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Jamming Detection Methods to Protect Railway Radio Communication

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Abstract*— more and more domains use wireless communications solutions to perform remote control actions or remote monitoring. However, in some cases, these solutions may be vulnerable to jamming devices readily available on the internet. In order to provide resiliency solutions against these jamming devices, we have investigated methods for detecting jamming signals. We were particularly interested in the European rail industry. Indeed, the European railway network is significantly evolving in order to increase its performances and to permit border crossing by the trains. For this purpose, a new and unique communication system is under deployment in Europe for ground-to-train radio operating, the Global System for Mobile communications – Railways (GSM-R). However, under specific conditions, this telecommunication system can be affected by certain jamming devices and in the case of absence of communication links for a given duration, the trains are forced to stop to guarantee the safety of the railway network. Thus, such jamming equipment can significantly impact railway exploitation. To avoid these situations, it becomes necessary to define and develop rapid and efficient methods for detecting such disturbances and quickly permit the implementation of adequate countermeasures. This is the scope of the SECRET FP7 project. It studies the vulnerability of this railway radio communication system against intentional electromagnetic interferences (IEMI) and develops supervised detection systems to detect the presence of jamming signals.

Index Terms—**Classification system, detection system, Error Vector Magnitude (EVM), GSM-R, Intentional Electromagnetic interference (IEMI), jammer, radio communication, railway.**

I. INTRODUCTION

FOR a long time, each of the European countries has implemented its rail network with its own techniques, derived from common concepts, but leading to distinct practical achievements. To enable the trains to cross national borders, European Rail Traffic Management System (ERTMS), the common standard for European countries, is under deployment. ERTMS aims to replace the different control command systems existing by a unique system used by all the railway operators. ERTMS manages the control of the train speed ensuring safety by the exchange of information between the ground and the trains. It is constituted by two basic elements: European train control system (ETCS) and Global System for Mobile communications - Railways (GSM-R) [1]. ETCS is progressively deployed in Europe to replace the national signaling and speed control systems. This system, composed by a network of beacons, called "Eurobalise" and placed between the tracks, permits to control the position and speed of trains to ensure their safety movements. The ETCS on-board equipment is an antenna placed under the train. This antenna activates the Eurobalise by emitting a tele powering signal and can receive messages from the beacon [2]. The GSM-R communication standard is designed for railway specifications and replaces various national railway communication systems in interurban and urban railway systems [3]. To ensure the ground-to-train communication, the GSM-R system is gradually implemented. The connection is established via a radio link between the mobile station on the train and antennas installed along the tracks. The GSM-R provides voice communications. It also provides signaling information, emergency calls, group calls (VGCS: Voice Group Call Service), the transfer of diagnostic data, or broadcast calls (VBS: Voice Broadcast Services). This communication system is then important to maintain the reliability of track-to-train links. Thus, its dysfunction could potentially lead to serious malfunctions and it is essential to provide its immunity notably against electromagnetic (EM) jamming. Meanwhile, the radio communication jamming devices are becoming more prevalent and easily accessible via the Internet, although their use is generally prohibited. Some jamming devices disturb the communication by sending a noisy signal covering the useful signal and making it unusable. In the case that these devices interfere strongly with the GSM-R signals, they can disrupt the communication link, and can cause the stop to train if it does not update its information for more than 20 s [4]. This emergency response can cause significant disruption of the rail network, especially if it occurs on a busy line.

To avoid such situations, it is essential to identify the cause of the communication breakdown if it is due to the use of a jammer to fall back on a degraded mode of circulation less disruptive than a stop. The European project SECRET (security of railways against electromagnetic attacks) aims to develop innovative solutions to improve the resilience of the ERTMS regarding the jamming threat. It aims notably to develop jamming detection systems included in the GSM-R terminals or placed in strategic locations of the railway network. This paper is organised the following way. A brief presentation of the railway communication infrastructure, followed by the characterisation of jamming devices is given. Thereafter, to make evident the interest of our work, we present the vulnerability on the railway communication and its limitations against electromagnetic jamming. The following sections are dedicated to the general presentation of the jamming detection methods considered. Then, we present one after the other the developments of the two detections methods used and their experimental results. The spectral evaluations, then, the quadratic evaluation are described. Finally, conclusions and future work are provided concerning the project.

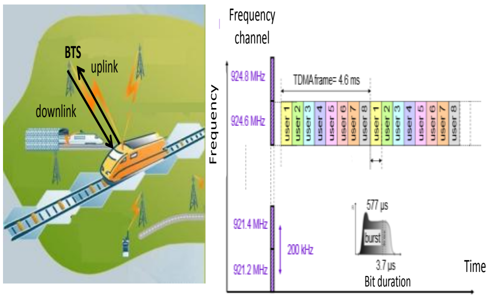

Fig. 1. Characteristics of the GSM-R protocol.

II. THE GSM-R COMMUNICATION INFRASTRUCTURE

The GSM-R is designed to allow operation up to a 500 km/h speed and even in difficult propagation conditions. This communication system is composed of four major elements [5].

- The cabradio, is the communication equipment on board the train. Dedicated to voice and data transfer, its transmitter usually delivers an 8 W maximum output power in the allocated pan-European frequency bands. Generally, the locomotives are equipped with at least two cabradios to provide redundancy in case of malfunction and one or more antennas are mounted on the train to ensure ground-to-train communications.
- The Base Transceiver Stations (BTS), consist of antennas and radio equipment installed along the tracks and providing radio coverage over a few kilometers. BTS is composed of transceivers that locally manage radio transmission (modulation, demodulation, equalization, error correction ...).
- The Radio Block Center (RBC), installed on the ground, receives and sends messages to the ETCS equipment on board trains. The RBC manages several consecutive GSM-R cells. Each message may contain one or more data packets. These data packets have the same structure as those transmitted by the beacons to the trains.
- Finally, the Base Station Controllers (BSC), manages the radio resources for the area covered by different base stations (BTS).

Then, the GSM-R communications are exchanged between the cab radios and the RBCs through the different BTSs and BSCs, this is described in Fig.1. The GSM-R standard incorporates the basic principles of the public GSM standard, a Gaussian Minimum shift keying (GMSK) modulation with specific assigned frequency bands across Europe, to cover railway needs. Twice 4 MHz frequency bands are available. Both ranges are used for the uplink from 876 MHz to 880 MHz and the downlink, from 921 to 925 MHz. Each band is divided into 200 kHz-wide channels. Thus, the GSM-R carries out 20 frequency channels, but only 18 are used to avoid interference problems with other cellular radio networks. It uses the principle of multiplexing to expand the capacity of the system. Time Division Multiple Access (TDMA) is employed for dividing the communication channel into frames of 8 time slots. The duration of each time-slot, called also a burst, is 577 µs and it consists of 157 bits of 3.7µs. Answering to the principle of TDMA, a user waits 7 time-slots before retransmitting again.

III. CHARACTERISTICS OF ELECTROMAGNETIC JAMMING DEVICES

The radio communication link between base stations and mobile stations can be affected by electromagnetic interferences emanating from natural sources (lightning, thunderstorm discharges...) or from the railway system itself (rolling stock, electric power supply: catenary, pantograph), these EM interferences appear occasionally. They can disturb the service but not necessarily break down the radio link. However, IEMI being generated continuously can lead to the interruption of the communication link. In [6], IEMI are described as "sources of malicious electromagnetic energy introducing noise or signal that could disrupt or damage the system for criminal or terrorist." They emerged for military purposes to create permanent damages on strategic equipment or to disrupt tactical communications. They are scaled on demand and thus, present more effective interference to scramble specific systems. For a long time, the concept of IEMI has only referred to very high power disturbances, such as High Altitude Electromagnetic Pulse (*HEMP)* or High-power electromagnetics (HP*EM*). However, today, with the role of telecommunications in our modern society, it is no longer necessary to emit very high power interferences to disturb critical systems. Jamming signals therefore fall into the category of intentional electromagnetic interferences. Covering a wide frequency range including the frequency bands allocated to GSM-R, they are able to disrupt various radio communication systems. Different types of jamming devices exist. Some devices are designed to avoid the establishment of communication. These scramblers work as receivers analyzing the communication signal to identify and block some mobiles. They deactivate ring tones or prevent the establishment of calls [7]. This technically advanced equipment can be cumbersome and may require an additional power source or conspicuous antennas. Our interest is focused on small and discreet equipment which can have a significant impact and which is easily accessible to the general public. In this category, the more current jamming devices consist of several independent frequency oscillators sweeping rapidly on large frequency range [7]. They can be very light weight and portable and are used to scramble radio communication links to and from base stations by transmitting a jamming signal that can disrupt many services. These devices are equipped with batteries and can deliver a significant output power. These devices are strictly illegal in most countries but products can be seen on the Internet.

III. VULNERABILITY OF THE COMMUNICATION SYSTEM TO INTENTIONAL ELECTROMAGNETIC INTERFERENCES

The base transceiver stations (BTSs) deployed along the railway tracks, are spaced several kilometers from each other. The distance is not necessarily identical everywhere in Europe, but it has to be sufficiently short to provide a -95 dBm minimum power level to the train, at middle distance between two BTS. This is a mandatory requirement coming from the EIRENE (European Integrated Railway Radio Enhanced Network) specifications [8]. This represents a very low power level with the potential of being easily jammed. Generally, jamming interference refers to the notion of jamming signal ratio (*JSR*) [9]. This parameter is the ratio between the power of the jamming signal and the power of the communication signal, as in (1). This parameter is employed to study the impact of the jammers on the quality of service (QoS) of the communication system. The criterion used to assess the QoS is the bit error rate (*BER*) calculated in (2).

$$JSR = \frac{\text{level of jamming}}{\text{level of a desired signal}} \qquad (1)$$

$$BER = \frac{\text{the number of incorrect bits transmitted}}{\text{the total number of bits transmitted}} \times 100\% \qquad (2)$$

The *BER* is generally estimated thanks to the learning sequence including in the GSM-R burst. The railway specifications require a maximal estimated value of 1.13 % for the *BER* to ensure a sufficient QoS [10]. Conversely, the reference *BER* value leading to a loss of connection is 12.8%. Considering these two parameters, the vulnerability of the railway communication system in presence of jamming signals can then be assessed. In order to evaluate the vulnerability of the railway communication, GSM-R transmissions were then simulated and superimposed to jamming signals to assess the deterioration impact of the *BER*. For this simulation study, a communication channel at 924.8 MHz is established, and two jamming signals are considered: a pure sine signal centered in the communication channel called J_s(t), and J_{sm}(t) a sine signal with 75 kHz modulation bandwidth around the carrier frequency, close to the modulation scheme used by GSM. The evolution of the *BER* as a function of the *JSR* for these two different jamming signals is presented in Fig. 2.

A communication and jamming signals centred in the GSM-R downlink channel are simulated, and the impact on the *BER* is calculated for different jamming signal powers. From a *JSR* of - 6 dB for J_{sm}(t) and - 2 dB for J_s(t), the deterioration exceeds the permitted level in rail specifications [11]. When the *JSR* reaches - 2 dB for J_{sm}(t) and 1 dB for J_s(t), the connection can be lost. This initial result illustrates the relevance to develop detection methods able to determine the presence of jamming signal for a relative low *JSR* in order to implement adequate countermeasures before the breakdown of the connection.

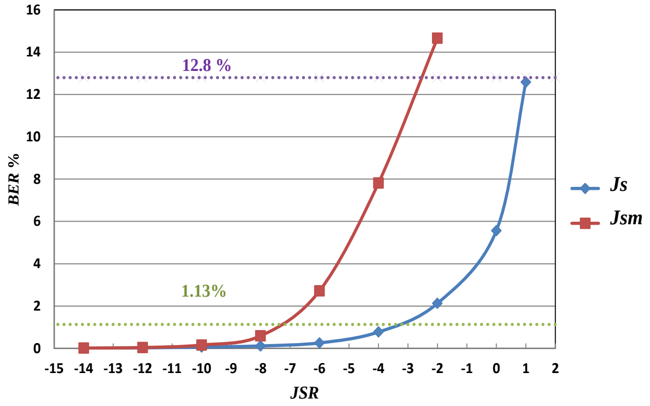

Fig. 2. Evolution of the BER in function of the *JSR* for J_s (t) a pure sine signal centered in the communication channel, and, J_{sm} (t) a sine signal with modulation bandwidth of 75 kHz around the carrier frequency.

IV. DESCRIPTION OF THE METHODS USED FOR THE DETECTION OF EM ATTACKS

Several approaches can be investigated to detect the presence of jamming signals. Each method can provide different performances in terms of detection delay or power of the jamming signals, and is more or less adapted to the operational context. On the one hand, on board a train, a relevant detection solution has to be able to detect very quickly the presence of a jamming signal even if its power is insufficient to disturb the GSM-R communication. A quick detection can prevent the triggering of automatic braking. On the other hand, inside a train station, the requirement can be different. The time delay of detection is less critical but it can be necessary to monitor several communication systems simultaneously. Indeed, several communication systems are employed for operational purposes in train stations. Two approaches were then studied. Knowing that the jamming devices generate wide band signals covering the frequency bands of several communication systems, the first approach studied is based on the statistical analysis of the power spectral densities (p.s.d). This method can be adapted to monitor several communication systems. The second method studied was focused on the monitoring of the jamming signal able to affect the GSM-R communication. This method is based on the analysis of the distortion of the In-phase and Quadrature phase (*IQ*) representation of communication signals received by the on-board terminal. Both methods consist in of so-called ‘supervised’ detection [12]. It requires a data representing the labelled "normal" and "attacked" situations allowing an initial learning step. For the method based on the analysis of the distortion of the In-phase and Quadrature phase (*IQ*) representation, a large number of data were recorded in “normal” condition, during a learning phase. The “normal” conditions mean the EM conditions of the railway domain without intentional jamming signal. During this learning phase, measurements were performed in different locations of the railway network (on board train, in train station and along the track). This learning phase permits us to determine the model of normality of the GSM-R system and the detection consists in comparing the monitored parameters with those representing the model of normality. For the approach based on the statistical analysis of the p.s.d, the "classification" method was applied [13]. That means that different models were learned for different EM attack signals and for the "normal" EM environment. In that case, the monitored data can be compared to the different attack and normal models in order to check if one of the models fit with the recorded data.

V. EVALUATION OF THE SPECTRAL REPRESENTATION TO DETECT THE PRESENCE OF EM JAMMING

Frequency distributions of the signals received by the GSM-R antenna were first studied in presence and in absence of jamming signals. The power spectral density (p.s.d) was then used as the "descriptor" of the situation to analyse the difference between the normal and the attacked situations. As an illustration, Fig. 3 presents the p.s.d between 850 MHz and 1 GHz of the signal corresponding to different jamming devices. It shows that the three jammers cover, with different power spectral densities, the frequency channels of GSM-R.

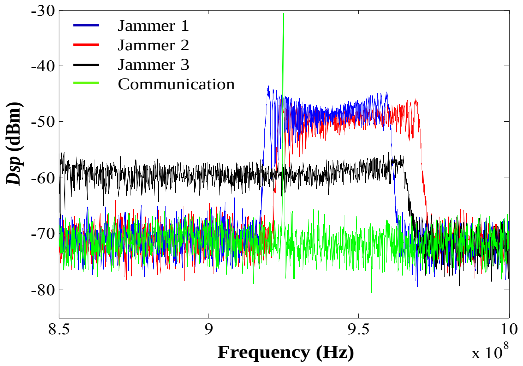

Fig. 3. Spectral representation of communication and three different jammers.

Different models were then established during the learning phase for "normal" conditions and for "attacked" conditions. Several models of "attacked" conditions were defined using different jammers. The process is implemented by estimating a statistical model (multi Gaussian) of the p.s.d for each frequency included in the studied spectral space. Then, the detection consists in testing if the data belongs to the different models. This identification of the corresponding environment is obtained by calculating the matching rate using the Bayesian rules [14]. Some tests were performed to assess the performance of this method. For this phase of tests, measurements were carried out along the tracks of a High Speed Train line, where the GSM-R is not yet deployed, in order to avoid disturbing the railway communications. In laboratory constraint environment, a GMSK frame was generated and the signal received by a GSM-R antenna was measured. A GSM jammer was activated on demand to jam the GSMK signal. Using this spectral methodology, we implemented a learning phase to create models, and after we proceeded to the detection phase. By this method, a perfect detection rate (100 %) was obtained. However, this method can lead to a high rate of false alarms (80 % in the worst case). The false alarms were mainly observed for measurements performed at proximity of a commercial cell phone GSM base station. Then at this location, the GSM down-link frequency band was very busy and the powers of the GSM communication signals were significantly higher than the power of the jamming signals. In conclusion, we noticed that this method can be efficient but, under the assumption that at the location of the monitoring device, the spectrum occupation of the monitored band was sufficiently sparse in absence of jamming signal. For certain train stations, where the characteristics of the p.s.d are relatively stable, the method can be relevant. Moreover, on board trains, due to the characteristics of the p.s.d evolving continuously along the train journey, this assumption cannot be guaranteed. The following methods using the *IQ* information directly from the receiver were then studied to propose an appropriate solution to the onboard situation.

VI. EVALUATION OF THE QUADRATIC REPRESENTATION TO DETECT THE PRESENCE OF EM JAMMING

This detection approach is based on the *IQ* information accessible in any digital transmission receiver. The preliminary analysis consists in analysing the distortions of the *IQ* representation in presence of jamming signal. To assess the availability of this method, preliminary simulations are carried out by transmitting a GMSK (Gaussian minimum-shift keying) signal to the GSM-R demodulator. A 30 dB Signal-to-Noise Ratio additive white Gaussian noise (AWGN) was applied and two types of jamming signals were injected: $J_s(t)$ a pure sine signal centered in the communication channel, and, $J_{sm}(t)$ a sine signal with modulation bandwidth of 75 kHz around the carrier frequency.

Fig. 4 presents the *IQ* constellation resulting for a *JSR* of -14 dB. Distortion appears for jamming situations and depends on the scrambling signals. For both jamming signals, the distortion is significant, whereas the *JSR* is relatively low. That means that the detection can be efficient while the QoS is not affected.

This representation is able to characterize the real environment and discriminate the normal situation from an attacked situation. However, the railway electromagnetic environment is characterized by the presence of transient EM interferences which can affect some samples of the constellation without disturbing the system, although these transients are really brief and can induce distortions over a very short time. To avoid false alarms provoked by the appearance of these transients, we do not consider the samples individually, but the sum of the distortions during a burst period.

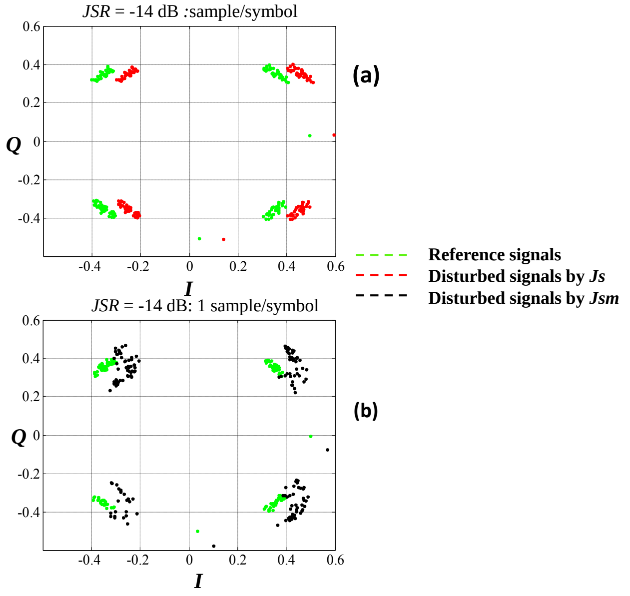

Fig. 4. Examples of I(t) and Q(t) signals constellation obtained for a GMSK modulation during a burst. a : GMSK constellation for normal situation and GMSK constellation for jamming signal J_s (t) a pure sine signal, b: GMSK constellation for normal situation and GMSK constellation for jamming signal J_{sm} (t) a sine signal with modulation bandwidth of 75 kHz.

In this way, the error vector magnitude (*EVM*) parameter commonly used to assess the quality of modulation for communication systems is selected as a descriptor.

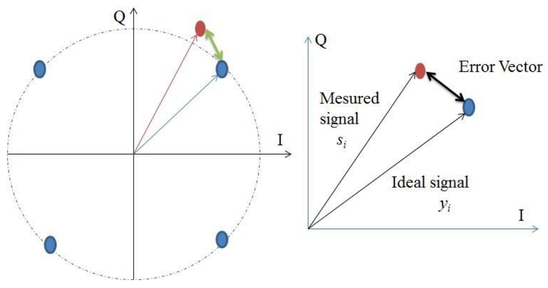

Fig. 5. *IQ* Constellation and EVM representation.

Calculating over a burst period, as presented in Fig. 5, *EVM* determines the vector difference computed between the samples of a reference constellation and the measured constellation of the *IQ* data. It is calculated from (3) where s_i is the i^{em} sample of the measured signal, and y_i the i^{em} sample of the reference signal.

$$EVM_{rms} = \sqrt{\frac{\sum_n |s_i - y_i|^2}{\sum_n |y_i|^2}} \Rightarrow \begin{cases} \|y_i\| = \sqrt{I_y^{\,2} + Q_y^{\,2}} \\ \|s_i\| = \sqrt{I_s^{\,2} + Q_s^{\,2}} \end{cases} \qquad (3)$$

This parameter evolves according to a Gaussian distribution and depends directly from the *SNR* of the communication channel [15]. In normal situations, mean and variance values are learned and represent the model of normality. A statistical model will consider these mean and variance values to represent the Gaussian law of electromagnetic environment in a normal state. From this statistical model, threshold values can be defined during a learning phase to represent the normal state. These threshold values define the interval in which the descriptor refers to a normal situation. Therefore, the detection consists in comparing the new values of the system to the thresholds, and, if they exceed, we consider that it is an attacked mode. This principle of detection is described by the flowchart in Fig. 6.

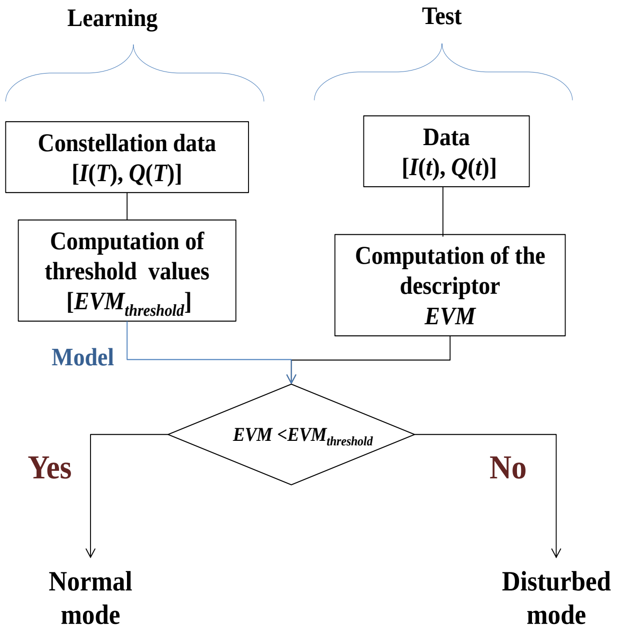

Fig. 6. Flowchart of the detection system based on the *IQ* domain.

Measurements were carried out along the railway tracks to test the method and the EVM data base for both environments ("normal" and "attacked") was recorded. This second detection method based on quadratic representation gave good performances (85.73 % of good detection). But some false alarms result with a rate of 2.45 %. A solution to delete the false alarms is to increase the observation time period. Indeed, we noticed that the false alarms are provoked by brief EM interferences present in the railway environment. However, these EM interferences are not permanent and observing the EVM over 8 successive bursts, the discrimination between the normal environment and the attacked one reaches a 100 % rate. The advantage of this approach is that it does not require any supplementary equipment; it directly uses the *IQ* signals from the receiver. This represents an advantage, since it limits the additional cost of the jamming detection equipment.

VII. DISCUSSION AND PERSPECTIVES

The research presented in this paper is among the very first dealing with the detection of intentional electromagnetic attacks against railway systems. The European railway communication system was introduced and its potential vulnerability to jamming signals was presented. Two methods were studied to detect the presence of electromagnetic jamming able to affect the radio communications dedicated to the railway network. A first approach based on the statistical analysis of the p.s.d was developed and assessed. This method delivers satisfactory detection performances, but can result in a high false alarm rate at specific locations. Moreover, this method requires the implementation of specific monitoring equipment for attack detection. However, observing different frequency bands and using appropriate antenna can permit monitoring of several communication systems and synchronization during the process is not needed. It is then completely independent of the communication chain and can then be very efficient in presence of high power level jamming signals. The second approach considers *IQ* data, available in any digital transmission receiver. To implement the solution, new generations of terminals could integrate the detection algorithm into the receiver processing unit. However, this detection method requires synchronization and remains operational until the connection link is not interrupted. Moreover, it permits detection of the presence of low power level jamming signals and prevents the risk of disconnection. These two methods can then be complementary. On the one hand, the spectral analysis method can be appropriate to monitor train stations where several communication systems have to be operational. On the other hand, the *IQ* method can be more adapted on board trains where the detection has to be very quick (before the interruption of the connection) to fall back on a degraded mode of circulation less disruptive than a stop.

VIII. ACKNOWLEDGMENT

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AUTHOR'S PROFILE

Souheir MILI was born in Constantine, Algeria 1987. She received Ph.D. degree in electronics engineering on 2014 from the University of Lille. She receives the M.Sc degree from the University of Constantine, Algeria and Magister degree in control systems on 2012 from the University Jijel, Algeria. In 2011 she received the master degrees from the University of Lille, France. Since October 2011, she is working toward at the French institute of science and technologies for transport development and networks (IFSTTAR) on Electromagnetic compatibility, signal processing and railway communications.

Virginie deniau was born in France on May 6, 1974. She received the M.S. and Ph.D. degrees in electronics from the University of Lille in 2000 and 2003, respectively. Since 2003, she has been a Researcher in electromagnetic compatibility (EMC) for the French Institute of Science and Technology for Transport, Development, and Networks (IFSTTAR), University Lille Nord de France, Villeneuve d'Ascq, France. Her research interests include EMC test facilities, the test methodologies, and the characterization of EM environments in the transportation domain. She notably worked on the mode stirred reverberation chambers and on the three-dimensional TEM cells. Currently, her research interests include the susceptibility of digital communication systems face to electromagnetic environments typically of the transports means.

David Sodoyer was born in Soissons, France, in 1976. He received the M.S. And Ph.D. degrees in signal processing from the INPG (Institute National Polytechnique de Grenoble), France, in 2001 and 2004, respectively. Between 2004 and 2010 he worked with several laboratories (INPG, CNRS, INT, INRETS) on signal statistical processing applied to signal localization and separation. In 2010, he joined the IFSTTAR-LEOST as a full-time Researcher. He is currently focused on Latent Variable Analysis, sources separation and detections events in signal processing.

Marc Heddebaut was born in Somain, France, in 1955. He received the M.S. and Ph.D. degrees in electronics from the University of Lille France in 1980 and 1983, respectively. He joined the French National Institute for Transportation and Safety Research (INRETS now IFSTTAR) in 1983 and became a senior researcher in 1988. Since 1979, he has been working in the field of land mobile communication and electromagnetic compatibility. His primary interests include telecommunication systems dedicated to land transport, EMC, mobile localization and command control of automated vehicles.

Sébastien Ambellouis received the Ph.D. degree in computer science and control from the University of Science and Technology of Lille, Villeneuve-d'Ascq, France. He is currently an Engineer of the ESIGELEC School, Rouen, France. Since 2001, he has been a Researcher within the LEOST Laboratory of the French Institute of Science and Technology for Transport, Development and Networks. He is involved in image and signal processing and machine learning for transport application. Recently, he has extended his application domains to the EM modeling for intentional and not intentional EM attack detections specifically dedicated to railway telecommunication systems.