Hybrid Power Line/Wireless Systems: Analyses of Normalized SNRs for In-home Broadband Scenarios

Nathan Cravo, Mateus de L. Filomeno, Moisés V. Ribeiro

Abstract— **This paper analyzes the normalized signal-to-noise ratios (nSNRs) of power line and wireless media to evaluate the suitability of hybrid power line/wireless systems in in-home broadband scenarios. In this sense, we assume that the transmitter node knows the channel state information, and then we seek to find the level of diversity between power line and wireless medium based on the amount of nSNR intersections in the frequency domain. In the numerical analysis, we show that power line and wireless media present nSNRs intersections in several scenarios. With this, it can be estimated whether or not the transmission power should be allocated. Moreover, we verify that greater diversity is found with the distance increasing, which favors hybrid power line/wireless systems.**

Keywords— **hybrid communication system, diversity, power line communication, wireless communication.**

I. INTRODUCTION

Power line communication (PLC) and wireless communication systems have been widely exploited worldwide, being relevant in many different scenarios. The former has been mainly considered as a telecommunication solution for smart grid applications. As it is deployed over electric power systems, its cost with installation and maintenance is considerably reduced. The latter, on the other hand, has been widely applied where mobility and connectivity with a minimum telecommunication infrastructure are required. Previous works [1] have shown that each of these data communication systems presents distinct and complementary features, which motivate us to pursue their joint use for improving the performance of data communication between source and destination nodes.

In the literature, different ways to combine these technologies have been presented [1], [2]. Among them, we have the option to combine PLC and wireless media in parallel, resulting in the so-called hybrid power line/wireless system [3]. A significant advantage of using such a system is to exploit the existing diversity between these media in a complementary manner. Diversity is a concept originally found in the field of antennas under different ways, being one of them spatial diversity, which takes into account a trade-off between the data communication system reliability and the spectral efficiency. In the scope of hybrid power line/wireless systems, however, it is described as an asymmetrical diversity[1], which is motivated by the different channel and noise characteristics of both media [4].

In this sense, several papers arose covering the use of hybrid power line/wireless systems for improving the performance of data communication system. For instance, [3] and [5] analyzed the data communication performance of this kind of hybrid communication system by proposing the optimal power allocation to improve either the achievable data rate or the average bit error probability. Furthermore, several signal combining techniques were investigated in [4], [6] in order to increase the data communication system reliability. Whereas [4] studied signal combining for a hybrid power line/wireless system within a narrowband context, [6] focused on combining techniques based on information of the noise characteristics of in-home broadband scenarios.

In [6], based on a measured data set from several residential facilities, the authors also estimated the average power line and wireless signal-to-noise ratios (SNRs) and showed that SNR values were approximately split by a linear relation. In other words, similar SNR ranges were found out for both media. Similar results were also obtained in [7] in office environment. These outcomes indicate that hybrid power line/wireless systems can be used to improve data communication performance within in-home broadband contexts if the transmitter side does not know the channel state information (CSI). To the best of the authors' knowledge, however, there is a lack in the literature in terms of a qualitative comparison between PLC and wireless media considering the CSI knowledge by the transmitter node, which would be better evaluated based on the normalized signal-to-noise ratio (nSNR) instead of the SNR.

In this sense, this paper carries out a comparative analysis between the nSNRs of PLC and wireless media in in-home broadband scenarios to assess the suitability of hybrid power line/wireless system when the transmitter node knows the CSI. In this regard, several channel impulse response (CIR) and power spectral density (PSD) estimates from measurements are considered to characterize the PLC medium, whereas the wireless medium is modeled based on well-accepted models under different distance and line-of-sight contexts. Based on the evaluation of the nSNR, this study analyzes the existing diversity between PLC and wireless media by considering the amount of intersections of nSNR curves. It is shown that PLC and wireless media have nSNR intersections in several scenarios, with an increasing number of intersections as the distance between data communication nodes increases.

II. HYBRID POWER LINE/WIRELESS SYSTEM MODEL

In this section, we briefly described the hybrid power line/wireless system [5]. We assume that the symbol time

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[1]"Asymmetrical diversity" is called "diversity" for simplicity in this study.

interval of the transmitted signals is shorter than the hybrid coherence time so that this hybrid communication system is modeled as linear time-invariant (LTI) during such time interval. The hybrid coherence time is hence the minimum coherence time of both media. Fig. 1 shows the hybrid power line/wireless system addressed in this paper. The solid lines correspond to the PLC medium (subscript "1") and the dashed lines to the wireless one (subscript "2").

Since power line and wireless channels are LTI within the above mentioned time interval, the CIR of the m^{th} medium can be expressed as a L_m-length sequence $\{h_m[n]\}_{n=1}^{L_m}$, $m \in \{1, 2\}$. Consequently, the discrete-time signal received in the m^{th} medium can be expressed as

$$y_m[n] = x_m[n] \star h_m[n] + v_m[n], \quad \forall m, \tag{1}$$

with $\{x_m[n]\}$ and $\{v_m[n]\}$ denoting the discrete-time sequences of the transmitted signal and additive noise in the m^{th} medium, respectively; and $\star$ indicating the linear convolution operator.

Note that the CIR of the m^{th} medium can be represented by the vector $\mathbf{h}_m = [h_m[1] \; h_m[2] \; \dots \; h_m[L_m]]^T$, in which T denotes the transpose operator. Then the N-length vector that denotes the channel frequency response (CFR) is $\mathbf{H}_m = [H_{m,1} \; H_{m,2} \; \dots \; H_{m,N}]^T = \mathbf{W}[\mathbf{h}_m^T \; \mathbf{0}_{1\times N-L_m}]^T$, where $\mathbf{W}$ denotes the N-size discrete Fourier transform (DFT) matrix, $\mathbf{0}_{1\times N-L_m}$ is a $(N - L_m)$-length row vector of zeros, and $H_{m,k} \in \mathbb{C}$ refers to the k^{th} element of $\mathbf{H}_m$, with $k \in \{1, 2, \dots, N\}$. Afterwards, we can assume an OFDM scheme with properly designed cyclic prefix and therefore the discrete-frequency representation of the symbol received at the k^{th} subchannel and m^{th} medium can be expressed as

$$Y_{m,k} = \sqrt{P_{m,k}} \; H_{m,k} \; X_{m,k} + V_{m,k}, \tag{2}$$

in which $X_{m,k}$ is a zero mean and unit variance random variable that represents the transmitted symbol at the k^{th} subcarrier and m^{th} medium; $P_{m,k} \in \mathbb{R}^+$ is the transmission power allocated to the k^{th} subcarrier and m^{th} medium; and $V_{m,k} \in \mathbb{C}$ denotes the additive noise at the k^{th} subchannel and m^{th} medium.

Now, we can describe the nSNR (or channel-to-noise ratio)[2], which can be used to characterize the hybrid power line/wireless system. The nSNR at the k^{th} subchannel and m^{th} medium is given by

$$\overline{\gamma_{m,k}} = \frac{|H_{m,k}|^2}{P_{V_{m,k}}}, \tag{3}$$

where $P_{V_{m,k}} = \mathbb{E}\{|V_{m,k}|^2\}$ is the noise power at the k^{th} subchannel and m^{th} medium. In addition, the SNR can be expressed as $\gamma_{m,k} = P_{m,k}\overline{\gamma_{m,k}}, \forall k, m$.

III. Problem Formulation

The literature shows interesting applications of the nSNR and SNR parameters under the scope of hybrid power line/wireless systems. In case of the absence of the knowledge of the instantaneous CSI at the transmitter side, the usefulness of the hybrid power line/wireless system can be evaluated based on the analysis of power line and wireless SNRs. In summary, the average SNR of power line and wireless media should be within similar ranges [6]. Otherwise, both media cannot support the same applications and hence only the medium with highest SNR is needed.

If the transmitter knows the instantaneous CSI, then the nSNR values are analyzed instead of the SNR values. In this case, [3], [5] demonstrated that the total transmission power should be allocated only to the following nSNRs:

$$\overline{\gamma_k} = \max_m \{\overline{\gamma_{m,k}}\}, \quad \forall k, \tag{4}$$

where $\overline{\gamma_k}$ is the equivalent nSNR for the k^{th} subchannel. Based on (4), if all nSNR values of one medium are greater than the nSNR values of the other, then only one medium will be used and consequently the hybrid communication system will be equivalent to the best between power line and wireless media. On the other hand, if there are intersections between the nSNR curves of the two media (i.e., there is no dominant medium), then the hybrid power line/wireless system will be a mixture of power line and wireless subchannels.

In this sense, this paper complements the discussions provided in [3], [5]. To do so, we consider the transmitter has actual knowledge of the CSI and can evaluate in which medium the transmission power should be allocated. With this in mind, the following questions arise: *Is there any intersections between the PLC and wireless nSNRs or only one medium is dominant? Can diversity between these media be properly exploited for in-home data communication?* Answers to these questions are given in the next sections.

IV. Data Sets

In this section, we present realistic data sets of CIRs and additive noise PSDs for power line and wireless media. Based on these data sets, the nSNR values can be computed and then analyzed to give answers to the aforementioned questions. Due to the complex modeling of CIR and additive noise PSD, measurement data is considered for PLC. Regarding wireless, the analyzed data is originated from well-accepted models. The data sets associated with power line and wireless medium are described below.

[2]A detailed discussion on the usefulness of nSNR for resource allocation purposes can be found in [8].

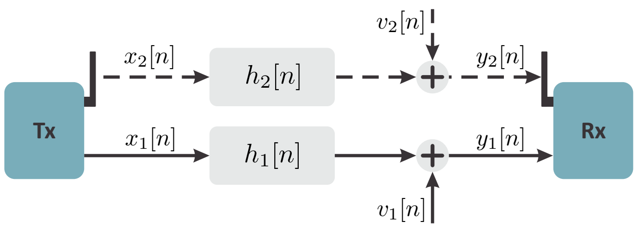


Fig. 1: A block diagram representation of the hybrid power line/wireless system.

TABLE I: Average channel gain (dB) of the Classes #1 up to #9.

Class	$\#1$	$\#2$	$\#3$	$\#4$	$\#5$	$\#6$	$\#7$	$\#8$	$\#9$
$G_{i,1}$	-52.26	-38.46	-33.43	-30.70	-27.31	-23.58	-17.58	-12.56	-7.13

A. *Power line medium*

Concerning PLC, we consider a data set provided by a measurement campaign, which was carried out in the city of Juiz de Fora, Minas Gerais, Brazil, covering seven different houses [2], [9]. This measurement campaign focused on residential PLC systems. The collected data was processed and then used to obtain estimates of CFRs and additive noise PSDs. The measured frequency band was in the range of $1.7 - 100$ MHz, being $N = 2048$. In total, 141 CIR and additive noise PSD samples were selected to be the most representative ones of a measurement campaign of over thousands of channel and additive noise measurements.

The available PLC CIRs were normalized to have an average gain according to the nine classes for indoor PLC channels stated in [10]. This was done because the distance between transmitter and receiver nodes were not reported for the measurements. Moreover, the average gain of PLC CIRs is mainly affected by the power line length, which can be considerably longer than the physical distance between data communication nodes. Hence, aiming for a reasonable comparison between wireless and PLC, a normalization procedure was applied to the latter.

Following [10], we considered the so-called Classes $\#1$ to $\#9$ in our analysis. These are frequency-dependent and given according to the attenuation level. Class $\#1$ has the lowest gain and Class $\#9$ the highest gain. Based on these two classes, the minimal and maximal average gain of PLC CIR can be inferred for indoor residential environments. The available PLC CIR were then normalized to meet these classes, which is explained below.

First, let G_a be the average gain of a given PLC channel, expressed as follows:

$$G_a = \frac{1}{N}\sum_{k=1}^{N} |H_{1,k}|^2. \quad (5)$$

If we assume there is a coefficient a_i that makes the current channel gain equals to $G_{i,1}$, then we have

$$G_{i,1} = \frac{1}{N}\sum_{k=1}^{N} |a_i H_{1,k}|^2, \quad (6)$$

where $i \in \{1, 2, \ldots, 9\}$ corresponds to one of the chosen classes and $G_{i,1}$ to the PLC channel gain as one of the classes are applied (i.e., Class $\#1$ and Class $\#9$). By comparing Eqs. (5) and (6), it follows that

$$a_i = \sqrt{\frac{G_{i,1}}{G_a}}. \quad (7)$$

The above coefficient (a_i) was calculated for the considered classes by analyzing all possible channels. In this perspective, Table I presents the average channel gain for Classes $\#1$ up to $\#9$. In addition, the mean value of the measured PLC average channel gain calculated without the normalization equals -19.27 dB, which is around Class $\#7$.

B. *Wireless medium*

Concerning wireless communication, the same number of PLC channels were generated based on the channel model proposed by the Task Group 802.15.4a [11], which describes a generic channel model within either $100 - 1000$ MHz or $2 - 10$ GHz. The last frequency range is considered since it covers the frequency of 5.8 GHz, which is the center frequency examined in this study. The mentioned report relies on the Saleh-Valenzuela model [12], where the authors developed an indoor multipath propagation model.

The described wireless channel model considers a distance-decay law for the path gain, expressed by

$$G_{l,2}[dB] = G_{0,l} - 10 n_l \log_{10} \frac{d}{d_0}, \quad (8)$$

in which $l \in \{\text{LOS, NLOS}\}$, $G_{0,l}$ is the path gain at a reference distance d_0 = 1 m, and n_l corresponds to the path-loss exponent - see Table II for the employed values [11]. Also, the valid distance range is from 7 to 20 m, as defined in the channel model [11].

TABLE II: Assumed path gain and path-loss exponent [11].

Parameters	LOS	NLOS
$G_{0,l}$	-43.9	-48.7
n_l	1.79	4.58

Finally, the noise power in the wireless medium was calculated as follows [13]:

$$P_{V_{2,k}}[dBm] = -173.8 + 10\log_{10}(B_w) + NF, \quad \forall k, \quad (9)$$

where B_w is the chosen frequency bandwidth and NF corresponds to the noise figure in the receiver. It was assumed $NF = 3.3$ dB [14].

V. Numerical Analysis

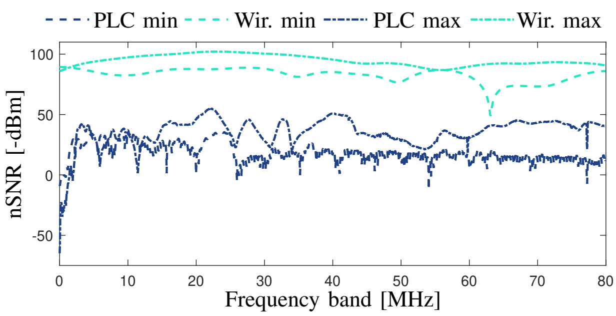
In this section, a numerical comparison between PLC and wireless nSNRs is carried out. We considered a frequency bandwidth equal to $B_w = 80$ MHz. Therefore, the $1.7 - 81.7$ MHz frequency band is assumed for the PLC, whereas the $5.76 - 5.84$ GHz frequency band is considered for the wireless medium. The subchannel frequency bandwidth is the same for both channels because the same total frequency bandwidth and number of subchannels, N, are adopted.

Moreover, four distinct scenarios are considered for assessing the nSNR for the conditions that characterize line-of-sight (LOS) and non-line-of-sight (NLOS). For the sake of simplicity, the values of distances equal to 7 m and 20 m were chosen when dealing with Classes $\#1$ and $\#9$, respectively. Note that the distances impact only on the nSNR of the wireless medium, whereas the classes affect the PLC one. Also, the former is the only one affected by the absence or presence of line-of-sight. By comparing the lowest and highest nSNR values of the wireless medium with the lowest and highest nSNR values of the PLC medium, we cover both the worst and best cases of diversity, i.e., the cases in which more and less intersections occur. For both media, we calculate the mean values of all nSNR realizations, resulting in a single parameter for each nSNR realization. In the sequel, the nSNR realizations were sorted in ascending order according to this new parameter and then the nSNR realizations with minimum and maximum values were selected for each medium. Based on these curves, we can infer the number of intersections between the nSNRs of these data communication media. It should be noted the nSNRs of minimum and maximum values can be considered the same for every class since they are estimates from in-home measured PLC channels and are not defined as the classes described by [10]. Also, the distance is not preponderant due to the length of the power line compared to the data communication node ones, as described in Section IV-A.

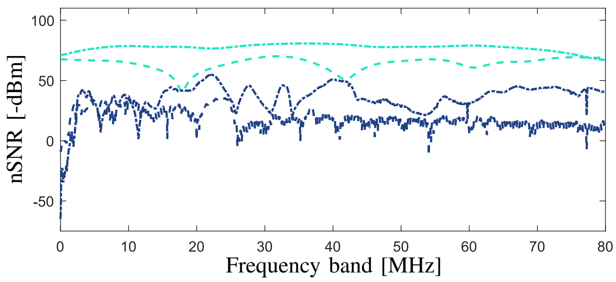
Fig. 2a and Fig. 2b show the nSNRs for PLC medium assuming Class $\#1$ and wireless medium assuming 7 m. Furthermore, LOS and NLOS scenarios are taken into account for the wireless medium. As can be seen in Fig. 2a, wireless nSNRs are considerably higher than PLC ones at all frequencies. Due to the absence of nSNR intersections between both media, diversity may not be exploited if the transmitter knows the CSI. Considering Fig. 2b, it is possible to see intersections between nSNRs curves around the frequencies equal to 18 MHz and 41 MHz. However, we can not state that diversity would be suitable, since wireless nSNRs clearly outperform PLC ones in the most part of the frequency band.

The nSNRs for PLC medium (Class $\#1$) and wireless medium (20 m) assuming LOS and NLOS scenarios are depicted in Fig. 3a and Fig. 3b, respectively. Observing Fig. 3a, wireless nSNRs have a shift of around -10 dB, compared to Fig. 2a. One can see that, if there is no obstruction to the line-of-sight, wireless surpasses PLC, thus being dominant. By looking at Fig. 3b, the nSNR between the two media has a significant change. For instance, both curves have intersections around the frequency bands $15-25$ MHz and $38-43$ MHz. Also, the PLC maximum nSNR is greater than wireless minimum nSNR for these frequency ranges, which means PLC may be a good alternative in this scenario. In other words, diversity may be applicable and thus the hybrid power line/wireless system can be an interesting option.

Fig. 4a and Fig. 4b show the nSNRs for PLC medium (Class $\#9$) and wireless medium (7 m) considering LOS and NLOS scenarios, respectively. Note that the nSNR difference between PLC and wireless changes dramatically compared to Class $\#1$. The PLC channel gain increases, which leads to an upward shift of the PLC nSNR. Notice that what changes for Class $\#9$ is only the PLC nSNR values. In other words, wireless nSNR curves remain the same as previous for each scenario. As we can see in Fig. 4a, there are nSNR intersections in the whole frequency band, and the difference between the maximum PLC and wireless nSNRs decreases. As for Fig. 4b, the maximum PLC nSNR surpasses wireless one over different parts of the assumed frequency band, and there are nSNR intersections over the entire frequency band as in the former LOS case. By changing the distance to 20 m (see Fig. 5a and Fig. 5b), the wireless nSNR values present a downward shift in both scenarios compared to $d = 7$ m, and the frequency bands in which PLC and wireless maximum or minimum curves surpasses one or another are distinct. Overall,

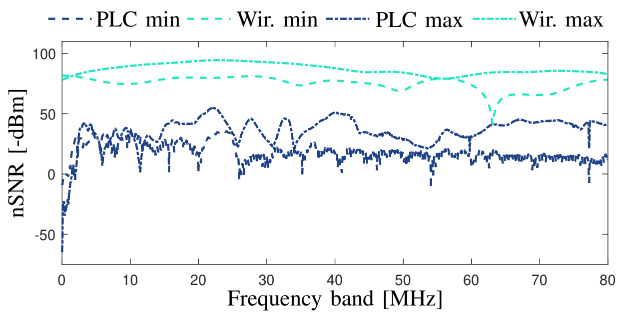


(a)

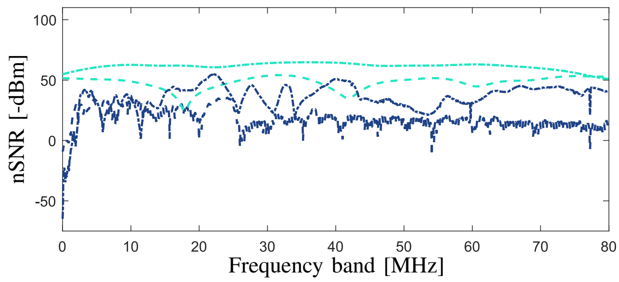


(b)

Fig. 2: Maximum and minimum nSNRs for power line (Class $\#1$) and wireless media ($d = 7$ m): (a) LOS, (b) NLOS.

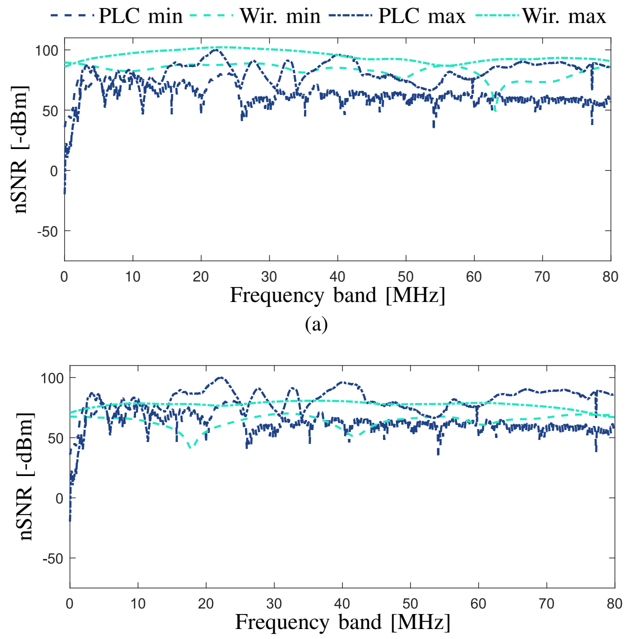


(a)



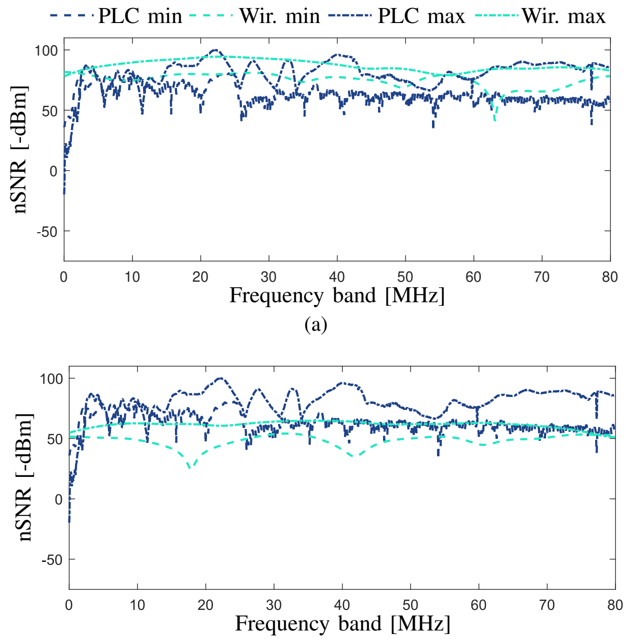
(b)

Fig. 3: Maximum and minimum nSNRs for power line (Class $\#1$) and wireless media ($d = 20$ m): (a) LOS, (b) NLOS.



(a) (b)

Fig. 4: Maximum and minimum nSNRs for power line (Class #9) and wireless media ($d = 7$ m): (a) LOS, (b) NLOS.



(a) (b)

Fig. 5: Maximum and minimum nSNRs for power line (Class #9) and wireless media ($d = 20$ m): (a) LOS, (b) NLOS.

PLC and wireless have similar nSNRs values within the entire frequency band regarding Class #9, then what rules is simply which one is the better according to the frequency band, thus giving space for diversity to be explored.

VI. Conclusion

This paper has analyzed the nSNR of power line and wireless media for in-home broadband data communication systems. In this regard, measured data have been used to characterize the nSNR of the power line medium, whereas well-accepted models have been considered to yield the wireless nSNR. By analyzing the combinations between power line and wireless media, we have shown that their nSNRs present intersections in several scenarios. For short distances, a low number of intersections occurs and, as a consequence, only one medium is recommended for data communication purposes. As the distance increases, the amount of intersections between the nSNR related to both media increases, which is more evident in a non-line-of-sight scenario. As a result, the diversity can be exploited in the context of hybrid power line/wireless systems to improve the data communication performance.

References

[1] 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, April 2018.

[2] T. R. Oliveira, F. J. A. Andrade, A. A. M. Picorone, H. A. Latchman, S. L. Netto, and M. V. Ribeiro, "Characterization of hybrid communication channel in indoor scenario," *J. Commun. Inf. Syst.*, vol. 31, no. 01, pp. 224–235, Sept. 2016.

[3] M. de L. Filomeno, M. L. R. de Campos, H. V. Poor, and M. V. Ribeiro, "Hybrid power line/wireless systems: An optimal power allocation perspective," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6289–6300, Oct. 2020.

[4] M. Sayed, T. A. Tsiftsis, and N. Al-Dhahir, "On the diversity of hybrid narrowband-PLC/wireless communications for smart grids," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4344–4360, July 2017.

[5] M. de L. Filomeno, M. L. R. de Campos, H. V. Poor, and M. V. Ribeiro, "Hybrid power line/wireless systems: power allocation for minimizing the average bit error probability," *IEEE Trans. Commun.*, vol. 70, no. 2, pp. 810–821, Feb. 2022.

[6] 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.

[7] S. W. Lai, N. Shabehpour, G. G. Messier, and L. Lampe, "Performance of wireless/power line media diversity in the office environment," in *IEEE Glob. Commun. Conf.*, 2014, pp. 2972–2976.

[8] G. R. Colen, L. G. de Oliveira, C. B. Zeller, A. J. Han Vinck, and M. V. Ribeiro, "Statistical analysis and modeling of a novel parameter for resource allocation in multicarrier PLC systems," *Trans. Emerg. Telecommun. Technol.*, vol. 28, no. 11, pp. 1–12, May 2017.

[9] M. S. P. Facina, H. A. Latchman, H. V. Poor, and M. V. Ribeiro, "Cooperative in-home power line communication: Analyses based on a measurement campaign," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 778–789, Feb. 2016.

[10] M. Tlich, A. Zeddam, F. Moulin, and F. Gauthier, "Indoor power-line communications channel characterization up to 100 MHz-part I: One-parameter deterministic model," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1392–1401, July 2008.

[11] 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., Nov. 2004.

[12] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 2, pp. 128–137, Feb. 1987.

[13] V. K. Garg, *Wireless communications & networking*. Morgan Kaufmann, 2007.

[14] M. Jeong, O. Lee, and S.-W. Kim, "WLAN transceiver for 802.11 a/b/g/n/ac with integrated power amplifier and harmonic LO frequency VCO," in *International SoC Design Conference*, 2017, pp. 81–82.