Communication System using OFDM on a Power Line Channel

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Abstract — The efficient communication systems development that use like environment of transmission the net of energy (Power Line Communication) needs a detailed knowledge of the channel's estates, such as the capacity, the noise, the setting of interference and the function of transference, currently the OFDM modulation is utilized in power line communication in information transference application with high debits, due to its robustness against interferences and spectral efficiency. It was with the objective of obtaining the transfer function of the power line that the experiences presented in this report were carried out.

Index Terms — Power line communications, orthogonal frequency division multiplexing, digital and analog signal processing, digital communication.

I. INTRODUCTION

Power line communications is not a new concept. Narrowband communications have been used for decades for domotic applications and by utility companies. Standards like X10 or INSTEON are used in remote control illumination, appliance management, security systems, remote meter reading, etc.

Electric power networks, due to its omnipresence, offer a tremendous potential for fast and reliable communication services. In the last years, there have been great developments in this area, not only in narrowband, but also in broadband communications. It is common to see power line channels being used by applications like home networking, high definition TV, high definition audio, VoIP, internet access and as a backhaul for other technologies, like Wi-Fi or WiMAX.

Currently, it is in course the approval of a standard by IEEE (Institute of Electrical and Electronics Engineers, Inc.), the proposal IEEE P1901, foreseen for 2009, which will define medium access control and physical layer specifications for broadband over power lines (BPL). This project develops a standard for high speed (>100 Mbit/s at the physical layer) communication devices and will use transmission frequencies below 100 MHz. This standard will be usable by all classes of BPL, including outdoor internet access and indoor LANs.

On the other side, power lines are a very noisy environment, which, allied to electromagnetic compatibility (EMC), result in small signal-to-noise ratio (SNR), which implies complex technologies, possibly more expensive than traditional communication systems. PLC is also sensitive to external interferences, as it is also a source of noise to others. There are several movements in USA, headed by amateur radio associations, against this technology.

Knowing some pros and cons, so as the state of art of this technology, it is intended with this work, to study the power line channel and obtaining the transfer function of the power line.

In this paper, chapter II exposes the typical channel characteristics, presenting the multipath model for PLC and the noise model. In chapter III are shown several modulation schemes, while in chapter IV the study is focused in the OFDM scheme applied to PLC. Chapter V presents the experiments done with a real channel and their results. The conclusions and are shown in chapter VI.

II. THE CHANNEL MODEL

The development of reliable power line communication systems is a severe challenge for a communications engineer, having to deal with very unusual channels that were not designed for signal transmission at high frequencies.

A typical power line channel in an European low-voltage network is characterized as a star-shaped bus structure, exhibiting strong branching, which considerably impairs the signal quality with a great number of reflection points. Due to such a network structure, a complex echo scenario arises, leading to a frequency-selective fading, represented as notches in the magnitude of the frequency response [1]. Also, there is a low-pass characteristic that superposes selective fading. Therefore, the length of a link becomes crucial whenever 300m are exceeded, or even a smaller length, if the network is strong branched or if higher frequencies are used (i.e., above 10 MHz).

A. Multipath Model for Power Line Channels

In the literature, there are some proposals for a PLC channel model, but their practical value is generally very limited, because most of them represent bottom-up approaches describing the behavior of a network by a large number of distributed components. In contrast to these approaches, Zimmerman and Dostert [2] presented a model that considers the communication channel as a black box and described its transfer characteristics using a very few relevant parameters. These parameters are obtained by measurements done in the channel and not derived from component properties,

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decreasing the complexity of the channel model. Also, Philips [3] proposed an echo model that describes the channel impulse response as the superposition of \( N \) Dirac pulses representing the superposition of signals from \( N \) different paths. Each of these impulses is delayed by a time \( \tau_i \) and is multiplied by a complex factor \( r_i \) that represents the product of reflection and transmission factors along each echo path. This leads to the complex channel transfer function:

\[
H(f) = \sum_{i=1}^{N} g_i e^{-j2\pi f \tau_i} \quad (1)
\]

This model is a realistic approximation of the effects of selective fading and, therefore, is well suited to indoor scenarios, where the low-pass characteristic is not relevant.

For outdoor channels, where low-pass characteristic is relevant, the most suitable model is presented by Zimmermann and Dostert [5].

\[
H(f) = \sum_{i=1}^{N} g_i e^{-j2\pi f \tau_i} \quad (2)
\]

This model represents the superposition of signals from \( N \) different paths, each of which is individually characterized by a weighting factor \( g_i \) and length \( \tau_i \). While the first exponential function represents attenuation and is modeled by parameters \( a_0, a_1 \) and \( k \), the second one, including propagation speed \( v_p \), describes the echo scenario. These parameters can be obtained from measurements of the channel complex transfer function. The attenuation parameters \( a_0 \) (offset of attenuation), \( a_1 \) (increase of attenuation), and \( k \) (exponent of attenuation) can be obtained from the magnitude of the frequency response. The path parameters \( \tau_i \) and \( g_i \) can be determined with the impulse response. The time delay \( \tau_i \) is proportional to \( \tau_l \) (\( \tau_l = \tau_i / v_p \)) and \( g_i \) is related to the amplitude of each impulse.

\[ B. \ The \ Noise \ Model \]

When designing a communication system over power lines, it is necessary, not only the transfer function, but also the noise model. In opposite to most of other channels that are designed from the beginning, the interference scenario in a power line channel is much more complex than typical additive white Gaussian noise. There is not only colored broadband noise, but also narrowband interference and different types of impulsive disturbance [1]. Zimmermann and Dostert defined five general classes for interferences [4]:

- Colored background noise, has relatively low power spectral density (PSD), varying with frequency. It is caused mainly by the summation of numerous noise sources with low power.
- Narrow-band noise, mostly sinusoidal signals, with modulated amplitudes caused by ingress of broadcast stations.
- Periodic impulsive noise synchronous to the main frequency, with a repetition rate between 50 and 200 kHz, with a discrete line spectrum spaced according to the impulse repetition rate. It is caused mostly by switched power supplies.
- Periodic impulsive noise synchronous to the main frequency, with a repetition rate of 50 or 100 Hz (in Europe). The impulses have short duration and have a PSD decreasing with frequency. Also caused by power supplies, mainly by the switching of rectifier diodes.
- Asynchronous impulsive noise is caused by switching transients in the network. The impulses have durations of some microseconds up to a few milliseconds with random occurrence. The PSD of this type of noise can reach values of 50 dB above the background noise.

The properties of the first 3 types of noise usually remain stationary over periods of seconds and minutes, or even hours, and may be summarized as background noise. The two last noise types are time-variant, in terms of microseconds to milliseconds and, during the occurrence of such impulses, the PSD of the noise rises considerably and may cause bit or burst errors in data transmission. On the other hand, as shown in [4], with practical measurements using frequencies between 0.2 to 20 MHz, even in heavily disturbed environments (e.g., industrial zone), although the impulse rate is quite high, the disturbance ratio is below 1% almost all time. This means that, even in this environment, more than 99% of the time is not affected by the impulse events and could, therefore (with appropriate transceivers), be optimally used for error-free communication.

Another important study about the noise model was done in 2002 [5], where measurements of the noise level in INESC-ID/SIPS laboratory during 48 h were presented. This laboratory is the same used for experiments presented in this paper. In [5] it is shown that the noise level for 1 to 30 MHz is almost constant at ~100 dBm while, for low frequencies, the noise level reaches ~60 dBm. It is also shown that the noise level is directly related to the hour of the day. During work time, there are many sources of noise that contribute to a much greater noise level.

III. MODULATION SCHEMES FOR PLC

The properties of power line channels differ considerably from other well-known channels. So, special care is necessary when selecting a modulation scheme that uses the channel optimally. It is important to know that:

- It has to have high robustness to impulsive noise;
- High levels of noise and electromagnetic compatibility (EMC) limitations impose to work at low Signal-to-Noise Ratio (SNR). In [6] it is shown that the maximum PSD varies from -79 dBV²/Hz to -53 dBV²/Hz, depending on network structure.
- The low-pass characteristic of the channel makes difficult to use high frequencies (> 20 MHz), so it is necessary to select a modulation scheme that uses the capacity of these channels optimally.

The following sections analyze some modulation schemes that come into consideration when finding an optimal solution for PLC systems.
A. Single-Carrier Modulation

This technique uses a single-carrier, at a frequency $f_c$, and the information is encoded in amplitude, phase or frequency changes of the carrier. The generated signal has a bandwidth $B$ around $f_c$. This type of modulation has low spectral efficiency, if one wants to implement high data rates transmission system, contiguous wideband will be used. Due to notches and the low-pass character of the channel, such signals are seriously affected. Thus, the application of expensive channel equalizers cannot be avoided, and the advantage of simplicity in single-carrier modulation is totally swallowed.

B. Spread Spectrum Modulation

Spread spectrum techniques (SST) seem to be a good choice for power line channels. The most used techniques are DSSS/CDMA (Direct-Sequence Spread Spectrum/Code Division Multiple Access), which has immunity to narrowband interferences, and FHSS (Frequency Hopping Spread Spectrum) which has great resistance to impulsive interferences. These properties are the result of spreading the power spectrum density in a wide range of frequencies. An additional interesting feature of SST, especially with regard to EMC, is the low power spectral density of the transmitted signals.

In both techniques presented here, there is the possibility of, in multi-user environments, being attributed to each user a pseudo-random code, if using DSSS/CDMA, or a pseudo-random sequence of frequencies, if using FHSS. These systems are very safe, as the code attributed to each user is unique and, in some way, encrypts the communication.

As a disadvantage, in multi-user scenario, as each participant uses all band, the more participants become active, the higher the background noise and the higher the probability of mutual disturbance. So, most experts in the field have concentrated on multicarrier techniques, in particular, orthogonal frequency-division multiplexing (OFDM).

C. Orthogonal Frequency Division Multiplexing

OFDM is a widely used technique in services like Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB), Asymmetric Digital Subscriber Line (ADSL) and, also, IEEE P802.11 wireless LAN standard.

Frequency division multiplexing, using orthogonal carriers, was proposed by Chang in 1966 [7]. In contrast, to spread spectrum, which uses only one carrier, it was demonstrated that it was possible to synthesize a set of orthogonal carriers, through a set of filters. This means that cross-talk between the sub-channels (ICI – Inter-channel interference) is eliminated and inter-carrier guard bands are not required. It allows high spectral efficiency, near the Nyquist rate. Also, channel equalization is simplified because OFDM may be viewed as using slowly-modulated narrowband signals rather than on rapidly-modulated wideband signal.

To diminish the complexity of the proposal of Chang, in 1971, Weinstein and Ebert [8] had demonstrated the possibility of using the inverse discrete Fourier transform (IDFT), to get orthogonal sub-channels, and applying the DFT in the receiver to demodulate the signal.

But, this technique has been difficult to implement until the last years. With the proliferation of low cost digital signal processors and, specially, the appearance of FPGA (Field Programmable Gate Array), with great power of parallel processing, became viable to apply OFDM in many commercial applications.

As disadvantages, OFDM presents a very sensitive behavior to frequency shifts, due to Doppler Effect, or frequency shifts in oscillators between emitter and receiver.

IV. OFDM Applied to PLC

Having presented some modulation techniques, its advantages and disadvantages, the study will be concentrated in the OFDM, due to its spectral efficiency and robustness to power line noise and attenuation characteristics.

Let us consider a simple OFDM emitter. Data stream with a period of $\Delta t = 1/f_0$ enter in the coder that does the sub-channel modulation, which can be, for example, QPSK (Quadrature Phase Shift Keying), or QAM (Quadrature Amplitude Modulation), etc. At the exit of this block, the data is grouped in $d(k) = a(k) + j_b(k)$ symbols. The first term is called in-phase component, while the second is the quadrature-phase component.

Then, the symbols modulate respective in-phase and quadrature subcarriers. The subcarriers frequencies are separated by multiples of $1/T$ so that, with no signal distortion in transmission, the coherent detection of a signal element in any sub-channel of the parallel system gives no output for a received element in any other sub-channel [9]. The transmitted waveform can be represented as

$$\mathbf{D}(t) = \sum_{k=0}^{N-1} (a(k) \cos(\omega_k t) + b(k) \sin(\omega_k t))$$

where $\omega_k = 2\pi f_k$, $f_k = f_0 + kdf$ and $df = \frac{1}{N\Delta t}$.

One of the main objections to the use of parallel systems is the complexity of the equipment required to implement the system. This problem can be greatly reduced by using the discrete Fourier transform. Next, it will be demonstrated that the OFDM modulated signal shown at equation (3) can be obtained applying an IDFT to a sequence of complex numbers.

Given a sequence of $N$ complex numbers $(x_0, x_1, ..., x_{N-1})$, its DFT is $(X_0, X_1, ..., X_{N-1})$, where $X_k$ is defined as

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j(2\pi \Delta f n k/n_0)} \quad k = 0, ..., N - 1$$

The inverse DFT (IDFT) is

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j(2\pi \Delta f n k/n_0)} \quad n = 0, ..., N - 1$$

Now let $X_k$ be $d(k) = a(k) + j_b(k)$.

$$D_k = \frac{1}{N} \sum_{n=0}^{N-1} d(n) e^{j(2\pi \Delta f n k/n_0)}$$
where $\tilde{A} = \frac{A}{\Delta t}$, $t_0 = n \Delta t$ and $\Delta t$ symbol time of $d(k)$ sequence. Applying a low-pass filter in $\Delta t$ interval, the real component is

$$
K_{\text{LPF}}(\omega) = \frac{1}{N} \sum_{k=0}^{N-1} a(k) \cos(2\pi \omega k/T) - b(k) \sin(2\pi \omega k/T)
$$

(7)

where $0 \leq n \leq N$. This is the same expression referred in (3), only differentiated by the signal in the imaginary component and the factor $1/N$. This demonstrates that an OFDM signal can be obtained by applying an IDFT and a few simple algebraic operations.

V. CHANNEL STUDY

During the development and test phases of a communication system, it is very important to have a real-world channel studied, that aids the communications engineer in his project choices and also assessing the system behavior.

In this phase of the project, there were used two circuits, called Analog Front End (AFE), developed during the project 2002-2003:TFC 148/2002, and two power supplies developed in 2004-2005:TFC 38/2005.

The study of the channel was focused in its transfer function. To do this two types of experiences were carried out. One first experience used the HP 4195A network analyzer, and a second experience used an oscilloscope of floating tips.

A. Experiences with network analyser

The network analyzer which is coupled to the power line channel by the two AFE (Figure 1).

As it can be seen in the figure, it were used the least components possible, to diminish the number of possible interferences. The capacitors Cline and the transformer 1:1 protect the rest of the circuit and behave like a high-pass filter, to attenuate most of the power from AC and its harmonics. Also, it has been developed the buffer circuit, which protects the network analyzer and has low input impedance (50 $\Omega$), from any input voltage peak. The buffer is implemented using an operational amplifier (opamp), TI OPA656, functioning with the non-inverting operation, with gain $G = +2$. This provides high input impedance and low output impedance, protecting the network analyzer.

Both AFE and power supply were inserted in a metal box, that acts like a Faraday cage, protecting the system from external electromagnetic interferences.

The scenario used to test the PLC system was the laboratory of SIPS/INESC. But, before running the tests to obtain the transfer function of some sections of the power line network in the laboratory, it is necessary to know the coupling circuit behavior.

There were made 3 different frequency response tests to the AFEs: only one AFE with its power line terminals (Line1/Line2) in short circuit or open circuit; and two AFEs linked directly to each other. In all tests, the signal was injected in the input gate and read at the output gate of the respective AFE. Figure 2 illustrates the scheme of the test bench, while Figure 3 represents the results of these measurements.

![Figure 2](image)

**Figure 2** – Test bench used to measure the frequency response (A) of a single AFE, (B) with two AFEs.

![Figure 3](image)

**Figure 3** – Frequency response of the AFEs.

In both cases, the high-pass behavior is present. This is very important in PLC, as most of the PSD is concentrated in low frequency harmonics. Another conclusion is that the internal net of each AFE is not affected by its terminal impedance (this is demonstrated by the superimposition of the respective two curves in Figure 3).

Knowing the AFEs, it is time to measure the frequency response of several channels, changing some parameters: distance, time, local of the test and number of branches. In Figure 4 there is presented some interesting results of the experiments done with the channel.

First of all, it is important to know the two tests scenarios represented in Figure 4. The first test channel consists in two cables with 1.5 meters long, linked to two adjacent power sockets. The second test channel is constituted by the same...
two cables and two power sockets distanced by 1.5 meters and 4 branches between.

Analyzing the frequency response, one observes that the attenuation is greater in the second test than in the first. This is caused, not by losses in cable material, but by the energy that is absorbed by electrical equipment that is attached to each branch of the channel. Also, there can be seen notches, representing the reflections caused by the branches and non-adapted terminations. To conclude, the frequency band more useful for data transmission is between 600 kHz and 4 MHz, where the attenuation is almost constant. Thus, it was decided to use a central carrier, which frequency is near 3 MHz.

There were made some changes from the interfaces used to measure channel frequency response. It was added a low-pass filter to the transmitter, to eliminate the high frequency replicas of the samples signal. At the receiver, it was added a band-pass filter. The full AFE interface is shown in Figure 5:

![Figure 5 – Analog interface with filters used to couple to power line.](image)

The frequency response of the two AFE in sequence, with and without a power line between them is shown in Figure 6. The responses were obtained with the Network Analyzer HP 4195A and the test bench used was the same used on Channel Study (Figure 2).

Comparing the Figure 6 with Figures 3 and 4, it is clear that the differences are, essentially, a greater gain in the near flat pass band and a greater attenuation in the lower frequencies, obtaining −60 dB for those lower than 90 kHz. This attenuation was only reached with the simplified AFEs for frequencies lower than 60 kHz.

**B. Experiences with oscilloscope of floating tips**

In the context of the knowledge improvement of Power line channel new experiences were carried out this time using a Digital oscilloscope of 4 channels Tektronix TPS 2024 in which the entry channels are isolated of the oscilloscope structure and between them. It was also used a Signal creator Hp 3336A that produced Sinusoidal Signs in the scale from 1 to 20 MHz.

Like in the first experiences with the Network analyzer also in these new Experiences the objective was to center the attentions in the channel. Being so, the AFE used circuits were minimized contenting it self with the Emission and Reception Transformers and with the AFE plate Coupling Condensers. In the emission Transformer there was put a 220 pF coupling condenser.

In Figure 7 is shown the emission AFE used in these experiences, which hardly differs from the reception AFE because of including of one more 220 pF Coupling condenser.

![Figure 7 – Analog interface used to couple to power line in the Oscilloscope Experiences.](image)

The followed model in these experiences consisted in injecting in the emission AFE and in the channel 1 of the Oscilloscope the originating signal from the Signal Creator. In the Channel 2 of the Oscilloscope was placed the exit signal of the reception AFE Transformer.

Were made two types of basic tests, with this model with sight to getting the transfer Function of Power line channel, one
with the AFE in short circuit without channel and another test without short circuit between the AFE but with the presence of the Power line Channel.

For a better visualization, the assembly Diagram of Short Circuit between AFE1 and AFE 2 is shown in Figure 8.

![Assembly Diagram with the AFE1 and AFE2 tied for Short circuit.](image)

Figure 8 – Assembly Diagram with the AFE1 and AFE2 tied for Short circuit.

In Figure 9 is shown the Assembly Diagram with the Presence of the Power line Channel.

![Assembly Diagram with the presence of Power line Channel.](image)

Figure 8 – Assembly Diagram with the presence of Power line Channel.

The used methodology injected a Sinusoidal sign, with a given reduction (-12.89dB) defined in the creator, and varying the Frequency. For a question of method, the Frequencies were used with whole numbers between 1 and 20 MHz, except in 7.5 MHz and 8.5 MHz, which were used, in order that a better attendance was obtained in this band in which there were quick variations of amplitude and phase.

In case of the amplitude answer there were obtained the very amplitude values of the entry and exit functions in case of short circuit between the AFE, and in case of the Presence of Power line Channel.

For the phase answer the exit was obtained regarding the entry, through the points where the functions were crossing the x axle.

With these values, it was possible to obtain the Amplitude and Phase answer for the experiences cases with the AFE tied between by short circuit and in the presence of the channel Power-line.

For the calculation of the Transfer Function of Power-line Channel we can think that if $T_2$ will go to answer received in the AFE of reception in the presence of the channel Power line and $T_1$ will go to answer received in the AFE of reception with two AFE tied between by short circuit, then the channel Power-line could be given for:

$$\frac{T_2}{T_1} = \frac{|T_2|e^{j\theta_2}}{|T_1|e^{j\theta_1}} = \frac{T_2}{T_1} e^{j(\theta_2 - \theta_1)} \tag{8}$$

There were initially fulfilled a series of five measurements in the Laboratory of the SIPS in the INESC-ID (Room 208). These were always fulfilled in two kinds, first of all an experience with short circuit between the AFE and another experience with the presence of channel, without short circuit between the AFE.

When it was necessary to use the power line channel in 208 room were always used the same captures of the room her around two meters of distance between them, to these two meters it is necessary to annex more three meters, which constitute two used connecting threads.

In the Figure 9 is presented the answer of average amplitude for the first five samplings carried out in the room, with short circuit between the AFE.

![Average Amplitude Response with the two AFE tied between them by short circuit.](image)

Figure 9 – Average Amplitude Response with the two AFE tied between them by short circuit.

In the scale of frequencies between 6 MHz and 9 MHz is visible that there is an obvious gain in Figure 9.

The Average Phase Response with the two AFE tied between them by Short Circuit is presented in Figure 10.

![Average Phase Response with the two AFE tied between them by short circuit.](image)

Figure 10 – Average Phase Response with the two AFE tied between them by short circuit.
The Phase response when the AFE is tied between them by short circuit is null up to approximately 7.5 MHz. From this frequency it increases fast even to the frequency of 8.5 MHz with a value of approximately -180 that remains constant until to the 20 MHz.

In figure 11 is presented the image in the oscilloscope for the frequency of 8 MHz. The yellow line represents the first channel that is the entry of the AFE 1. The blue line represents the second channel of the Oscilloscope which is the exit of the AFE 2. The exit scale costs four times entry scale.

The next experience was carried with the presence of Power-line Channel. The obtained results for the Middle Amplitude are presented in Figure 11.

The Amplitude Answer of the Power-line channel is presented in Figure 13. This response was calculated with resource to the equation 8.

It is visible in Fig. 13 that between 3 and 8 MHz there is a bigger attenuation nevertheless it exists an elevation in the zone of the 7 MHz.

With resource to the same equation 8 it was calculated the Phase answer of the Channel PLC which is presented in Figure 14.
With the objective to prove the independence regarding the time of the channel PLC there were carried out new experiences which consisted of a new five samplings series in the same conditions of last and in the same room.

Nevertheless the conditions in the laboratory were not exactly the same in this second experience one more portable computer of a colleague was tied in the emission capture zone what it will be able to be a justification for the differences of amplitude and phase found.

In Figure 14 is presented the Average Amplitude Response with Power-line Channel of the new experiences.

![Figure 14 – Average Amplitude Response with Power-Line Channel.](image)

In the first experiences case in the amplitude response presented in the Fig. 11there was a clear overelevation between 6 and 10 MHz, in this second experience of repetition the overelevation exists only between 5 and 7 MHz.

New Experiences were carried in the 201 room of INESC-ID. The objective was to check if in a different place the behaviour of the PLC channel is likened to previously measured.

There was the attempt of which the modules used in this experience were the same of the previous experiences, to check the maximum of possible truthfulness to the experiences.

The distance between the used captures was perceptibly same that in the room 208.

In Figure 15 is presented the Average Amplitude Response with Power-Line Channel captured in 201 room of INESC-ID.

![Figure 15 – Average Amplitude Response with Power-Line Channel Room 201 INESC-ID.](image)

In Figure 15 it is visible that the overelevations with width of band of the order of several existent MHz in the answers of the room 208 do not exist, being the answer constituted by many consecutive notches.

VI. CONCLUSIONS

In this paper, the frequency responses of indoor power line channels were obtained by two methods. It was noticeable the main effects of a PLC channel, such as: notches, low-pass filter behavior, and also, the sensitiveness of the frequency response to variations on PLC network. In the SIPS/INESC-ID laboratory, the less affected band of frequencies in the tests with network analyzer between 600 kHz and 4 MHz.

In the Experiences Experiences with oscilloscope of floating tips briefly it can be said that the amplitude and phase answer of the Power-line Channel is influenced by the number and type of loads that are tied to the Power-Line Channel. The frequencies differences of the passage bands in case of the experiences with the network analyser and in case of the experiences with the floating tips oscilloscope are justified because the two AFE weren’t initially projected to be tied by Short Circuit.

REFERENCES