Train Antenna Requirements, Design and Integration for 5GRAIL Project

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Abstract—**Although it was a great success, the Global System for Mobile communications - Railways (GSM-R) has to step down as it is approaching its obsolescence planned in 2035. Moreover, the equipment suppliers are no more willing to support legacy GSM-R networks or provide spare parts for it, starting 2030. The Future Railway Mobile Communication System (FRMCS) is the candidate to replace the GSM-R. It will be based on the fifth generation (5G) of mobile communication to leverage the benefits that 5G enables, including extreme bitrate, high mobility as well as low latency and high reliability to enable the digital transformation and automation of railway operation. In this context, we propose, in this article, an on-board antenna system that will be used in the European 5GRAIL project aiming to demonstrate the first FRMCS prototype that will be validated in both laboratory and real-field environments. We present our setup in designing an efficient antenna system for the rolling stock so that we could demonstrate different functional and performance related use-cases including their key performance indicators. Finally, we share our preliminary results regarding antenna isolation, while discussing our lessons-learned.**

Index Terms—**Future Railway Mobile Communication System (FRMCS), Railway operation digital transformation, GSM-R successor, on-board antenna isolation**

I. INTRODUCTION

The French national society for railway networks (SNCF-Réseau) is engaged in a consortium called “5GRAIL” [1] that is coordinated by the International Union of Railways (UIC) to develop and test the first prototype of the Future Railway Mobile Communication System (FRMCS) that will be the successor of the Global System for Mobile communications - Railways (GSM-R). “5GRAIL” is a key project in the European Union (EU)-funded Horizon 2020 5G for Connected and Automated Mobility (CAM) program. Accordingly, a dedicated consortium for 5GRAIL was established in 2020. Such consortium is composed of 18 partners covering the whole railway ecosystem including infrastructure managers, telecommunication equipment and railway signaling suppliers, railway applications providers, standards developing organisations as well as academic partners. The aim of the project is to validate the first set of the FRMCS specifications and then feed the whole ecosystem back with the lessons learned acquired through the conducted tests.

The FRMCS is driven by multiple factors that will enable railway operation digital transformation as well as its automation. On the second hand, leading railway operators and industrial players are collaborating closely to specify the FRMCS requirements in the standardisation groups including the UIC [2], [3], [4], the European Telecommunications Standards Institute (ETSI) and the 3rd Generation Partnership Project (3GPP) [5], [6]. The Electronic Communications Committee (ECC) in the European Conference of Postal and Telecommunications Administration (CEPT) has regulated the spectrum that will be used for the FRMCS as railway mobile radio (RMR) [7]. Due to the high demand of data rate, an additional 10 MHz of spectrum was granted to the railway sector for FRMCS operations in the 1900 MHz Time Division Duplex (TDD) band, where the transmission and reception of signals to and from the train are multiplexed in time. Such bandwidth will be used as a complement to the 2x 5.6 MHz in the already used 900 MHz Frequency Division Duplex (FDD) spectrum. This was concluded in the ECC (20)02 decision [7].

In this context, we investigate in this paper, the requirements to design an antenna network (onboard system) for the 5GRAIL project. Note that such design is constrained by the available space (physical length) on the rooftop of the rolling stock that will accommodate both of the 900MHz and the 1900MHz spectra. Indeed, multiple antennas have to be installed on the rooftop to support the 900MHz and 1900MHz bands to ensure reception diversity as well as multiplexing gains leveraging Multiple Input Multiple Output (MIMO) techniques. However, the presence of numerous antenna in a limited space causes interference which harms the performance of the throughput of the system. Indeed, for antennas that share a common ground plane, the isolation can be low. This will cause a degradation in the antennas efficiency. Accordingly, antenna isolation is a technique for separating antennas that coexist so that there is only acceptable levels of interference between systems. It is a challenging task as antenna to antenna isolation is a measure of how are the antennas coupled.

Our contributions could be summarized as follows:

- We review the state-of-the-art antennas in the market
- We model an antenna system and formulate its isolation
- We discuss the performance of our proposed system using simulation and field measurements.

The rest of this article is organized as follows. We first present our system model and problem formulation. Then, we discuss the choice of the rooftop antenna as well the related experimental setup. Finally, we present the simulations and measurements that allowed to determine the isolation between antennas in the target configuration and we discuss the obtained results before concluding.

II. SYSTEM MODEL

In this section, we will present the antenna system model used for the 5GRAIL project. Ideally, the isolation between ports of an antenna network should be as large as possible, expressed in terms of multiple wavelength (λ) but this cannot be easily achieved due to the previously mentioned physical constraints (available footprint and length of the rooftop). The method of measuring isolation is typically done by connecting both antennas to a Vector Network Analyzer, and measuring Scattering (S) Parameters between port x and port y (S_{xy}, S_{yx}) (the transmission coefficient). For instance, S_{12} represents the power transferred from Port 2 to Port 1. S_{21} represents the power transferred from Port 1 to Port 2. Accordingly, S-parameters S_{12} and S_{21} describe the effect on port 2 due to port 1 and vice versa and determine the insertion loss and isolation between the antennas. In practice, antenna to antenna isolation can be increased by: i) increasing the physical separation between the antennas, ii) using different polarization for the antennas in question, and iii) when the antennas employ different frequencies, using filters to reduce the efficiency at the opposite antenna frequency, which results in reducing the correlation coefficient between the antennas radiation patterns. This implies to have an antenna peak radiation in different or opposite direction.Unfortunately, this is not always applicable or feasible (our case) and this is why, a careful design is needed and a validation of the achieved isolation is required and a validation in both simulated and realistic environments is suggested.

The FRMCS modem ports are connected to the antennas ports as shown in the basic electrical schematic depicted in Fig. 1. Due the physical constraints of the rooftop of the train, a special attention is paid to i) ensure a minimum distance separation of 3 meters between the transmission and reception antennas, as stipulated by the FRMCS modem supplier and ii) secure a minimum of 20 lambdas (λ) spacing between the two reception antennas to maximize the reception diversity gain.

To implement hardware redundancy of the FRMCS modems as depicted in Fig. 2, we employ a power combiner. This allows us to demonstrate the concept of hot redundancy. Such power combining has some benefits as i) it is supports hot redundancy, while being ii) a passive part which means that no power supply or control wire would be required. Moreover, it features an insignificant inter-modulation. However, power combining has also some drawback that is the 3dB electrical loss that would be added to the link budget which negatively impacts the cell coverage by reducing it. To compensate for the introduced 3dB loss, we opt to operate the two modems in parallel to double the data stream, every time the throughput metric is demonstrated instead of hardware redundancy.

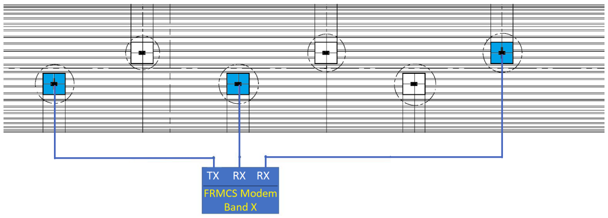


Fig. 1. FRMCS modem ports connection to the antennas ports [8]

On the second hand, as we will be testing the bearer-flex feature that consists of operating multiple radio bearers simultaneously, it is necessary to make sure that many different technologies (up to 3 in our context, i.e. GSM-R/4G/5G) can be run simultaneously without interfering to each other. Ideally, 60 dB isolation, between 2G, 5G or 4G standards, is recommended to guarantee the safe operation of the whole radio access technologies. Usually, antenna spacing and various antenna polarization arrangement cannot provide such a large level of isolation. Extra filtering is to be considered to provide the necessary 60 dB isolation. Accordingly, we present in Fig. 3, a possible configuration based on a diplexer unit usage. Note that i) filters shall comply with the selected frequency bands, ii) also, a careful selection of frequency bands X and Y is needed to avoid inter-modulation with the GSM-R network.

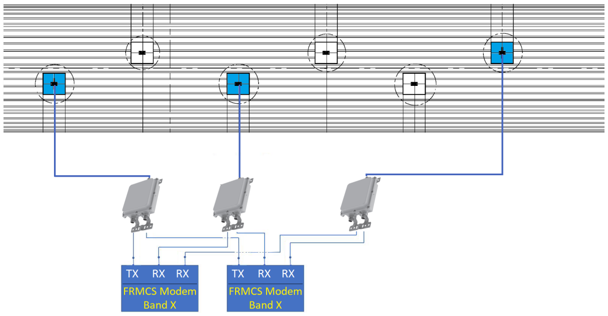


Fig. 2. Antennas ports wiring for hardware redundancy

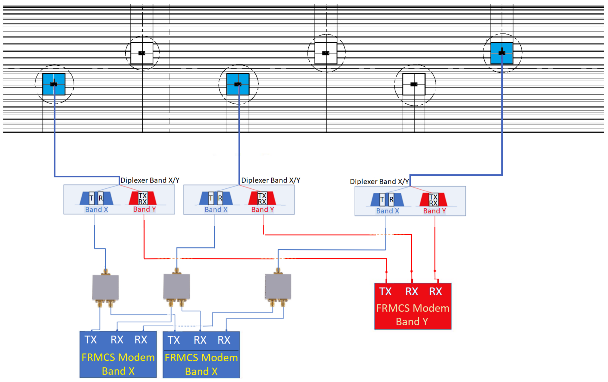


Fig. 3. Antennas ports wiring for demonstrating the bearer-flex concept

III. PROBLEM FORMULATION

We can formulate our isolation requirements as follows. Considering a n input by N output network depicted in Fig. 4, let us denote by j the index of the input port and by i the index of the output port. Similarly, k denotes a loop index. Moreover, let us denote by V the voltage wave injected on a port, with a plus superscript when it is an incoming wave (inbound) and a minus superscript when it is a reflected wave (outbound). Finally, let us denote by Z_{0k} the characteristic impedance of a port. We can denote the characteristics impedance of all the ports as a diagonal matrix elaborated in Eq. 1.

$$\mathbf{Z_0} = \begin{bmatrix} Z_{01} & 0 & \dots & 0 \\ 0 & Z_{02} & \dots & 0 \\ 0 & 0 & \dots & Z_{0N} \end{bmatrix} \tag{1}$$

Provided that the excitation wave is entered at port j and the resulting outbound wave is measured at port i, the general formula of the S-parameter S_{ij} is given in Eq. 2:

$$S_{ij} = \frac{\sqrt{Z_{0j}}}{\sqrt{Z_{0i}}} \frac{V_i^-}{V_j^+}\bigg|_{V_k^+=0, k\neq j} \tag{2}$$

In particular, considering a 2x2 network, we have 4 S-parameters. We can say that S_{11} is the reflection coefficient at Port1 and S_{22} is the reflection coefficient at Port2. However, S_{12} is the isolation (reverse) and finally, S_{21} is the insertion loss (passive device case). Accordingly, the formula for antenna isolation using S-parameters is given in Eq. 3:

$$Isolation(dB) = 20 * log_{10}(|S_{21}|) \tag{3}$$

where S_{21} is the complex transmission coefficient from antenna 1 to antenna 2, and the magnitude of S_{21} represents the power ratio between the signals received by antenna 2 and transmitted by antenna 1.

IV. PERFORMANCE EVALUATION

In this section, we present the set-up of the testing environment, as well as the achieved results for both simulated and real-field measurements.

A. Testing environment set-up

1) Candidate Antenna Review and Choice: There are several types of railway rooftop antennas that support both the 900 MHz and 1900 MHz bands. We can distinguish: dual-band or multi-band antennas on first hand, as well as omni-directional (OD) or directional antennas (DAs) on the second hand. In particular, the DAs are ideal for long-range communication.

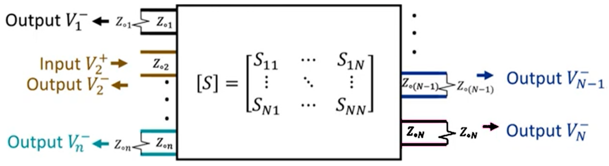
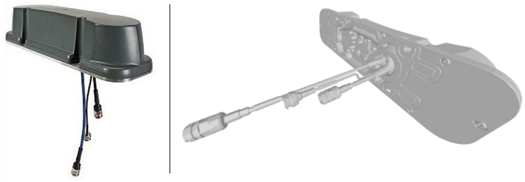


Fig. 4. Scattering Parameters Matrix



(a) Product Picture (b) 3D model

Fig. 5. Train Rooftop Antenna by Huber Suhner [9]

In practice, the choice of antenna depends on the specific requirements of the application, including the desired coverage area, frequency band, and type of communication.

We investigated the data sheets for multiple suppliers (Huber+Suhner [9], Kathrein [10], Rosenberger [11], Antonics [12], Polo-Marconi [13], NetModule [14], Tallysman [15] and TE Connectivity [16]), which cover some European and international antenna manufacturers. Having explored the state-of-the-art on their available antennas, and provided that we were looking for Railway rooftop antenna that offers a rugged design, and meets EN 50155 Railway Standard [17] while supporting cellular and Wi-Fi bands including 2x2 Cellular MIMO for 3G, 4G and 5G in addition to 2x2 Wi-Fi MIMO in all Wi-Fi 6E bands, we have chosen to install an antenna provided by Huber+Suhner and namely, the SENCITY® Rail MIMO Antenna with Dualband Global Navigation Satellite System (GNSS) and low-noise amplifier (LNA) [9]. The chosen onboard antenna product picture (#1399.99.0152) as well as its official 3D model are depicted in Fig. 5.

2) Antenna Measurement Tool Details: We have used Anritsu S332E "Site Master Cable and Antenna Analyzer" with bundled spectrum analyzer (SA) [18]. This tool allows to measure the performance for frequencies going from 2 MHz to 4 GHz. It is combined with 9 kHz to 4 GHz SA, to allow analyzing challenging field conditions.

3) Rolling Stock And Test Trajectory Details: To accomplish the test campaigns, SNCF through the Agency of Railway Trials (AEF) has availed a dedicated test train, named "Martine" as depicted in Fig. 6 consisting of a BB60137 locomotive and a VENG 234 Corail car [19].

Fig. 6. VENG 234 Corail car, part of "Martine" Rolling Stock

We depict in Fig. 7, the physical dimensions and the antenna footprint for the test car. Precisely, this test train will be used to conduct trials between Vitry and Montereau in suburbs of Paris region as depicted in Fig. 8, in order to test various FRMCS use-cases with a focus on data usage scenarios including the European Train Control System (ETCS) and digital interlocking systems as the new control and safety technology as well as the highly automated driving part of the Automatic Train Operation (ATO) according to Grade of Automation 2 (GoA2) [20] and the remote vision system envisioned to serve the remote control of engine use case.

B. Simulation Results using CST Studio Suite

We conducted exhaustive simulations to characterize the isolation between the antennas that will be installed on the rooftop of the test train. To do so, we employed the Electromagnetic (EM) simulation software CST Studio [21]. Knowing that the exact antenna details are private to each supplier, the first step and main challenge at this stage was to determine an antenna model so that its simulated characteristics corresponded to those in the supplier's data sheet. The antenna was modelled as a patch network covered by a Polycarbonate Radome which parameters were adapted to fit the radiation pattern in [9]. Fig. 9 shows a comparison between the simulated and the actual radiation pattern (as communicated by the supplier) at 1900MHz, which allows to validate our antenna model.

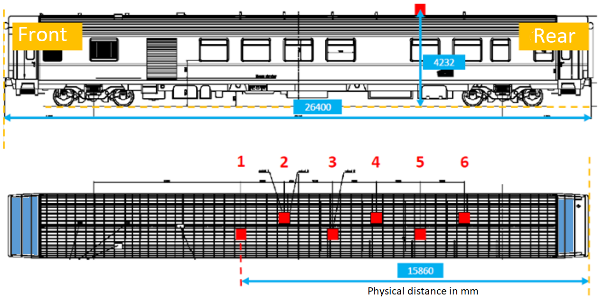


Fig. 7. Test Car Physical Dimension and Antenna footprint

Fig. 8. Test Sites in the suburbs of Paris Region, France

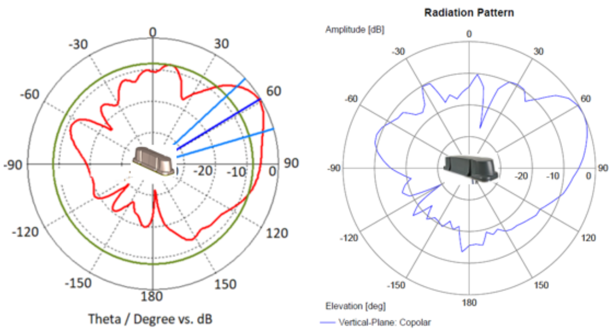


Fig. 9. Simulated radiation pattern of the antenna at 1900 MHz (left) and radiation pattern present in supplier's datasheet (right)

TABLE I
EXCERPT OF SITE MASTER PARAMETERS

Parameter	Value
INPUT_ATTEN	25
START_FREQ	1895
STOP_FREQ	1915
FREQ_STEP	1
IMPEDANCE_LOSS	0
Resolution Bandwidth (RBW)	0.03
Video Bandwidth (VBW)	0.01

Three antennas are to be placed on the rooftop, which means only three of the six available slots are to be occupied. The next step consisted in placing the antennas in a model containing a 3D representation of the train so that their positions on the rooftop corresponded to those presented in Fig, 7. Two different configurations were tested: the first configuration considers the three antennas placed at slots 1, 3 and 6 while the second configuration considers the same antennas placed at slots 1, 2 and 4. Once this was done, the S parameters that account for isolation between antennas could be directly computed at the frequencies of interest (that is, the 1900MHz frequency range) for each scenario. Simulation results containing S_{12} parameters between the antennas at different slots of the rooftop are presented as dotted lines in Fig. 10. It can be concluded that simulated isolation between antenna pairs is under -40 dB while most of the antenna pairs present isolation values between -50 dB and -60 dB. Indeed, the weakest isolation is obtained for the shortest possible distance between antennas (that is between the antennas placed at slots 1 and 2).

C. Field-Measurements Results using Anritsu Site Master

In order to be able to cross-test the isolation between the different antenna mounted on the rooftop of the rolling stock, we have configured the Antenna Measurement Tool (Site Master) presented in section IV-A2 with the necessary parameters for which we only report Table I, an excerpt of it due to the space limitation. In particular, we configured the start and stop frequencies to cover the 1900 MHz range specified by the ECC CEPT [7].

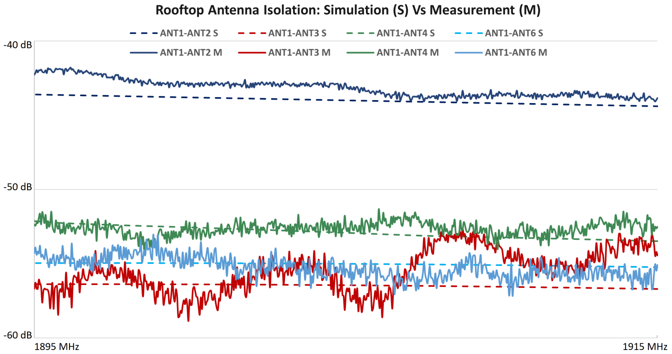


Fig. 10. Isolation plots for antennas pairs in the 1900 MHz band (simulation and measurements)

We depict in Fig. 10 the measured isolation between the antennas. It is concluded from measurement values in Figure 10 that simulations manage to predict the behavior of antenna isolation in the 1900 MHz band. We can notice some discrepancy between simulated and measured values, especially the one that corresponds to isolation between antennas (1 and 3) provided that three antennas are installed in slots 1, 3 and 6. Such gap between the simulation and the real-field measurements may be explained by the presence of noise when measuring, as well as, some non-ideal behavior of the antennas which were not considered in modelling.

Finally, we can see that, in both of simulations and measurements, the isolation between the antenna pairs is roughly between -50 dB and -60 dB, except for the isolation between antennas 1 and 2, where the distance is the shortest due to the physical distance of the rooftop for the antenna and in this case, the isolation is approximately -43 dB in average.

V. CONCLUSION

In this paper, we have investigated the requirements, design and integration of a rooftop antenna network for FRMCS. It is then evaluated in both simulations and onsite measurements. Different possible scenarios regarding antennas location on the rooftop were assessed in order to evaluated their isolation, which constitutes an indicator of interference between antennas and is therefore an important performance criteria. We found out that the isolation could be as weak as -40 dB in the worst case scenario, corresponding to two of the antennas being placed at two contiguous slots. Roughly, isolation was estimated to be in the interval [-60 dB, -50 dB], which is considered sufficient for the desired application.

In addition, modelling was proven to be an efficient way of predicting antenna isolation, although some additional considerations can be added to the initial model in order to account for non-ideal behavior, such as losses in cables and external environmental factors such as noise presence in order to increase simulation results precision.

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