. When implemented mainly in software, like in OAI, it is a very CPU consuming task. So, when intensively testing with IPERF, any bug or not protected overflow makes the system lose the real-time behavior and fail. Hence, the reported packet losses in the different tests are not only generated by the RF impairments but also by SW congestion, particularly in UL. This is confirmed by observing DL tests that are much better than the UL ones, due to the use of a commercial LTE dongle in charge of the hard processing.

Nevertheless, OAI is a very interesting and promising tool, able to emulate a real LTE network in which real commercial equipment can connect with a specific SIM card. The very last software version (last trimester of 2020) seems to be able to offer much better performance to handle intensive network tests, when different bandwidths and packet sizes are used. This point will be investigated with experts from OAI Alliance in the future.

VII. CONCLUSION

This article provides a rich literature analysis of existing railway channel models, obtained with measurements and some times with Ray Tracing tools. We highlighted that the literature is incomplete and not all railway scenarios have a model that can be used for channel emulation and radio link performance evaluation. The work has permitted to identify a set of suitable TDL-based channel models for the following railway-related scenarios:

- Hilly
- Rural
- Cutting
- Viaduct

Unfortunately, during the Emulradio4Rail project duration, we did not found TDL-based model for tunnel related to HSL or metro line. Consequently, a novel TDL-based model for railway tunnels has been developed using ray-tracing [91].

The selected TDL-based channel models for Railway have been implemented in the Propsim F32 channel emulator from Keysight, for experimental assessment of IP impairments considering the Emulradio4Rail platform.

We have described the emulation platform with a focus on LTE and we gave preliminary results obtained with 2 channel models: Hilly 3 taps and Cutting 5 taps. Even if we did not obtain all the expected results, particularly in UL direction, due to hardware and software limitations of the OAI platform, the results obtained clearly validate the proof of concept of the possibility for *zero on site testing* of new wireless railway communication system, with hardware and software emulation platforms developed within the European Emulradio4Rail project, in the Shift2Rail program.

This conclusion opens important perspectives. First, we consider that there is an urgent need for further work on channel characterization and modelling in railway environments, and especially the need for some specific measurement campaigns in the Railway frequency bands, in the 900 MHZ and 1900 MHz, to allow evaluation of future FRMCS prototypes. Second, a very important perspective is to consider more adapted OAI software and hardware configurations, able to work with IPERF, at high bit rates, and taking into account evolution towards 5G features.

Finally, the possibility to introduce MIMO transmissions and geometric channel models, as well as Winner model widely considered in the standardization bodies, is another important perspective to consider for the enhancement of the Emulradio4Rail platform in order to satisfy *zero on site testing* requirements.

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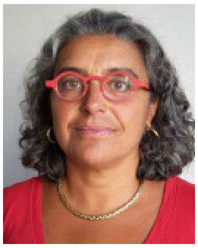

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