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Assessment of the GSM-R susceptibility to repetitive transient disturbance

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Abstract

The transients produced by the pantograph electric arc and captured by a GSM-R antenna mounted on the roof top are characterized in the time domain and in the joint time-frequency domain, in order to quantify the noise produced on the GSM-R channels. The recorded signals are also characterized also in order to evaluate the behavior of the GSM-R protocol in relation to burst noise. To this aim the GSM-R protocol is considered in particular with respect to data bit protection and for the relationship between signal-to-noise ratio, bit error rate and frame error rate. The measurements were performed on a 25 kV 50 Hz French railway line.

Keywords: Guideway Transportation Systems, Radiated Interference, Spectral analysis, GSM-R

1 Introduction

The GSM-R is a GSM based communication system used on European railways [1]; it is used for the purpose of train and wayside bidirectional communication and in particular for the transmission of data and commands, related to train operation, control and protection. More specifically the GSM-R implements the ERTMS/ETCS Level 2; ERTMS stands for "European Rail Traffic Management System", ETCS for "European Train Control System", and they represent the modern train control system at large adopted for interoperability of rolling stock and ensuring a high level of performance in terms of travelling speed and safety distance between trains. The Radio Block Centers (that correspond to the Radio Base Stations of the public GSM) exchange the said data and commands on the GSM-R physical link and, in particular, are responsible for issuing Movement Authorities (MAs) to the trains. MAs represent the commands sent to the train (speed reduction, stop signal ahead, emergency stop, etc.), for which a safe and certain delivery must be ensured and this will be considered later on in this paper. The GSM-R is thus safety relevant and

1 electromagnetic interference is one of the aspects to consider when evaluating the GSM-R
2 reliability and robustness.

3 The electric arc at the sliding contact point on the locomotive pantograph is an intermittent
4 source of electromagnetic emissions [22]. Multiple elementary arcs appear and disappear in a
5 chaotic manner, producing transient intermittent plasma columns with a variable lifetime and
6 successive extinction and re-ignition events [2][3]. Several elements and variables influence the
7 electric arc emissions: the contact wire surface and the sliding contact conditions (ruggedness of the
8 surface, wearing, oxidation, the type of the materials used), the environmental conditions (such as
9 temperature and humidity), the train speed, the amplitude of the collected current (since the arcs
10 appear superimposed on the main absorbed current waveform, variable in AC railways between the
11 two negative and positive peaks), the mechanical suspensions reaction and in general the
12 mechanical characteristics of the catenary system.

13 The measurements were carried out in France on a 25 kV 50 Hz line between Saint Pierre des
14 Corps and Nantes with a train composed of one locomotive and eight cars. The travelled distance
15 was about 200 km with a cruising speed of about 160 km/h. The GSM-R antenna was mounted on
16 the roof of the fourth car, at approximately 80 m from the pantograph. The radio antenna is a bi-
17 band antenna, working in the frequency bands of the French railway radio system [420–520] MHz
18 and of the GSM-R system [820–1000] MHz; this means that the effects of both bands will be seen
19 in the free response mode of the antenna, excited by the transient electromagnetic field produced by
20 the arcs and visible as persistent oscillations in the recorded waveforms.

21 **2 GSM-R characteristics**

22 In this section the characteristics are reported relevant for the following analysis and for the
23 understanding of the interference mechanism; to this aim the characteristics of the GSM-R are those
24 of GSM. To cope with the prescribed maximum speed of 500 km/h with respect to the GSM 250
25 km/h, the channel equalization algorithm (in charge of reducing Doppler effect and fading) was
26 modified by the manufacturers of railway equipment. The considered elements are the general
27 structure of the GSM-R transmitted data (that define the time duration of channel symbols, slots and
28 frames, to be compared with the time characteristics of the recorded transients), the use of data
29 encoding and data protection by means of error control codes, the signal-to-noise ratio performance
30 on the single symbol, and the resulting error rates at the slot and higher levels.

2.1 GSM-R data structure

The GSM-R system employs two frequency bands of the GSM frequency interval: [921–925] MHz for the downlink, from the RBC to the train, and [876–880] MHz for the uplink, from the train back to the RBC; each band is subdivided into 20 frequency channels of 200 kHz each. The nominal GSM raw data rate is 270 kbit/s, for which a bandwidth efficiency of 1.35 bit/s/Hz may be derived; for GSM-R the data rate over one timeslot (assigned to a single train) is 9600 bit/s, so a total of 76.8 kbit/s. The channel-frame-slot structure is the same as GSM: after the subdivision in physical frequency channels (FDMA, Frequency Division Multiple Access) on which a train tunes its on-board GSM-R equipment, the communication occurs with a TDMA (Time Division Multiple Access). For each frequency channel data are organized as a periodic TDMA frame, with a period of 4615 μ s; each TDMA frame is divided into 8 time intervals of 576.92 μ s called "time slots" and each user (train) occupies a frequency channel only one eighth of the time with a period of 576.92 μ s; each "time slot" includes 156 bits, so the transmission time of one bit, or "bit time", BT, is 3.692 μ s [4][5]. This structure is depicted in Fig. 1.

Figure 1. TDMA structure of a GSM frequency physical channel

The 26 bits in the center identified as "midamble" are a training sequence aimed at channel estimation.

By inspection of the timeslot structure it is immediate to recognize that a transient, and the consequent bit error, can occur at all positions within it, for both data bits (in total of 114 bits out of 156) and the other bits, used for control, synchronization, etc. From this the fact that bits can be protected by error control codes at different degrees depending on their function and importance.

2.2 Channel encoding

GSM signal $x(t)$ is the result of a Gaussian filtering of a Minimum Shift Keying signal, derived from a bit sequence $\{s_i\}$ [9].

$$x(t) = \exp(j\varphi(t)) \quad (1)$$

$$\varphi(t) = \varphi_0 + \sum_i k_i \Phi(t - iT) \quad (2)$$

where φ_0 is an unknown initial phase, Φ is the Gaussian shaped signal and k_i are the differential encoded bits from the sequence $\{s_i\}$, as defined below.

$$k_i = s_i s_{i-1} \quad (3)$$

$$\Phi(\xi) = \frac{\pi}{2} \left[G(\xi - \frac{1}{2}) - G(\xi - \frac{3}{2}) \right] \quad (4)$$

$$G(\xi) = \xi \int_{-\infty}^{\xi} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{t^2}{2\sigma^2}\right) dt + \frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{\xi^2}{2\sigma^2}\right) \quad (5)$$

The expression of the GMSK modulation is non-linear and thus for an easier treatment attempts are done to manipulate it, in order to obtain a linearized version. MSK is often used in place of GMSK for calculations and channel equalization schemes. In [9] the linearization process proceeds through the identification of four reference points on the slope of the time response of Φ ; the results in terms of Bit Error Rate after channel equalization show an improvement of about a factor of two for various signal-to-noise ratios. For our analysis the signal to noise ratio is used directly in the bit error probability expression, with a practical corrective factor for the estimated difference between MSK and GMSK (see below sec. 2.4).

2.3 Data protection

When using the GSM channel for data transmission (as for GSM-R), if the full rate channel speed of 9.6 kbit/s is considered, the following logical coding mechanism is used. An input block of 240 bits is encoded for data protection with a convolutional code with half rate, so becoming a 480 bit block, brought to 456 bit by removing 1 bit every 15 (called "1 out of 15 puncturing") so to fit 4

slots with 114 data bits each. Even with slower data rates and input block lengths, the rates of the convolutional code and of puncturing action are adapted for a final output block of 456 bits. The output block is subdivided into a variable number of burst portions depending on the data rate and distinguishing speech and data traffic, in a process that is called "interleaving", aiming at increasing the robustness with respect to interference [7]. It is thus evident that a complete modeling of the data protection algorithm with respect to interference and final frame error rate values is as difficult as useless, if a reverse approach may be followed: the efficiency of data protection can be estimated by repeated tests under controlled conditions in terms of SNR and location of interfering transients and building up look-up tables that relate these parameters, the raw BER and the FER. Any sharp increase of the latter for small changes of the former will indicate a critical threshold for the data protection and error recovery algorithms.

2.4 Signal-to-noise ratio and bit error rate

From a general point of view the GSM sensitivity level (the minimum detectable signal at receiver) is very low and around -85 to -95 dBm, depending on the type of service. For a railway environment the minimum signal strength (giving sufficient coverage) has been made correspond to -90 dBm for 95% of time, but a more conservative value of -80 dBm was suggested [2] to account also for burst noise occurrence and to reduce drastically the bit error rate in worst case circumstances. In the determination of the minimum signal strength other phenomena come into play, such as the signal decay with distance, in order to manage correctly the hand-over between two RBCs (or Radio Base Stations), that at the maximum speed of 500 km/h is not a trivial aspect. A higher signal strength or sensitivity value, of course, comes at the price of a larger transmitted power and closer separation of RBCs.

Considering a stationary disturbance with Gaussian distribution in the channel bandwidth (the so called AWGN), from which a classical signal-to-noise ratio concept can be derived, the expression of the raw Bit Error Rate (BER) is ([17], pp. 241-257)

$$P_{be} = BER = Q\left(k\sqrt{SNR_b}\right) \quad (6)$$

where SNR_b is the signal-to-noise ratio per bit, $Q(\cdot)$ indicates the area under the tail of the Gaussian distribution and k identifies a coefficient that takes into account the type of modulation, and in particular how the information is conveyed and the shape of the used symbol waveform. For MSK this coefficient is equal to two (since for an optimum receiver MSK symbols are considered antipodal signals, [17], pp. 271) and for GMSK this coefficient is generally assigned the value 1.8, based on experimental observations, since the theoretical treatment is not straightforward (as

already commented in sec. 2.2). The result of 1.8 is a compromise between the inter-symbol interference introduced by the Gaussian filter (that in turn compacts the occupied band) and the resulting error performance degradation with respect to MSK.

2.5 Frame error rate and Movement Authority reliability

The FER identifies the error probability of a corrupted message, identified with the word "frame", as given by communication testers. The FER depends on the BER and the FEC action described in the previous subsections. If FEC details are to be neglected, the FER may be put in relationship with an equivalent BER (BER_{eq}), simply related to it by the number of message bits L

$$FER = (BER_{eq})^L \quad (7)$$

Neglecting any problem of hand-over, connection establishment and connection loss (mentioned later on in sec. 6), even if more relevant than the simple data corruption by transient noise, the MA reliability may be put in relationship to the FER using a simple pure repetition approach at the highest allowed rate. Even if this does not correspond to a real situation, it is useful to set a reference maximum value for FER, that meets the MA constraints.

$$MAER = 1 - (1 - FER)^M \quad (8)$$

where the number of attempts M depends on the time required to cycle to a new message transmission and on the maximum time interval within which a valid MA must be delivered and acknowledged. These values, together with other QoS indexes, are reviewed in sec. 6.

3 **Measurement setup for on-site transients recording**

The roof top GSM-R antenna is exposed to the electric arc emissions and the signal at its output connector was recorded with a Digital Storage Oscilloscope (DSO). The antenna signal $s(t)$ is the result of the electromagnetic field captured by the antenna and the transient response of the antenna itself; the goal of the activity was to evaluate the potential interference to GSM-R receiver. Variable sampling rate (5 and 20 GS/s) and record lengths (8 k to 4 M words) were used, to get the single transient signal and to explore any repetitive pattern over a longer time interval. Measurements were temporarily interrupted several times in the vicinity of towns due to the high level of noise induced by radio base stations and other radiofrequency emitters operating over the same or nearby frequency intervals. During about 100 min of measurement, the DSO collected about 25700 transient signals. The general waveshape shows a first peak (that triggers the acquisition), followed by subsequent smaller peaks and oscillations with decaying amplitude. Any offset or low frequency fluctuation has been corrected by adjusting to zero the mean value based on the evaluation on the

first pre-trigger time interval. The joint time-frequency domain was considered in [2]: three relevant bandwidths were identified, two confirming the technical characteristics of the roof top antenna and one at about 1250 MHz; a transient oscillatory response is expected for each bandwidth, superimposed to the recorded transients. With a frequency domain approach the spectral content versus time is used to compute the error probabilities considered in sec. 2 and to evaluate the GSM susceptibility level (results shown later in sec. 6).

The equipment used for the on-site tests is depicted in Fig. 2, where two pictures taken inside and outside the measurement coach are shown.

Figure 2. Instrumentation for tests on-board: frequency and time domain equipment for recordings (left) and roof top antenna (right)

The recordings were all made in open air sections, while it is expected that in tunnels the behavior could be different due to the several reflections and the consequent multipath interference [21].

4 Time domain characterization

The time domain waveforms were acquired with two sampling rates, one to capture the full bandwidth with adequate oversampling (20 GS/s), but with a duration of the time window limited by the DSO memory to 4 μ s, and another one to allow long enough time window (400 μ s) to record more than one transient. Two examples of recorded transients and related parameters are shown in Fig. 3 [2].

Figure 3. Examples of waveforms and of the parameters of interest

The time domain parameters of interest are as follows:

- rise time RT of the first peak, possibly preceded by a “pre-peak”, as shown in Fig. 3, upper curve;
- amplitude A of the first peak, distinguishing positive peaks A_+ and negative peaks A_- ; the peak-to-peak amplitude $AA = A_+ - A_-$ is calculated over a movable time window;
- time duration TD, taken from the occurrence of the first peak up to the crossing of a convenient threshold, set to 30% and 50%;
- the frequency of ringing FR, quantified by the time distance of adjacent zero crossings and compensating for fluctuations and offsets of the recorded signal;
- repetition interval RI, that characterizes the occurrence of subsequent transients on longer time windows, and that is the most relevant parameter in order to define the amount of interference to the frame bits in terms of repeated corrupted bits and their time distance.

The time domain parameters above are evaluated as histograms, sample mean and dispersion and probability density functions (pdf), that best fit the sample data.

4.1 Statistical distributions of pulse parameters

During the analysis, we noticed that in some cases, first, the pdfs are not unimodal and, second, several recordings have weird or inconsistent data, due to several reasons: superposition of two or more electric arc events, external disturbance (in particular in the same GSM bands), wrong scale setting. Up to 5% of the collected recordings was discarded during the analysis, using an automatic pre-processing routine based on heuristics derived from a set of physical phenomena and expected

behaviors of the electric arc emissions, such as minimum time domain decay, maximum number of oscillations, metrological quality of the recorded waveform (such as visible quantization artifacts and amount of broadband noise).

The histograms of the waveform parameters (RT, TD, FR and RI) are shown in Fig. 4, where some pdfs are proposed to fit the experimental histograms.

Figure 4. Statistical distributions of RT, A, TD50%, RI

It is underlined that the width of the bins of the histograms has to be selected carefully, as pointed out in [2], because of a peculiar behavior: since any crossing of a given threshold is influenced by oscillatory behavior occurring at the antenna self resonance frequencies, the time duration TD values are clustered around equally spaced reference values in relationship to the oscillation period.

The single spike has a short time duration, well below the bit time of $3.7 \mu\text{s}$, but we may assume that it is able to corrupt the bit which it occurs onto. The RI is a particularly relevant parameter for the evaluation of the interference, occurring repeatedly at several message bits and so in relationship to the forward error correction capability of GSM with respect to the so-called "burst"

noise. It was noticed that the RI estimation depends heavily on the sample set composition, that in turn depends on: i) the threshold chosen to count successive pulses, ii) the gating time interval (set slightly larger than the estimated TD, and variable between a hundred of ns and 1 μ s during preliminary evaluations), within which all the detected peaks are assumed to belong to the same spike and related oscillations and are not counted as repeated peaks. The sample size and three statistical indicators (sample mean, sample standard deviation and inter-quartile range) are shown as a function of the threshold in Fig. 5 for a medium size sample of data (about three hundreds recordings).

Figure 5. Statistical parameters for RI evaluation: number of RI samples x 1000 (grey thick curve), sample mean (black curve) in μ s, standard deviation (dotted curve) in μ s, inter-quartile range (75%-25%) (dashed curve) in μ s

With reference to the solid black curve of Fig. 5 the sample mean varies from 3 to 100 μ s approximately. The exact value is related to the used threshold, as it is evident from Fig. 4 (lowest graph), where the histogram of RI values counts rare occurrences up to 370 μ s, that can increase the sample mean if included in the calculation. The fact is witnessed by the increasing dispersion versus threshold value, so that versus the number of considered RI samples (the dispersion is the dotted curve in Fig. 5). If all collected RI values are considered, then the RI mean value increases to 100 μ s, with a similar estimated dispersion, that indicates that the more frequent low value RI samples are masked by the less frequent larger values. With a threshold smaller than about 30%, the number of discarded samples decreases (the size of the sample increases) and the mean value approaches a more sensible value of 2-10 μ s, supported by a dispersion of less than 1 μ s; this is due to the increased relevance of small RI values in the statistics, as it should be.

The evaluation of the statistics of the RI parameters have been extended to a total of about 1200 recordings, with variable amplitude thresholds and time gating (to identify an isolated high level of

signal as a transient pulse and not as a "rebound" due to un-damped oscillations, as explained at points i) and ii) above). The results are reported in Table 1 below.

Table 1. Statistics of the RI parameter for 1200 recordings

	Amplitude threshold in % of largest peak				
	30%	35%	40%	50%	55%
RI_av [μs]	0.431	0.953	1.60	7.13	11.6
RI_sd [μs]	8.87	14.4	19.9	46.4	60.1
RI_iqr [μs]	0.0822	0.116	0.113	0.260	0.251
RI samples	1162989	520850	307706	67926	41592

The results shown in Table 1 show that several pulses are present in the recorded signals and that the RI value is normally very small, as confirmed not only by the average value, but also by the inter-quartile range, that even for a very large threshold remains below 60 μ s. This means that a robust estimate in favor of longer RI in any case indicates a transient pulse at least every 16 bits of message.

The RI mean value computed only on short time recordings triggered by a transient itself (such as those used so far and lasting for 400 μ s each) is of course a biased estimate of the RI mean value over a much longer observation time interval. To cope with the limited recording capabilities of time domain equipment (DSO) running at maximum sampling rate, longer time intervals were obtained by pre-processing in real time adjacent 400 μ s records and only the counted number of transients is stored; this result appears in [12] and it is reproduced here for reader's ease (see Fig. 6). The counting of the transients was performed with a resolution of 3.7 μ s: when a transient is detected, a 3.7 μ s margin is applied to avoid counting the same transient event twice. The time duration of 3.7 μ s was taken equal to the transmission time of one bit.

Figure 6. Counting of recorded transients over 1568 adjacent time windows of 400 μ s each [12]

There are time windows with a transient count as large as 40 and even 85 in one case, that brings the RI value down to 10 μ s and 4.7 μ s respectively, confirming the analysis above. Yet, there are several time windows with a negligible number of transients, so that the long-term RI mean value computed from the total of 2152 transients over 1568 time windows is as high as 291 μ s. It is underlined however that the lower sampling frequency used in this case to execute the post-processing routine in real time has a poorer representation capability for fast narrow transients, that could be skipped in the count and that are those occurring in clusters and bringing the lowest RI values.

Since the RI parameter and its statistics are a crucial point for the quantification of the interference to the GSM-R transmissions, a different approach for the correct count of repeated transients over a much longer time interval is under investigation: a Spectrum Analyzer (SA) is locked in zero-span mode on the frequency band of interest of the GSM-R physical channel and the Intermediate Frequency output is acquired with a DSO at a conveniently low sampling frequency, in order to make real time processing possible. The use of this approach is supported by the observed flat spectral density over the frequency axis in the considered frequency interval. A Resolution Band-Width (RBW) of 3 MHz for an assumed Gaussian filter gives a RBW filter rise time t_r of 106 ns and represents a minimum value for the correct detection of electric arc transients; slightly larger RBW values are advisable, such as 10 MHz. The threshold for the transient count, in analogy with what was done above, will be set accordingly, provided that the correct de-sensitization factor is used, to account for the limited rise time and low pass behavior with respect to fast pulses.

4.2 Statistical evaluation of pulse sequences

To the aim of evaluating GSM-R interference, not only the RI statistical distribution is of concern, but also the probability of occurrence of sequences of pulses. The time separation between transient pulses is the repetition interval RI; if the RI_i values are independent, the probability associated to any RI_i sequence is given by the product of the single probabilities. On the contrary, to take account of the distribution of successive RI_i time series determined by the sequence of adjacent pulses, higher moments are needed. At the moment the large part of the DSO stored records has no time continuity, being the result of successive acquisitions triggered by incoming transients.

5 **Frequency and joint time-frequency domain characterization**

The recorded transients have all a sharp initial peak with a fast oscillatory behavior (triggered by the electric arc itself) and followed by an amplitude decay, showing oscillations at a lower

1 frequency, probably due to the antenna modes (as already pointed out in sec. 4, while discussing the
2 time domain behavior). It is thus evident that these signals are non-stationary and that a direct
3 approach by Discrete Fourier Transform will not deliver the necessary information, in terms of time
4 resolution, if the required frequency resolution is the GSM-R channel or even the entire GSM band.
5 More generally a joint time-frequency representation allows to define the spectral content as a
6 function of time with adequate resolution and to evaluate the susceptibility of the GSM-R receiver,
7 down to the single bit time. As it will be shown, being the transients broadband phenomena
8 Frequency Hopping is ineffective to reduce interference, while it is for adjacent channel
9 interference.

10 In [2] the spectral behavior of recorded transients was first analyzed with the spectrogram (i.e.
11 Short Time Fourier Transform), identifying an oscillatory behavior, but without the required
12 frequency resolution. Then, a quadratic transform of the Choi-Williams type was used to both better
13 identify the frequency of oscillations (found corresponding to the GSM-R antenna resonant modes)
14 and to calculate the average power spectral density over the GSM channel.

15 The entire set of recorded transients have been analyzed again in order to derive a more
16 complete statistical representation of the disturbance spectrum: a confidence interval is associated to
17 the variability over both the time axis (during the occurrence of the transient) and the frequency axis
18 (thus checking and quantifying the statement on the broadband behavior in the GSM frequency
19 interval). Spectra are all shown in terms of power spectral density expressed in dBm/MHz. In the
20 absence of any evidence of biasing elements and systematic errors the confidence intervals are
21 expressed for an underlying Gaussian pdf, assured by the Central Limit Theorem and by the
22 numerous analyzed records.

23 The use of the CW transform may be questioned, considering the weak point of cross-
24 modulation terms and comparing the results with those obtained with other transforms of the same
25 type [19][20]. The measurement through the GSM-R antenna on-board gives a narrow band shape
26 to the recorded waveforms, due to the antenna bi-band behavior at the 450 and 900 MHz bands. In
27 this case, other out-of-band spectral components are attenuated by the antenna gain function, that is
28 up to several tens of dB, as shown below in Fig. 7, and this reduces any by-product of the CW
29 transform, in the form of interference components produced by the combination of the signal
30 components, to fall back inside the analyzed frequency bands.

Figure 7. Example of time-frequency spectrum obtained with a Choi-Williams transform and identification of the 900 and 450 MHz bands

To improve the robustness of the estimate of the power spectral density (PSD) within the GSM channel, after verification of the flatness of the same, the recorded waveforms have been analyzed by means of a periodogram [18] with a 4th order Blackman-Harris smoothing window and the PSD values for the frequency samples over the GSM downlink antenna band (910-940 MHz) have been extracted. The results shown in Table 2 consist of the average (PSD_av), the standard deviation (PSD_sd) and the inter-quartile range (PSD_iqr) for different time intervals T , including the initial transient pulse and the remaining signal decay.

Table 2. Statistical properties of the Power Spectral Density over the 860-940 MHz frequency band obtained by applying the periodogram for different time intervals

	Time interval T [ns]					
	25.6	37.5	51.3	75.0	102	150
PSD_av [dBm/MHz]	-83.5	-85.2	-87.0	-90.6	-90.9	-89.6
PSD_sd [dBm/MHz]	4.36	4.57	5.47	5.45	5.10	4.76
PSD_iqr [dBm/MHz]	5.71	6.78	7.79	7.11	6.72	6.82

It is evident that the average PSD is quite stable and reaches its maximum over a time interval that is the minimum to contain the transient pulse (shorter time intervals have been omitted since they do not contain the full transient pulse). An example of the computed PSD is shown below in Fig. 8 where the 450 MHz band is visible, together with other spurious responses at lower frequency, while the GSM-R channel is visible around 930 MHz with no lateral components due to frequency leakage, that was suppressed by the use of the B-H window (the smoothing window with the highest roll-off among those available, at the expense of a main lobe two times larger than the rectangular implicit window).

Figure 8. Example of Power Spectral Density in [dBm/MHz] computed with the *periodogram*, $T = 51.2$ ns and 2048 samples (a 4th order Blackman-Harris window was used): mean value (solid black), $\pm 1 \sigma$ boundaries (dashed black), sample of overlapped spectra (gray); the values can be transformed to power in a single GSM channel of 200 kHz bandwidth by subtracting 6.99 dB (approximated to 7 dB, as already commented in [2])

It is possible to note that the dispersion around the mean value is approximately constant over the entire frequency range. The values reported in Fig. 8 and in Table 2 can be converted to power in a single GSM channel of 200 kHz under the assumption of flat PSD by subtracting 6.99 dB (corresponding to the ratio of bandwidths, 1 MHz and 200 kHz).

6 GSM-R Quality of Service and susceptibility

Reference is made to a set of QoS indexes that are part of the GSM-R operation and functions or of the GSM protocol; the attention is focused on indexes related to data transfer and not to the connection establishment and connection loss, so concentrating on data frames, rather than on control frames:

- *transfer delay*: the end-to-end transfer delay of a user data block of 30 bytes (240 bits) shall be ≤ 0.5 s (99% probability) [15];
- *transmission interference period* (TIP) T_{TI} and *error-free period* (EFP) T_{Rec} : a TIP is the period during the data transmission phase of an existing connection in which, caused by the bearer service, no error-free transmission of user data units of 30 bytes is possible; a transmission interference happens, if the received data units of 30 bytes deviate partially or completely from the associated transmitted data units; T_{TI} shall be < 0.8 s (95% prob.), < 1 s (99% prob.); an EFP shall follow every TIP to retransmit user data units in error (e.g. wrong or lost) and user data units waiting to be served; the EFP shall be > 20 s (95% prob.), > 7 s (99% prob.) [15];

Establishing a reference for the evaluation of GSM-R susceptibility is a difficult task, in particular to find an agreement on the estimation of bit and frame error rates (BER and FER). To support this consideration, the Eurosig Subset 093 in [15], in App. A, states that "it is not possible to define relationships between both rates; the channel behavior is not known: error bursts and interruptions of data transmission during radio cell handover can happen."

BER is here considered before any forward error correction (FEC), but the standards do not clarify if after channel equalization or not. If not, Doppler effect represents a limiting factor in decreasing the BER below a however demanding threshold value. A rapid calculation can be made assuming a train speed $v_{tr} = 250$ km/h, that at the GSM-R frequency gives a Doppler frequency $F = v/\lambda = 208$ Hz, giving a random FM phase change over one bit time of $7.7 \cdot 10^{-4}$, causing an average BER of slightly less than $2 \cdot 10^{-4}$ if not compensated by equalization.

6.1 Susceptibility to a single transient

Each single transient pulse is processed in the joint time-frequency domain and the average power density over the GSM-R frequency interval is computed. The noise spectrum has an almost flat power density versus the frequency axis over the GSM band and a net decay versus time following the transient pulse; it was shown in [2] that in reality there are two classes of recorded transients with respect to time behavior of the spectrum: those with a net decay and those characterized by pronounced oscillations.

A data set larger than the one considered in [2] has been considered and statistically processed to derive a comprehensive spectral representation of the transients, with respect to the GSM interference (that remains the target of the analysis). The results were reported in Fig. 8 for the analysis done with the *periodogram* and thus referring to the average behavior of the DFT squared over a conveniently short time interval, as reported in Table 2.

The GSM sensitivity level (the minimum detectable signal at receiver) is very low and around -85 to -95 dBm, depending on the type of service. For a railway environment the minimum signal strength (giving sufficient coverage) has been made correspond to -90 dBm for 95% of time, but a more conservative value of -80 dBm was suggested [2] to account also for burst noise occurrence and to reduce drastically the bit error rate in worst case circumstance. A higher sensitivity value, of course, comes at the price of a larger transmitted power and closer separation of Radio Base Stations. It is observed that the average power of recorded transients in the GSM-R channel is $P_{av,200kHz} = -83.5 - 7 = -90.5$ dBm and accounting for a $\pm 2\sigma$ confidence interval with 95% probability

the maximum power $P_{av \pm 2\sigma, 200kHz} = -90.5 + 2 \times 4.36 = -81.8$ dBm that requires a signal strength for a SNR of 0 dB that corresponds to the estimated -80 dBm level [2].

6.2 Effect of multiple pulses

In [11] the repetition interval of only four arcs per second (reported in the cited paper written by Konefal) was used and compared with the limit $2\rho_0 R_s$, where ρ_0 stands for the target BER and R_s is the data rate in bit per second. It is evident that for the accepted BER of 10^{-3} , such a low repetition interval meets the requirement even for the data rate of a single slot. However, successive elaboration of recorded transients yielded much higher repetition rates, thus representing a relevant aspect.

The repetition of transients is not a uniform phenomenon, as already anticipated in subsection 4.2, so the average RI value represents only a first approximation, as confirmed by the accompanying estimated standard deviation shown in Table 1.

7 **Laboratory test setup for GSM-R susceptibility**

The Quality of Service (QoS) of a GSM-R unit may be tested in the laboratory against the recorded impulsive disturbance, selected and reproduced by a RF arbitrary function generator. The goal of the test bench is to host a GSM-R mobile terminal (at present a SAGEM GSM-R terminal), reproducing a GSM network by means of a Communication Vector Signal Generator (indicated with the brand name SMIQ by Rohde-Schwarz [13] and that represents the GSM-R network simulator) and coupling the recorded impulsive disturbance (generated by an arbitrary waveform synthesizer with controllable amplitude and repetition rate). Thus the real conditions observed during the former test campaign are simulated and applied repeatedly during a complete QoS test, with the possibility of controlling the signal-to-noise ratio SNR and the repetition rate (identified above as the Repetition Interval, RI). The QoS indexes may be evaluated by means of a Radio Communication Tester (CMU 200 by Rhode & Schwarz [10]).

The test setup above was designed and assembled for a wide test program, with the aim of evaluating several properties of the GSM-R: the SNR parameter and the related BER, the error correcting capability (so the relationship between BER and FER), the influence of the repetition interval, the introduction of a certain amount of probability distributions besides the average values. At the moment the results are limited to a preview of the relationship between BER and FER and the dependency on SNR and at a certain extent on RI. It is foreseen to develop a method to send a transient disturbance that is synchronized with the GSM frame, so to interfere with selected bits,

depending on the degree of protection and on them being data or control bits, thus evaluating the performance of the implemented FEC with a black box approach. To this aim the synchronization of the signal generator with the SMIQ is required and is obtained by means of a physical trigger signal.

Figure 9. Block diagram of the laboratory test bench and of the main equipment

8 Conclusions

In this paper a review is presented first of the GSM properties and characteristics that are deemed relevant for the evaluation of the interference caused by the transient electromagnetic emissions produced by the electric arc at the pantograph sliding contact. Then, the characteristics of the recorded transients in real conditions are considered: time domain properties consist of rise time, time duration, peak amplitude and repetition interval, the latter particularly relevant for the evaluation of the relevance of the disturbance over several GSM frames; frequency domain and joint time-frequency domain properties consist of the spectral power density, of the power decay versus time and of the statistics of the power spectra. The latter are first compared with the GSM-R sensitivity based on some literature references, in order to give a first estimation of the signal-to-noise ratio in a classical sense and of the so-called basic or raw bit error rate. Then the forward error correcting capabilities of the GSM protocol must be considered in order to derive a more complex relationship between the raw bit error rate and the frame error rate, that is relevant for the safety function of the GSM-R, that is the delivery of a correct movement authority to the train within the allotted time. A test bench for the evaluation of GSM-R susceptibility with respect to the recorded transients and their statistical and spectral properties has been presented together with some

preliminary results, in the form of look up tables between the raw BER and the FER for various conditions.

9 References

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