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Intra-vehicle digital communications: characterization and simulation of the electromagnetic environment

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Abstract

Most of the studies on electromagnetic noise and the potential sources of interference were conducted to protect analog communications and have now appeared to be insufficient given the widespread development of digital communications. New approaches appropriate for digital communications are currently under development. We have chosen to illustrate these recent approaches by focusing on the particular application of intra-vehicle transmission. In this article, we consider two examples of data transmission: wire transmissions over a power line network, better known as *power line communication*, and wireless links inside the vehicle's passenger cell. We focus on characterizing the electromagnetic environment but we also highlight the potential of reverberation chambers for reproducibly simulating multi-path environments. ***To cite this article: F. Rouissi et al., C. R. Physique 10 (2009).***

Résumé

Communication intra véhicule : caractérisation et simulation de l'environnement électromagnétique. La plupart des travaux sur les bruits et les sources potentielles d'interférences ont été menés en vue de la protection des communications analogiques et s'avèrent actuellement insuffisants, compte tenu de la généralisation des communications numériques. De nouvelles approches sont en cours de développement et nous avons choisi d'illustrer les démarches actuelles en s'appuyant sur une application particulière qui concerne les transmissions au sein d'un véhicule. Le cas d'une transmission filaire sur le réseau d'énergie, connue sous le nom de courants porteurs en ligne, et celui de liaisons de type sans fil, seront successivement envisagés. Nous nous intéresserons à la caractérisation de l'environnement, du point de vue brouillage électromagnétique, mais nous mettrons également en évidence les potentialités des chambres réverbérantes pour simuler, de façon reproductible, un environnement multi trajets. ***Pour citer cet article : F. Rouissi et al., C. R. Physique 10 (2009).***

Keywords: Intra-vehicle communication; Propagation channel; Power line communication; Noise; Interference

Mots-clés : Communication intra véhicule ; Canal de propagation ; Communication sur ligne d'énergie ; Bruit ; Interférence

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1. Introduction

Intra-vehicle systems for data transmission—or, more generally, for information exchanges—are rapidly becoming widespread. There has been a real explosion in the field of intra-vehicle communications for applications targeting both vehicle control commands and passenger comfort, offering every possible opportunity to receive information and images and information through multimedia techniques.

Obviously, all these data transmission systems must be able to function correctly in their operating environments, and developers frequently find themselves confronted with Electro Magnetic Compatibility (EMC) problems. In order to highlight the inherent difficulties to use existing standards for characterizing conducted or radiated noise, as well as to underline the necessity of developing new test methods, we chose to consider two communication techniques.

The first example concerns data transmissions that use a power line network as the physical support for transmission. This type of transmission is beginning to appear in the automobile industry. Better known as Power Line Communications (PLC), such transmissions are disturbed not only by white noise, but also by the impulsive noise generated by the electrical devices connected to the network. Methods for classifying and characterizing impulsive noise were, of course, proposed by Middleton many years ago [1]. One of the objectives of these methods was to determine the susceptibility of analog communication systems to interference, but Middleton's methods have proved to be inadequate for dealing with digital communications. For this reason, other methods are being developed [2,3], as noted in Section 2.

In Section 2, we focus specifically on the method that we used to extract the significant parameters of impulsive noise, since the choice of these parameters is closely linked to the signal processing techniques applied to digital communication. To obtain low error rates, the simplest solution would be to increase the power of the transmitter, but in this case, other EMC problems, connected to the radiation of the power line network, would quickly arise. It must be emphasized that, for the time being, no automotive standards specify the maximum authorized transmission power.

Though the wire transmissions needed for a vehicle to function correctly are safety critical and, consequently, are a crucial concern for the automobile industry, both technically and economically, wireless transmissions are also becoming increasingly important for this industry. More and more vehicles are being used as mobile offices. Then, certain office applications must continue to function correctly inside vehicle cells. Thus, numerous devices equipped with WLAN (Wireless Local Area Network) and/or WPAN (Wireless Personal Area Network) communication capacities are also expected to function efficiently inside the vehicles. Although the aeronautic industry has chosen to impose that nomadic terminals be shut down during certain critical flight phases, it is hard to imagine this requirement being enforceable for road transportation. The result is a complex situation in which the number of signals in a frequency range extending from 1 to several GHz has increased significantly, presenting a major challenge in terms of electromagnetic compatibility. This challenge is even more critical given that the passenger cell of a vehicle can behave as a lossy resonant cavity, provoking local increases in the amplitude of the electromagnetic field, as shown in Section 3. In Section 4, we consider mode-stirred reverberation chambers (MSRC) in an effort to determine to what degree MSRC could be used to simulate the environment inside a vehicle's passenger cell, and, more generally, to test inter-system compatibility.

2. Characterizing impulsive noise in PLC systems

As mentioned in the introduction, the number of PLC systems in a vehicle is likely to increase over the next few years, in an effort to reduce the complexity and the weight of the wire transmission networks dedicated to communication between on-board sensors and control-command systems [4,5]. In order to avoid too much signal attenuation during propagation, the transmitting frequencies used in PLC systems are usually low, ranging from 1 MHz to around 30 MHz. Furthermore this frequency band is also chosen to avoid disturbing the reception of the FM broadcast band. In the following only intrinsic PLC communication will be considered, i.e. communication using the global power line network, and not Power over Data (PoD) systems where there is a dedicated two wire line connecting the transmitter and the receiver. Consequently, for a PLC communication, the geometrical and electrical structure of the power line network also generates numerous wave reflections, both on terminal equipment and at each branching. These reflections create multiple paths between the transmitter and the receiver, making the transmission channel frequency selective [6,7]. To deal with the transfer function variations in the frequency domain, OFDM (Orthogonal Frequency Division Multiplexing) transmission techniques are usually adopted. Since impulsive noise also has an impact on the

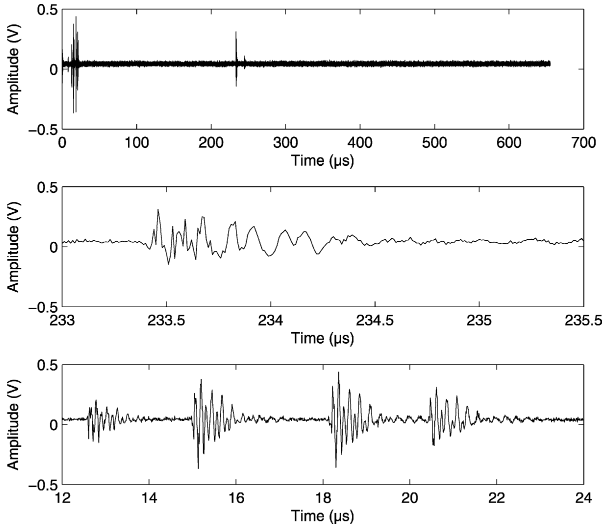

Fig. 1. An example of a typical noise recording – (a) observation window of 650 μs, (b) single pulse, and (c) burst.

link, appropriate channel coding must be used, for example, based on the Reed–Solomon codes, data interleaving or turbo codes. To predict the effect of disturbances on digital systems, modifications of the standardized measurement techniques and of the transmission standards themselves have recently been imagined [2,3]. However, in their current form, these modifications do not allow the channel coding to be optimized nor the link performance to be predicted satisfactorily.

The approach we adopted involved taking, in the time domain, a great number of measurements of impulsive noise in different types of vehicles in order to elaborate statistical noise models, which were then inserted into software for simulating digital transmissions. After a brief description of the experimental conditions, we describe the procedure we used to characterize impulsive noise.

2.1. Measurement principle and impulse classification

A capacitive coupler was inserted between the PLC network and the acquisition device. This coupler had an input/output impedance of about 50 Ω and its bandwidth was between 500 kHz and 40 MHz. A protective device limited the maximum amplitude of the acquisitions to 3.5 V. Preliminary testing showed that the background noise could be considered as white noise, with a power spectral density (PSD) between -110 dBm/Hz and -130 dBm/Hz. When an impulsive noise exceeded a certain threshold, it was recorded during an observation window of 650 μs. At the end of this window, a clock with a period of 400 ns was triggered in order to determine the time intervals separating 2 successive recordings. The signals, sampled at a frequency of 100 MHz, were then stored in memory. After numerous tests, the triggering threshold of an acquisition was chosen varying between few mV and 200 mV. This value allowed low amplitude pulses to be recorded, while preventing the background noise from continually triggering a recording. The result from a typical recording is shown in Fig. 1(a).

Next, it was necessary to extract the noise impulse(s) from the background noise, during this 650 μs recording. The chosen method involved calculating the cumulative variance of the sampled signal. Given the presence of white noise, this variance was a linear function of time, with a change in the slope indicating the appearance time of a pulse.

Signals were recorded at a number of points in the electrical system of diverse types of vehicles (both diesel and gasoline engines) while the vehicles were following a 20-minute itinerary through an urban or semi-urban environment. Indeed, noise can be due, of course, to motors activated by the driver, such as the windscreen wipers, but also to all control/command systems whose characteristics and activation depend both on the type of car and on the driving conditions. It is important to remember that the objective of this study was not, in any way, to identify and/or characterize the different sources of disturbances, but to determine statistically the characteristics of the impulsive noise at any given point in the network. For this reason, all the recordings were analyzed, regardless of the location of the

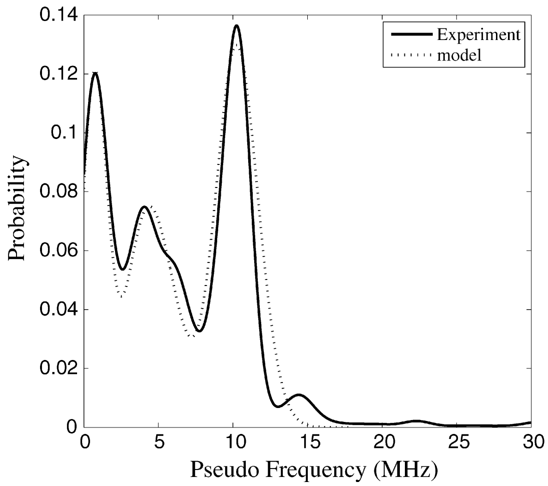

Fig. 2. Probability density of the pseudo frequency.

measurement point. In practically all cases, the pulses had the form of damped sinusoids, present as either a single pulse (Fig. 1(b)) or a series of pulses, called a burst (Fig. 1(c)) [8].

2.2. Impulsive noise characteristics

Given the form of the pulses, their main characteristics in the temporal domain are the pseudo-frequency associated to the maximum power spectral density (PSD), the peak amplitude, the pulse duration, the damping factor and the inter-arrival time (IAT), which is the time separating two successive pulses. Based on the recordings of several thousands of pulses, it appears that the occurrence probability of a single pulse or a burst is, respectively, 89% and 11% and the median IAT value is 8 ms [9].

The "Experiment" curve in Fig. 2 shows the variation of the probability density of the pseudo-frequency of the pulse.

To determine the error probabilities for a given channel coding in the presence of impulsive noise, it is necessary to have a model of this noise that can be integrated into a digital transmission simulation software.

3. Modelling impulsive noise

3.1. Middleton's model

One of the most commonly used noise models is that described by Middleton in various articles. He proposed a unique analytical expression for describing interference as the sum of Gaussian noise and impulsive noise [1]. This model has different classes, with Class A referring to the case in which the bandwidth of impulsive noise is lower than or comparable to the frequency bandwidth of the receiver. For the applications considered here, the useful bandwidth of the OFDM signals, and thus of the receiver, ranges from 1 MHz to 30 MHz, while the impulsive noise, with its damped sinusoidal form, has a high spectral density only in the vicinity of its pseudo-frequency. Thus, to deal with the total bandwidth of the OFDM transmission, a Class A model would seem to be appropriate.

To characterize impulsive noise, Middleton used 3 parameters, called $P3$. The first is the impulsive index A, which is the product of the received average number of impulses in a second and the duration of the impulse ($A \leqslant 1$). The two other factors are the Gaussian factor Γ which is the mean power ratio between the channel noise and the non-Gaussian component of the impulsive noise, and the variance factor Ω_{2A}, which is the variance of impulsive noise component.

Middleton's unique analytical expression allows noise characteristics to be described, assuming that the channel is stationary. However, our measurements of impulsive noise indicate that the channel characteristics vary greatly from one observation window to another. We thus calculated a $P3$ for each observation window, with a duration of 655 µs, in order to deduce the distribution of the $P3$ for all the windows. The next step was to use a known function to bring the distribution of each of the three $P3$ terms closer together. Middleton's model can thus generate noise by choosing the values A, Γ, and Ω_{2A} from the values drawn randomly from their distribution functions [10]. However, following this procedure leads to a form of generated noise that is quite different from the measured noise. In fact, this model cannot take into account the correlation between the successive noise samples, given the pseudo-periodic form of each pulse, or the statistical distribution of the inter-arrival times.

Since, to our knowledge, there are no other noise models described in the literature that would be useful with digital communication techniques, we developed a purely stochastic approach based directly on our measurements.

3.2. Stochastic noise model

The basic idea was to find the distribution functions that best reproduced the measured distributions for each of the parameters that characterize the noise (e.g., duration, pseudo frequency, amplitude, IAT). This would allow the pulses to be reconstructed by drawing their characteristics randomly from the distribution functions. Different tests were conducted using a variety of functions: Gamma, Weibull, Log and Normal, to name several. The parameters intervening in the chosen function were then optimized by applying the Kolmogorov test to compare the values generated with the model with the measured values from our experiments [8].

As an example, the "model" curve in Fig. 2 shows that the distribution function of the pseudo-frequency of the pulse can be approximated by 3 Gamma functions. Each of them is valid for frequencies under 1.2 MHz, between 1.2 and 6.5 MHz and over 6.5 MHz, respectively. The scale and shape parameters in these functions have a value of 6.03 and 0.12, respectively, for the first interval, 10.79 and 0.43 for the second interval and 79.22 and 0.13 for the last interval.

This type of model, which can be associated with Markov models, highlights the temporal characteristics of the disturbing signals. For example, if an interleaving technique is used for the channel coding, its depth will be chosen in terms of the inter-arrival time of the pulses. The disadvantage of the method described above is that it is awkward to implement because it requires numerous temporal acquisitions and a judicious choice of the approximate distribution functions. Research is currently under way to try to find simpler model, like Middleton's, but able to be used for digital communications systems.

To better highlight the evolution of the needs in the field of digital link compatibility, we chose another example with a completely different application, since it concerns wireless networks inside vehicles.

4. Characterizing and simulating the electromagnetic environment in a road vehicle

The use of on-board transmitters, both vehicle-mounted and personal, will become widespread in the future. Typical examples include mobile phone, Bluetooth systems and data transmission within the passenger cell. The cohabitation of such wireless networks in the vehicle can be particularly problematic because, at high frequencies, the vehicle chassis behaves as a lossy resonant cavity, which can provoke significant local increases in the amplitude of the electrical field, thus interfering with other on-board systems. Since the movement of the passengers can also dynamically affect the field distribution, this kind of environment appears to be similar to a mode-stirred reverberation chamber (MSRC). It would be thus possible to quantify the field variation, both in space and time, by the parameters usually used for characterizing a MSRC (i.e., a quality factor and an equivalent stirring coefficient). After presenting the measurement results obtained in a vehicle, we discuss the possibilities of using a MSRC as a way to make reproducible tests of a multi-path environment. It must be outlined that we do not intend to present an exhaustive analysis of the actual electromagnetic environment that can be encountered in a car, but to briefly describe what approach can be used, either from a theoretical or experimental point of view. In the following, we thus restrict the analysis to the field distribution due to a single transmitting source placed inside the vehicle.

4.1. Characterizing the electromagnetic environment

Using a Finite-Difference Time-Domain (FDTD) model with the SEMCAD$^{\mathrm{TM}}$ software, we simulated the radiation of a $1/4$ wave dipole placed in the vehicle's passenger cell using a highly simplified model of the vehicle chassis, composed of an empty perfectly conducting structure with openings. A metal plate was placed between the passenger cell and the motor compartment. This plate had a circular opening that was 10 cm in diameter in order to allow

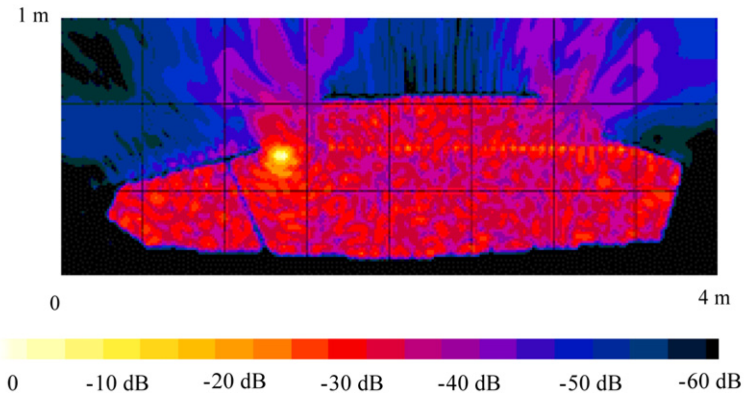

Fig. 3. Distribution of the field amplitude at 2.45 GHz in an empty perfectly conducting structure.

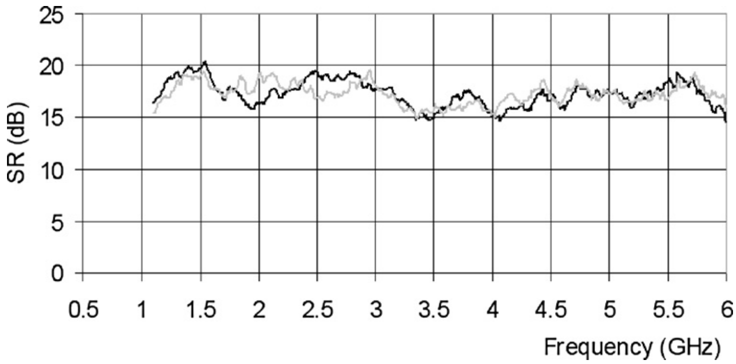

Fig. 4. Stirring coefficient corresponding to passenger movement in the vehicle's passenger cell. Curve in black and in grey refer to passengers with a cotton vest and with a metallic vest, respectively.

the coupling between these two zones to be simulated. The windshield and the lateral windows were assumed to be perfectly transparent to the transmitted signals. The calculations were done at 2.45 GHz.

Fig. 3 shows the results obtained for the particular case of an antenna placed on the dashboard. Two conclusions emerge from these results:

- High field levels appeared locally, which could potentially provoke electromagnetic compatibility problems for nomadic systems as compared to on-board systems;
- Field fluctuations of several dozen dB were observed over a distance of several centimeters.

This simple model provides an idea of the orders of magnitude of the field levels, but it does not take into account the presence of lossy dielectric materials (e.g., seats, upholstery) or the passenger's small-scale movements, which are nevertheless significant in terms of wavelengths.

To characterize the propagation more realistically, measurement campaigns are often carried out on diverse configurations, with measurement methods based on S-scattering parameters. As previously outlined, a statistical study of the transfer functions shows that it is possible to assimilate a non-empty vehicle passenger cell with a mode-stirred reverberation chamber with a low quality coefficient; in this case, the passengers act as mode stirrers.

In an MSRC, the stirring ratio SR is equal to the ratio of the square $S_{21\max}/S_{21\min}$ for one complete period of the stirrer. It is usually considered the MSRC will function normally if SR is higher than 20 dB. Fig. 4 represents the variation of SR in terms of frequency, with the curves being deduced from the measurements taken in the vehicle. The random part of the measurement is due to passenger movements. The curve in black was obtained with 4 cotton-clothed passengers in the vehicle; the curve in grey was obtained with these same 4 passengers, who had donned a metallic vest in aluminum.

Table 1
Influence of the number of absorbers.

N	0	1	2	4
Q_{measured}	62 000	9200	5300	2500
Q_{theory}		9200	5000	2600
S_τ (ns)	2000	300	170	80

A stirring ratio of 15 to 18 dB was obtained for frequencies between 1 and 6 GHz; we noted no impact due to the addition of the metallic vest [11]. The measurements also show that, in a frequency bandwidth between 2.4 and 6 GHz and with several passengers, the quality factor Q varied from 100 to 500, depending on, for example, the position and radiation pattern of the antennas or the type of car [11,12].

Thus, in order to use a MSRC to test the behavior of a digital communication system, alone or with other transmitters/receivers, the MSRC must be able to reproduce the real environment in which the system or systems are embedded, whether it be specifically in a vehicle passenger cell or more generally in any multi-path environment with numerous reflecting obstacles [13,14]. In either case, each position of the mode stirrer must correspond to a propagation channel realization.

4.2. Potential of reverberation chambers as a means for testing digital communication systems

In the EMC domain, a reverberation chamber is characterized by its quality factor Q, by another coefficient τ_{RC} that reflects the exponential decrease in the energy stored in the cavity when the transmitting source is stopped, and by the mode bandwidth B_m. It is thus important to link these last two terms to the delay spread S_τ and the coherence bandwidth B_c, which are used to characterize any propagation channel. We have previously shown analytically [15] that S_τ has the same mathematical expression as τ_{RC}, and thus can be related to Q for a given frequency f_c:

$$S_\tau = \frac{Q}{2\pi f_c} \tag{1}$$

Similarly, B_m can be associated with the coherence bandwidth calculated for a value of the amplitude of the correlation coefficient, equal to 0.7, which yields:

$$B_c = \frac{f_c}{Q} \tag{2}$$

The numerical application shows immediately that, for a usual reverberation chamber with a volume of several dozen m^3, the delay spread is measured in microseconds. To simulate environments similar to those encountered in a vehicle—or, more generally, in any confined space—it is necessary to greatly reduce the delay spread. Given Eq. (1), one solution would be to damp the cavity by positioning absorbers [16]. For example, if an absorber is placed against a wall, the resulting quality coefficient Q_{new} can be expressed in terms of the Q_{empty} of the empty chamber and the Q_{abs} of the absorber:

$$\frac{1}{Q_{\text{new}}} = \frac{1}{Q_{\text{empty}}} + \frac{1}{Q_{\text{abs}}} \tag{3}$$

Under the normal operating conditions of an MSRC with a volume V, Q_{abs} is expressed as:

$$Q_{\text{abs}} = \frac{2\pi V}{\lambda S_{\text{eff}}} \tag{4}$$

where λ is the wavelength and S_{eff} is the effective absorbing surface of the absorber. For example, the MSRC used in this experiment had a volume of 65 m^3. Preliminary measurements in this MSRC, in which a single absorber of 1.4 m^2 had been placed, allowed us to determine an absorbing surface of 0.8 m^2. Other measurements were then carried out, increasing the number N of absorbers; Table 1 shows the results obtained.

As Table 1 shows, it is possible to simulate environments characterized by very different delay spreads. However, it must be noted that if the MSRC is greatly damped, the direct path from the transmitter to the receiver may no longer have a negligible energy compared to the energy of the “stirred” components. This would notably be the case if non-directive antennas were used. The environment would become a Rice environment instead of the Rayleigh environment, which, depending on the real environmental characteristics to be simulated, could be more, or less, disadvantageous.

Since the transmission/reception system to be tested can be placed in the MSRC, an antenna connected to a white noise and/or impulsive noise generator(s) and/or other communication devices could be added to the equipment in the chamber to determine the robustness of this system in terms of noise or interference.

5. Conclusion

With a couple of examples, we have illustrated the evolution now occurring in the characterization of an electromagnetic environment. It is important to note that the benefit that can be drawn from the signal processing algorithms, associated with new channel coding techniques, is even better if the channel is known in fine statistical detail.

This is true for noise, but also for propagation. Although, to predict the link performance in "simple" systems, it is enough to know the received power distribution in terms of the position of the mobile unit, the same is not true for the actual multi-antenna systems. In the latter case, bi-dimensional channel characterization is necessary, which implies statistical knowledge of other parameters, such as the angular spread of the arriving and departing rays on the transmitting and receiving antennas.

Another important element would be to have efficient in-laboratory testing facilities for telecommunications systems, which are easy to implement and able to simulate highly diverse environments. MSRC have their place in such facilities, but a number of questions remain unanswered. Future research in this field is thus needed.

Acknowledgements

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