Measurement and Characterization of a MV Distribution Network for Data Communication

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***Abstract*—This study discusses a measurement campaign carried out over medium-voltage distribution networks, covering the frequency band 100-500 kHz. From the obtained data set, magnitude of channel frequency responses, average channel attenuation, additive noise power spectral density, and achievable data rate are investigated. A numerical analysis shows that the magnitude of the channel frequency response presents a low level of frequency selectivity in the analyzed frequency band. Also, the measured channels can achieve data rates over 3 Mbps.**

***Index Terms*—Channel characterization, sounding, power line communication, medium-voltage.**

I. Introduction

Recently, the use of electric power grids to perform data transmission, known as power line communication (PLC), has been received considerable attention. In fact, PLC is a cost-effective technology that takes advantage of the existing and ubiquitous infrastructure of electric power grids. In this sense, its application has been considered, for instance, in Smart Grids scenarios [1], [2], to implement monitoring, operation, management, and maintenance services.

However, electric power grids were originally designed for delivering energy to a variety of appliances and electrical devices. Hence, the signal transmitted over electric power grids, in much higher frequencies than the mains frequency, is severely attenuated and degraded by high power impulsive noise inserted by load dynamics [3], [4]. Thus, the knowledge of factors that affect signal propagation over power lines is crucial for exploiting the potentialities of electric power grids for data communication.

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In this sense, several studies have been carried out for characterizing electric power grids as a data communication media in different countries. Different frequency bands are considered, resulting in a classification of PLC systems as narrowband [5] or broadband [3]. Also, the majority of these characterization efforts are generally concentrated in low-voltage (indoor and outdoor) scenarios. However, only a few research efforts related to the characterization of medium-voltage (MV) distribution networks for data communication purposes can be found in the literature [6], [7]. This is mainly due to high costs involved in the measurement setup and campaign, which demands appropriate equipment, such as MV-PLC couplers, besides trained staff to deal with MV-power lines (PLs).

Aiming to increase the understanding of electric power grids as a communication media, this study presents some results related to a measurement campaign over a 13.8 kV MV distribution network, in an urban (feeder #1) and rural (feeder #2) areas, in Curitiba, Brazil. The considered PLC features in the analysis are the magnitude of the channel frequency response (CFR), the average channel attenuation (ACA), and the achievable data rate, estimated from all three phases of the MV distribution network. Covering the frequency band $100-500$ kHz, the following findings can be summarized:

- The magnitude of CFR estimates shows a low level of frequency selectivity within the considered frequency band.
- The ACA values of PLs in an urban area are lower than those observed from the rural ones.
- Achievable data rate as high as 3 Mbps can be attained by adopting a total transmission power of 20 dBm.

This study is organized as follows: Section II describes the adopted setup for obtaining CFR and additive noise estimates. The measurement campaign is presented in Section III. Section IV describes the parameters used for the channel characterization, while the numerical analysis is carried out and discussed in Section V. The conclusions related to this research are summarized in Section VI.

II. Measurement Setup

To obtain CFR estimates and additive noise samples of a 13.8 kV MV distribution network, a measurement setup constituted by two parts, named TX and RX, were considered. Figs. 1 and 2 show the measurement setup parts TX and RX, respectively. Despite similarities, they are quite different. In this regard, a brief description of their components is presented as follows:

- *NI PXI/PCI-5412*: it is a waveform generator board installed into the NI PXIe-1071 chassis and controlled from a computer. To operate it, a designed sounding sequence [8] is sent to the generator board and then converted to an analog signal.
- *Power Amplifier F30PV*: it is an equipment used in TX for amplifying the sounding signal before being injected into the MV-PL.
- *Demultiplexer/Multiplexer*: they are circuits used to select the phase whose the sounding signal will be injected/extracted into/from the MV distribution network.
- *Clamper 800 - 812.X.050/BNC*: it is a surge protection device (SPD) used in each phase of TX and RX to preserve the measurement equipment from occasional electrical discharge.
- *Inductive Coupler*: it is a circuit used to inject/extract the sounding signal into/from MV-PL. Basically, it works as a high-pass filter with cutoff frequency equal to 100 kHz and aims to protect the measurement equipment from electrical damage. Three couplers are used in each part of the measurement setup, i.e., one per phase.
- *Low-pass Filter*: it is a circuit used in RX to limit the maximum frequency of the received signal in 500 kHz in order to avoid radio signal interference.
- *Razor CompuScope 1642*: it is a waveform digitizer board installed into the computer of RX. Its function is to convert the received analog signal in a digital signal that will be analyzed later.

To estimate CFRs of a MV distribution network, the sounding-based methodology addressed in [8] is adopted. Differently from other methods, this one does not rely on the use of the vector network analyzer (VNA). Using the sounding-based methodology, a CFR estimate is collected every time interval $T = 1.536$ ms. Furthermore, as this method is based on orthogonal frequency-division multiplexing (OFDM) scheme, T can be easily changed.

As depicted in Figs. 1 and 2, TX is used for injecting the sounding signal into the MV-PL whereas RX is used for collecting it. Through the waveform generator, the sounding signal covering the frequency band $100 - 500$ kHz and with a peak amplitude of 1.5 V is sent to the amplifier. Next, a gain of 9 dB is given by the amplifier and then it is injected into a selected phase of MV distribution network through the inductive coupler. At RX, the sounding signal is extracted from the respective phase by the inductive coupler, filtered, and then converted into a discrete sequence by the data digitizer with a sampling frequency of 1 MHz. It is important to state that the sounding signal is composed of successive OFDM symbols and its parameters are summarized in Table I.

Regarding the additive noise, its measures were obtained by using only RX, i.e., there was no sounding signal being injected into MV distribution network during the measurement procedure. Similar to the CFR estimates, the additive noise samples were filtered by the low-pass filter and converted into the discrete sequence by the data digitizer board considering a sampling frequency of 1 MHz.

TABLE I
ESTIMATION METHODOLOGY PARAMETERS.

Description	Value
Frequency Bandwidth	$100 - 500$ kHz
Sampling Frequency	1 MHz
Number of subcarriers	512
Modulation	BPSK
Cyclic prefix length	512
Frequency resolution	97.66 kHz
Symbol duration	1.536 ms

III. MEASUREMENT CAMPAIGN

The measurement campaign was carried out in a 13.8 kV MV distribution network in Curitiba, PR, Brazil. To do so, twelve PLs were considered such that seven belong to feeder $\#1$ and five are from feeder $\#2$. Phases A, B, and C were measured, except two links from feeder $\#2$, where only phases A and B were available. The distances of the measured MV-PLs varied from hundreds of meters to a few kilometers. Furthermore, each measure was constituted of $1,953$ successive estimates of CFR. Three measures were performed per phase, corresponding to $5,859$ CFR estimates each. Then $123,039$ and $76,167$ CFR estimates were obtained from feeders $\#1$ and $\#2$, respectively. In total, $199,206$ CFR estimates were collected. Regarding the additive noise, one measure with 3×10^6 samples per phase were obtained, totalizing 21 and 13 measures from feeders $\#1$ and $\#2$, respectively.

IV. DATA ANALYSIS

This section briefly states the parameters used in the numerical results.

A. Average Channel Attenuation

ACA of given CFRs is described by

$$\bar{A} = -\frac{1}{B_w}\int_{B_w} |H(f)|^2 df, \tag{1}$$

where $H(f)$ is CFR and B_w is the frequency bandwidth. $\bar{A}$ is usually represented in decibel (dB) as $\bar{A}_{dB} = 10\log_{10}\bar{A}$. Note that ACA indicates the attenuation profile of a communication channel. Additionally, ACA may be useful to come up with a simple channel model.

B. Achievable Data Rate

Assuming that PLC channels are linear time-invariant (LTI) during a time interval shorter than its coherence time and the measured additive noise can be modeled as a Gaussian colored random process, the achievable data rate, C, can be expressed as

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

subject to $\int_{B_w} S_x(f)df \leq P_x$, $S_x(f)$ and $S_v(f)$ denote, respectively, the power spectral density (PSD) of the transmitted signal and the additive noise, and $P_x \in \mathbb{R}^+$ is the total transmission power.

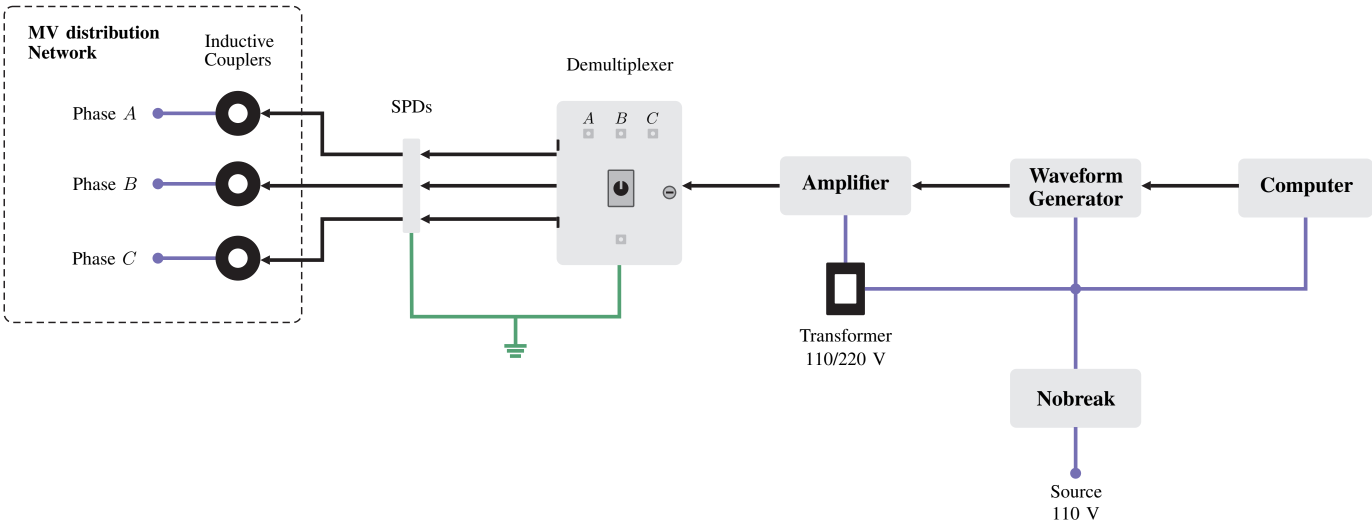

Fig. 1. Block diagram of the sounding-based measurement setup, TX.

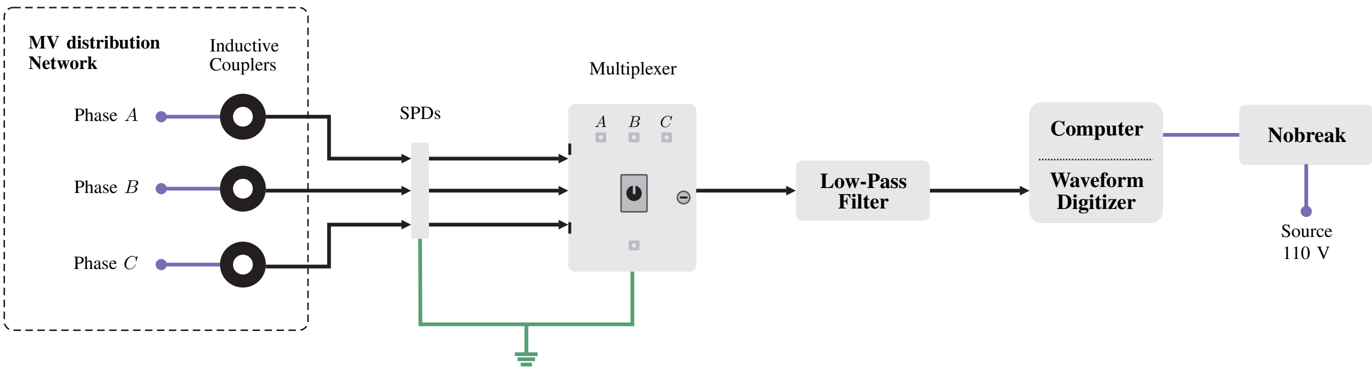

Fig. 2. Block diagram of the sounding-based measurement setup, RX.

V. Numerical Analysis

In this section, the numerical analysis related to the expressions presented in Section IV is discussed. All results comprise the frequency band 100 – 500 kHz and, when required, the total transmission power $P_x \in \{0, 2.5, \cdots, 20\}$ dBm. These ranges are in accordance with the regulatory constraint [9].

To start our analysis, maximum, mean, and minimum values of the magnitude of CFRs are shown in Fig. 3. Notice that the maximum values of the magnitude are around -15 dB, while the minimum magnitude is approximately -100 dB. This difference results from the distinct distances between TX and RX in the measurement campaign. It is also observed that the mean values of the magnitude ranges from -50 to -30 dB, depending on the frequency value. However, the magnitude of CFRs has a low level of frequency selectivity.

Table II shows maximum, mean, minimum, and standard deviation (SD) values of ACA for the feeders and phases used in the measurement campaign. In both feeders,ACA values do not vary significantly with respect to the phase. For instance, considering feeder #1, the mean values of ACA have a maximum variation of 1.65 dB (between phases A and C). Also, ACA values observed in feeder #1 are lower than the ones noticed in feeder #2. This occurs due to the greater distances between TX and RX in the feeder #2.

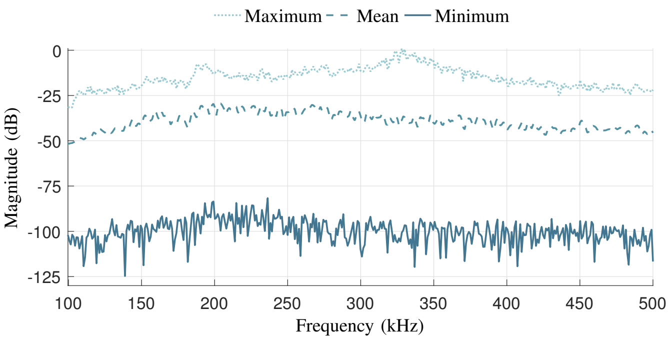

Fig. 3. Magnitude of channel frequency responses.

For computing the achievable data rate, it is needed to first obtain the additive noise PSD. For this purpose, several estimates of the additive noise PSD were obtained by the Welch's method [10]. Maximum, mean, and minimum values of such PSDs are shown in Fig. 4. Also, an estimate of the thermal noise PSD generated in RX is presented for comparison purposes. Analyzing all of them, it is observed that the additive noise PSD ranges from approximately -87 to -67 dBm/Hz within the considered frequency band. In

TABLE II
STATISTICS OF ACA FOR ALL FEEDERS AND PHASES.

Average channel attenuation (dB)					
Feeder	**Phase**	**Maximum**	**Mean**	**Minimum**	**SD**
#1	A	50.21	35.38	24.14	4.97
	B	49.51	35.14	25.04	5.13
	C	50.52	37.03	26.34	4.64
#2	A	53.34	45.86	33.69	4.80
	B	52.87	44.83	31.66	5.33
	C	55.32	41.11	27.29	5.99

addition, the variation between minimum and maximum values is significant, which indicates that the additive noise PSDs may vary considerably depending on the measurement point. By comparing the obtained curves with the instrument reference, it is observed that the measured noise power is relatively low. However, the noise power varies over the entire frequency band and presents peaks in specific narrow frequency bands.

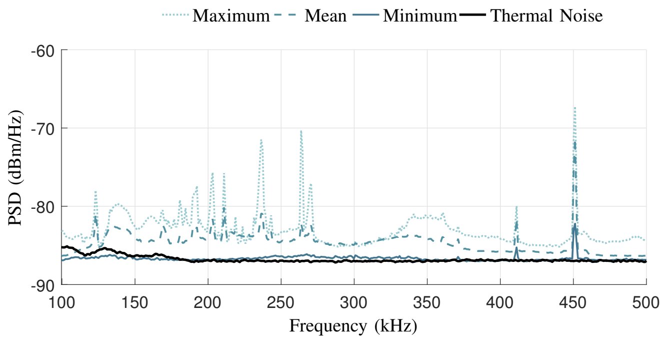

Fig. 4. Estimates of the additive noise PSDs.

Finally, the results for the achievable data rate are shown in Fig. 5. Observe that the achievable data rate values do not vary significantly among the phases, being such variation less than 0.5 Mbps within the considered range of transmission power. Such result is expected since all phases have similar lengths. Also, the maximum achievable data rate surpasses 3 Mbps for a total transmission power of 20 dBm. Nonetheless, the difference between maximum and minimum values can reach 3 Mbps.

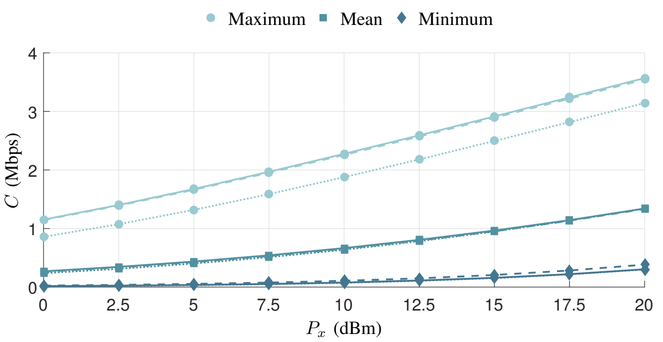

Fig. 5. Achievable data rate versus total transmission power for phases A(-), B(- -), and C(:).

VI. CONCLUSIONS

In this study, a measurement campaign over a 13.8 kV medium-voltage distribution network has been addressed for data communication purposes. Measured data were collected from two feeders and all three phases of the medium-voltage distribution network in the city of Curitiba, Brazil. Based on that, analysis of the magnitude of channel frequency response, average channel attenuation, additive noise power spectral density, and achievable data rate have been carried out for the frequency band $100 - 500$ kHz.

Numerical results have shown that the level of frequency selectivity of the magnitude of channel frequency response is low within the considered frequency band. In addition, these results are quite similar comparing all phases. Also, the mean values of the average channel attenuation are around to 35 and 45 dB, being the lower ones associated with the urban area while the higher ones are related to the rural area. Finally, achievable data rates higher than 3 Mbps may be reached due mainly to the low power of the measured noise.

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