The wireless signal propagation in hybrid PLC-wireless channels: A first analysis

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***Abstract*— This work advances the study of indoor hybrid PLC-wireless channels when the frequency band delimited by 1.7 MHz and 100 MHz is taken into account. In this sense, a measurement campaign was carried out in a building facility to investigate the wireless signal propagation of these kind of channels. Based on the collected measures of PLC-wireless channels and additive noises, it is reported a agreement with previous works, in terms of average channel gain, power spectral density of additive noise and achievable data rates. Also, numerical results show that wireless signal propagation part of PLC-wireless channels can offer several hundreds of Mbps if a wireless device is located up to 6 meters from the power lines. Also, they show that PLC-wireless systems can be powerful tools to benefit wireless communication inside an office.**

***Keywords*— channel measurement, hybrid channel, power line communication, wireless communication.**

I. INTRODUCTION

Power line communication (PLC) has expanded the usage of electric power grids to deal with data communication. Recent findings about the concatenation of power line and wireless media, which is called hybrid PLC-wireless (HP-W) medium [1], [2], is enlarging the usefulness and potential of electric power grids to assist the hungry demands for data communication in smart grids (SG) and the Internet of Things (IoT) devices. Economic issues sharpen the motivation for the use of HP-W media, as it give another usage for electric power grids [1], which is to perform data communication. Also, HP-W medium is a tool to introduce mobility in the well-established PLC systems.

In HP-W systems, a half duplex information flow can be established among devices or "things" physically connected to a power cable or through the air. In fact, HP-W systems take as advantage the use of electromagnetically unshielded power cable to exchange data-carrying signals among PLC and wireless devices, which are supposed to operate in the same frequency band. Basically, part of the data-carrying signal, which was injected by a PLC device, radiates to the air and this radiated signal can be sensed by a wireless device, which operate in the vicinity of the power line. On the other hand, a wireless device radiates its data-carrying signal in the surrounding environment and part of this radiated signal is induced into a power line and, as a consequence, it can be sensed by a PLC device [1]. Also, [1] showed impressive achievable data rates related to a measurement campaign carried out in seven residences. Such work showed that data communication through HP-W media is challenging since it can impose great attenuation and signal distortion due to frequency selectivity, besides the presence of colored additive noise.

Only few results on the usefulness of HP-W systems have been reported in the literature, as it can still be considered an incipient technology for assisting emerging applications, such as IoT, smart grid and smart city. Regarding in-home facilities, [2] addressed statistic analysis of parameters applied to analyze the suitability of HP-W media for data communication purposes; [3] discussed a statistical model of the channel frequency response (CFR) magnitude in in-home facilities; [4] dealt with the physical layer security of PLC system threatened by a malicious wireless device, and [5] focused on energy harvesting aspects related to these channels.

Aiming to advance HP-W systems, it is recognized the necessity of obtaining more insights about signal propagation characteristics regarding the wireless part of HP-W media , which is defined by the environment surrounding the power lines used by a PLC system. In this regard, this work offers an initial analysis of the wireless signal propagation of HP-W channels. Considering the frequency band delimited by 1.7 MHz and 100 MHz, a measurement campaign carried out in a building facility is detailed. The measures show that HP-W channels attain average channel attenuation (ACA) lower than 17 dB and average data rates ranging from 10 Mbps up to 1200 Mbps, which agree with [1],[2]. Moreover, the power spectral densities (PSD) of the measured additive noise agree with [1]. Consequently, similar performances are attained in different indoor facilities, such as home and building. Moreover the footprint associated with the wireless signal propagation part of PLC-wireless channels, which was obtained from the data set provided by the measurement campaign, shows that high data rates can be attained considering wireless distances up to 6 meters from PLC devices.

The rest of the work is organized as follows: Sec. II formulated the investigated problem; Sec. III discussed the measurement setup; Sec. IV addresses the measurement campaign;

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[1]Electric power grids were designed and deployed for delivering energy to consumers.

Sec. V discusses numerical results; and, finally, conclusions are stated in Sec. VI.

II. Problem formulation

According to [1], expressive data rates can be offered by HP-W systems. However, information about power cable location inside the residences were not available during the measurement campaign reported in [1]. As a consequence, it does not allow us to infer the influence of power line location in the signal propagation associated with this channel. Also, wireless signal propagation associated with an HP-W channel were not addressed in [1]. This is another important issue because it can allow us to take come up with models for supporting the development of of HP-W systems.

In order to address both issues, assume that Fig. 1 illustrates the block diagram of an HP-W system. According to [1], $h(t,\tau) = h_{wp}(t,\tau) = h_{pw}(t,\tau)$, where $h(t,\tau)$ is the channel impulse response (CIR) in the time instant t for an impulse injected in τ, $h_{wp}(t,\tau)$ and $h_{pw}(t,\tau)$ are the CIRs covering the wireless to PLC and PLC to wireless transmission directions, respectively.

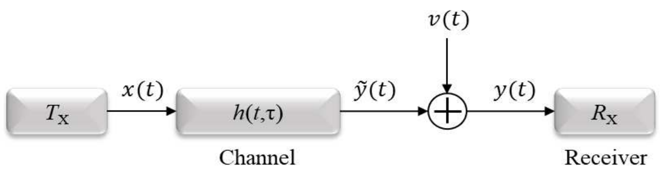

Fig. 1. The block diagram of an HP-W system, in which both wireless to PLC and PLC to wireless transmission direction apply.

Assuming PLC to wireless transmission direction and HP-W channel is linear and time invariant during a time interval shorter than the coherence time, the channel output is given by

$$y(t) = \int h(t-\tau)x(\tau)d\tau + v(t), \tag{1}$$

where $h(t)$ is a baseband and bandlimited CIR of a HP-W channel, $x(\tau)$ is the input signal and $v(t)$ is the additive noise (i.e., additive random process). Also, $h[n] = h(nT)$, the n^{th} sample of the L_h-length discrete time CIR of a HP-W channel, where $h(t)$ is the continuous time HP-W CIR, $T = 1/f_s$ is the sampling period and $f_s = 2B$ is the sampling frequency and B the frequency bandwidth of this channel. In its turn, $H[k], k = 0, 1, ..., 2N-1$ denotes the k^{th} coefficient of the HP-W CFR given by the discrete Fourier transform (DFT) of the HP-W CIR. In addition, $v[n]$ is the n^{th} sample of the additive random process.

Based on this formulation, a new measurement campaign can show the influence of the electric network topology in the HP-W channel. In this case, the knowledge of the exact position of the wires, belonging to the electric circuit of the PLC portion of an HP-W channel, is available. Moreover, a systematic measurement of several locations near the power line, through it the PLC signal propagates, can allow to characterize the wireless signal propagation associated with HP-W channels. Aiming to address both issues, Sections III and IV details the measurement setup and campaign for providing estimates of $n[n]$ and samples of $v[n]$. The use of these information will allow to anlyse both issue in Section V.

III. Measurement setup

The methodology adopted to estimate CFRs of HP-W channels is depicted in Fig. 2. This methodology relies on the use of the sounding technique, in which a well-designed signal is injected in a certain point and acquired in other point of a data communication medium. In other words, the HP-W channel is defined by the paths between both points. An estimate of the CFR of HP-W channels can be obtained after processing acquired signal and comparing it to the transmitted one. In this sense, the channel estimation methodology can be summarized in the following steps [7]:

- **Step # 1 - Signal generation and injection:** The sounding signal is assembled. It is composed of Hermitian symmetric orthogonal frequency division multiplexing (HS-OFDM) symbols [7], with discrete-time domain representation of finite length and equal to $2N + L_{cp}$, where N and L_{cp} denote the number of subcarriers and the length of cyclic prefix, respectively. These symbols are loaded into the signal generation board to performs the digital-to-analog conversion. The outputted analog signal is injected into the power line through a PLC coupler, which is responsible for blocking the mains signal (e.g., 60 Hz in Brazil) and avoiding damage of the signal generator board.
- **Step # 2 - Data acquisition:** An antenna is used as a probe to sense the portion of the signal that radiates from the power line to the air. A digitized version of this signal is stored by a data acquisition board. Note that only the direction from PLC device to wireless device is measured because [1], [2] demonstrated the symmetric property of these channels. Also, the knowledge of additive noise in in-home power lines is well-established in the literature.
- **Step # 3 - Offline processing:** A symbol synchronization technique is applied to the acquired signal in order to correctly extract all HS-OFDM symbols in the received signal. The symbol synchronization technique exploits the existing redundancy in the cyclic prefix [7]. After that, it is verified which transmitted HS-OFDM corresponds to each acquired and extracted HS-OFDM symbol, by using a correlation technique. Finally, CFR estimates of HP-W channel is obtained in the discrete frequency domain.

The values of the main parameters in the adopted methodology are listed in Tab. I [1]. With this set of parameters, each HP-W CFR corresponds to a time interval of, approximately, 23.04 μs, which is shorter than the coherence time of HP-W channels, reported in [2]. Also, the choice of N and B impose a frequency bandwidth of 48.8 kHz for each subchannel. Note that the frequency bandwidth is shorter than the coherence bandwidth of HP-W channels, as can be accessed in [2].

The measurement setup was assembled as follows: the signal generation board from Gage (CG4302) with 12 bits of resolution and 200 MHz of sampling frequency, set to your

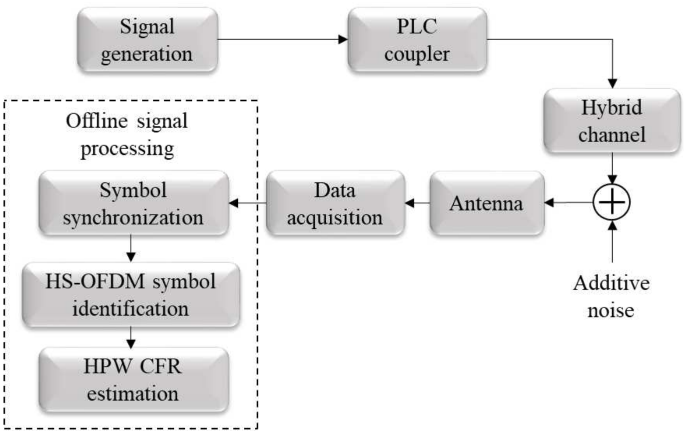

Fig. 2. Block diagram for the channel estimation methodology.

TABLE I

MAIN PARAMETERS OF THE CHANNEL ESTIMATION METHODOLOGY.

Parameter	Value
Sampling frequency	$f_s = 200$ MHz
HS-OFDM length	$2N = 4096$ samples
Cyclic prefix length	$L_{cp} = 512$ samples

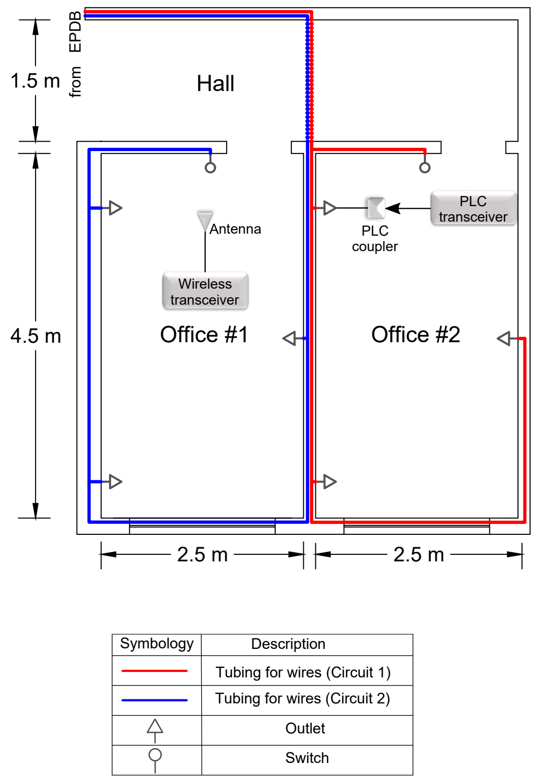

Fig. 3. Floor plant of the offices considered to carry out the measurement campaign.

maximum output range, which is of approximately ± 700 mV. The acquisition board was the Gage PCIe Digitizer with 14 bits of resolution and set to work at the same sampling frequency of the generation board. The PLC coupler was designed to block signals in frequencies below 1.7 MHz and offer small attenuation (e.g., below 5 dB) in the frequency band delimited by 1.7 MHz and 100 MHz. The antenna used as a probe was a telescopic one with 1.5 m of length.

IV. MEASUREMENT CAMPAIGN

By applying the measurement setup briefly described in Sec. III, a measurement campaign was carried out in a scenario composed of two neighbor offices, connected by a hall in which the floor plan can be accessed in Fig. 3. The left wall of the Office #1 is of masonry, as well as the walls at the bottom of the figure, while the other ones are made of polyvinyl chloride. These offices are part of a building in the Federal University of Juiz de Fora (UFJF). The offices have the same dimensions and each one has 11.25 m^2, while the hall has 7.5 m^2. Also, each office is fed by a distinct single phase and low-voltage electric circuity, composed of three outlets and one illumination point, from the same electric power distribution board (EPDB).

In the measurements, the sounding signal was injected only in the outlet named as TX which is composed of a PLC transceiver and a PLC coupler in Office #2. In its turn, the antenna used as a probe was placed in 55 different random locations inside the two offices and the hall facility. The probe was mounted in a support in order to keep it in the same position during all the measurements. In each probe position, two different signals were acquired: one when the sounding signal was injected into the power line, allowing the estimation of CFR of HP-W channels, and other signal related to the additive noise, turning off the signal generator. Finally, by adopting $f_s = 200$ MHz and the acquisition time of 5 ms, each measurement returned 190 consecutive CFR estimates of HP-W channels.

V. NUMERICAL RESULTS

The results presented in this section comprises the frequency bandwidth ranging from 1.7 MHz up to 100 MHz. Also, the parameters of HP-W channels analyzed in this work are the wireless signal propagation, which relies on the values of ACA, PSD of additive noise and achievable data rate.

A. Average Channel Attenuation

Assume each measurement (i.e., combination of the signal injection into the power cable and acquisition of radiated signal with an antenna) is constituted by M consecutive CFR estimates. In this regard, $H_m[k]$, with $k = 0, ..., N-1$ and $m = 0, ..., M-1$, denotes the k^{th} coefficient of the m^{th} HP-W CFR estimate, which is measured in a certain location. As a result, ACA can be calculated using [8]

$$\mathrm{ACA} = \frac{1}{M}\sum_{m=0}^{M-1} -10\log_{10}\left(\frac{1}{N}\sum_{k=0}^{N-1}|H_m[k]|^2\right) \qquad (2)$$

because it allows to reduce the additive noise influence in the CFR estimates. In this work, $M = 190$.

The maximum, minimum, mean and the standard deviation of the ACA considering all location of wireless receiver are listed in Tab. II. Also, two examples of CFR estimates related to HP-W channels showing the highest and lowest values of

TABLE II
ACA OF THE MEASURED HP-W CHANNELS.

Maximum	Mean	Minimum	Standard deviation
33.73 dB	30.38 dB	26.47 dB	1.53 dB

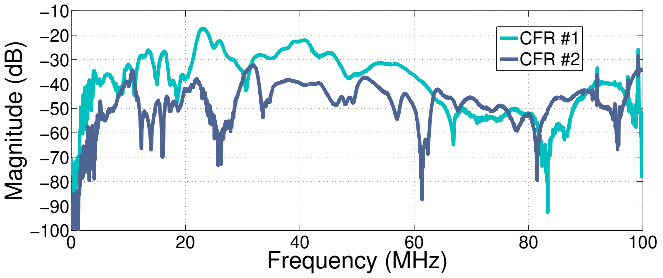

Fig. 4. The HP-W CFRs related to the highest and lowest ACA values observed.

ACA are represented, respectively, by magnitude functions named CFR #1 and CFR #2 in Fig. 4. It is worth noting that the magnitudes of CFRs estimates show high attenuation for the frequencies below 1.7 MHz because the PLC coupling device, in which was designed to perform this task. It can be observed that the values of ACA and their respective CFRs agree with [1], despite the measures have been performed in different environments.

B. Additive Noise

The maximum, mean and minimum PSD values of the additive noise measured in each considered position can be accessed in Fig. 5. As can be noted, the measured additive noise is notably composed of narrow band components as, for instance, those near 100 MHz are FM signals. The reported PSD is similar to the PSD associated with the additive noise in in-home facilities, see [1].

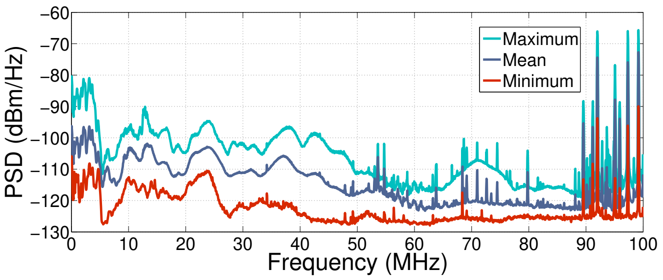

Fig. 5. PSD of the measured noise.

C. Achievable Data Rate

To obtain the achievable data rates, assume the HP-W channel is frequency selective, the additive noise is a colored Gaussian random process and the subchannel frequency bandwidth is shorter than the coherence bandwidth of the normalized signal to noise ratio. Then, the achievable data rate can be calculated using [2]

$$R = \max_{S_X[k]} \frac{B}{N}\sum_{k=0}^{N-1}\log_2\left(1+\frac{S_X[k]|H[k]|^2}{S_{\mathcal{N}}[k]}\right) \text{ [bps]}, \quad (3)$$

subject to $\frac{B}{N}\sum_{k=0}^{N-1} S_X[k] \leq P_X$, where $S_X[k]$ and $S_{\mathcal{N}}[k]$ are, respectively, the kth coefficient of the PSDs of transmitted signal and measured additive noise, while $B = 98.3$ MHz denotes the used frequency bandwidth.

The achievable data rates are shown in Fig. 6 as the PSD of the transmitted signal changes between -90 dBm/Hz and -50 dBm/Hz, in steps of 5 dBm/Hz. These results reflect the combination between the CFR estimated in each position with the maximum, mean and minimum values observed from the additive noise PSD, depicted in Fig. 5. In this case, the PSD of the transmitted signal comply with regulation constraints and, as a consequence, it is constant over the whole frequency band from 1.7 MHz up to 100 MHz. As can be seen, achievable data rates over 1 Gbps is reached when $S_X = -50$ dBm/Hz ($P_X \approx 1$ W), while more than 200 Mbps can be delivered with $S_X = -60$ dBm/Hz ($P_X \approx 100$ mW).

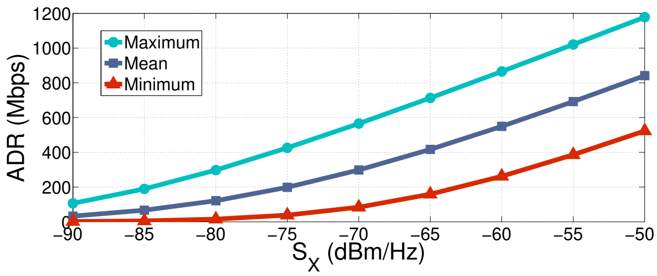

Fig. 6. Achievable data rate.

D. Wireless Signal Propagation

The footprint of ACA is the information applied to analyze the wireless signal propagation. In addition, the footprint of achievable data rate values are relevant to see the potential of HP-W channels for data communication purposes. In this sense, an interpolation among the estimated ACA values associated with the 55 positions is shown in Fig. 7. Also, the footprint related to achievable data rates when $S_X = -60$ dBm/Hz and the maximum PSD curve in Fig. 5 are adopted. The values obtained are a good approximation of reality, but it is worth mentioning that they can vary, since equation 3 used for the calculation of ADR represents the maximum transmission rate, and may have other factors not considered that influence the throughput.

Fig. 7 shows, as expected, the attenuation observed in the measurements performed inside Office #2 is lower in comparison to other positions in the Office #1. Regarding achievable data rates, higher values are attained inside Office #2 than inside Office #1, which agree with the higher values of ACA and the fact that the changes of the PSD of additive noise is

[2]Note that (3) is a discrete version of the achievable channel capacity of a frequency selective channel corrupted by a additive colored Gaussian noise in [9].

irrelevant regarding the location inside the office. Indeed, the lowest values of ACAs and achievable data rates observed in Office #2 occurs in the areas far from the location of electric circuit, in which the signal is being injected. Furthermore, as the electric circuit in Office #2 does not surround Office #1, an increase in ACA values can be observed in the region of Office #2, which is near the wall without the presence of power lines. These results show that HP-W channels are powerful for fulfilling a large range of data communication applications inside an office.

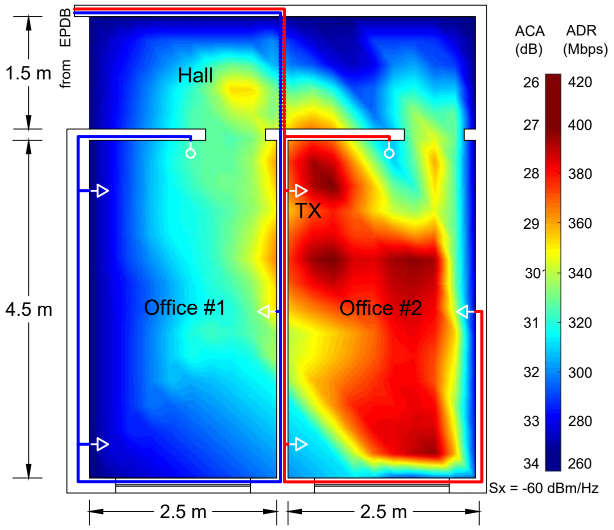

Fig. 7. ACA and ADR over the evaluated scenario.

The values of achievable data rates are higher than 200 Mbps in all locations. Under this circumstance, HP-W systems can be competitive to some wireless technologies, such as Bluetooth technology, in some applications. Also, a HP-W system can be an interesting option to provide high-speed mobile feature to novel generation of PLC systems, which is supposed to be flexible. Giving the achievable data rates associated with HP-W channels, Fig. 8 illustrates the scenarios in which HP-W systems may benefit applications demanding low and high data rates.

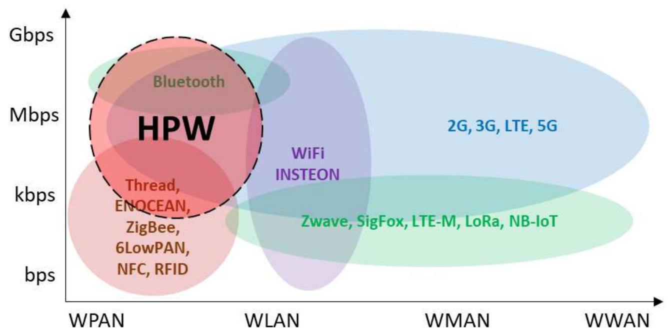

Fig. 8. Some data communication technologies.

VI. Conclusion

This work discussed a measurement campaign that was carried out to analyze the wireless signal propagation part of hybrid PLC-wireless channels in a building facility when the frequency band from 1.7 MHz up to 100 MHz is considered. The numerical results showed the agreement of the reported results with the ones presented in [1], [2], concerning ACA, PSD of the additive noise and achievable data rates. Moreover, these results showed that the wireless signal propagation part of hybrid PLC-wireless channels inside a building can surpass hundreds of Mbps if the wireless device is located up to 6 meters far from the PLC device. As a consequence, HP-W systems can compete with wireless technologies designed to cover distances of few meters and high data rates.

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