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Ambient Energy Harvesting: The Potential of Additive Noise in Urban and Rural Medium-Voltage Electric Power Networks

Victor Fernandes, Thiago R. Oliveira, Thiago F. A. Nogueira and Moisés V. Ribeiro

***Abstract*— This paper deals with the medium-voltage (MV) power line communication (PLC) in the context of energy harvesting. To do so, a measurement campaign was carried out in urban and rural environments of Curitiba city, Brazil. This measurement campaign estimated the MV-PLC additive noise in these electric power networks. Numerical results show that the mean power, for distinct RF-to-DC conversion factors, in the urban environment is higher than in the rural one. Also, the achievable data rate analysis over the MV electric power networks shows the usefulness of this additive noise for feeding low-bit-rate devices.**

***Keywords*— energy harvesting, power line communication, medium-voltage, electric power network.**

I. Introduction

With the growing environmental awareness about the energy crisis and the concern about the scarcity of non-renewable energy sources, research efforts have been deserving attention to the increase of the diversity of the energy matrix for generating energy from renewable sources. In this regard, energy harvesting (EH) techniques have appeared in the context of energy-efficient [1], self-sustainable networks [2], and green communications [3]. Therefore, several works have focused on harvesting energy from the environmental radio-frequency (RF) signals to postpone the batteries life or even make devices self-sustainable. However, as the harvested energy from the environmental RF signals has an intermittent behavior over time, energy harvesting for data communication purposes is a challenging problem [4].

Focusing on the signals flowing through the power cables, the energy contained in the additive noise may be useful for feeding low-power consumption devices, such as IoT devices. This noise, from now on called power line communication (PLC) additive noise [5], is composed of RF signals and disturbances. The former are the RF signals induced into power cables because the majority of these cables are unshielded and the latter is related to the dynamics of loads connected to the electric power system. While the induced RF signals are considered unwanted interference [6], the disturbances (e.g., harmonics, supraharmonics, and transients) are seen as source power quality problem in the electric power system. On the other hand, this noise can be useful for energy harvesting purposes.

In [7], for instance, was evaluated the energy harvesting of the induced signal radiated from the power lines while in [8] the energy efficiency in a cooperative PLC system is assessed by exploiting the PLC additive noise. Also, the achievable data rate of a communication channel formed by the parallel of PLC and wireless communication (WLC) channels, named hybrid PLC/WLC channel, was analyzed when a hybrid EH-relaying node is considered [9]. These works have shown that ambient energy harvesting from the signals flowing through the electric power systems may be useful and, as a consequence, comprehensive investigations have to be carried out.

In this sense, this study aims to estimate the amount of energy that can be potentially harvested from the additive noise in medium-voltage (MV) electric power grids in urban and rural areas in Curitiba city, Brazil. In this regard, several measurements of the MV-PLC additive noise were obtained from 13.8 kV MV power line (PL) in the frequency band from 100 kHz up to 2.5 MHz. The numerical analyses are based on power spectrum density (PSD) and mean power of the MV-PLC additive noise. Also, the achievable data rate is evaluated when the energy is harvested from the PLC additive noise and the data communication is through MV-PLC channels. By considering the chosen frequency band, the attained results are as follows:

- The majority of the harvested energy in the MV-PLC additive noises is from AM signals induced in the power cables. Also, mean PSD values of the MV-PLC additive noise ranges from -90 dBm/Hz up to -45 dBm/Hz and from -90 dBm/Hz to -50 dBm/Hz in urban and rural areas, respectively.
- The mean powers of up to -1 dBmW and -6.5 dBmW may be harvested from urban and rural environments, respectively. Based on these values, the maximum achievable data rate for these environments can reach 1.5 Mbps and 215 kbps, respectively, if data communication occurs through MV-PLC channels.

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The remainder of this work is organized as follows: Section II briefly describes the measurement setup and the data set acquired with it during the measurement campaign. Section III details the parameters used for analyzing the suitability of the MV-PLC additive noise for energy harvesting purposes, while the numerical results are discussed in Section IV. Finally, concluding remarks are summarized in Section V.

II. Measurement Setup and Data Set

The MV-PLC additive noise, which constitutes the data set, was acquired through a measurement campaign carried out in an outdoor MV electric power network of 13.8 kV in urban and rural areas of Curitiba, Brazil. The applied measurement setup, illustrated in Fig. 1, covers the frequency band from 100 kHz to 2.5 MHz. This measurement setup is composed of the following main components:

- Inductive coupler: circuity adopted to inject or acquire the signal into/from the PL. Its main function is to block the AC mains voltage that can damage the data acquisition board. The adopted coupler is the inductive MICU 300A-S/LF model from PREMO [10], as shown in Fig. 2, it works as a high-pass filter with a cutoff frequency equal to 100 kHz.
- Data acquisition board: an analog-to-digital converter board from GaGe with 16-bits of resolution [11], which is in a rugged computer (refer to Fig. 3), and operates with a sampling frequency of 5 MHz.

The data set of the MV-PLC additive noise was obtained from 15 and 3 selected measuring points in urban and rural MV electric power networks, respectively. Also, a realization of 6×10^6 samples from each measuring point has been recorded.

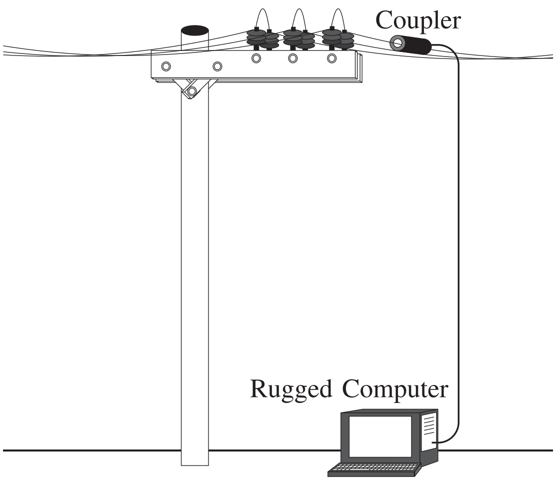

Fig. 1. Measurement setup to acquire the MV-PLC additive noise.

The channel frequency response (CFR) estimates, applied in the evaluation of achievable data rate, were derived from a total of 12 MV PLs, – from the same ones that the additive noise was measured – in which 7 belongs to the electric power network in urban areas and 5 are situated in rural areas. Approximately $123,039$ and $76,167$ CFR estimates were

Fig. 2. Inductive coupler (MICU 300A-S/LF from PREMO).

Fig. 3. Rugged computer with the data acquisition board.

obtained from the aforementioned environments, respectively. The urban MV channels corresponds to PL segments from 10 m up to 1,300 m. In relation to rural channels, these lengths range from 2,000 m and can reach up to 4,360 m. The CFR estimates cover the frequency band from 100 kHz to 500 kHz, which is lower and upper bounded by the adopted inductive coupler and an analog low-pass filter. For more details about the CFR estimation, the applied measurement setup and its components see [12].

III. Parameters for Analysis

This section describes the parameters applied to estimate the mean power of the MV-PLC additive noise and to evaluate the achievable data rate when the only source of power is the mean power harvested from the MV-PLC additive noise and the data communication channel is the MV-PLC one, see the Appendix for more details about its magnitude.

A. Mean Power

The mean power extracted from the MV-PLC additive noise $V(t)$ in Watts (i.e., the power dissipated by a load of 1 Ω) can be calculated through

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

where $T_{AC} = 1/f_{AC}$ is the period of a single AC mains voltage cycle and f_{AC} is the corresponding frequency. Also, $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [3]. It is important to point out that the mean power is being evaluated for each AC mains voltage cycle.

B. Achievable Data Rate

The achievable data rate can be calculated by using

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

subject to $\int_{-\infty}^{\infty} \varrho(f) df \leq P_M$, where $\varrho(f)$ is the PSD of the transmitted signal; $H(f)$ is the CFR estimate; B_w is the frequency bandwidth of the MV-PLC channel and $S_V(f)$ is the PSD of the MV-PLC additive noise at the receiver. Further, the full channel state information (CSI) is available and the optimal power allocation is applied to $\varrho(f)$ by means of the water-filling (WF) technique [13].

IV. Numerical Results

In accord with the Brazilian electric power system, $f_{AC} = 60$ Hz and $T_{AC} \approx 16.67$ ms. Further, in order to comprehend the influence of RF-to-DC conversion efficiency, $\eta \in \{0.2, 0.4, 0.6, 0.8, 1\}$, which ranges from the worst to the best case in terms of power reuse. Also, $\eta = 1$ and $\eta = 0.4$ refers to ideal and practical cases, respectively. The achievable data rate analysis considers that the only source of power is the mean power of the MV-PLC additive noise in the frequencies from 100 kHz to 2.5 MHz, while the data communication is through the MV-PLC channel, which covers the frequency band between 100 kHz and 500 kHz and, as a consequence, $B_w = 400$ kHz. The analysis assumes that the power is being continuously and consecutively harvested from the additive noise, over time, and that the PSD is estimated through the application of Welch's method [14].

Figs. 4 and 5 show the PSD of the MV-PLC additive noise in the urban and rural environments, respectively. At these figures, we can see that both curves minimum have a PSD-floor around -90 dBm/Hz, where its power-per-hertz pattern is almost flat all over the measured frequency band. Overall, the PSD of the MV-PLC additive noise has lower values in the rural environment in almost all the frequency bandwidth than in the urban one.

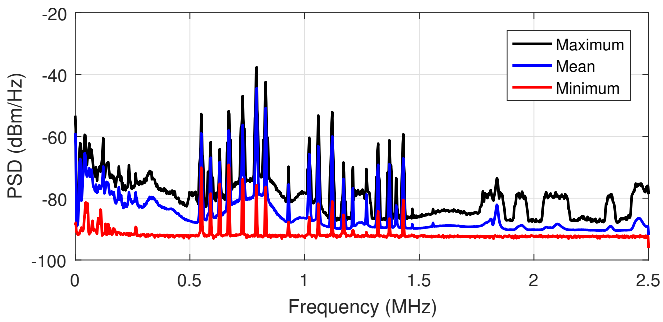

Fig. 4. Urban Environment: PSD of the MV-PLC additive noise.

Furthermore, by analyzing Fig. 4 (urban environment), the curve mean shows values of PSD between -90 dBm/Hz and -45 dBm/Hz, in which the lowest values occur for the highest frequencies as well as the highest values appear on the frequency bandwidth of 0.55–1.45 MHz. This behavior is associated with the presence of AM signals from the broadcast radio stations. These stations operate in the frequency range of 0.5–1.7 MHz and, due to the unshielded nature of power line cables, the electromagnetic waves associated to the AM signals are induced into power cables. As a result, most of the power that can be observed in the PSD of the MV-PLC additive noise comes from AM broadcast radio stations.

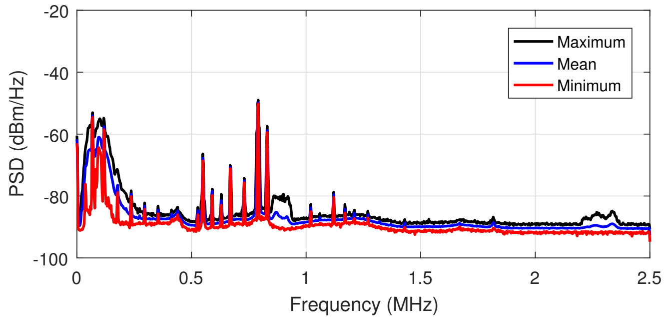

Fig. 5. Rural Environment: PSD of the MV-PLC additive noise.

Extending the analyses to Fig. 5 (rural environment), it is clear that the curve mean presents values of PSD between -90 dBm/Hz and -50 dBm/Hz, where the lowest values occur for the highest frequencies and the highest values are in the frequency band of 0.55–0.85 MHz. This shows the less influence of the AM broadcast radio stations in the rural environment rather than in the urban environment.

Figs. 6 and 7 show the complementary cumulative distribution function (CCDF) of the mean power that can be extracted from the MV-PLC additive noise in the urban and rural environments, respectively, by evaluating equation (1) with $P_M[\text{dBmW}] = 10\log_{10}(P_M[\text{W}]) + 30$. In general, the mean power varies from -19 dBmW up to -1 dBmW and from -18 dBmW up to -6.5 dBmW by considering the urban and rural environments, respectively.

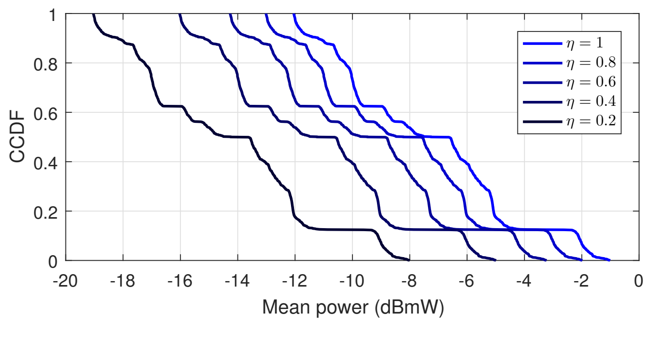

Fig. 6. Urban Environment: CCDF of the mean power of the MV-PLC additive noise by considering distinct values of RF-to-DC conversion factor.

Specifically, in the urban environment (Fig. 6) by assuming an ideal scenario ($\eta = 1$) and a probability equal to 0.8, an amount of -10.2 dBmW can be harvested from the MV-PLC additive noise on average. On the other hand, in a more realistic scenario ($\eta = 0.4$) and with the same probability threshold, the mean power of -14.2 dBmW is yielded.

As expected, in the rural environment (Fig. 7), lower values of mean power are observed than in the urban environment, for a given η. For example, the ideal scenario ($\eta = 1$) with a probability equal to 0.8, results in an amount of -10.7 dBmW of harvested power from the MV-PLC additive noise on

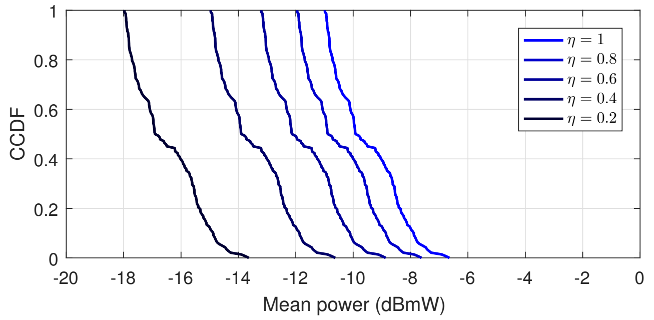

Fig. 7. Rural Environment: CCDF of the mean power of the MV-PLC additive noise by considering distinct values of RF-to-DC conversion factor.

average. On the other hand, the realistic scenario ($\eta = 0.4$) with the same probability threshold, achieves -14.8 dBmW of mean power.

Figs. 8 and 9 show the CCDF of the achievable data rate over MV-PLC channels in the urban and rural environments, respectively, by means of equation (2). The maximum achievable data rate obtained ($\eta = 1$) in the urban and rural environments are, respectively, 1.5 Mbps and 215 kbps.

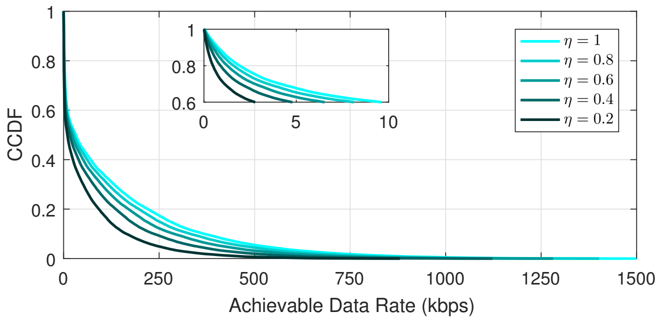

Fig. 8. Urban Environment: CCDF of the achievable data rate over the MV-PLC channel by considering distinct values of RF-to-DC conversion factor.

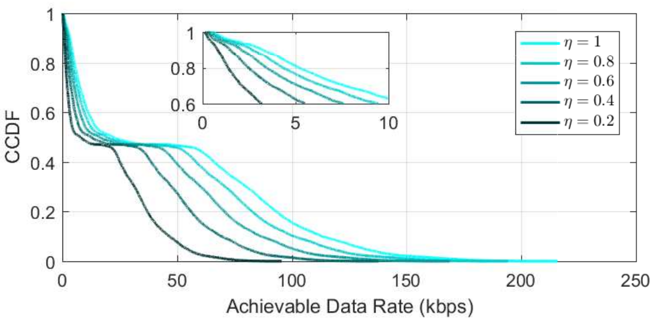

Fig. 9. Rural Environment: CCDF of the achievable data rate over the MV-PLC channel by considering distinct values of RF-to-DC conversion factor.

Furthermore, assuming $\eta = 0.4$ and a probability equal to 0.8, the achievable data rates yielded are 1.0 kbps and 2.5 kbps in the urban and rural environments, respectively. This interesting result shows that although the urban environment results in higher mean power than the rural one, when considering the additive noise's PSD (denominator of equation (2)) in the frequency band of 100–500 kHz and optimal power allocation, for the achievable data rate evaluation, the rural environment presents higher values of achievable data rate, at high probabilities, rather than the urban one. In other words, as in both cases (urban and rural), the PSD is the lowest in the frequency range, approximately, from 250 to 500 kHz, thus, the optimal power allocation concentrates most of the power in this frequency bandwidth. However, in this frequency range, the rural environment has lower PSD, in the mean sense, than the urban one. As a result, the achievable data rate attained by the rural environment is higher than the urban one, in these conditions.

Overall, the energy reuse caused by the application of EH in the MV-PLC additive noise, resulted in an achievable data rate from tens to thousands of kbps in a MV-PLC channel. Even in a more realistic scenario ($\eta = 0.4$ and a probability of 0.8), these values were, at least, 1.0 and 2.5 kbps in the urban and rural environments, respectively.

V. Conclusion

This work has discussed the energy that can be potentially harvested from the MV-PLC additive noise, in the frequency range of 100 kHz–2.5 MHz. The obtained data set was evaluated in terms of power spectrum density, mean power, and achievable data rate by assuming that the only source is the energy harvested from the MV-PLC additive noise and that the data communication occurs through MV-PLC channels in the frequency band delimited by 100 kHz and 500 kHz.

Numerical results have shown that the MV-PLC additive noise's power spectrum density in the urban environment has higher power-per-hertz values than in the rural one. As expected, this behavior was mirrored in the mean power for a given RF-to-DC conversion factor. Also, most of the power contained in the MV-PLC additive noise, in both environments, comes from the signals from AM broadcast radio stations, which are usually induced in power cables. The achievable data rate analysis has shown the usefulness of this additive noise for supporting low-bit-rate applications.

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Appendix

This appendix shows the maximum, mean, and minimum values of the magnitude associated with the MV-PLC CFRs in Figs. 10 and 11 for the urban and rural environments, respectively [12].

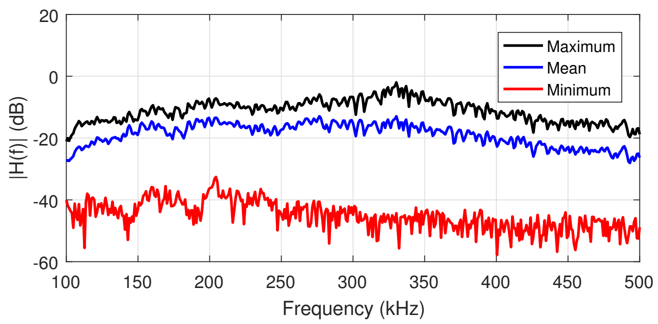

Fig. 10. Urban Environment: Magnitude of the MV-PLC CFRs.

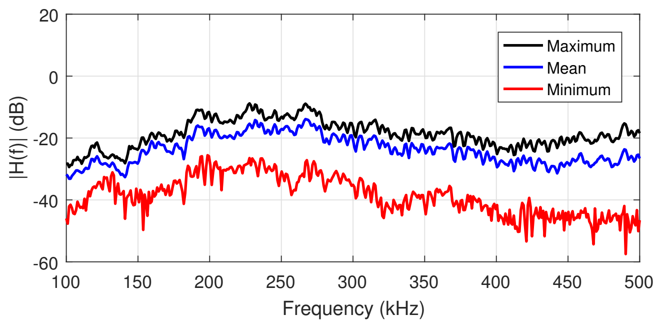

Fig. 11. Rural Environment: Magnitude of the MV-PLC CFRs.