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Eurobalise-Train communication modelling to assess interferences in railway control signalling systems

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Abstract

The evolution of the railway sector depends, to a great extent, on the deployment of advanced railway signalling systems. These signalling systems are based on communication architectures that must cope with complex electromagnetical environments. This paper is outlined in the context of developing the necessary tools to allow the quick deployment of these signalling systems by contributing to an easier analysis of their behaviour under the effect of electromagnetical interferences. Specifically, this paper presents the modelling of the Eurobalise-train communication flow in a general purpose simulation tool. It is critical to guarantee this communication link since any lack of communication may lead to a stop of the train and availability problems. In order to model precisely this communication link we used real measurements done in a laboratory equipped with elements defined in the suitable subsets. Through the simulation study carried out, we obtained performance indicators of the physical layer such as the received power, SNR and BER. The modelling presented in this paper is a required step to be able to provide quality of service indicators related to perturbed scenarios.

Keywords: balise, BTM, ERTMS, Eurobalise, interference, model, simulation.

1 Introduction

The boost towards a more sustainable society considerably relies on the use of public guided transport systems such as the railway. In these environments, signalling systems are a critical component. Specifically, the railway signalling system makes use of railway communication technologies and specific architectures linked to a very complex electromagnetical environment.

In the European Union, the signalling system for high speed lines is the European Rail Traffic Management System (ERTMS). In fact, ERTMS is also spreading to regional railways and main lines out of the European Union.

ERTMS consists of two subsystems: the European Rail Train Control System (ETCS)—focused on the control of the safety of the trains—and GSM-R—aimed at a permanent radio communication between the command centre and the trains. Nowadays, many railway operators are deploying some of the levels of ERTMS. Thus, the in-lab analysis and simulation tools are critical with the aim of reducing significantly the required activities for the deployment (studies, checks and validation).

The context of the work presented is the development of a full ERTMS simulation framework to allow the analysis of the signalling system, safety and availability of the railway service under normal or abnormal conditions such as a disturbed electromagnetical environment. In fact, the model here presented integrates in a railway simulation framework [1] that models all the protocol stack required for the ETCS application and the permanent communication technology (GSM-R, LTE, . . .) between the train and the command centre (RBC).

The objective of this paper is to detail the way to model the Eurobalise-train communication, which is one of the key communication interfaces between ground and train defined in ERTMS. A preliminary version of this work was already presented in [2]. Now, in this paper, we provide a fully detailed explanation of the modelling process with an special emphasis in the measurements that were performed in order to characterize the communication airgap before modelling and validating it.

The most powerful tool available today for electromagnetic analysis is the computer simulator. There are several commercial packages capable of performing accurate 3D simulations, taking into account different boundary conditions [3, 4, 5]. These platforms can replicate virtually any physical system. However, there are two main drawbacks: On the one hand, the use of computational resources may be high even for simple models, and on the other it may be difficult to relate the performance obtained with the basic design parameters. BTM antennas are defined as almost rectangular loops, and therefore, the analysis of this particular system may be carried out applying the basic electromagnetic equations to the system [6]. This is the approach followed by our proposal. We obtain greater insight into the physical problem, and as a consequence, the conclusions obtained can be used to optimize the system with quantitative and qualitative rules. In order to simplify the expressions, a symbolic mathematical solver has been used. This methodology requires less computational resources than the conventional EM simulator.

This document is structured as follows: Section 2 introduces ERTMS and particularly the operation of the Eurobalise-train communication; Section 3 details the in-lab setup to characterize this communication, a previous required step to successfully model the commu-

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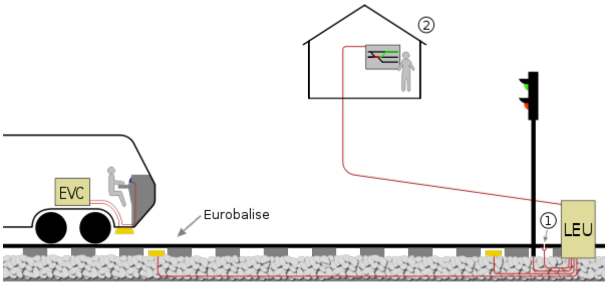
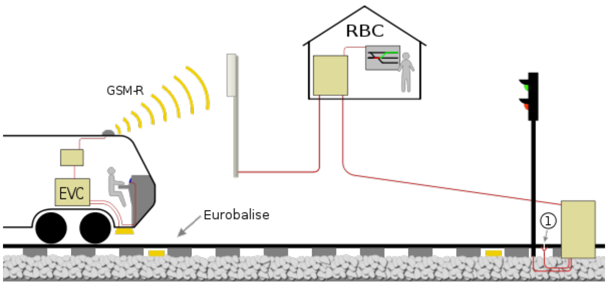
nication; then, Section 4 explains the process to model it and details all the assumptions and simplifications presented in every model of the reality; finally, Section 5 shows the tests carried out to validate the model and the results obtained from the simulations.

2 Eurobalises in ERTMS

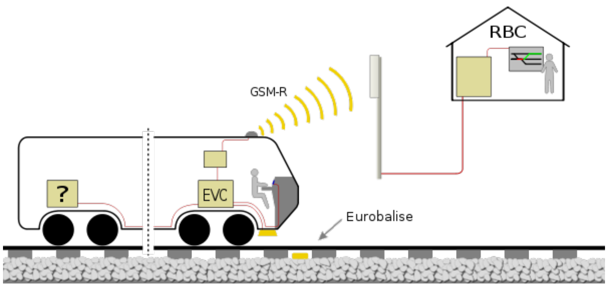
Physically, the European Rail Traffic Management System (ERTMS) [7] is composed of two subsystems: the On-board subsystem and the Trackside subsystem. Each of these blocks is made up of different parts, according to the required ERTMS level of each line.



(a) ERTMS Level 1



(b) ERTMS Level 2



(c) ERTMS Level 3

Figure 1. ERTMS Level 1, 2 and 3 (©Wikimedia Commons, CC BY-SA 3.0).

ERTMS can be configured to operate in the following levels:

- STM Level: The train includes ERTMS and operates in an infrastructure with a national safety system with the STM interface. At this level, national safety balises (ASFA or LZB, for example) are recognized, and their messages are processed as ETCS data. At this level, a certain degree of compatibility and harmonization between national systems and ERTMS is achieved, depending on the particular characteristics of each system.

- Level 0: The train includes ERTMS but the infrastructure is equipped with no ERTMS or any compatible system. At this level, ERTMS does not take part on any track-train communication, therefore is not recommended for normal operation. It may be useful in special situations, for instance in case of a system break down.
- Level 1 (see Fig. 1(a)): The train includes ERTMS, and the railway contains Eurobalises. Euroloop may be also present. The RF communication between the train and the balises provides the appropriate speed limit for each spot.
- Level 2 (see Fig. 1(b)): In this case, the operation is controlled by a Control Centre (RBC) and Eurobalises. This system allows continuous communication between the train and the control centre. The most relevant transmitted data are real time train position, speed limits and dynamic signals. Train integrity and position is still managed through track circuits.
- Level 3 (see Fig. 1(c)): This level is similar to Level 2, but the supervision of train integrity and position is based on the information transmitted by the train. In order to accomplish this task, GNSS positioning systems are incorporated. One of the crucial advances of this level is the possibility to adapt moving block operation, which is a key point to improve traffic optimization and safety. Nowadays, this Level is still under development, due to the massive complexities of the integration of all the subsystems required.

Currently, most part of the ERTMS signalling systems deployed are Level 1 and Level 2. Therefore, the communication between the train and the Eurobalise is a key point of ERTMS. Any error introduced at this level may compromise the correct development of the entire system. Moreover, the communication channel is particularly challenging due to the inherent interferences present in the railway environment.

Next, the two components of this communication, the Eurobalise in the track and the Balise Transmission Module (BTM) On-board the train, are explained in detail.

2.1 Eurobalise

The Eurobalise is a device placed between the rails of a track that transmits messages to the On-board ERTMS, more precisely to the BTM of the On-board ERTMS.

There are two types of balises: Fixed Data Balise, which transmits always the same message, and Switchable or Controllable Eurobalise, which are able to communicate dynamic data to the train such as signal indications. The former are programmed to send the same information each time they are activated, e.g. balise track position, speed limit or track geometry. On the other hand, if the balise is connected to other elements, it may receive and send dynamic data to the train. In any case, the information is sent as fixed length messages, referred in ETCS documentation as telegrams.

The Eurobalises are passive devices, with no external battery required. Most part of the time the Eurobalise is in sleep mode, being activated when a train provides an appropriate telepowering signal. This activation is carried out by the BTM, purposely located at the bottom of the cab. The interaction between the Eurobalise and BTM is depicted in Fig. 2.

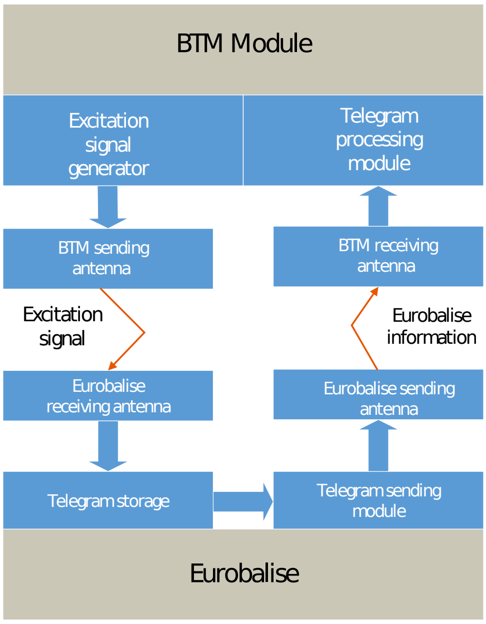


Figure 2. Interaction between Eurobalise and BTM On-board.

The activation of the Eurobalise takes place when the voltage generated by the electromagnetic field, which is ultimately induced by the BTM, reaches a minimum value. Once these values are achieved, the Eurobalise enters the active mode and sends the corresponding messages, according to the specified format, modulation and bit rate. The process ends when the tele-powering signal is too weak to assure the operation of the Eurobalise.

During the activation period, the telegram is sent in a cyclic manner. Since the bit rate of this message is constant, the number of messages received depends on two main factors: The telegram length (341 bits for short telegrams and 1023 bits for long telegrams) and the train speed. In order to validate the communication process, the BTM must receive at least one complete and valid telegram.

In order to successfully transmit the information, the balise must meet the following requirements defined in the ERTMS specification documents [8][9, page 21]:

- Frequency range: 3.951–4.516 MHz
- Transmission bit rate: 564.48 kbits/s
- Modulation scheme: CPFSK
- Eurobalise activation volume (related to the BTM antenna):
  - X into [-1300 ; +1300] mm
  - Y into [-1400 ; +1400] mm
  - Z into [+220 ; +460] mm

2.2 Balise Transmission Module

The on-board train equipment receives the Eurobalise signal through the Balise Transmission Module (BTM). This system is defined by each signalling product manufacturer and carries out several functions: Balise tele-powering, signal acquisition, filtering, demodulation and decoding and finally, communication with the rest of the equipment.

3 Communication characterization

The communication airgap between the Eurobalise and the BTM needs to be defined and described in terms of distances and power losses in order to implement it into the communication modelling. For that, the standard laboratory setup has been built with the appropriate subsystems. The following subsection shows the process and the results.

3.1 Antennas and equipment

The measurements have been carried out with an Agilent 8714ET network analyser, Agilent E4432B signal generator and a HP E4402B spectrum analyser. The antennas have been implemented following the instructions included in SUBSET-085 [10] and SUBSET-116 [8], with the main characteristics listed below:

- Measuring Antenna: This antenna has been fabricated as indicated in SUBSET-116. The loop has been implemented laying out a Cu 200 mm x 200 mm squared track on a PCB board. An additional metallic plane of 400 mm x 400 mm has been fixed to the PCB by means of four plastic material columns. The separation between both planes is 75 mm. This antenna is also proposed for measuring the interferers at the BTM location, on-board [11].
- Balise antenna: A 488 mm x 358 mm Standard Reference Loop has been implemented according to SUBSET-085 [10]. This component emulates the behaviour of the Eurobalise itself. It has eight sections of 5mm x 20mm copper bar. A 3 mm air gap separates each part. At each joint a PCB has been fixed with the required LC tuning circuit. The procedure for the calculation of the components can be found in Annex H of the subset. In this case the loop was tuned to 4.23 MHz and 29.095 MHz.

3.2 Measurement methodology

The first step has been the characterization of the balise antenna emulating the Eurobalise and the BTM receiving antenna. The S11 parameter of the receiving antenna has been measured with a network analyser - Agilent 8714ET. Fig. 3 shows the S11 of the BTM receiving antenna. Even if the values of the port reflection are relatively high for an antenna, it shows that it has been designed for 4.2 MHz.

Now, the current flowing through the measuring loop has to be determined. The transmission test has been carried out injecting -10 dBm signal at 4.2 MHz into the Eurobalise antenna with the signal generator - Agilent E4438C. For this characterization, both antennas are situated face to face, centred. The power received by the BTM receiving antenna has been registered with the spectrum analyser - HP E4402B. Fig. 4 shows the expected current for a -10 dBm power input. As it can be observed, from 1 MHz to 5MHz, the loop is effectively tuned to 4.2 MHz and then, the communication Balise antenna - BTM receiving antenna is maximized at that frequency. The measurements are repeated for different vertical and horizontal displacements. The most significant values are shown in the next subsection.

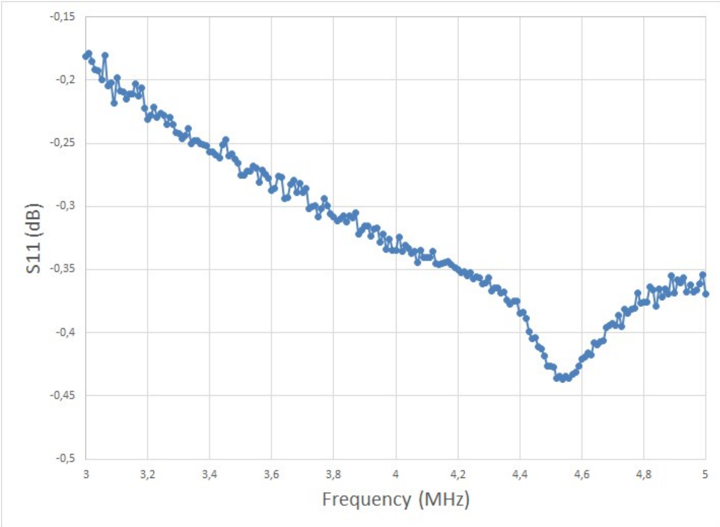


Figure 3. S11 of the BTM receiving antenna.

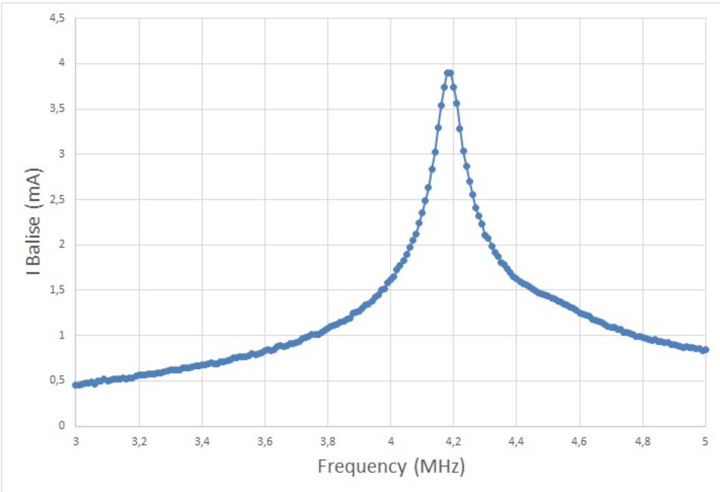


Figure 4. Current measured on the standard reference loop - Eurobalise.

3.3 Results

Fig. 5 shows the power received at the Measuring receiving antenna when a power of -10 dBm is applied to this Balise antenna, at 4.2 MHz. The power received is maximum for a centre separation equal to zero. In this position both antennas present their vertical symmetry axis aligned. The induced flux decreases when the antennas are displaced. The figure also shows the distinctive lobe pattern of the curve. This is due to the cancellation of electromagnetic flux at a specific point caused by the different sign of the contribution of each balise antenna arm. As expected, the measurement procedure with a lower airgap distance presents higher values, at least up to 0.7 m from the centre. From that curve and considering a -10dBm input power, the airgap losses can be deduced in order to implement the communication modelling in the next section.

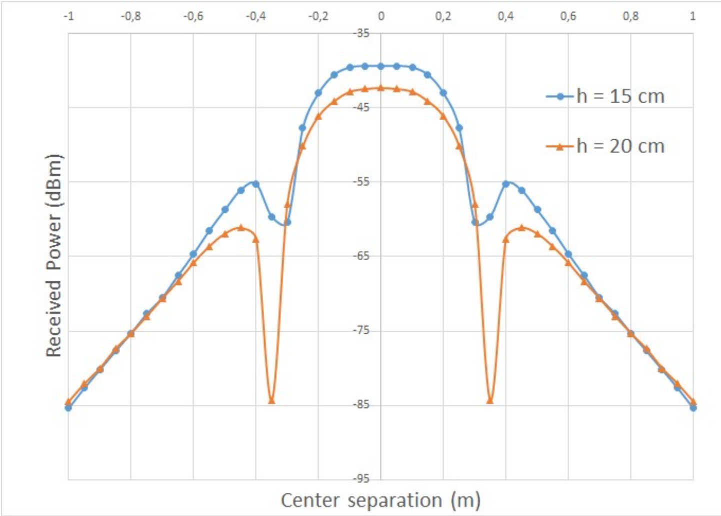


Figure 5. Received power depending on the airgap distance to the centre of the Balise antenna.

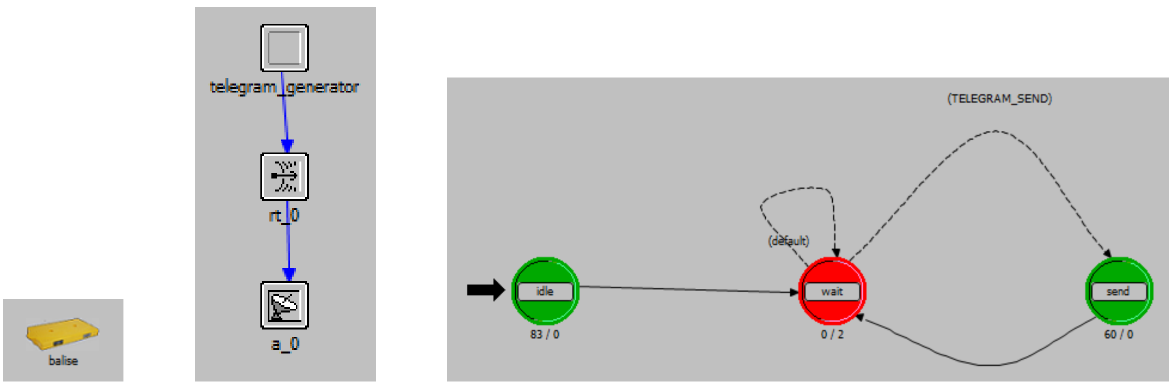
4 Communication modelling

The study of the communication channel between the track and the train has been carried out with the Discrete Event Simulator (DES) Riverbed Modeler, formerly known as Opnet Modeler. This simulator provides a wide range of libraries, allowing us to model real networks and make use of most of the technologies. One of its disadvantages is the lack of models which include near field communications used by Eurobalises. Thus, a specific model for near field communications has been developed. Next, a detailed explanation of the model is presented.

4.1 Nodes

The first step in this study is the creation of the nodes that are going to implement the functionalities for the Eurobalise and the BTM. The models used by Riverbed Modeler are composed of modules and processes so those elements are the ones which have been designed for our models.

Fig. 6 shows the Eurobalise. It consists of 3 modules as shown in Fig. 6(b): telegram generator, radio transmitter and antenna.

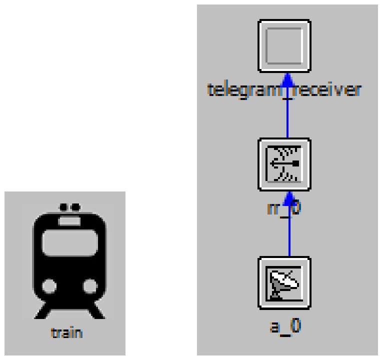


(a) Node (b) Modules (c) *telegram_generator* module

Figure 6. Model of the Eurobalise.

The main module of the balise, telegram generator (see Fig. 6(c)), is responsible for generating the telegrams. It is constantly monitoring the area around the balise to detect if any train is within the activation volume. In that case, the Eurobalise creates the telegram with the adequate length and format and starts transmitting it periodically until no train is inside the activation area. Although the Eurobalise sends a continuous flow of bits and Riverbed Modeler only works with packets, which are called telegrams in the case of Eurobalises, we adjust the periodicity of sending telegrams according to the transmission rate of the Eurobalise and the size of the telegram in order to send a continuous flow of bits as it happens with real Eurobalises.

On the other hand, the model for the BTM is detailed in Fig. 7. The BTM also consists of 3 modules shown in Fig. 7(b): telegram receiver, radio receiver and antenna.



(a) Node (b) Modules

Figure 7. Model of the BTM.

The telegram receiver of the BTM only receives from the lower modules the telegrams which are transmitted without errors once they have passed correctly through the wireless channel of Riverbed Modeler. Thus, this module can count the number of correct telegrams that are received from the Eurobalise.

4.2 Wireless channel

Riverbed Modeler allows to exhaustively model the physical characteristics of the wireless communications. The wireless channel is modelled as a pipeline of stages, which are processed sequentially. Those stages are divided in transmission stages and reception stages. Each of them is in charge of a specific function (verification of frequency ranges, antenna gaining calculation, bit error rate calculation, . . .). For example, Fig. 8 shows the transmission stages for the transmission module of the Eurobalise.

Both modules, the radio transmitter and receiver modules of the Eurobalise and BTM respectively, use the default pipelines provided by Riverbed (known as *dra*). However, some of them have been modified in order to adapt them to the specific characteristics of the Eurobalise-BTM communication.

Thus, in the radio transmitter two stages have been modified:

- *closure* stage: this stage defines if a wireless node can receive a packet sent by a transmitter. A new stage called *eurobalise_closure* has been created to verify if the receiver,

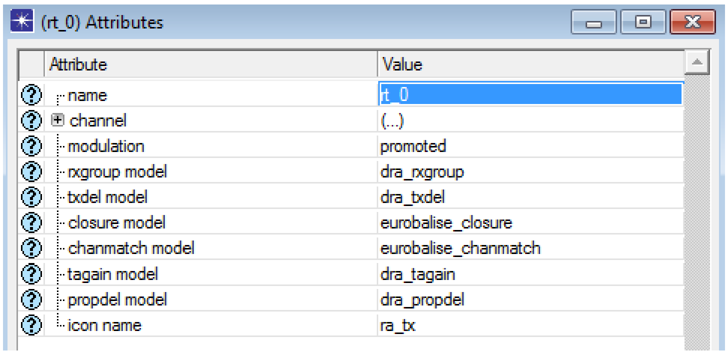


Figure 8. Transmission stages of the wireless pipeline in the transmission module of the Eurobalise.

the BTM, is within the activation area. If not, that node does not receive the telegram sent by the balise.

- *chanmatch* stage: the new stage called *eurobalise_chanmmatch* checks if the transmitter and receiver share the same frequency range, bandwidth, data rate and modulation. If any of the previous parameters do not match, the receiver will consider that packet as noise.

Furthermore, in the radio receiver other stages have been modified:

- *power* stage: this stage calculates the the power of the telegram received at the BTM. The modifications done at this pipeline are explained in detail in Section 4.2.1.

- *BER* stage: this stage calculates the Bit Error Rate (BER) based on the Signal to Noise Ratio (SNR) value obtained by previous stages and the modulation used in the communication. We use the default *dra_ber* stage provided by Riverbed Modeler, but it was required to implement the *CPFSK Coherent* (1) and *CPFSK Non-Coherent* (2) modulations, which are the modulations used in the Eurobalize-BTM communication and are not implemented in Riverbed Modeler:

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{2N_o}}\right) \tag{1}$$

$$P_b = \frac{1}{2} e^{-\frac{E_b}{N_o}} \tag{2}$$

where P_b is the bit error probability, E_b/N_o is the energy per bit to noise power spectral density ratio and $erfc(z)$ is the complementary error function.

- *error* stage: once the BER is known, this stage calculates the number of wrong bits in the packet or telegram. Depending on the number of erroneous bits and the error correction algorithm implemented by the wireless communication, the packet is finally accepted or discarded. The Cyclic Redundancy Check (CRC) algorithm implemented in the Eurobalise-BTM communication checks the integrity of not only the actual packet but also part of previous packet. So, we implemented a new stage called *eurobalise_error* to cope with this peculiarity.

4.2.1 Near field transmission

The *power* stage uses the *dra_power* implementation by default to calculate the received power of one packet by utilizing the Friis transmission equation:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{3}$$

where P_r/P_t is the ratio between the received power by the receiving antenna and the transmitted power by the transmitting antenna, G_t and G_r are the antenna gains of the transmitting and receiving antenna respectively, λ is the wavelength and R is the distance between the antennas.

In order to use this equation antennas must meet the far field requirement:

$$R > \frac{2D^2}{\lambda} \tag{4}$$

where D is the is the largest physical linear dimension of the antenna, for example, the diameter of a dish antenna.

However, Eurobalise-BTM communications do not meet the far field requirement (4) and thus, they are considered to be near field communications, where the Friis transmission equation should not be used to estimate the received power.

Consequently, instead of using the Friis transmission equation we have implemented a new *eurobalise_power* stage that implements the measurements obtained in Section 3. More precisely, this new pipeline stage implements the Fig. 5 in a matrix to obtain the received power of the transmission depending on the distance between the Eurobalise and the BTM when the packet was transmitted.

5 Validation & Results

The main objective of the simulations carried out in this section is to validate the model developed in Section 4 by crossing it with the real measurements obtained in Section 3. In order to perform the simulations we define a basic simulation scenario that consists of one Eurobalise and one BTM inside a train. The train has a trajectory that emulates a rail track and the Eurobalise is located somewhere in that rail track (see Fig. 9). In this way, we are able to validate the activation of the Eurobalise when the train enters in the activation volume and the pass to sleep mode when the train leaves that activation volume.

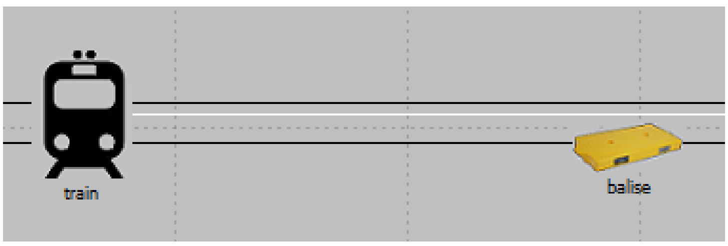


Figure 9. Simulation scenario.

Table 1 shows the configuration parameters of the balise. The value of these parameters has been defined from the requirements of the Eurobalise detailed in Section 2.1.

Table 1. Configuration parameters of the Eurobalise for the simulation.

Parameter	**Value**
Data rate (bps)	564,480
Bandwidth (KHz)	565
Min Frequency (MHz)	3.951
Power (W)	0.316[a]
Bit capacity (bits)	Infinity
Pk capacity (bits)	1,000

[a]This value must not be zero to avoid problems with the simulator but in fact it is not used for the calculation of the received power, the values measured in Fig. 5 are used instead.

In order to verify the correct modelling of the Eurobalise and BTM in the simulator we have to verify three main issues: the connectivity, the received power in near field, and the BER and SNR of the communication.

Firstly, we collect statistics about the number of telegrams sent by the Eurobalise and received by the BTM. Fig. 10 shows that the number of sent and received telegrams is the same and so, it is verified that the communication between both devices is performed correctly. Furthermore, that figure proves that the sent and reception of telegrams is performed in a specific period of time, only when the train is inside the activation volume of the Eurobalise.

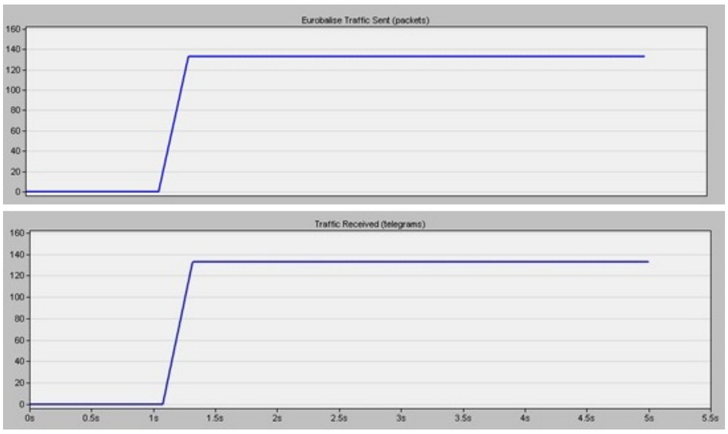


Figure 10. Transmitted and received telegrams in the simulation.

Once verified that the transmission of telegrams is performed successfully, the objective is to verify that the received power of the telegrams is correct according to the measurements done in the laboratory. Thus, Fig. 11 shows the variation of the power of the received telegrams while the train is moving over the balise. This figure is identical to the Fig. 5 and consequently we can assure that we have modelled realistically the received power of the Eurobalise-BTM communication channel.

Finally, we also measure in the model the SNR and BER to evaluate in the future the impact of the electromagnetical noise in the quality of the signal received. Fig. 12 shows the evolution of the SNR during the period of communication between the Eurobalise and the

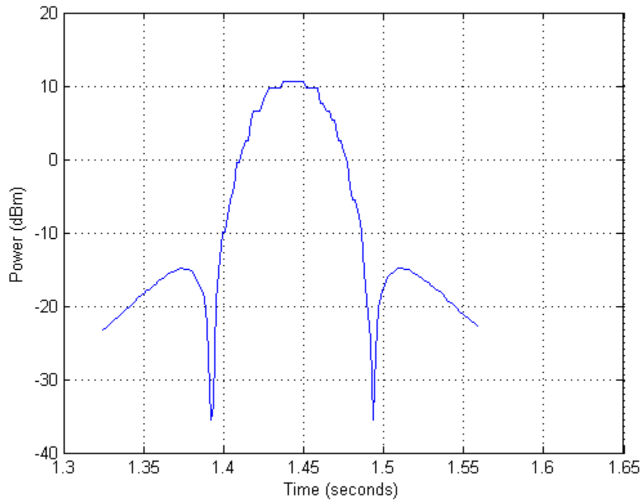


Figure 11. Power of received telegrams in the simulation.

BTM. The shape is similar to the power received because currently we are only applying a default background noise which is a kind of white noise. Otherwise, the BER value shown in Fig. 12 is constant. Its value is very close to zero because the SNR value is so good that there are no errors in the transmission.

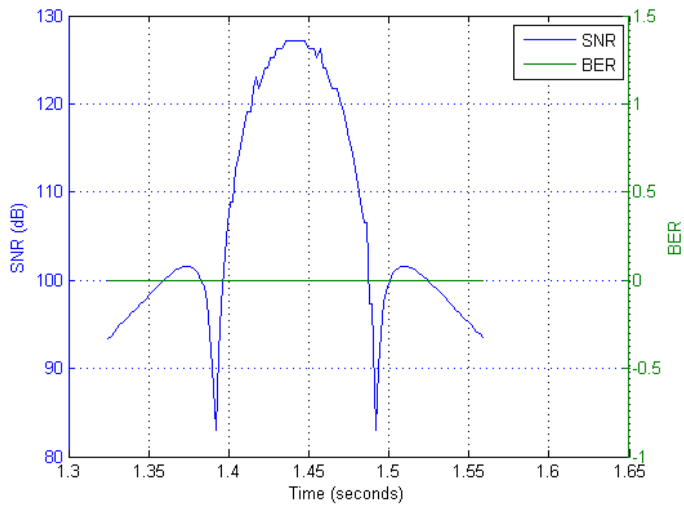


Figure 12. SNR and BER of received telegrams in the simulation.

6 Conclusion

The Eurobalise-BTM communication is part of the train-ground communications of the ERTMS railway signalling system. It suffers interferences and perturbations due to the complex electromagnetical environment of the railway domain. This is a risk that could lead to communication problems and, finally, to affect the railway operation. Since this signalling communication is critical for safety, a wrong reception of the information provided by the Eurobalise could provoke the activation of the service brake as it is indicated in the SUBSET-026 [12, Section 3.16.2].

In this paper we describe the modelling of the communication between the Eurobalise and the BTM located on-board the train in a general purpose DES tool, Riverbed Modeler. This model provides indicators of the physical layer such as the power received, SNR and BER, which have been modelled and verified according to real measurements.

The next step of our research work will be the characterization and modelling of the most common interferences in this environment and the integration of this model in our railway simulation framework [1]. In this way, it would be possible to analyse and establish the relationship between the interferences and the quality of service indicators of ERTMS in order to guarantee the availability of the train service.

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