Modeling of UIC Cables in Railway Systems for Their Use as Power Line Communication Channels

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Abstract – In this paper the authors investigate the possibility of using the preexisting electrical-control grid onboard trains as a wideband communication channel. In particular the attention is focused on a particular class of cables (UIC) present in most trains. A model and a set of simulations are presented in the paper, showing that the PLC technology can be used in this new environment.

Index Terms**:** PLC, channel modeling, railway systems and onboard communications.

I. INTRODUCTION

Signal transmission over power lines (Power Line Communications, PLC) is not a new technology, but it is gaining a growing interest for applications such as Internet or data services. The main reason for this new interest is that the PLC technology's infrastructure is based on the pre-existing electrical grid reaching each user in the locations where such applications are required; this is leading towards cost saving since there is no need for creating a new signal transmission network, and a LAN can be created (for instance in a group of offices, house, industry plant, etc.) by simply equipping the power grid with the proper couplers [1] – [6]. The use of new protocols allows a broadband transmission, hence the same technology is referred to as Broadband Power Line (BPL).

The accurate modeling of the PLC channel is of fundamental importance since the performance of the power grid as a communication channel depend on characteristics such as impulse response, frequency response, and noise.

The calculation of the system's impulse response is fundamental in analyzing the robustness of modulation schemes (usually Orthogonal Frequency Division Modulation (OFDM)) with regard to the channel performance: from the impulse response duration we can obtain the actual "guard interval" to avoid Inter Symbol Interference (ISI), and from the frequency response we can derive the upper and lower bounds for the attenuation of each sub-channel, thus selecting the more stable and better performing sub-channels [7] – [9].

Modern railway systems are provided with an increasing number of electronic equipment to be placed on each hauled stock. We are moving towards more comfortable trains with modern travelers demanding for enhanced services; from this fact comes the need for increasing the trip's quality (onboard entertainment, high speed internet connection, etc.) while travel security (additional information and video vigilance) is becoming relevant.

With the actual trend, this additional setup would require a new set of dedicated cables, which could have a high impact in the global cost of the train.

The use of PLC in vehicles is a new application that looks very promising. First studies regarding BPL in automotive vehicles and aircrafts show potential success of this technique ([10] – [16]) and are mainly dedicated to the analysis of the issues related to this new use of the power grid. Nevertheless PLC technology onboard trains is a new field of study, and the present paper is the first approach to this new application.

The paper is organized as follows: section II is dedicated to the PLC channel selection; section III to the modeling of the selected channel and section IV to the results obtained and to their evaluation.

II. CHANNEL SELECTION

The power grid of a train is a very complex systems, and is composed of several apparatuses and devices onboard the traction-stock and each hauling-stock. They include, besides the traction engines, a lighting system, heating, air conditioning, batteries,

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converters, and transformers. These devices are present (in different configurations, complexity, and redundancy) in all kind of trains. An additional characteristic of the power grid of trains is that, besides its complexity, it is highly affected by several noise sources, i.e. the electric arcs of the pantograph-catenary system, or disturbances created by motor drives.

In addition, different train types are characterized by a completely different power grid topology and characteristics. This is a very important point, since our main goal is to approach the problem of implementing a PLC system onboard trains in a general way, which means that the system could be setup onboard different kind of trains with little variations, i.e. with little hardware/software changes making it more versatile and practically convenient from an economic point of view.

For this reason the attention of the authors has been focused on the remote control and communication line, described in [17]. The most important characteristic of this line is that it is present in most trains, and the characteristics of the cables are unified by the above mentioned regulation. It is the only set of cables which crosses the whole train (traction-stock and hauling-stocks) and for safety reasons particular care is taken in order to avoid any possible disconnection. At the same time all the connectors (plugs and sockets) are unified according to international regulations, making an exact analysis of the electrical parameters possible.

As described in [17] most modern trains are equipped with UIC cables, being the main core of the remote control and communication line. In particular an 18 conductors flexible shielded cable (terminated by a plug) connects the stocks to one another and it is connected (inside each stock) to a connection box (present at both ends of each vehicle). Inside the vehicle the 18 conductors are split in two different cables: a 16 conductors and a two conductor cables, both shielded. The outline of these connections is reported in Fig. 1 while Fig. 2 shows the section of the 16 conductors cable with the cable numbering as explained in [17].

The 16 conductors have different roles in the train control, and they are divided in functional groups: each single group has one conductor serving as a reference and one or more conductors as signal line. Amongst the available functional groups the authors have chosen the one in charge of the doors opening and closure: it is composed of conductors 9, 10, 11, 12, 14, 15 and 16, with conductor 12 as common return. The reason for this choice is the following: among the different functional groups the ones carrying ac signals (in different frequency bands) have been excluded in order not to interfere with the OFDM signal and vice versa. Among the remaining groups characterized by DC signals, the peculiarity of the above mentioned group is that the signals it is carrying are DC pulses of maximum 2 sec duration.

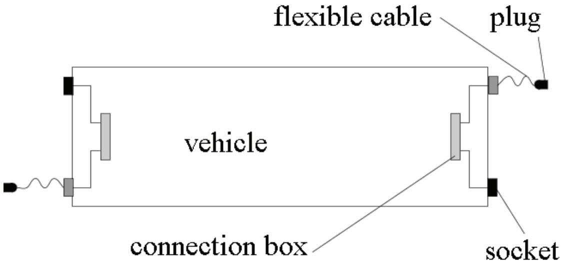

Fig. 1. Outline of the remote control line.

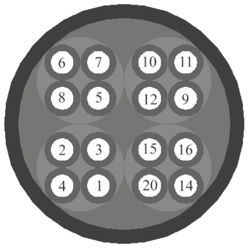

Fig. 2. Section of the 16 conductors cable.

Conductor number 12 will be used as a return and conductors number 10 or number 11 (dedicated to the switching on and off of the light signals “stop” and “go”) will be the one dedicated to the data transmission. The reason for this choice comes from the fact that any possible interference (even if not desired) caused by this additional use seems not to damage the proper operation of the light signals.

Even though a safety assessment is not within the aim of this paper it is worth mentioning that further studies shall be devoted to the verification that OFDM signals will not corrupt the ones which normally flow through selected and nearby conductors.

In the next section we will show the developed channel model together with the results of a preliminary set of measurements on a cable.

It is fundamental to underline that these result show eventual theoretical feasibility of the PLC implementation, but a thorough experimental measurement campaign is needed to assess the simulation results.

Section 4 is dedicated to the development of the channel model and to the analysis of its behaviour with respect to the transmission rate.

III. CHANNEL MODEL

The first step to be performed when modeling a multiconductor transmission line is to obtain its per unit length parameters. In this case a FEM model of the cable section (Fig. 2) has been implemented, obtaining the R, L, C and G matrices. In this case the frequency range typical of the OFDM protocol is between 1 and 30 MHz, for this reason the p.u.l. parameters have been calculated for 3 frequencies in the above mentioned range, and the frequency behavior has been modeled as described in [18]. The values of resistance, capacitance and inductance at a frequency of 15 MHz is here reported.

1.708E-10	-1.19E-11	-5.89E-11	-1.41E-11	-8.67E-12	-2.62E-11
-1.19E-11	1.596E-10	-6.27E-11	-1.81E-11	-4.57E-12	-5.27E-12
-5.89E-11	-6.27E-11	1.97E-10	-4.52E-11	-7.15E-12	-1.31E-11
-1.41E-11	-1.81E-11	-4.52E-11	1.690E-10	-2.39E-11	-6.30E-11
-8.67E-12	-4.57E-12	-7.15E-12	-2.39E-11	1.292E-10	-5.47E-11
-2.62E-11	-5.27E-12	-1.31E-11	-6.30E-11	-5.47E-11	1.701E-10

Capacitance Matrix of the cable (F/m)

0.78955	0.34807	0.4452	0.40162	0.35895	0.42051
0.34807	0.7809	0.43699	0.3835	0.32168	0.3502
0.4452	0.43699	0.89924	0.41954	0. 34653	0.39102
0.40162	0.3835	0.41954	0.98015	0.45056	0.53954
0.35895	0.32168	0.34653	0.45056	0.79845	0.4546
0.42051	0.3502	0.39102	0.53954	0.4546	0.86429

Resistance Matrix of the cable (Ω/m)

3.7412E-7	1.5297E-7	2.1868E-7	1.977E-7	1.7432E-7	2.064E-7
1.5297E-7	3.7545E-7	2.2166E-7	1.9614E-7	1.6279E-7	1.7617E-7
2.1868E-7	2.2166E-7	4.0733E-7	2.5111E-7	2.0524E-7	2.278E-7
1.977E-7	1.9614E-7	2.5111E-7	4.6352E-7	2.5752E-7	3.0605E-7
1.7432E-7	1.6279E-7	2.0524E-7	2.5752E-7	4.5657E-7	2.8878E-7
2.064E-7	1.7617E-7	2.278E-7	3.0605E-7	2.8878E-7	4.9198E-7

Inductance Matrix of the cable (H/m)

The simulated p.u.l. parameters have been compared to the values obtained by measurements operated on a 6m UIC cable provided by Trenitalia S.p.a. In particular the measurements have been performed on a couple of conductors whose distance was the least (i.e. 9-11 or 14-16). The experimental setup is shown in Figure 3, while the p.u.l. behavior in a range [0 30] MHz is shown in Figures 4 – 7, showing good agreement with the parameters obtained by the FEM simulation.

The relative error between measurements and simulations in the frequency range of interest is below 10%. Some small divergences are caused by the measurement system, but the global frequency behavior of the measured p.u.l. parameters is well reproduced by the FEM model. While the p.u.l. L, R and G have been both calculated and measured, the simple FEM model could not allow us to calculate the conductance (mainly because the dispersive properties of the insulating material composing the cable were not known); for this reason the value of G used in the channel simulations is taken directly from the measurements.

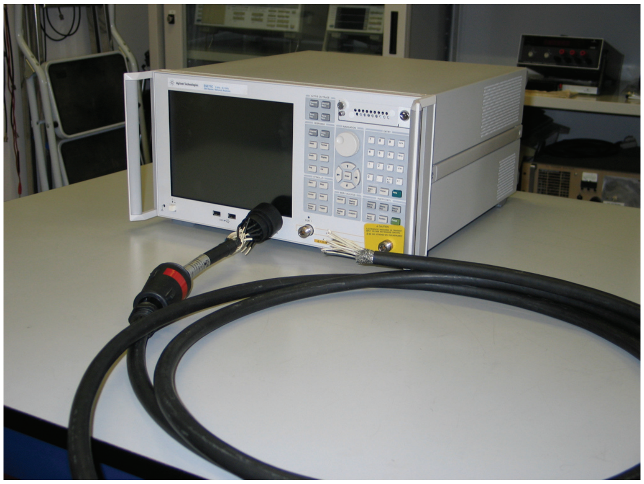

Fig.3. Experimental setup.

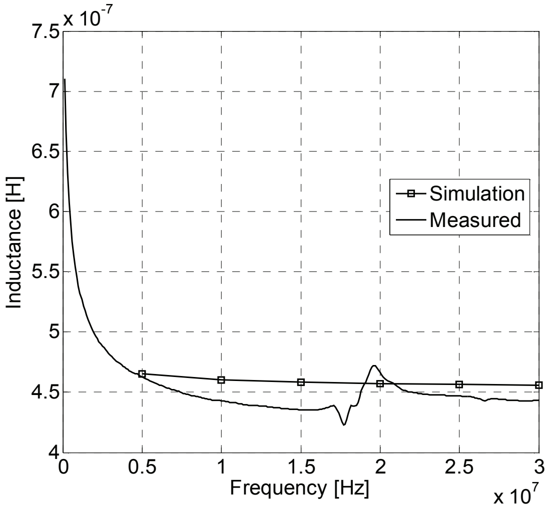

Fig.4. Measured and simulated inductance.

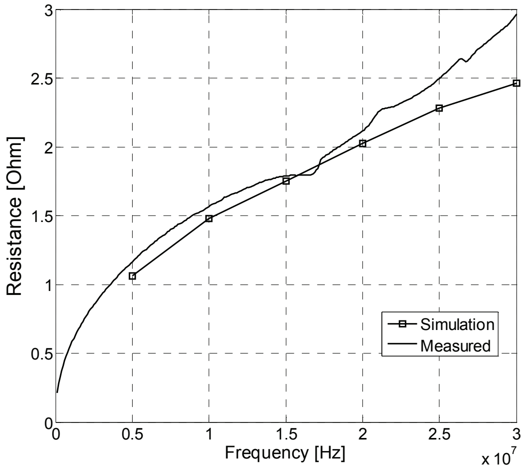

Fig. 5. Measured and simulated resistance.

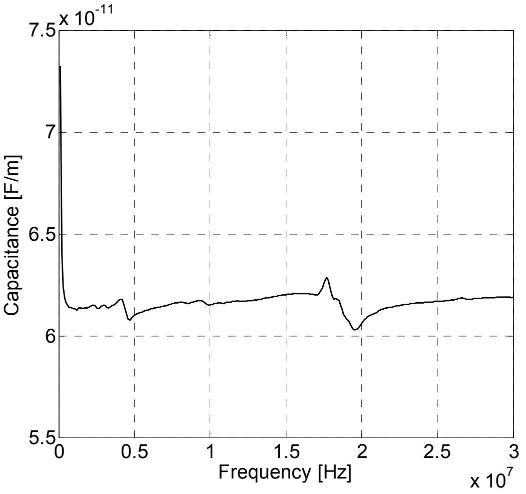

Fig. 6. Measured capacitance.

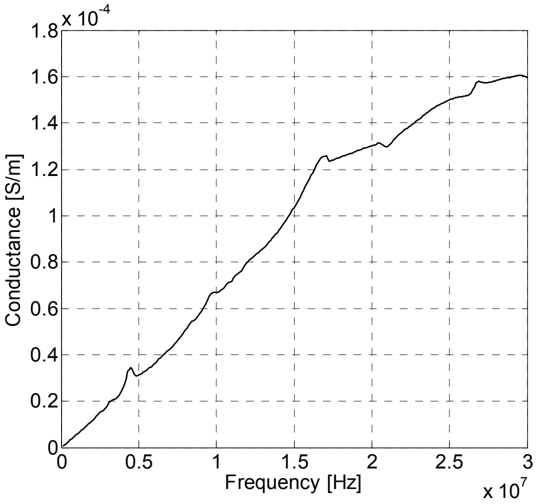

Fig. 7. Measured conductance.

The MTL inside each single stock can be described as in Fig. 7: conductors 9, 10, 11, 14, 15, 16 are carrying the signals (in particular, we are interested in the performances of conductor 10 in carrying the OFDM signals for PLC) while conductor 12 is the reference conductor.

The impedance between conductor 16 and 12 is not specified a priori, thus it is assumed to be comparable with that of relays operating door locks: according to [17] this value must be not lower than 1200 Ω. Although Figure 8 shows such impedances for conductor 16, all the conductors have derivations with the same resistance values. There is not a general topology for these parallel connections, so we have decided to place them at the beginning, at the end, and in the centre of the lines. As a matter of fact, their high value does not practically affect the channel's behavior, as it will be shown afterwards. Further work in this area will be to measure the input impedance of these relays, in order to have a more accurate modeling.

According to [17] conductors 9 to 15 carry pulses of amplitude between 18V and 33V (their nominal value is 24V) with a duration of $t \leq 2$ sec; for this reason the crosstalk between conductors 9 to 15 and conductor 16 is fundamental to verify its use as a PLC channel, since this is a noise which could limit the bandwidth of the OFDM signal, hence the channel's performance.

The lines are modeled according to [18], while in case there is uncertainty in the p.u.l. parameters value the problem can be approached according to [18] and [19].

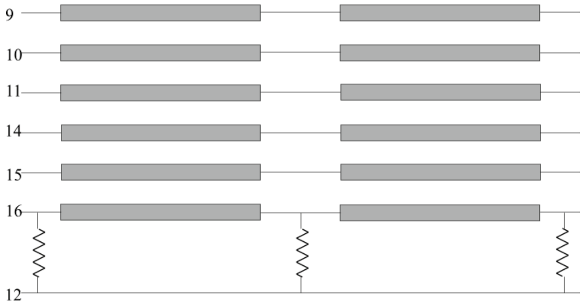

Fig. 8. MTL inside each stock.

The electrical length of the cable inside each stock is of l = 20m, plus 5m can be considered the length of the connection between the two coaches. A model of 6 hauled stocks has been considered (length = 150m) and the voltages have been calculated at the end of the first stock (length = 20 m, referred to as short path) and at the end of the last stock (145m, referred to as long path), respectively being the best and worst case in terms of transmission quality.

The outline of the implemented system is shown in Figure 9.

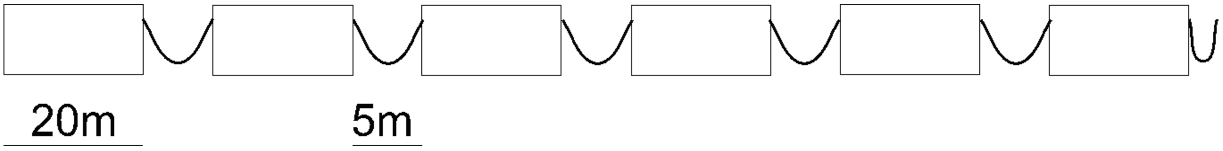

Fig. 9. Outline of the simulation

At the moment, the cable is terminated with an open circuit, but in order to optimize the communication performances a termination of 50 Ω can be set up. In fact both the situations have been simulated. As input signal, an impulse generator has been connected to conductor number 10, while a step input with amplitude of 24 V has been connected to the other conductors.

IV. SIMULATIONS RESULTS

A. Frequency responses of the direct channels

Figures 10 and 11 show the frequency responses of the first channel (short path) when the line at the end of the long path is matched (Fig. 4) and open (Fig. 5). It is evident that in the matched case the frequency response exhibits a flatter behavior, although in both cases strong fading is not present, resulting in a high-quality channel for multicarrier broadband communication in the frequency band 2-30 MHz. It can be assessed, at this point of the analysis, that the termination at the end of the line does not significantly influence the frequency response at intermediate receivers. When we move towards the end of the line, the effect of the unmatched termination increases, reaching a maximum for the last vehicle.

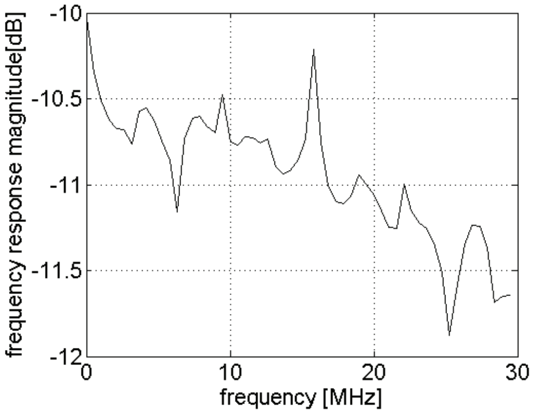

Fig. 10. Frequency response of the short path (matched).

Figures 12 and 13 show the frequency response of the second simulated channel (long path) respectively in the matched and non matched cases.

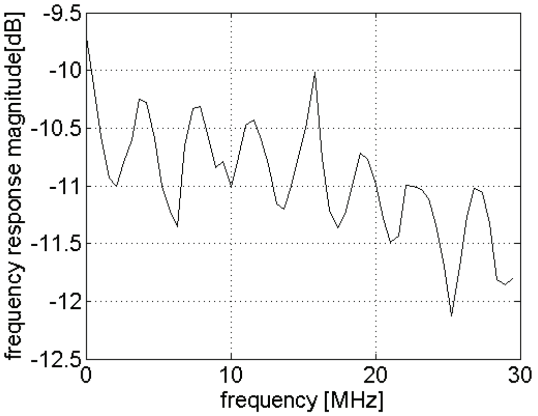

Fig. 11. Frequency response of the short path (non matched).

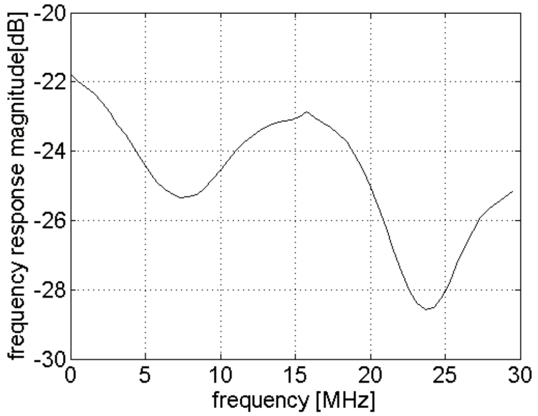

Fig. 12. Frequency response of the long path (matched).

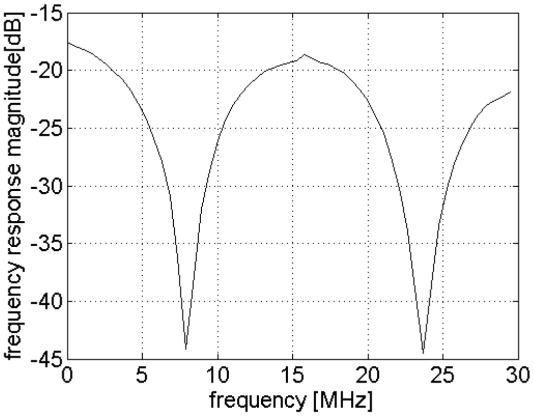

Fig. 13. Frequency response of the long path (non matched).

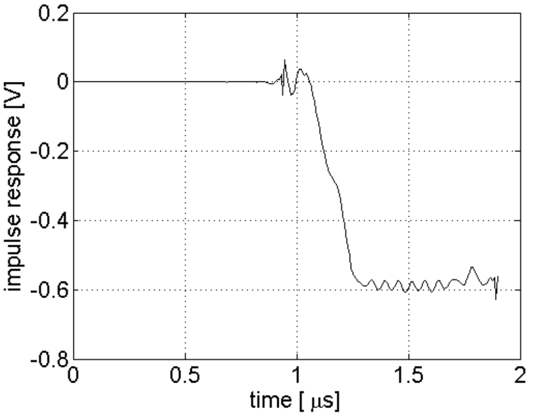

Fig. 14. Time response to the step signal (matched).

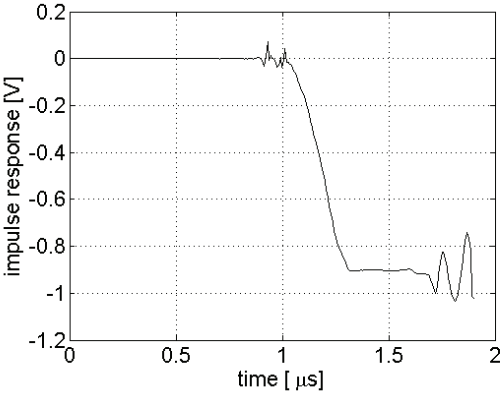

Fig. 15. Time response to the step signal (non matched).

We observe that the two situations are now rather different: the matched case behaves as a smooth channel with amplitudes between -15 and -25 dB, whereas if the line is open, there is more destructive interference which produces strong fading.

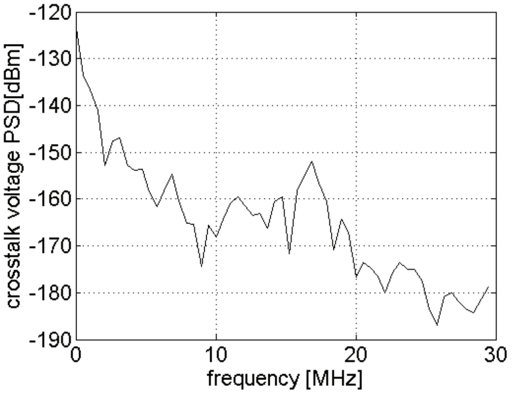

Fig. 16. Crosstalk PSD (matched).

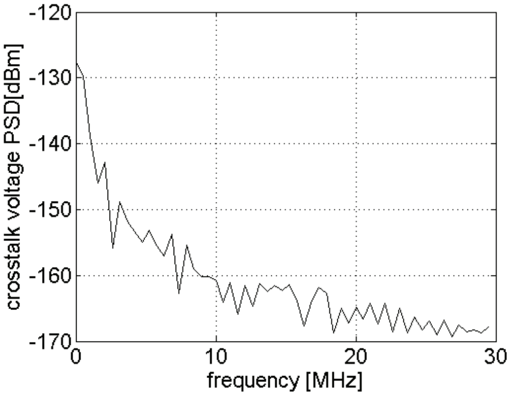

Fig. 17. Crosstalk PSD (non matched).

In particular the frequency response vanishes (values below -30dB) in two frequency ranges: from 7.5 MHz to 9MHz, and from 22MHz to 24.8 MHz. Transmitted data in the carriers inside these frequency intervals are likely to be lost. Hence, for the receiver to better exploit the channel, in the last car a matched line termination is recommended.

B. Crosstalk interference

The next figures are relative to the case of conductor number 11 excited by the 24V step signal, in order to evaluate its effect on the selected PLC channel: the crosstalk in this case is seen as a noise source. Figs. 14 and 15 show the computed crosstalk voltage present at the end of the long path in the cases of matched and open line termination respectively. In both cases there is a steady state produced by the constant voltage in conductor 1. The matched case reaches a steady state with a voltage offset of -0.6 V, while in the open case a steady state of -0.9V is observable. For an OFDM multicarrier communication an instantaneous variation of the DC component does not affect communication, since it is removed from the high pass filter at the receiver. By taking the power spectral density (PSD) of the received crosstalk signals we obtain Figures 16 and 17. The absolute power is expressed in dBm/Hz. In order to understand if this interference PSD can affect the communication we need to estimate the PSD of the received useful signal. Considering a transmitted power P_{TX} of the OFDM useful signal of -50 dBm/Hz equal for all frequencies, the received power $P_{RX}(\omega)$ can be obtained by the link budget equation:

$$P_{RX}(\omega) = P_{TX}(\omega) + W(\omega)$$

where $W(\omega)$ is the channel frequency attenuation expressed in dB, and absolute powers are expressed in dBm/Hz. Considering the frequency response of the matched channel in Figure 13, we take an average value of $W(\omega) \approx -20dB$, obtaining an average received useful power of $P_{RX}(\omega) \approx -70dBm/Hz$. A comparison of the power of the received useful signal with the power of the crosstalk interference signal in 16 and 17, we can conclude that this interference is 70 dB lower and there are not communication drawbacks.

Based on the link-budget equation and the previous result, the OFDM signal have a power of -50 dBm/Hz, that considering an occupied band of 30MHz gives a total transmitted power of 0.3Watt .We consider an OFDM signal with 256 carriers uniformly distributed in the frequency range from 117kHz to 30MHz. Figure 18 shows a $2\mu s$ window of the OFDM signal, which has been used as input voltage to conductor number 10.

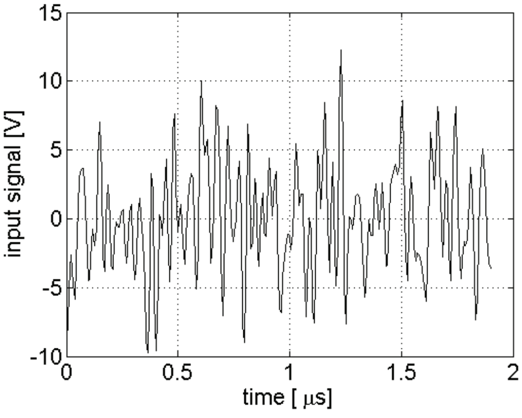

Fig. 18. Input OFDM signal.

Figures 19 and 20 show the crosstalk of the short and long path (only in the matched case), relative to the input shown in Figure 18.

The figures confirm that the effects of the data signal on the other conductors are negligible, practically being a low amplitude noise compared to the low frequency – high amplitude signals characteristics of their use.

Based on this preliminary analysis of the frequency response of the channel and the crosstalk effects the selected channel is found to be an appropriate medium for a digital transmission. To further characterize the transmission channel an analysis of the background noise and impulsive noise is necessary in order to establish the maximum theoretical bitrates attainable.

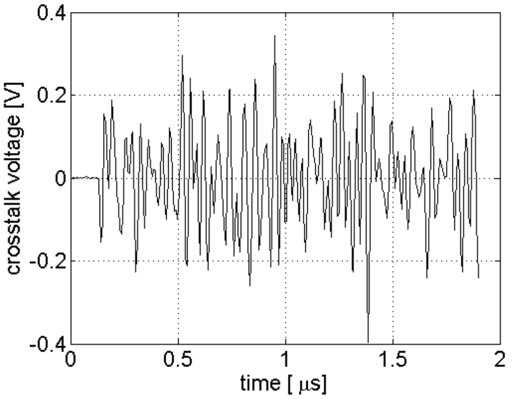

Fig. 19. Short path crosstalk, for OFDM signal.

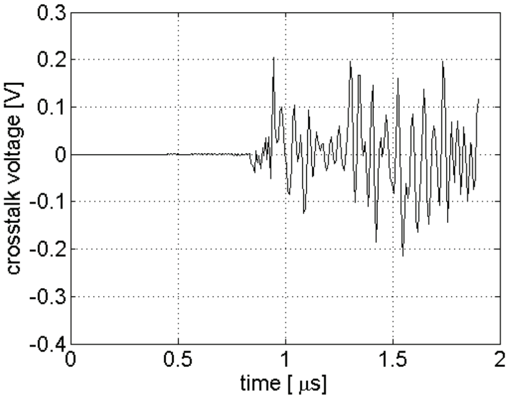

Fig. 20. Long path crosstalk, for OFDM signal.

V. CONCLUSIONS

The present paper shows the feasibility of implementing a PLC communication system onboard trains using part of the pre-existing grid. A PLC channel has been chosen among the different ones (selection based on functional issues) and an accurate model is here presented. The simulation results are encouraging, showing that the selected channel is characterized by good performances. In particular it seems to be appropriate for a high speed data communication system, where transmission rates of several MB/s could be reached.

Further work will be to perform a set of field tests to validate the presented results and to acquire some components characteristics which will lead to a more accurate channel model.

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