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Perturbation in Railway communications (Stream c)

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1. Executive Summary

To avoid a complicated validation process with costly on-site testing for new Train-to-Ground (T2G) communication systems, the European EMULRADIO4RAIL Project will provide an innovative emulation platform for tests and validation of various radio access technologies (RAT) like Wi-Fi, GSM-R, LTE, LTE-A, 5G and Satcoms, aligned with the X2RAIL-3 project. The emulation platform will combine simulations of the communication core network and emulation of various RATs thanks to the coupling of discrete event simulator such as RIVERBED Modeler, Open Air Interface, several radio channel emulators, models of IP parameters and real physical systems.

Given that railways are a very complex and hostile environment for the radio propagation, it is needed to address the potential sources of degradation of the radio links appropriately and to quantify their impact as well. In this report, we investigate perturbations that may happen in the railway environment or can be expected in the future as well as the first identification of ways to implement them in a channel emulator. Most of the addressed perturbation sources are common to the different RATs and frequency bands. However, some of the models, still under research, will have to be adapted to the very specific use context. This deliverable gives the general framework for the inclusion of perturbations in the emulator and further investigation is needed to adapt the models to the specific frequency bands or network topologies considered.

The considered electromagnetic interference (EMI) includes interference induced by other communication networks using the same or adjacent frequencies, transient EM interferences, produced by the catenary-pantograph contact loss (broadband and able to cover the frequencies of the different communication networks), Intentional EM Interferences (IEMI), produced by jammers onboard train or on the trackside. In many situations, EMI in a railway environment exhibits non-Gaussian statistics, and its power is not a sufficient statistic to determine its impact. Its dynamicity is also a strongly impacting factor. To consider interferences in both simulation and emulation, it is necessary to take into account that, depending on their origin, they do not have the same impact on the uplink and downlink, as it can be clearly illustrated by the sliding contact between the pantograph and the catenary. In defining the scenarios, it will be necessary to analyze if the interferences act on either links or only one link and if their statistics are the same in the uplink and downlink. This will permit to adapt the models to the railway operational conditions and to define the injection points of the interference models in the communication chain.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
BER	Bit Error Rate
CF	Characteristic Function
EFT	Electrical Fast Transients
EM	Electro Magnetic
EMI	Electro Magnetic Interference
FPGA	Field Programmable Gate Arrays
GSM-R	Global System for Mobile Communication-Railway
IEMI	Intentional EM Interferences
MAC	Medium Access Control
MCM	Multi Carrier Modulation
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Duplex Multiplexing
PDF	Probability Density Function
PHY layer	Physical Layer
RAT	Radio Access Technology
RF	Radio Frequency
RFID	Radio Frequency IDentification
SDR	Software Defined Radio
USRP	Universal Software Radio Peripheral
Wi-Fi	Wireless-Fidelity

3. Background

The present document constitutes "the Deliverable D 1.2: Perturbation in Railway communications (Stream c)" according to Shift2Rail Joint Undertaking programme of the project titled "EMULATION OF RADIO ACCESS TECHNOLOGIES FOR RAILWAY COMMUNICATIONS" (Project Acronym: EMULRADIO4RAIL, under Grant Agreement No 826152).

In December 2018, the European Commission awarded a grant to the EMULRADIO4RAIL consortium of the Shift2Rail / Horizon 2020 call (H2020-S2RJU-OC-2018 S2R-CFM-IP2-01-2015).

EMULRADIO4RAIL is a project connected to the development of a new Communication System planned within the Technical Demonstrator TD2.1 of the 2nd Innovation Programme (IP2) of Shift2Rail JU: Advanced Traffic Management & Control Systems. The IP2 "Advanced Traffic Management & Control Systems" is one of the five asset-specific Innovation Programmes (IPs), covering all the different structural (technical) and functional (process) sub-systems related to control, command and communication of railway systems.

The document has been prepared in the framework of the EMULRADIO4RAIL project (GA 826152), WP1/Task 1.2.

4. Objectives

This document covers the different solutions to include perturbations in the emulator. It also provides a selection of the most relevant solutions to be evaluated.

Therefore, the main objectives of the document are:

- To propose a state-of-the-art study of the perturbations encountered in Railway environment.
- To select the significant perturbations for the selected Radio Access Technologies, mainly Wi-Fi and 5G (but the proposals can be applied to any other RATs).
- To propose solutions for their inclusion in the EMULRADIO4RAIL platforms.

5. Electromagnetic (EM) environment

The main elements characterizing a complete railway system are vehicles, the line, and the supply substations. A wide range of operations describe these elements, and they feature different electromagnetic phenomena. If other equipment and subsystems are considered, (*e.g.*, telecommunication, heating, air conditioning and ventilation, passenger announcements and information, alarm system, lighting, escalators and elevators, ticketing and fare collection, *etc.*), the overall picture becomes more complicated. For effective management of the EM environment in railways, the principles of EM zoning is applied, as illustrated in Fig. 1. The railway boundary is defined as an area up to 10 m from the nearest running rail and extends 3 m beyond a sub-station boundary. The area is generally characterized as being equivalent to a heavy industrial environment. Railway EM environment is classified as follows [OM12].

- **Train or onboard EM environment**: it refers to all onboard equipment including communication and signaling devices, IT equipment, *etc.* A strong magnetic field characterizes this environment at the traction frequency. It is produced by all the traction system apparatus and its connections (main transformers, filters, traction converters and motors, braking choppers, circuit breakers, etc.), and by a significant transient magnetic field in some cases.
- **Line and track EM environment**: line and track environment refers to the equipment installed at a short distance from the line (or the track) or with a specific EM connection to the track and line, even at a more significant distance (*e.g.,* signaling devices and their cable connection).
- **Substation EM environment**: this environment refers to the equipment installed at fixed power supply installations, *e.g.,* programmable logical counters and terminal units located inside the electric substations and technical rooms.
- **Residential and industrial EM environment**: residential and industrial environments include CE marked equipment, although they are not used and installed in critical zones, they can fall under the other railway environments.

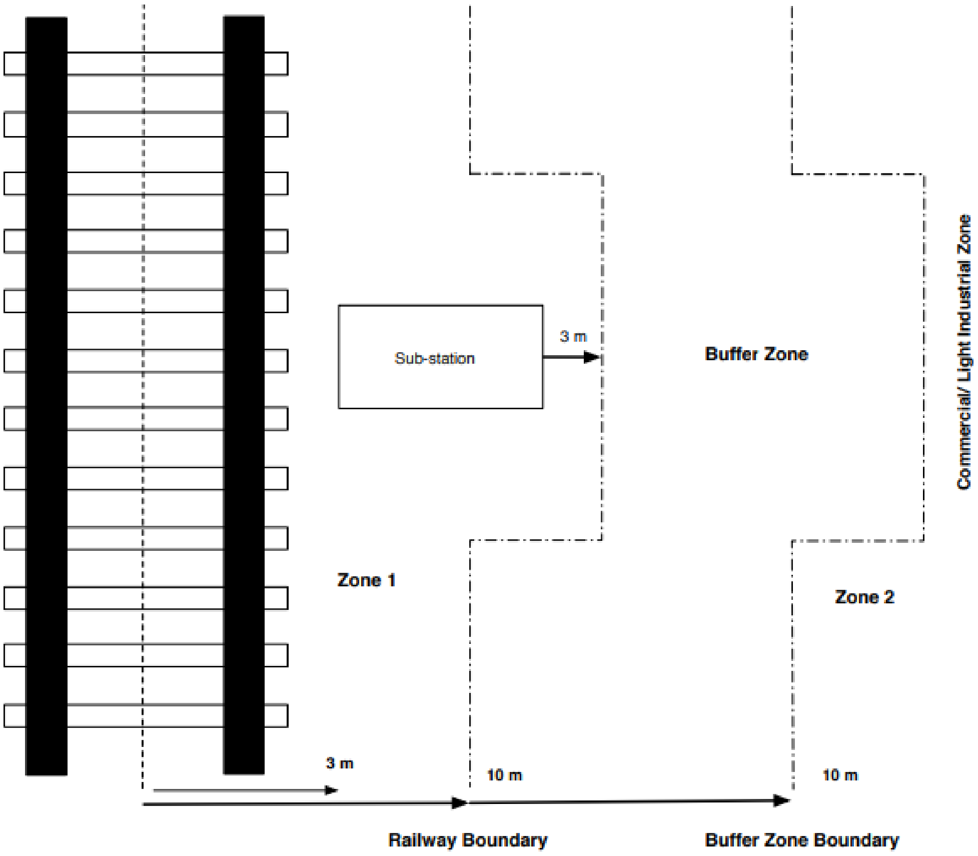

Figure 1. : Railway Electromagnetic Zones [OM12]

EM compatibility is regulated by the 2004/108/EC directive and the more recent directive 2014/30/EU, applicable since 20 April 2016. Other recommendations have also been published like the ITU-T recommendation K.136 (11/2018) on the EMC for radio equipment but without anything specific for railways. For the railway environment, the European harmonized standards series EN 50121 define how to show that the EMC requirements are fulfilled [EN15].

Most of the perturbations resulting from this EM environment will not impact the radio communications that use higher frequency bands. In the following of the document we will describe the most significant perturbation that can threaten the radio link reliability, especially in the WI-FI band (2.4 GHz) and the large spectrum covered by 5G.

6. Network Interference

6.1. Intentional EMI sources.

Such perturbations include equipment having a communication functionality like RFID Ticket Validation Systems. Standards take care of the perturbations outside the useful frequency bands so that their impact is shallow in bands covered by wireless communication links.

6.2. Coexisting systems.

In the following, a channel is defined as a frequency and time resource used by a desired user. If non orthogonal multiple access are used, in power or code domain, residual interference is expected, even with multiple user detectors and has to be taken into account. Other users transmitting at the same time and in the same band than the useful user can create interference. We can have different types of such interference [S03]:

- Coexisting networks refers to an interfering signal that is transmitted in the same frequency band as the useful signal but with a different PHY layer and protocol. For instance, WI-FI and Bluetooth communicate in the same frequency band at 2.4 GHz, as well as many other systems.
- Co-channel interference refers to an interfering signal that has the same carrier frequency as the useful information signal.
- Adjacent channel interference refers to users using a different frequency band that partially overlap with the useful information signal. It can be classified as either in-band or out of band interference if the centre of the interfering signal bandwidth falls within or outside the bandwidth of the desired signal.

6.2.1. In licensed bands (2G-3G-4G-5G)

Coexisting networks should not exist in a licensed band, which is reserved by an operator for his specific network.

Co-channel interference can exist when users communicate with two different base stations while sharing the same band. This can happen in the uplink or the downlink. Resource allocation will try to avoid this situation and this type of interference could be avoided in railway communications due to the particular topology of the network, but a specific network planning for railways is not envisioned. Besides, it could create some interference in stations or when trains are in cities in open spaces. In addition, measurement campaigns performed during 2013-2014 concluded that current GSM-R receivers were affected in specific places by intermodulation generated from wideband or narrowband signals from public operators. It occurs even though both railway and public operators use their assigned radio spectrum in compliance with the relevant European and national regulations [EUAR16, DDAS12].

6.2.2. In unlicensed bands

6.2.2.1. Introduction and Motivations

Wireless communication systems are usually designed assuming Gaussian noise. This fundamentally impacts many solutions that are used in transmitters and receivers. This is especially the case when it comes to the design of the receiver decision strategy which is typically directly derived from Gaussian assumptions. When these assumptions are not satisfied, or the interference is far from Gaussian, the receiver is significantly sub-optimal in its performance. One frequently encountered type of noise is designated by the term impulsive. This means that large noise values can appear from time to time [GT08]. However, this term covers a lot of different statistical models and each model gives rise to many different communication strategies.

6.2.2.2. Standard models

Interference term is not modelled adequately with a simple Gaussian distribution assumption. We present here some of the key results in this regard that we summarized in Table 1.

Table 1: Different interference models.

Where does the model come from?	**What are the main results**	**Examples, comments, simplification**
Work from Middleton [Mid77, Mid99]	Distribution expressed as infinite series	Simplification to the most significant terms: ε-contaminated [AB07, PLZB03], Bernoulli- Gaussian [HTL12, VTNH14, BK17, CQA17], Gaussian mixtures [GDK06, HB08], Markov [NAV14, FC09]
Empirical approach based on fitting of data and improvement of the receiver	Many different distributions	Laplace [BN10], Cauchy [GCAS10], Cauchy- Gaussian mixture [MJGC17], Generalized Gaussian [F06,BSF08,KLC09], Normal Inverse Gaussian [GPCS12]
Based on stochastic geometry [HG09, WA12]	Distribution expressed as infinite series	If no near-field effect, falls in the attraction domain of an α-stable distribution [S92, WPS09, GCAS10].

Some example of noise realisations can be found in Fig. 2. We notice the different behaviour that can be observed in large events. Some links exist between the different models, depending on the parametrization that are chosen. For instance, the ε-contaminated is an approximation of the Middleton considering two terms of the series, while the Gaussian belongs to the α-stable family with α=2.

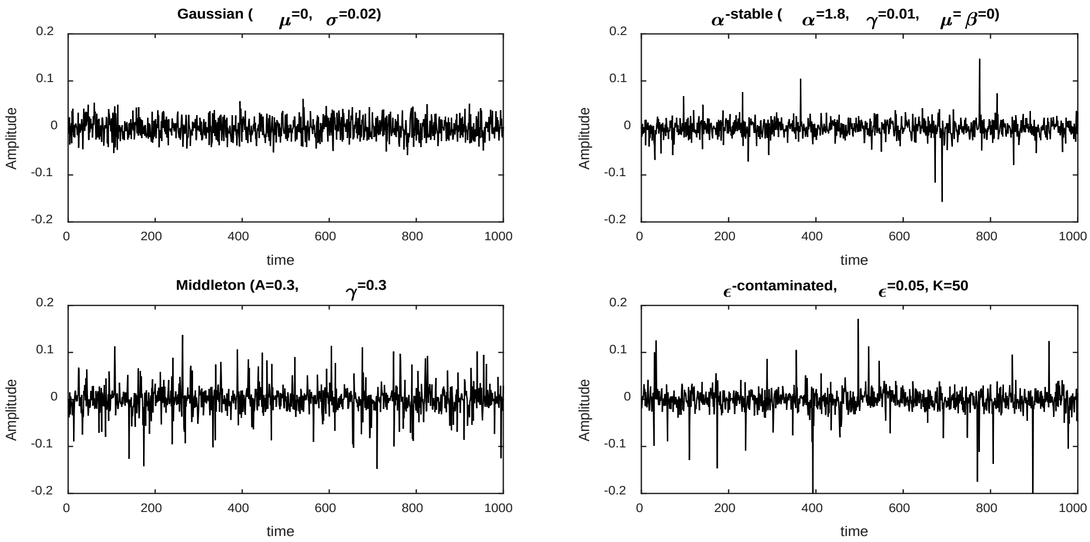

Figure 2: Some examples of simulated noises.

6.2.2.3. Middleton model

We can trace back some works on non-Gaussian noise to 1960 [FI60] and 1972 [GH72] about atmospheric noise. Assuming Poisson distributed sources, the Characteristic Fuction (CF) of the impulsive noise can be obtained. Furthermore, appropriate assumptions on the transmission medium and source waveforms allow one to obtain the interference Probability Density Function (PDF). A similar approach based on the CF was used by Middleton [Mid77, Mid99]. He obtained more general expressions based on series expansions. He classified interference in two main categories depending if the noise bandwidth is less than the useful signal (class A) or greater (class B). Class C is a sum of class A and B. Canonical expressions of the distribution functions are obtained.

Middleton models have been widely used in different contexts [ON17, AALM17] (MIMO [CGET09], OFDM [III07] or power line communications [AP10]). It is clear however that this popular model is challenging to work with since the density function involves infinite sums. Consequently, several approximation models have been proposed. The main approach is to consider only the most significant terms. For instance, it is claimed in [V84] that, in many situations for the class A, two or three terms can be sufficient to obtain a good approximation leading to a Gaussian mixture [GDK06]. The two terms case is often denoted as the ε-contaminated noise, see [56, AB07, AALM17] or expressed in the form of a Bernoulli-Gaussian noise [HTL12, VTNH14].

In [FC09a, NAV14, AETW17], the class A model is represented by a Markov process: the noise distribution depends on the state of the process. It reduces to the ε-contaminated case when only two terms are present, but with an additional feature of time dependence structure, see [FC09b]. The well-known Class B model can be approximated by an α-stable distribution [Mid99], still difficult to use in practice.

6.2.2.4. Empirical approaches

More recently, many works have been done concerning Time Hopping Ultra-Wide Band (TH-UWB) [ZOSM09]. After showing that the standard Gaussian model is not accurate [DR02], non-Gaussian models were developed. Many works have also proposed empirical choices that allow analytical analysis of the receiver, justified by simulations, observations of the estimated PDF and/or gains in Bit error Rate (BER).

The main solutions that have been proposed include Gaussian-Laplace mixture [BN10], Generalized Gaussian [F06, BSF08, KLC09], Gaussian mixtures [HB08] or Cauchy-Gaussian mixture [MJGC17]. In this last report it is mentioned that the heavier tail of the Gaussian Mixture allows better performance than the Laplace approach. Some surveys can be found in [BY09, S12].

All these approaches target a specific class of interference and are not supposed to be robust or adaptive to changing interference environments. Another class of model of direct relevance to interference modelling is the α-stable. It has often been used in the UWB context [PCGC06, WPGC06, RQPO07, NB08, BY09, GCAS10]. But on the contrary to the previously discussed approaches, it relies (when no power control is done) on a theoretical derivation (that can be related to a physical interpretation), closely linked to the Middleton's work and finding its foundation in stochastic geometry [BB10a, BB10b, WA12].

6.2.2.5. Stochastic geometry and α-stable

Although the first reports were published in the nineties [S92, TNS95, IH98], the analysis of networks has recently attracted a lot of works relying on stochastic geometry. As in Middleton's work, interferers are assumed spatially distributed according to a Poisson field, as shown in Fig. 3.

In this context, the distribution of interference is expressed as (1):

$$I = \sum_{i \in \Phi} l(d_i) Q_i, \qquad (1)$$

where d_i is the distance between interferer *i* and the destination and $l(d)$ the attenuation as a function of the distance; a classical model is $l_{\gamma,\varepsilon}(d) = d^{-\gamma} I_{r \geq \gamma}$, $d \in R^+$, where γ is the channel attenuation coefficient; ε accounts for a minimum distance between the receiver and the transmitter for physical reasons or due to some MAC layer protocol like carrier sensing; Q_i accommodates various propagation effects such as multipath fading and shadowing as well as the physical layer of the transmitters and the receiver; and Φ is the set of interferers.

If applied in an ad hoc network, an unbounded received power assumption makes the interference fall in the attraction domain of a stable law. This unbounded assumption means taking the limit as $\varepsilon \to 0$; in that case the received power tends to infinity when d tends towards zero. The accuracy of the approximation has been questioned in [IWCP09, C10], but working without the unbounded received power assumption does not allow an analytical derivation of the characteristic function [WA12, DG14]. A truncated α-stable distribution is proposed in [RQSW11, ECFD17] to solve the infinite variance problem.

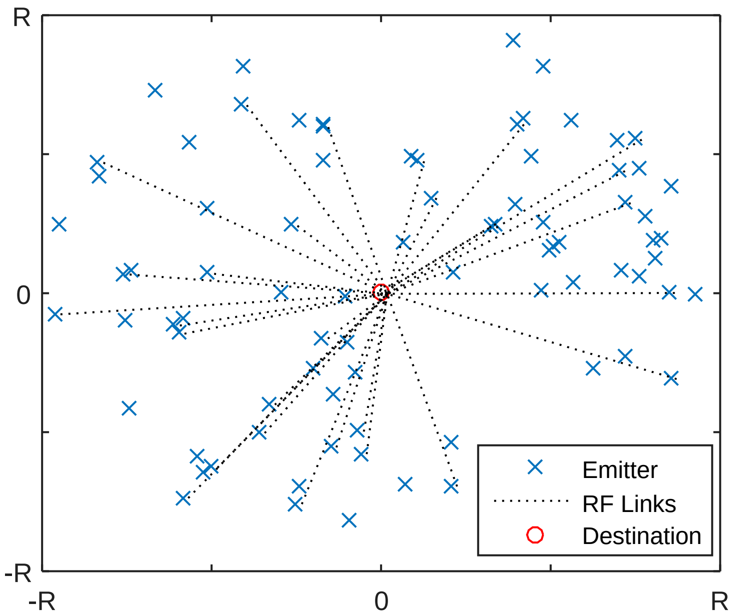

Figure 3: A large number of source transmit simultaneously their signals which add at the receiver and create interference.

This result can be seen as a consequence of the generalized central limit theorem [ST94, NS95]. The main advantage of the heavy tailed stable distributions is their ability to represent rare events. In many communication situations, these events are in fact those that will limit the system performance. The traditional Gaussian distribution ignores them leading to poor results. The proof of this result is generally done considering the log-CF of the total interference (cf. [S92, WPS09, GCAS10] for instance). Another solution for the proof, based on the Lepage series, was proposed in [IH98].

6.2.3. Other systems effect

Inter Carrier Interference can result from Doppler shift (high speed) in OFDM and in general in multicarrier modulation (MCM). This assumes that two different links are affected by different Doppler effect: for instance one ground to ground communication interfering with a train to ground link. If communications are not properly designed, this can harm the link performance. This could especially be the case in WI-FI signals in unlicensed bands where no frequency planning is done, while in licensed band network planning should be able to avoid this effect. However, standard WI-FI signals are not designed for train-to-ground or ground-to-train communications and should only support such situations at low or moderate speed (up to 130 km/h) or even in the station when the train is stopped. In that case, the Doppler effect is negligible. In other conditions where it can influence the useful link, the interfering link should also be emulated and the Doppler is introduced in the channel model.

Keyholes is a phenomenon that restricts the MIMO (Multiple Input Multiple Output) capacity of the channel [CFGV02, MHRC15], even if the diversity in both the transmitter and the receiver is high. In such a situation the channel matrix only has one significant Eigenvalue, the others being significantly lower, and the expected diversity is not reached. This can significantly impact the communication, especially in tunnels, where the achievable rate of the communication can suddenly decrease so that transmission fails. It is however a channel effect and has to be taken into account in the channel model.

6.3. Unintentional jamming

Unintentional jamming refers to equipments which do not have an electromagnetic radiating functionality (antenna). As illustrated in Fig. 4, such perturbations are likely to be produced by many sources: high voltage overhead power lines, arcing and lightning, power converters and battery chargers, and other railway systems nearby [OM12].

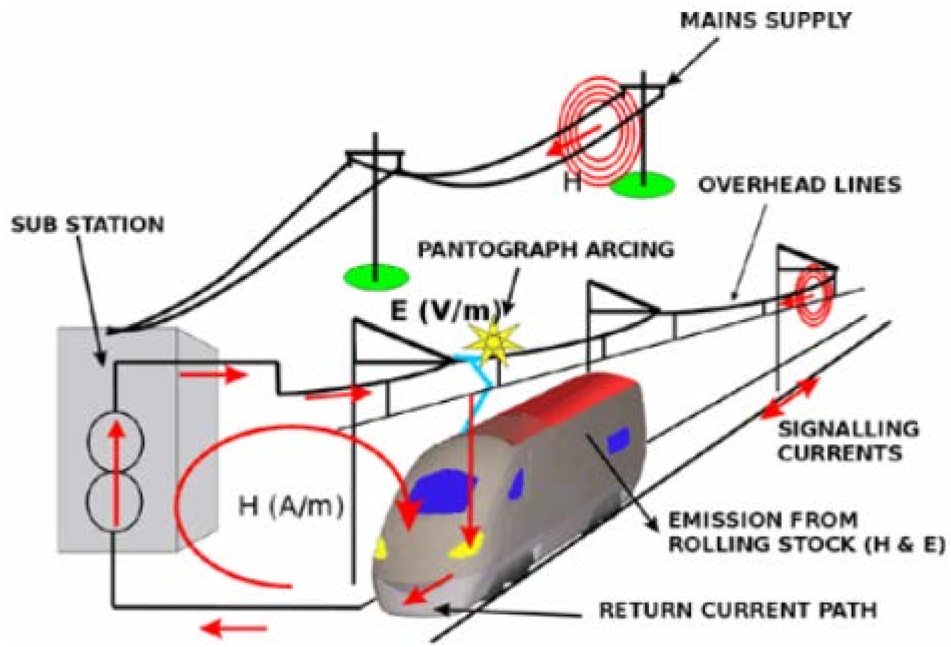

Figure 4: EMI influences between Railways – Infrastructure -surroundings [MWGK12].

6.3.1. Radiated emissions for the on board apparatus

Emissions radiated to on board apparatus correspond to spurious emissions. This category includes on board equipment, whose radiated emissions requirements are defined in EN

50121-3-2 [EN15]. Under this classification are considered equipment as traction system, auxiliary converter, brake system, access doors, heating, ventilation, and air conditioning (Cabin and passengers). For instance, in the band 1 to 3 GHz, the maximum radiated emissions are 76 dBµV/m Peak and 56 dBµV/m Avg.

Several types of such disturbances can be identified:

- Harmonic disturbance: generally derived from equipment with non-linear voltage/current characteristics. The harmonic components are sinusoidal components with a frequency integer multiple of a supply fundamental frequency.
- Flicker disturbance: flicker is caused by rapid voltage variations with an amplitude generally much lower than the threshold of immunity for electrical equipment.
- Supply voltage variations (interruptions, swells, sags, dips): a voltage dip is a sudden voltage attenuation at a particular point of an electricity supply system below a specified dip threshold - within a time period no shorter than 10 ms - followed by its recovery after a brief time interval.
- Radiofrequency conducted emissions: represent the radio frequency noise present in the physical wiring or traces of an electrical system. This noise is generated by switching operations or harmonic resonances within a circuit.

Their impact at the frequencies of the communication systems, above one or half a GHz, that we study is very limited and can be included in the ambient Gaussian noise.

6.3.2. Natural EMI sources

Conducted impulsive disturbance (surges, electrical fast transients (EFT)): may be classified as slow pulses (with a rise time between 1 and 10 µs and a duration time, or time to half-value, between 50 and 700 µs, depending on the type of test and recalled standard) with high energy content, and fast pulses (with rising time and time duration equal to 5 and 50 ns), thus, featuring a much lower energy. The power bandwidth of the two types of impulsive signals extends up to a few or a ten of kHz for surges, while it is much larger (around a dozen of MHz) for the EFT. A significant source of impulsive disturbance is arcing produced by the sliding contact between the pantograph and the catenary or by the third rail [DDAS12, MWGK12].

This is probably the main perturbation, specific to railways communication, which can significantly impact the reliability of radio links. It has to be taken into account in a radio channel emulator. The main solutions to include such a perturbation are the following:

- If a baseband model is used or if a signal can be added at the baseband level at the receiver side (after sampling), an impulsive noise model can be used. Such statistical models will be similar to those presented in section 3.2 (Coexisting systems, unlicensed band). They can indeed be applied to such impulsive perturbations and, for instance, an uncorrelated α-stable distribution has sometimes been used [HGDB14, KDZS18].
- Another way is to directly consider the analog perturbing signal, which can be modeled as a damped sine [DDAS12]. A statistical model for amplitude, frequency and inter-arrival times has

then to be defined and parameterized. This requires a signal generator which emits this specific damped sinusoid that has to be added to the useful signal at the receiver. Note that other EM phenomena may exist like coupled voltage on cables and EM field in the reactive region, but with a more limited impact in radio communication links.

7. Illegal jamming

The development of telecommunication solutions makes easier the access to EM signal generation equipment (like with Software Defined Radio (SDR) modules), which can be used for either legitimate or malicious purposes [DGRS17, KE15]. The existence of telecommunication jammers is widely noticed and it constitutes a risk for a large number of civilian communication services [TBBL15].

Many types of radio jammers are for sale on the market, battery operated, pocket size, or more powerful. Some can block the signals of only one frequency band; some can block up to five frequency bands at the same time [HDRG17]. They operate between several hundred MHz up to a few GHz. Most of the proposed solution use a sweeping strategy where a transmitted sine wave with a changing frequency rapidly covers the frequency band. Their instantaneous frequency varies as a linear function of time.

Five classes of jammer devices were identified, noted A to E [HMSJ14]:

- Type ‘A’: they use several independent oscillators transmitting ‘jamming signals’ that blocks the frequencies used by mobile communication equipment.
- Type ‘B’: they detect signals in quiet areas and they send a signal to inform the base station to interrupt the communication.
- Type ‘C’: they work on the control channels as ‘beacons’, they send instructions to mobile devices in a quiet area to disable ringer or its operation.
- Type ‘D’: the jammer is predominantly in receiving mode and block the cell phone if it is close to the jammer.
- Type “E” devices ‘EMI Shield – Passive Jamming’: These jamming solutions consist in suppressing electromagnetic signals by using the properties of the Faraday cages.

In this task, we are mainly interested in type ‘A’ devices that can corrupt a radio communication link.

8. Including these perturbations in the channel emulator

8.1. Transposed band

We generate the perturbation signals (waveform generator or SDR boards such as USRP) in the transposed band and adding it at the input of the channel emulator or at the input of the receiver. This can be difficult if the perturbation is very wideband, which can be difficult to generate and we would need a band-limited version of it. If it is another radio signal, from the same or another standard, it can be generated by the waveform generator but it should cross a second (different) channel. So it cannot be injected on the same antenna as the useful signal. This case may cause some interference between the two signals at the input of the channel emulator which is not desired and isolation may be difficult to obtain unless radio signals are emitted through cables. The baseband version would avoid such a problem.

We need in this case to be able to generate the “true” perturbation signal (or to record it and play it). We can also use a down converted version of the signal depending on the input of available at the channel emulator input or at the receiver input.

8.2. Baseband

We generate the perturbation signals (waveform generator or FPGA) in baseband. It can be injected again as the input of the channel emulator or the receiver. They could probably also be directly generated into the channel emulator or the receiver. We need in this case to have a statistical model of the perturbation signal in the band of the useful signal. In the best case it can be white and Gaussian. But, at least for the contact between the pantograph and the catenary it is not the case and not neither for Coexisting networks / Co-channel interference in unlicensed bands, probably the two main perturbations we have to include in the emulator.

8.3. Possible solutions to introduce perturbations

We can identify six possibilities

1. Transposed signal at the channel emulator input

   Isolation between the input for the useful signal and the input for the interfering signal has to be very high, which can be difficult in practice. A coaxial cable can be used instead of antennas and RF signals to feed the channel emulator input. It significantly reduces the isolation complexity.

2. Analog baseband signal at the channel emulator input.

This approach separates the interfering signal and the useful one at the channel emulator input. An analog baseband equivalent of the interfering signal can be obtained in-network interference. Still it can be more difficult for natural interference and we did not find such models in the literature.

3. Transposed signal at the receiver input

   This approach is especially adapted to another radio signal (Wi-IFiI interference for instance), particularly especially if we consider a train-to-infrastructure (or infrastructure-to-train) useful link and a ground-to-infrastructure (or train-to-train) interfering link.

4. Analog baseband signal at the receiver input

   This approach reduces isolation problems. It can be adapted to interfering radio signals (Wi-Fi interference, for instance), especially if we consider a train-to-infrastructure (or infrastructure-to-train) useful link and a ground-to-infrastructure (or train-to-train) interfering link.

5. Digital baseband signal at the channel emulator input (or inside the channel emulator)

   This approach avoids isolation problems but requires a digital baseband model of the interfering source.

6. Digital baseband signal at the receiver input

   This approach avoids isolation problems but requires a digital baseband model of the interfering received signal.

Depending on the emulator itself and of the possible inputs for the interfering signal, the adapted solution will be developed.

9. Implementation solutions

9.1. Selected perturbations

We select three perturbations which are the main causes of communication degradation:

1. **Network Interference**: this is an important issue, both for cellular networks where adjacent cells can create interference, especially if a reuse factor of one is used. This is also a major issue in Wi-Fi The number of connected devices increases in the train and in the station and interference is a limiting factor, especially if some critical communications are planned in such bands.

2. **Natural EMI sources**: one source that definitely impacts the reliability of the communications is arcing produced by the sliding contact between the pantograph and the catenary or by the third rail. This gives rise to short pulses with large amplitude.

3. **Illegal jamming**: one jamming tool that can be bought are frequency sweeping based solutions. They allow to cover a rather wide bandwidth with a limited cost and can be very perturbing even with a reduced transmission power. They will be included because they can be a severe threat to communications.

We can classify them in two types, Type I for perturbation originating from the same place (ground or train) than the useful signal, and Type II for perturbations arising from a different location:

(Type I) Signals generated for a concurrent communication originating from the same place as the useful signal. They do cross a channel, with the same (or at least similar) statistical properties. This is the case of network interference but it could also be the case of illegal jamming depending where the jammer is located. In that case it can be useful for them to emulate a channel.

(Type II) Signals that directly impact the receiver. It is of no interest to make them go through a channel emulator. It can be natural EMI signals but also network interference or illegal jamming if they originate from the same place as the receiver (ground or train) when the transmitter is in the other place.

9.2. The channel emulation

The channel emulator can be divided in 3 parts (Fig. 5):

- A signal generator, connected to the network emulator – it generates the useful signal depending on the studied protocol.
- A channel emulator – it gets the signal from the Signal Generator, either in baseband (it can be a cable input) or in transposed band through an antenna. Its output is the signal that has crossed the channel (either baseband or transposed band).
- A receiver that will decode the packet and transmit it to the receive side of the network.

Figure 5: Simple schematic of the channel emulation.

9.3. Where to introduce perturbation?

As shown in Fig. 6, we can identify two possible inputs:

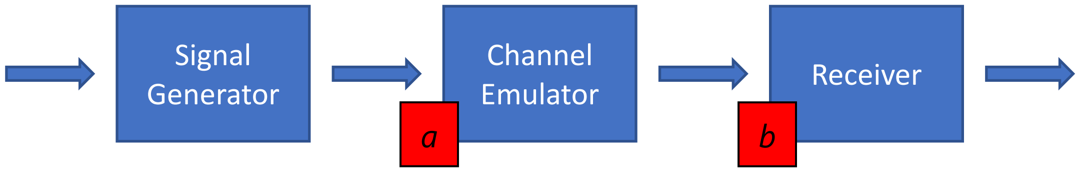

Figure 6: Possible inputs for perturbations.

a) *At the channel emulator input*
- This is problematic if the signals (desired and perturbing) are generated in transposed band because they will mix at the antenna input and both cross the same channel(s).
- The channel emulator needs to have the capability to emulate two independent channels simultaneously
- Working in baseband, at least for one of the two signals (desired or perturbing) with *cable* inputs may be a solution.

b) *At the receiver input*
- This is problematic if we have to take into account that the perturbing signal crosses a channel that should be emulated.
- Isolating the input antenna from the channel emulator from the perturbing signal should be more straightforward if both are in transposed band.

10. The three selected scenarios

10.1. Scenario I: Single Interfering Radio Signal

Emulated Interferer – we generate the true interfering signal.

There is only one interferer that causes trouble. This is the case with illegal jamming or from another unexpected communication at the same frequency. In this scenario, the interfering signal generator is used to emulate a true signal

- Either from a communications standard (WI-FI, LTE, other)
- Or emulating a jammer (sweeping frequency – the exact parameters of this signal have to be defined.)

Solution 1: (Type I – Fig. 7) the interference is another signal from the same network (LTE, WI-FI) or a jammer. Both cross independent channels.

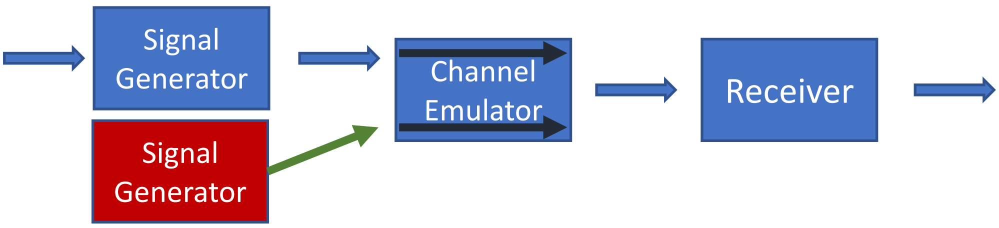

Figure 7: Network interference or jammer, type I.

Solution 2: (Type II – Fig. 8) Interference: another signal from the same network (LTE, Wi-Fi) or a jammer. Any combination baseband/transposed band should be feasible. Both cross independent channels.

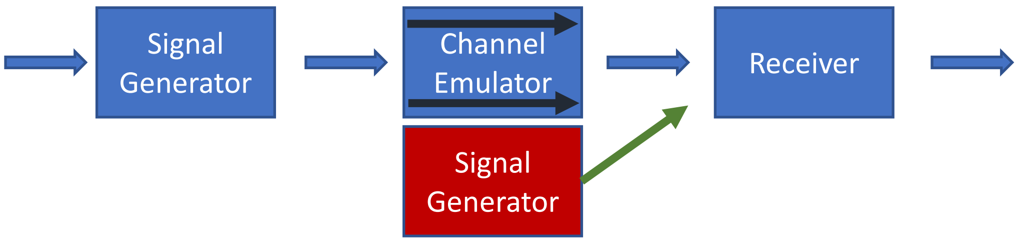

Figure 8: Network interference or jammer, type II.

10.2. Scenario II: Multiple Interfering Radio Signal

In that scenario we cannot emulate all the interferers and we need to rely on *simulated Interferers*. It means we need a model for the interfering signal. This can arise in Wi-Fi or cellular networks where multiple interferers can impact the communication. We propose to inject a model of this interference at the receiver side, preferably in baseband. In this scenario, the interfering signal will be simulated from a statistical model. Different models can be used:

- Rather simple Gaussian mixtures (for instance epsilon-contaminated). A Markov model can be used to simulate the time dependence.
- More sophisticated models like Middleton or alpha-stable and copulas for the dependence structure.

The emulator configuration is the same as in Fig. 8, but the interfering signal is the statistical process representing the contribution of the sum of all interferers.

Remark: heavy-tail process like alpha-stable can be sub-exponential which means that the behavior of the strongest dictates the tail behavior. The consequence could be that this case could be emulated with scenario Type I, only accounting for the strongest user. It has to be verified.

10.3. Scenario III: contact pantograph-catenary

We have to emulate the perturbing signal. The signal can be generated either in baseband as non-Gaussian impulsive noise models (alpha-stable [KDZS18]) or in transposed band as specific damped sinusoid with random amplitudes and inter-arrival rate and added to the desired signal at the input of the receiver. In this scenario, a statistical model of the signal (damped sine wave) has to be defined:

- Exponentially decaying amplitude
- The statistical distribution of the maximum amplitude, the speed of the decay, the frequency, the inter-arrival rate.

The emulator configuration is the same as in Fig. 8, but the interfering signal is the statistical process representing the EMI.

11. Conclusions

Identification of perturbations has been done and the different solutions to include them in the EmulRadio4Rail project have been identified.

The main perturbations to be considered are:

- Network interference in the ISM band,
- Sliding contact between the pantograph and the catenary,
- Illegal jamming.

It is important to develop models for impulsive noises, at least for the two first cases.

We will include in EMULRADIO4RAILs three types of perturbations.

- Type I: From another transmitter on the same frequency band (network interference) or from a jamming signal
    - Type I-m: From multiple interfering signals (dense network interference)
- Type II: natural interference from the contact pantograph-catenary

Different approaches are necessary to cope with the different noises that also depend on the capabilities of the equipment.

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