# On the characterization of pantograph arc transients on GSM-R antenna

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***Abstract-***The transients produced by the electric arc at pantograph and recorded at the output of a GSM-R antenna are characterized statistically in the time domain and in the joint time-frequency domain, in order to quantify the noise produced on the GSM-R channel itself. The measurements have been performed on a French line with a 25 kV 50 Hz supply system.

## I. Introduction

The GSM-R is a GSM based communication system in use in railways for the purpose of train to wayside transmission of a series of data and commands, related to train operation, control and protection. The GSM-R standard operates in a frequency band adjacent to the band used for the cellular phones and has been adopted for the implementation of the ERTMS standard. Since the GSM-R system is thus safety relevant, there is much interest in understanding the electromagnetic phenomena influencing and affecting the GSM-R operation and the level of interference that is likely to occur. It is evident that the GSM-R must ensure correct operation in hostile environment, featuring also bursty noise sources, such as the electric arc at locomotive pantograph during current collection, under widely variable conditions.

The GSM-R system employs two specific frequency bands within the broad frequency interval used for GSM transmission: [921–925] MHz for the downlink, from the control center to the train, and [876–880] MHz for the uplink, from the train to the control center. Each frequency band is divided into 20 frequency channels of 200 kHz. The GSM-R is a TDMA (Time Division Multiple Access) system, thus, for each frequency channel, data are organized per periodic TDMA frame, with a period of 4.615 ms. Each TDMA frame is divided into 8 time intervals of 577 μs called "time slots" and each user occupies a frequency channel only one eighth of the time with a period of 577 μs; each "time slot" includes 156 bits, so the transmission time of one bit is 3.7 μs [1].

## II. Problem description

The electromagnetic emissions from the electric arc at the pantograph sliding contact for current collection are produced by the intermittent nature of the arc, formed by a group of plasma channels (ionized air where conduction takes place) that a variable lifetime and that go through several extinction and re-ignition events.

As for the electromagnetic emissions the electric arc may be considered as a Hertzian dipole of short length and approximately vertical (with increasing inclination for higher speed); the radiation patter is thus omni-directional, that is approximately a donut in the horizontal plane. The variables that influence the behavior of the electric arc emissions are many: the contact wire surface conditions, the pantograph sliding contact conditions, the temperature, the train speed, the amplitude of the collected current, the mechanical suspensions reaction and in general the mechanical characteristics of the catenary system. It is observed that the occurring of the electric arc induces a second indirect emission phenomenon: when sparks occur, a transient current (broadband) appears on the metallic elements constituting the pantograph, the catenary, the power line on the roof of the train; consequently, the pantograph and the other elements may form a complex antenna whose radiated emissions are received by the GSM-R antenna.

In this phase the attention is on the preliminary analysis of the electric arc emissions as they appear on the GSM-R antenna connector, so taking into account the specific behavior of the train antenna; the other variables have not been recorded singularly, but they are assigned average values either measured during the measurement campaign itself or derived from the knowledge of the traction line conditions.

The results presented in this paper are extracted from the transient events measured on a train including one locomotive and eight cars. Measurements were carried out in France on a 25 kV AC 50 Hz line between Saint

Pierre des Corps (SPC) and Nantes; the travelled distance was about 200 km with a cruising speed of about 160 km/h, limited by the maximum speed of 200 km/h. A Digital Storage Oscilloscope (DSO) was connected to a radio antenna fixed on the roof of the fourth car, at approximately 80 m from the pantograph. The radio antenna is a bi-band antenna working in the frequency bands of the French railway radio system [420–520] MHz and of the GSM-R system [820–1000] MHz. Even if the antenna transfer function modifies the recorded transients with respect to the original transient e.m. field induced by the electric arc, the attention here is on the quantification and characterization of the transients really appearing at the antenna receiver, in particular the GSM-R receiver, since the antenna is the main element of the problem, that cannot be removed. The generalization of the present analysis may be pursued by accounting for the antenna transfer function; the antenna parameter of interest is the effective area $A_e$, or, as it is commonplace for antennas characterization, the antenna factor $AF$.

The setting of the DSO consists of a 20 GS/s sampling frequency $f_s$ and 200 ns time window $T$; the trigger level was adjusted slightly above the noise observed at low speed. Measurements were temporarily interrupted several times in the vicinity of towns due to the high level of noise induced by permanent emitters. During about 100 min of measurement, the oscilloscope collected about 25700 transient signals, that are a significant part of the total number of occurring transients. The recorded transients have a general waveform that exhibits a first peak (triggering the acquisition), followed by subsequent small peaks and oscillations, with a general decaying waveshape; yet, it happened that a superimposed oscillatory signal was often observed, and since it was present before the occurrence of the first peak, it may influence the accurate estimate of the rise time. Two examples of recorded transients and the related parameters are shown in Figure 1.
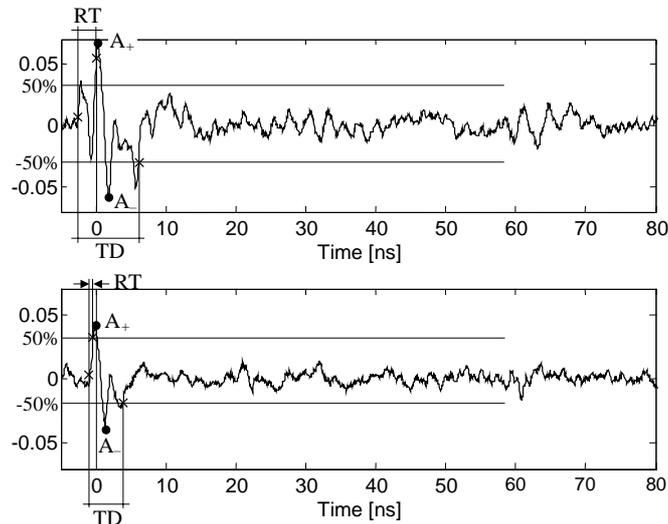


Figure 1. Examples of waveforms and of the parameters of interest

The parameters of interest that characterize the recorded transients in the time domain were identified as follows:
- the rise time RT of the first peak, with some problems of definition when a peak is preceded by a "pre-peak", as shown in Figure 1, upper curve;
- the amplitude A of the first peak, by distinguishing in positive peaks $A_+$ and negative peaks $A_-$; the peak-to-peak amplitude AA that measures the overall excursion of the signal, by calculating the difference $A_+ - A_-$ between any positive peak and following negative peak within a given movable time window: its distribution is almost similar to that of peaks $A_+$ and $A_-$, with an amplitude that is about 60% larger than the maximum between $A_+$ and $A_-$;
- the transient time duration TD, taken from the occurrence of the first peak up to the crossing of a convenient threshold, set to 30% and 50%, while observing the influence on the TD values and distribution; the TD parameter has been calculated with reference to both positive and negative peaks, by defining two different thresholds 50P (corresponding to +50% of positive peak) and 50N (corresponding to −50% of negative peak);
- the frequency of ringing FR, quantified by the time distance of adjacent zero crossings; the algorithm for the detection of zero crossings must account for fluctuations of the whole recorded signal or amplitude offset; to this aim 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, before any transient occurs;
- the repetition interval RI (or conversely the repetition rate RR), that characterizes the occurrence of subsequent transients, recorded on longer time windows, and that is not shown in the presented results.

The time domain properties are always described in terms of histograms, sample mean and dispersion and probability density functions (pdf), that best fit the sample data are identified.

An additional analysis in the joint time-frequency domain is then made, in order to better characterize the oscillations and ringing phenomena, trying to lead them back to the characteristics of the antenna, that is suspected to be at the origin of this specific behavior. More generally a time-frequency representation helps in the definition of the spectral content and its comparison with susceptibility levels, that for radio receivers are generally defined by the standards and by the manufacturers in the frequency domain.

The parameters of interest that characterize the recorded transients in the joint time-frequency domain have been identified as follows: the bandwidth BW as a function of time, computed as the frequency interval occupied by the spectrum with a convenient definition of attenuation at the extremes with respect to the center band value; if the frequency domain distribution is markedly "bimodal", as it could be due to the bi-band antenna, then the bandwidth will be calculated for the two bands separately ($BW_1$ and $BW_2$); the power over the GSM-R bandwidth $P_{GSM}$, to be compared directly with the susceptibility and sensitivity specifications of a GSM receiver.

### III. Results

The preliminary analysis of the time domain properties gave similar results to [1], obtained independently. The RT and the TD have been considered; the fitting of the pdf shows that there is no unique solution and that in some cases the pdf is not unimodal.

Furthermore, during the analysis it was evident that a criterion was utmost necessary to exclude those recordings bringing weird or inconsistent data; probably due to the superposition of two or more electric arc events several peaks clusters occurred during the recording, deformed by the previous peak relaxation and thus with no clearly defined TD due to several crossings of the thresholds in different time intervals. The percentage of discarded recordings has been always below 1% of the total number of recordings in each data set.

The synthesis of the time domain properties (rise time RT, time duration TD and peak A) is shown in Figure 1, where some pdf are proposed to fit the experimental histograms. The proposed pdfs are willingly shown without the quantification of the goodness of fit; the purpose is illustrative and a sound and robust pdf identification should be based on the elaboration of a huge amount of data representative of the various and variable operating conditions, from which by experience several different distributions are alike to come out.
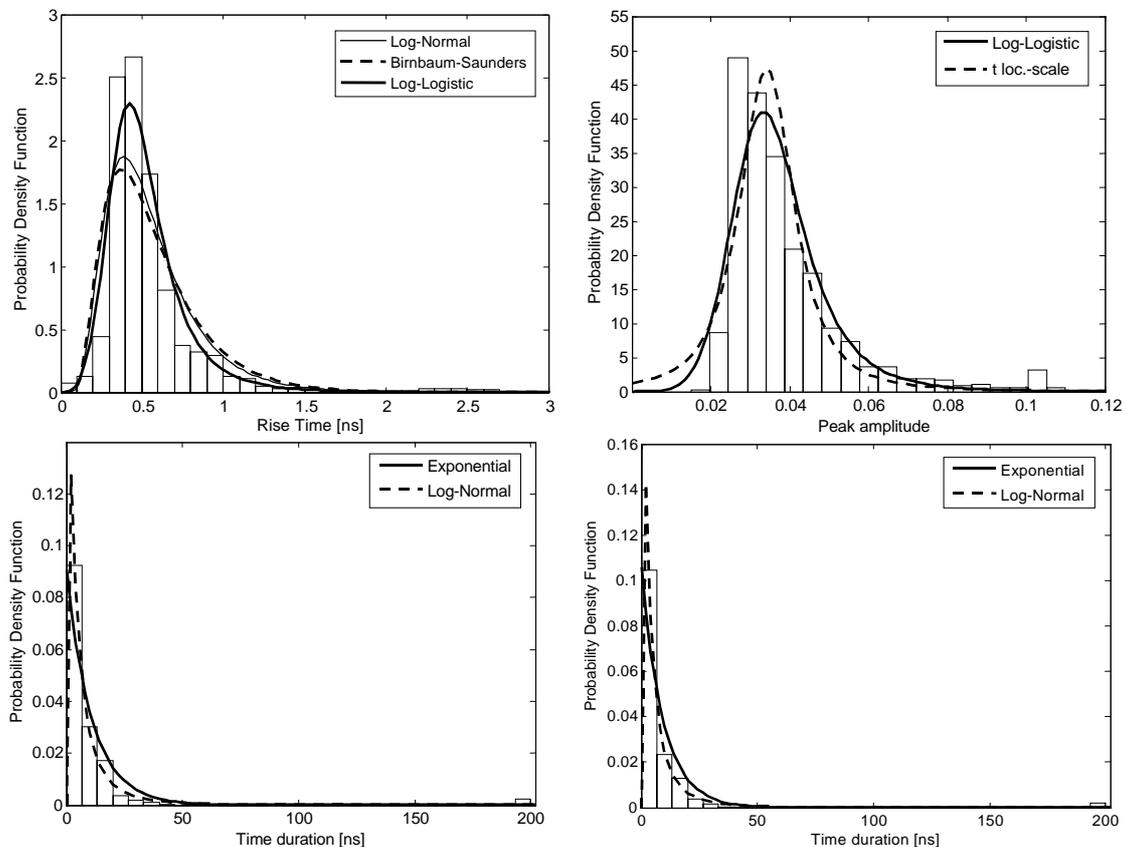


Figure 2. Statistical distributions of RT, A, $TD_{50\%}$

It is underlined that the width of the bins of the histograms has been selected carefully, especially for the TD parameters, since it was observed the following peculiar behavior: the TD is defined by the crossing of the given threshold for a signal with a relaxing oscillation, largely occurring at given frequency values (considered below); then the TD values are clustered around equally spaced reference values in relationship to the oscillation period. This phenomenon is evident for lower thresholds (like 30%), crossed by the signal many times; an example is shown in Figure 3 for two different and non optimal selections of the bin width.
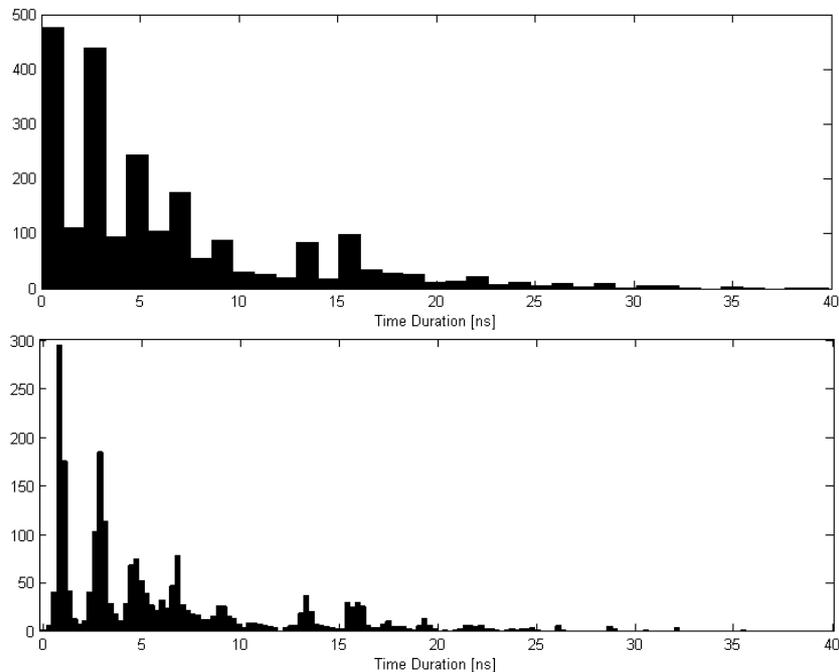
Figure 3. Influence of bin width on the histogram behavior for Time Duration TD

The analysis of the data has proceeded with the calculation of the spectrogram, deriving a Fourier based representation on the joint time-frequency axes [4]. The simple periodogram, based on Short Time Fourier Transform (STFT), is calculated by applying a Hanning window of width *M* bin to the series of time windows of duration *Mdt* (*dt* the sampling time) cut and overlapped along the signal. An example is shown in Figure 4.
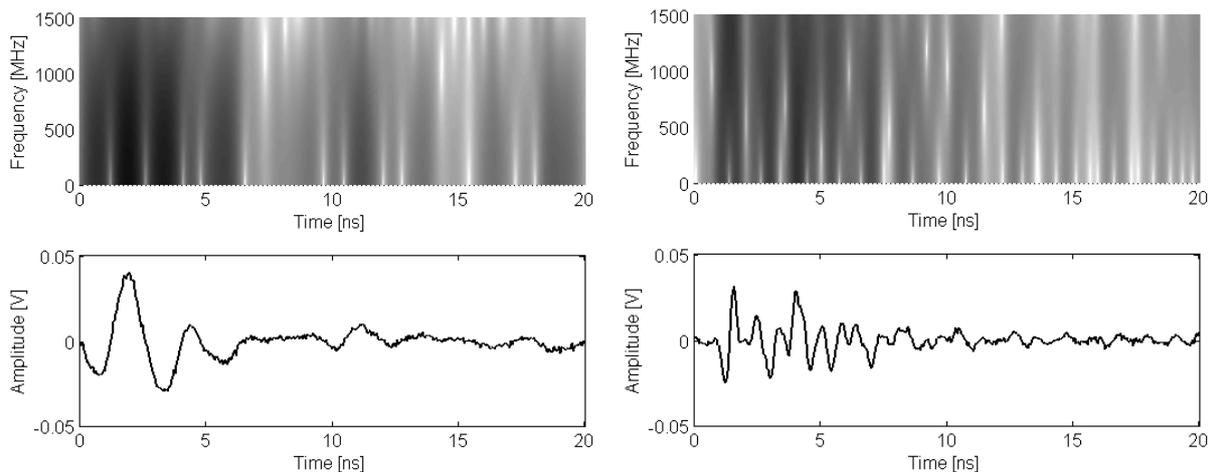
Figure 4. Two examples of spectrograms calculated on *N*=1028 bins, Hanning window of *M*=31 bins

With reference to the results shown in Figure 4, it may be stated that:
- the first signal on the left is dominated by a broad peak with an oscillation even lower than the lowest resonance frequency located in [420, 500] MHz, corresponding to a period of about 2.2 ns; the largest energy components extinguish in the first 5 ns, with no evident oscillatory behavior in the remaining part;

- the second signal on the right has several smaller peaks in the first 8-9 ns, exhibiting a "carved" spectrum with more evident highs and downs of the energy content; also the oscillation during the relaxation of the signal features a higher frequency content.

To better understand the oscillatory behavior and to undoubtedly locate the free response modes (that could be expected located in the antenna frequency bands), the recorded signals have been analyzed with a finer time-frequency resolution by means of a Choi-Williams quadratic transform.
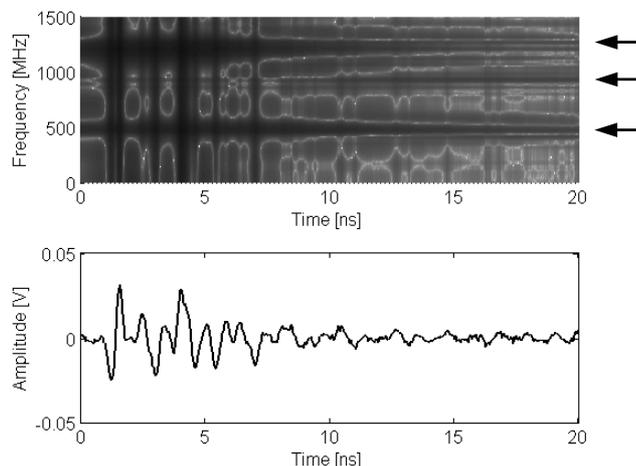


Figure 5. Exploration of self resonance frequencies by Choi-Williams transform (quadratic transform)

The quadratic spectrum shown in Figure 5 confirms that there are three main oscillating responses of the antenna, two of which are naturally related to the transient response of the bandpass structure tuned on the [420–520] and [820–1000] MHz; the other one located at approximately 1250-1300 MHz might be an unwanted spurious behavior of the antenna or the result of the mutual effect of the first two resonances through a non-linearity. These free responses are responsible for the oscillations in the recorded signals.



(a)                                                                 (b)
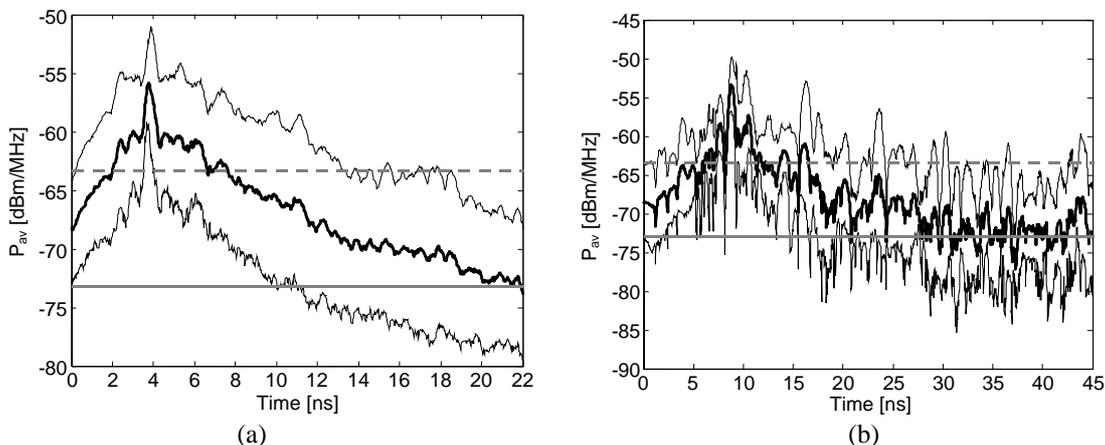
Figure 6. Noise power density [dBm/MHz] in the [850-970] MHz band computed over 100 independently acquired traces for two different data sets: (a) impulsive waveform with defined decay (see Figure 1, lower part), (b) impulsive waveform with periodic bursts (see Figure 1, upper part); both figures show mean profile (heavy black) and mean ± 1 std. dev. profile (thin black); the gray lines are the corrected GSM ref. levels

In Figure 6 two different behaviors are shown: the leftmost figure was derived for a more regular waveform where the first impulse is followed by a more or less defined decay that keeps the instantaneous value below an approximate ±30% threshold (see Figure 1, lower part); the rightmost figure identifies a periodic re-ignition of oscillations in the form of burst appearing every about 7 ns from the first peak. The average peak power is equal for the two data sets within a few dB and within the respective standard deviation profiles.
To evaluate the relevance of the processed signals as far as the interference to the GSM-R channel is concerned, the bandwidth $B_{GSM}$ of a single GSM-R channel is considered, under the assumption of a flat noise power density

$N(f)$ vs. frequency, confirmed by the close similarity of $N(f)$ for different 10 MHz sub-bands within the considered 850-970 MHz frequency interval. The used bandwidth of the GSM physical channel is $B_{GSM} = 200$ kHz. The calculated power density spectra must be divided by five (the ratio of $B_{GSM}$ to the reference bandwidth of 1 MHz used to calculate the power density), or –7 dB, to obtain an estimate of the level of disturbance within one physical channel; to this aim the sensitivity or interference reference level chosen for GSM has been increased by 7 dB and superimposed to the calculated power densities. While the GSM sensitivity level is very low and around –85 to –95 dBm, depending on the type of service, and represents the minimum detectable signal level for the receiver alone, a more consistent level is considered to account for various practical reasons and for a minimum signal-to-noise ratio: this level is chosen to be –80 dBm.

Since GSM uses TDMA access to the physical channel the interference should be evaluated also taking into account its time behavior. The average time separation of subsequent electric arc impulses belonging to different transients was estimated in [1] to be 3.7 μs based on an empirical Weibull distribution, so close to the bit time duration; however the large part of the samples amounting to 48% were not included in the estimation of the distribution itself were above 400 μs.

The statistical distribution of the power density components at each time instant is assumed normal in the following, to ease the interpretation of the mean and standard deviation in terms of associated probabilities. Since the traces were acquired independently, their number is quite large and the amplitude of each component intended as a random variable is almost alike, the Central Limit Theorem may be invoked to uphold the gaussian distribution assumption.

For both the calculated spectra the GSM reference level is overcome by all transients. For the spectra of Figure 6 left this occurs in a very short time interval: taking the mean profile we have interference over about 25 ns with 50% probability and over 11 ns with 63% probability. Yet the time duration of the interference indicated by the spectra of Figure 6 right is longer than the shown time axis (restricted to 45 ns for display purpose) and amounts in the tests done to about 70 ns, and is however very difficult to be quantified exactly since the static in band noise is quite large, due to presence of several GSM sources in the tested environment.

For these reasons the use of a GSM reference level of –70 dBm, brought after correction to –63 dBm, is highly advisable, so that the in-band interference is always limited to 10 ns on average. This level is similar to the one normally adopted for coverage studies, when a safety margin is taken for second order effects (such as diffraction and fading) that are not fully considered by the analysis tools; it may be ensured by higher transmission power levels and/or closer distance between adjacent radio base stations.

## IV. Conclusions

The results are presented of a measurement campaign concerning the transient disturbance appearing on the on-board antenna used for train-to-wayside communication of SNCF trains produced by the electric arc at the train pantograph. The process is non-stationary due to several factors, in particular the intermittent and chaotic nature of the electric arc itself and the variable conditions of the contact wire. The large number of acquired recordings allows a statistical treatment of the signal parameters, both in the time domain as histograms and in the joint time-frequency domain, as Short Time Fourier Transform (for a description of the energy content of the signal) and Choi-Williams Transform (for a finer time-frequency resolution). The collected signals have been thus characterized in terms of energy and band occupation, with respect to the problem of possible interference to GSM-R radio system, and the contribution of the antenna due to self oscillating free response terms has been isolated and recognized. The analysis of the noise power in a frequency interval containing the GSM-R frequency channel has confirmed that even if interference exists at the lowest signal levels, close to receiver sensitivity, a comfortable minimum receiver signal of –70 dBm ensures a tolerable interference.

## References

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