Dedicated Energy Harvesting in Concatenated Hybrid PLC-Wireless Systems

Victor Fernandes, H. Vincent Poor, *Fellow, IEEE*, and Moisés V. Ribeiro, *Senior Member, IEEE*

***Abstract*— This work addresses the use of hybrid power line-wireless channels, which are defined as the concatenation of power line communication (PLC) and wireless communication (WLC) channels, for dedicated energy harvesting purposes in in-home facilities. Based on a measured data set of hybrid PLC-WLC channels, we discuss statistical analyses concerning distinct power masks and two different regions that are associated with typical distances from the electric power grids to the wireless device. Moreover, based on the harvested energy from the hybrid PLC-WLC channels, we report the achievable data rates for data communication through narrowband PLC and WLC channels as well as through the hybrid PLC-WLC channels. The analyses show that feasible values of energy can be harvested from the hybrid PLC-WLC channels and that the high power nature of the PLC noise significantly contributes to the total harvested energy. Finally, we point out that interesting achievable data rates can be attained when the harvested energy is used for data communication purposes.**

***Index Terms*— Achievable data rate, energy harvesting, power line communication, wireless communication.**

I. Introduction

THE advance of energy-efficient and self-sustainable networks is a trend that is highly related to smart grid (SG), the Internet of Things (IoT), and Industry 4.0. As part of this trend, telecommunications technologies are being investigated, specified and designed to be flexible and adaptable. In this sense, the use of cognitive, full-duplex, massive MIMO, cooperative communication concepts that are capable of optimizing channel resources for data communication purposes is being deeply studied. However, the evolution of these technologies collides with limitations on the available sources of energy at untethered terminals.

Currently, power line communication (PLC) systems [1]–[3] have been considered as powerful technologies for assisting the aforementioned applications because the PLC devices are physically connected to the electric power grids and, as a consequence, they can easily harvest flowing energy through the electric power grids. Furthermore, the use of wireless communication (WLC) systems is being systematically reported as very convenient for fulfilling the needs and demands related to the aforementioned applications, as pointed out in [4]. The major advantages of WLC systems over PLC ones are the mobility due to the lack of necessity of physical connection of modems to a cable and the simplicity to built a wireless network.

Recently, the opportunity of harvesting energy from WLC sources, based on energy harvesting (EH) strategies [5], [6], has been investigated. Focusing on the EH strategies for PLC systems, a few works have addressed this topic in the literature [7]–[9]. More specifically, [7] considered a dual-hop PLC system with an EH-relaying node and showed that it is possible to provide energy efficiency improvements of more than 30% in comparison to the conventional relaying scheme when energy is harvested from the impulsive noise. In the sequel, [8] extended this conclusion by relating the noise impulsiveness with the harvested energy amount. As well, [9] showed that the non-flat power spectral density (PSD) feature of the PLC additive noise contributes to the increase of the achievable data rate of a hybrid power line/wireless dual-hop system with an energy harvesting relay. An interesting and missing point in these contributions is the lack of discussion based on measurements to confirm the veracity of these statements.

Different from the aforementioned works, this paper addresses dedicated energy harvesting in hybrid PLC-WLC[1] channels, which are the result of the concatenation of PLC and WLC channels. In the hybrid PLC-WLC systems, the PLC and WLC channels are not used in parallel for the purpose of increasing diversity [10]–[13], but in a concatenated configuration so that a PLC or WLC device can harvest energy from this kind of channel in indoor and outdoor facilities. This data communication medium, defined as the hybrid PLC-WLC medium, is constituted by unshielded power cables belonging to the electric power grids and the air. In addition

Manuscript received February 22, 2019; revised January 10, 2020; accepted February 17, 2020. Date of publication March 12, 2020; date of current version June 10, 2020. This work was supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES) under Grant 001, in part by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), in part by Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), in part by Financiadora de Estudos e Projetos (FINEP), in part by Instituto Nacional de Energia Elétrica (INERGE), in part by Smarti9 LTD, and in part by the U.S. National Science Foundation under Grant CCF-0939370, Grant CCF-1513915, and Grant CCF-1908308. The associate editor coordinating the review of this article and approving it for publication was L. Galluccio. *(Corresponding author: Victor Fernandes.)*

Victor Fernandes is with the Department of Electrical Engineering, Federal University of Juiz de Fora, Juiz de Fora 36036 330, Brazil, and also with the Electrical Engineering Department, Centro de Ensino Superior de Juiz de Fora (CES/JF), Campus Academia, Juiz de Fora 36016 000, Brazil (e-mail: victor.fernandes@engenharia.ufjf.br).

H. Vincent Poor is with the Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA (e-mail: poor@princeton.edu).

Moisés V. Ribeiro is with the Department of Electrical Engineering, Federal University of Juiz de Fora, Juiz de Fora 36036 330, Brazil, and also with the Smarti9 LTD., Juiz de Fora 36036 330, Brazil (e-mail: mribeiro@engenharia.ufjf.br).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TWC.2020.2978825

[1]The use of hyphen between PLC and WLC means that the channel concatenation takes place.

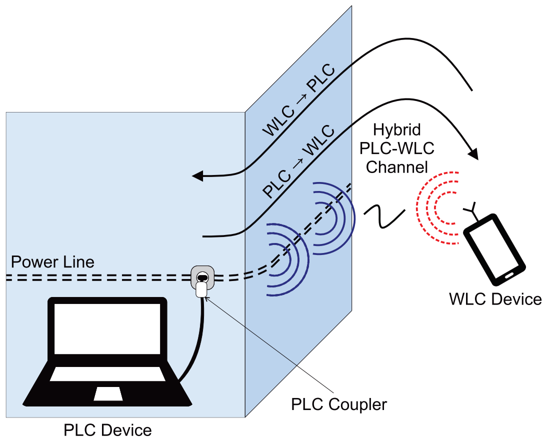


Fig. 1. The hybrid PLC-WLC environment in in-home facilities.

to establish a data communication system constituted by PLC and WLC devices operating in the same frequency band, the main idea is to use the electromagnetic characteristic of unshielded power lines for energy harvesting purpose. A pivotal work had offered the first characterization of this kind of channel by means of statistical characterization of average channel gain, coherence bandwidth, coherence time, root mean squared delay spread, and channel capacity [14]. Further, a second study has made the statistical modeling of these parameters [15]. However, none of the aforementioned works focus on the energy harvesting perspective for this kind of channel.

According to [14], a typical illustration of the hybrid PLC-WLC medium can be shown in Fig. 1. In this setting, the signal carrying information (transmitted signal) can travel in two possible and opposite directions because the same frequency band is used for data communication by both PLC and WLC devices. In the first direction, which is named PLC-to-WLC (PLC → WLC), the transmitted signal is injected into the power line by a PLC device through a PLC coupler and, posteriorly, its distorted version is captured by a nearby WLC device using an antenna that is capable of sensing the energy radiated by electromagnetic shieldless power lines. On the other hand, the signal injected into the air by a WLC device with the use of an antenna is induced into the power line and the induced signal is later extracted from the power line by the PLC device, defining the so-called WLC-to-PLC (WLC → PLC) direction. It is important to emphasize that both PLC and WLC devices operate in the same frequency band, which is supposed to be in the baseband.

Aiming to provide a comprehensive and deeper investigation of energy harvesting in this medium, this contribution focuses on the additive noise's energy as well as the energy coming from the signal that traveled in the hybrid PLC-WLC channels (so-called free-of-noise (FoN) received signal). In this regard, some power masks are considered for evaluating the effectiveness of energy harvesting in these channels if the dedicated energy harvesting approach applies. Concisely, the main contributions of this work are as follows:

- The presentation of the hybrid PLC-WLC channel and additive noise formulations in terms of the harvested energy, the expected harvested energy, and the time interval to achieve a specified amount of energy at the receiver side by considering the PLC → WLC and WLC → PLC link directions. Also, the statistical analyses of this kind of channel and the additive noises for harvesting energy based on five transmission power masks and the use of a measured data set of indoor hybrid PLC-WLC channels, which are associated with two relevant sets of distances between the WLC device and the power line.
- A comparative discussion about the energy contributions of the FoN received signal and the additive noise in the PLC → WLC and WLC → PLC directions for EH purposes and the quantitative evaluation of the theoretically achievable data rates of indoor narrowband PLC and WLC channels if only the energy harvested from the hybrid PLC-WLC channels is available. As well, the same achievable data rate analysis is made when the hybrid PLC-WLC channel is used as both the source of energy and the communication medium.

According to the aforementioned analyses, the following statements are made:

- Based on the measured data set, we show that the energy harvested from the FoN received signal can achieve feasible values with high probability in both PLC → WLC and WLC → PLC directions. Also, the type of power mask significantly impacts the amount of harvested energy. Further, numerical results show that the high power nature of the PLC noise greatly contributes to the amount of harvested energy from the received signal at the input of the PLC device. As well, the WLC noise, which is at the input of the WLC device, yields a significant contribution to the total harvested energy.
- The attained values of achievable data rates based on the energy harvested from the hybrid PLC-WLC channels in narrowband PLC and WLC channels as well as in hybrid PLC-WLC channels may be feasible for assisting the implementation of SG, IoT, and Industry 4.0 solutions when the availability of energy is limited.

The rest of this work is organized as follows: Section II formulates the problem investigated in this contribution. Section III details the energy harvesting in hybrid PLC-WLC channels while Section IV describes how the dataset was obtained based on the measurement setup and campaign. In the sequel, Section V discusses numerical results. Finally, Section VI provides concluding remarks.

II. Problem Formulation

At the beginning of the XX Century, the electromagnetic shieldless of power lines was exploited for data communication purposes [16]; however, the limitation of communications technologies at that time did not allow its further development. As a consequence, the electromagnetic shieldless characteristic of power lines has only been treated as a relevant problem for telecommunication systems operating in the same frequency band (e.g., interference with amateur radio, policy radio, etc) [17]–[19]. Recently, [14] has presented an interesting investigation about the concatenated hybrid PLC-WLC medium by means of a measured data set, which was obtained from a measurement campaign carried out to characterize these channels in in-home facilities. Essentially, it was shown that the shieldless feature of the power lines can potentially benefit indoor data communication. Indeed, this work concluded that PLC and WLC devices can communicate with each other if both of them operate in the same frequency band and, most important, data rates as high as hundreds of Mbps may be achieved if the frequency band between 1.7 and 100 MHz applies. Furthermore, this pivotal analysis showed that the PLC → WLC and WLC → PLC channel impulse responses (CIRs) are symmetric and, therefore, their channel frequency responses (CFRs) are the same in both directions if the access impedance of the PLC and WLC devices are equal (i.e., 50 Ω). On the other hand, the additive noises, which are named PLC noise and WLC noise, are different.

With the recent advances in the self-sustainable and energy-efficient networks, the concept of EH was brought to the center of discussion [20] regarding the usability of data communication media for feeding communication nodes. The main idea behind EH is to capture the energy from ambient or dedicated sources of power that are constantly present in the environment. More specifically, dedicated radio frequency (RF) sources have been studied [21]–[23] in order to charge the battery of a data communication node that makes use of an intermittent or even unavailable source of power.

Based on the fact that the nodes, which constitute a data communication system operating over the concatenated hybrid PLC-WLC medium, can be connected to the power line or to the air, the EH becomes a timely research problem for investigation. In fact, the quantification of the harvested energy from this kind of ambient is appealing because the presence of signal carrying information, which is transmitted through PLC and other signals (i.e., WLC operating in the same bandwidth and man-made noise), are sources of power which can potentially be used for charging batteries. As a matter of fact, this quantification is a *sine qua non* condition for properly verifying the feasibility of the concatenated hybrid PLC-WLC medium for EH purposes and, as a consequence, for powering a node with self-sustainable energy capacity. Also, it is relevant to point out that the electromagnetic unshielded nature of power lines means that radiated and induced signals can be sensed by WLC or PLC devices, respectively. In other words, the use of PLC or WLC devices always result in energy losses if a WLC or PLC device is not used for harvesting the radiated or induced energy, respectively.

In this regard, we aim to answer the following research questions: i) *Could we extract a significant amount of energy from the transmitted signal propagating through a concatenated hybrid PLC-WLC medium in the PLC → WLC or WLC → PLC direction*?; ii) *In terms of harvested energy, the additive noise at the input of PLC and WLC devices may be useful*?; and, finally, but not the least, iii) *Quantitatively speaking, what is the theoretical channel achievable data rate that can be obtained by means of the dedicated energy harvesting from the hybrid PLC-WLC channels*?

III. Harvesting Energy From the Concatenated Hybrid PLC-WLC Channels

For carrying out mathematical analyses, the term hybrid PLC-WLC channels will designate both PLC → WLC and WLC → PLC concatenated channels, in which the symmetry property of the CIR associated with both links applies, and $q \in \{\text{PLC} \rightarrow \text{WLC}, \text{WLC} \rightarrow \text{PLC}\}$ will denote the data communication link associated with the two directions. Assuming that a hybrid PLC-WLC channel is modeled as a linear and time-varying stochastic process, then the output of the time-varying and stochastic channel (e.g., the received signal) is a random process that is represented by

$$\begin{aligned} Y^q(t) &= \tilde{Y}^q(t) + V^q(t), \\ &= \int_{-\infty}^{\infty} X^q(\tau) h^q(t,\tau) d\tau + V^q(t), \end{aligned} \tag{1}$$

in which $X^q(t)$ is a sample function of the transmitted signal; $h^q(t,\tau)$ is a sample function of the CIR of the hybrid PLC-WLC channel at the instant t when an impulse is applied at the instant τ at the channel's input; and $V^q(t)$ is the sample function of the additive noise at the receiver's input, which is modeled as a random process. It is important to highlight that $V^{\text{PLC}\rightarrow\text{WLC}}(t)$ refers to the (additive) WLC noise while $V^{\text{WLC}\rightarrow\text{PLC}}(t)$ represents the (additive) PLC noise. Furthermore, $\tilde{Y}^q(t)$ is a sample function of the FoN received signal. Also, note that $X^q(t)$ and $V^q(t)$ are independent stochastic processes.

A. FoN Signal's Received Power

Assume that $X^q(t)$ has a PSD equal to $S_X^q(f) = \rho^q(f) S_{\tilde{X}}^q(f)$ and the signal generated (i.e., the stochastic process) by the transmitter is expressed as $\tilde{X}^q(t)$ with a PSD of $S_{\tilde{X}}^q(f) = 1, B_w \geq f \geq 0$, in which B_w is the frequency bandwidth and $\tilde{X}^q(t)$ is an uncorrelated and wide sense stationary process. It is important to emphasize that $X^q(t)$ is the resulting signal after the submission of the generated signal to a bit and power allocation technique. The rationale for multiplying $S_{\tilde{X}}^q(f)$ by $\rho^q(f)$ is that its usage facilitates the application of a power mask, which is defined as $\rho^q(f)$, for powering the transmitted signal. In other words, $\rho^q(f)$ denotes the result of the allocation of the total transmission power, which is given by $\mathcal{P}_x^q = \int_{-\infty}^{\infty} \rho^q(f) df$, to transmit information through the hybrid PLC-WLC channel.

Let $H^q(t,f) = \boldsymbol{\mathcal{F}}\{h^q(t,\tau)\}$ be the CFR of the sample function of the hybrid PLC-WLC channel's CIR, in which $\boldsymbol{\mathcal{F}}\{\cdot\}$ is the Fourier transform operator. Furthermoe, we can state that the hybrid PLC-WLC channel CFRs are time-invariant during the coherence time, $T_c \in \mathbb{R}_+$, of such channels. Mathematically, $H^q(t,f) = H_i^q(f)|_{t \in [iT_c,(i+1)T_c]}, \forall i \in \mathbb{Z}_+$. That said, the received power from the FoN received signal at the output of a hybrid PLC-WLC channel within the time interval T_c is given by

$$\mathcal{P}_{\tilde{Y},i}^q = \int_{B_w} \rho_i^q(f) |H_i^q(f)|^2 df, \tag{2}$$

where $|H_i^q(f)|^2$ and $\rho_i^q(f)$ denote the squared magnitude of $H_i^q(f)$ and the power mask of the i^{th} channel realization, respectively.

Let $T_{AC} \in \mathbb{R}_+$ denote the cycle duration of the AC mains voltage, we rewrite (2) as

$$\mathcal{P}^q_{\tilde{Y},c} = \sum_{i=1}^{N_P} \mathcal{P}^q_{\tilde{Y},i} p_i \tag{3}$$

in which $\mathcal{P}^q_{\tilde{Y},c}$ is the FoN signal's expected received power per cycle, p_i is the probability of occurrence of $\mathcal{P}^q_{\tilde{Y},i}$ (or $H_i^q(f)$), and $\{N_P \in \mathbb{Z} | N_P = \lfloor T_{AC}/T_c \rfloor\}$, where $\lfloor x \rfloor = \max\{m \in \mathbb{Z} | m \leq x\}$.

B. Additive Noise's Received Power

When the additive noise comes to the center of the discussion, we need to apply distinct approaches to deal with PLC and WLC noises. First, we model the PLC additive noise as a cyclostationary random process [24]. As a consequence, the PLC noise has both periodic mean value and autocorrelation function with respect to the AC mains cycle. Furthermore, the WLC additive noise is modeled as a colored Gaussian random process. For both of them, we can evaluate the expected power per cycle as

$$\mathcal{P}^q_{V,c} = \frac{1}{T_{AC}} \int_{T_{AC}} |V^q(t)|^2 dt. \tag{4}$$

C. Total Harvested Energy per Cycle

Now, by assuming that the electronic circuit responsible for storing the energy harvested from the hybrid PLC-WLC channel makes use of an RF-to-DC efficiency factor [21], $\eta^q \in \mathbb{R}_+, 1 \geq \eta^q > 0$, the harvested energy during a time interval duration equal to T_{AC} can be expressed as

$$\begin{aligned} \mathcal{E}^q_Y &= \eta^q \ \mathcal{P}^q_{Y,c} T_{AC}, \\ &= \eta^q \ \mathcal{P}^q_{\tilde{Y},c} T_{AC} + \eta^q \ \mathcal{P}^q_{V,c} T_{AC}, \\ &= \mathcal{E}^q_{\tilde{Y}} + \mathcal{E}^q_V, \end{aligned} \tag{5}$$

where $\mathcal{E}^q_{\tilde{Y}}$ is a random variable that models the harvested energy from the FoN received signal of the hybrid PLC-WLC channel, while $\mathcal{E}^q_V$ is a random variable that models the harvested energy from the additive noise associated with the q direction. Further, $\mathcal{E}^q_Y$ is the random variable that models the total harvested energy (FoN received signal + additive noise) as well as the expected (total) received power per cycle is given by $\mathcal{P}^q_{Y,c}$. Each AC mains cycle yields a value of $\mathcal{E}^q_{\tilde{Y}}$ and $\mathcal{E}^q_V$. Moreover, expected value of $\mathcal{E}^q_{\tilde{Y}}$, $\mathcal{E}^q_V$, and $\mathcal{E}^q_Y$ are expressed as $\mu_{\mathcal{E}^q_{\tilde{Y}}} = \mathbb{E}\{\mathcal{E}^q_{\tilde{Y}}\}$, $\mu_{\mathcal{E}^q_V} = \mathbb{E}\{\mathcal{E}^q_V\}$, and $\mu_{\mathcal{E}^q_Y} = \mathbb{E}\{\mathcal{E}^q_Y\} = \mu_{\mathcal{E}^q_{\tilde{Y}}} + \mu_{\mathcal{E}^q_V}$, respectively, in which $\mathbb{E}\{\cdot\}$ denotes the expectation operator.

Furthermore, it is possible to associate the expected values of harvested energy at the receiver, which was obtained from the received signal (i.e., the FoN received signal, the additive noise, and the sum of both their contributions) with an specific time interval. In this context, the time interval to achieve an energy threshold at the receiver side can be calculated. More specifically, if this threshold is made equal to the energy of a single signal transmission, i.e. $E^q_x = \mathcal{P}^q_x T_{TX}$, then the receiver achieves this energy in a time interval given by

$$\Delta T^q_y = T_{AC} \frac{E^q_x}{E^q_y}, \tag{6}$$

in which $E^q_y = \{\mu_{\mathcal{E}^q_{\tilde{Y}}}, \mu_{\mathcal{E}^q_V}, \mu_{\mathcal{E}^q_Y}\}$ assuming, respectively, that the EH is obtained only from the FoN received signal, from the additive noise, or from both the FoN received signal and additive noise. Also, this notation is straightforwardly related to $y \in \{FoN, AN, T\}$ for the FoN received signal, additive noise, or total received signal, respectively. These time intervals are very important for designing real-time energy harvesting solutions or assessing the time period for charging the communication node's battery.

D. Harvesting Energy Based on Distinct Power Masks

Based on the fact that both PLC and WLC devices perform dedicated energy transfer through the hybrid PLC-WLC channels, it is important to investigate some typical situations in which the energy at the output of the hybrid PLC-WLC channel is available for being harvested. In this sense, we can come up with five different transmission power masks, $\rho^q(f)$, for being applied to the generated signal. These masks vary from the most practical (uniform power allocation) to the most theoretical (the availability of complete channel state information (CSI) for power allocation) assumptions. These power masks are described as follows:

- Power Mask # 1 (Uniform): in this case, the PLC or WLC device performs a uniform power allocation. In other words, the transmission power $\mathcal{P}^q_x$ is equally distributed all over the whole frequency bandwidth. Mathematically, $\rho^q(f) = \mathcal{P}^q_x / B_w, \forall f \in \mathcal{S}_{B_w}$, in which $\mathcal{S}_{B_w}$ denotes the range of frequencies which are contained in the frequency bandwidth.
- Power Mask # 2 (IEEE 1901): basically, the PLC or WLC device applies the power mask defined by the IEEE 1901 Standard [25], in which $\rho^q(f) = -55$ dBm/Hz is used in the frequency band covered by $1.7-30$ MHz and $\rho^q(f) = -85$ dBm/Hz applies in the remaining frequency band, which is delimited by 30 MHz and 100 MHz.
- Power Mask #3 (Uniform B_u): based on the knowledge of the statistical expectation of the squared magnitude of CFRs, which constitute the data set, $\overline{|H^q(f)|^2} = \mathbb{E}_i\left\{|H_i^q(f)|^2\right\}$, an uniform power mask is applied to a shorten frequency bandwidth $B_u < B$ by means of the median operator. For applying the median operator, we discretize $\overline{|H^q(f)|^2}$. To do so, we assume that the discrete-time representation of the statistical expectation of the CFRs squared magnitude of the hybrid PLC-WLC channel is given by

$$\overline{|H^q[k]|^2} = \overline{|H^q(f)|^2}|_{f=kf_s}, k = 0, 1, \ldots, 2N-1, \tag{7}$$

where $2N$ is the discretized CFR's length of the hybrid PLC-WLC channel and $f_s = 2B_w$ is the sampling frequency. This shortened frequency bandwidth, B_u, covers a range of frequencies that is centered at the frequency

$f_c = N_C f_s$, in which $\overline{|H^q[N_C]|^2} = \max_k\{\overline{|H^q[k]|^2}\}$ and, upper and lower, bounded by the frequencies $f_c \pm f_u$. Such bounds are given by maximizing B_u subjected to $10\log_{10}(\overline{|H^q[N_C]|^2} - \textbf{median}\{\overline{|H^q[\ell]|^2}\}) \leq A$ dB, where $\ell \in \{N_C - N_u, N_C - (N_u - 1), \ldots, N_C, \ldots, N_C + (N_u - 1), N_C + N_u\}$, $N_u = \lceil f_u/f_s \rceil$, and $\lceil x \rceil = \min\{n \in \mathbb{Z} | n \geq x\}$. Also, the median is chosen as the metric for this power mask because it neither has a high sensitivity to the $\overline{|H^q[k]|^2}$ variations over distinct frequencies, which is different behavior of mean and variance, nor a low sensitivity to it, which characterizes the mode. In the way it was designed, we ensure that $\overline{|H^q[\ell]|^2}$ has an odd length equals to $2N_u + 1$ and its median is given by the N_u-*th* term. That said, $\rho^q(f) = \mathcal{P}_x^q / B_u, \forall f \in \mathcal{S}_{B_u}$, in which $\mathcal{S}_{B_u}$ denotes the range of frequencies which follow this restriction.

- Power Mask #4 (Optimal B_o): in this situation, the power mask optimally allocates $\mathcal{P}_x^q$ to the set of frequency tones associated with the highest squared magnitudes of CFR. This kind of power allocation is performed in the frequency bandwidth equal to $B_o = \gamma B_w$, $1 \geq \gamma > 0$, and $\rho^q(f) = \mathcal{P}_x^q / B_o, \forall f \in \mathcal{S}_{B_o}$, in which $\mathcal{S}_{B_o}$ denotes the set of frequency bandwidths (consecutive or not) of the highest squared magnitudes of the CFR.
- Power Mask #5 (Single Tone): it is similar to the Power Mask #4, except that $\mathcal{P}_x^q$ is totally allocated to the single frequency tone associated with the unique highest squared magnitude of the CFR. The bandwidth of this sole tone is equal to the bandwidth occupied by one subchannel, B_s, i.e., $\rho^q(f) = \mathcal{P}_x^q / B_s, \forall f \in \mathcal{S}_{B_s}$, in which $\mathcal{S}_{B_s}$ denotes the range of frequencies occupied by the Single Tone with the highest squared magnitude value of the CFR.

It is important to emphasize that the data transmission (i.e., the FoN received signal) occurs in the frequency band from 1.7 to 100 MHz [25]. However, the EH is realized in the frequencies from 0 to 100 MHz. In this context, it is worthwhile to mention that the additive noise in the frequency band below 1.7 MHz is attenuated by the capacitive coupling circuit, which was designed with a cutoff frequency equal to 1.7 MHz. Although the low frequencies are not interesting for data communication purposes due to interference with AM broadcasting stations and others, its use can be advantageous in terms of energy harvesting because the high level of man made noise in this frequency band.

IV. Data Set

The data set of this work consists of several CFRs of hybrid PLC-WLC channels provided by [14], in which a measurement campaign was carried out in indoor facilities located at Juiz de Fora, a Brazilian city belonging to Minas Gerais State (see more details about the measurement places, methodology, equipment, and the PLC coupler, respectively, in [26]–[29]). During this measurement campaign, seven middle-class residences were taken into account. The measurement setup is based on the use of the methodology presented in [27] and equipment discussed in [28]. The block diagram of the adopted measurement setup is shown in Fig. 2. Basically, it was designed for measuring the hybrid PLC-WLC channel. This setup is composed of the following components [14]:

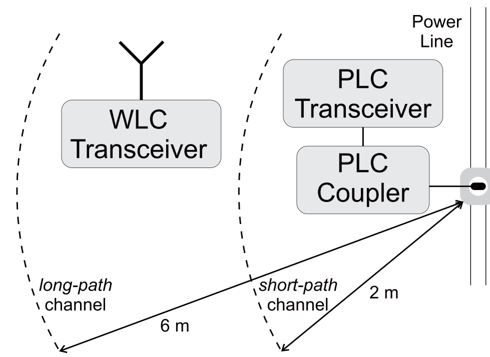


Fig. 2. The block diagram of the measurement setup.

- The PLC transceiver: it is connected to the outlet. It is responsible for injecting/receiving sounding signals into/from the electric power grids.
- The PLC coupler: it is a passband analog filter that promotes the interface between the PLC transceiver and the electric power grids, blocking the mains frequency to prevent damage to the PLC transceiver and limiting the maximum frequency of the injected/extracted signal (more details about its design can be found in [29]).
- The WLC transceiver: it refers to the device for transmitting data or receiving sounding signals through the wireless medium.
- The antenna: it is a transducer designed to inject/extract signals into/from the wireless medium by the WLC transceiver.

The following two kinds of hybrid PLC-WLC channels, which defines two ranges of distances from the power lines, were considered during the measurement campaign [14]:

- *short-path* (SP) Channel: the WLC transceiver was randomly positioned within a 2 meter radius circle centered at the outlet in which the PLC transceiver is connected. This kind of channel will be called hybrid SP PLC-WLC channel.
- *long-path* (LP) Channel: the WLC transceiver was randomly placed into an area defined as a swept circle, having an outer and inner radius of 6 meters and 2 meters, respectively, centered in the outlet in which the PLC transceiver is connected. The channel associated with LP channels will be called hybrid LP PLC-WLC channel.

The WLC transceiver was positioned near to (SP channel) and far from (LP channel) the outlet in 200 and 93 measurements, respectively. As a result, 293 distinct position combinations for both PLC and WLC transceivers were measured. Also, approximately 600 estimates of the CIR and, as a consequence, of their CFRs were obtained for each combination. Consequently, $175,428$ estimates of the hybrid PLC-WLC CFRs were obtained during the measurement campaign. In addition, samples of the PLC and WLC additive noises at the inputs of both PLC and WLC transceivers, respectively, were acquired. At the current work, we make use of the data set obtained by this measurement campaign.

It is important to emphasize that one CFR estimate is obtained during a time interval corresponding to one hermitian symmetric orthogonal frequency-division multiplexing (HS-OFDM) [30] symbol period duration (T_{sym}) and, as a consequence, it assumes that the time interval duration of the HS-OFDM symbol must be shorter than the coherence time of the hybrid PLC-WLC channel. Based on the set of parameters of the channel estimation technique, a channel estimate is obtained every $T_{\text{sym}} = (2N + L_{cp})T_s = 23.04\ \mu$s, where $N = 2048$ is the number of BPSK modulated subcarriers of the HS-OFDM symbol, $L_{cp} = 512$ samples is the length of the cyclic prefix, $f_s = 200$ MHz is the sampling rate, and $T_s = 1/f_s = 5$ ns is the sampling period. According to [14], $T_c = 156\ \mu$s is the minimum time period within which the hybrid SP PLC-WLC channel can be considered time-invariant, while for the hybrid LP PLC-WLC channel, the minimum time period of time invariance is $T_c = 39.5\ \mu$s. Regardless of the channel distances, the time interval duration to yield a CFR estimate (T_{sym}) complies with the coherence time. Moreover, the assumed value of N and the chosen frequency bandwidth results in CFR estimates with a corresponding frequency resolution of $\Delta f = 48.83$ kHz, which is shorter than the coherence bandwidth of Brazilian in-home hybrid PLC-WLC channels [14]. Δf being shorter than the coherence bandwidth means that each sample of the magnitude of a CFR estimates is representative of the whole subband and, as a consequence, it can be used for carrying out statistical analyses.

V. Numerical Results

This section focuses on numerical analyses of the harvested energy from the hybrid PLC-WLC channels when the data set of measured CFRs and additive noises described in Section IV is taken into account. Also, it offers a discussion about the achievable data rates of narrowband and indoor PLC and WLC channels as well as the ones obtained through the use of hybrid PLC-WLC channel, when the energy harvested from the hybrid PLC-WLC channels is considered the only available source. Based on the provided data set of measured hybrid PLC-WLC channels [14], the numerical simulations assume that $B_w = 100$ MHz, $B_u \approx 7$ MHz (with $A = 6$ dB and the frequencies ranging from approximately 20 MHz to 27 MHz, taken from the statistical average of the CFR squared magnitudes), $B_o = 10$ MHz ($\gamma = 0.1$ is heuristically chosen), and $B_s \approx 48.83$ kHz for the PLC $\rightarrow$ WLC and WLC $\rightarrow$ PLC directions; $\mathcal{P}_x^q \approx 20$ dBm is adopted based on the power mask of the IEEE 1901 Standard [25]; and $\eta^q = 1$ is chosen to illustrate the case of an ideal RF-to-DC conversion. Also, it is assumed that $T_{TX} = T_{\text{sym}}$ because it allows us to easily and quantitatively relate the harvested energy to a time interval necessary to reach a given energy threshold in terms of the time interval of an HS-OFDM symbol. Further, the Brazilian AC mains frequency is $f_{AC} = 60$ Hz, then $T_{AC} = 1/f_{AC} \approx 16.67$ ms and the realizations of each CFR are assumed to be equally likely ($p_i = 1/N_P, \forall i$).

Subsection V-A drives attention to the numerical results and discussions concerning the harvested energy only from the FoN received signal; Subsection V-B from the receiver's additive noise; Subsection V-C from the received (total) signal. In the sequel, the expected harvested energy is discussed in Subsection V-D, while the necessary time interval to achieve an energy threshold at the receiver side is analyzed in Subsection V-E. Finally, Subsections V-F and V-G focus on the numerical analyses of the achievable data rate when the harvested energy from the hybrid PLC-WLC channel is used for performing data communication through narrowband PLC or WLC channels and through hybrid PLC-WLC channels, respectively.

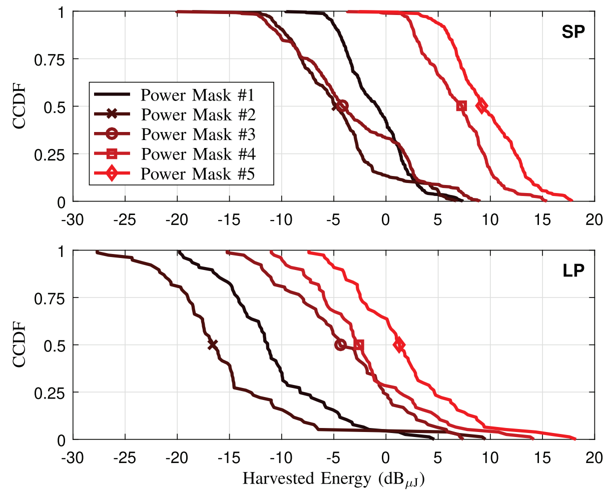


Fig. 3. The CCDFs of the harvested energy from the FoN received signal over a hybrid SP PLC-WLC channel (top) or hybrid LP PLC-WLC channel (bottom).

A. Free-of-Noise Received Signal Analyses

The discussion carried out in this subsection is useful to bring attention to the importance of choosing a power mask. In fact, this choice can either make an energy threshold to have a high or low probability of occurrence. Also, it can make a given probability of harvesting an energy value decreases to a lower one and vice-versa. It is important to highlight that the term FoN received signal is used to denote the transmitted signal that traveled through the hybrid PLC-WLC channel and is without the noise corruption.

The complementary cumulative distribution function (CCDF) of the harvested energy taken from the FoN received signal in both directions are shown in Fig. 3 for the hybrid SP PLC-WLC channel (top) and hybrid LP PLC-WLC channel (bottom), when the five suggested power masks are taken into account. Here, we define $\text{dB}_{\mu\text{J}} \triangleq 60 + 10\log_{10}(\text{Energy [J]})$. By means of this figure and for probabilities above 0.75, it can be seen that the best power mask is the Power Mask #5 for both SP and LP channels while the worst is the Power Masks #3 for hybrid SP PLC-WLC and the Power Masks #2 for hybrid LP PLC-WLC channels. It is important to point out that the Power Mask #1 yields better results than the Power Mask #2 because the highest values of CFR squared magnitudes occur around $26 - 50$ MHz frequency range (refer to Fig. 5 in [14]), in counterpart the Power Mask

#2 imposes the allocation of most of the power below the 30 MHz frequency.

For the Power Mask #4 and a given probability, the chosen $\gamma = 0.1$ makes this mask as the second better option in terms of harvested energy. Moreover, it may yield results ranging from the best to the worst (uniform) power masks due to its high flexibility. For instance, if $\gamma \rightarrow 0$, then this power mask mimics the Power Mask #5. On the other hand, if $\gamma \rightarrow 1$, then it will yield similar results to the Power Mask #1. As expected, due to the short distance to the power line and, as a consequence, less channel attenuation, hybrid SP PLC-WLC channels present higher values of harvested energy than hybrid LP PLC-WLC ones for a given probability.

Moreover, the use of the Power Mask #3 shows interesting behavior. It yields similar values of harvested energy from hybrid LP PLC-WLC channels compared to hybrid SP PLC-WLC channels, which is a different behavior to the other power masks. In other words, the CCDF of Power Mask #3 is located between the ones of Power Mask #1 and #2 for hybrid SP PLC-WLC channels and between Power Masks #2 and #4 for hybrid LP PLC-WLC channels. In this context, this shows that the criteria adopted for this power mask may not be good in order to better take advantage of the FoN received signal's energy in both SP and LP channels. Also, it is important to mention that this power mask is the one offering the best trade-off between theoretical (CSI availability) and practical (low complexity) assumptions.

That said, we will focus our numerical analyses mostly on Power Masks #1 and #2 because they are associated with the most practical assumptions due to their uniform shape and no CSI need. Regarding the hybrid SP PLC-WLC channels, it is noticed that 0 $\text{dB}_{\mu\text{J}}$ of energy can be obtained with a probability of 0.42 and 0.13 by using the Power Mask #1 and the Power Mask #2, respectively. Furthermore, the probability of 0.04 is achieved for the same 0 $\text{dB}_{\mu\text{J}}$ of harvested energy when hybrid LP PLC-WLC channels are considered for both Power Masks #1 and #2.

B. Additive Noise Analyses

The aim of this subsection is to figure out the usefulness of additive noises at the input of either PLC or WLC device for EH purposes. In this sense, Fig. 4 shows the CCDF of the harvested energy from the PLC and WLC noises. Note that PLC and WLC noises refer to the noises at the inputs of the PLC and WLC devices, respectively.

Based on Fig. 4, we see that the PLC noise offers higher values of harvested energy than the WLC one, for a given probability. Furthermore, if the target is to harvest at least 0 $\text{dB}_{\mu\text{J}}$ of energy from the noise, then the PLC noise has a probability of 0.77 and the WLC noise has only 0.47 of probability to yield it. In other words, the PLC noise, which is commonly considered as an unwanted signal, can bring a lot of benefits in terms of EH. For instance, if an energy of 5 $\text{dB}_{\mu\text{J}}$ is wanted, the WLC noise is not useful; however, the PLC noise has a probability of 0.60 of yielding this amount of energy. Also, it is important to note that most of the PLC noise's energy comes from the frequency band between

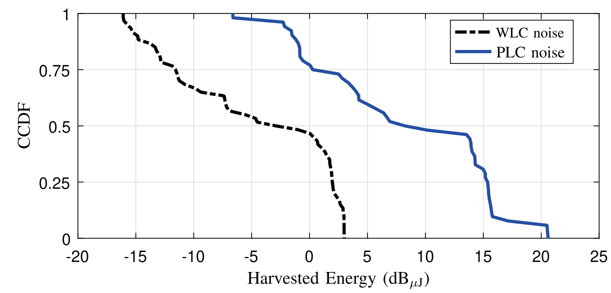


Fig. 4. The CCDFs of the harvested energy from the PLC and WLC noises.

$0 - 1.7$ MHz, which is due to the AM broadcasting stations and other man-made noise close to the low frequencies.

An important and necessary comparison involves the values of the harvested energy from the FoN received signal and additive noise. If the target is 5 $\text{dB}_{\mu\text{J}}$, then the Power Mask #1 achieves probabilities up to 0.03 and 0.0 for hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. A comparison among these probabilities with the ones offered by PLC (0.60) and WLC (0.0) noises shows that, sometimes, PLC noise can bring much more benefits in terms of EH than the FoN received signal. However, if the WLC additive noise is taken into account, then the FoN received signal may offer a higher contribution than this kind of noise. It is important to point out that this analysis heavily depends upon the chosen power mask.

C. Received (Total) Signal Analyses

In real and practical scenarios, the additive noise cannot be physically separated from the received signal. Therefore, this subsection contemplates the case in which the energy is harvested from the received signal, composed of FoN received signal and additive noise. In this context, Fig. 5 shows the CCDF of the harvested energy from the received signal at the output of hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively, when the receiver is the WLC device. Also, Fig. 6 shows the same kind of information when the receiver is the PLC device.

By performing a comparative analysis between Figs. 5 and 3, we notice similar trends in their plots (i.e., the order of the best to the worst power mask does not change, as expected). As a consequence, the results in Fig. 5 are similar to the ones discussed in Subsection V-A with a slight shift to the right, which corresponds to the WLC noise contribution to the harvested energy. When the discussion is about Fig. 6, a visible increasing on the values of the harvested energy is observed due to the high power of the PLC noise. For hybrid SP PLC-WLC channels, a probability of 0.70 for harvesting, at least, 5 $\text{dB}_{\mu\text{J}}$ of energy is observed with the Power Mask #1. On the other hand, regarding hybrid LP PLC-WLC channels and the same power mask and energy threshold, the value of probability decays to 0.67, which still is a good result.

The key rationale behind the distances among the CCDFs in Fig. 6 associated with hybrid SP PLC-WLC and hybrid LP PLC-WLC channels is the fact that in the former the

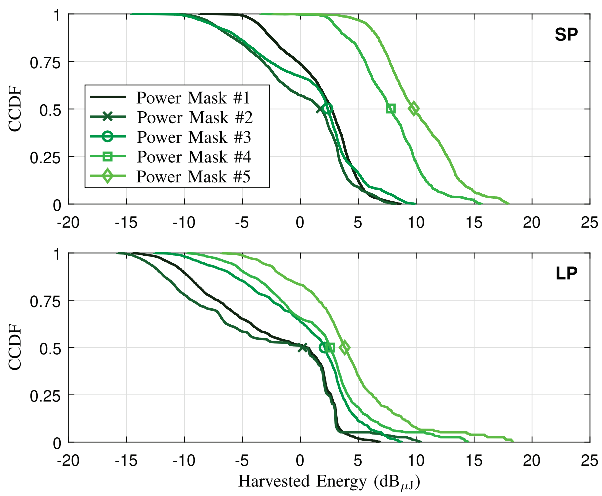


Fig. 5. The CCDFs of the harvested energy from the received signal in hybrid SP PLC-WLC channel (top) and hybrid LP PLC-WLC channel (bottom) considering the PLC → WLC direction.

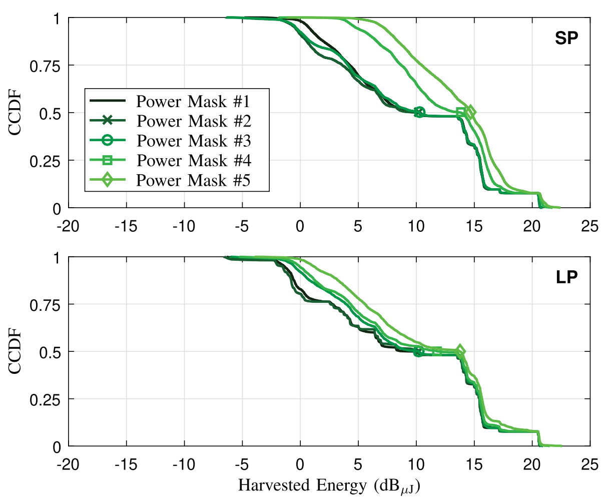


Fig. 6. The CCDFs of the harvested energy from the received signal in hybrid SP PLC-WLC channel (top) and hybrid LP PLC-WLC channel (bottom) considering the WLC → PLC direction.

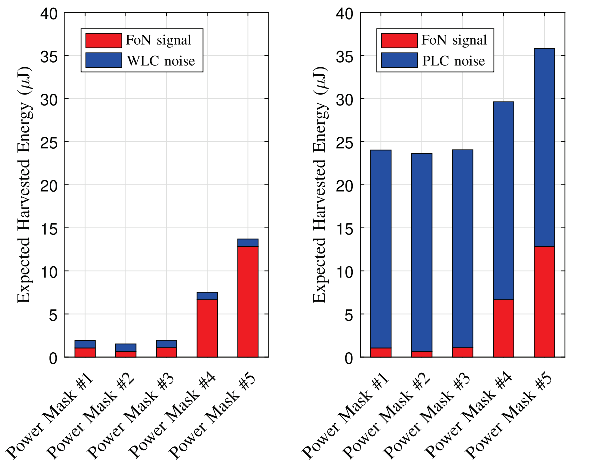


Fig. 7. The expected values of the harvested energy from the received signal in a hybrid SP PLC-WLC channel corrupted by the WLC (left) and PLC (right) noises, respectively.

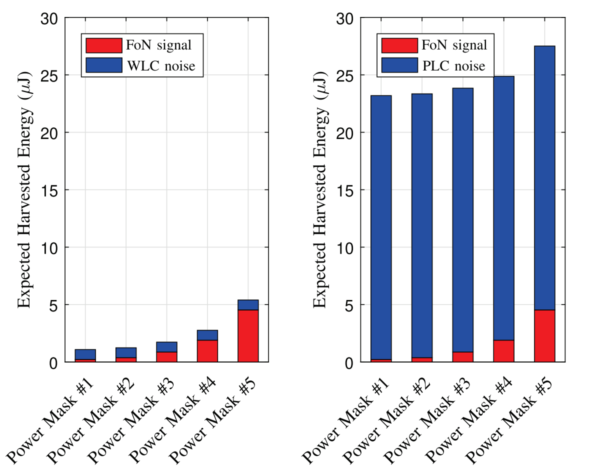


Fig. 8. The expected values of harvested energy from the received signal in a hybrid LP PLC-WLC channel corrupted by the WLC (left) and PLC (right) noises, respectively.

contribution of the FoN received signal is relevant, while in the latter the PLC noise has a greater contribution to the total harvested energy. Therefore, the power mask may not exert a very important role when the energy is harvested from the received signal if PLC noise is present.

D. The Expected Values Analyses

Figs. 7 and 8 show the expected values of the harvested energy from the FoN received signal ($\mu_{\mathcal{E}^q_{\tilde{Y}}}$) and the additive noise ($\mu_{\mathcal{E}^q_V}$) at the output of hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. These plots are interesting for revealing the individual contribution of each component of the received signal for energy harvesting purposes. Looking at Fig. 7 (hybrid SP PLC-WLC channels) and the Power Masks #1 and #2, it is shown that the FoN received signal contributes to a small amount of the harvested energy in comparison to the additive noise when a WLC device applies. Note that, the energy associated with the WLC noise is low in the mean sense. Further, the PLC noise shows the highest contribution to the harvested energy, for all power masks.

Furthermore, Fig. 8 (hybrid LP PLC-WLC channels) shows a clear difference between the expected harvested energy from the FoN received signal in terms of the power mask usage. Again, the amount of $\mu_{\mathcal{E}^q_V}$ from the PLC noise in Fig. 8 is greater than the one yielded by $\mu_{\mathcal{E}^q_{\tilde{Y}}}$ for all power masks. Nevertheless, the greatest contribution in the PLC → WLC direction comes from the FoN received signal in the Power Masks #4 and #5. In contrast, for all power masks, the highest contribution in the WLC → PLC direction is related to the additive noise because the PLC noise has a high power feature due to its PSD nature.

For instance, looking at the hybrid SP PLC-WLC channels (Fig. 7) and considering the Power Mask #1, the yielded expected harvested energy is 1.9 and 24.0 μJ, by considering WLC or PLC noise, respectively. For the same power mask and hybrid LP PLC-WLC channels (Fig. 8), these values are

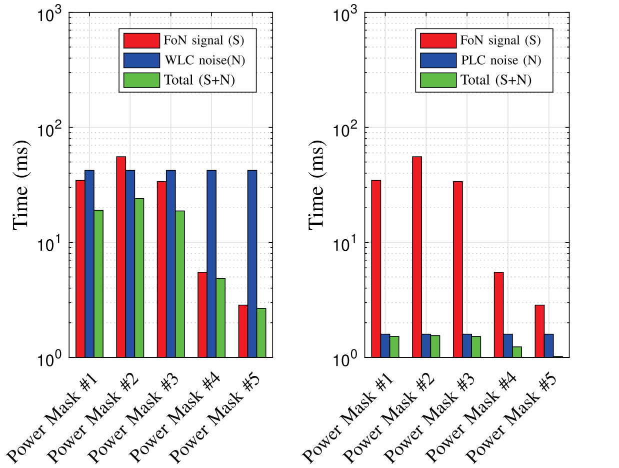


Fig. 9. The time interval to achieve E_x^q based on the expected harvested energy from the received signal over hybrid SP PLC-WLC channel corrupted by WLC (left) or PLC (right) noises.

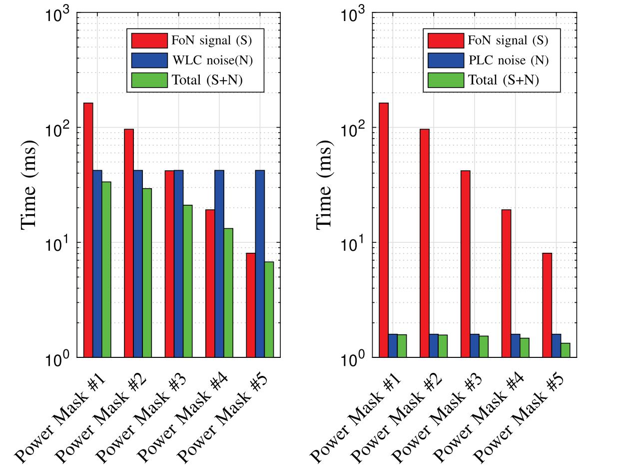


Fig. 10. The time interval to achieve E_x^q based on the expected harvested energy from the received signal over hybrid LP PLC-WLC channel corrupted by WLC (left) or PLC (right) noises.

1.1 and 23.0 μJ, showing a predicted, but low, decrease in the expected value of the harvested energy.

Overall, we point out that the WLC noise has a low contribution to the total amount of harvested energy in comparison to the PLC noise. On the other hand, the PLC noise constitutes the greatest portion of harvested energy in all of the cases associated with hybrid SP PLC-WLC and hybrid LP PLC-WLC channels.

E. Time Interval Analyses

Figs. 9 and 10 show the time intervals needed to yield the energy of a single signal transmission, which is chosen to be equal to $E_x^q = \mathcal{P}_x^q T_{TX} \approx 2.3$ μJ, at the receiver side when the energy is harvested only from the FoN received signal (ΔT_{FoN}^q), from the additive noise (ΔT_{AN}^q), and from the received signal (ΔT_T^q). The analysis of this subsection is important for evaluating the time interval that a receiver, with the same specifications of the transmitter, would demand in order to achieve the same amount of energy that was used in a single HS-OFDM symbol transmission by the transmitter. This comparison, which is in terms of the chosen power masks, addresses the hybrid SP PLC-WLC and hybrid LP PLC-WLC channels.

Concerning Fig. 9, it is important to mention that the WLC noise has a relevant energy harvesting contribution to the Power Masks #1, #2, and #3 because it takes around 42.3 ms to achieve E_x^q, which is close to the times needed by these power masks – 34.6 ms, 56.0 ms, and 33.0 ms, respectively – to achieve the same energy threshold. On the other hand, the PLC noise is a very good option for EH as it needs only 1.6 ms for yielding the same amount of energy.

When the discussion refers to the FoN received signal, the comparison between Fig. 9 (hybrid SP PLC-WLC channels) and Fig. 10 (hybrid LP PLC-WLC channels) is of utmost importance. The Power Mask #1 would take 34.6 ms or almost 162.9 ms to achieve E_x^q by only harvesting energy from the FoN received signal that travels through the hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. If the WLC noise is taken into account, these time intervals decrease to 19.0 and 33.6 ms, respectively. On the other hand, when the PLC noise is considered, these values reduce to 1.5 ms and 1.6 ms, respectively.

Overall, Figs. 9 and 10 confirm the fact that the PLC noise has a high contribution to the harvested energy. In other words, when the PLC noise and the Power Mask #1 are considered, the time interval necessary to achieve an energy threshold at the receiver side decreases $34.6/1.5 \approx 23.06$ and $162.9/1.6 \approx 101.81$ times in comparison to the sole use of the FoN received signal for harvesting energy from the hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. Furthermore, the energy associated with the WLC noise makes a relevant, but a lower impact in the resulting time interval when it is added to the energy related to the FoN received signal. Finally, but not the least, it is important to emphasize that the PLC additive noise is free of charge. Also, its harvesting can increase the quality of energy delivered by the electrical utilities.

F. Achievable Data Rate Analyses: Data Communication Through Narrowband Channels

This subsection aims at evaluating the performance of the narrowband PLC and WLC channels in terms of achievable data rate when the available transmission power is that one harvested from the received signal that traveled through the hybrid PLC-WLC channels. This is an important investigation because a large number of devices in SGs, the IoT, and Industry 4.0 demands low-data-rate communication interfaces.

In possession of the harvested energy, the achievable data rates of the narrowband-PLC (NB-PLC) and low power radio frequency (LP-RF) wireless channels are calculated by using

$$C = \max_{\varrho_j^\ell(f)} \int_{B'_w} \log_2 \left(1 + \frac{\varrho_j^\ell(f) S_{\tilde{X}}^\ell(f) |H_j^\ell(f)|^2}{S_V^\ell(f)} \right) df, \quad (8)$$

subject to $\int_{-\infty}^{\infty} \varrho_j^\ell(f) df \leq \mathcal{P}_{Y,c}^q$, in which $|H_j^\ell(f)|^2$ is the CFR squared magnitude of the sample function of the channel's

CIR associated with the ℓ^{th} communication medium, where $\ell \in$ {P,W} represents the NB-PLC and LP-RF wireless communication media and $j \in \mathbb{Z}$ is the index of the channel realization. Also, q and ℓ are related as follows: if $q =$ PLC $\rightarrow$ WLC, then $\ell =$ W, else $q =$ WLC $\rightarrow$ PLC, then $\ell =$ P. Further, the PSD of the signal generated by the transmitter is expressed as $S^{\ell}_{\tilde{X}}(f)$, in which $\int_{B'_w} S^{\ell}_{\tilde{X}}(f)df = 1$ with $B'_w \approx 500$ kHz being the frequency bandwidth. Also, $S^{\ell}_V(f)$ refers to the PSD of the ℓ^{th} communication medium receiver's additive noise, which is supposed to be modeled as a stochastic process.

In order to carry out numerical simulations regarding the NB-PLC and LP-RF wireless channels, the transmitted signal is assumed to occur in the industrial, scientific, and medical (ISM) frequency band (5.8 GHz) for wireless communication and in the narrow-regulated frequency band ($9 - 500$ kHz) for PLC [31]. The occupied frequency bandwidth is approximately 500 kHz in both media to ensure fairness.

Brief descriptions of the adopted NB-PLC and LP-RF wireless channel models are as follows:

NB-PLC Channel Model: we make use of the well-known Zimmermann and Dostert [32] channel model using the parameters taken from the IEEE 1901.2 standard [31, Annex D]. The additive noise in this NB-PLC channel is modeled as a zero mean colored Gaussian random process. Adopted from [33], its PSD is expressed by $S^P_V(f) = \eta/2 \exp(-\nu|f|)$ dBm/Hz, where $\nu, \eta \in \mathbb{R}_+$ are constants equal to 1.2×10^{-5} and 1.0×10^{-15}, respectively, and f is the frequency in Hertz.

LP-RF Wireless Channel Model: we obtained this channel from a wideband wireless one by adopting the procedure suggested in the 802.15.4a IEEE wireless channel model report [34]. Essentially, it is accomplished by filtering the wideband wireless channel model. The zero-mean circularly symmetric complex Gaussian assumption is made for the LP-RF wireless additive noise. From [35], the PSD of the additive noise in the LP-RF wireless channel is considered to be $S^W_V(f) = -173.8 + NF$ dBm/Hz, where the receiver noise figure NF is equal to 7 dB.

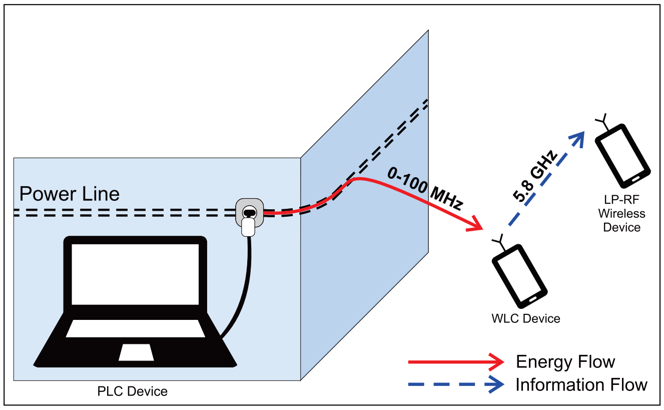
Furthermore, for the channel achievable data rate evaluation, it is relevant to assume that $\int_{B'_w} |H^P_j(f)|^2\, df = \int_{B'_w} |H^W_j(f)|^2\, df$ and $\int_{B'_w} S^P_V(f)df = \int_{B'_w} S^W_V(f)df$ due to the need for ensuring fairness. Also, we consider that the full CSI is available and the optimal power allocation is applied in $\varrho^{\ell}_j(f)$ by means of the water-filling (WF) technique [36]. Moreover, the PLC device, which realizes the data communication through NB-PLC channels, harvests its energy from the received signal at the output of the hybrid PLC-WLC channels in the WLC $\rightarrow$ PLC direction. On the other hand, the WLC device that performs data communication through the LP-RF wireless channels, harvests its energy from the received signal at the output of the hybrid PLC-WLC channels in the PLC $\rightarrow$ WLC direction. As well, the harvested energy in both cases is associated with a time interval equal to $T_{AC} \approx 16.67$ ms.

At this point, we come out with three distinct scenarios, they are:

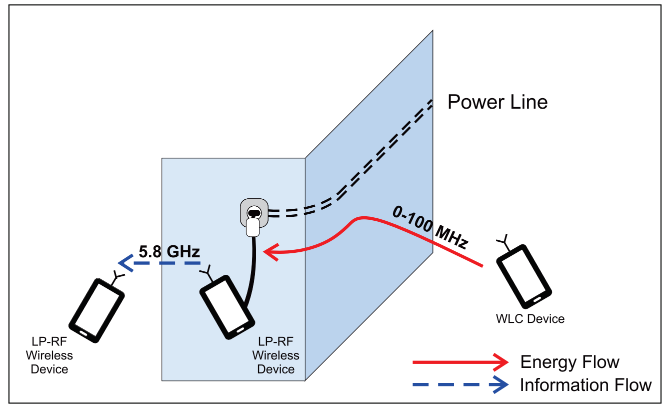
- Scenario #1 (Fig. 11(a)): the energy is harvested at the WLC device (energy harvester) from the hybrid PLC-WLC channel (PLC $\rightarrow$ WLC direction), assuming the use of the frequency band from 0 to 100 MHz. Therefore, the resulting energy is the sum of FoN received signal and WLC additive noise energies in this frequency range. After that, this amount of energy is used for data communication from this WLC device, which is supposed to be a LP-RF wireless device, to another LP-RF wireless device. In this case, the data communication is realized at one of the unlicensed ISM frequency band, which is centered at 5.8 GHz, with a frequency bandwidth of 500 kHz.
- Scenario #2 (Fig. 11(b)): a (energy harvester) PLC device harvests the energy from a WLC device by means of the hybrid PLC-WLC channel in the WLC $\rightarrow$ PLC direction by considering the frequency band delimited by 0 and 100 MHz. Thus, the energy extracted from this scenario is used for data communication from the aforementioned PLC device, which is supposed to be a NB-PLC, to another NB-PLC device at the frequency band from 9 kHz up to 500 kHz [31]. In this case, the total extracted energy is the sum of the FoN received signal and the PLC additive noise energies.
- Scenario #3 (Fig. 11(c)): a WLC device is connected to the power line outlet and it harvests the energy from the electric power grid by means of the hybrid PLC-WLC channel. It occurs in the frequency band delimited by 0 and 100 MHz. Thus, the energy extracted from this scenario is used for data communication from the aforementioned WLC device, which is a LP-RF wireless device, to another LP-RF wireless device with a frequency bandwidth of 500 kHz and centered at 5.8 GHz. Therefore, the total extracted energy is the sum of the FoN received signal and the PLC additive noise energies.

Also, assume that the communication through the hybrid PLC-WLC channel occurs during κT_{AC} seconds per AC mains cycle period, in which $0 < \kappa < 1 \in \mathbb{R}_+$. In other words, in the first scenario the PLC device is using its power to transmit information to the (energy harvester) WLC device during κT_{AC} seconds and the remaining $(1 - \kappa)T_{AC}$ seconds is available for data communication between this WLC device and its destination node, the LP-RF wireless device. At the second scenario, the WLC device uses its power to transmit information to the PLC device during κT_{AC} seconds, while the remaining $(1 - \kappa)T_{AC}$ seconds is available for data communication between the energy harvester PLC device and the NB-PLC device (destination node).

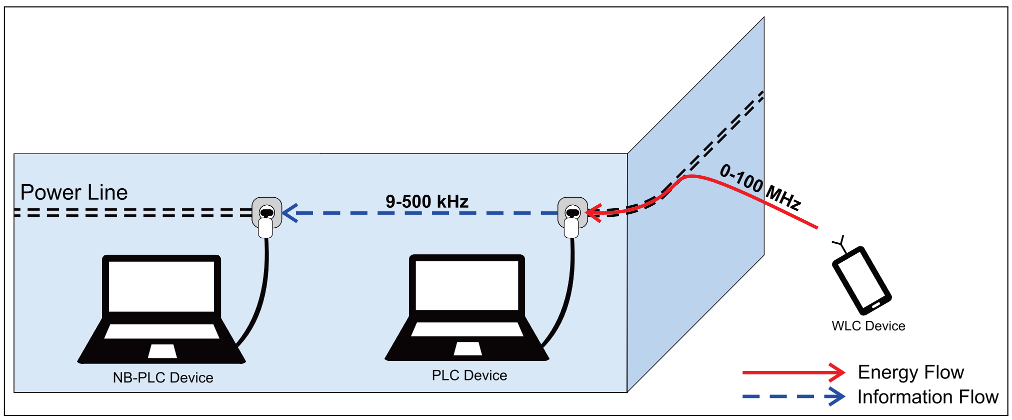
Concerning the third scenario, the WLC device is using its power to transmit information to the LP-RF wireless device during κT_{AC} seconds and $(1 - \kappa)T_{AC}$ seconds is used for data communication between the LP-RF wireless device that is connected to the electric power grid and another LP-RF wireless device. In the three cases, we assume $\kappa = 0.5$ and the use of the Power Masks #1 and #2 as they represent the most practical and implementable features. In fact, these power masks do not demand complete CSI as they have always the same power distribution pattern over the whole frequency bandwidth.



(a) Energy harvester WLC device with LP-RF wireless communication.



(c) Energy harvester LP-RF wireless device with wireless communication.



(b) Energy harvester PLC device with NB-PLC communication.

Fig. 11. Three distinct scenarios: (a) Scenario #1, (b) Scenario #2, (c) Scenario #3.

Fig. 12 shows the CCDFs of the achievable data rates for the Power Masks #1 (labeled as PM #1) and #2 (PM #2) in the Scenario #1 when EH is, respectively, carried out by means of a hybrid SP PLC-WLC channel (top) or hybrid LP PLC-WLC channel (bottom) with two distinct values of η^q, in which $\eta^q = 0.5$ is represented by dashed line and $\eta^q = 1$ is drawn in continuous line. The same information is depicted for the Scenario #2 in Fig. 13.

Looking at Fig. 12 (Scenario #1) and focusing on the Power Mask #1 with $\eta^q = 1$, the data communications through the LP-RF wireless channels yield, with a probability of 0.75, achievable data rates of, at least, 10 bps and 3 bps with the energy harvested from the hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. On the other hand, by inspecting Fig. 13 (Scenario #2), for the same power mask, $\eta^q = 1$, and probability value, the data communications through the NB-PLC channels offer more than 17 kbps and 15 kbps for the energy harvested from the hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. It is important to point out that the data communication through the NB-PLC channels achieves higher data rates due to the high power associated with the PLC noise, which was carefully discussed in the previous subsection.

When $\eta^q = 0.5$ (dashed lines), both the yielded achievable data rate and the probability of a given achievable data rate threshold reduces in comparison to $\eta^q = 1$, as it is expected. These figures represent a more realistic scenario,

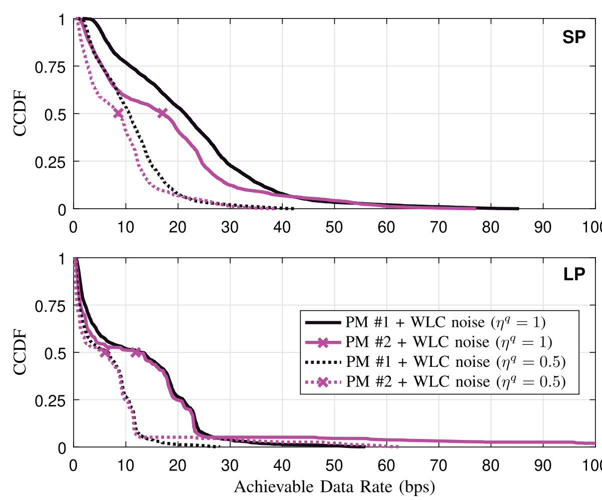


Fig. 12. The CCDFs of achievable data rates yielded by the energy harvester WLC device in Scenario #1 for $\eta^q = 1$ (continuous line) and $\eta^q = 0.5$ (dashed line).

in which the receiver is capable of harvesting only 50% of the energy associated with the received signal due to the RF-to-DC conversion factor (see Table III in [20] for more details). Furthermore, assuming a probability of 0.75 and the Power Mask #1, the LP-RF wireless channels yield an achievable data rate of, at least, 6 bps and 1 bps by using the energy harvested from the hybrid SP PLC-WLC and hybrid

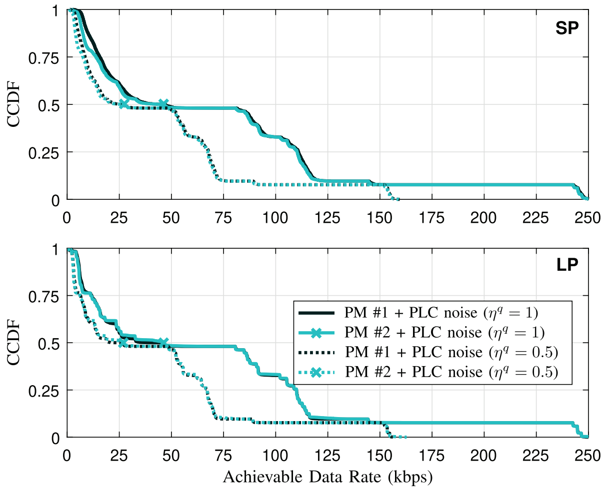


Fig. 13. The CCDFs of achievable data rates yielded by the energy harvester PLC device in Scenario #2 for $\eta^q = 1$ (continuous line) and $\eta^q = 0.5$ (dashed line).

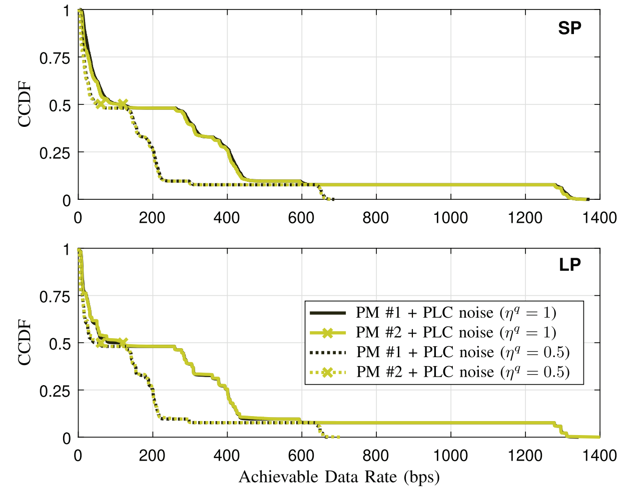


Fig. 14. The CCDFs of achievable data rates yielded by the energy harvester PLC device in Scenario #3 for $\eta^q = 1$ (continuous line) and $\eta^q = 0.5$ (dashed line).

LP PLC-WLC channels, respectively. Also, for the same probability threshold, the chosen power mask, ($\eta^q = 0.5$), the NB-PLC channels yield more than 9 kbps or 7 kbps with the energy harvested from either one of the hybrid SP PLC-WLC or hybrid LP PLC-WLC channel, respectively. This analysis illustrates the decrease of the achievable data rates when η^q reduces.

Although the values of achievable data rates have decreased with the use of $\eta^q = 0.5$, see the values for 0.75 of probability for example, these values – 6 bps (hybrid SP PLC-WLC channels) and 1 bps (hybrid LP PLC-WLC channels) for the LP-RF wireless channels and 9 kbps (hybrid SP PLC-WLC channels) and 7 kbps (hybrid LP PLC-WLC channels) for the NB-PLC channels – may be significant for fulfilling several low-data-rate demands associated with SG, IoT, and Industry 4.0 applications. Finally, but not the least, it is important to highlight that the harvested energy could be used in other applications or even for charging the battery of devices belonging to sensors networks.

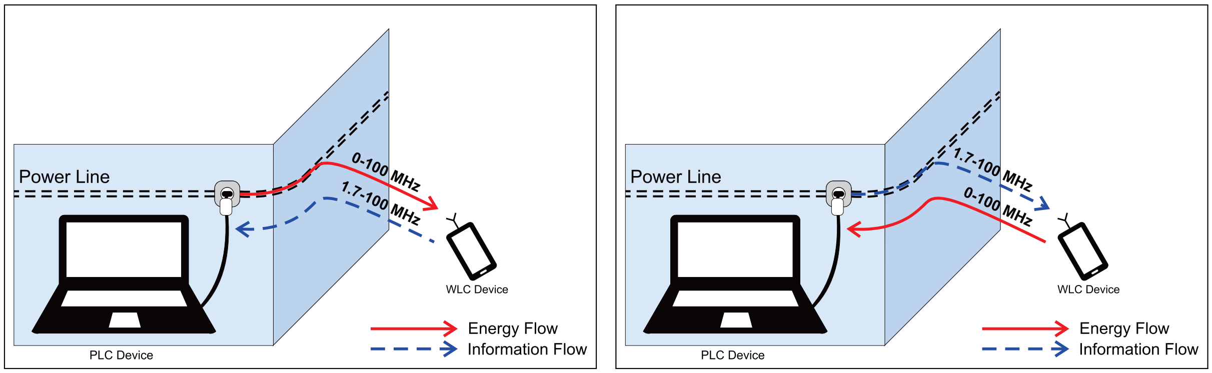
Regarding the third scenario, Fig. 14 shows the CCDFs of the achievable data rates for the Power Masks #1 and #2 in the Scenario #3 when EH is done by means of a hybrid SP PLC-WLC channel (top) or hybrid LP PLC-WLC channel (bottom) with two distinct values of η^q. In this scenario, the values of the achievable data rate are up to 1400 bps in both cases. However, when considering the high-probability ones (0.75), these values are 30 bps for the hybrid SP PLC-WLC channels and 22 bps for the hybrid LP PLC-WLC channels with both considered power masks. This scenario shows the usefulness of the EH together with hybrid channels for wireless communications applications. Also, it is important to emphasize that the PLC noise is being recycled and this process will improve the quality of energy delivery by electric utilities.

G. Achievable Data Rate Analyses: Data Communication in the Hybrid PLC-WLC Channel

In order to bring attention to the usefulness of the data communication through the hybrid PLC-WLC channel, we introduced another two scenarios. These scenarios are described as follows:

- Scenario #4 (Fig. 15(a)): the WLC device harvests energy from the hybrid PLC-WLC channel (PLC → WLC direction), assuming the use of the frequency band from 0 to 100 MHz. That is, the total harvested energy is the sum of FoN received signal and WLC additive noise energies. After that, this amount of energy is used for data communication from this WLC device to a PLC device thorough the hybrid PLC-WLC channel (WLC → PLC direction), in the frequency range from 1.7 to 100 MHz. Thus, the hybrid channel acts as a source of energy in the PLC → WLC direction and then it works as a communication medium in the WLC → PLC direction.
- Scenario #5 (Fig. 15(b)): the PLC device harvests the energy from the hybrid PLC-WLC channel in the WLC → PLC direction by considering the frequency band delimited by 0 and 100 MHz. In other words, the total harvested energy is the sum of FoN received signal and PLC additive noise energies. In the sequence, the energy extracted is used for data communication from the aforementioned PLC device to a WLC device (PLC → WLC direction) in the frequency band from 1.7 up to 100 MHz. Note that the frequencies under 1.7 MHz are not used for data communication due to the high interference with AM broadcast stations.

The mathematical formulation in the previous subsection is used to evaluated the achievable data rates of the hybrid PLC-WLC channels. For the sake of simplicity, we define $\overline{q} \triangleq$ PLC → WLC, if $q =$ WLC → PLC and $\overline{q} \triangleq$ WLC → PLC, otherwise. With this definition, we can easily indicated that the data communication occurs in the $\overline{q}^{th}$ direction while the energy flows in the opposite direction (i.e., the q^{th} one). Mathematically, we calculate the achievable data rate by means of (8) substituting ℓ with $\overline{q}$, therefore (8) is subject to $\int_{-\infty}^{\infty} \varrho_j^{\overline{q}}(f)df \leq \mathcal{P}_{Y,c}^{q}$. Here, both the CFRs and additive noise' PSDs are the ones obtained from the measured data set (see Section IV) and both are associated with $\overline{q}$. Furthermore,



(a) WLC EH device with WLC → PLC communication. (b) PLC EH device with PLC → WLC communication.

Fig. 15. Two distinct scenarios: (a) Scenario #4, (b) Scenario #5.

the PSD of the signal generated by the transmitter is $S_{\tilde{X}}^{\overline{q}}(f)$ with $\int_{B'_w} S_{\tilde{X}}^{\overline{q}}(f)df = 1$ and $B'_w \approx 98.3$ MHz being the data communication's frequency bandwidth. Also, $S_V^{\overline{q}}(f)$ refers to the PSD of the $\overline{q}^{th}$ communication direction receiver's additive noise. Moreover, we consider that the full CSI is available only for the data communication through the hybrid PLC-WLC channel, thus the optimal power allocation is applied in $\varrho_j^{\overline{q}}(f)$ with the use of WF technique.

In general, we make similar assumptions as the ones in the previous scenarios, i.e., that the energy harvester has κT_{AC} seconds per AC mains cycle period to perform EH while the remaining $(1-\kappa)T_{AC}$ seconds are used for data communication through the hybrid PLC-WLC channel in the opposite direction. As well, κ is made equal to 0.5 and the Power Masks #1 and #2 are applied.

In this sense, Fig. 16 shows the CCDFs of the achievable data rates for the use of the Power Masks #1 and #2 in the Scenario #4 when both EH and data communication are carried out by means of a hybrid SP PLC-WLC channel (top) or hybrid LP PLC-WLC channel (bottom), with $\eta^q = 0.5$ represented by dashed line and $\eta^q = 1$ in continuous line. The same information is shown in Fig. 17, for the Scenario #5.

Looking at Fig. 16 (Scenario #4), we can see that for Power Mask #1, $\eta^q = 1$, and a high probability (0.75), an achievable data rate of 9 and 1 Mbps can be yielded in hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively. In comparison, when assuming Scenario #5 (Fig. 17) and same power masks and conditions, these values increase to 57 and 4 Mbps for hybrid SP PLC-WLC and hybrid LP PLC-WLC channels, respectively.

Now, by assuming $\eta^q = 0.5$ with Power Mask #1 and a probability of 0.75, the Scenario #4 results in an achievable data rate of 6 and 1 Mbps, respectively, for hybrid SP PLC-WLC and hybrid LP PLC-WLC channels. When considering Scenario #5 with the previous assumptions as well, these values are 38 Mbps for the hybrid SP PLC-WLC and 2 Mbps for the hybrid LP PLC-WLC.

As expected, the decrease in the value of η, resulted in a reduction of the achievable data rate values for the same conditions. As well, it can be seen that the Power Mask #1 always outperforms the Power Mask #2. Lastly, but not

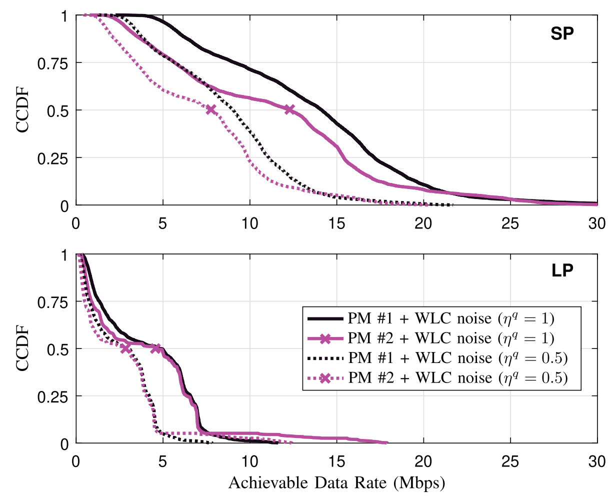


Fig. 16. The CCDFs of achievable data rates yielded by the energy harvester WLC device in Scenario #4 for $\eta^q = 1$ (continuous line) and $\eta^q = 0.5$ (dashed line).

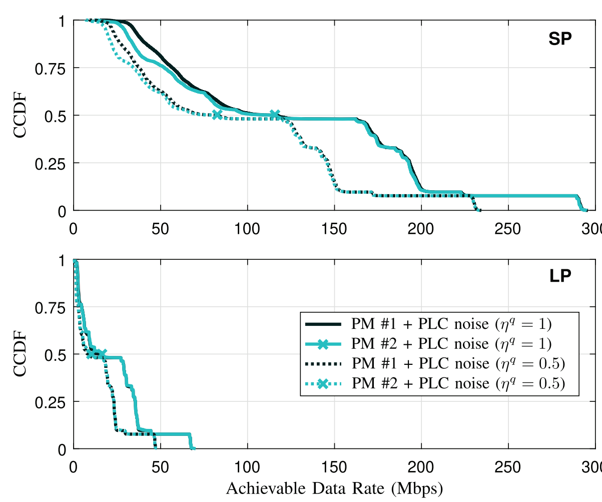


Fig. 17. The CCDFs of achievable data rates yielded by the energy harvester PLC device in Scenario #5 for $\eta^q = 1$ (continuous line) and $\eta^q = 0.5$ (dashed line).

the least, the achievable data rate values related to Scenarios #1 and #2 are lower than the ones obtained in Scenarios #4 and #5 mainly due to the use of a narrowband channel (NB-PLC and LP-RF wireless), in the former scenarios, while a broadband one (hybrid PLC-WLC channel) was used in the latter ones. This occurs because, the broader is the frequency bandwidth of a frequency-varying channel, the higher is the probability of occurrence of a high SNR value in a single subchannel, resulting in a better choice for optimal power allocation technique. Therefore, the values changed from dozens of bits or kbps to dozens of Mbps.

VI. Conclusion

In this work, we have formulated the use of the concatenated hybrid PLC-WLC channels for dedicated energy harvesting purposes. In particular, the CCDFs of the harvested energy from these channels have been evaluated for two different position regions, namely *short-path* and *long-path* and five power masks (Uniform, IEEE 1901, Uniform B_u, Optimal B_o, and Single Tone). Furthermore, the expected harvested energy and the time interval to achieve a specified energy threshold at the receiver side have been analyzed as well. Moreover, we have presented the achievable data rates for narrowband PLC and WLC channels as well as hybrid PLC-WLC channels, by using the harvested energy from the hybrid PLC-WLC channels in in-home facilities when the RF-to-DC conversion factor is equal to 1 (ideal) and 0.5 (practical).

Based on the numerical analyses of the data set of measured hybrid PLC-WLC channels, we have shown that the PLC noise significantly contributes to increase the harvested energy and to decrease the time interval to achieve an energy threshold due to the high power nature of this noise. Also, the attained results have shown how the harvested energy is impacted by the type of harvesting signal and the choice of the power mask. Lastly, but not least, we have concluded that the hybrid PLC-WLC channels are valuable for EH purposes because feasible values of energy can be harvested from this kind of channels with high probability. In this sense, the use of the harvested energy from this channels for data communication purposes may offer satisfactory low data rate for assisting SG, the IoT, and Industry 4.0 applications, even for the cases in which the RF-to-DC conversion factor is equal to 0.5, which constitutes a practical assumption.

References

[1] M. Nassar *et al.*, “Local utility power line communications in the 3–500 kHz band: Channel impairments, noise, and standards,” *IEEE Signal Process. Mag.*, vol. 29, no. 5, pp. 116–127, Sep. 2012.

[2] T. R. Oliveira, A. A. M. Picorone, S. L. Netto, and M. V. Ribeiro, “Characterization of brazilian in-home power line channels for data communication,” *Electr. Power Syst. Res.*, vol. 150, pp. 188–197, Sep. 2017.

[3] F. J. Cañete, J. A. Cortés, L. Díez and J. T. Entrambasaguas, “A channel model proposal for indoor power line communications,” *IEEE Commun. Mag.*, vol. 49, no. 12, pp. 166–174, Dec. 2011.

[4] L. de M. B. A. Dib, V. Fernandes, M. de L. Filomeno, and M. V. Ribeiro, “Hybrid PLC/Wireless communication for smart grids and Internet of Things applications,” *IEEE Internet Things J.*, vol. 5, no. 2, pp. 655–667, Apr. 2018.

[5] D. Mishra, S. De, S. Jana, S. Basagni, K. Chowdhury, and W. Heinzelman, “Smart RF energy harvesting communications: Challenges and opportunities,” *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 70–78, Apr. 2015.

[6] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. Liang Guan, “Wireless energy harvesting for the Internet of Things,” *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015.

[7] K. M. Rabie, B. Adebisi, A. M. Tonello, and G. Nauryzbayev, “For more energy-efficient dual-hop DF relaying power-line communication systems,” *IEEE Syst. J.*, vol. 12, no. 2, pp. 2005–2016, Jun. 2018.

[8] K. M. Rabie and B. Adebisi, “Enhanced Amplify-and-Forward relaying in non-Gaussian PLC networks,” *IEEE Access*, vol. 5, pp. 4087–4094, 2017.

[9] V. Fernandes, H. V. Poor, and M. V. Ribeiro, “A hybrid power Line/Wireless dual-hop system with energy harvesting relay,” *IEEE Internet Things J.*, vol. 5, no. 5, pp. 4201–4211, Jul. 2018.

[10] S. Güzelgöz, H. B. Çelebi, and H. Arsian, “Analysis of a multi-channel receiver: Wireless and PLC reception,” in *Proc. 18th Eur. Signal Process. Conf.*, Aug. 2010, pp. 1106–1110.

[11] S. W. Lai and G. G. Messier, “Using the wireless and PLC channels for diversity,” *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3865–3875, Dec. 2012.

[12] V. Fernandes, W. A. Finamore, H. V. Poor, and M. V. Ribeiro, “The low-bit-rate hybrid power line/wireless single-relay channel,” *IEEE Syst. J.*, vol. 13, no. 1, pp. 98–109, Mar. 2017.

[13] V. Fernandes, H. V. Poor, and M. V. Ribeiro, “Analyses of the incomplete Low-Bit-Rate hybrid PLC-wireless single-relay channel,” *IEEE Internet Things J.*, vol. 5, no. 2, pp. 917–929, Apr. 2018.

[14] T. R. Oliveira, F. Andrade, A. A. M. Picorone, H. Latchman, S. L. Netto, and M. V. Ribeiro, “Characterization of hybrid communication channel in indoor scenario,” *J. Commun. Inf. Syst.*, vol. 31, no. 1, pp. 224–235, Sep. 2016.

[15] T. R. Oliveira, A. A. M. Picorone, C. B. Zeller, S. L. Netto, and M. V. Ribeiro, “On the statistical characterization of hybrid PLC-wireless channels,” *Electr. Power Syst. Res.*, vol. 163, pp. 329–337, Aug. 2018.

[16] M. Schwartz, “Carrier-wave telephony over power lines: Early history [History of Communications],” *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 14–18, Jan. 2009.

[17] M. Gebhardt, F. Weinmann, and K. Dostert, “Physical and regulatory constraints for communication over the power supply grid,” *IEEE Commun. Mag.*, vol. 41, no. 5, pp. 84–90, May 2003.

[18] *Electromagnet Compatibility (EMC)—Part 3: Limits-Section 8: Signaling on Low-voltage Electrical Installations–Emission Levels, Frequency Bands and Electromagnet Disturbances Levels*, IEC, document 610003-8, Geneva, Switzeland, 2002.

[19] *Code of Federal Regulations-Title 47: Telecommunication-Chapter I: FCC Part 15-Radio Frequency Devices*, FCC, Washington, DC, USA, 2002.

[20] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” *IEEE Commun. Surveys Tutr.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[21] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, “Relaying protocols for wireless energy harvesting and information processing,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[22] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[23] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, “Power allocation strategies in energy harvesting wireless cooperative networks,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 846–860, Feb. 2014.

[24] N. Shlezinger and R. Dabora, “On the capacity of narrowband PLC channels,” *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1191–1201, Apr. 2015.

[25] *IEEE Standard for Broadband Over Power Line Networks: Medium Access Control and Physical Layer Specifications*, IEEE Standard 1901, 2010.

[26] *Measured Brazilian Places*. Accessed: Apr. 2018. [Online]. Available: https://sites.google.com/a/ifsudestemg.edu.br/thiagooliveira/plc

[27] T. R. Oliveira, W. A. Finamore, and M. V. Ribeiro, “A sounding method based on OFDM modulation for PLC channel measurement,” in *Proc. IEEE 17th Int. Symp. Power Line Commun. Appl.*, Mar. 2013, pp. 185–190.

[28] G. R. Colen, C. A. G. Marques, T. R. Oliveira, F. P. V. de Campos, and M. V. Ribeiro, “Measurement setup for characterizing low-voltage and outdoor electric distribution grids for PLC systems,” in *Proc. IEEE PES Conf. Innov. Smart Grid Technol. (ISGT Latin Amer.)*, Apr. 2013, pp. 1–5.

[29] L. G. da Silva Costa *et al.*, “Coupling for power line communications: A survey,” *J. Commun. Inf. Syst.*, vol. 32, no. 1, pp. 8–22, Jan. 2017.

[30] M. V. Ribeiro, G. R. Colen, H. V. Poor, Z. Quan, and F. V. P. de Campos, “Clustered-orthogonal frequency division multiplexing for power line communication: When is it beneficial?” *IET Commun.*, vol. 8, no. 13, pp. 2336–2347, Sep. 2014.

[31] *IEEE Standard for Low Frequency (Less Than 500 kHz) Narrow Band Power Line Communications for Smart Grid Application*, IEEE Standard 1901.2, 2013.

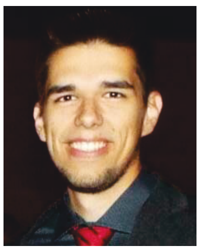
[32] M. Zimmermann and K. Dostert, "A multipath model for the powerline channel," *IEEE Trans. Commun.*, vol. 50, no. 4, pp. 553–559, Apr. 2002.

[33] M. Katayama, T. Yamazato, and H. Okada, "A mathematical model of noise in narrowband power line communication systems," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 7, pp. 1267–1276, Jul. 2006.

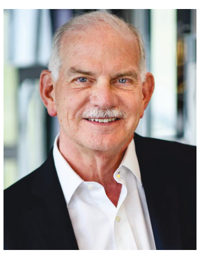
[34] A. F. Molisch *et al.*, "IEEE 802.15.4a channel model-final report," IEEE 802.15 WPAN Low Rate Alternative PHY Task Group, Tech. Rep. Document IEEE 802.15-04-0662-02-004a, Nov. 2004. [Online]. Available: https://mentor.ieee.org/802.15/dcn/04/15-04-0662-04-004a-channel-model-final-report-r1.pdf

[35] J.-H. Lee and Y.-H. Kim, "Diversity relaying for parallel use of power-line and wireless communication networks," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1301–1310, Jun. 2014.

[36] J. M. Cioffi. *Chapter 4: Multi-channel modulation*. Accessed: May 2018. [Online]. Available: http://web.stanford.edu/group/cioffi/book/chap4.pdf



Victor Fernandes received the B.S. and M.Sc. degrees in electrical engineering from the Federal University of Juiz de Fora (UFJF), Brazil, in 2015 and 2017, respectively, where he is currently pursuing the D.Sc. degree in electrical engineering. He has been a Professor with the Department of Electrical Engineering, Centro de Ensino Superior de Juiz de Fora, Brazil, since 2019. His research interests include signal processing, digital communication, power line communication, smart grids, and the Internet of Things.



H. Vincent Poor (Fellow, IEEE) received the Ph.D. degree in EECS from Princeton University in 1977. From 1977 to 1990, he was on the faculty of the University of Illinois at Urbana–Champaign. Since 1990, he has been on the faculty at Princeton University, where he is currently the Michael Henry Strater University Professor of Electrical Engineering. From 2006 to 2016, he served as the Dean of Princeton's School of Engineering and Applied Science. He has also held visiting appointments at several other universities, including most recently at Berkeley and Cambridge. His research interests are in the areas of information theory, signal processing and machine learning, and their applications in wireless networks, energy systems, and related fields. Among his publications in these areas is the recent book *Multiple Access Techniques for 5G Wireless Networks and Beyond* (Springer, 2019).

Dr. Poor is a member of the National Academy of Engineering and the National Academy of Sciences, and is a foreign member of the Chinese Academy of Sciences, the Royal Society, and other national and international academies. Recent recognition of his work includes the 2017 IEEE Alexander Graham Bell Medal and a D.Eng. *honoris causa* from the University of Waterloo in 2019.

Moisés V. Ribeiro (Senior Member, IEEE) received the B.S. degree in electrical engineering from the Federal University of Juiz de Fora (UFJF), Brazil, in 1999, and the M.Sc. and D.Sc. degrees in electrical engineering from the University of Campinas, Brazil, in 2001 and 2005, respectively. He was a Visiting Scholar with the University of California at Santa Barbara, Santa Barbara, CA, USA, in 2004, a Visiting Professor from 2005 to 2007 and an Assistant Professor from 2007 to 2015 with UFJF. Since 2015, he has been an Associate Professor with UFJF. He co-founded Smarti9 LTD., in 2012, and Wari LTD., in 2015. He had served as the Secretary of the IEEE ComSoc TC-PLC. His research interests include signal processing, power line communication, wireless communication, computational intelligence, and the Internet of Everything. In these fields, he has advised 38 graduate students and authored more than 191 peer-reviewed articles, nine book chapters, and hold 13 issued/pending patents.

He was a recipient of Fulbright Visiting Professorship at Stanford University, Stanford, CA, USA, in 2011, and at Princeton University, Princeton, NJ, USA, in 2012. He was awarded Student Awards from 2001 IEEE IECON and 2003 IEEE ISIE, Winner of 2014 I2P Global Competition, Honorable Mention in 2014 Global Venture Labs Investment Competition, 3rd Place Prêmio Mineiro de Inovação 2014, Engie Brazil Innovation Award 2016, and Unicamp Inventor Award in 2017 and 2018. He was the General Chair of the 2010 IEEE ISPLC, 2013 IWSGC, and SBrT 2015. He was a Guest Co-Editor for Special Issues in the *EURASIP Journal on Advances in Signal Processing* and *EURASIP Journal of Electrical and Computer Engineering*.