

POWER LINE COMMUNICATION, OVERVIEW OF STANDARDS AND APPLICATIONS

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Abstract – In recent years, power line communications (PLCs) become to grow in importance due to power line diffusion and new robust communication protocols. In this paper, an overview of PLC is presented, including the advantages and disadvantages provided by different transmission protocols and related signal modulations. The state of the art in this field is discussed, focusing the attention on G3 and Prime Alliance standards. The main results obtained during the on field application of a PLC prototype are presented and discussed, underlining different modulation schemes in order to identify the most performant configuration.

Keywords: Power line communication, PLC, G3, Prime, Alliance.

1. INTRODUCTION

The power distribution network is always used to provide electricity to various customers. In addition to this, in the past it was also used for communications, for example in the railway sector. In recent years the idea of exploiting this structure also to allow access to private data has become increasingly marked. The communication between devices via power supply line introduces the concept of Power Line Communications (PLCs). This approach provides for data transmission on high frequency bands (for example a few tens of kHz) compared to the power supply frequency of 50 Hz (or 60 Hz).

The transmission of data on a power line is made difficult by several factors, such as the:

- attenuation at frequencies of interest;
- noise;
- interference from electronic devices connected to the system;
- channel variability in both time and frequency [1].

Nevertheless, this type of structure also presents some strengths which are very important for its adoption in telecommunications:

- the network is already constructed and spread throughout the world, so it is easier to reach customers;
- the possibility to use the same channel to provide both electricity and data to users [2].

The PLC can be divided into three different classes:

- **Ultra Narrowband (UNB):** this type of technology works with a very low data rate (about 100 bps) in the field of Ultra Low Frequency (0.3-3 kHz) or at the top of the Super Low Frequency (30-300 Hz). Very long distances, even exceeding 150 km, can be reached. The UNB-PLC transmissions are already "mature", and implemented by at least two decades, but unfortunately they adopt proprietary technologies.
- **Narrowband (NB):** a standard that operate in the frequency bands VLF/LF/MF (3-500 kHz). This range includes the European CENELEC band (3-148.5 kHz), the American FCC band (10-490 kHz), the Japanese ARIB band (10-450 kHz) and the Chinese band (3-500 kHz). The NB-PLC can be further divided between:
 1. **Low Data Rate (LDR):** single-carrier technology with capacity data rate of a few kbps.
 2. **High Data Rate (HDR):** multicarrier technology capable of data rates ranging from tens of kbps to 500 kbps.
- **Broadband (BB):** this technology operates at frequencies of HF/VHF (1.8-250 MHz) with a data rate range from a few Mbps to several hundred Mbps.

Considering the NB, in different regions of the world there are different allocations of the frequency band. The main organizations that regulate the use of the frequency bands are:

CENELEC: European Committee for Electrotechnical Standardization;

ARIB: Association of Radio Industries and Businesses;

EPRI: Electric Power Research Institute;

FCC: Federal Communications Commission.

Table 2.1 shows the frequencies made available for NB-PLC by these organizations.

A very popular PLC technology around the world and also in Italy is that based on the LonWorks protocol, now also ISO 14908-1-2-3-4. The energy meters installed by the electrical energy distributing company (Enel Distribuzione) is based on this protocol. The operator in this way is able to remotely read the electricity consumptions and to implement changes in the hourly rate.

Table 1. Available frequencies for narrow band

REGION	ORGANIZATION	FREQUENCY BAND (kHz)
EUROPE	CENELEC	3-95
		95-125
		125-140
		140-148.5
JAPAN	ARIB	10-450
CHINA	EPRI	3-90
		3-500
USA	FCC	10-490

The Broadband PLC (BB-PLC) was initially used for Internet applications, and then move to the field of Home Area Network (HAN).

Early research on Internet applications with BB-PLC began in Europe on behalf of Nortel and Norweb Communications, Siemens and Ascom in the late '90s, but without obtaining satisfactory results.

Only in the last 15 years several companies have been working in this area, including HomePlug Powerline Alliance (HomePlug), Universal Powerline Association (UPA), High Definition Power Line Communication (HD-PLC) Alliance, and The HomeGrid Forum, achieving data rates at the physical level increasing, from 14 Mbps to 85 Mbps, up to 200 Mbps.

2. BASIC CONCEPTS

The principle which is the basis of the system is that of carrier waves. A typical scheme of a PLC modem is shown in figure 1. At the transmitter it combines the low-frequency voltage wave (50-60 Hz) with modulated higher frequency data signals. Signals at different frequencies are admitted on the same cable, and separated with appropriate filters by the receiver.

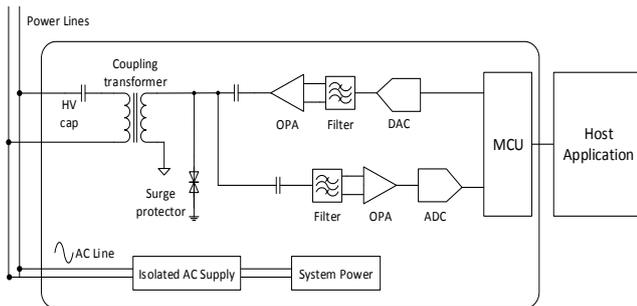


Fig. 1. Schematic block of a typical PLC modem

A substantial step forward was made with the application of sophisticated algorithms of signal modulation: data signal is encoded with a modulation that assigns different frequencies to the different subcarriers that convey information relating to medium / high frequency.

These two types of signals are separated by filters with the technique of phasing, that recognizes the number of subcarriers according to the frequency. The modulation scheme requires particular attention in order to maximize the number of channels and to ensure strong noise immunity. Below we analyze the possible schemes considered for the PLC channel, which are shown in Fig. 2.

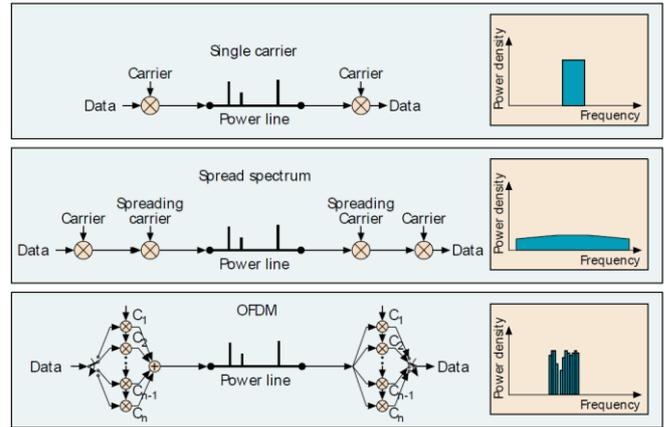


Fig. 2. Transmission methods for Power Line Communication.

2.1. Single Carrier Modulation

For low cost and low data rate applications the Single-Carrier Modulations (SCMs) appears to be a good solution. These are the most basic modulations, based on the use of a single principal frequency f_0 . The information is conveyed through the carrier variation of phase, frequency, or amplitude. The main modulation techniques are four: BPSK (Binary Phase-Shift Keying), QPSK (Quadrature Phase-Shift Keying), DPSK (Differential Phase-Shift Keying) and QAM (Quadrature Amplitude Modulation).

BPSK modulation is the simplest form of PSK. Modulation is achieved by varying the phase of the sinusoidal basis function. Depending on the data bit to be transmitted, the sinusoidal phase is modulated obtaining two different waves separated of 180° . This choice makes this modulation very robust, since a high level of noise or distortion is required to produce a wrong demodulated bit. The ability to modulate only 1 bit (symbol) per cycle makes BPSK unsuitable for application with high bit-rate, furthermore in the presence of a phase shift introduced by the channel, the demodulator is unable to define the right bit value.

QPSK modulation uses four phases and encodes two bits for symbol with Gray coding to minimize the BER (Bit Error Rate). This modulation can be used to double the data rate, compared to that of the BPSK, maintaining the same band, or to maintain the same data rate but with the band halved, in the latter case the BER remains the same. Since the maximum bandwidth available is very often already assigned, the advantage compared to the BPSK modulation is in the fact of being able to transmit with a data rate equal to double bandwidth and BER. The disadvantage would be the greater complexity of both transmitter and receiver, even if with modern modems costs are still limited, however also in this case there are problems of phase ambiguity in the reception, so often it's better to use the differential version. In Fig. 3 a comparison of BER curves for the phase modulations is shown.

DPSK version is used to solve the problems of phase ambiguity of the modulations earlier, that can occur if the constellation is rotated by some effects in the channel through which the signal passes. In this system, the demodulator determines the changes in the phase of received signal rather than in the phase relative to a reference wave. In this way the demodulator does not require a copy of the reference signal to determine the exact phase (non-coherent

scheme). In DQPSK the phase variations are 0° , 90° , 180° and -90° corresponding to the symbols 00, 01, 11, 10. As a disadvantage, with this modulation error rate is doubled compared to BPSK.

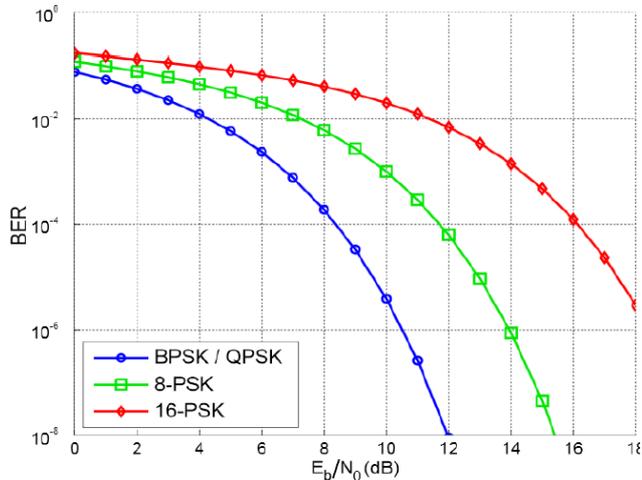


Fig. 3. Comparison of BER curves for phase modulations

QAM transmits digital data by changing the amplitude of two carrier waves, usually sinusoids shifted in phase by 90° . The resultant output consists of both amplitude and phase variations. In view of the fact that both amplitude and phase variations are present QAM may also be considered as a fusion of both amplitude and phase modulation. The advantage that is achieved is to have high spectral efficiency by appropriately dimensioning the size of the constellation, limited by both channel noise and nonlinearity. QAM is able to carry higher data rates than ordinary amplitude modulated schemes and phase modulated schemes, even if with higher order constellations, it is susceptible to noise and corruption.

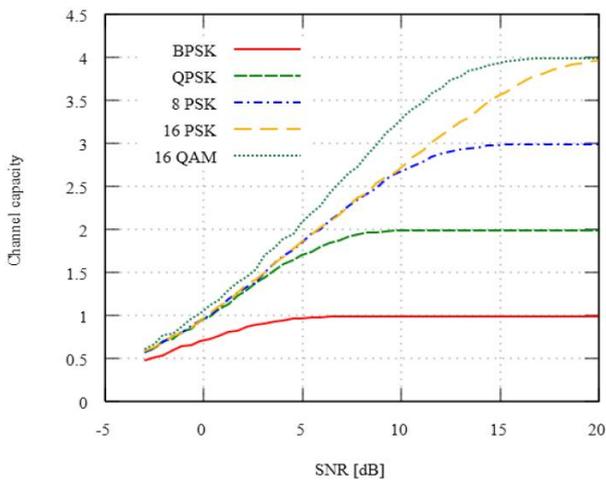


Fig. 4. Comparison between modulation channel capacity

2.2. Spread Spectrum Modulation

In the Spread Spectrum Technique (SST) a signal, generated in a certain band, is transmitted in the frequency domain on a much wider band. The main advantage is a better resistance to interference and noise, very important for PLC. A further advantage of this modulation is the low power spectral density of transmitted signals.

In a system of this type a single carrier frequency f_0 is used and a different transmission code $p_i(t)$, orthogonal to any other assigned code, is assigned to any system linked to the grid. Each new participant brings an increase in the background noise; in this way, more participants become active, more increases the probability of disorders.

Using the Code-Division Multiple Access (CDMA) technique, it is possible to transmit several sets of data independently on the same carrier and then reconstitute them at the receiver without mutual interference. In this way a base station can communicate with several mobiles on a single channel. The bandwidth of the CDMA spread spectrum signal will be much wider than the original data stream. The system efficiency can be quantified by the Processing Gain (PG), defined as the ratio between the spread transmission bandwidth and the unspread baseband bandwidth. In CDMA systems, the value of PG must be high to avoid narrowband interference and noise from the other participants. With a low PG, robustness to interference and noise is lost and the signal quality can be unacceptable to all participants. For high values of both data rate and PG is logical to expect a large transmission bandwidth and this can be a problem, especially for PLC applications. The CDMA system that implements SST can be a suitable solution for data rate up to 1 Mbps.

2.3. Orthogonal Frequency Division Multiplexing

OFDM (Orthogonal Frequency Division Multiplexing) is a modulation technique based on multiple carrier frequencies; complex but very effective, it's able to transmit high-data-rate. As seen for Spread Spectrum modulation, OFDM also has a good robustness to various types of interferences and allows multiple accesses. Unlike the SST, the OFDM divides the used spectrum used in many narrowband subchannels. The main advantage of these schemes is the ability to operate in critical channel conditions, for example in presence of attenuation of high frequencies on a long copper wire, or narrow band interference or selective fading due to multipath. Filters are simplified using many slowly modulated narrowband signals rather than one broadband fast [3]. Moreover OFDM offers a high modulation efficiency that meets the need to have high bit-rate applications. This is obtained with a high signal-to-noise that may cause interference with other parties at high frequencies; for this reason it is important the definition of a law regulating this aspect [4].

The OFDM is the more suitable modulation scheme for PLC applications.

3. STANDARDS AND PLC PROTOCOL

In Europe, CENELEC (European Committee de Normalisation Electrotechnique) established the ranges of frequencies for powerline communications systems in low voltage with EN 50065-1. It introduced a unique regulation in the countries that join it, among which Italy.

Table 2. Comparison of modulation technique

MODULATION	SPECTRAL EFFICIENCY [b/(s•Hz)]	MAX DATA RATE [Mb/s]	ROBUSTNESS TO DISTORTION CHANNEL	ROBUSTNESS TO IMPULSIVE NOISE	EMC AND REGULATION
SST	<0.1	≈0.5	-	0	+
SCM, NO EQUILIZER	1-2	<1	-	+	-
SCM, NO EQUILIZER	1-2	≈2	+	+	-
MULTICARRIER	1-4	≈3	+	0	0
OFDM	>>1	>10	++	0	+

As described in the introduction, four different bands of use are defined:

- CENELEC A: 3 kHz - 95 kHz. The frequencies in this band are to be used only for monitoring and control applications for low voltage distribution network, including the use of energy equipment and premises connected including energy use of the equipment and premises connected.
- CENELEC B: 95 kHz – 125 kHz. Can be used by all applications, everyday, no protocol required for access.
- CENELEC C: 125 kHz – 140 kHz. Used for home networking system.
- CENELEC D: 140 kHz - 148.5 kHz. Used for security and alarm systems.

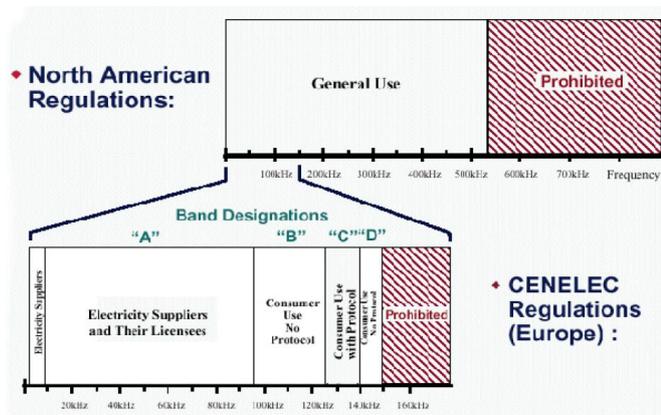


Fig. 5. Comparing between CENELEC and US legislation

PLC actually comprises several standards focusing on different performance factors and issues relating to particular applications and operating environments (Table 1). Two of the most well-known are G3 and PRIME. In general, across multiple standards, G3 or its cousin IEEE P1901.2 focus more on robustness. Given the varied environments in which PLC can operate and the different kinds of interference present in them, the robustness of G3 to withstand noise often makes it a more compelling choice for worldwide deployments [5].

In this paper we focused on two narrowband standards, PRIME and G3-PLC, which have been implemented in the prototype. A comparison between their performances is reported and discussed in the paper. Moreover some measured parameters are also compared with other

broadband protocols, such as HomePlug GreenPHY and IEEE P1901.

3.1. Prime

PRIME is a standard physical layer (PHY) and MAC, open, and prone to search of interoperability between equipment of different operators. PRIME defines a transmission system PLC narrowband network implemented on the low-voltage supply network. The PHY layer of PRIME is designed to transmit and receive on electrical networks distribution at 50-60 Hz AC. Physical layer exploit a frequency band ranging from 3 kHz to 95 kHz, as defined by EN50065-1, and so included in the CENELEC A band. The noise and distorting effects introduced by the channel frequencies below 40 kHz make that PRIME works in his sub-interval of 41.992 kHz and 88 867 kHz with a 47 kHz bandwidth, which is the best part of the band A of CENELEC. The transmission scheme of PRIME is based on OFDM modulation, implemented with mechanisms of Forward Error Correction (FEC) and data interleaving.

3.2. G3-PLC

G3 operates on CENELEC-A band (3-95 kHz) in Europe and can be extended across the full band FCC to provide a higher data rate in other countries. G3 is bi-directional with an effective data rate of 20-40 kbps in CENELEC-A band and up to 200-400 kbps whole gang FCC (G3-FCC. G3 uses OFDM to provide high resilience to interference and attenuation. As a result, reliable communications up six miles can be obtained, while crossing between medium voltage transformers. The standard also allows communication on the low voltage and medium voltage (LV/MV) crossing transformation for a total distance of up to 2-3 km, depending on the condition of the channel.

4. TESTS

In this chapter results of tests performed on the implemented power line carrier communication system are reported. Specifically, two Texas Instruments power line modems based on the C2000 TMS320F28069 control CARD and AFE031PLC analog front end have been adopted.

Aim of these tests is the performance analysis of communication over Power Line between the two PLC modules installed on a specific microgrid. In particular, we implemented different microgrids, reproducing the structures of common medium size civil apartments. The

communication protocols analysed are: G3-PLC and PRIME using commercial and customized firmware implementations.

4.1. G3 test

With this protocol we focused the attention about the transmission of data through a three-phase transformer, powered in both single and three-phase configurations. In both configurations, the tests showed positive results: it has been possible with this protocol to perform the communication between the two PLC modules through the transformer [6]. It's interesting to note that the communication between the modems has also been successful even these ones were powered by two different phases.

In the second test we added a five poles cable FG7OR between the two modems, with section of 16 mm², in single-phase configuration with a maximum length of 114 m and a $R_{20^{\circ}C} = 1.21 \Omega \cdot km$. Figures 5a e 5b show the results; the length of the cable doesn't change the value of RSSI (Received Signal Strength Indicator) and SNR.

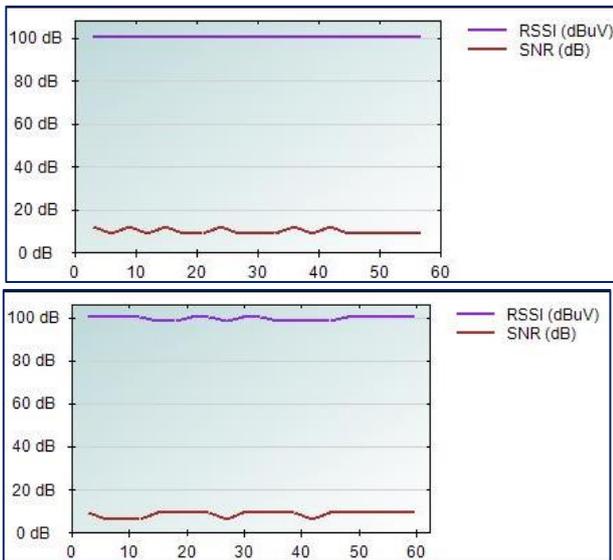


Fig. 5a, 5b. G3 Results without cable between modems (up) and with one.

4.2. Prime test

For this protocol we tested both commercial and customized firmware versions, implementing also a graphical interface developed in LabVIEW [7]. This made it possible to analyze the transmitted and received packets, calculate the BER (Bit Error Rate) and PER (Packet Error Rate), and display the frequency response of Power Line channel. The connection diagram, shown in Figure 6, is based on an isolation transformer, two modems, two earth leakage circuit breakers, three energy saving lamps (load) and the same cable used in the previously test. The first test was made with only one earth leakage circuit breaker, without the load, a 5 m cable. We transmitted 2000 packets, each of 100 bytes, obtaining 0% BER and PER, an SNR that varies from 19 dB to 21 dB and an ASSR of 100 dB μ V. Successively we connected the load obtaining 0% BER and PER, a SNR that varies from 9dB to 18 dB and an ASSR of 100 dB μ V.

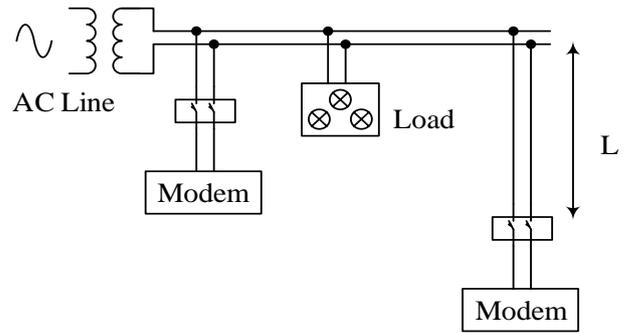


Fig. 6. Prime test connection diagram

The second test was similar to previous one but with two RCD (Residual Current Device) and without the load. We transmitted 2000 packets, each 100 bytes, obtaining a BER of 0%, a SNR in the interval from 15 dB to 17 dB and a ASSR 100 dB μ V. Successively we connected the load, obtaining both BER and PER equal to 0%, SNR from 9 dB to 14 dB and an ASSR of 100 dB μ V.

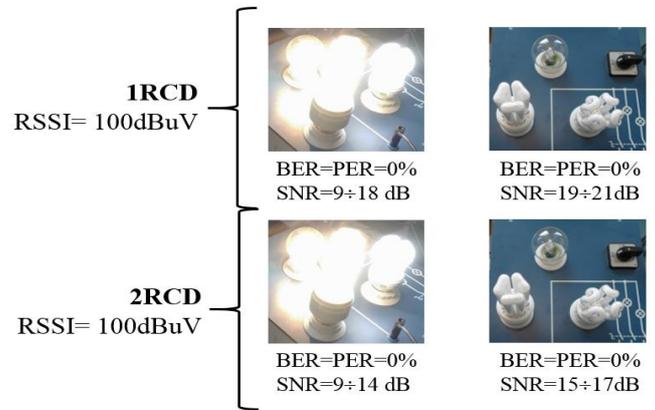


Fig. 7. Summary diagram for prime test with L = 5 m

The other test has made with L = 120 m. Six different tests were done, each of which was repeated for five times. For each test and for each repetition of it, we transmitted 49 packets of 132 bytes over the line constituted by the 120 m five-pole cable, a single-phase insulation transformer, two circuit breakers and the load. In all test the number of received packets was always different from the sent packets, from a minimum of 1 to a maximum of 3 lost packets. With the three energy savings lamps lit up, the number of lost packets didn't change, but like in the second test, a 6dB reduction of SNR was measured (Fig.9).

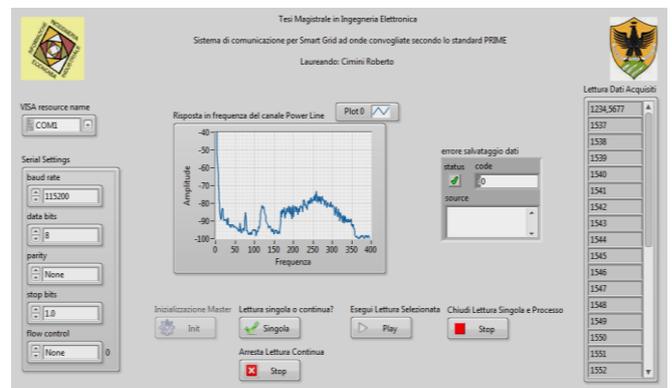


Fig. 8. Prime test LabVIEW interface

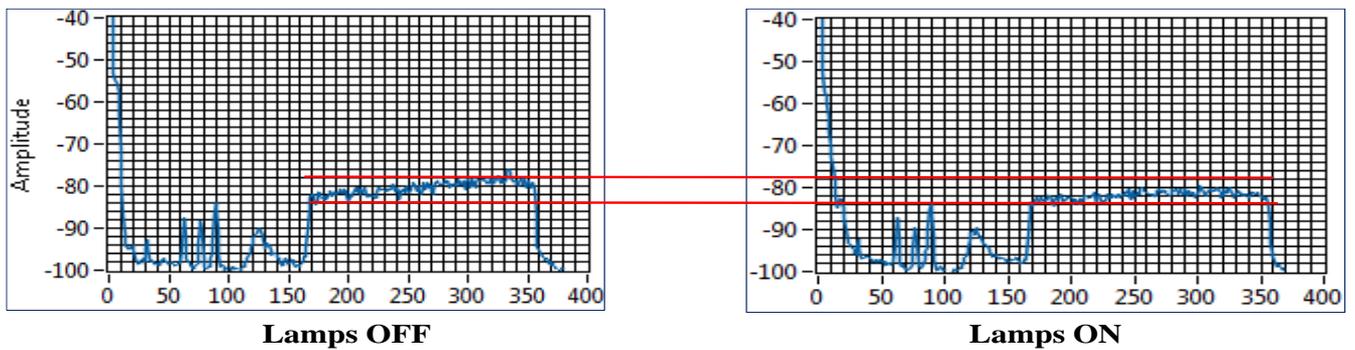


Fig. 9. Signal received spectral analysis

5. CONCLUSIONS

In this paper, an overview on power line communication has been presented. Three modulations have been analysed and implemented, underlining the reasons for which the OFDM is then more suitable for PLC applications. For an experimental verification of the performance of the system it has been assembled a low-voltage network, using commercial devices. In particular, we made different network topologies, using an isolation transformer, one or two differential switches, some connecting cables for a maximum length of 120 m and the load previously described.

By analysing the obtained results it was verified that the electric network may be subject to disturbances of various kinds, depending on its topology, length, type of protection devices crossed by the signal and type of electrical loads connected [8]. For example, in the network performed in the laboratory, a significant source of interference was represented by the load of figure 7.

All tests were carried out using the encoding technique DBPSK + FEC, which provides mechanisms for error correction, but which, in contrast, does not exceed in transmission speed. Nevertheless it can be said that this is a possible solution to the problems of power line communications.

Results carried out by applying the G3 communication protocol are very interesting, allowing the transmission of signals between two different phases of a low voltage transformer.

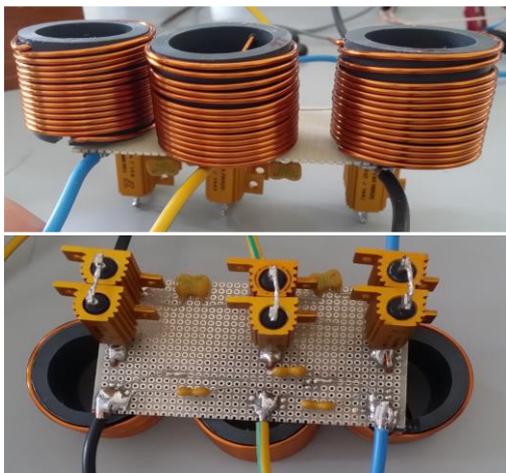


Fig. 10. One of RLC blocks used to simulate line impedance

As future work, in order to recreate in the laboratory network architecture more close to reality, we began to create a test structure configuration that include a larger number of nodes and the connection of multiple loads. It is based on two-ports blocks with which represent each section of the lines on a traditional electrical system. Each block is a RLC block as shown in figure 10.

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