URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Evaluation of the Transient EM Interferences Impact on the Clear Channel Assessment in Wi-Fi Communications

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Abstract

This paper presents a study about transient electromagnetic (EM) interferences produced by contact losses between the catenary and the pantograph and their impact on the Internet access on board trains. This study is focused on the assessment of the impact of these transient EM interferences on the Clear Channel Assessment (CCA) mechanism used in the Wi-Fi protocol. A series of tests was carried out to analyze the effects of the transient EM interferences on the Wi-Fi communication bit rate. The results reveal the relation between the parameters of CCA mechanism and the characteristics of the transient interferences, then explaining the degradation of the achieved bit rate.

1 Introduction

Nowadays, high-speed train operators work on improving services by offering Internet on board. However, the railway environment is rich in electromagnetic (EM) interferences, including transient EM interferences produced by contact losses between the catenary and the pantograph, able to affect the Wi-Fi frequency band. Therefore, it is necessary to evaluate the clear channel assessment (CCA) mechanism used in the Wi-Fi communication in the presence of these transient interferences. The CCA is a mechanism determining whether the medium is busy or not. The paper first describes the transient EM signal used for the experimental tests and then details the experimental setup. Finally, the measurement results are presented and discussed.

2 Railway transient ElectroMagnetic (EM) Interferences

In High-speed trains, the catenary to pantograph contact provides the energy for the traction and all the auxiliary equipment [1]. When the pantograph loses contact with the catenary, electric arcs are produced. Electric arcs are electric discharges with high current density, involving short duration transient EM interferences [2], [3]. Thus, these interference signals are able to cover wide frequency bands, including the Wi-Fi band. Note that in the literature, the major part of the studies to characterize the railway environment are carried out up to 1 GHz [4]. Indeed, the presence of very high power low frequency signals and the significant difference of powers between the low frequency and high frequency signals make the high frequency signals undetectable in the measurement results. Therefore, it is necessary to employ specific measurement techniques focused on the high frequencies, by using adapted sampling frequencies, antennas and filters for studying these interferences in the Wi-Fi band.

2.1 Transient EM interference in the Wi-Fi band

We performed measurements to check if the EM interferences associated to the catenary-pantograph contact cover the Wi-Fi frequency band. A 1 GHz - 9 GHz wide frequency band antenna was placed on a train roof and connected to an oscilloscope. To allow the high frequency signals analysis, a 2 GHz – high pass filter was connected to the oscilloscope input and a 20 Gsamples/s rate was applied. Fig. 1 presents a measurement result from the oscilloscope and shows the short duration of the transient signals and the variable time interval between the transient signals. Fig. 2 shows the Time-Frequency representation of the measured signal obtained with the spectrogram algorithm. The frequency band covered by these transient signals includes the Wi-Fi band, i.e., 2.4 GHz.

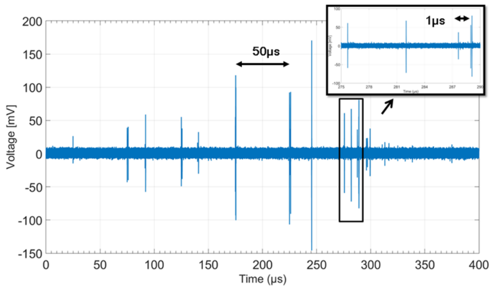

Figure 1. Time domain representation of transient EM interference signals measured by the oscilloscope.

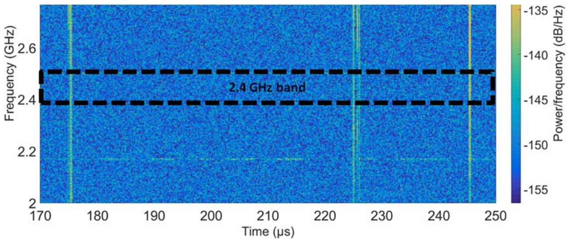

Figure 2. Time - Frequency representation of transient EM interference signals measured by the oscilloscope.

2.2. Model used

These measurements demonstrate that transient EM interference signals can cover the Wi-Fi frequency band. However, we did not measure enough data to conduct a statistical study of the interference characteristics.

We have then been interested in [5], in which a large number of measurements and a statistical analysis were performed in the GSM-R frequency band. This study presents time characteristics, which are partially depending on the GSM-R antennas employed for the measurements. If the measurements would be carried out with Wi-Fi antennas, the frequency and time characteristics would be slightly different. Then, we adopted the general model extracted from this study in [5] but we adapted the parameters values to be relevant regarding our study in the Wi-Fi frequency band. In [5], the transient EM interference model is a double exponential function, which characteristic parameters are the time duration (D), rise time (T_{rise}) and amplitude (A). The general expression is defined by [6] as:

$$i(t) = \mathrm{A}\left(e^{-\frac{t}{\mathrm{D}}} - e^{-\frac{t}{\mathrm{T}_{rise}}}\right) \tag{1}$$

The values selected for the time duration (D) and the rise time (T_{rise}) were defined taking into account that the frequency spectrum of a transient interference signal measured by a Wi-Fi antenna is necessarily concentrated in the Wi-Fi bandwidth. Moreover, in order to have a flat frequency response in a Wi-Fi channel and concentrate the power in the frequencies of interest, we modulated Eq. (1) at the center frequency (f_0) of Wi-Fi channel.

$$i(t) = \mathrm{A}\left(e^{-\frac{t}{\mathrm{D}}} - e^{-\frac{t}{\mathrm{T}_{rise}}}\right)\sin(2\pi f_0 t) \tag{2}$$

3 Experimental method

2.2. Signal parameters

Fig. 3 depicts the signal defined in Eq. (2) with a 10 ns time duration, 0.5 ns rise time and f_0 = 2,412 GHz. The transient interference signal band is centered over the Wi-Fi channel between 2.402 GHz and 2.422 GHz. The variation over the channel is within 3 dB, that is to say, the transient signal has a quasi-flat response within the channel.

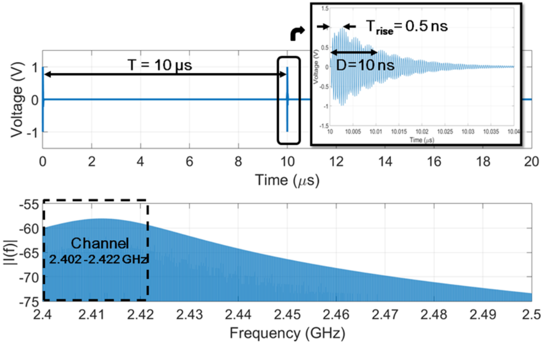

Figure 3. Double exponential signal with D=10 ns, T_{rise}=0.5 ns. FFT with a 20 µs window.

In Fig. 1, the repetition interval between successive transients varies between 50 µs and 0.5 µs. We defined this interval between successive transients as the repetition period (T). Thus, T and the power level of transient EM interferences are considered as test parameters in order to study their impact on the IEEE 802.11n performance. T is varied by an Arbitrary Waveform signal Generator (AWG) and the power by using an attenuation control unit.

2.3. Test setup

Fig. 4 presents the equipment and the test setup employed. The test network was constituted by a server connected to the access point (AP) by an IEEE 802.3 connection and the AP was connected to the client by the IEEE 802.11n connection.

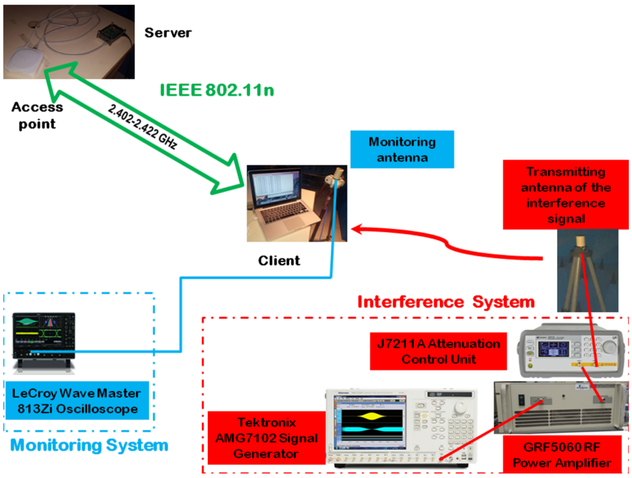

Figure 4. Scheme of the experimental setup, including the monitoring and interference systems, and the test network.

On the one side, the interference system comprised an AWG signal generator in which we loaded the model (Eq. (2)) obtained through Matlab. To reach higher interference power levels, we connected a power amplifier to the generator output. Next, a variable attenuation control unit was connected to the amplifier output in order to vary the power of the interference signal transmitted by the omnidirectional antenna.

On the other side, we used a monitoring antenna next to the client and connected to an oscilloscope with a sampling rate (f_s) of 10 Gsamples/s, in order to measure the interference and IEEE 802.11n signal powers. The power received by this monitoring antenna is indicative and not necessary identical to those received by the client.

The experiment was carried out in a semi-anechoic chamber at the University of Lille. Inside the chamber, we placed the test network, the interference transmitting antenna and the monitoring antenna. The monitoring antenna was located near the client in order to assess the received power similarly to those received by the client. The locations of the equipment inside the semi-anechoic chamber are illustrated in Fig. 5.

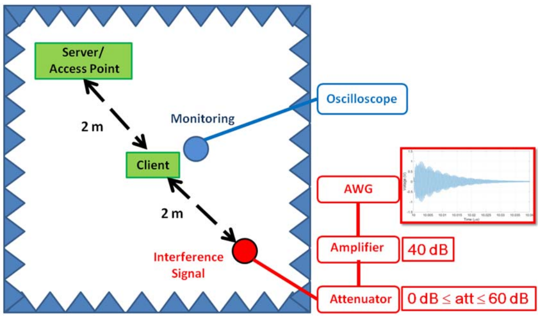

Figure. 5. Location diagram of the equipment inside the semi-anechoic chamber.

3 Measurement Results and Interpretation

We applied a transient interference signal with a defined repetition period (T) and the attenuation level was decreased step by step, starting from 60 dB until the bit rate reached zero (communication interrupted). For each attenuation value, the bit rate was measured, by means of Iperf3 program [7] run on the client side. This procedure was repeated for each repetition period T from 25 µs to 1 µs. Fig. 6 presents the results including four areas:
Area A corresponds to T = 25 µs where the communication is maintained even with 0 dB attenuation. Area B corresponds to the repetition periods between 24 µs and 10 µs for which the bit rate decreases progressively before a total communication interruption at a 20 dB attenuation. Area C corresponds to the repetition periods between 9 µs and 3 µs for which the communication is abruptly interrupted at attenuation levels between 19 dB and 26 dB. Area D corresponds to T = 1 and 2 µs where the communication is suddenly interrupted with a strong attenuation levels in relation to area C.
These results show that the communication is interrupted for transient interference signals with T below 24 µs. In order to analyze this behavior, we consider the Clear Channel Assessment (CCA) mechanism of the protocol.

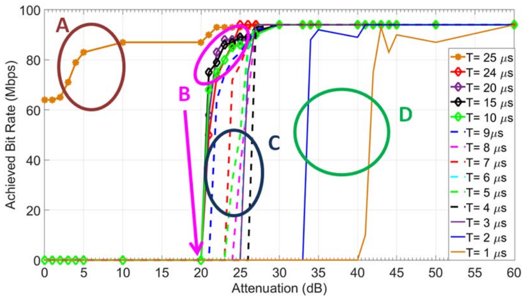

Figure 6. Bit Rate measurements of an IEEE 802.11n network, as a function of the attenuation levels and different T values.

Clear Channel Assessment- Energy Detect (CCA-ED) is the mechanism applied to sense the medium at the PHY layer [8]. According to [9], it consists in measuring the highest average power over the channel during the DIFS period. The DIFS (Distributed coordination function Interframe Space) period (28 µs) is the minimum duration during which the channel has to be free to allow the WLAN station to access the medium. The acquisition method of the highest average power is not precisely described in the standard. The standard only states that the CCA-ED indicates a channel busy condition when the received signal strength exceeds the threshold of - 72 dBm (for 20 MHz bandwidth), within a 4 µs maximum time [9, p. 1614]. Fig.7 illustrates a way to estimate the highest average power induced by a transient signal with T = 10 µs. The interference was measured by the monitoring antenna and without attenuation. We then subtract the attenuation level applied to lose the communication and thus obtain a power value indicative of those measured by CCA-ED mechanism, denoted by *PHighestAvg*. To determine *PHighestAvg* within the DIFS period (28 µs), we divide this 28 µs in seven consecutive time windows of 4 µs which corresponds to the maximum time mentioned in the standard [9, p. 1623]. In every time window (*j*), the average power during 4 µs is determined by Eq. (3)

$$P_{avg}(j) = \frac{1}{N}\sum_{i=1}^{N}\frac{x_j^2(i)}{Z},\ j = 1,2,...,7 \tag{3}$$

where x_j is the signal of the time window *j, i* is the sample index, *Z* is the oscilloscope input impedance, and *N* is the number of samples or vector *x* length. This latter parameter is obtained as $N = f_s \times w$; f_s is the sampling rate and *w* is 4 µs. We determine *PHighestAvg*, defined as:

$$P_{HighestAvg} = \max[P_{avg}(j)],\ j = 1,2,...,7 \tag{4}$$

In Fig.7, *PHighestAvg* is -44 dBm without taking account the attenuation. This procedure was repeated for the other values of T. The results are presented in Fig. 8 for 0 dB attenuation and in Fig. 9 by subtracting the attenuation level required to lose the communication.

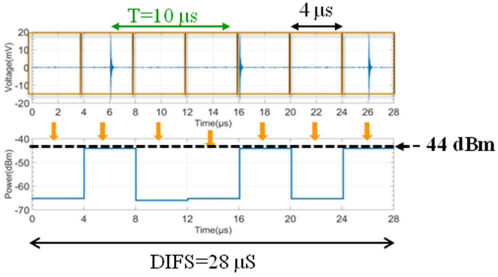

Figure 7. Representation of the CCA evaluation in the presence of a transient EM interference of T=10 µs.

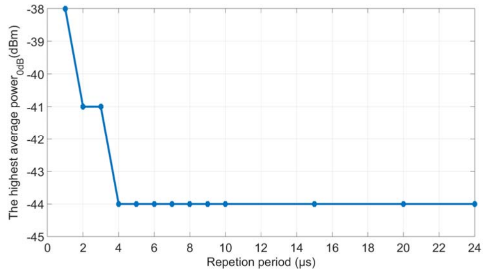

Figure 8. The highest average power values within 28 µs with 0 dB attenuation, as a function of T.

In Fig. 8, the power is constant for T ≥ 4 µs because only one transient can be present within a 4 µs time window. The power increases when T decreases and is inferior to 4µs because the time window can include several transient interferences.

Fig. 9 contains *PHighestAvg* values required to interrupt the communication, as a function of T.

For 10 µs ≤ T ≤ 24 µs, the *PHighestAvg* values are above the threshold of -72 dBm [9, p. 1614]. Moreover, for these values of T in Fig. 6, the bit rate progressively decreases with the attenuation. This demonstrates that the Modulation and coding schemes (MCS) mechanism adjusts the bit rate to reduce errors caused by the interferences, until the power reaches the threshold for which the CCA-ED considers the medium busy.

For T ≤ 2µs the communication is interrupted with power levels below the threshold. This indicates that the CCA-ED mechanism does not cause the interruption, but probably the too frequent errors in the frames due to the short interval of time between successive transient interferences.

For 3 µs ≤ T ≤ 9 µs, the *PHighestAvg* values varies and are slightly above -72 dBm. Knowing that this power is measured by the monitoring antenna, it can be different from the power received by the client. It is likely that the real power obtained at the client level by the CCA mechanism varies around the threshold. By consequence, the interruption of the communication can be due to the CCA-ED mechanism as well as to the errors.

Then, for Internet on board trains, if transient interferences appear with *T* lower than 25 µs the performances of the Wi-Fi network could be degraded due to the CCA-ED mechanism and errors. Thus, the interferences should be taken into account in the design of the Wi-Fi system. Indeed, access point locations have to be defined to reduce coupling with transient interferences in such a way that the received interference power is < -72 dBm. For T bigger than 25 µs, the performance of the network is limited by the CCA mechanism.

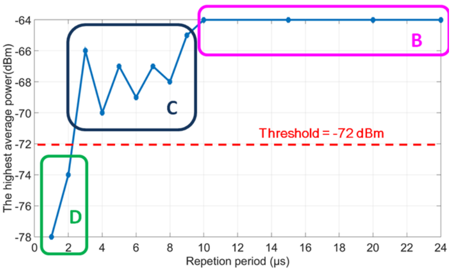

Figure 9. The highest average power values within 28 µs with attenuation level

5 Conclusions

This paper presents a study of the performances of IEEE 802.11n communication network under transient EM interferences, representative of those present in the railway environment.

We studied the impact of the repetition interval between consecutive transients and the impact of the transient signal power. The experimental results show that the transient EM interference signals present on board trains may significantly affect Wi-Fi communications. In particular, if their power is sufficient and if they occur at intervals below the DIFS, they may prevent any communication from being established. In perspective, measurement campaigns have to be carried out inside the railway cars in order to select relevant Access Point locations, where the interference power levels does not affect the CCA mechanism.

6 Acknowledgements

This work was performed in the framework the ELSAT2020 project which is co-financed by the European Union with the European Regional Development Fund, the French state and the Hauts de France Region Council.

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