The Characterization of Hybrid PLC-Wireless Channels: A Preliminary Analysis

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***Abstract*—This work aims at measuring, characterizing, and analyzing hybrid channels for mobile data communication with power line communication (PLC) technologies. These channels denote the concatenation of power line and wireless as only one channel. A measurement setup and OFDM-based technique for channel estimation were applied to carry out a measurement campaign of hybrid channels in the $PLC \rightarrow wireless$ and $wireless \rightarrow PLC$ directions. Preliminary results as well as analysis when estimates of the hybrid channels cover the frequency band between 1.7 up to 100 MHz are presented. The attained results reveals that these hybrid channels are very challenging ones. Also, they could be useful for data communication if more investigation concerning the PLC coupling device, the antenna geometry, and theoretical formulation for the signal propagation through the hybrid channel is deeply investigated.**

I. Introduction

The demands for anytime, ubiquitous, mobile, green, and low-cost telecommunication systems to address digital inclusion as well as smart grid communication needs are renewing the interest in pursuing the electric power grid as communication medium for low and high bit-rate data communication. Such a renewed research wave has devised a new generation of power line communication (PLC) technologies that encompasses diversity, cognitive, and cooperative aspects [1]–[4]. The advantages and disadvantages related to PLC technologies, which are well-addressed in the literature, reveal that electric power grids are attractive and competitive communication medium for the digital inclusion of low-income populations and for data communication applications of electric utilities [5], [6].

Although the standardization and regulatory efforts are focusing on the frequency band between 9 kHz and 100 MHz, PLC technologies can use the frequency band from 0 up to 300 MHz for data communication. The use of this spectrum for data communication combined with low-power transmission signals can result in, for instance, a healthy communication system for human being. However, according to the current telecommunication regulations the PLC systems are secondary users, what can severally restrict their deployments in the aforementioned frequency band.

A very challenging restriction related to PLC is the fact that a physical connection between the transceivers and the electric power grid is required, making absolutely impossible the mobility of users connected to a PLC network. To offer mobility to PLC users, however, the industry is introducing product that encompasses both PLC and wireless transceivers. Then, the user can benefit from the advantages of both technologies in only one product to overcome the limitations of each other. That is a very interesting solution because a huge research effort have been applied to conceive both technologies and if they are very-well combined, then improved performance, in terms of coverage and quality of service (QoS) guarantee, can be expected.

Although hybrid (PLC + wireless) devices can offer improved performance, the cost related to then can be twice in comparison to a standard device, i.e., PLC or wireless one. To deal with this issue, we envisage the following three possibilities to reduce the cost of devices based on hybrid concepts: i) the design of hybrid transceiver to maximize the system performance in the baseband and passband channels; ii) the introduction of resource management techniques for dealing with PLC and wireless constraints; iii) the use of hybrid channel (PLC + wireless) in the baseband.

Regarding the third possibility, we can state that a so-called flexible network can be constituted over a hybrid channel. In this kind of network, the transceivers communicate to each other through the air or/and the electric power grids by considering the bandwidth that is supposed to occupy the frequency band between 0 and 300 MHz. Currently, all research efforts related to channel characterization are toward single input single output (SISO) and multiple input multiple output (MIMO) configuration of electric power grids [7]–[10], and, to the best of the author's knowledge, no major research has addressed the characterization of hybrid channels yet.

The present contribution focuses on the preliminary characterization of SISO and hybrid channels (PLC + Wireless) in an indoor environment by assuming that the frequency band is from 1.7 up to 100 MHz. All the presented results were obtained by using a sounding approach based on *Orthogonal Frequency Division Multiplexing* (OFDM) [11]. A measurement setup constituted by signal generation board,

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signal acquisition board, PLC coupler, and an omnidirectional antenna was built to characterize the hybrid channel. Channel capacity results related to a measurement campaign reveals what kind of performance results can be expected using hybrid channel with the adopted antenna and PLC coupler and gives directions for future research efforts to offer models of hybrid channels.

This work is organized as follows: Section II formulates the estimation problem for hybrid PLC-wireless channel using a OFDM-based sounding technique. Section III briefly describes the setup for the measurement campaign. Section IV presents preliminary results related to hybrid channel characterization as well as the channel capacity. Finally, Section V presents the conclusions and emphasizes the main contributions of this paper.

II. Problem Formulation

Figure 1 illustrates a scenario in which a handheld device – with wireless connection – and a personal computer (PC) – with a PLC connection to low voltage electric power grid – can communicate to each other. In this case, the modem, which we have named “PLC coupler”, injects the signal in the electric power grid and part of the energy of this signal is irradiated. The irradiated signal is partially captured by the antenna of the handheld device. In the opposite direction, the handheld device injects the signal in the air using an antenna, then part of this signal is induced in the electric power grids, enabling the PLC modem to extract this signal from the power line.

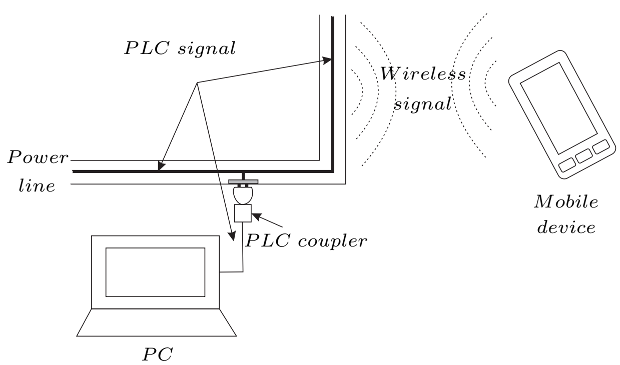


Fig. 1: Hybrid PLC-wireless channel.

If the symbol period is longer than the coherence time of the channel and the channel is linear and time-invariant during the symbol period, then the additive channel models for hybrid channels in the $PLC \rightarrow wireless$ and $wireless \rightarrow PLC$ directions can be represented as in Fig. 2. By assuming that the signal is in the baseband, i.e. $[0, B)$, then the input signal is $x(t) \in \mathbb{R}$ and the outputs of the hybrid channels are expressed by

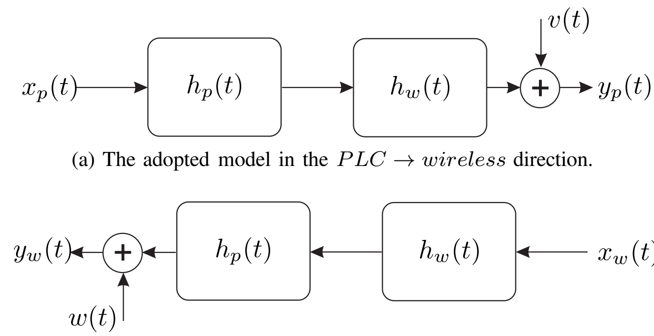
$$y_p(t) = x_p(t) \star [h_p(t) \star h_w(t)] + v(t) \tag{1}$$

or

$$y_w(t) = x_w(t) \star [h_w(t) \star h_p(t)] + w(t), \tag{2}$$

in which $y_p(t)$, $y_w(t)$, $x_p(t)$ and $x_w(t)$ denote the outputs and the inputs of the PLC and wireless transceivers, respectively; $h_w(t)$ and $h_p(t)$ the impulse response of wireless and PLC channels; $v(t)$ and $w(t)$ are the additive noise in the PLC and wireless channels, respectively; and the symbol $\star$ denotes the convolution operator.

Analyzing these kinds of hybrid channels, the following issues are brought into attention: i) the additive noise in the PLC and wireless channels can not be modeled as the same random process; ii) the input impedance of electric power grids and wireless medium are a priori totally different; and iii) the coupling devices for PLC and wireless transceivers differ considerably. As a result, the measurement and modeling of the hybrid channels is a very challenging issue to be pursued.



(a) The adopted model in the $PLC \rightarrow wireless$ direction.

(b) The adopted model in the $wireless \rightarrow PLC$ direction.

Fig. 2: The models for the hybrid PLC wireless channels.

If the OFDM-based sounding technique presented in [12] is applied for estimating the hybrid channel with a measurement setup, the following procedure can be applied: Let $\mathbf{X}_i \in \mathbb{C}^{N \times 1}$ be a frequency domain representation of the *i*th OFDM symbol, then $\mathbf{x}_i = \frac{1}{\sqrt{N}} \mathbf{W}^{\dagger} \mathbf{X}_i$, in which $\mathbf{W}$ is the $N \times N$ discrete Fourier Transform (DFT) matrix and † is the hermitian operator. The insertion of the cyclic prefix results in $\mathbf{x}_{cp,i} = [x_{cp,i}(N - L_{cp} - 1) \ldots x_{cp,i}(N-1)\ x_{cp,i}(0) \ldots x_{cp,i}(N-1)]^T$, in which L_{cp} is the length of the cyclic prefix and $x_{cp,i}(j)$ is the *j*-th coefficient of vector $\mathbf{x}_i$. A representation of the concatenation of OFDM symbols in the discrete time domain is expressed by

$$x[n] = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N+L_{cp}-1} x_{cp,i}(j) \delta[n - i(N + L_{cp}) - j], \tag{3}$$

where δ denotes the unit impulse.

If this signal is transmitted through the hybrid channel, in the PLC→wireless direction, the discrete-time representation is given by

$$y_p[n] = \tilde{y}_p[n] + v[n], \tag{4}$$

where,

$$\tilde{y}_p[n] = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N+L_{cp}-1} x_{cp,i}(j) h_{pw}[n - i(N + L_{cp}) - j) \tag{5}$$

or, in the opposite direction,

$$y_w[n] = \tilde{y}_w[n] + v[n], \quad (6)$$

where,

$$\tilde{y}_w[n] = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N+L_{cp}-1} x_{cp,i}(j) h_{wp}[n - i(N + L_{cp}) - j), \quad (7)$$

in which $h_{wp}[n] = h_w[n] \star h_p[n]$, $h_{pw}[n] = h_p[n] \star h_w[n]$, $h_p[n] = h_p(t)|_{t=nT_s}$ and $h_w[n] = h_p(t)|_{t=nT_s}$, as the frequency band of both channels is equal to $B = 1/(2T_s)$.

Assuming a perfect synchronization and a cyclic-prefix removal at the receiver end, we can constitute the vectors $\mathbf{y}_{p,i} \in \mathbb{R}^{N\times 1}$, $\tilde{\mathbf{y}}_{p,i} \in \mathbb{R}^{N\times 1}$ and $\mathbf{v}_{p,i} \in \mathbb{R}^{N\times 1}$ from the signal at the input of the PLC modem, $y_p[n]$. Then, we can write that

$$\begin{aligned} \mathbf{Y}_{p,i} &= \frac{1}{\sqrt{N}} \mathbf{W}(\mathbf{y}_{p,i}) \\ &= \frac{1}{\sqrt{N}} \mathbf{W}(\tilde{\mathbf{y}}_{p,i} + \mathbf{v}) \\ &= \tilde{\mathbf{Y}}_{p,i} + \mathbf{V} \\ &= \mathcal{H}_p \mathbf{X}_{p,i} + \mathbf{V}, \end{aligned} \quad (8)$$

where $\mathcal{H}_p = \mathbf{diag}\{H_{p,0}, H_{p,1}, \ldots, H_{p,N-1}\}$, $H_{p,l}$ is the lth coefficient of the vector $\mathbf{H}_p = (1/\sqrt{N})\mathbf{W}[\mathbf{h}_p^T \mathbf{0}_{L_0}^T]^T$, $\mathbf{h}_p \in \mathbb{R}^{L_p \times 1}$ is the vector constituted by the samples of $\{h_p[n]\}_0^{L_p-1}$, $\mathbf{0}_{L_0}$ the L_0-length column vector constituted by zeros, so that $L_0 + L_p = N$. If the zero-forcing criterion is adopted, then the estimation of the hybrid channel in the $PLC \to wireless$ direction is expressed by

$$\begin{aligned} \hat{\mathcal{H}}_p &= [\mathbf{diag}(\mathbf{X}_{p,i})]^{-1} \mathbf{Y}_{p,i} \\ &= \mathcal{H}_p + [\mathbf{diag}(\mathbf{X}_{p,i})]^{-1} \mathbf{V}, \end{aligned} \quad (9)$$

where $\mathbf{diag}(\mathbf{X}_{p,i}) = \mathbf{diag}\{X_{p,i,0}, X_{p,i,1}, ..., X_{p,i,N-1}\}$. The same equation applies if the signal transmission direction is $wireless \to PLC$.

Regarding the estimation of hybrid channel, the following questions arise:

1) Can the channel impulse response be symmetric if the impedance of the signal generation and acquisition systems are equal, i.e., 50 Ω?
2) What kind of attenuation can be expected?
3) What are the differences between $v(t)$ and $w(t)$?

III. Measurement Setup

The block diagram of the measurement setup applied to measure the hybrid channel is depicted in Fig. 3. This setup is composed of the following components: i) two industrial PCs; ii) a PCI-based acquisition board with 16 bits and 200 Msps; iii) a PCI-based signal generation board with 14 bits and 300 Msps; iv) an omnidirectional antenna covering the frequency band between 1 MHz up to 1 GHz; v) and a PLC coupler that acts as a high-pass filter, blocking the main signal (50/60 Hz) in the electric power grid as well as the signal that occupies the frequency range up to 1.7 MHz. These devices allowed to assemble the signal generation and signal acquisition systems deployed to estimate the communication channels. These systems are denoted as, for the sake of simplicity, "device Tx" and "device Rx", respectively. The directions for hybrid channel estimation are chosen according to the position of the Tx and Rx devices in PLC and Wireless blocks, as indicated in Fig. 3.

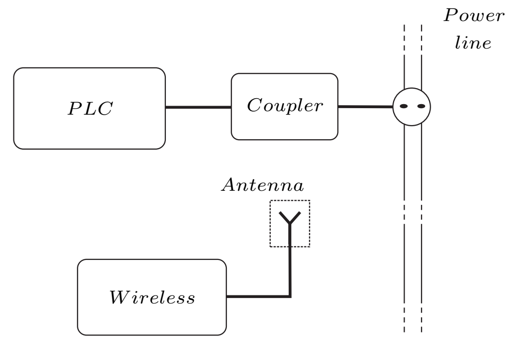


Fig. 3: Block diagram of the measurement setup.

Figure 4 shows the low-voltage electric circuit built at the laboratory facility to carry out the measurement campaign. In this figure, the letters A, B and C denote outlets where the Rx and Tx devices can, by using a PLC coupler, be connected to the electric circuit. The letter D refers to the connection of the built electric circuit with the electric circuit of the laboratory. The letter O defines the origin of a two-dimensional (x, y) cartesian coordinate system. Table I informs the length (in meters), with respect to the origin (O), of power lines that constitute the build electric circuit. With this electric circuit, the Tx or Rx device can be connected to an antenna and positioned in a location so that the hybrid channel in the $PLC \to wireless$ or $wireless \to PLC$ directions can be estimated. In our experiment, however, for the sake of simplicity, the Tx or Rx device is only connected to the outlet A.

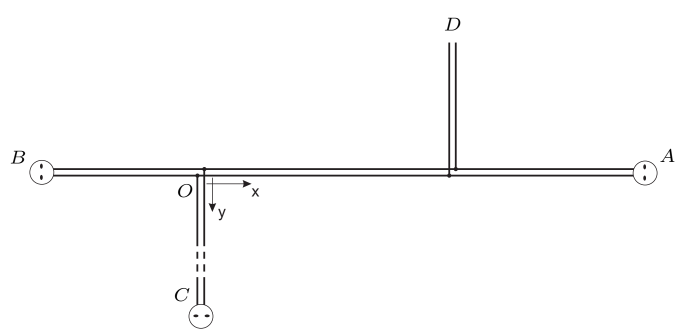


Fig. 4: The electric circuit constituted to measure hybrid channels.

IV. Results

This section presents some preliminary results obtained with the measurement setup deployed to measure the hybrid channels with the built electric circuits. All results were obtained in the Signal Processing and Telecommunication Laboratory

Path	Length (m)
$A-O$	1.50
$B-O$	0.50
$C-O$	1.70
$D-O$	1.70

TABLE I: Lengths of power line belonging to the electric circuit.

(LAPTEL) at the Federal University of Juiz de Fora, Brazil and using the method presented in [12].

The estimates of frequency responses of the hybrid channel in the $wireless \rightarrow PLC$ direction is presented in Fig. 5. In this plot, the legend informs the position of wireless device (Rx device together with the antenna) with respect to the adopted cartesian coordination system. These curves show that the attenuation increases with frequency and distance to the electric circuit. Also, the $wireless \rightarrow PLC$ hybrid channel shows frequency selectivity. As can be noted, short variations in the antenna position, of few centimeters, did not produces significant variations of the channel frequency response. The attenuation as function of the distance is pronounced in frequencies near 100 MHz. Overall, one can note that the attenuation profile of such kind of hybrid channel can be as high as -100 dB close to 100 MHz.

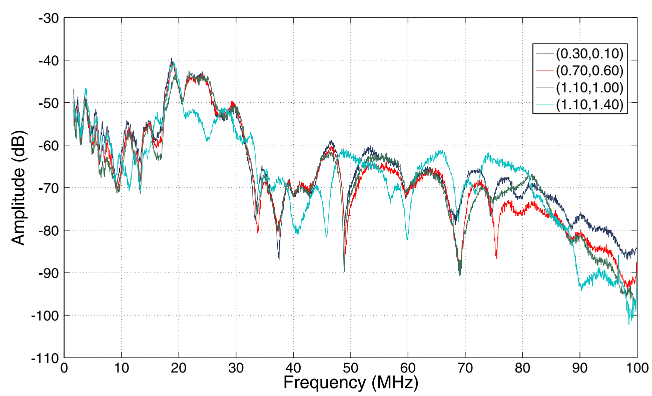


Fig. 5: Frequency responses of the $wireless \rightarrow PLC$ channel.

The measured hybrid channels in the $PLC \rightarrow wireless$ direction are illustrated in Fig. 6. For obtaining these measures, the wireless equipment is composed of the Rx device and an antenna, while the PLC one is of the Tx device and PLC coupler connected to electric circuit. These measures highlight the fact that the attenuation of the signal does not increase considerably when the frequency increase for the range of adopted distances from the built electric circuit. Also, frequency selectivity characterize such channels.

By analyzing the estimated hybrid channels in both directions, we can not verify that the channel-symmetry property is guaranteed even when the signal generation and acquisition systems present the same access impedance. On the other hand, we can recognize that the signal attenuation in the $PLC \rightarrow wireless$ direction is lower than in the opposite one. Based on Fig. 7, we can note that the hybrid channel in the $PLC \rightarrow wireless$ direction is much better for data communication. For some frequency bands, the attenuation in the hybrid channel in the $wireless \rightarrow PLC$ direction can be as high as 50 dB in comparison to the ones in the $PLC \rightarrow wireless$ direction.

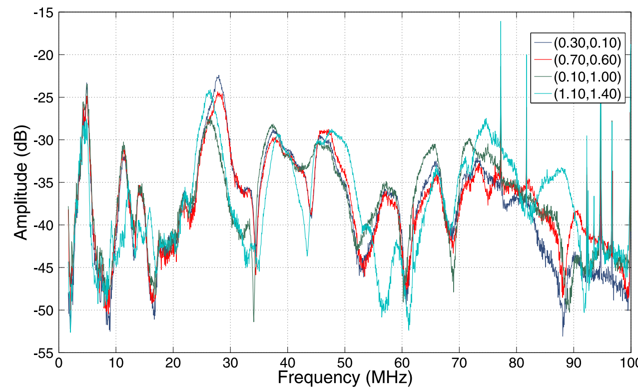


Fig. 6: Frequency responses of the $PLC \rightarrow wireless$ channel.

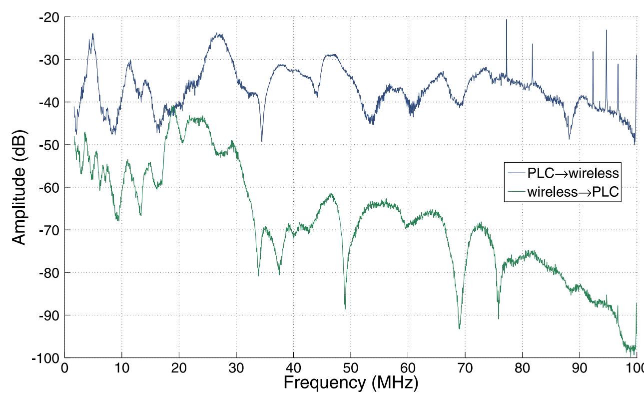


Fig. 7: Frequency responses of the hybrid channel evaluated in both transmission directions in the position $(0.70, 1.00)$.

To evaluate the channel capacity of both hybrid channels, a noise measurement campaign was carried out with the same electric circuit. The noise signal was measured at the outlet in which the PLC coupler of the Rx device is connected to the electric circuit and at the antenna connected to Rx device. The power spectrum density (PSD) of the measured noise in both hybrid channels are portrayed in Fig. 8. As it is expected, the PSD of the noise in the power line is higher than in the wireless channel for the low frequencies, mainly, due to the noise components yielded by the loads connected to electric power grids. For the high frequencies, the signal acquired from the air reveals the presence of narrowband signals (probably due to amateur and FM radio stations), what is somewhat attenuated in the power-line signal. Overall, the additive noise components for both hybrid channels are quite different.

Table II shows the evaluated channel capacity for both hybrid channels when the transmitted power is equally distributed in the frequency band. While the hybrid channel in the

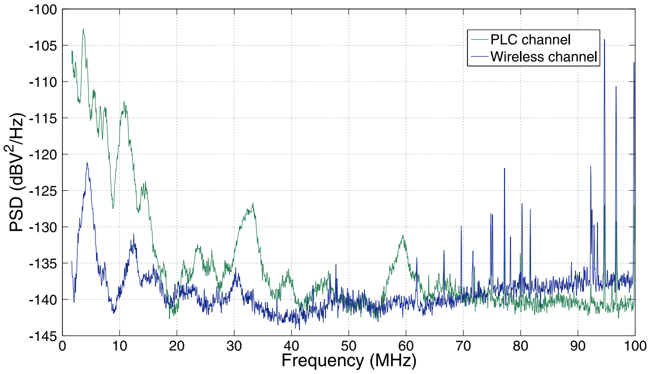


Fig. 8: PSD of the noise in the PLC channel and in the wireless channel.

$PLC \rightarrow wireless$ direction can reach more than 73 Mbits/s of capacity, the hybrid channel in the $wireless \rightarrow PLC$ direction reaches only a little more than 570 kbits/s, when the signal is transmitted with 0 dBm of power. The worst case scenario for the hybrid channels, which is associated with the power of the transmitted signal equal to -50 dBm, the channel capacity is around 1 kbits/s for the $PLC \rightarrow wireless$ direction against only 6 bits/s for the hybrid channel in the opposite direction.

The attained results in terms of channel capacity can indicate that hybrid channels are the worst choices as communication medium. However, we have noted that the behavior of the coupling devices (transducers) is a very important issue and, therefore, more investigations are needed to address PLC coupler and antenna impact in the hybrid channels and, finally, to highlight what kind of gains can be expected in such channels.

$Signal$ $Flow$	Power of the transmitted signal (dBm)					
	-50	-40	-30	-20	-10	0
$PLC \rightarrow wireless$	1.071 $\times 10^{-3}$	10.771 $\times 10^{-3}$	0.108	1.083	10.196	73.470
$wireless \rightarrow PLC$	0.006 $\times 10^{-3}$	0.063 $\times 10^{-3}$	0.611 $\times 10^{-3}$	6.414 $\times 10^{-3}$	58.827 $\times 10^{-3}$	0.578

TABLE II: Channel capacity in Mbits/s.

V. Conclusion

This work has presented a preliminary measurement, characterization, and analysis of hybrid channels, which are constituted by the concatenation of power line and wireless channels. A measurement setup and electric circuit were developed and built to carry out a measurement campaign of hybrid channels in a controlled laboratory facility.

With the measurement setup and electric circuit, both hybrid channels were estimated when the wireless equipment was located in positions showing different distances from the electric circuit. Also, the noise PSDs in both hybrid channels were estimated.

The measurement campaign revealed that the hybrid channel in the $PLC \rightarrow wireless$ direction offers lower attenuation than the hybrid channel in the opposite direction. Both hybrid channels, however, show frequency selectivity and the channel symmetry can not be guaranteed even when the signal generation and acquisition system present the same access impedance.

The analysis of the noise signals shows that the PSD of such signals in both hybrid channels are quite distinct from each other. Basically, the noise in the power line channel is more pronounced that in the wireless one when low frequencies are considered.

A preliminary channel capacity analysis of both hybrid channels indicate that the channels in the $wireless \rightarrow PLC$ direction present a very low capacity in comparison with hybrid channel in the opposite direction.

Generally speaking, this work has indicated some interesting directions for further investigations on the hybrid-channel performance, particularly with respect to the the impact of PLC coupler and antenna in the hybrid channels. Also, the introduction of hybrid channel models for both directions is of ultimate importance.

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