# In Vehicle Communication Networks : A Power Line Communication Study and Demonstrator for Infotainment Applications

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*Abstract*—**The paper deals with in-vehicle communication networks and the use of emerging Power Line Technology (PLC) for infotainment application. It appears that with the increase of Electronic Devices Unit (ECU) both for real time application and infotainment, there is a wire harness bottleneck. So, PLC seems to be a promising in-vehicle network for high data rates applications.After reviewing possible issues, in-vehicle PLC channels and noise measurements are presented. We discuss the Physical Layer (PHY layer) PLC system parameters based on these measurements. Finally, an embedded demonstrator is proposed in order to improve them in a real in-vehicle channel environment.**

***Keywords-Intra-vehicle communication; power line communication; impulsive noises; SDR.***

## I. INTRODUCTION

As the Electronic Control Unit (ECU) in vehicles has experienced an exponential demand in the last decades [1][2], the automotive industry has introduced dedicated buses as the Control Area Network (CAN) [5], Local Interconnect Network (LIN) [7],Flexray and Media Oriented Systems Transport(MOST) [7]. CAN and FlexRay have been designed for real-time delivery of messages. However, they do not support high data-rate applications.MOST is used for infotainment applications, and provides a bandwidth of about 50 Mbps. The last version increases the bandwidth up to 150 Mbps and offers a physical layer to implement Ethernet in vehicles. It supports both optical and electrical layers. It allows up to 15 stereo audio channels or MPEG1 channels.Although these networks reduce the amount of wires, they use specific wires and specific protocols. However, the use of the power distribution channels inside vehicles both for power and communication purposes is a promising alternative. It would answer the vehicle requirements namely, cost, decrease of the amount of wires and weight, and offer more flexibility to introduce new applications.

Taking into account both the In-Vehicle Infotainment (IVI) and X-by-wire (X means any mechanical system) requirements, we can observe the necessity to find a limited set of networks which answer to the growing of the multiple applications. These new networks may be able to dynamically optimize their parameters according to the loads on the network (that means active ECUs), the data rate needs (bandwidth sharing) and the state of the vehicle (motor ON/OFF, vehicle in motion, speed), etc. Furthermore, Vehicle to Vehicle (V2V)and Vehicle to Infrastructure (V2X)are currently in active development by automakers like the well-known BMW, Audi, and Volvo [19]. One idea is to propose a new communication protocol which will be compliant both for in vehicle requirements and V2X applications. Among alternatives to existing on-board networks, PLC seems attractive. Many studies are carried out on PLC and focus both on channels and noise in order to optimize the PHY layer and the MAC layer [3].Commercial solutions based on PLC for CAN are provided by Yamar Electronics Ltd. Their PLC-based product families provide maximal data rates of 1.3 Mbps and carrier frequencies in the 1.75 to 13 MHz range. However, they are not yet introduced in vehicles. The current PLC solutions presented by Ferreira et al. [3] show it is possible to achieve data rate more than 50 Mbps, which is consistent with video or audio applications. PLC can be applied also to critical control application. However, the automakers are still reluctant about the transformation of the well known protocols by this PLC solution.Currently, the infotainment area seems to be more open for PLC. In fact, more and more vehicles offer IVI systems and driving technologies, through MOST or wireless connection. The disadvantages of these solutions are the lack of flexibility and the necessary compatibility of devices.One idea is to be able to plug and play any devices offering anTransport Control Protocol/ Internet Protocol (TCP/IP)access, anywhere in the passenger cell of the vehicle. In indoor application, PLC is already used for multimedia application. Latchman et al. [4], the authors provide an overview of the development of the MAC and PHY layers. Repeating functions have been introduced to achieve higher data rate while using frequency bands above 30 MHz.PLC modems may answer theses new challenges, while maintaining bandwidth, data rate and multiplexing flexibility.

In order to introduce PLC in cars, it is necessary to know the channels and the possible scenarios. Section 2 will review previous vehicle networks studies, and focus on PLC. In order to propose PLC solution, it is necessary to study in-vehicle Direct Current (DC) channels to extract the main parameters for the PHY and MAC layers. Section 3 provides a description of the experimentations under in-

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vehicle DC electrical wires and the main results. Taking into account those in-vehicle measurements, the channel characteristics will allow us to define the best parameters for the signal processing and communication system, like the bandwidth, the modulation, the equalization. The practical approach is discussed in Section 4. In the next step, it seems to be interesting to test several algorithms under real channel while keeping algorithms flexibility. That is why we propose to study a fast prototypingsolution to perform this task using Software Defined Radio(SDR)principle. In this case, the PHY layer is developed in software thanks to Matlab or Labview tools. We used the flexible SDR platform USRP2 [17][18]developed by ETTUS and actually commercialized by National Instrument (NI). This demonstrator is presented in Section 5. Finally, we will conclude the paper in the last section.

## II. COMMUNICATION NETWORKS FOR VEHICLES

First of all, the introduction of communication networks was due to that the use of point-to-point communication links was not scalable with the increasing number of electronic components. The demand for efficient networking, including requirements on providing the physical medium (i.e., wires) for communication, has only increased with modern cars being high technology mechatronical systems. This is the main incentive for considering automotive PLC. The Society of Automotive Engineers (SAE) [20] defines four classes (A to D) of automotive communication networks based on transmission speed and applications. The two first classes use low-speed event triggered protocols for low data rate. High-speed real-time communication in Class C and Class D networks relies on high-speed event and time-triggered protocols, respectively.The latter are used for multimedia data, such as audio/video streaming, video games or cameras monitoring, and safety critical applications, such as, e.g., X-by-wire systems, which impose high requirements on availability of resources and reliability of communications.

If we consider these two classes and the reduction of the number of wires, technology originally developed for in-home PLC, namely HomePlug AV, and HD-PLC, seem to be attractive. During the last decades, many studies have been carried out on direct current (12/42 V) voltage for embedded application in vehicles (cars, aircraft) like in [5][6][7]. The results are very promising in that data rates of up to 10 Mbps could be achieved using an approximately 30 MHz bandwidth.Since the medium access control (MAC) protocol is based on the hybrid time-division multiple access (TDMA) and CSMA/CA of HomePlug AV and HD-PLC, it could support both class C and D networks.

Furthermore, Electric Vehicles (EV) may be considered. PLC in EVs has been studiedby Bassi et al. [14].Experiments of Guerrieni et al. [16] using commercial modems from Yamar [16] for PLC in an EV demonstrate reliable communication with data rates of about 1 Mbps.PLC has also been considered for communication between the EV and the charging infrastructure. The IEC 61851 standard defines two charging modes, which require a control pilot signal. Both narrowband and broadband PLC solutions have been proposed for EV to electric vehicle service equipment communication, e.g.,in SAE J2931/2-4 [21]. Recently, the ISO/IEC 15118-3 standard adopts the broadband HomePlug Green PHY as the mandatory PHY/MAC layer technology. The narrowband G3-PLC (ITU-T G.9955) is specified as an optional mode [8].

Among the other solutions for high data rates, we can mention the optical fiber transmission and optical wireless communication.Considering the fiber, this solution has been chosen for the MOST protocol using plastic fiber, from 25 Mbps up to 1 Gbps. The MOST technology is alsoconsidered to be the transmission support for the advanced Driver Assistance Systems (ADAS). One attractive solution is to propose a new modulation scheme like multi-carriers over this channel. A simple single carrier modulation is used but does not exploit all the bandwidth offered by the fiber.On the other hand, Visible Light Communication (VLC) technologycan be used as a medium for data transmission, both for in-vehicle and V2X communication, while achieving high data rates as compared to conventional wireless technologies like for example Wi-Fi or Wimax. In the early 2000s, researches started using visible light from LEDs as the medium for communication. VLC communication can achieve about 800Mbps data rate for short range communications. Researchconductedby Deok-Rae Kim et al. [9] demonstrates the possibility of combining VLC and CAN protocol. Furthermore, we can notice the studies on using Orthogonal Frequency Division Multiplex (OFDM) techniques over these two channels [10]. On restriction of VLC solution is the need to have light and preferred line of sight.We will now discuss about the in-vehicle power lines.

## III. CHANNEL MEASUREMENTS

Characterization of PLC channels has been reported according to two major scenarios on four vehicles: front to rear, front to front. These configurations represent possible scenarios for infotainment applications. The measurement setup is presented in detail by Tanguy and Nouvel[7]and is represented in Figure 1. The reference points [A..I] represent both the communication and measurement nodes and a channel between point X to Y point is called XY path. The frequency range goes from DCup to 50 MHz.

Taking into account all the measurements, we have observed an insertion loss of about -15 dB up to -36 dB in the considered band. The maximal attenuation occurs with the longest past GF. The coherence bandwidth $BC_{0.9}$ (90% of the maximum sub-carriers autocorrelation) is given from the autocorrelation of the channel frequency obtained with different paths,as proposed Vallejo-Mora et al. [11].

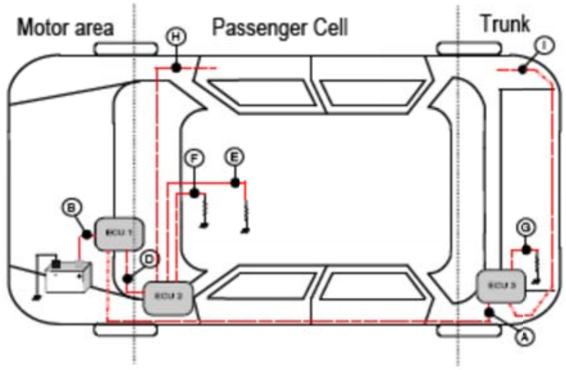


Figure 1.In vehicle test-bed for channel and noise measurements

The channel frequency response H(f) depends of both the sources and loads and is correlated with the transfer function S21 by the approximated relation:

$$H(f) \approx S_{21} \tag{1}$$

As presented in [13], the mean $BC_{0.9}$is greater than 500 KHz and can reach 2 MHz.Furthermore, we have observed its value is not correlated with the path's length. For example, $BC_{0.9}$values are respectively equal to 533 KHz and 4.7 MHz for paths GF (≅ the longest path) on Peugeot 407SW and Renault Laguna vehicles and equal to 2 MHz and 744 KHz for path HD (≅ the shortest path) on the 407 SW and Laguna vehicles.

Additionally, the Root Mean Square(RMS) delay spread is calculated as defined by Ferreira [3]andTlich[13]. In order to define the maximum delay spread a threshold of -30dB has been chosen. If we compute the cumulative density function of the RMS delay, we can observe that 90 % of the channel measurements have a $\tau_{RMS}$ delay spread lower than 210 ns with a smallest value of about 50 ns.

If we compare our results with the results obtained in indoor [11], $BC_{0.9}$ in vehicles is as twice as large as those obtained in indoor; the mean $BC_{0.9}$ is of the order of 291.9 KHz in indoor. Keeping the same transmission bandwidth, one can suggest the sub-channel spacing can be reduced. In the case of OFDM technique used, the FFT size may be reduced and the OFDM symbol duration will be shorter. With regard to delay spread, the delay spread obtained in vehicles (maximum value of 242 ns) is two times shorter than the mean value in indoor (0.413 µs). This will allow us to reduce the Cyclic Prefix (CP) length and therefore increase the data rate. These initial results confirm thatthe PLC communication parameters defined for indoor must be optimized for in-vehicle PLC.

## IV. PHY PLC PARAMETERS

### A. PLC Transmitted signal

In our study, Orthogonal Frequency Division Multiplexing (OFDM) [14] technique has been adopted as for indoor PLC, thanks to its high frequency diversity. OFDM modulation can be realized through the IFFT/FFT processing block to which the original stream is applied. Several complementary operations are achieved to the information bits before they are submitted to the IFFT processing. As presented in Section 2, the in-vehicle channels are frequency selective, noisy and multi paths will affect the transmission. For these reasons, OFDM is a good candidate as it divides the bandwidth in flat sub-channels. This solution is applied in other wired or wireless systems and is now well known. The transmitted OFDM waveform can be expressed as:

$$s(t) = \frac{1}{\sqrt{N_p}} \sum_{m=0}^{N_p-1} R_{eal} \left\{ c_m \prod(t) e^{2j\pi F_m t} \right\} \tag{2}$$

With NFFT the FFT size, Np= NFFT /2 , $c_m$ the complex symbol on sub-carrier $F_m$. The sub-carrier spacing Δf is defined as 1/TOFDM with TOFDM the OFDM symbol duration. During the first experimentation, the OFDM parameters are based on indoor PLC ones like HPAV and HD-PLC [15]. Those standards have been applied in vehicles to measure data throughput on DC channels [16]. The first results demonstrate the feasibility of PLC, and allow about 25 Mbps/s data transmission.

In order to be compliant with vehicle electromagnetic compatibility, we adopt a constant transmit Power Signal Density (PSD) of -60 dBm/Hz in the [4-30] MHz range and 0dBm outside. The additive white gaussian noise has a PSD of -110dBm/Hz. We choose a sub-carrier spacing of 24.4 KHz and a sampling rate of 75 MHz. A bit loading algorithm with a maximum of 10 bits per hertz is accomplished. For the channel, we have considered the channel's measurements, as described in Section 2.

Taking into account those default values, two parameters at the PHY layer are studied and optimized, namely, the guard interval CP and the FFT size.

### B. PLC optimization

Two parameters have been considered: the CP length and the FFT length, which impact the capacity of transmission given by the equation :

$$R_{OFDM} = \frac{N_{FFT}}{N_{FFT+CP}} \Delta f \left( \sum_{m=0}^{N-1} \log_2 \left( 1 + \frac{|H_m|^2 \sigma^2}{\Gamma(\sigma_n^2 + N_{ISI+ICI})} \right) \right) \tag{3}$$

with σthe signal power, $\sigma_n$the noise power, $H_m$ the channel coefficient at frequency m, Γ the margin gain for a BER of $10^{-3}$, N the number of used sub-carriers (for example 1148 tones with a FFT size of 3072). The interferences $N_{ISI+ICI}$ are assumed first null. Considering a SNR of 40dB and a BER of $10^{-3}$, we have noticed the capacity achieves a maximum of 500 Mbps/s with a CP of 200 ns (15 samples), 186 (14 samples) and 133 ns (10 samples) respectively for paths GF, GH and HD. The higher the channel attenuation is, the higher the value for CP is that maximizes capacity as for high SNR the performances are MOST driven by interference mitigated by long CP.

Then it is possible to combine the CP length adaptation with bit loading algorithm [9], while keeping 1148 used tones. Three different engine states are considered as previously discussed. The theoretical data rate achieved combining the CP optimisation and bit loading is in the range [100 – 200]Mbps. It has been observed the data rate decreases when the engine is turn on, except for the short front paths HD and FD. These results are closed to the measurements carried out by Degardin et al. [6]. These comparisons between measurements and simulations demonstrate the accuracy of our model.

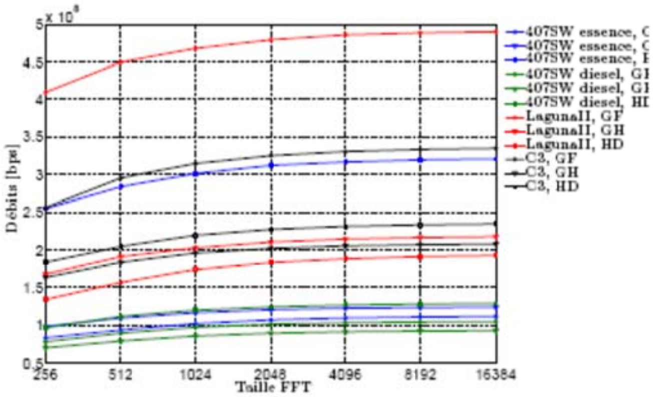


Figure 2.Data rate according FFT size.

The second parameter, the FFT size,has been consideredfor the same scenarios. Taking the $BC_{0.9}$we have obtained, it is obvious the FFT size may be reduced. Four FFT sizes, from 3072/1536 used ($\Delta f$ = 24,4 KHz<$BC_{0.9}$) down to 128/64 used ($\Delta f$ = 585 KHz<$BC_{0.9}$) tones are rather interesting. Figure2 gives the data rate we can achieve using those different FFT sizes on different vehicles. The optimal CP is respectively equal to 14 and 50 samples for FFT= 128 and FFT=256, 1024, 3072.

We can observe that when the FFT size increases (FFT > 1024), the ratio ($N_{FFT}/(N_{FFT}+CP)$) is closed to 1, the data rate tends toward a fixed value. One can conclude it is not necessary to increase the FFT size to increase the data rate. If we consider a BER of $10^{-3}$, a SNR of 35 dB is necessary for all the FFT sizes while keeping the sub-carrier spacing lower than the $BC_{0.9}$.

Following this system communication analysis, it maybe necessary to integrate these solutions in an embedded network. A demonstrator using the parameters will be presented in next section.

## V. VEHICLE POWER LINE SDR PLATFORM

In our vehicular demonstrator, Software Defined Radio approach can be considered as a “wired” communication system, where some of its functional components, such as modulations, equalization, etc., will be implemented in software. This makes it possible to configure the signal according to the requirements of the application and the characteristics of the communication channel (wired or wireless). The software generated signal, thanks to tools like Matlab [21] or Labview [22], combined with the GNU-Radio user interface and according to the parameters defined previously, is then applied to an USRP platform. The platform is detailed in [17]. Next part will review our Vehicle PLC (VPLC) demonstrator using this approach.

### A. VLC demonstrator

The demonstrator, named VPLC platform, is based on USRP2 boards [19] combined with daughter boards and presented in Figure 3. Using these daughter boards, the possible operation frequency range is very modular (from DC up to 5.9 GHz). The mother board includes ADC, DAC, a FPGA (Xilinx Spartan XC3S2000) and a Gigabit-Ethernet interface with the PC. The two slots of the board are for the front-end daughter boards. The 14-bit ADC and the two 16-bit DAC of the daughter board are independent and can work up to 100 M samples per second. To interface with the DC lines, we use the LFTX and LFRX cards as they allow transmitting and receiving signal from DC up to 30 MHz. These daughter boards include differential amplifiers and low pass filters for antialiasing. The outputs of the platform are linked to the DC lines through a lower band filter and transformer for better isolation.

### B. Results

The USRP2 TX and RX boards are arranged in the vehicle according to Figure 1 at points G, F, H and D. We will focus on link GF. In Figure4, one can observe the spectrum of the LFTX daughterboard output with a DSP of -80dBm/Hz. In this figure, only the bandwidth [2-12.5] MHz is used; but it is possible to transmit up to 25 MHz. We can observe that there are no notches compared to HomePlug AV standard as we do not have to consider the same electromagnetic constraints. In Figure 5, we observe the received spectrum, through the longest GF path. The signal is affected by the channel and not flat.

Taking into account a referred bit error rate of $10^{-3}$ and a transmitted power of -80dBm/Hz, we can achieve a mean data rate of about 30 Mbps when the motor is OFF and 7 Mbps when it is ON. This lower result is caused by the lowest SNR when the motor is ON (lower than 5 dB). When we modify the CP, we obtain a little variation according to its length. We respectively obtain 33 Mbps and 30 Mbps with CP=60 and CP=139. If we analyse the best HD path, this last one achieves a mean data rate of 70 Mbps and no errors are detected during the two scenarios. These data rates are compliant with infotainment applications in-vehicle transmission. Furthermore, the PHY layer parameters can be applied for wireless V2X transmission, allowing nearly seamless transmission between in-vehicle and out-vehicle transmission.

### C. *Video transmission/ MAC layer*

In order to transmit video or image file, a simple MAC layer has been defined. The stream or file is divided in payloads blocks, called Packet Data Unit (PDU), of 512 up to 2048 bytes. For each PDU, we add a two bytes preamble, a header and a cyclic redundancy code. These PDUs are then inserted in OFDM symbols. One OFDM symbol can include more than one PDU and similary one PDU can be spread over two OFDM symbols. The PHY parameters are summarized in Table I.

With such MAC and PHY layers, it is possible to achieve up to nearly 70 Mbps for the HD path and about 25 Mbps for the longest path GH. The data rate is a bit lower than when we use random bits (Section B). The results show optimisations need to be carried out, as the source and channel coding, the MAC layer. However, it is still large enough for infotainment application.

The results are also limited by the platform as the transmit and received samples are 16 bits length with a maximum 25 M samples /s over the Ethernet link between the laptop and the USRP2 board.

TABLE I. PHY PARAMETERS

| | |
|---|---|
| Bandwidth | [2-12]MHz |
| FFT size/used sub-carriers | 1024/412 |
| CP length | 15 samples |
| Mapping ( for eahc sub-channel) | BPSK to 1024 QAM |
| Sampling rate | 25Msamples/s |

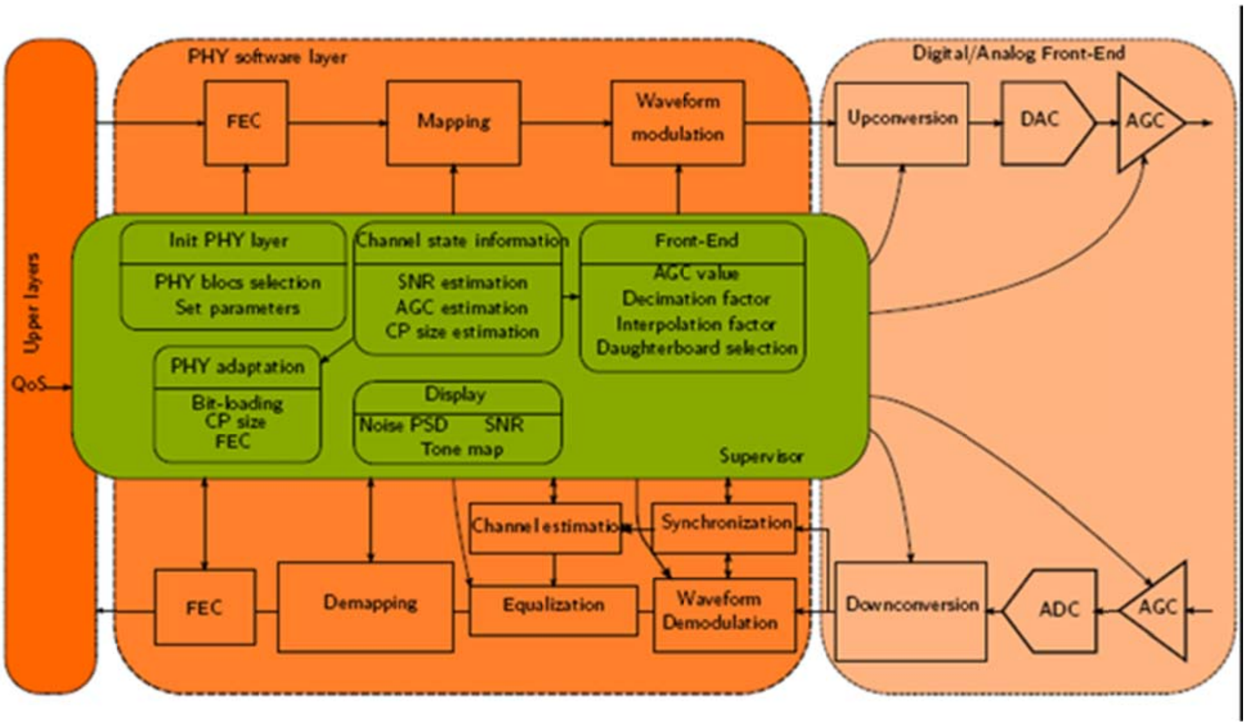


Figure 3.VPLC platform.

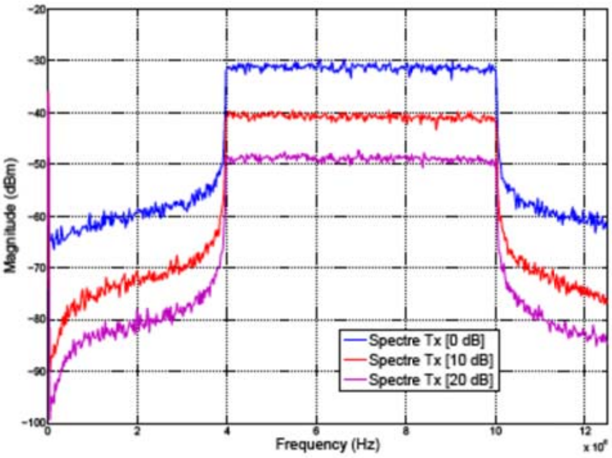


Figure 4.PLC spectrum– TX output, with different attenuations.

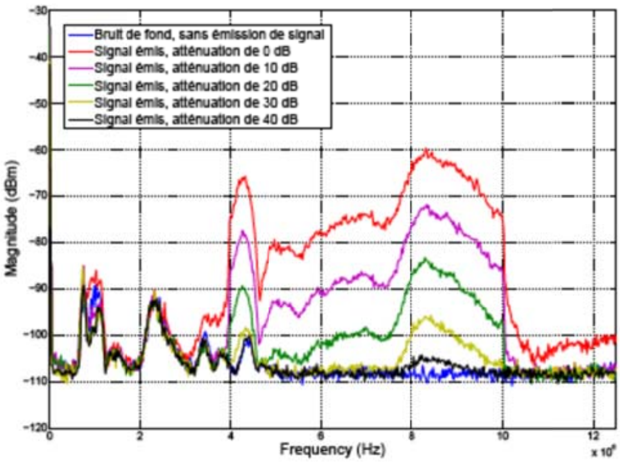


Figure 5.PLC spectrum – RX spectrum, longest path GF, with different attenuation.

## VI. CONCLUSION AND FUTURE WORK

In this paper, a PLC communication system has been presented in order to reduce the amount of wiring while offering high data rate for multimedia and infotainment applications.The channel measurements show that OFDM may be applicable, resulting in a good spectral efficiency and high data rate transmission.We have optimized the prefix cyclic length and the FFT sizeof theOFDM signal by taking into account the channel measurements. In order to optimize the network layers, the proposed demonstrator allows us to explore various configurations by adjusting parameters to fully meet expected system requirements. The work in progress focuses on the source coding, the MAC layer and multiple access, using both frequency division multiplexing and time sharing.The objectives are to find the better fit between the PDU and OFDM symbol to achieve a higher data rate.

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