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Broadband Access in Complex Environments: LTE on Railway

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SUMMARY This paper assesses the main challenges associated with the propagation and channel modeling of broadband radio systems in a complex environment of high speed and metropolitan railways. These challenges comprise practical simulation, modeling interferences, radio planning, test trials and performance evaluation in different railway scenarios using Long Term Evolution (LTE) as test case. This approach requires several steps; the first is the use of a radio propagation simulator based on ray-tracing techniques to accurately predict propagation. Besides the radio propagation simulator, a complete test bed has been constructed to assess LTE performance, channel propagation conditions and interference with other systems in real-world environments by means of standard-compliant LTE transmissions. Such measurement results allowed us to evaluate the propagation and performance of broadband signals and to test the suitability of LTE radio technology for complex railway scenarios.

key words: *LTE, railway, propagation, broadband, channel modeling*

1. Introduction

Commercial 3GPP standard, Long Term Evolution (LTE), is being deployed in several countries and it is expected to be deployed globally in 2014. At the same time Global System for Mobile communications Railway technology (GSM-R), which is currently used as a standard for most railway operators, can only support narrowband applications, with strong limitation factor for enhancing both the commercial and the technical aspects of network operation. Against this background, the TECRAIL Project [1] funded by the Spanish Ministry of Economy and Competitiveness, has been launched in October 2011 to evaluate if current LTE 3GPP standard can give support to railway operators and coexists with current radio systems used in railways. Technological reasons to use LTE are linked to the improved performance and capacity of this new broadband communication system for both railway operation and passengers.

GSM-R used in most railways for voice and data transmissions has low data capacity and is approaching the end of life cycle [2]. On the other hand, it is clear that future train radio systems' advanced features and capabilities like real time video or high capacity data transmissions will allow railway operators to support strong Quality of Service (QoS) demanding applications and added value services. Therefore, these advanced features will play a key role in the provision of advanced passenger services, signaling applications or operational services [3], [4].

The main challenges related to the LTE capabilities and features to implement the required railway functionalities are: LTE network coverage design process in high speed environments, QoS, access control mechanisms, performance of LTE handover mechanisms in high speed railway scenarios, spectrum deployment considerations and LTE capabilities to meet the environment RAMS (Reliability, Availability, Maintainability and Safety) requirements [5].

To evaluate the challenges listed above, in this paper a complete review of the process of deployment and testing of a new communications technology on railway environment is given. This process is often followed in railway environment, it is usual to make test trials and research projects [6], [7] to evaluate the impact of a new system on the railway service.

The paper is organized as follows: In Sect. 2 the principal radio systems used in railways are described. In Sect. 3, the particularities of characterizing radio propagation in railway environments are assessed. In addition, a ray-tracing radio propagation simulator for complex environments, including open areas, tunnels or any geometry defined scenario is described. It is clear that the accuracy of the ray-tracing based simulator depends on the proper 3D modeling of the considered scenarios, which can be a cumbersome task in open areas, for example. Under this scope, in Sect. 4, a review of analytical channel models for mobile networks is presented. Besides, their feasibility and drawbacks for being employed in railway environments are analyzed.

Also in railway it is necessary to make test and measurements to validate new technologies and to evaluate the impact on other systems. For this purpose a complete LTE test bed has been developed and it is described on Sect. 5.

Test trials and measurements play a key role for assessing the feasibility and suitability of a new system for railway environments. In Sect. 6, the accuracy and reliability of the results obtained in the validation process are presented. Also, the predicted signal levels obtained with the ray tracing propagation simulator and the LTE propagation

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measurements performed are compared, allowing validation the propagation model developed for the LTE system in railway environments.

Section 7 addresses the problem of evaluation of the link-QoS in these environments. The developed channel models presented in Sect. 4, are now used for the LTE broadband link performance evaluation. This performance evaluation in high speed railway environments is made by means of simulations and test trials. A developed standard-compliant model of transmitter, receiver and configurable wireless channel is also presented in this section. This model has been developed using the Synopsys SPW software and the Synopsys SPW LTE/LTE-A Library.

In Sect. 8, some of the most important concerns when installing LTE in railway environments are identified. The authors describe and analyze the approaches and the process for evaluating and minimizing the interferences between railway radio systems and LTE. The proposed approach takes advantage of the already developed demonstrator and the characterized channel models for obtaining accurate results in the interferences assessment process.

2. Radio Communications in Railways

Railway it is a very hard environment for communications due to factors such as propagation, fast changes in the channel due to high speeds, interferences with other systems, etc. For these reasons, when a new systems is considered it is necessary to evaluate all these points before to be deployed. To evaluate the impact of a new radio technology on existing systems a classification of railway communication systems based on the high-level service they help to provide is presented. From this view, three main groups have been identified: *operational critical services*, *operational non-critical services* and *services for passengers,* for example, Internet access. Obviously, the requirements for each one of them are very different.

2.1 Radio Communications for Critical Services

This family involves every service related to and essential for the safe movement of the train (signaling and voice services). Here we find four subgroups:

TETRA (Terrestrial Trunked Radio) is a professional mobile radio for public safety. It is mostly used by police, ambulances, fire departments, military, government agencies and railways. It is an ETSI standard [8], and it is able to carry both data (up to 12 kbps) and voice. The media access procedure is TDMA, with four time slots, and each carrier has four channels. It supports device-to-device communication, group calls, semiduplex and emergency calls. All of them are very interesting for railways.

GSM-R is the GSM extension for railways specified by both ETSI and UIC [9]. It is the basis for the ERTMS [10] system. Also it gives support for voice communication between the train and OCC (Operations Control Center), or any agent holding a GSM-R terminal. It allows group calls, functional addressing and emergency calls. Nowadays it is more than a mere European standard because China, Australia and some Middle East countries (among others) are commissioning GSM-R standardized projects for their high speed railways and even commuter lines [11].

CBTC (Communication-Based Train Control) is an IEEE [12] standard for Automatic Train Protection (ATP), Automatic Train Operation (ATO) and Automatic Train Supervision (ATS). It plays the same role in subways that ERTMS plays in high speed railways and regular lines. Unlike ERTMS, the radio communication system is not standardized, but *Direct Sequence Spread Spectrum (DSSS)* [13] radios working on *ISM band* (2.45 GHz) is a de facto standard. However, in the last years, some vendors have begun to migrate to *LTE-based radios* [14].

Special systems are *legacy systems* for both signaling and voice still survive in many lines around the world. LZB is an example of signaling systems still in use in high speed railways, but in some cases in process to migrate to new technologies like ERTMS [15]. In the voice field we still can find some *analog professional mobile radios (PMR)* dating from the 1980's or even the 1970's.

2.2 Radio Communications for Non-critical Services

Here are services that are useful for operational purposes, but their failures do not have impact on the reliability of the train or the whole railway network. The most common examples are CCTV, 'infotainment', remote maintenance, access control, ticketing, etc. However, with the boom of automation, the frontier between critical and non-critical services has become fuzzy, because when the driver is removed from the train, the OCC needs more information from the auxiliary systems of the train, the status of the track, real-time video of the passengers area, etc.

Most of these systems use train-to-wayside radio systems based on the IEEE 802.11 family of standards, but the future tendency points to LTE [16] or WiMAX.

2.3 Radio Communication for Internet Access for Passengers

Finally, we should mention the radio communication systems devoted to provide Internet access to train passengers. This is not a very common feature (as of today) because it is expensive to implement. However, some high speed railways operators are starting to offer this service using ad-hoc networks deployed to provide this service. Of course, the requirements for this service are very far from the two previous families of services mentioned before. On the other hand, telecommunications companies may extend its coverage area to railway tracks, to let passengers access to it. This is very common in both subway and commuter train, but as here there is no interface between any train equipment, it cannot be considered a railway communication.

One of the European high speed railway operators started in 2005 to offer Internet access to its customers [17].

The access technology was a combination between satellite access and terrestrial access through 802.11. This leads to a 80% of track coverage, far from being enough for operational services but it is more or less adequate for passenger Internet access.

There are many other technologies (in use or in development stage) devoted to provide passenger access to the Internet, like MOWGLY (Mobile Wideband Global Link System) [18].

3GPP working group for LTE standardization will likely pay more attention on high speed railways needs and introduce a feature ad hoc for trains and buses, the mobile relay [19]. This device will provide high savings in terms of signaling traffic and will increase handover efficiency because eNodeB (Evolved NodeB) will not need to manage a large number of UE (User Equipment) handovers but only one, the mobile relay itself.

IEEE 802.11 deployments on railway platforms and halls are now very common [20]. However, they do not have the complexity of a train-to-wayside radio communication system.

3. Propagation in Railway Environment

The propagation of radio signals in railway environment has some important differences compared to the radio propagation in other areas or systems such as public telephony. This is due to the special characteristics of the environment where the trains travel through tunnels, viaducts, terrain cuts and the specific requirements of the communication systems used for signaling of trains and passenger communications. Moreover, railway radio communication systems are predominantly designed to meet high requirements of QoS. For these reasons accurate radio planning is much more important in all cases.

Another difference is that railway networks require linear coverage with low capacity while in public communication systems normally it is necessary to cover a large geographic area with high capacity. Therefore, the radio planning of a railway environment is necessary to obtain the radio coverage in a narrow and well defined area. So that, the simulation time is shorter and it is possible to use accurate techniques for computing the radio propagation in the track, with higher accuracy than in a 2D scenario. Techniques such as ray tracing that in zonal coverage would demand a computation time of few hours [13], with a complex modeling of the environment, can be much more easily applicable on a linear railway coverage study. This technique provides and accurate prediction of signal power on the track, that is very important for the installation and validation of a railway communication system. Usually, on these environment is necessary to specify and measure the minimum level of signal strength in the track [21]. This requirement is much more stringent than the one used in mobile communications where statistical techniques are used to evaluate the coverage and therefore this is much more ambiguous. Therefore, all the process must be much more rigorous and precise regarding the radio planning and with the strict process employed to measure the radio coverage.

Another distinguishing aspect is that railway lines significantly alter the environment creating dumps, viaducts, cuts, bridges and frequently tunnels are built on modern railway lines. In most cases, the stations are usually located near the track for operational reasons, and tend to concentrate several services on the same base: GSM-R, TETRA, 3G, LTE, so the location is far from optimal in terms of radio communications making it necessary to design the radio coverage with this compromise. Moreover in modern railways running at 300 km/h or higher, the effect of the speed in the radio link is very important. All these characteristics make the design of radio networks in railway environment complex. For these reasons the study and modeling of propagation requires a high precision cartography data and the use of powerful mathematical tools to simulate propagation. These simulations must be validated with measurements and test trials in special regions like tunnels, stations, sharp cuts and others. Therefore, the use of methods, such as ray optical approaches, predicts waves with an adequate precision in a finite time. Also, these methods allow to obtain wideband channel characteristics of the channel like the power delay profile (PDP), delay spread, Doppler spread, etc. that are mandatory for modern digital communications systems design and evaluation [16]. To overcome these problems a ray-tracing simulator has been designed and built.

3.1 Ray-Tracing Radio Propagation Simulator

Ray-based techniques have been widely used in research on radiation and propagation of radiofrequency signals both indoor and outdoor [26]–[29]. Their success is mainly due to the trade-off of the computational burden and accuracy of different ray techniques already mentioned.

Ray tracing/launching techniques are usually formed by two separated computation processes.

- First, the trajectory of every ray is traced or launched, which involves computational geometry or minimization algorithms to find out the path of every ray, between transmitter and receiver.
- Second, the computation of electromagnetic fields associated to every ray is done by taking into account propagation phenomena that occurred along the way, such as reflections or diffractions.

In turn, there are several ways to address the determination the path of a ray, what makes different ray tracing and ray launching techniques. Ray tracing enables to find out the exact path between transmitter and receiver, whilst in ray launching the aim is to compute a predefined and discrete set of paths that are homogenously distributed around a transmitter and later to check which of these hit or pass near a receiver. Ray launching techniques bear few problems associated to discrete set of predefined trajectories that are difficult to tackle, making them less accurate and cumbersome. Nevertheless, some heuristics solutions have been recently proposed to overcome these problems, such as tube launching or Ray Density Normalization technique [24], [25], [27].

The choice of one of these techniques is conditioned by the problem to be solved, its size and the type of geometric primitives to represent the elements within it.

The ray tracing approach enables to compute the exact path traveled by the rays between transmitter and receiver, taking into account the interactions occurred with one or more objects in the geometric model. The most general method to compute these paths is based on the generalized Fermat's principle. Even though this applies to any geometric model, the required minimization procedures entail an increase of computational burden in complex models with many objects which may not be suitable for open areas or large tunnels [28]. Nevertheless, if the elements in the model are defined by planar approximations such as B-Rep with facets, a different approach is available: the method of images. This technique is based on computing the mirror image of a point (transmitter or receiver) in every facet and later repeating this procedure with the images already mirrored as many times as needed, till the desired interaction degree or minimum signal level is reached [29].

Received power is obtained by adding the fields associated to the direct and every reflected and diffracted ray at each receiver location. The expressions to compute these fields and received power are described and developed in detail in [30].

Another important aspect is the geometric and electromagnetic modeling of the elements forming the environment such as tunnels or buildings that are modeled by defining their triangular facets and properties. The advantages of this approach are:

- Fast and reliable computational geometry algorithms: some of the most widely used procedures in ray tracing/launching methods are intersection test of two objects such as lines and planes, visibility test, etc.
- These procedures are executed repeatedly and represent a large part of the computation time spent during simulation, so it is an important advantage to count on fast and reliable algorithms developed.
- Imaging technique: Planar geometry enables to use the image techniques and avoid the high computational burden associated to minimization algorithms to implement the generalized Fermat's principle.
- Homogenous representation: Planar facets are used to model every object, what reduces the representation complexity and makes uniform the objects generations of different geometries.

Figure 1 represents a 3D simulation model for urban environment where buildings and other objects along the track are included over a Digital Elevation Model (DEM) such as the one provided by ASTER or SRTM. The ray tracing approach enables to compute the exact path traveled by the rays between transmitter and receiver, taking into account the interactions occurred with one or more objects in the geometric model. Therefore and accurate graph of received power along distance can be obtained as shown in Fig. 2.

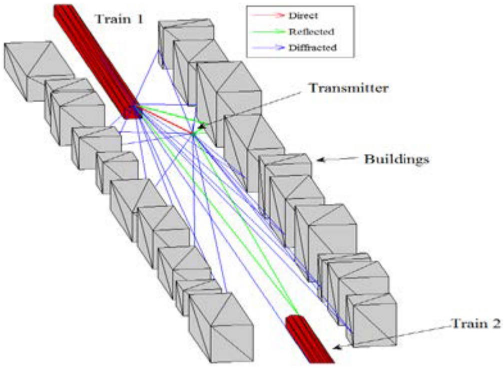


Fig. 1 Simulation of trains passing urban environment.

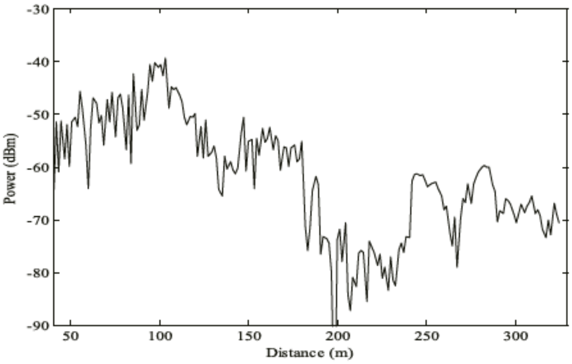


Fig. 2 Received power by the train along distance.

3.2 Simulation of Complex Environment

With a ray tracing simulator propagation can be simulated in open areas, tunnels and in any geometrically defined environment with several transmitters and receivers. In any case it is necessary to model precisely the 3D environments and to define the trains track and position of base stations. On railway there are important simulation environments as tunnels, viaducts and stations.

The most important features for electromagnetic modeling of tunnels are the cross section, longitudinal shape, permittivity and conductivity of the side walls, ceiling and floor. The cross section is here defined by a polygon of arbitrary shape, whilst the longitudinal shape requires few additional parameters such as length and, in case of curves, its curvature. The material walls and floor are made, as concrete or ballast, shape the radio propagation within the tunnel.

An example of simulations of a train passing inside a tunnel it is shown on Fig. 3. In this case, the transmitter is located close to the track in the wall of the tunnel and there are two trains passing inside the tunnel. The frequency used is 2 GHz, with base stations located close to the track. Transmitters have 20 dBm power and use omnidirectional antennas on the transmitter and directive antennas on the

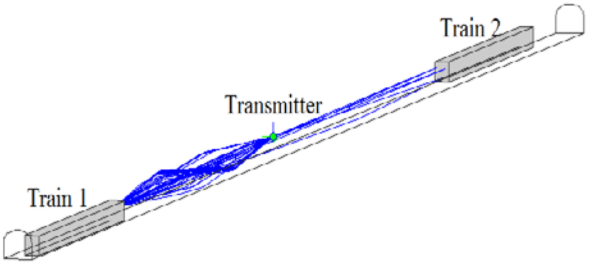


Fig. 3 Simulation two trains running inside a tunnel.

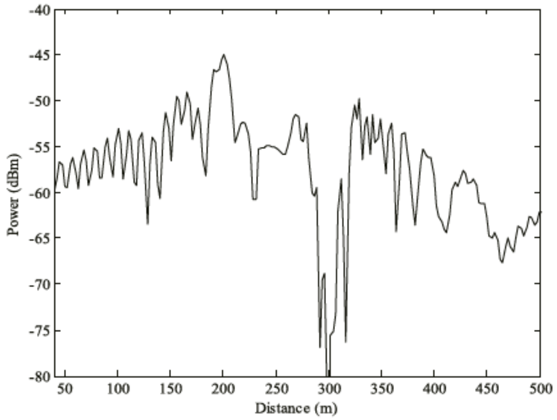


Fig. 4 Received power by the train 1 along distance passing transmitter and train 2.

front of the trains. In Fig. 3, we can see that there are a lot of reflections and diffractions on the walls and on the second train approaching. These reflections affect the signal level. The results of this simulation are shown in Fig. 4. The received signal has fast fading due to multipath and a deep shadowing due to the self-blocking effect of the train when passing the transmitter antenna.

These simulations show the capacity and power of ray tracing algorithm to analyze complex cases in railway environment and in any other complex environment where propagation has to be modeled with high accuracy. Ray tracing simulator is a powerful research tool for broadband communications in high mobility environments.

4. Channel Modeling in Moving Networks

In the last few years, several radio channel models were proposed based on measurement campaigns in different environments [31], such as those developed by the research projects COST207 ("COST" stands for "European Co-operation in the Field of Scientific and Technical Research") for the development of the Second Generation of Mobile Communications (GSM) [32], COST231 (GSM extension and Third Generation systems) [33], COST259 [34] and COST273 [35], which form the basis of International Telecommunication Union (ITU) standards for channel models of Beyond 3G systems. Code Division Test bed (CODIT) [36] and Advanced TDMA Mobile Access (ATDMA) [37] focus on wideband channel modeling, specifically for 3G systems.

The ITU channel models [38] were used during the development of the Third Generation radio access systems. Although they include a vehicular radio environment, no high-speed propagation conditions are explicitly considered. The ITU channel models were also the basis for the specification of propagation conditions in the 3rd Generation Partnership Project (3GPP) for Universal Mobile Telecommunications System (UMTS) [39]. In fact, the HST environment was first proposed by Siemens in 2005 [40]. The increase in bandwidth of LTE techniques compared to UMTS motivated the definition of Extended ITU models. Thus, the 20 MHz LTE channel models were defined based on previous existing models such as the ITU and 3GPP models [41]. It is worth noting that LTE conformance tests also include propagation conditions for HST non-fading propagation channels with speeds of 300 and 350 km/h [42].

In order to allow for the evaluation of multiple antenna schemes for High Speed Downlink Packet Access (HSDPA), 3GPP and 3rd Generation Partnership Project 2 (3GPP2) developed a geometry-based stochastic channel model known as Spatial Channel Model (SCM) [43], which was later extended under the name of *SCM-Extension (SCME)* by the IST-WINNER project [44], increasing the channel bandwidth up to 100 MHz. A simplified version of SCME channel models was used in the LTE design [45]. Additionally, WINNER radio channel models were developed. The so-called Phase II model [46] covers the frequency range from 2 to 6 GHz and defines 13 propagation scenarios, including moving networks.

In 2008, the ITU Radiocommunication Sector (ITU-R) approved radio channel models for the evaluation of IMT-Advanced technologies, like LTE-Advanced (LTE-A) [47], [48] partially based on WINNER Phase II. Four test environments were defined, including HST.

Existing standardized channel models assume that channels are Wide-Sense Stationary Uncorrelated Scattering (WSSUS) [49] which, according to some authors, is not satisfied in the HST environment [50]. Furthermore, *HST channel models* differ significantly from those available for other mobile cellular systems [51]:

1) Different scenarios and propagation conditions must be considered: communication channel environment is highly variable (e.g. viaducts, hilly terrain or tunnels).
2) Line of Sight (LoS) conditions dominance given that current HST routes and network plans ensure LoS in most of the cases.
3) Doppler Frequency relevance: due to the high-speed condition, the Doppler-spread magnitude becomes high for any carrier frequency, varying rapidly when the train approaches a base station as the angle between transmit-receive antennas and the track-side changes rapidly.

Additionally, to the variability of the scenarios mentioned, it is difficult that traditional models focused on static links can reliably characterize general HST propagation conditions. Therefore, measurement campaigns are necessary for modeling the propagation condition based on efficient channel sounding methods [52].

As we have mentioned above, there are very different scenarios to be modeled in the context of HST communications. The first scenario to be considered is the so-called rural macro-cell, which is encountered when the train goes by an open space in a rural area with large cells and direct LoS, while the height of the antennas is much larger than that of the surrounding elements. Several measurement campaigns were carried out to model such a scenario [46]–[53].

The next scenario to be analyzed is the termed as hilly terrain, in which a high density of scattering objects appear non-uniformly distributed. Again, the LoS condition is dominant and the antennas are much higher than the obstacles. Several measurement-based analysis have been carried out to characterize the hilly terrain scenario. Among all, in [54] the authors make use of the so-called high-resolution Subspace-Alternating Generalized Expectation-Maximization (SAGE) algorithm to analyze the statistical fading properties of the wireless channel. Path loss, shadowing fading as well as the K-factor were modeled based on a measurement campaign in a passenger-dedicated line in China [55].

Viaducts are very frequent in railway tracks. Therefore, such a special scenario has to be considered. In fact, many papers in the literature focused on this scenario for its experimental modeling [56]–[59]. The path loss as and the standard deviation of shadowing have been analyzed in [60] when the viaducts are located in different areas such as suburban, open, mountain or urban. The small-scale fading is studied in [58] as well as the K-factor, Doppler frequency and delay spread.

Another frequent scenario in railway environments is a canyon or the so-called cutting (U-shape) in which the train goes by with tall walls on both sides of the track. Even though the LoS component is still observed, it is not as dominant as in the previous scenarios. In [61] and [62], the propagation conditions and the fading characteristics are respectively analyzed.

Finally, the last scenario to be considered is the tunnel, which exhibit the waveguide effect on the transmitted signals. Several measurements were carried out to analyze the behavior of the wireless channel in tunnels, e.g. [63]–[65].

5. Broadband Communications Test Bed

As it has been pointed out, it is necessary to start an assessment process of LTE feasibility for railway environments. For this purpose a demonstrator LTE that can play a key role for evaluating the LTE RF performance in railway environments has been developed. Besides, it can be used for narrowband and broadband channel characterization and modeling in railway complex environments, like *urban, tunnels, stations and viaducts.*

The block diagram of the demonstrator is shown in Fig. 5. It is composed of a RF front end, baseband test bed and controlled with a test and measurements software. Such hardware is complemented with the open-source USRP Hardware Driver (UHD) for USRP devices [66] and GNU Radio [67]. The USRP N210 together with the UHD constitutes the basis of the test bed measurement nodes. On top of those, the high-frequency RF front-end and a frequency reference based on rubidium oscillators completes the node architecture.

The *baseband and low-frequency hardware* for each node consists of the following components for two transmit/receive half-duplex nodes:

- *Host*. Each node is based on a PC equipped to handle high data rates and perform real-time processing tasks such as time and frequency synchronization of LTE frames.
- *Motherboard.* It consists of a USRP N210 connected to the host by means of a dedicated Gigabit Ethernet.
- *Intermediate frequency.* The RFX900 daughter board covering frequencies from 700 to 1050 MHz.
- The Trimble Thunderbolt E GPS plus the SRS PRS10 *Rubidium oscillators.*

5.1 RF Front Ends

The RF front ends (see Fig. 6) are composed of a broadband transmitter and receiver. The system includes all the circuits and RF systems required for a correct interface with the base band system. The technical specifications of RF front end are shown in Table 1. One of the principal advantages of the RF front end is that both equipment are mounted on different racks and can be used separately as a transmitter and a receiver. Therefore the system can be used to make all types of measurements and tests: narrow band, broadband, Doppler, LTE performances on any uplink and down-link.

5.2 Baseband Testbed

Measurements in high-mobility scenarios demand for testbed nodes capable of transmitting and acquiring signal autonomously, without auxiliary connections between them. Therefore, traceability and error tolerance become critical for documenting the results as well as for detecting (and solving) problems during the course of a measurement. Hardware and software verification and validation is also fundamental to avoid problems during the measurements.

Based on the requirements imposed by the high-speed train environment, we have decided to use the Ettus Universal Software Radio Peripheral (USRP) N210 [68] as the baseband and low-frequency front-end for the testbed nodes.

5.3 Testbed Software Description

The hardware described in the previous section is complemented with a custom-made sophisticated software system consisting of three main parts:

- *Low-level and real-time processing* software module built on top of the UHD and responsible for configuring and

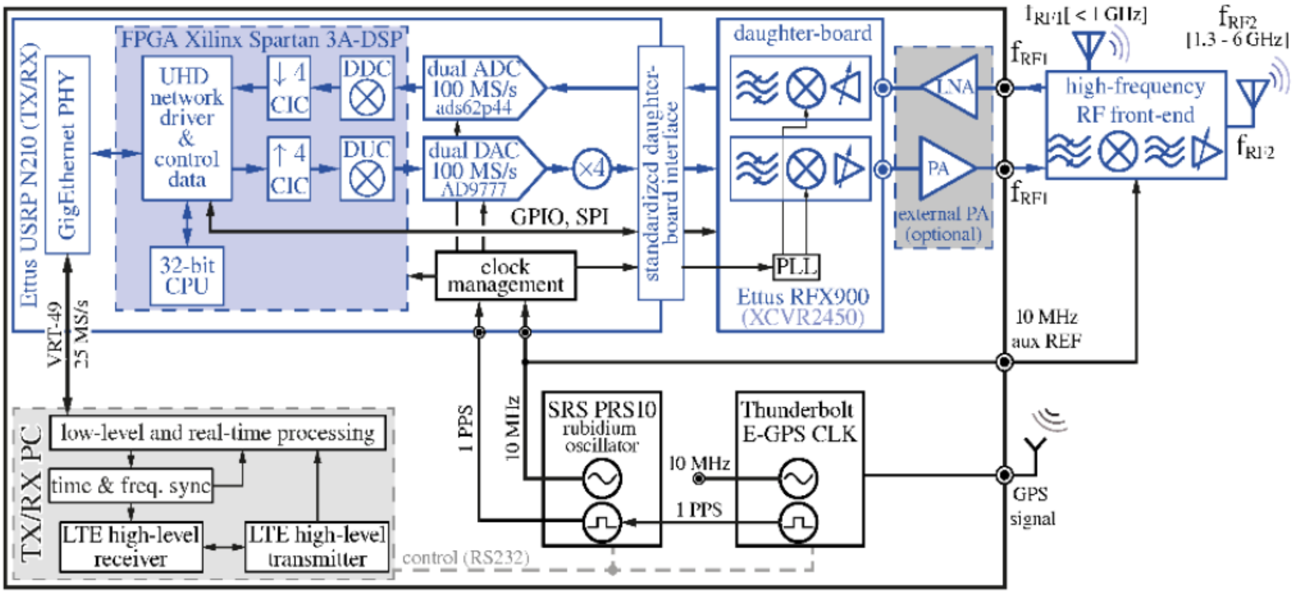
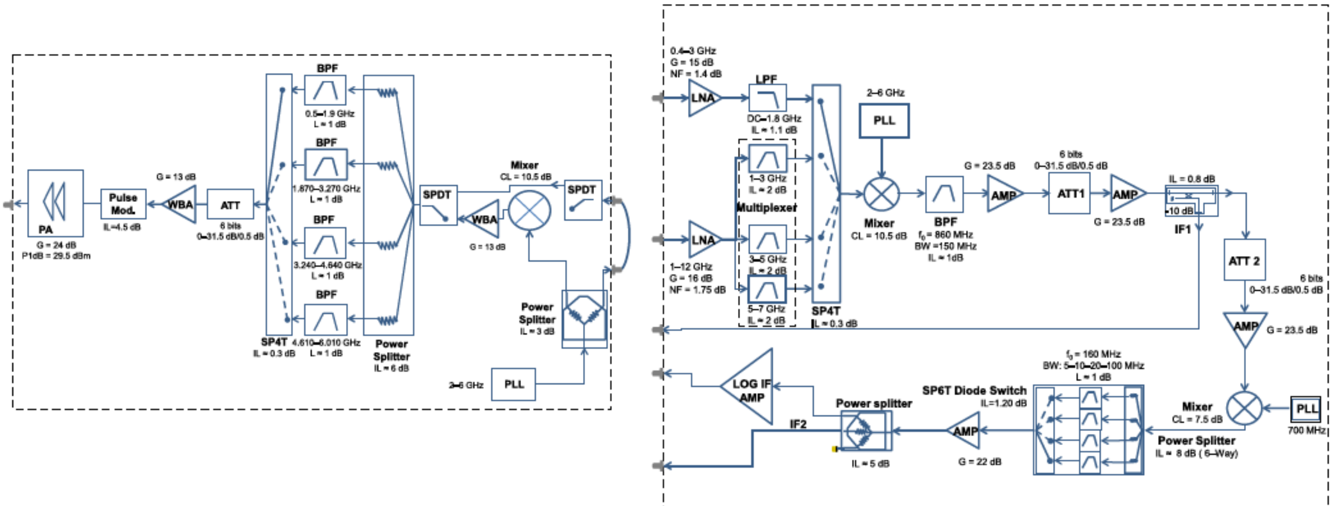


Fig. 5 Block diagram of the LTE demonstrator.



a) Transmitter

b) Receiver

Fig. 6 RF front end of the LTE demonstrator: Transmitter and Receiver.

Table 1 RF front end specifications.

	TRANSMITTER	
Frequency range	500-6010 (4 bands)	MHz
Output power	42	dBm
IF bandwidth	1-100	MHz
Modulation	Pulse/external	10 ns/ LTE
	RECEIVER	
Frequency range	400-7000 (4bands)	MHz
IF dual conversion	860/160	MHz
Noise figure	3	dB
IF bandwidth	5/10/20/100	MHz
Demodulation	Logarithmic detector /LTE	
Dynamic range	90	dB

controlling all the hardware, sending and acquiring LTE frames, and informing about the progress of the measurement together with some important parameters (e.g. receive signal strength, hardware status, etc.).

- *Receiver synchronization module*, which is in charge of synchronizing the acquired LTE frames.
- *High-level LTE transmitter/receiver* modules that are responsible for generating the LTE frames to be transmitted as well as processing the acquired signals in order to estimate the performance of the link by using throughput and error-rate figures of merit.

6. LTE Test Trials on Railway Environments

Since the development of the mobile cellular networks, measurements and trials have performed a key role in the assessment of such systems as well as in the design of later versions. Focusing on LTE, although channel modeling has attracted most of the measurements and trials due to the relevance of new scenarios as for example those faced by high-speed railway communications, measurement-based performance evaluation has been also considered and documented in the literature, for example [69]–[71] and the references therein. Multiple-antenna configurations have gained more importance in LTE with respect to previous systems, therefore the impact on the system performance caused by multiple-antenna configurations has been evaluated by measurements [72]–[75]. A few measurement-driven studies can be found about the performance of LTE in real-world scenarios employing commercially-available LTE implementations, in indoor scenarios (e.g. [76]), or in coordinated multipoint networks using realistic setups (e.g. [77], [78]).

Wireless communication in railways has been considered in the literature, e.g. [79], [80], and the references therein. However, to the knowledge of the authors, very few LTE measurements can be found in the literature focused on high-speed railway scenarios [81].

One example of measurements is the validation of the propagation models and channel models developed for LTE system in railway environments. For this purpose propagation measurements were made in open areas in especially complex zones such as tunnels, stations and viaducts. In these zones propagation measurements were made. The results have been compared with simulations obtained with the propagation simulator.

6.1 Measurements in Complex Environments: Tunnels

The validation of the predictions and signal level obtained by the ray tracing propagation model has been carried out making narrowband measurements in tunnels and open areas using the set-up described in [63] on a complete campaign of measurements that has been carried out in the network of Metro de Madrid. Different types of open areas, tunnels and stations have been measured at three frequencies: 980, 2450 and 5800 MHz with a transmission power of 30 dBm. To carry out these measurements, the antenna of the transmitter was placed on a mast on the track and the reception system was on board the train. The reception antenna was placed on the train windshield. The results obtained with these measurements have been compared with simulations made carefully modeling the environment and following to specification of European Railway Agency [21].

In Fig. 7 we can see the antennas used in the measurements in tunnels. The transmitter test bed was equipped with three antennas for 900/2400 and 5700 MHz and was deployed in the tunnel and the receiver was on board the train and uses a multiband antenna on the front windscreen.

Fig. 7 Radio link measurements on subway tunnels.

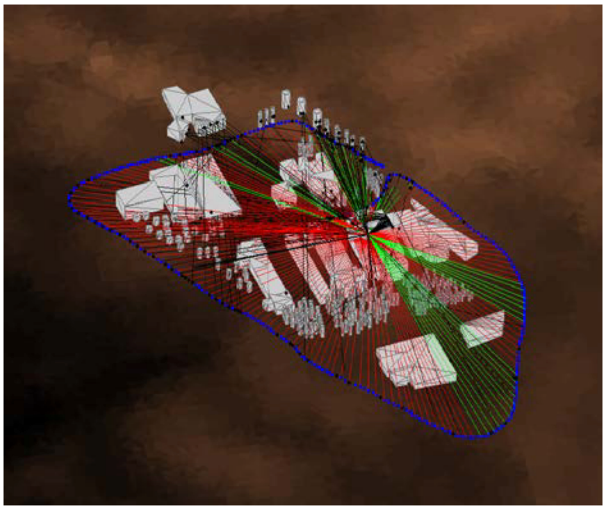


Fig. 8 Ray tracing simulation of an urban environment.

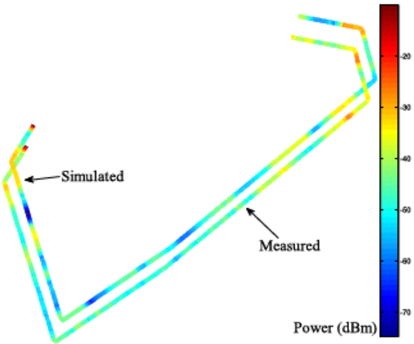


Fig. 9 Validation of simulations with measurements.

6.2 Measurements in Open Areas

Similar process has been followed to validate simulations making measurements in open areas. Figure 8 shows and example of open area urban environment modeled in 3D and simulated at 2.4 GHz with the ray tracing technique. The figure represents Line of Sight propagation together with diffracted and fist reflection rays. On Fig. 9 the results of simulations have been compared with measurements made. The measurements have been averaged every 10 m and compared with simulations. The accuracy of the ray tracing simulator has shown to be better than 10% for averaged signal power and $< 15\%$ for standard deviation of signal. With these results the design of a complete network is much more accurate than with conventional techniques.

7. LTE Physical Layer Link-Quality Evaluation

After careful modelling and measurements of the propagation, it is necessary to evaluate the QoS of the link. For this purpose a standard-compliant model of the transmitter, receiver, and configurable wireless channel was developed using the Synopsys SPW software and the Synopsys SPW LTE/LTE-A Library [82]. The whole downlink physical layer of LTE Rel. 8 is implemented. Besides the downlink resource elements, Physical Broadcast Channel (PBCH) contents, reference signals, and synchronization signals as defined in [83] are also considered. At the receiver side, perfect channel estimation and equalization is assumed in order to avoid distorting the evaluation of the Doppler effects introduced by the custom-made implementation of the high-speed train model defined in [84]. The remaining of the receiver implementation does not use additional knowledge or assumptions. Time synchronization is performed following the frame structure of LTE, while a simple frequency synchronization scheme is used with the aim of illustrating the high-speed propagation effects on the LTE downlink.

The synchronization scheme is similar to the one described in [85], however it is performed at OFDM symbol level instead of at subframe level. The receiver also evaluates the data from control channels such as Physical Downlink Control Channel (PDCCH), Physical Control Format Indicator Channel (PCFICH), Physical hybrid-ARQ Indicator Channel (PHICH) as well as user data contained in the Physical Downlink Shared Channel (PDSCH) and the contents of the PBCH.

For the evaluations we consider 1024 subcarriers, non-adaptive Quadrature Phase-Shift Keying (QPSK) modulation, Frequency-Division Duplex (FDD), 7 Orthogonal Frequency-Division Multiplexing (OFDM) symbols per slot, Minimum Mean-Square Estimation (MMSE) channel equalization, and a Max-Log-MAP Turbo decoder based on soft decisions.

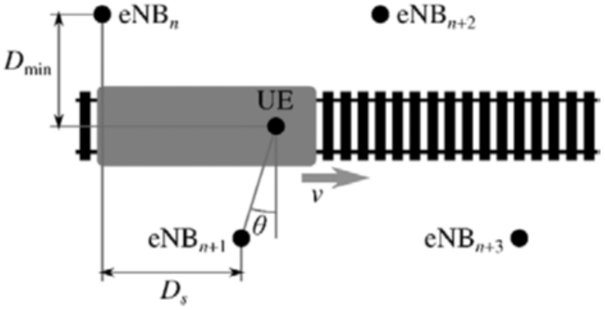


Fig. 10 High-speed train propagation scenario.

Figure 10 shows the propagation scenario consisting of eNodeBs deployed alternatively along both sides of the rail track. The distance between consecutive eNodeBs is $D_s = 300\,\text{m}$, while the minimum distance between the antenna at the train corresponding to the user equipment and any eNodeB antenna is $D_{\min} = 2\,\text{m}$. We also assume a single-antenna LTE scheme with permanent line-of-sight propagation condition and a maximum Doppler shift $f_d = 750\,\text{Hz}$ corresponding to a speed of 300 km/h and a carrier frequency of 900 MHz. Therefore, multipath effects are not considered and thus the HST scenario is modelled as a non-fading propagation channel with a single tap Doppler shift is given by:

$$f_s(t) = f_d \cos(\theta(t)) \tag{1}$$

where

$$\cos(\theta(t)) = \begin{cases} \dfrac{\frac{D_s}{2} - vt}{\sqrt{{D_{\min}}^2 + \left(\frac{D_s}{2} - vt\right)^2}}, & 0 \le t \le \frac{D_s}{v} \\[2ex] \dfrac{-\frac{3D_s}{2} + vt}{\sqrt{{D_{\min}}^2 + \left(-\frac{3D_s}{2} + vt\right)^2}}, & \frac{D_s}{v} < t \le \frac{2D_s}{v} \\[2ex] \cos\left[\theta\left(t \bmod \frac{2D_s}{v}\right)\right], & t > \frac{2D_s}{v}, \end{cases} \tag{2}$$

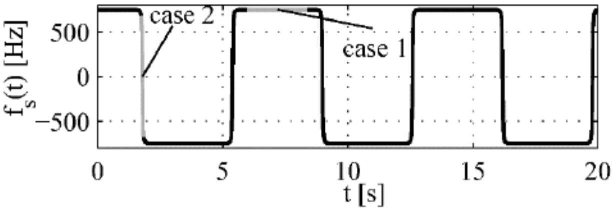
and f_d is the maximum Doppler shift, which can be easily derived from the train speed as well as the carrier frequency. Notice that the resulting Doppler shift is applied to all frequency bands.

In our analysis, the performance of LTE downlink under the high-speed train propagation scenario is evaluated by means of simulations in order to estimate the effective mean user data throughput, uncoded Bit Error Ratio (BER), coded BER, Symbol Error Ratio (SER) and error ratios for PHICH and PDCCH packets. In order to get statistically significant results, 900 LTE subframes are considered per simulation.

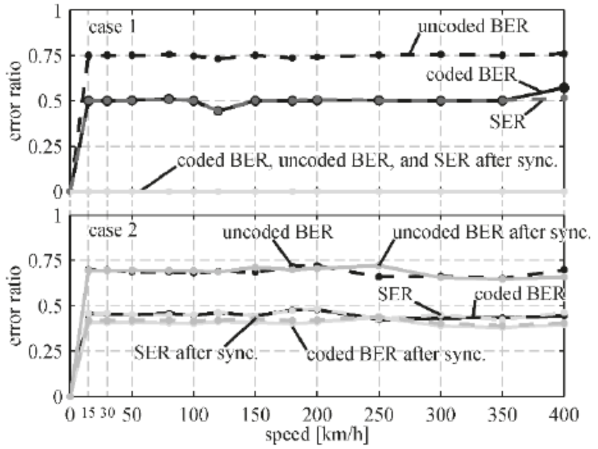
Given that the Doppler shift response of the high-speed train channel model is periodic, the Doppler shift, simulations were performed by considering two parts of the Doppler shift Response, namely “case 1” and “case 2” as shown in Fig. 11(a).

Figure 11(b) shows the simulation results for the coded BER, uncoded BER, and SER in both case 1 (top) and case 2 (bottom). For speed values as low as 15 km/h, BER and SER surpass 0.5 in absence of frequency synchronization. On the other hand, when frequency synchronization is included in the case 1, all errors related with the Doppler shift can be corrected, thus all coded BER, uncoded BER, and SER curves fall down to zero.

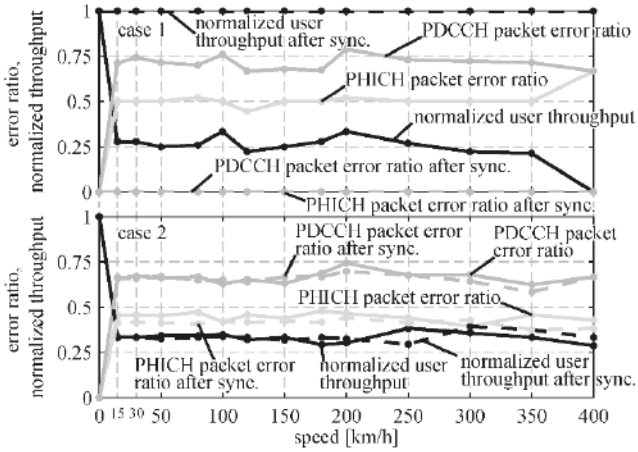
On the other hand, in case 2 the proposed synchronization method is not capable of correcting the errors due to the highly variable Doppler shift. Fortunately, the amount of data transmitted during the case 2 is much less than that transmitted in case 1. Finally, Fig. 11(c) is similar to Fig. 11(b) for the normalized throughput of the user data and packet error ratio of PDCCH and PHICH.



(a) High-speed train Doppler Shift over time.



(b) User-data error ratio in case 1 (top) and case 2 (bottom).



(c) Error ratio for control packets and normalized throughput for user data for both case 1 and case 2.

Fig. 11 Influence of the speed and Doppler shift on a LTE link.

8. Coexistence of LTE and Railway Communications Systems

GSM-R is the current communication system used in railway communications for voice and train control data. Nowadays, several researches have suggested the possibility of interferences into GSM-R from public mobile radio networks [86], [87]. Under this scope, it is important to evaluate the need to establishing a coordination process between railway operators and public mobile broadband services operators.

Besides, as it was stated in the introduction, it is expected that LTE system will become the future broadband railway communication system. The migration process may be divided into two phases: In the first one, LTE system is used for supporting non-critical operational data and voice services, as well as business process support services, while current GSM-R system will still be used for supporting critical voice and data services. In the second phase, LTE system shall give support to both critical and non-critical applications and services. Regarding this coexistence problem, it is important to evaluate the unwanted emission coming from LTE eNodeB and other mobile communication services like UMTS, leaking into the GSM-R band, which may provoke risk of harmful interferences [88], [89].

The outcome of this assessment process shall cover to the definition of several key planning and dimensioning parameters for minimizing the interference between both systems in the 900 MHz frequency band. For example, the minimum physical distance between the GSM-R systems and the new broadband services, the system carrier frequencies, maximum transmitted power, receivers blocking characteristics, etc... [90].

For a complete interference analysis it is necessary to cover several topics, such as, spectral re-growth due to distortion caused by nonlinear devices, victim's receiver blocking response and distortion caused by inter-modulation effects due to multiple LTE transmitters (Carrier-Aggregation) or by wideband and narrowband transmitter deployed on the same frequency band.

Spectral re-growth is an effect caused by distortion of nonlinear devices, for example, Power Amplifiers (PA). The effect of these non-linearities is closely related to the operating point of the PA, and the leakage into adjacent bands is mainly provoked by the Intermodulation Distortions (IMD) [91], [92]. The 3GPP LTE standard specifications define two different kinds of unwanted emission: Out-Of-Band (OOB) and spurious emissions [93]. In LTE, OOB emissions are defined by means of Spectrum Emission Masks (SEMs) and/or Adjacent Channel Leakage Ratio (ACLR) requirements. The ACLR requirement is stricter than the SEM one. While the SEM measures the performance of the transmitter, the ACLR measures the power which actually leaks into certain specific nearby radio channels, which allows for assessing the interference levels due to unwanted emissions from LTE systems operating in adjacent frequency bands into GSM-R systems [93].

Another important topic to be evaluated in the interferences analysis process is the receiver blocking response. It is defined as the maximum interfering signal level expressed in dBm which reduces the specified receiver sensitivity [88], [94]. The last parameter that must be considered is the intermodulation products generated by two or more broadband transmitters, like carrier aggregation in LTE-A, or one broadband transmitter, like LTE, and one narrowband system, like GSM. Due to the nonlinear behaviours of broadband receivers, the distortion products of these interferences could fall into the band of interest.

It is clear that the characterization of the transmitter and receiver has definitely an impact when assessing the previously defined interference requirements, and therefore, in the whole interference process. However, achieving accurate results in this process also requires from a proper and reliable characterization of the radio propagation conditions in the considered environments for both the desired link and the interferer one. Undoubtedly, propagation channels have a considerable impact on the results obtained regarding the complexity of propagation channel conditions in high speed environments. Under this scope, the already developed demonstrator, which is a key element for modelling the broadband (LTE; UMTS) and narrowband (GSM, GSM-R) propagation channel in railway environments, can boost the accuracy of the results obtained in the interference evaluation process. Therefore, the characterized and modelled propagation channels derived from measurement campaigns have be incorporated into the analysis of coexistence between public broadband communication systems and GSM-R.

9. Conclusions

In this paper several methods for assessing the performance of a broad band system in high-mobility railway environments are described. The process is useful to validate a new technology on a complex environment where reliability and safety are involved.

Firstly, a ray tracing simulator has been described and validated using propagation measurements made in open areas and tunnels. Based on those measurements and with the help of the proposed Ray tracing simulator, those scenarios have been simulated and the corresponding high-accuracy models have been obtained.

Secondly, a multiband demonstrator has been developed to carry out the aforementioned channel propagation measurements as well as to evaluate the performance of LTE in railway environments.

Thirdly, simulation results based on the HST channel model were assessed in terms of BER, SER, throughput, and control packet error ratio. The results showed the dramatic impact of the Doppler effects, which is noticeable at speeds as low as 15 km/h.

Finally the coexistence of LTE with other radio system in railway environment is analysed, providing reference parameters for evaluating the impact of interferences.

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