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"Virtual" Signal Integrity Test on High-Speed Ethernet Cables in a Reverberation Chamber

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***Abstract*— In this paper, a "virtual" signal integrity method applied on twisted-wire pairs (shielded or not) is presented. The method is based on *S*-parameter measurements made in a reverberation chamber. From these balanced measurements, an impedance imbalance approximation is added in post-processing through the introduction of a given common-mode rejection ratio. Then, the signal integrity can be tested for any level of the average electromagnetic field generated within the chamber. The method is illustrated in the simple case of a square useful signal in order to demonstrate the relevance of the method.**

I. INTRODUCTION

In reason of the appearance of autonomous vehicles full of sensors, the volume of digital data to be transmitted within an automobile requires networks that support increasing data rates. It seems that twisted pairs of conductors inserted in Ethernet and LVDS cables will be the most commonly used cables for high-speed wired communications. Although high-speed networks solve the problem of data throughput, the study of their immunity is a new issue in the automotive industry. These types of studies are usually based on transfer impedance measurements at low frequencies [1]-[2] (when propagation effects along the cable are negligible) and shielding efficiency measurements at higher frequencies [3]. Immunity measurements on cables is generally made through the calculation of the induced signals (current and voltage) on the cable by an external disturbance [4] and do not involve checking the quality of the transmitted signal. To go further, a "virtual" method for verifying the signal integrity of high-speed networks is proposed in this paper. The method is based on the measurement of S-parameters in a mechanically stirred reverberation chamber (RC). It is shown that it is possible to predict the integrity of data transmission for a cable under any electromagnetic disturbance occurring at a given frequency.

II. METHOD DESCRIPTION

A. Experimental setup

The proposed method consists of *S*-parameters measurement between an antenna (port 1) and an under-test twisted pair (shielded or unshielded) Ethernet cable inserted in a reverberation chamber for a given number *N* of positions of the rotating mode stirrer. The experimental setup is presented in Fig. 1. Ports 2 and 3 correspond to the termination (with respect to the ground) of each conductor of the twisted pair at one side of the cable, the conductors being connected to a 50 Ω load on the other side of the cable.

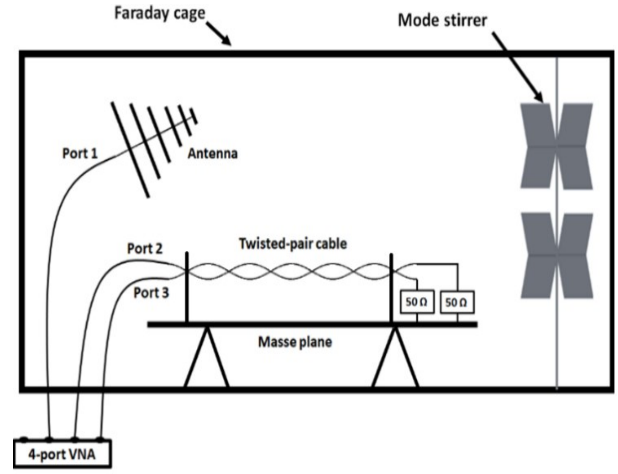

Fig. 1. Schematic description of the experimental setup.

B. Principle of the method

The different steps of the method are presented successively in this section.

1) Calculation of ⟨|E$_T$|⟩

The parameter S_{11} is used to calculate the quality factor Q of the RC [5]:

$$Q = \langle |S_{11} - \langle S_{11} \rangle|^2 \rangle \frac{Z_0\, \omega\, \varepsilon\, V}{\left(\frac{\lambda^2}{4\pi}\right)(1 - |\langle S_{11} \rangle|^2)^2\, \eta^2} \tag{1}$$

where Z_0 is the wave impedance, ω the pulsation, λ the wavelength, η the antenna efficiency, ε the dielectric permittivity of the propagation medium and V the RC volume.
Knowing the RC quality factor Q, it is therefore possible to calculate the average total electric field strength $\langle |E_T| \rangle$ in the RC [6] for any power accepted by the antenna P_{inj}.

$$\langle |E_T| \rangle = \sqrt{\frac{QP_{inj}}{\omega \varepsilon V}} \tag{2}$$

2) *Common mode induced voltage*

The parameters S_{21} and S_{31} measured allow the common mode voltages V_{mc1} & V_{mc2} generated on each of the 2 conductors of the twisted pair by the electromagnetic disturbance produced in the RC to be calculated. In the case of a twisted wire pair, the useful signal is generally transmitted in differential mode. The different ports of the measurement are illustrated in Figure 2 according to the S-parameter theory:

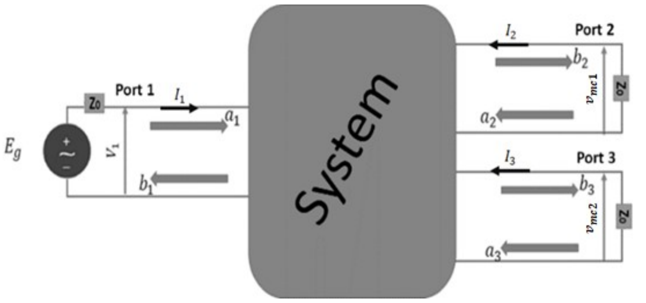

Fig. 2. Diagram of the measurement setup according to S-parameter theory

Common-mode (CM) voltages V_{mc1} & V_{mc2} can be written as follows [7]

$$\begin{cases} V_{mc1} = \frac{S_{21} E_g}{2} \\ V_{mc2} = \frac{S_{31} E_g}{2} \end{cases} \tag{3}$$

where E_g is the internal voltage source of port 1 related to the power accepted by the antenna P_{inj}

$$E_g = \sqrt{\frac{8 Z_0 P_{inj}}{1-|S_{11}|^2}} \tag{4}$$

According to the measurement configuration shown in Fig.1, the impedances used at the end of each conductor of the twisted pair are equal. Due to this symmetry, the induced common mode voltages V_{mc1} & V_{mc2} are similar and the differential signal related to the common mode disturbance $V_{md} = V_{mc1} - V_{mc2}$ is almost equal to zero. In a real system, these impedances are often unbalanced which induces an important conversion of the parasitic common mode signal to the differential mode (DM). Of course, the amplitude of this CM/DM conversion can have important effect on the possible perturbation of the useful signal due to the EM disturbance.

3) *Common mode rejection rate*

The CM/DM conversion at the input of the equipment connected at the end of the twisted pair under test can be represented by the common mode rejection ratio (CMRR) [8]. This parameter defines a relationship between the common mode and differential mode induced voltages and therefore quantifies the CM/DM conversion as shown in Fig.3. The CMRR (in dB) is defined as below

$$CMRR = 20\,log\left(\frac{V_{mc1}+V_{mc2}}{2\,V_{md}}\right) \tag{5}$$

4) *Induced voltage in differential mode*

By applying a given CMRR, we can calculate the differential voltage V_{md} induced at the end of the under-test twisted wire pair (shielded or unshielded) by the EM disturbance produced in the RC for a given power accepted by the antenna

$$V_{md} = \frac{V_{mc1}+V_{mc2}}{2\times 10^{\left(\frac{CMRR}{20}\right)}} \tag{6}$$

It is understood here that a high value of CMRR represents a good balance of the common mode impedances and therefore a low disturbance in the differential mode. The S-parameter theory makes it possible to calculate $V_{md}(f_p)$ obtained for each position of the mode stirrer and for any power accepted by the antenna or even according to equation (3) for any value of the average total electric field $\langle|E_T|\rangle$ in the RC. This reasoning is valid for any frequency f_p for which the S-parameters have been previously measured.

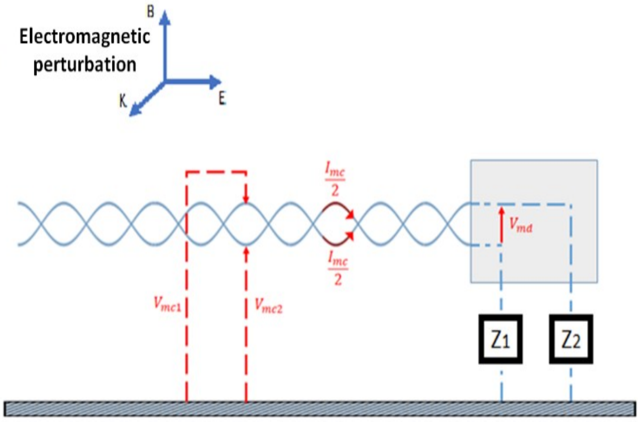

Fig. 3. Common mode rejection rate for a twisted pair

5) *Virtual test of signal integrity*

The last step of the method is the "virtual" verification of the quality of the transmitted signal in post-processing. To do this, the interfering sinusoidal signal at the frequency $V_{md}(f_p)$ is added to the “fictitious” useful signal in the time domain. The sinusoidal signal related to the perturbation is characterized by its peak amplitude A_p and its frequency f_p. We see here a parallel with the traditional radiated immunity test where the electromagnetic disturbance is generally carried out in CW (constant wave) mode, i.e. for a single disturbance frequency.

This operation being performed in post-processing is therefore applicable to any type of time-domain useful signal. Once the transmitted signal (i.e. the sum of the useful and the parasitic signal) is calculated, it can be directly compared with the undisturbed useful signal. The result of this comparison makes it possible to study the integrity of the transmitted signal through the EM disturbance generated in the RC, for each position of the mode stirrer and any considered frequency.

The analysis depends on the characteristics of the useful signal. It means that different metrics can be used to judge the quality of the transmitted signal. For instance, it can vary from a simple comparison between the amplitudes of the useful signal and the sinusoidal perturbation until a bit error rate study (at the price of course of a much more complex post-processing program).

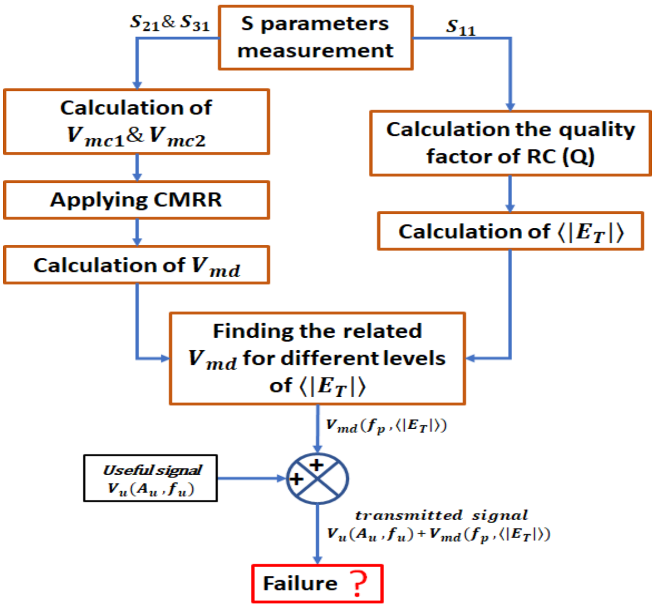

Fig. 4. Flowchart presenting the different steps of the method.

III. RESULTS ON A SQUARE USEFUL SIGNAL

A. *Calculation of* $\langle|E_T|\rangle$

To illustrate the method, a setup based on the experimental setup shown in Fig.1 has been installed in the RC of the XLIM laboratory having the following dimensions: 3.57 m long, 2.45 m wide and 2.46 m high corresponding to a volume of about 21.5 m^3. The used antenna is a log-periodic one covering a frequency band from 200 MHz to 2 GHz. In order to deal with many samples, the measurement was carried out for 360 positions of the mode stirrer (rotation of 1° between two successive positions). The measurements have been performed for two types of Ethernet cables of 1 m length. The first is an unshielded twisted pair (UTP) while the second cable is a double shielded twisted pair (F/STP) covered by an aluminum foil and a braided shielding also made of aluminum. After the measurement of the *S*-parameters, the RC quality factor shown in Fig. 5 has been calculated using (1).

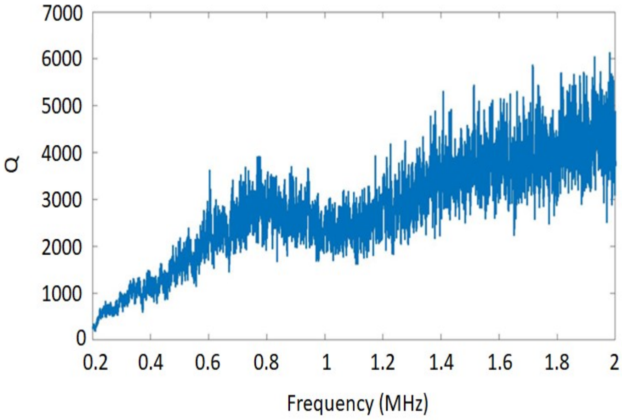

Fig. 5. Quality factor of the XLIM RC as a function of frequency

The RC XLIM is considered to be well stirred [2] for the frequencies above 400 MHz when left empty (no absorber inserted inside). Using equation (3), the needed P_{inj} to obtain $\langle|E_T|\rangle = 100\,V/m$ is calculated.

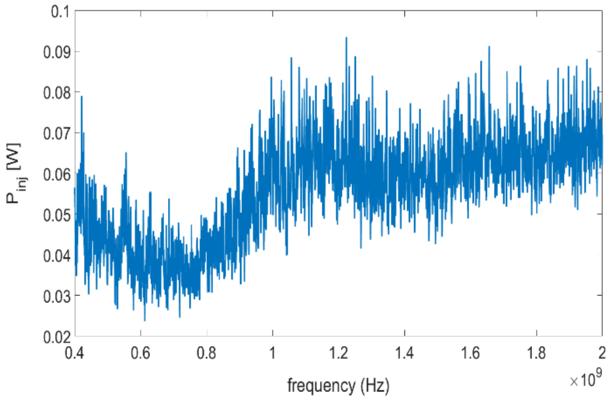

Fig. 6. Injected power P_{inj} (f) to get $\langle|E_T|\rangle$ = 100 V/m in the XLIM RC

B. *Calculation of* V_{md}

Figure 7 shows the differential voltage obtained for the unshielded cable for different values of the CMRR for a $\langle|E_T|\rangle = 100\,V/m$. As mentioned before, it is also important to note that V_{md}(f) can be calculated for each position of the mode stirrer.

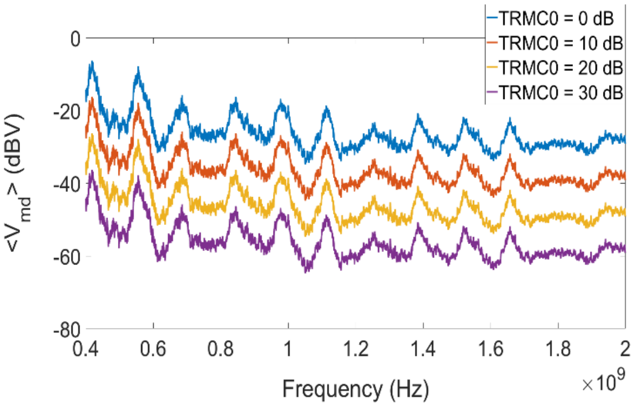

Fig. 7. Differential voltage induced on the unshielded cable for $\langle|E_T|\rangle = 100\,V/m$ dBm (for one mode stirrer position) and for different values of CMRR.

C. *Virtual signal integrity test*

The last step of the method is applied for the case of a square useful signal as shown in blue in Figure 8. This signal is defined in our work by a "high" state of value A_u and a "low" state of value $-A_u$ and a repetition frequency of f_u. Figure 8 also represents the parasitic signal defined by its peak amplitude A_p and its frequency f_p (with $f_p > f_u$ in the figure) as well as the total amplitude of the so-called "disturbed" signal representing the sum of the two signals. The "failure" of the communication is then defined for each position of the mode stirrer and each value of considered $\langle|E_T|\rangle$ in the following way: if during a "high" state of the useful signal, the transmitted signal is less than 0 at a given moment (and inversely for a low level), a failure in the signal integrity is considered. The "failure rate" is defined, for a given $\langle|E_T|\rangle$, as the number of mode stirrer positions for which the failure occurs divided by the total number of considered mode stirrer positions.

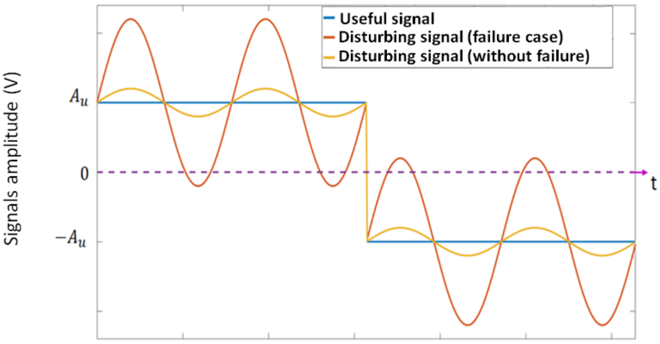

Fig. 8. Failure criterion in the case of a square useful signal.

Figure 9 shows the failure rate calculated for both cables as a function of the level of $\langle|E_T|\rangle$, fictitiously applied in the RC for a CMRR of 10 dB. The amplitude A_u of the considered useful signal is equal to 2V, its repetition frequency f_u is 100 MHz and the frequency of the disturbing signal f_p is 1 GHz.

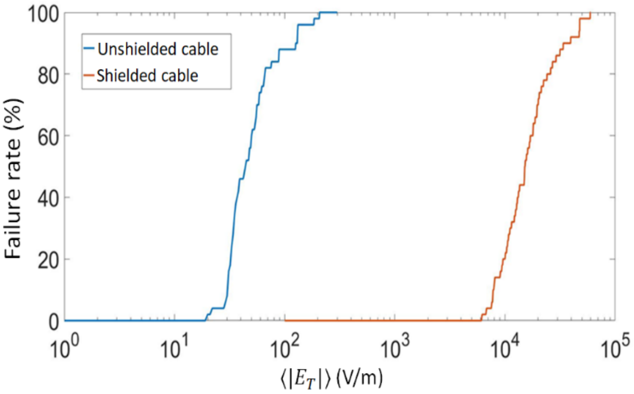

Fig. 9. Failure rate calculated for both cables (fu = 100 MHz, fp=1GHz, TRMC =10 dB, Au = 2 V) as a function of $\langle|E_T|\rangle$ generated in the RC.

In figure 9, the effect of the shielding on the signal integrity of the useful signal is clearly evidenced. A perfect transmission of the useful signal (i.e. a failure rate of 0 %) is obtained until $\langle|E_T|\rangle < 20$V/m and $\langle|E_T|\rangle < 5000$V/m for the unshielded and the shielded cable respectively.

IV. CONCLUSION

This paper presents an original method for virtually testing the integrity of information transmission on shielded and unshielded twisted pairs based on S-parameter measurements performed in an RC. Due to the S-parameter principle, the analysis performed in post-processing can be performed for any level of the mean total electric field present in the RC. Apart from the (rapid) S-parameter measurements, the rest of the method is carried out in post-processing, which makes it applicable for any type of digital communication.

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