A Contribution for Spectrum Sensing in Power Line Communication Systems

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***Abstract*—In Brazil, the introduction of telecommunication and electric energy regulations for power line communications (PLC) is pushing forward R&D efforts towards the development of this technology. Therefore, the will to improve the usage of the regulated spectrum and its further increase, combined to the necessity of PLC system coexistence with other users of the regulated bandwidth made spectrum sensing an important matter to be addressed. To do so, it is needed to determine the best way to acquire information of the surrounding spectrum: using an antenna or measuring the interference on the power line cable. To offer subsidy to this discussion, measured data for spectrum sensing, which were acquired in Brazil, are presented and analyzed. Also, the performance of energy-detection technique for PLC spectrum sensing is evaluated with this measured data. Based on the qualitative and quantitative analysis, this contribution indicates that an antenna can be a very interesting sensor for cognitive PLC systems.**

I. INTRODUCTION

*C*urrently, field trials and measurements are being carried out for the characterization of electric power grids in Brazil. They aim at the analysis of possible solutions for the deployment of a *power line communication* (PLC) system [1]. The main reason for it is the introduction of PLC regulations by the telecommunication and Electric Energy regulations from Brazil [2], [3] in April and August of 2009, respectively.

According to the Brazilian telecom regulation, the allowed frequency band for PLC systems is between 1.705 and 50 MHz. Despite this fact, many frequency bands in between this authorized one are designated for the use of other interests, like amateur radio, radio localization, aeronautics, army and coaster protection zones, and therefore, are prohibited for PLC use. However, during a considerable period of time, these bands of the spectrum, and even other portions of it, are sparsely used. To overcome this situation, cognitive radio concepts [4], [5] can be applied in a way that PLC systems could use the frequency bands in an opportunistic way as secondary (unlincensed) users: they can transmit in an specific band when it is not being used by its licensed (primary) user, or the transmission does not damage this user's activities.

The first and most important aspect of cognition is *spectrum sensing* [6], [7], which determines if the primary user is present in the band at a specific time, as well as the moment it gets in or leaves the band. Therefore, tools that can localize those users in the time and in the frequency domains are needed. Knowing that, the investigation of the so-called PLC spectrum sensing, which is part of the conception of cognitive PLC system, is a timely and important issue to be addressed for devising a new generation of PLC technology that can be capable of fulfilling the introduced regulations.

In [8] a supportive analysis for the use of cooperative spectrum sensing for indoor PLC applications is presented. In this contribution, the suitability of the power line cable to monitor the FM signals in the frequency band from 87.5 up to 108 MHz is highlighted. However, in the desired case of study, PLC technology is applied in outdoor communications and another approach must be taken, choosing the most suitable sensor for monitoring the availability of such a scarce spectrum.

In this context, this contribution presents and discusses PLC spectrum sensing based on measured data covering the frequency band between 1.705 and 100 MHz, acquired with an antenna and on the power line cable. The qualitative and quantitative analyzes indicate that the use of an antenna can offer improved detection ratio if the energy-based technique is applied for PLC spectrum sensing. To establish a statistic comparison among the selected methods, the detection of previously known localized signals will be made using the energy detection technique, the most simple and applied one [6], which uses a threshold to determine if a signal is present or not. The percentage of detection and false alarm will be calculated and, consequently, conclusions will be taken.

This paper is organized as follows: in Section II the investigated problem is formulated. In the sequel, a discussion about the use of signal measured on the power line cable or by an antenna for PLC spectrum sensing is presented. In Section IV, some results obtained with the energy detection technique for PLC spectrum sensing are exposed. Some conclusion remarks are stated in Section V.

II. PROBLEM FORMULATION

Let us assume that the nth sample of a received signal in an antenna or a power line cable is given by

$$\begin{aligned} r(n) &= x(n) + v(n) \\ &= \sum_{k=1}^{M} x_k(n) + v(n), \end{aligned} \tag{1}$$

where $x_k(n)$ is the kth narrowband signal, in which analog or digital information is transmitted, and $v(n)$ denotes the additive noise that can be expressed by [9]

$$v(n) = v_{bkgr}(n) + v_{nb}(n) + v_{pa}(n) + v_{ps}(n) + v_{imp}(n), \tag{2}$$

in which $v_{bkgr}(n)$ is the background noise, $v_{nb}(n)$ is a narrow band noise, $v_{pa}(n)$ is a periodical impulsive noise asynchronous to the fundamental component of power system, $v_{ps}(n)$ is a periodic impulsive noise synchronous to the fundamental component of power system, and, finally, $v_{imp}(n)$ is an asynchronous impulsive noise, which is the hardest one due to its time unpredictability and high power.

As the signal is unknown to the receiver, the energy detector will be used, since it does not need a priory knowledge of the signal [10], [6]. Then, applying the *discrete Fourier transform* (DFT) [11] in the vector $\mathbf{r}_i$, one obtains

$$\begin{aligned} \mathbf{R} &= \mathbf{X} + \mathbf{V} \\ &= \sum_{k=1}^{M} \mathbf{X}_k + \mathbf{V} \end{aligned}, \tag{3}$$

where $\mathbf{R} = \text{DFT}(\mathbf{r})$ is the N-length vector, and $\mathbf{r}_i = [r(n+iN) \;\; r(n+iN+1) \;\; \ldots \;\; r(n+(i+1)N-1)]^T$.

For more accurate analysis the vector $\mathbf{R}$ is divided into S frames, called observation vectors, as shown in Figure 1.

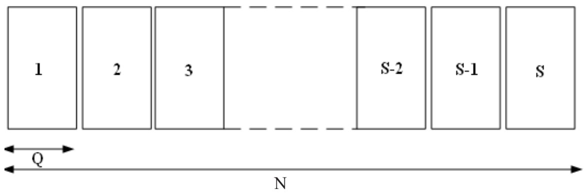


Fig. 1: Spectrum divided into observation vectors.

Based on [10], the energy of the signal of each observation vector, known as decision metric, can be written as

$$\gamma_j = \sum_{p=jQ}^{(j+1)Q-1} |R_i(p)|^2, \qquad j = 1, 2, \ldots, \frac{S}{2}, \tag{4}$$

where Q is the length of the observation vector in the frequency domain and $S = \frac{N}{Q}$.

The decision on the occupancy of a band can be obtained by comparing the decision metric γ_j against a fixed threshold, $\lambda_{Q,\mathbf{x}_j,\mathbf{v}_j}$, which depends on the noise floor [6] in the jth frame. This is equivalent to distinguishing between the following two hypothesis

$$\begin{aligned} H_0 &: \; \mathbf{R} = \mathbf{V} \\ H_1 &: \; \mathbf{R} = \mathbf{X} + \mathbf{V}, \end{aligned} \tag{5}$$

in which H_0 is the hypothesis of signal absence, and H_1, the hypothesis of signal presence.

The accurate identification of signal presence by the energy detector is threatened by the difficulty of selection of a fixed threshold, inability to differentiate interference from primary users and noise, and poor performance under low *signal-to-noise ratio* (SNR) values. These problems lead to a decrease in the probability of detection and to an increase in the probability of false alarm, respectively represented by P_D and P_F, influencing the value of $\lambda_{Q,\mathbf{x}_j,\mathbf{v}_j}$. Then,

$$\lambda_{Q,\mathbf{x}_j,\mathbf{v}_j} = \max P_D, \min P_F, \tag{6}$$

where

$$\begin{aligned} P_D &= P_r(\gamma_j > \gamma_{Q,\mathbf{x}_j,\mathbf{v}_j} | H_1) \\ P_F &= P_r(\gamma_j > \gamma_{Q,\mathbf{x}_j,\mathbf{v}_j} | H_0). \end{aligned} \tag{7}$$

Regarding data communication through electric power grids, one can note that spectrum sensing is an open issue to be addressed and presents different characteristics in comparison with wireless communications.

First of all, PLC systems, which current bandwidth varies between 1.705 kHz and 100 MHz, are very much exposed to different kinds of noise. The hardness of man-made noise is very pronounced in the lower frequencies. Also, the switch on/of of loads in the electric power grids yields impulsive noise that corrupts a burst of data.

Secondly, the electric power grids are constituted by unshielded cables. It means that electric power grids are like a meshed antenna. In other words, PLC system can dialectically interfere in any other telecommunication systems, which are operating in the same bandwidth.

Thirdly, military and essential telecommunication services own considerable bandwidth between 1.705 kHz and 100 MHz that, in the majority of situations, is sparsely used for data communications.

Finally, but not the least, PLC system can only operate with satisfactory efficiency and performance in this frequency bandwidth.

The aforementioned comments reveal the need of investigating the use of spectrum sensing techniques for improving PLC systems performance. Among several issues to be addressed in this regard, the following questions arise:

1) Is it better PLC spectrum sensing to be based on measured data from a power line cable or an antenna?
2) What kind of performance can be expected if a typical energy detection technique is applied for PLC spectrum sensing?

In Section III, measured data collected in Brazil is presented and discussed. Its analysis give some directions

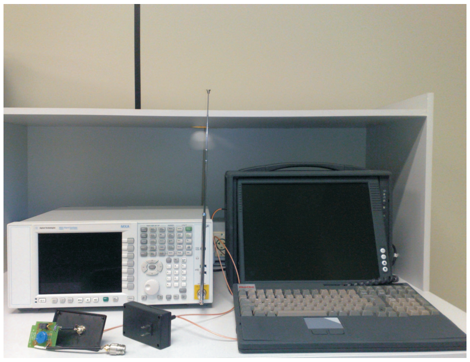


Fig. 2: Spectrum sensing setup using the antenna and the power line cable.

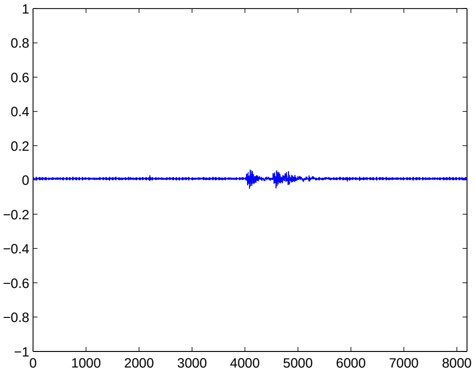
regarding the first question. Some numerical results which are highlighted in Section IV address limitations and convenience of energy detection technique for PLC spectrum sensing.

III. DATA MEASUREMENT

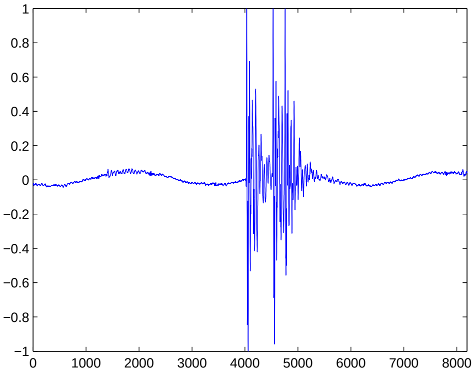
Measurements were made using Gage Razor CompuScope 1642 [12] data acquisition board, which consists of an A/D converter of 16 bits of vertical resolution with up to 200 MS/s sampling per channel, with an omnidirectional antenna and a coupler, to acquire data simultaneously with both devices. The system setup is depicted in Fig. 2. The omnidirectional antenna presents a 50 Ω coupling impedance and covers a frequency bandwidth up to 1 GHz and the power line measurement front end is constituted by a plug for the connection to the outlet, and a filtering and coupling device that eliminates power line signal with frequencies lower than 1.705 MHz.

The acquisition board was configured to start a new acquisition every time the value of the voltage in the power line cable surpassed a chosen threshold. For this contribution, one hundred measurements were taken and each measure was constituted by 8192 samples. By looking at the measured data in Fig. 3, one can notice that the impulsive noise in the power line cable is also captured with the antenna. Moreover, this capture of the impulsive noise is reduced in power, if compared to the data measured on the cable.

The *power spectral density* (PSD) shown in Fig. 4 gives a general idea of the difference of the measurements made with the antenna and on the cable. It can be observed in Fig. 5 that the measurements made on the power line cable have higher energy in lower frequencies, due to the man-made noise present in this medium and, in higher frequencies, according to Fig. 6, this signal is more attenuated. The FM radio signals measured on the cable visibly have lower energy than the ones measured with the antenna. Although the measurements made with the antenna are more attenuated than the ones made on the cable, they do not have influence of the man-made noise in the lower frequencies. It indicates that the antenna can be a better measurement sensor for spectrum sensing. To confirm this behavior, measurements were made in a second environment and plotted in Fig.7.



(a) Antenna.



(b) Power line cable.

Fig. 3: Measured data.

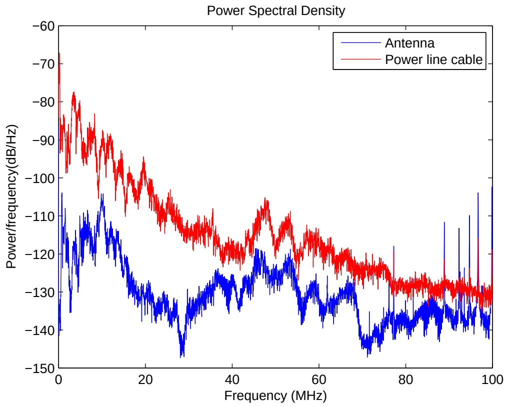


Fig. 4: Power spectral density from up to 100 MHz.

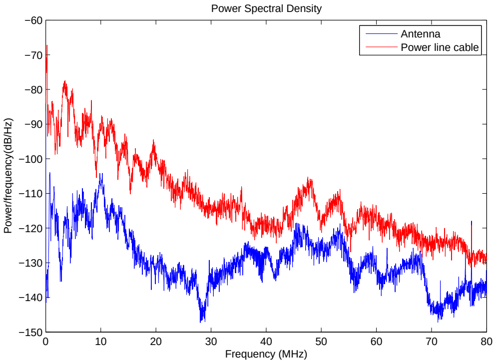


Fig. 5: Power spectral density from 0 to 80 MHz.

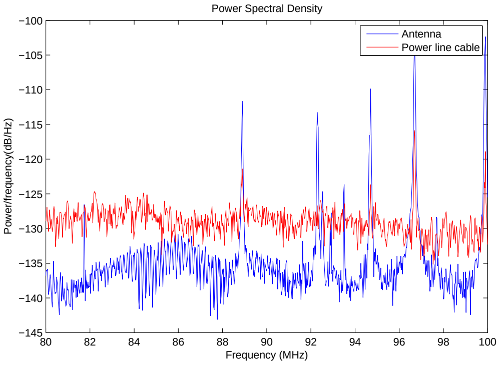


Fig. 6: Power spectral density from 80 to 100 MHz.

Comparing Figs. 4 and 7, it can be observed that the measurements made with the antenna and on the cable present the same behavior in both environments, what is relevant for the analysis made in this work.

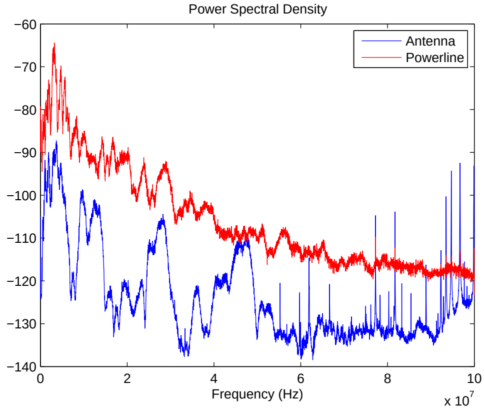
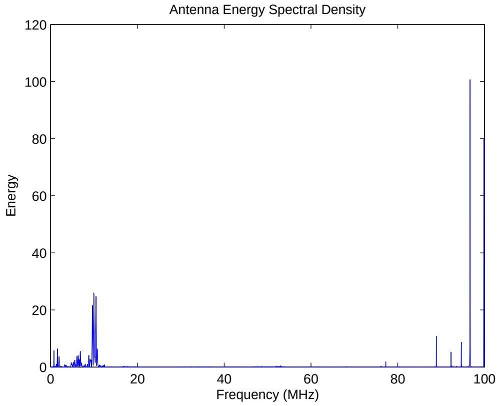
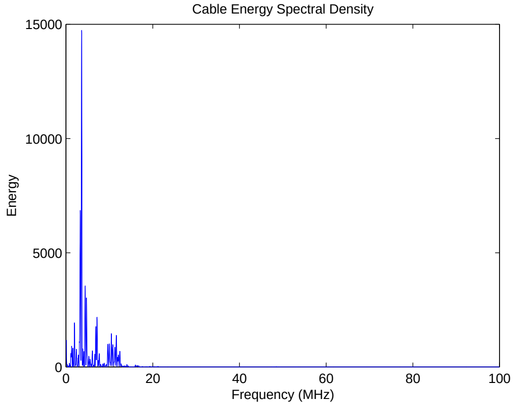


Fig. 7: Power spectral density from 0 to 100 MHz in a second environment.

The *energy spectral density* (ESD) for each of the measurement mediums (cable and antenna), shown in Figs. 8a and 8b, explicit better the signals acquired by them. The low frequency signals, known to be amateur radio, radio localization, maritime, aeronautic and special research frequencies were detected by both, although it is noticeable that the high energy level of man-made noise on the power line cable can lead to error detection. Also, high frequency signals are perfectly viewable in Fig. 8a, and not seen in Fig. 8b. A close up of them, seen in Figs. 9a and 9b show that the cable detects only a few of the FM signals present with a very low energy level, while the measurement data provided by the antenna offers more significant information that can be useful for PLC spectrum sensing. As a consequence, the antenna can capture more detailed information of the environment, such as the changes in the spectra and the previously mentioned FM bands.



(a) Antenna

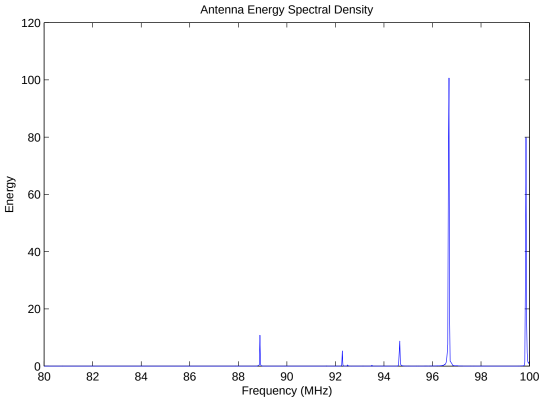


(b) Power line cable

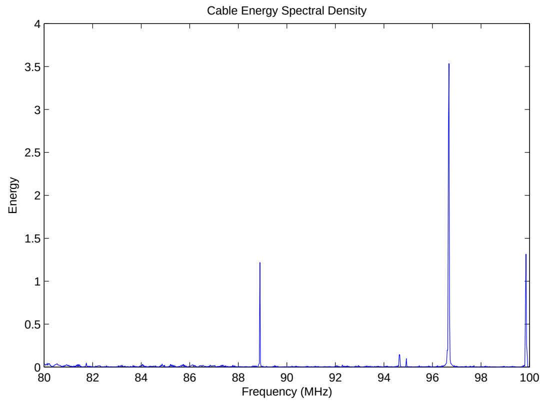
Fig. 8: ESDs of the measured data from 0 to 100 MHz.

IV. NUMERICAL RESULTS

Numerical simulations were carried out with the measurement data in order to analyze the performance of PLC



(a) Antenna



(b) Power line cable

Fig. 9: ESDs of the measured data from 80 to 100 MHz.

spectrum sensing approach based on the energy detection technique. Each measured data has $N = 8192$ samples. Then, the total spectrum of 100 MHz was divided into equally spaced observation vectors, and energy was calculated for each of them, as in (4). It was chosen to use from 20 to 100 observation vectors, four by four, to have observation vectors with resolutions (the length Q of the observation vector) varying from 1 to 5 MHz. After that, combining the energy information of each observation vector with the PSD of the measures taken the detection threshold was determined to be a value in between the maximum noise and the minimum signal energy levels.

By looking at Fig 8, three different noise patterns are noticed, what made reasonable the didactic division of the spectrum in same number of regions: the first one from 1.705 to 25 MHz, the second one from 25 to 75 MHz and the third one from 75 to 100 MHz. Each region, then, has a different threshold. If one compares Fig. 8a and 8b, it will be seen that the noise level of the first region of the measurement made on the cable (the man-made noise) is higher than in the one made with the antenna . It is also evident that FM signals are almost unnoticed in the cable measurements, while very well defined in the ones made with the antenna, looking at the last section of the spectrum.

The effectiveness of the energy detection procedure was determined statistically for 100 frames in each one of the cases and shown in Tab. I. Although the statistical treatment is the best way to determine the accuracy of the measurements, the results obtained for each frame were observed to be the same, due to the constancy of the nearby uses and, therefore, of the radio frequency environment.

TABLE I: Detection rates or the measurements made with the antenna and on the cable.

Observation Vectors #	**Resolution bandwidth (MHz)**	**Antenna detection rate (%)**	**Cable detection rate (%)**
20	5.00	44.44	55.56
24	4.17	77.78	66.67
28	3.57	81.82	63.64
32	3.13	90.00	80.00
36	2.78	84.62	76.92
40	2.50	83.33	75.00
44	**2.27**	**92.86**	**78.57**
48	2.08	85.71	78.57
52	1.92	86.67	80.00
56	1.79	87.50	75.00
60	1.67	88.24	70.59
64	1.56	93.75	87.50
68	1.47	88.24	82.35
72	1.39	84.21	78.95
76	1.32	89.47	78.95
80	1.25	89.47	78.95
84	1.19	90.00	80.00
88	1.14	85.71	80.95
92	1.09	90.00	80.00
96	1.04	90.48	80.95
100	1.00	90.91	81.82

It can be seen in Tab. I that for the adopted observation vector resolution for spectrum sensing with energy detection technique, see (4), the rate signal detection for the measurements made with the antenna is higher than the rate for the ones made on the cable. For 5MHz resolution bandwidth, the detection on the cable is more efficient due to the detection of an extra power line narrowband signal, in the high frequencies. The 1.56 MHz spectrum resolution for the energy detection technique provided the highest detection rates for both the antenna and power line cable measurements which are, respectively, 93.75 % and 87.50 %. Therefore, it can be said that the antenna is more efficient to detect the presence of signals than the power line cable, although its measures are more attenuated than the later one's. However, to make detection statements trustworthy, is also necessary to consider the false alarm detection rates, which are exposed in Tab. II.

TABLE II: False alarm detection.

Observation Vectors #	**Antenna false alarm rate (%)**	**Cable false alarm rate (%)**
20	0	18.18
24	6.67	20.00
28	5.88	17.65
32	4.55	18.18
36	13.04	21.74
40	14.29	17.86
44	**6.67**	**13.33**
48	14.71	17.65
52	16.22	16.22
56	12.50	20.00
60	11.63	16.28
64	14.58	16.67
68	21.57	21.57
72	18.87	20.75
76	19.30	22.81
80	14.75	16.39
84	18.75	26.56
88	20.90	22.39
92	23.61	22.22
96	20.00	20.00
100	20.51	26.90

By looking at Tab. II one can check that, except for 1.09 MHz resolution bandwidth, all power line cable false alarm probabilities were greater than or equal to the antenna false alarm probabilities. The lowest antenna false alarm rate was null, achieved for 5 MHz resolution bandwidth, while the cables lowest one occurred for 2.27 MHz resolution bandwidth and equal to 13.33 %. For this resolution bandwidth, the antenna false alarm rate is equal to 6.67 %, half of the power line cable rate, what again indicates the appropriacy of the antenna for spectrum sensing, rather than the power line cable. It is important to emphasize that, as the number of measured data in the environment was limited, a single false alarm detection represents a high percentage of the total. Combining the results from Tabs. I and II (the detection and false alarm rates) it is possible to say that the most accurate measurements for both the antenna and the power line cable were made when the window had 2.27 MHz resolution bandwidth.

It is important to emphasize that, as the measurements were made in the same environment and the devices did not have their location altered, there was not a significant change in the rates obtained for each measure. Further analysis for different environments are planned for other experiments.

V. CONCLUSION

This work aimed to analyze the differences of spectrum measurements made on the power line cable and with an antenna and the performance of the energy-based detector on both scenarios to decide the best way to monitor the outdoor radio frequency environment in the frequency band ranging from 1.705 up to 100 MHz. This detector was chosen because it is the most simple method to be implemented and it is not necessary to have any knowledge of the primary users signal to determine the detection threshold. However, it has some limitations, as it does not differentiate primary users from noise and it is difficult to determine the threshold in noisy environments.

From the rates of detections and false alarm obtained from simulations using the energy detector on the measured data and presented in Tabs. I and II, it can also be concluded that it was more efficient to localize primary users of an environment using measurements made with the antenna with resolution bandwidth equal to 2.27 MHz in the selected environment. Based on these observations, there is an indication that the antenna can be the best way to acquire outdoor radio frequency information for PLC spectrum sensing. Further studies will be developed in this regard to check the behavior of these measurements for different environments.

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