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RESEARCH ARTICLE

IP Impairment Models for Performance Evaluation of Wireless Systems in Railway Environments

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ABSTRACT Validation measurements for the Future Railway Communication System in railway environments is a very challenging task and should be reduced to a minimum for cost and time efficiency. “Zero-on-site testing” consists of using simulation/emulation tools and testing procedures to allow validation and verification activities in the laboratory to avoid complex and expensive trials with trains on real-world sites. A solution to test a communication network in a laboratory under realistic conditions consists of injecting perturbations at the IP level (such as additional delay, packet losses, or jitters). It is essential to correlate the IP impairments with the radio environment, their effects on end-to-end transmission, and how the network and its elements react. To do so, IP impairments (or the conditions that lead to them) should be generated in such a way that allows assessing their impact on the performance of transmissions. This paper presents the results of an experimental research based on an original emulation platform (Emulradio4Rail platform), able to emulate and test wireless systems taking into account both physical layer as well as IP traffic in realistic railway environments. Different types of IP traffics are injected at the application layer and go through the platform. The work aimed at extracting various statistical distributions of classical IP metrics (delay, packet loss, jitter, throughput) versus time, as a function of radio channel conditions for Wi-Fi and LTE transmissions in typical railway environments. Then, the modeled IP impairments statistical distributions can be considered at the IP level to test very easily wireless system modems. The results and methodology can be considered for the evaluation of the Future Railway Mobile Communication System modems.

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

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I. INTRODUCTION

The development of safe and secure railway applications such as remote driving, remote diagnostics, platooning of trains, and autonomous trains has led to an unprecedented need for reliable radio links. Several recent papers highlight the

different challenges and trends related to the development of wireless communications systems for railways [1], [2], [3], [4]. In [5] the authors present a methodology to deploy LTE along high speed line. In the mean time, the Future Railway Mobile Communication System (FRMCS) is under development at a European level to fulfill all these needs [6] and to serve as a successor to the soon-to-be-deprecated GSM-R system. It will be 5G based, multi-bearer and resilient to technology evolution and interferences [7]. It has the ambition to bring bearer flexibility to the railway telecommunication essential services. The FRMCS deployment is crucial and urgent in railway environments to contribute to the modal shift (from road and air) towards rail via the generalization of intelligent and interconnected transport systems.

Railway environments are very complex and harsh from a radio point of view. Various obstacles, such as pylons supporting the catenary and rapid transitions between different scenarios (cutting/tunnel, cutting/viaduct, etc.) can create severe radio impairments. In fact, due to the high-speed (currently, up to 350 km/h), the train can go through diverse environmental scenarios rapidly.

In addition, performing measurements in railway environments is a very challenging task. Cost and availability of test trains, their insertion among normal traffic, installation of temporary base stations along the tracks, and other equipment like antennas on the train are among the various constraints to be solved when planning trials there. FRMCS deployment in Europe to replace GSM-R will represent at least 150,00 km of railway lines. On-track systematic system validations should be reduced to a minimum for cost and time efficiency but also due to the urgency to replace GSM-R.

One solution to avoid on site tests is called “*zero-on-site testing*” and consists of using simulation/emulation tools and testing procedures to allow validation and verification activities, including certification in the laboratory in order to avoid complex and expensive trials on real sites [8]. The test framework can also allow remote connection of different components/subsystems located in various testing labs. The necessity for emulation of real radio environments is the main objective of the Over The Air (OTA) testing method for performance evaluation of wireless system [9], [10]. Applications for railway environments are proposed in [11], [12], and [13]. [14] focus on the high speed railway channel emulation with three scenarios. The Emulradio4Rail presented in [15] goes a step further and relies on emulation at RF and IP levels.

Based on the “*zero-on-site testing*” approach, two strategies can be followed to validate that the FRMCS prototypes fulfill the expected end-to-end key performance indicators defined in the requirements without intensive on-site testing. First, the FRMCS modem assessment can be performed directly using software and hardware platforms such as the Emulradio4Rail one and following the methodology presented in [16]. The second strategy consists of assessing FRMCS modems at IP level considering IP metrics models (jitter, Packet Error Rate, bandwidth, end-to-end delay) versus time. In this case, the challenge is the availability

of IP metrics models representative of the railway domain. Consequently, it is very important to correlate the IP impairments to the radio environment, their effects on end-to-end transmission, and how the network and the network elements react to them. In order to do so, IP impairments (or the conditions that lead to them) should be generated in such a way that allows assessing their impact on the performance of transmissions.

The aim of this paper is to present the results of an experimental research, whose objective is to extract statistical distributions of several IP metrics (jitter, Packet Error Rate, bandwidth, end-to-end delay) versus time as a function of radio channel conditions in typical railway environments emulated with radio channel emulator. Different types of IP traffics are injected at the application layer of the system under test and go through the platform. The work aimed at extracting the statistical distributions of the IP metrics versus time, as a function of radio channel conditions for Wi-Fi and LTE transmissions in typical railway environments. We analyse the acceptability of several classical distributions (log-normal, Rayleigh, Weibull, Gamma, alpha-Stable, Nakagami). Then, we perform a Kolmogorov-Smirnov (KS) [17] goodness-of-fit hypothesis test and we identify the appropriate characteristic parameters of the different statistical laws to model IP impairments statistical distributions.

The paper is organized as follows: Section II presents some IP metric models considered in the literature. Section III details the methodology followed to obtain IP impairments models derived from experimental results obtained with the Emulradio4Rail software and hardware platform. Section IV and section V highlight the statistical results obtained respectively with Wi-Fi and LTE bearers in different representative radio channel environments. Finally, section VI gives conclusions and perspectives.

II. IP IMPAIRMENTS FOR PERFORMANCE EVALUATION

Network performance is vital to both service providers and customers. A general framework to achieve end-to-end IP performance objectives is detailed in Recommendation ITU-T Y.1542 [18]. The ITU document provides the main approach and methodology to adopt in order to guarantee acceptable levels of IP network performance based on some use cases and related impairments that can occur during the end-to-end transmission chain. IP streams, from any type of network device, can be evaluated using this model. The following are parameters and impairments that affect the quality of service (QoS) and IP network performance:

- Network architecture
- Types of access links
- QoS-controlled edge routing
- Maximum Transmitting Unit (MTU) size
- Network faults
- Link failure
- Route flapping
- Reordered packets
- Packet loss (frame loss)

- One-way delay (latency)
- Variable delays (jitter), and
- Background traffic (i.e network load).

Performance can be measured at application level with metrics such as throughput, end-to-end delay, jitter, and packet loss. Currently, there is no standard for QoS performance measurement, hence various methods are used, namely actively by insertion of test traffic and passively by observing user-generated traffic.

The Telecommunications Industry Association (TIA) has proposed the TIA-921 “Network Model for Evaluating Multimedia Transmission Performance Over the Internet Protocol” [18]. This standard specifies an IP network model and scenarios for evaluating and comparing communications equipment connected over a converged wide-area network. This standard is broadly applicable to evaluating any equipment that terminates or routes traffic using the Internet Protocol. It can also be used to evaluate media streams or other protocols carried over IP networks. The IP network model can be used to test an IP stream in real-time using an emulation of the network impact based on the model.

ITU G.1050 Recommendations specify an IP network model based on scenario-based impairment combinations. These time-varying IP network impairments provide a significant sample of transmission conditions [3]. Emphasis is given to the fact that manufacturers of communications equipment and service providers are interested in a specification that accurately models the IP network characteristics that determine performance. Evaluators desire a definitive set of simple tests that properly measure the performance of communications devices from various manufacturers. Therefore, this Recommendation aims to define a technology-independent model that is representative of the IP network, that can be simulated at reasonable complexity, and that facilitates practical evaluation times.

In [19], an evaluation methodology for some of the Next Generation Mobile Networks requirements with some scenarios is proposed. In [20] the authors detailed a practical and economical solution to achieve testing IP impairments for LTE Networks. In [21], the authors describe the effect of both physical and link on IP QoS. We can also mention various network impairment emulators for IP Networks such as [22] and [23], but as far as we know, none of them take into account the direct effect of radio environments.

III. IP IMPAIRMENTS IN THE EMULRADIO4RAIL PLATFORM

A. HIGH LEVEL VISION

The Emulradio4Rail testing platform comprises two real-time LTE platforms built with Open Air Interface (OAI) [24], a Wi-Fi platform, and a satellite platform. Railway radio environments and their statistical behavior are emulated with a radio channel emulator. Two different channel emulators have been considered for the project: the Keysight (Propsim F32 [25]) radio channel emulator and an FPGA-based

channel emulator developed by IKERLAN [26] shown on Fig. 1 in the lab. Any Tapped-Delay Line (TDL) channel model, and more complex ones as geometrical ones, can be easily configured with respect to the performance limits of each channel emulator. The satellite platform is IP native and connected directly at the IP level.

In this paper, we focus on the use of the LTE and Wi-Fi modules of the platform. We considered four specific railway TDL channel models detailed in [16].

- **Hilly I**, is a 3-taps TDL channel model obtained with measurements at 2.6 GHz [27] with a maximum delay equal to 216.79 ns. The speeds considered for the tests are 10 km/h and 100 km/h.
- **Rural II**, is a 3-taps TDL channel model obtained with measurements at 2.1 and 2.6 GHz [28] with a maximum delay equal to 600 ns. Speed is equal to 100 km/h.
- **Viaduct I**, is a 2-taps TDL channel model extracted from measurements at 2.35 GHz [29] with a maximum delay equal to 1300 ns. Speed is equal to 100 km/h.
- **Cutting II**, is a 5-taps TDL channel model extracted from measurements at 2.15 GHz [30] with a maximum delay equal to 1180 ns. Speed is equal to 100 km/h.

The statistical distribution of generated taps fadings is Rayleigh, and a Jakes Doppler spectrum is considered for each individual channel tap. In order to have a more realistic scenario, the same fading channel (Doppler/multipath) is applied on both Uplink and Downlink for all tests when FDD (Frequency Duplex Division) is considered, e.g., for LTE (Wi-Fi is TDD-based).



FIGURE 1. Propsim (left) and FPGA-based (right) channel emulator.

The higher level concept of the Emulradio4Rail platform is given in Fig. 2 [16]. Fig. 3 gives a view of the Wi-Fi and LTE platforms integrated into one laboratory. We can see in the same figure the two OAI platforms that mimic the two LTE networks and the Wi-Fi one. All the bearers are connected at radio frequency level to the PROPSIM channel emulator (UpLink and DownLink channel are separated for

the case of LTE). All the elements are controlled by a unique PC, as shown on the screen where all the Graphical User Interface (GUI) windows are shown. Within the Emulradio4Rail project, intensive tests were performed using the developed platform for a long period of time with Wi-Fi and LTE radio bearers in the selected railway radio channel models to derive statistical distributions for the different metrics measured. These metrics are packet error rate (PER), jitter, end-to-end delay, and throughput with UDP traffic injected using the Iperf3 tool [31]. Iperf3 is a cross-platform tool providing standardized performance measurements for any IP network. Operating as a client or server, it creates highly configurable data streams to assess the performance parameters (bandwidth, loss, etc.) between the two ends in any or both directions. Iperf3 considers TCP, UDP, and SCTP protocols with IPv4 and IPv6. Its simplicity and efficiency make Iperf3 one of the most trusted tools to provide standardized performance for an IP network [32], [33]. About the exchanged data, i.e., the content of the packets or datagrams, from the client side, the data can be randomly generated or read from a file, and from the server side, the read data can be thrown away or written to a file. As our experiments are generic, i.e., not content-related or data-specific tests, the packets/datagrams are randomly generated and discarded once received and employed for measurements. In this paper we focus on the methodology followed, illustrated by some results obtained for Wi-Fi and LTE radio bearers.

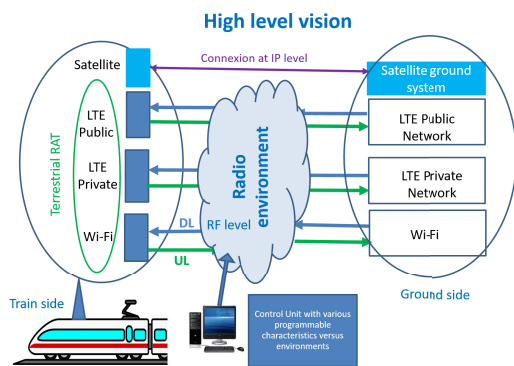


FIGURE 2. High level vision of the Emulradio4rail platform.

B. METHODOLOGY FOLLOWED

The different steps of the methodology followed are illustrated in Fig. 4. Different types of IP traffics are injected at the application layer and go through the Emulradio4Rail platform. The results obtained versus time in different radio channels, representative of railway environments, are processed to obtain some representative statistical distributions of the different metrics versus time. Then, the modeled IP impairments statistical distributions can be considered at the IP level to test the FRMCS modems. We propose a methodology to derive statistical models from the experimental results obtained with the Emulradio4Rail platform. The methodology is quite general and can be easily extended to more

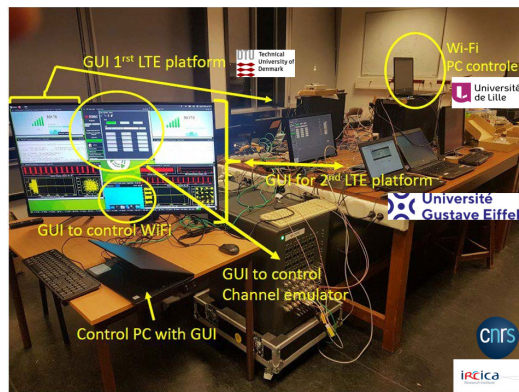


FIGURE 3. GUI controller for the Emulradio4rail platform.

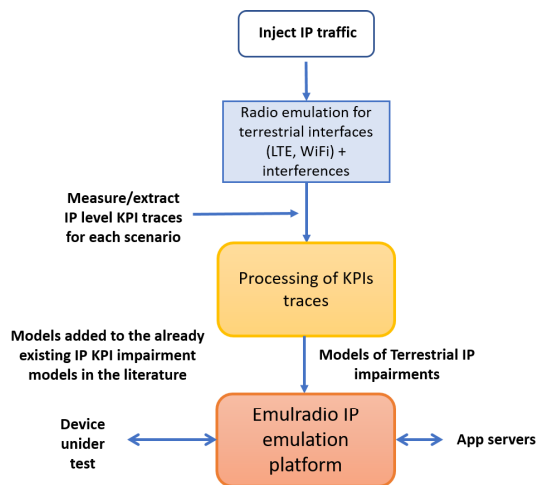


FIGURE 4. Principle of the considered methodology.

complex models if necessary. However, the proposed models (statistical and linear relationship as will be explained) result in a good fit in almost all the encountered cases.

From a general point of view, we draw attention to two points. First, rare events will impact the choice of distribution used for modeling. For example, regarding the Jitter, it is important to consider that large values can happen, but only rarely. They can impact the targeted quality of service. Heavy-tailed distributions will prove to be better models. Second, as parameters are dependent, good models have to account for joint modeling.

IV. IP IMPAIRMENTS WITH WI-FI
A. WI-FI MEASUREMENTS SET-UP

We consider the end-to-end transmission between two Wi-Fi (IEEE 802.11g) access points. The radio channel is emulated in both downlink (DL) at 2.412 GHz and 2.462 GHz, and uplink (UL) as illustrated in Fig. 5. The test cases are summarized in Table 1.

TABLE 1. Tests considered for the Wi-Fi emulation platform.

Test number	Test characteristics
T0	Reference test - Flat channel with 50 dB attenuation
T1	Hilly I channel model with no Doppler
T2	Hilly I channel model 10 km/h (Doppler 22 Hz)
T3	Hilly I channel model 100 km/h (Doppler 220 Hz)
T4	Rural II channel model with no Doppler
T5	Rural II channel model 100 km/h (Doppler 220 Hz)
T6	Viaduct I channel model with no Doppler
T7	Viaduct I channel model 100 km/h (Doppler 220 Hz)
T8	Cutting II channel model with no Doppler
T9	Cutting II channel model 100 km/h (Doppler 220 Hz)
T10	Cutting II channel model 50 km/h and additional interfered on receiver side

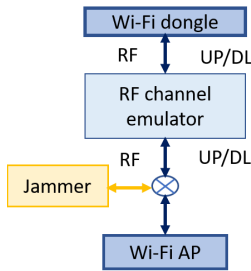


FIGURE 5. Diagram of the Wi-Fi emulation testbed.

B. WI-FI RESULTS

Fig. 6 presents the evolution of the throughput, jitter, and packet loss versus time in a flat channel with 50 dB attenuation. In that scenario, the channel is of good quality and no packets are lost. Fig.7 highlights the correlation between the jitter and the throughput.

Two steps are considered to set up a model. First, we model the jitter. We analyze the acceptability of several distributions (log-normal, Rayleigh, Weibull, Gamma, alpha-Stable, Nakagami). We perform a Kolmogorov-Smirnov (KS) [17] goodness-of-fit hypothesis test. If a value of 0 is obtained, this means that the proposed distribution cannot be rejected. We also evaluated the effect size, which is an essential component when evaluating the strength of a statistical claim. To do so we used the Cohen’s d, a standardized effect size, which measures the difference between two group means: $C_d = \frac{\mathbb{E}[X] - \mathbb{E}[Y]}{\sigma}$, where $\mathbb{E}[\cdot]$ is the mean of the data and of the estimated distribution and σ the standard deviation of the data. We obtained in all cases $|C_d| < 0.1$, which means that the effect size does not impact. The only non relevant case is T10 without interference where C_d cannot be estimated because, when $\alpha < 1$, the theoretical mean is infinite.

Second, we consider a linear relationship between the throughput and $-\log_{10}(jitter)$. The residue res is modeled with a Gaussian random variable with $res = a \cdot throughput + b + \log_{10}(jitter)$, where a and b are the parameters estimated by the linear regression.

Table 2 summarises the results of the goodness of fit test. Four distributions pass the test. The highest p -value is obtained with the alpha-stable distribution. To illustrate the good fit, the two distributions with the highest p -value are presented in Fig. 8 (probability density and cumulative

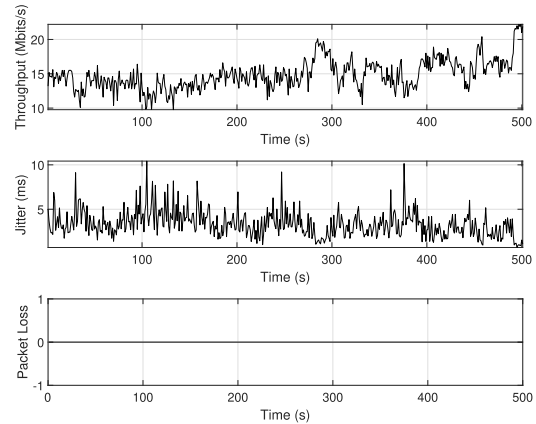


FIGURE 6. Network throughput, jitter, and packet-loss versus time in a flat channel with 50 dB attenuation and no Doppler.

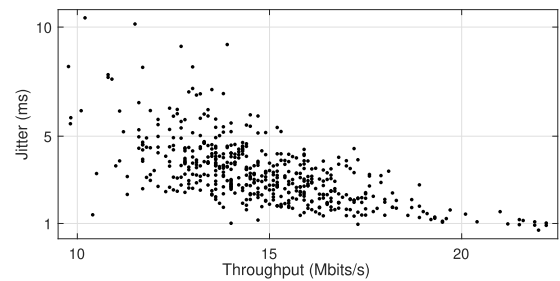


FIGURE 7. Jitter as a function of throughput in the case of flat fading with no doppler.

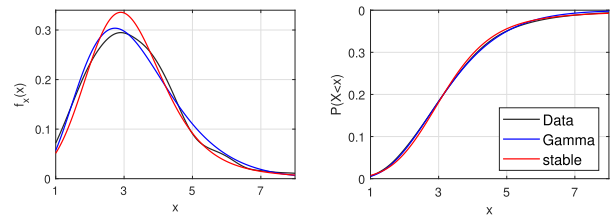


FIGURE 8. Probability density function and cumulative distribution of the jitter (data, Gamma distribution, alpha-stable distribution in the case of flat fading with no doppler.

distribution) along with the distribution estimated from the data. Besides the fit, this figure also emphasizes the importance of the tail of the distribution indicating the presence of large, but rare, jitters. This explains the best fit obtained with the stable distribution. Slow fading case means that a train is stopped or slowly approaching or leaving a train station. KS is the result of the KS goodness-of-fit hypothesis test, $KS=0$ meaning that the proposed law is selected.

Fig. 9 represents $-\log_{10}(J)$ as a function of T , where T is the throughput and J the jitter. A strong correlation exists between throughput and jitter, we propose the following model (1):

$$-\log_{10}(J) = a \cdot T + b + N \tag{1}$$

where N is a noise, a and b are constants that have to be fitted. A straight-line tendency is observed. The figure

TABLE 2. Example of results of the statistical analysis and model selection of the jitter for flat fading case.

Distribution	KS	p-value	parameter			
Log-normal	0	0.386	1.113	0.4418		
Rayleigh	1					
Weibull	1					
Gamma	0	0.473	0.6084			
alpha-stable	0	0.834	$\alpha = 1.67$	$\beta = 1$	$\gamma = 0.836$	$\delta = 2.98$
Nakagami	0	0.154	$\mu = 1.52$	$\Omega = 13.3$		

caption gives the equation of the estimated (using minimum mean square error) straight line. Fig. 10 represents the residue $res = a.T + b + \log_{10}(J)$ and its probability density function, which exhibits a close fit to a Gaussian distribution. The statistical analysis also includes the evaluations of the adjusted R-squared (2)

$$R^2_{Adj} = 1 - \frac{(N - 1) \sum_{i \in \Omega} (X_i - \hat{X}_i)^2}{(N - 3) \sum_{i \in \Omega} (X_i - \bar{X})^2} \quad (2)$$

where X_i are the samples ($-\log_{10}(J)$ in our case), \hat{X}_i the estimated values ($a.T + b$) and \bar{X} the mean of the X_i . R^2_{Adj} gives the proportion of variation explained by the two parameters a and b of the linear approximation. In the case of the flat channel with 50 dB attenuation, $R^2_{Adj} = 0.495$. In addition, the fit with the Gaussian estimation is evaluated with a KS test and the p value is evaluated. The standard deviation of the estimated Gaussian distribution gives the variability about the linear approximation (see Fig. 10).

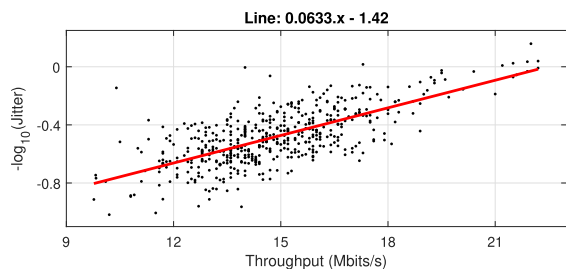


FIGURE 9. Link between jitter and throughput.

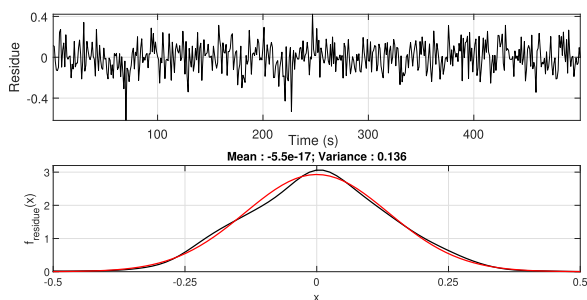


FIGURE 10. $N = T + a \cdot \log_{10}(U) - b$ and its probability density function (from the data ' and the fitted Gaussian model).

To summarize, the statistical model is given by (i) a distribution for the jitter with a given set of parameters; (ii) a linear relationship between the log of the jitter and the throughput

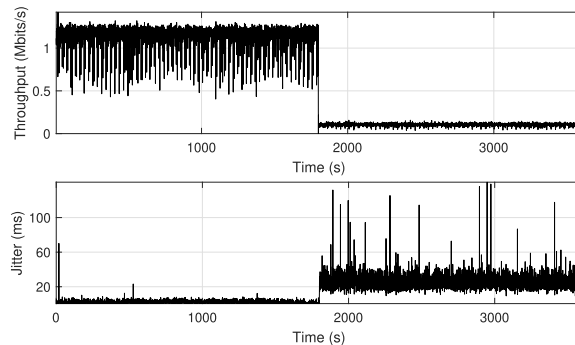


FIGURE 11. Jitter and throughput in scenario T10, without interferer during the first half and with an interferer during the second half.

(two coefficients a and b) and (iii) the mean and variance of the residual noise. To generate a new sample, the jitter J is drawn from the specified distribution and the residue res from the Gaussian distribution. The resulting throughput (3):

$$T = \frac{1}{a} (res - \log_{10}(J) - b) \quad (3)$$

is then obtained. The jitter is given in ms and throughput in Mbits/s. Table 3 summarizes different models obtained for the different tested configurations.

For the last test case, in the Cutting II channel model, an interferer is applied after 30 min on the receiver side, using the testbed described in Fig. 5. The resulting Jitter and throughput illustrated in Fig. 11 clearly show the change in behavior and loss in performance, both in Jitter and Throughput, after 30 minutes.

To cope with the non-stationary environment, we need to extract the parameters of our model before and after the application of the interferer. The interference does not change the model but significantly modifies its parameters. As shown in Fig. 12, the main impact of the presence of the interference is to increase the location (δ) and dispersion (γ) parameters, which corresponds to a higher Jitter and larger fluctuations. If we now plot the measured points in the $Throughput, -\log_{10}(Jitter)$ plane, Fig. 13 again clearly shows the two states with and without interference and the change in the equation of the line connecting the two. Finally the residue can be obtained and is shown in Fig. 14.

V. IP IMPAIRMENTS WITH LTE

A. LTE MEASUREMENTS SET UP

1) INTRODUCTION

Different long tests have also been carried out with the LTE emulation platforms based on the OAI platform [24] in UL and DL with Iperf3 to obtain the KPIs' evolution (effective throughput jitter and PER) versus time. The same railway channel models were considered (see III-A).

2) OPEN AIR INTERFACE EMULATION PLATFORM

Several LTE emulation platforms exist. Among them, srsLTE [34], OpenLTE [35] and OAI 4G platform are open

TABLE 3. Parameters for the different models of the Wi-Fi KPIs (jitter and throughput). The mention (R) means that the null hypothesis is rejected at a 5% significance level by a Kolmogorov-Smirnov test.

Environment	Jitter model		Parameters				$ax+b$			Gaussian $\mathcal{N}(0, \sigma^2)$	
	Law	p -value	α	β	γ	δ	a	b	R^2_{Adj}	σ	p -value
T0	alpha-stable	0.834	$\alpha=1.67$	$\beta=1$	$\gamma=0.837$	$\delta=2.98$	0.063	-1.42	0.495	0.136	0.472
T1	Log-normal	10^{-6} (R)	$\mu=2.18$	$\sigma=0.823$			0.1	-1.71	0.824	0.149	0.365
T2	alpha-stable	0.830	$\alpha=1.60$	$\beta=1$	$\gamma=1.24$	$\delta=4.90$	0.0567	-1.36	0.391	0.136	0.967
T3	alpha-stable	0.0878	$\alpha=1.38$	$\beta=1$	$\gamma=3.87$	$\delta=13.9$	0.132	-1.76	0.795	0.0863	0.14
T4	Log-normal	0.933	$\mu=1.07$	$\sigma=0.451$			0.0714	-1.54	0.310	0.163	0.894
	alpha-stable	0.481	$\alpha=1.48$	$\beta=1$	$\gamma=0.767$	$\delta=2.69$					
T5	Log-normal	0.890	$\mu=2.25$	$\sigma=0.262$			0.0817	-1.5	0.445	0.0847	0.927
	alpha-stable	0.639	$\alpha=1.71$	$\beta=1$	$\gamma=1.57$	$\delta=9.24$					
T6	alpha-stable	0.914	$\alpha=1.57$	$\beta=1$	$\gamma=0.949$	$\delta=4.49$	0.0709	-1.42	0.324	0.122	0.785
	Log-normal	0.0860	$\mu=1.56$	$\sigma=0.341$							
T7	alpha-stable	0.677	$\alpha=1.74$	$\beta=1$	$\gamma=7.68$	$\delta=39.6$	0.155	-1.92	0.457	0.0951	0.931
	Log-normal	0.537	$\mu=3.70$	$\sigma=0.298$							
T8	alpha-stable	0.833	$\alpha=1.48$	$\beta=1$	$\gamma=0.917$	$\delta=3.86$	0.0748	-1.48	0.386	0.128	0.774
	Log-normal	0.377	$\mu=1.44$	$\sigma=0.377$							
T9	alpha-stable	0.131	$\alpha=1.26$	$\beta=1$	$\gamma=6.50$	$\delta=24.5$	0.211	-1.98	0.771	0.0898	0.904
T10 without interferer	alpha-stable	$1.25 \cdot 10^{-10}$ (R)	$\alpha=0.955$	$\beta=1$	$\gamma=0.461$	$\delta=1.37$	0.209	-0.51	0.01	0.263	$4.31 \cdot 10^{-23}$ (R)
T10 with interferer	alpha-stable	$7.06 \cdot 10^{-6}$ (R)	$\alpha=1.59$	$\beta=1$	$\gamma=4.40$	$\delta=23.2$	2.38	-1.64	0.0373	0.125	$2.03 \cdot 10^{-6}$ (R)

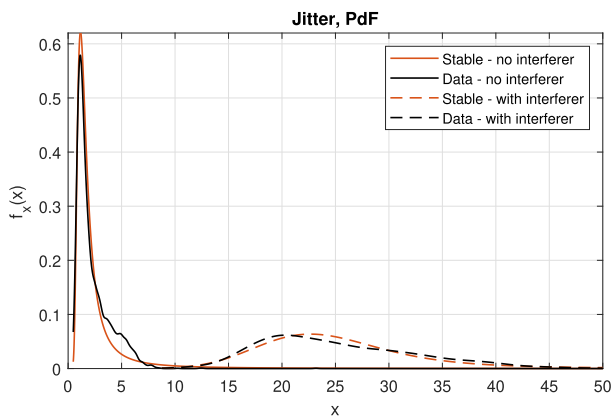


FIGURE 12. Jitter probability density function in T10, without and with an interferer. The two different regimes are clearly observed.

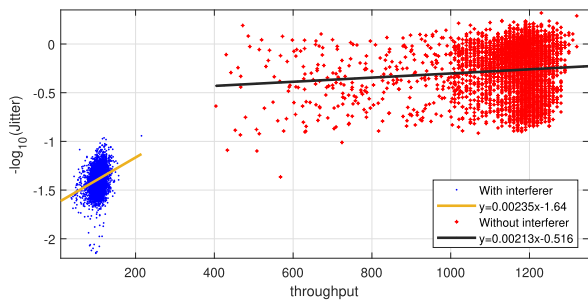


FIGURE 13. Jitter as a function of throughput in T10. The red parts is the case without interferer while the blue one includes one interferer.

source products compliant, respectively, with LTE release 8 and LTE release 10. AmarisoftLTE is a commercial platform [36]. We have chosen the OAI platform as it is widely used in research and industrial fields. The OAI 4G system emulates all the LTE blocks, namely the user equipment (UE), the eNodeB and the Evolved Packet Core (EPC). The EPC and the eNodeB are using two different hosts running on Ubuntu 16.04 with high computing capability in order to cope with the extensive real-time baseband processing of

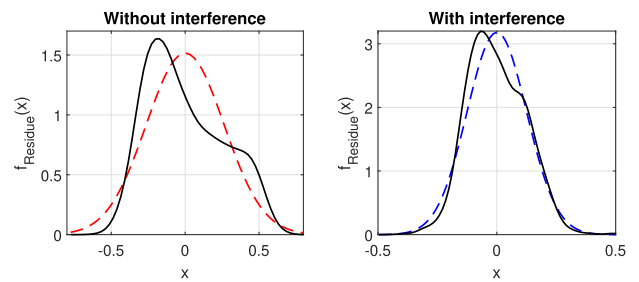


FIGURE 14. Residue probability density function in T10, without and with an interferer. The two different regimes are clearly observed.

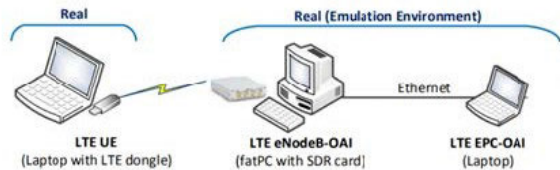


FIGURE 15. Open air interface structure.

the LTE system. The EPC emulates all four LTE network blocks: the Home Subscriber Service (*HSS*), the Mobility Management Entity (*MME*), the Serving Gateway (*S-GW*) and the Packet Data Gateway (*P-GW*). All the connections between the different *EPC* elements are handled internally by the OAI software on the *EPC* system.

The hardware used as an eNodeB front-end is a USRP 2944 from NI [37]. It operates from 10 MHz up to 6 GHz, with two RF channels, each consisting of a transceiver and another one dedicated only to the reception with 160 MHz bandwidth. The UE is a Huawei 4G Dongle E8372, which supports up to 150 Mbps DL data rate and 50 Mbps UL over a maximum 20 MHz bandwidth. The tests are performed with LTE transmission mode 1 (single antenna). Fig. 15 illustrates the installed architecture. Thanks to a PXA equipment from Keysight, the measured EPRE (Energy per resource element)

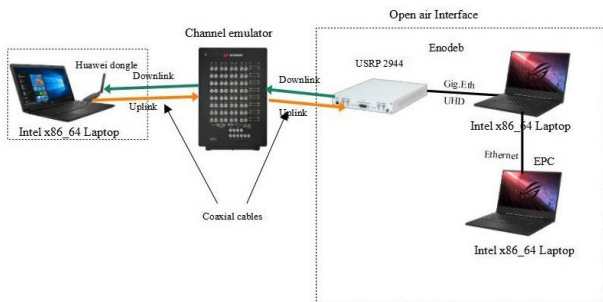


FIGURE 16. Measurement testbed.

TABLE 4. Measurements parameters.

Measurements parameters	Value
Downlink/Uplink Frequency	2.66 / 2.54 GHz
System bandwidth	10 MHz
Packet length	1400 bytes
Bitrate	1 Mbit/s
Average	1 s
Downlink Tx power	-3 dBm
Uplink Tx power	-45 dBm
Downlink Rx power	-33 dBm
Uplink Rx power	-75 dBm

TABLE 5. Results of the statistical analysis and model selection of the jitter.

Distribution	KS	p-Value	Parameters			
Log-normal	0	0.178	-2.47	0.614		
Rayleigh	1					
Weibull	1					
Gamma	1					
alpha-stable	1	0.0421	$\alpha p = 1.15$	$\beta = 1$	$\gamma = 0.025$	$\delta = 0.068$
Nakagami	1					

is equal to -24 dBm, and this value is included in the eNodeB configuration file.

3) LTE SYSTEM STRESS TEST

Fig. 16 gives a schematic view of the overall measurement test bed. A 30 dB attenuation is applied by the PropSim channel emulator on both UL and DL. Measurement parameters are summarized in Table 4.

B. LTE RESULTS

As an example of results, Fig. 17 presents the evolution of the Key Performance Indicators (KPIs) (PER, jitter, and Throughput) in DL measured during 40 minutes when the train speed is 200 km/h considering the Hilly I channel model in the emulator. The transmission is performed with iperf3 at 1 Mbits/s. The effect of speed on PER is illustrated and also on the Jitter. The throughput in DL is constant during the whole emulation; that is why we do not model it, but consider the PER instead. The jitter and the PER are correlated random variables, as shown in Fig. 18.

To identify the model for the Jitter, we first consider the Kolmogorov-Smirnov goodness-of-fit hypothesis test for several distributions: Log-normal, Rayleigh, Weibull,

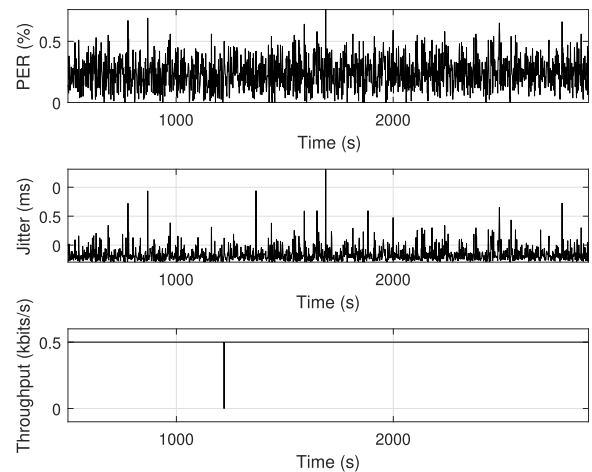


FIGURE 17. PER, jitter and throughput in DL during 40 minutes with Hilly I channel model at 200 km/h.

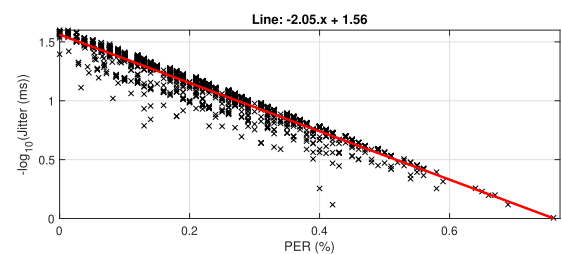


FIGURE 18. Link between jitter and PER.

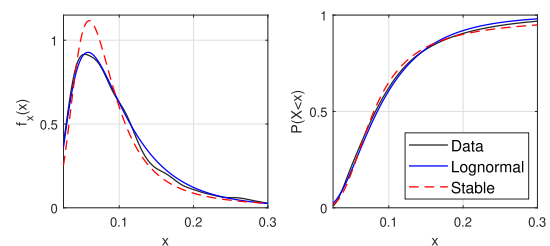


FIGURE 19. Probability density function and cumulative distribution of the jitter in ms (data, Gamma distribution, alpha-stable distribution).

Gamma, alpha-Stable, and Nakagami. We again consider a linear relationship given in (1) where the PER replaces the throughput. An example is given in Fig. 18. The equation of the mean straight line is given in the same figure. The residue is then modelled. Fig. 20 represents the residue and its probability density function (from the data and the fitted Gaussian model). The Gaussian model does not fit as well as in the Wi-Fi case, and we also use a skewed stable distribution, which gives a better fit. This is mainly due to the LTE behavior that adapts its behavior to reach a given throughput leading to some nonlinear behavior depending on how fast the throughput is reached. The results are given in Table 5. Only the Log-normal distribution passes the test. To illustrate the good fit, Fig. 19 presents the Log-normal and the alpha-stable distributions. The PER P is then given in (3) where the PER replaces the throughput.

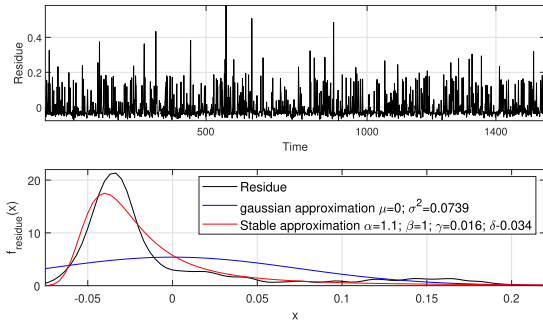


FIGURE 20. $residue = a.P + b + \log_{10}(J)$ and its probability density function (from the data, the fitted Gaussian and the fitted stable).

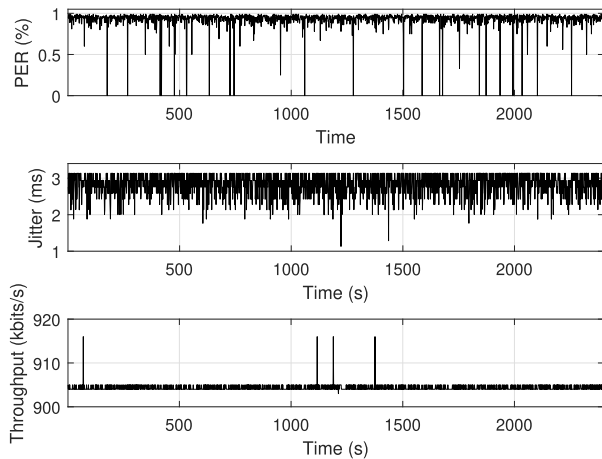


FIGURE 21. PER, jitter and throughput versus time in Hilly I channel model at 200 km/h for LTE in UL during 40 min.

TABLE 6. Parameters for the models of LTE KPIs in hilly I channel model at 200 km/h.

Environment	Jitter model	Parameters				ax+b		Gaussian	
		μ	σ	γ	δ	a	b	ν	σ
LTE - Hilly I - DL	Log-normal	$\mu=-2.47$	$\sigma=0.614$			-2.05	1.56	0	0.0739
LTE - Hilly I - UL	alpha-Stable	$\alpha=1.31$	$\beta=-1$	$\gamma=0.151$	$\delta=2.95$	0.0334	-0.416	0	0.0498

Similarly to the WI-FI case, the statistical model is then given by: (i) a distribution for the jitter with a given set of parameters; (ii) a linear relationship between the log of the jitter and the PER (two coefficients a and b); (iii) the mean and variance of the residual noise. The same analysis is done in UL in the same channel for 40 minutes at 200 km/h. The PER, jitter, and throughput curves versus the time are given in Fig. 21. In this case, the jitter is modeled by an alpha-stable distribution. Table 6 summarised the distribution parameters for the two cases.

VI. CONCLUSION

This paper provides a methodology and some contributions to develop “zero-on-site-testing” solutions to allow validation and certification activities for the development of the Future Railway Communication System. We have proposed a simple methodology to set up IP-impairment models based on intensive experiments and statistical analysis in realistic radio

channel sounders using channel emulators, real modems, and Open Air Interface.

For the considered test cases, the main statistical laws that fit better are the log-normal, alpha-stable, and stable ones. It is also important to account for the tail of the distributions that will model rare events. These events are those that will degrade communications. Especially if safety is involved, it is very important to consider them. Thus, the use of stable distribution is recommended. The linear model between the log of the jitter and the bandwidth or the PER is a good fit.

The interference does not change the model but significantly modifies the parameters and increases the tail; indeed, the characteristic exponent is slightly smaller than one, corresponding to a significantly heavier tail.

In most cases, the characteristic exponent of the stable distribution modeling the jitter is between 1.35 and 1.75. In some cases, it can be smaller, meaning stronger impulsiveness in the jitter. This happens in the Wi-Fi case with an interferer. The skewness is always 1, the jitter being always positive. Important variations can be noticed in the dispersion and in the location parameters.

The next step to go further in the statistical analysis will be to analyze and model the time evolution of the KPIs. Nevertheless, we consider that the proof of concept related to the methodology for the derivation of IP impairment models from the experimental assessment is done. Thanks to an intensive experimental evaluation in the laboratory with an RF channel emulator, several statistically representative IP impairments models can be set up for various railway environments, speed, and interference sources. Then, these different IP impairments models can be used simply with software tools to emulate the air-gap impact over real IP traffic without using a complex RF channel emulator. It is however important to mention that the control loop in the LTE system has a significant impact on the IP impairments models. The choice of accurate models is then more complicated and our proposal did not pass the Kolmogorov-Smirnov test. It would be also important to establish a set of meaningful environments, to identify the corresponding parameters and to model the temporal evolution of the KPIs in order to precisely evaluate technologies.

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REFERENCES

[1] B. Ai, A. F. Molisch, M. Rupp, and Z. Zhong, “5G key technologies for smart railways,” *Proc. IEEE*, vol. 108, no. 6, pp. 856–893, Jun. 2020.

- [2] R. He, B. Ai, Z. Zhong, M. Yang, R. Chen, J. Ding, Z. Ma, G. Sun, and C. Liu, "5G for railways: Next generation railway dedicated communications," *IEEE Commun. Mag.*, vol. 60, no. 12, pp. 130–136, Dec. 2022.
- [3] G. Fodor, J. Vinogradova, P. Hammarberg, K. K. Nagalapur, Z. T. Qi, H. Do, R. Blasco, and M. U. Baig, "5G new radio for automotive, rail, and air transport," *IEEE Commun. Mag.*, vol. 59, no. 7, pp. 22–28, Jul. 2021.
- [4] B. Allen, B. Barth, M. Grec, S. Erl, U. Geier, K. Keil, N. Kumar, D. Seetharamdoo, and E. O. Zaballa, "Next-generation connectivity in a heterogenous railway world," *IEEE Commun. Mag.*, vol. 61, no. 4, pp. 34–40, Apr. 2023.
- [5] Y. Song, J. Kim, S. W. Choi, and Y. Kim, "Long term evolution for wireless railway communications: Testbed deployment and performance evaluation," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 138–145, Feb. 2016.
- [6] UIC. (Feb. 2020). *Future Railway Mobile Communication System, User Requirements Specification, V5.0.0*. Accessed: Dec. 13, 2022. [Online]. Available: https://uic.org/IMG/pdf/frmcs_user_requirements_specification-fu_7100-v5.0.0.pdf
- [7] B. Allen, B. Eschbach, and B. M. Mikulandra, "Defining an adaptable communications system for all railways," in *Proc. Int. Workshop Commun. Technol. Vehicles*, 2018, pp. 53–55.
- [8] *Shift2Rail JU*. Accessed: Dec. 13, 2022. [Online]. Available: <https://shift2rail.org/>
- [9] P. Berlt, F. Wollenschläger, C. Bornkessel, and M. A. Hein, "Cluster-based radio channel emulation for over-the-air testing of automotive wireless systems," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 2440–2444.
- [10] Y. Qi, G. Yang, L. Liu, J. Fan, A. Orlandi, H. Kong, W. Yu, and Z. Yang, "5G over-the-air measurement challenges: Overview," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 6, pp. 1661–1670, Dec. 2017.
- [11] H. Neema, X. Koutsoukos, B. Poteiger, C. Tang, and K. Stouffer, "Simulation testbed for railway infrastructure security and resilience evaluation," in *Proc. 7th Symp. Hot Topics Sci. Secur.* New York, NY, USA: Association for Computing Machinery, Sep. 2020, doi: [10.1145/3384217.3385623](https://doi.org/10.1145/3384217.3385623).
- [12] M. Heinrich, T. Arul, and S. Katzenbeisser, "Demo: Railway signalling security testbed," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2020, pp. 1–2.
- [13] A. Calderone and R. Giuliano, "Emulation of rail and automotive applications based on adaptable communication system," in *Proc. AEIT Int. Conf. Electr. Electron. Technol. Automot. (AEIT AUTOMOTIVE)*, Nov. 2021, pp. 1–6.
- [14] R. Jiang, Y. Zhao, and H. Zhu, "Performance emulation of mobile video transmission in high-speed rail environment," in *Proc. Int. Symp. Commun. Inf. Technol. (ISCIT)*, Oct. 2012, pp. 12–17.
- [15] *Emulradio4rail H2020 Project*. Accessed: Dec. 13, 2022. [Online]. Available: <http://www.emulradio4rail.eu/>
- [16] M. Berbineau, R. Behaegel, J. M. Garcia-Loygorri, R. Torrego, R. D'Errico, A. Sabra, Y. Yan, and J. Soler, "Channel models for performance evaluation of wireless systems in railway environments," *IEEE Access*, vol. 9, pp. 45903–45918, 2021.
- [17] F. J. Massey, "The Kolmogorov–Smirnov test for goodness of fit," *J. Amer. Stat. Assoc.*, vol. 46, no. 253, pp. 68–78, Mar. 1951.
- [18] *Series G: Transmission Systems and Media, Digital Systems and Networks, QoS and Performance—Generic and User-Related Aspects Network Model for Evaluating Multimedia Transmission Performance Over IP*, document ITU-T Y.1542, ITU G.1050, 2005, Accessed: Dec. 13, 2022. [Online]. Available: https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.1050-200511-S!!PDF-E&type=items
- [19] *A White Paper by the NGMN Alliance Next Generation Mobile Networks Radio Access Performance Evaluation Methodology*. Accessed: Dec. 13, 2022. [Online]. Available: https://www.ngmn.org/wp-content/uploads/NGMN_Radio_Access_Performance_Evaluation_Methodology.pdf
- [20] A. Rusan and R. Vasii, "IP impairment testing for LTE networks," in *Proc. Int. Conf. Electron. Commun. Syst. (ECS)*, in Recent Advances in Electrical Engineering Series, N. E. Mastorakis, I. Rudas, M. V. Shitikova, and Y. S. Shmaliy, Eds. Barcelona, Spain, vol. 46, 2015, pp. 99–105.
- [21] J. H. Dunn and C. E. Martin, "The effect of physical and link layers on IP QoS," *Bell Labs Tech. J.*, vol. 8, no. 2, pp. 49–63, 2003.
- [22] *Spirent*. Accessed: Dec. 13, 2022. [Online]. Available: <https://www.spirent.com/products/network-impairment-emulation-testing>
- [23] *Itrinegy*. Accessed: Dec. 13, 2022. [Online]. Available: <https://itrinegy.com/solution-by-task/wan-network-simulation/>
- [24] *Open Air Interface*. Accessed: Dec. 13, 2022. [Online]. Available: <https://openairinterface.org/>
- [25] *PropSim F32 Channel Emulator 6 GHz*. Accessed: Oct. 7, 2023. [Online]. Available: <https://www.keysight.com/us/en/products/channel-emulators/prop-sim-f32-f8-fs8-rf-channel-emulators.html>
- [26] I. Val, F. Casado, P. M. Rodriguez, and A. Arriola, "FPGA-based wideband channel emulator for evaluation of wireless sensor networks in industrial environments," in *Proc. IEEE Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2014, pp. 1–7.
- [27] W. Qian, X. Chunxui, Z. Min, and Y. Deshui, "Results and analysis for a novel channel measurement applied in LTE-R at 2.6 GHz," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2014, pp. 177–181.
- [28] L. Liu, C. Tao, T. Zhou, Y. Zhao, X. Yin, and H. Chen, "A highly efficient channel sounding method based on cellular communications for high-speed railway scenarios," *EURASIP J. Wireless Commun. Netw.*, vol. 2012, no. 1, p. 307, Dec. 2012. [Online]. Available: <https://link.springer.com/article/10.1186/1687-1499-2012-307>
- [29] L. Liu, C. Tao, J. Qiu, H. Chen, L. Yu, W. Dong, and Y. Yuan, "Position-based modeling for wireless channel on high-speed railway under a viaduct at 2.35 GHz," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 834–845, May 2012.
- [30] R. Sun, C. Tao, L. Liu, and Z. Tan, "Channel measurement and characterization for HSR U-shape groove scenarios at 2.35 GHz," in *Proc. IEEE 78th VTC-Fall*, Sep. 2013, pp. 1–5.
- [31] *Iperf3*. Accessed: Dec. 13, 2022. [Online]. Available: <https://iperf.fr/>
- [32] G. Miranda, E. Municio, J. Haxhibeqiri, D. F. Macedo, J. Hoebeke, I. Moerman, and J. M. Marquez-Barja, "Evaluating time-sensitive networking features on open testbeds," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPs)*, May 2022, pp. 1–2.
- [33] V. Raida, P. Svoboda, M. Kruschke, and M. Rupp, "Constant rate ultra short probing (CRUSP): Measurements in live LTE networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.
- [34] *SRS. Software Radio Systems*. Accessed: Dec. 13, 2022. [Online]. Available: <https://www.srs.io/>
- [35] S. Forge. *Open LTE*. Accessed: Dec. 13, 2022. [Online]. Available: <https://sourceforge.net/projects/openlte/>
- [36] *Amarisoft LTE*. Accessed: Dec. 13, 2022. [Online]. Available: <https://www.amarisoft.com/>
- [37] (2021). *U. NI2944*. Accessed: Dec. 13, 2022. [Online]. Available: <https://www.ni.com/fr-fr/support/model.usrp-2944.html>



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