PANTOGRAPH ARC TRANSIENTS OCCURRENCE AND GSM-R CHARACTERISTICS

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Abstract: The transients produced by the pantograph electric arc and captured by a GSM-R antenna mounted on 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 channel. The recoded signals are characterized also to evaluate the behavior of the GSM-R protocol to burst noise. The measurements were performed on a 25 kV 50 Hz French line.

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

1. INTRODUCTION

The GSM-R is a GSM based communication system designed and now in use in European railways [1]; its overall performances and openness allow its application also abroad on other railway systems. It is used for the purpose of train and wayside bidirectional communication and in particular for the transmission of series of data and commands, related to train operation, control and protection. The GSM-R implements the ERTMS/ETCS Level 2, where Radio Block Centers exchange the said data and commands on the GSM-R physical link. The GSM-R is thus safety relevant and electromagnetic interference is one of the aspects to consider in evaluating the GSM-R reliability and robustness.

The electric arc at the sliding contact on the locomotive pantograph is an intermittent source of electromagnetic emissions. Multiple elementary arcs appear and disappear with chaotic nature, producing transient intermittent plasma columns with a variable lifetime and successive extinction and re-ignition events [2]. Several elements and variables influence the electric arc emissions: the contact wire surface and the sliding contact conditions, such as temperature, train speed, the amplitude of the collected current, the mechanical suspensions reaction and in general the mechanical characteristics of the catenary system.

The GSM-R system employs two frequency bands of the GSM frequency interval: [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 band is subdivided into 20 frequency channels of 200 kHz. The protocol is a TDMA (Time Division Multiple Access), and, for each frequency channel, data are organized as a periodic TDMA frame, with a period of 4615 μs. 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, or "bit time", BT, is 3.7 μs [3].

The measurements were carried out in France on a 25 kV 50 Hz line between Saint Pierre des Corps and Nantes with a train consist of one locomotive and eight cars. The travelled distance was about 200 km with a cruising speed of about 160 km/h. The GSM-R antenna was mounted 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.

2. PROBLEM FORMULATION AND MODELING

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 (8k to 4M 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 compared to GSM susceptibility levels [4][5].

Two examples of recorded transients and related parameters are shown in Fig. 1 [2].

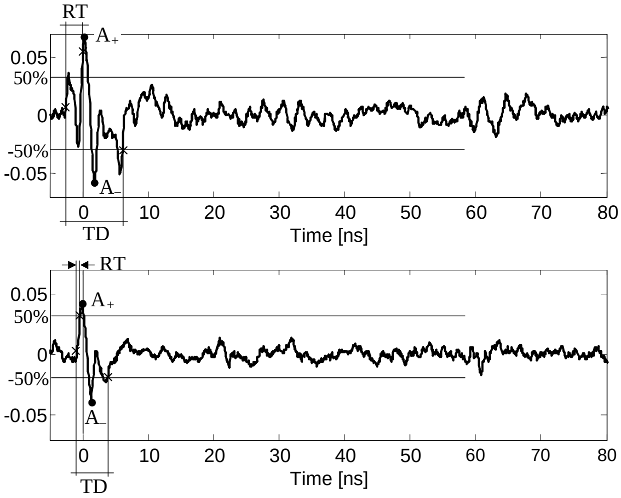

Figure 1. Examples of waveforms and of the parameters of interest

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. 1, 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.

The time domain parameters above are evaluated as histograms, sample mean and dispersion and probability density functions (pdf), that best fit the sample data. More generally a time-frequency representation allows to define the spectral content as a function of time and to evaluate the interference to GSM-R receivers, by comparison with susceptibility levels [4][5].

3. PROCESSING OF MEASUREMENT RESULTS

3.1. Statistical distributions of pulse parameters

During the analysis, we noticed that in some cases the pdfs are not unimodal and several recordings bringing weird or inconsistent data, due to several reasons: superposition of two or more electric arc events, external disturbance, wrong scale setting. However, only 1% of the collected recordings was discarded during the analysis.

The histograms of the waveform parameters (RT, TD, FR and RI) are shown in Fig. 2, where some pdfs are proposed to fit the experimental histograms.

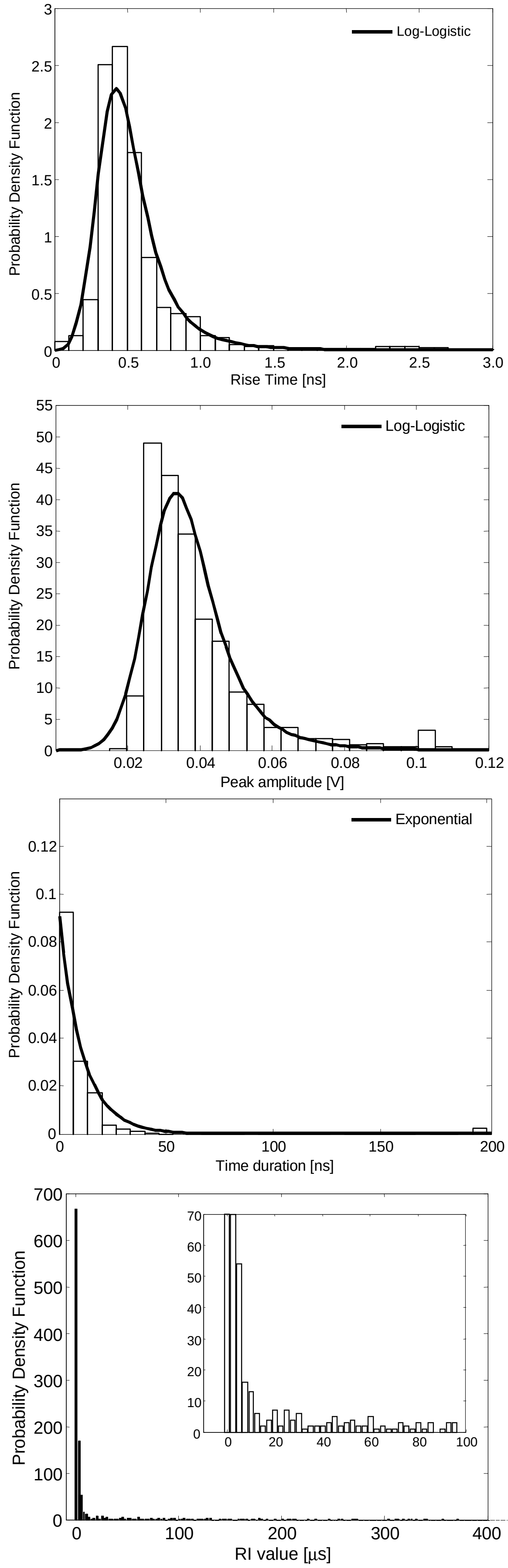

Figure 2. Statistical distributions of RT, A, TD50%, RI

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 BT = 3.6 μs. RI is particularly relevant 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 RI estimation depends heavily on the sample set composition, that in turn depends on: i) the threshold chosen to count successive spikes, ii) the gating time interval (set slightly larger than the estimated TD), 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. 3.

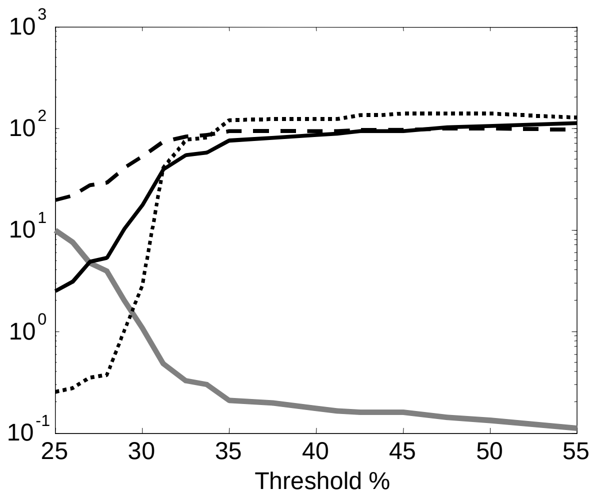

Figure 3. Statistical parameters for RI evaluation: number of RI samples x 1000 (grey thick curve), sample mean (black curve) in μs, standard deviation (dotted curve) in μs, inter-quartile range (75%-25%) (dashed curve) in μs

With reference to the solid black curve of Fig. 3 the sample mean varies from 3 to 100 μs approximately. The exact value is related to the used threshold, as it is evident from Fig. 2 (lowest graph), where the histogram of RI values counts rare occurrences up to 370 μs, that can increase the sample mean if included in the calculation. The fact is witnessed by the increasing dispersion versus threshold, so that versus the number of considered RI samples (the dispersion is the dotted curve in Fig. 3). If all collected RI values are considered, then the RI mean value increases to 100 μs, 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 μs, supported by a dispersion of less than 1 μs; this is due to the increased relevance of small RI values in the statistics, as it should be.

3.2. 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. If the pulse time separation random variables PS_i (namely the respective repetition intervals) are independent, following the previously determined statistical distribution, the associated probability of any pulse sequence and related combination of PS_i values is given by the product of the single probabilities. These sequences and their high order moments are particularly relevant if the frames transmitted over the GSM-R channel are coded with error correcting codes, and in particular if the used codes have a specific robustness against burst noise, so noise with a time duration longer then a single bit time. These codes are in use in particular for radio channels that are the most exposed to transient noise due to natural events, and in particular thunderstorms and lightning. In the following the GSM-R will be assumed operating without error correcting codes, so that one wrong bit corresponds to the whole wrong frame.

3.3. GSM-R susceptibility to a single pulse

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; it is shown in Fig. 4 versus the time axis for two classes of recorded transients: those with a net decay and those characterized by pronounced oscillations [2].

In Fig. 4 two different behaviors are shown: Fig. 4(a) refers to 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 Fig. 1, lower part); Fig. 4(b) shows a re-ignition of oscillations appearing every about 7 ns from the first peak. This peculiar aspect indicates that not only the pulse separation PS is relevant for burst noise definition, but that the single impulse may last for up to a hundred ns or – in some cases – 1 μs, due to natural oscillations of the roof top antenna triggered by a transient. The average peak power is however equal for the two data sets within a few dB and within the respective standard deviation profiles.

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.

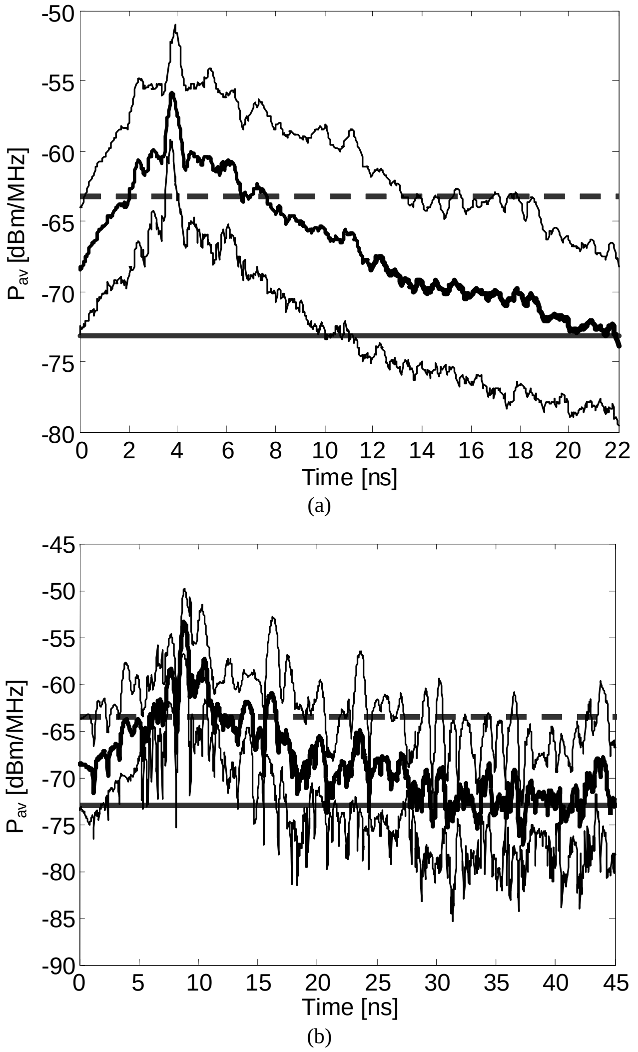

Figure 4. Noise power density in dBm/MHz over the [850-970] MHz band computed with 100 traces and two data sets: (a) transient with defined decay, (b) transient with periodic bursts. Mean value (heavy black), ± 1 std. dev. boundaries (thin black), corrected GSM reference levels (grey lines)

3.4. GSM-R susceptibility to pulse sequences

Since GSM uses TDMA access to the physical channel to transmit frames that amount to 30 bytes (240 bits) of payload (plus additional headers and overhead, for about 300 bits overall), the interference must be evaluated also on a longer time scale. With reference to sec. 3.2 the occurrence of pulse sequences with PS_i approximately equal to one or few BT represents the so called "burst noise". Burst noise occurs in bursts and represents thus a challenge also for several error correcting codes (basically normally referred to as "forward error correcting" codes), that can correct more easily isolated bit errors. The PS_i values are such that the impulsive noise may repeat every 1 to 30 BT (bit times), the lower values being more likely, so that any interference due to an excessive channel noise power will affect several bits of the same message. In GSM-R [6] the frame is considered in error if just one bit of the sequence is wrong, so the probability of 1 wrong frame P_{fe} corresponds to the probability of at least 1 wrong bit, that is the complement to unity of the probability that all bits are correct:

$$P_{fe} = 1 - (1 - P_{be})^n \quad (1)$$

where P_{be} is the bit error probability and $n = 300$.

A noisy sequence S is made of a set of noisy spectra $N_i(f)$ with time separation PS_i. The $N_i(f)$ components at each time instant are assumed normally distributed by the Central Limit Theorem, since the traces were acquired independently, their number is quite large and the amplitude of each component is almost equiprobable over a limited amplitude interval [7]-[9]. The PS_i values correspond to an approximately exponentially distributed random variable with the statistical properties of the RI parameter, as shown in Fig. 2. P_{be} is thus related to the maximum amplitude of the noise with respect to the amplitude of the signal when the disturbance occurs (i.e. SNR value), and not simply to a worst case analysis performed with the minimum signal amplitude (i.e. SNR_{min}). When the SNR decreases only by 5 to 10 dB the associated probability increases dramatically, so that the attention is focused only on those portions of the route where the SNR reaches its minimum, that is midway between two Radio Base Stations. By the way, this route portion is the one where handover occurs and where the GSM-R system is mostly exposed to interferences.

The EUROSIG specifications concerning wrong frames are given in terms of maximum delay for correct reception, that is 7 s at 95% and 20 s at 99% confidence intervals respectively; these delays were selected to identify the maximum time interval that a train is allowed to operate without a correctly received Movement Authority message, beyond which a safe configuration is reached by either reducing speed, braking to stop or other actions decided by the procedures agreed by the operators, the infrastructure owner and the authority. By assuming a continuous transmission of frames over the GSM-R channel and a continuous fair retransmission in case of frame error, we have F different frames sharing the channel, together with their retransmissions, in number of M on average for each different frame. The number of different frames F is equal to the number of different trains served under the same channel frequency; usually two different frequencies are assigned to a Radio Base Station and the maximum number of trains per channel may be considered around 30. The throughput f is thus only F frames in the unity of time (1 s), while channel occupation is MF frames in the unit of time, that is $M f$,.

So, assuming a high channel utilization percentage, a channel speed of $B = 9600$ bps and a Gaussian Minimum Shift Keying modulation, that assigns 2 bits to each transmitted symbol, a full frame is transmitted in $T_F = 300/B/2 = 15.6$ ms, during which $q = 3000$ to 15000 noise pulses may occur on average for a RI value between 2 and 10 μs (the most likely and sensible values as shown in Fig. 3). The number of possible repetitions M over the unity of time is thus about $M = 1/(F\ T_F) \cong 2$. The exponent n in (1) may be thus replaced by q, since an error may occur only for those bits interested by a noise pulse; in reality also adjacent bits may be affected in case of a low SNR, because of, first, damped noise oscillations that extend beyond 1 BT, and, second, the noise power indicated by SNR is still large enough, despite the damping, to interfere with subsequent bits.

The probability of a wrong frame repeated MT_{obv} times over a T_{obv} = 7 s observation time interval is given by

$$P_{fe,tot} = (P_{fe})^{MT_{obv}} \quad (2)$$

It represents the case of a train that is unable to receive correctly a Moving Authority frame over the allowed T_{obv} time interval beyond which an action is automatically triggered in favor of safety, such as a speed reduction or braking.

Eq. (1) may be then re-written for clarity for a GMSK symbol that encodes two bits, using thus P_{se}, that is the probability of a wrong symbol rather than a wrong bit:

$$P_{fe} = 1 - (1 - P_{se})^q \quad (3)$$

P_{se} may be lead back to the signal power E_b (normalized by the data rate) and noise power density N_0 by the following expression, that is valid for orthogonal base signals under the assumption of an optimal receiver.

$$P_{se} = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (4a)$$

where $Q(\,)$ indicates the $erf(\,)$ function, that is the complement to 1 of the integral of the normal distribution. The ratio E_b/N_0 is nothing but the SNR.

$$P_{se} = Q\left(\sqrt{SNR}\right) \quad (4b)$$

The values of P_{fe} and $P_{fe,tot}$ for an assumed bit error probability (BER), for the minimum and maximum values of q and for an assumed value of MT_{obv} are reported in Table 1 below.

Table 1. P_{fe} and $P_{fe,tot}$ for some assumed SNR, disturbing pulse density q and average number of retransmissions MT_{obv}

	SNR				
	0	**+10**	**+12**	**+14**	**+16**
P_{se}	0.159	$8\ 10^{-4}$	$3.4\ 10^{-5}$	$2.7\ 10^{-7}$	$1.4\ 10^{-10}$
P_{fe}	1.0	0.905	0.098	$8.1\ 10^{-4}$	$4.2\ 10^{-7}$
$P_{fe,tot}$	1.0	0.246	$7.3\ 10^{-15}$	$5\ 10^{-44}$	$5\ 10^{-90}$

It is clear that a SNR of about 10 dB represents the limit for a satisfactory exchange of frames over the GSM-R channel, with the criterion of ensuring the safety of the circulation over a convenient time interval T_{obv} = 7 s. The estimated SNR threshold is in agreement with the 10 dB margin proposed in [2] for the sensitivity threshold of the GSM-R (see sec. 3.3 and Fig. 4). In some countries, the time interval before a speed reduction or braking is issued in the absence of a correct frame, is even increased to about 20 s, thus reducing the requirement on the minimum SNR.

These results are however approximate for the variability of several of the used parameters: RI mean value, noise power, assumed maximum number of frames F, assumed lack of error correcting codes (whilst GSM uses a sort of speech reconstruction to improve speech quality that can be used somehow as a forward error correction technique). Moreover, the measured data refer to an open-air configuration and we could expect some signal degradation due to multi-path interference when the transmission occurs inside tunnels, as investigated in [10] for highly reflecting narrow environments.

4. CONCLUSION

The results of a measurement campaign and of the successive analysis are presented: the aim of the activity is evaluating the transient disturbance appearing on the GSM-R roof top antenna used for ERTMS/ETCS train-to-wayside communication on SNCF trains. The transient disturbance is produced by the electric arc at the train pantograph and may be considered a non-stationary process, featuring an intermittent and chaotic nature due to the electric arc behavior and influenced by the variable conditions of the contact wire, the weather conditions and other practical factors. The attention here is on the statistical characterization of the burst noise spanning over several bit slots of the same GSM-R message and the capability of the GSM-R protocol to react to burst message corruption. The statistical properties in the time and frequency domain of the resulting random process are derived and compared with the susceptibility thresholds and error correcting capabilities of the GSM-R standard.

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