

The Usefulness of the Energy Harvested from Additive Noises in Power Line and Wireless Media

Victor Fernandes, Thiago R. Oliveira, and Moisés V. Ribeiro

Abstract—Aiming to come up with strategies for harvesting energy in hybrid power line communication (PLC)-wireless systems, this work focuses on the amount of energy that can be potentially harvested from the additive noise in electric power grids and in the air within residential facilities when the frequencies from 1.7 up to 100 MHz are taken into account. Based on statistical analyses of a residential data set, we show that the average power of the measured additive noise in the power line is higher in the morning than other periods of the day. Also, it is higher than the values from the energy harvested from in the air, in the same frequency band. Moreover, we show that the amount of energy harvested from these additive noises can yield achievable data rates between hundreds of kbps up to dozens of Mbps if hybrid PLC-wireless channels are used for data communication purposes.

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

I. INTRODUCTION

ENERGY harvesting (EH) has emerged as one of the promising solutions in the context of green communications. The possibility of allowing the reuse of a wasted resource can exert a pivotal role in advancing self-sustainable telecommunication networks. As stated in [1], EH allows the savings of non-renewable energy and also makes the communication media environmentally friendly. In the context of radio-frequency (RF), EH can be subdivided into two distinct approaches named as ambient or dedicated, according to the power source [2]. In the former approach, a device harvests its energy from an ambient source of power, which can be the RF signal irradiated by analog or digital TV, radio station (e.g., amplitude modulation (AM) and frequency modulation (FM)), WiFi and Bluetooth devices, cellular base stations, among others. On the other hand, the latter approach aims at powering a particular device by means of directional power transfer.

Nowadays, the opportunity of harvesting energy from wireless communication (WLC) sources, based on EH strategies,

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has been investigated due to the possibility of creating wireless self-sustainable networks [2], [3]. However, [1] showed the importance of electric power grids when the uninterrupted delivery of energy is necessary. In this context, [4] related the power line communication (PLC) noise impulsiveness with the harvested energy amount while [5] studied the energy harvesting potential when the induced signal that is radiated from the power lines is taken into account. Also, [6] demonstrated the usefulness of the medium-voltage PLC additive noise in urban and rural environments as well as [7] exploited the diversity of both wired and wireless media for EH purpose and showed that they can be used in tandem for improving achievable data rates of low-bit-rate devices.

Due to the spectrum scarcity and the necessity of maximizing the use of channel resources, the (concatenated) hybrid PLC-WLC channel was introduced in [8]. As shown in Fig. 1, this channel is composed of unshielded power cables of the power grid and the air. Thus, a PLC device sends a signal carrying information that partially radiates from the power cable and, as a consequence, it can be sensed by a WLC device operating in the same frequency band, defining the PLC \rightarrow WLC direction. On the other hand, a signal transmitted by a WLC device can be irradiated into the power cable and, as a consequence, the induced signal is received by a PLC device through a PLC coupler, which defines the WLC \rightarrow PLC direction. This kind of concatenated data communication medium can be seen as a way of introducing mobility in PLC systems. The use of data communication between WLC and PLC devices defines the so-called hybrid PLC-WLC systems.

None of the previous works considered a concatenated version of the hybrid PLC-WLC channel for data communication when the ambient EH is exploited in each medium (power cable and air), for feeding the transceivers. As well, the frequencies which are usually considered for data communication in broadband-PLC (up to 100 MHz) are assumed to be used for EH purposes. Furthermore, this work is based on a data set of measured additive noise samples, which is usually not considered in the majority of the works about EH.

This work focuses on the evaluation of the suitability of EH from PLC and WLC additive noises inside residences for data communication purposes through hybrid PLC-WLC systems [8], [9]. These analyses are based on a set of measured additive noises, which were acquired from the power cable (PLC additive noise) and the air (WLC additive noise) measurement campaign [10]. Furthermore, the amount of energy that can be harvested from the additive noise in these media is used to evaluate achievable data rates in hybrid PLC-WLC systems. Numerical results show that recycling the wasted energy in

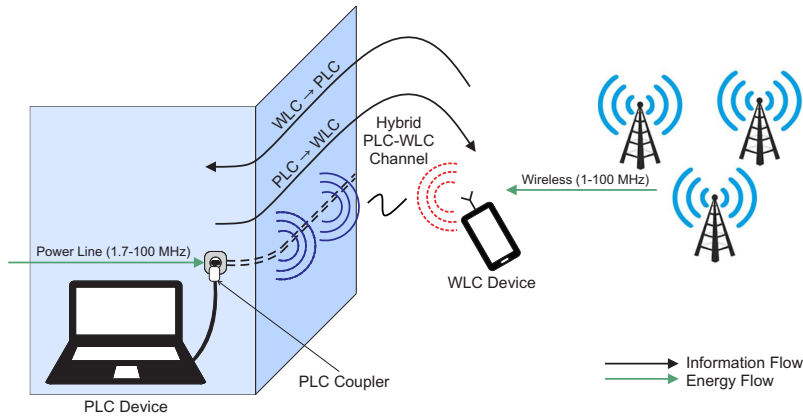


Fig. 1: A typical concatenated hybrid PLC-WLC system.

the additive noises (i.e., harvesting the energy associated with the additive noise in PLC and WLC media) can result in data rates suitable for several applications related to smart grids, IoT, and Industry 4.0.

II. MEASUREMENT DATA SETS

The numerical analyses of the harvested energies are carried out with a data set composed of measures of additive noises, which was obtained from a measurement campaign carried out to measure the additive noise in the power lines and the air in in-home facilities. This data set was originally applied to analyze the PLC channel in the context of the spectrum sensing problem [10] in the frequencies of up to 100 MHz. The measurement campaign was carried out in 16 distinct residences spread over the urban area of Juiz de Fora, Brazil. Inside each residence, 300 measures of the additive noises in the power line and in the air were obtained. This amount of measures was divided equally into three different periods of the day: morning, afternoon and night. Each of 4,800 measures of the additive noise in both media (PLC and wireless) is converted to an average power value (in Watts – as the power dissipated by a load of 1 Ω) by using

$$P_M = \frac{\eta}{T_{AN}} \int_{T_{AN}} |V^q(t)|^2 dt, \quad (1)$$

where $V^q(t)$ is the additive noise signal associated with the q^{th} data communication direction, in which $q \in \{\text{PLC} \rightarrow \text{WLC}, \text{WLC} \rightarrow \text{PLC}\}$ denotes the PLC to WLC and PLC to WLC directions, respectively; $T_{AN} = 40.96 \mu s$, which is the multiplication of 8192 samples by T_s ; $T_s = 1/f_s$ is the sampling period and $f_s = 200$ MHz denotes the adopted value of the sampling frequency for carrying out the measurement campaign; and $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [2].

Assuming that the additive noise is a colored and Gaussian random process, the frequency band from 1.7 MHz up to 100 MHz, and the hybrid PLC-WLC channels are frequency selective [8], then channel frequency responses (CFRs) estimates and additive noise sequences are combined with the average power provided by (1) to calculate the achievable data

rate in the hybrid PLC-WLC by using

$$C = \max_{\varrho^q(f)} \int_{B_w} \log_2 \left(1 + \frac{\varrho^q(f) |H^q(f)|^2}{S_V^q(f)} \right) df, \quad (2)$$

subject to $\int_{-B_w}^{B_w} \varrho^q(f) df \leq P_M$, where $\varrho^q(f)$ is the power spectrum density (PSD) of the transmitted signal's power mask; $|H^q(f)|^2$ is the CFR squared magnitude associated with the q^{th} data communication direction. Further, $B_w \approx 100$ MHz is the frequency bandwidth and $S_V^q(f)$ refers to the PSD of the additive noise at the receiver of the q^{th} data communication direction. Further, we consider that the full channel state information (CSI) is available and the optimal power allocation is applied in $\varrho^q(f)$ by means of the water-filling (WF) technique [11].

The data set related to the estimates of hybrid PLC-WLC channels were obtained from a measurement campaign performed in 7 residences in Juiz de Fora, Brazil [8], [12]. It is important to highlight that this data set was acquired from distinct time and places from the previous one. The CFRs of these channels are estimated by applying digital signal processing in accord with [13]. In the adopted channel estimation methodology, a sounding signal is injected into the power line, through a PLC coupler [14], and its distorted version is extracted from the air by using an antenna. In this sense, two different scenarios were taken into account according to the distance between the outlet in which the estimation signal was injected in the power line and the antenna used to measure the received signal. The former scenario, which is associated with the so-called *short-path* (SP) channels, covers the distances from 0 up to 2 meters and comprise those channels with the lowest attenuation profile while latter scenario, which refers to the so-called *long-path* (LP) channels, covers distances between 2 and 6 meters and encompasses the channels with high attenuation and distortions. During the measurement campaign of the PLC-WLC channels, 200 and 93 different combinations of outlet and antenna positions were considered for SP and LP channels, respectively. From each combination, 600 consecutive estimates of CFRs were obtained, resulting in a total of 175,428 CFRs estimates. Also, 52 and 60 measures of the additive noise in the power line and in the air, respectively, were obtained. The length of a single sequence of measured additive noise is constituted by 3,000,000 samples.

III. NUMERICAL RESULTS

The complementary cumulative distribution function (CCDF) of the 4,800 values of average power of PLC and WLC additive noises are shown in Fig. 2. In this plot, we adopt $P_M[\text{dBmW}] = 10 \log_{10}(P_M[\text{W}]) + 30$. As can be seen, the average power in PLC additive noise is higher than in WLC one. For instance, 80% of the PLC additive noises in power lines show values of average power higher than -9 dBmW, while, for the WLC case, this value is higher than -17 dBmW. Also, the maximum value of average power observed in the PLC additive noise is of approximately 29 dBmW, against approximately 11 dBmW for the WLC additive noise.

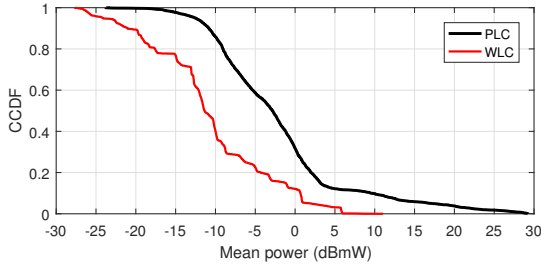


Fig. 2: The average power of PLC and WLC additive noises obtained with the measured data sets.

The CCDF of average power in the PLC and WLC additive noises, considering different periods of the day, can be seen in Fig. 3. In the PLC scenario, the average power of the additive noise is higher in the morning than in other periods of the day. This is related to the dynamic of the loads which are connected to the electric power grid. Also, this behavior suggests that the users of the measured places are using more electricity during the morning period, which coincides with the daily house cleaning routine. It is important to mention that it can vary depending upon the profiles of energy consumers. On the other hand, the average power of the additive noise in the WLC channel is more uniform in the different periods of the day due to the randomness and the large number of the various sources of WLC additive noise. For instance, AM and FM radio broadcast signals, and other telecommunication systems operating in the chosen frequency band constitute the measured WLC additive noise.

The PSDs of the additive noise data sets discussed in [10] are shown in Fig. 4. As expected, the PLC additive noise has more power in the low frequencies, while the PSD of the WLC additive noise is more uniformly distributed within the chosen frequency band, which agree with the theory. According to this plot, the difference between PLC and WLC additive noises' average power reaches a peak of 36.11 dBm, approximately, in 1.5 MHz, against to the minimum value of 0.02 dBm in 71.4 MHz. Also, as can be noticed, the signals yielded by wireless stations are induced into power line cables¹ – the induced part of these signals in the power lines are usually named as narrow-band noise. Also, it is relevant to see that, for instance, through some peaks observed in the PSD of the PLC

¹The power cable used in the electric power systems are unshielded and, as a consequence, it works as an antenna

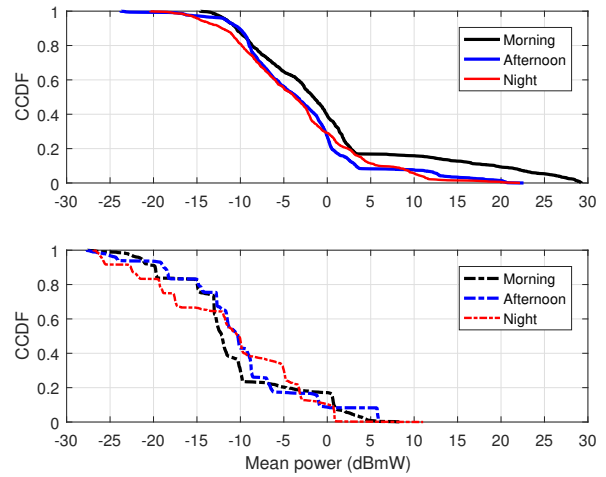


Fig. 3: The average power of the PLC (top) and WLC (bottom) additive noises per period of the day.

additive noise just below 100 MHz, in which FM broadcasting radio signals prevail over other components of the PLC and WLC additive noises.

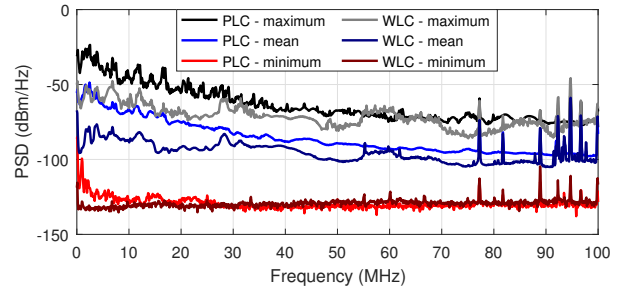


Fig. 4: PSD of the PLC and WLC additive noises.

A. Achievable Data Rate

This subsection deals with the theoretical achievable data rate that can be obtained by considering the following cases:

- Case #1: a PLC device that harvests the energy from the PLC additive noise and communicates through the hybrid PLC-WLC channel in the PLC to WLC direction.
- Case #2: a WLC device which harvests the energy from the WLC additive noise and communicates through the hybrid PLC-WLC channel in the WLC to PLC direction.

To this end, we assume that the source of power (i.e., the additive noise) is uninterruptible. Also, we use $\eta = \{1, 0.5\}$ to investigate the situations which constitutes an ideal scenario ($\eta = 1$) and a practical scenario ($\eta = 0.5$). Furthermore, [8] showed that both data communication path directions result in similar CFR estimates. Thus, the differences between cases #1 and #2 is the amount of harvested energy at the transmitter device and the PSD of the receiver's additive noise in each possible communication direction.

The CCDF of the achievable data rates obtained in cases #1 (top) and #2 (bottom) are shown in Figs. 5 and 6 for the SP and LP channels, respectively, when two distinct values of η apply. By comparing these figures, we can notice that the SP channels offer higher values of achievable data rates than LP ones in both cases. Also, as can be seen in both figures,

the case #1 achieves a better performance than the case #2 in terms of achievable data rate due to the high power nature of PLC additive noise. For instance, at Fig. 5 and assuming $\eta = 0.5$, 80% of the data sets yielded achievable data rates greater than 27 Mbps and 4 Mbps in cases #1 and #2, respectively. Looking at Fig. 6 (LP channels), using the same values of η and other aforementioned assumptions result in achievable data rates greater than 310 kbps and 20 kbps in cases #1 and #2, respectively.

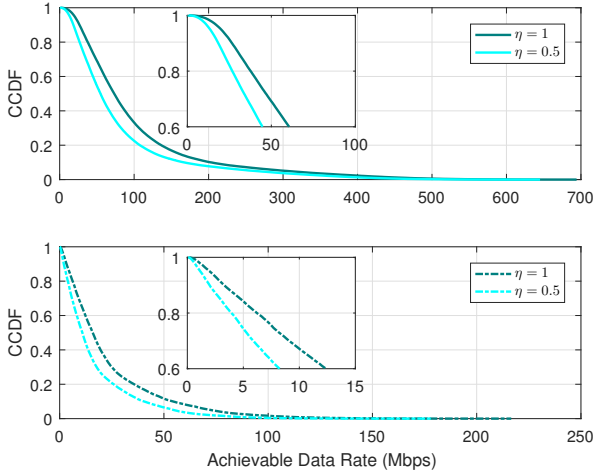


Fig. 5: Achievable data rates: The CCDF for the case #1 (top) and the case #2 (bottom) when SP channels apply.

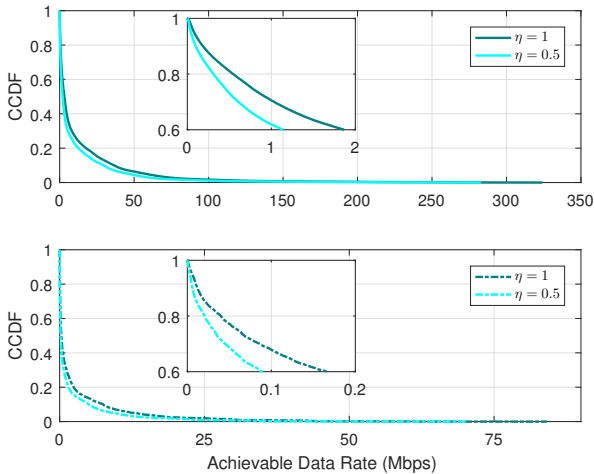


Fig. 6: Achievable data rates: The CCDF for the case #1 (top) and the case #2 (bottom) when LP channels apply.

Another interesting value is the maximum data rate. In accord with Fig. 5 (SP channels and $\eta = 1$), case #1 the maximum data rate is 694 Mbps while case #2 is 216 Mbps. For the same value of η and LP channels (Fig. 6), the maximum data rates are 324 Mbps and 84 Mbps in cases #1 and #2, respectively. This comparison also supports the previous paragraph's statements.

Aiming to capture the influence of the noise in distinct periods of the day, the CCDFs of the achievable data rates yielded in cases #1 and #2 during the morning, afternoon, and at night are shown in Fig. 7 for the SP channels (top) and for

the LP channels (bottom) when $\eta = 1$. In this figure, it is clear that case #1 is better than case #2 for both SP and LP channels at any period of the day. Here, the same trends observed in Fig. 3 (top) can be seen in both SP and LP channels for case #1, i.e., the average power harvested from the PLC additive noise is the highest in the morning, which makes the case #1 in the morning as the best one in terms of offering the highest achievable data rates. Also, the WLC noise has an average power that does not change a lot during the day, thus the achievable data rate in case #2 follows the same behavior.

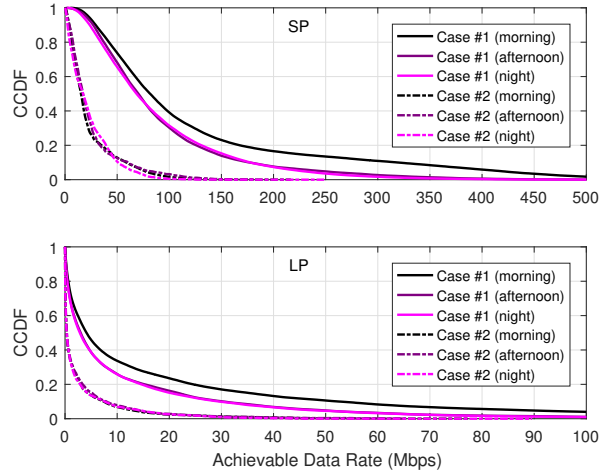


Fig. 7: Achievable data rates: The CCDF of per period of the day for case #1 (continuous line) and case #2 (dashed line).

IV. CONCLUSION

This work has statistically evaluated the amount of energy that can be harvested from PLC and WLC additive noises. This evaluation was performed in terms of the average power. A practical perspective applied because data sets constituted by measures, which were obtained from urban residences and in different periods of the day (morning, afternoon and night), applied. The numerical results showed that the average power of the additive noise is higher in PLC than in the WLC medium. In fact, while 80% of the average power of the PLC additive noise is higher than -9 dBmW, this value is around -17 dBmW in WLC one. The PLC additive noise yields more average power in the morning than in another period of the day, while such relation is not observed for the WLC additive noise.

Furthermore, the achievable data rates were analyzed using a set of channel estimates of the hybrid PLC-WLC channel and the transmission power harvested from the additive noise in both, PLC and WLC media. In this sense, two scenarios were taken into account by varying the distance between the WLC device and the power line outlet where the PLC device was connected, in a radius between 2 and 6 m as well as the two possible transmission directions (e.g., from PLC to WLC device and from PLC to WLC device) were evaluated. The numerical results have shown the potentialities of harvesting the existing wasted energy in the additive wireless and power line noises. Indeed, data rates from hundreds of kbps up to tens of Mbps can be achieved with the harvested energy from these additive noises.

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