Improving the Performance of MIMO PLC System with Feedback Information: Time-Varying Channel Analysis

Ândrei Camponogara, Renato Machado and Moisés V. Ribeiro.

Abstract— **This contribution aims to improve the data transmission performance of a power line communication (PLC) scheme with quantized feedback channel. It is considered a 2×2 PLC time-varying channel. A quantized channel state information is fed back to update the transmitter aiming at maximizing the instantaneous signal-to-noise ratio. In order to evaluate the system performance under a time-varying channel, single- and multi-carrier modulation schemes are taken into account. The results reveals that for single-carrier modulation the performance can considerably change because the spread of the coefficients of the channel and, as a consequence, the choice of center frequency is relevant to motivate the use of feedback channel to improve the performance (up to 5 dB). On the other hand, the use of multi-carrier modulation with feedback channel state information can offer improvements as high as 2.5 dB.**

Keywords— **Transmit diversity, power line communications, quantized channel state information, multiple-input multiple-output systems.**

I. INTRODUCTION

Currently, a great deal of attention is toward to power line communication (PLC) because it is envisioned as one of the key data communication technology for massive deployment of smart grid concepts into the electric power grids. Additionally, it can be useful for deploying network access infrastructure to provide high data-rate internet access.

The ubiquitousness of electric power grids is one of the greatest motivation for driving effort to design the new generation of PLC technology. However, the hardness of such data communication medium (i.e., signal attenuation that considerably increase with distance and frequency, impedance mismatching, high power impulsive noise) can result in a poor performance of a PLC system. An interesting manner to handle or minimize this hardness is to exploit the spatial diversity offered by multiple-input multiple-output (MIMO) [1] low- and medium-voltages distribution grids. MIMO communication was initially considered in wireless communications with the transmit diversity technique proposed by Alamouti [2] and afterwards extended to a more general class of codes, namely orthogonal space-time block codes (OSTBCs) [3]. The main advantage provided by the OSTBCs is the diversity gain, which is proportional to the number of transmit and receive antennas of the system.

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Recently, the use of MIMO techniques in PLC systems has been proposed in several works, e.g. [4]–[6]. In these papers, the authors show that channel performance improvement can be obtained when the PLC spatial diversity is well exploited.

In [7], the feedback channel is used to explore in a more effective way the spatial diversity in a conventional MIMO wireless communication system. By using the feedback channel, the transmitter can access the channel state information (CSI) and, if this information is used properly, the maximum diversity gain can be achieved even when an orthogonal code design is not considered.

In this paper, , aiming to explore the benefits of MIMO PLC channels, we analyze a transmission technique for MIMO PLC applications considering the use of a quantized feedback channel (sometimes named by limited feedback channel), which is a more realistic assumption. Based on the scheme presented in [8], we come up with a pre-processing design that uses the quantized feedback information to update the transmitter (Tx modem) at each new frame, aiming to maximize the instantaneous signal-to-noise ratio (SNR) at the receiver (Rx modem). To evaluate the proposed technique we consider a single-carrier and multi-carrier modulation schemes. Through the simulation results we verify that for a single-carrier modulation, the spread of the channel coefficients and, as a consequence, the choice of center frequency is relevant to motivate the use of feedback channel to improve the performance. Considering a center frequency equal to 244.14 kHz, we obtained an improvement of 5 dB. However, using a multi-carrier modulation scheme the improvements were not higher than 2.5 dB.

The rest of this paper is organized as follows. In Section II the system model and the proposed technique are presented. Section III shows the simulation results. Finally, Section IV addresses the conclusions and some final remarks.

II. THE SYSTEM MODEL

Let a 2×2 single-carrier scheme that uses two PLC channels to transmit data from the Tx modem to the Rx modem and one additional error-free and zero-delay channel to feed back quantized channel state information (CSI) from the Rx modem to the Tx modem as shown in Fig. 1. In this plot, we disregard the use of index n to denote the discrete time domain representation, because we are interested in to pay attention to only one symbol period. Additionally, for sake of simplicity, we assume that PLC channels are flat and linear

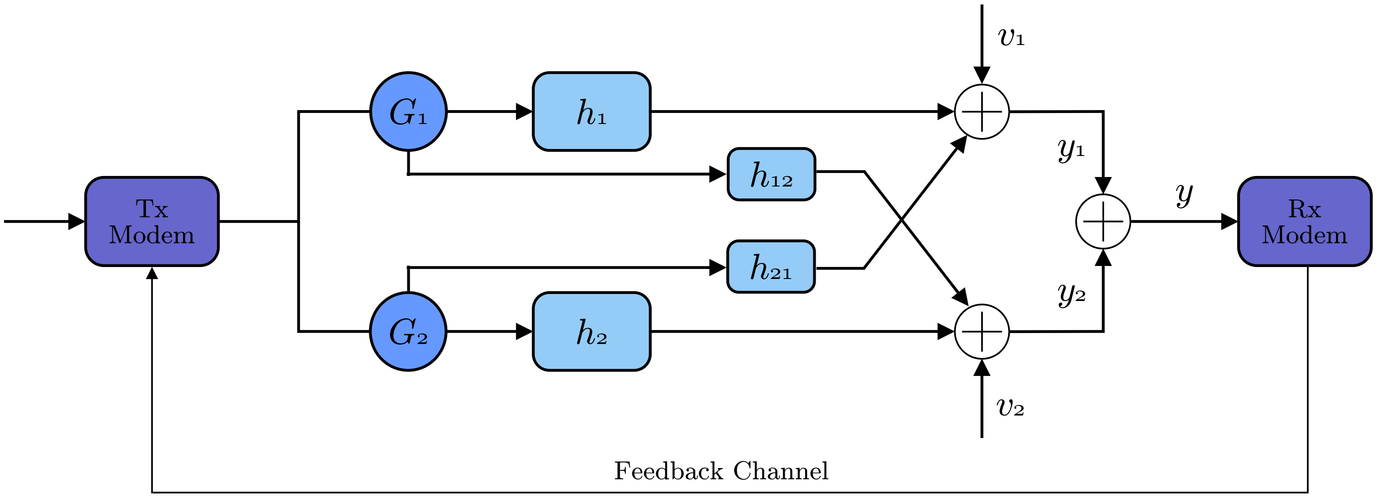

Fig. 1. Block diagram for the system model.

time invariant during each symbol period; perfect symbol synchronization at the Rx modem; the transmitted symbol, s, is a random variable obtained from unitary average-energy and coherent constellation set, S, such as M-ary phase-shift keying (M-PSK), in which $\mathbb{E}\{s\} = 0$, $\mathbb{E}\{ss^*\} = \sigma_s^2 = 1$ and $\mathbb{E}\{\cdot\}$ denotes the expectation operator. Also, we consider that additive-based combination of the received signals is adopted, then the resulting signal is given by

$$\begin{aligned} y &= y_1 + y_2 \\ &= h_1 G_1 s + h_{21} G_2 s + v_1 + h_2 G_2 s + h_{12} G_1 s + v_2 \\ &= (h_1 G_1 + h_{21} G_2 + h_2 G_2 + h_{12} G_1) s + v_1 + v_2, \end{aligned} \quad (1)$$

where y_1 and y_2 are outputs of PLC channels #1 and #2, which are corrupted by additive noise; the terms h_{12} and h_{21} denote coupling between both PLC channels due to the fact that the data is transmitted in the same frequency band; G_1 and G_2 are pre-processing weights, which are obtained from the feed back CSI; the additive noises are stationary random process modeled as additive white Gaussian (AWGN) such that $\mathbb{E}\{v_i\} = 0$, $\mathbb{E}\{v_i v_i^*\} = \sigma_{v_i}^2$, in which $i \in \{1, 2\}$, $\mathbb{E}\{v_1 v_2^*\} = \mathbb{E}\{v_1\}\mathbb{E}\{v_2^*\} = 0$ and $\mathbb{E}\{s v_i^*\} = \mathbb{E}\{s\}\mathbb{E}\{v_i^*\}$.

A. The Transmission Technique

The proposed transmission technique is based on [8], in which the information symbol is pre-processed at the transmitter based on the quantized feedback CSI. We mean quantized feedback CSI the phase information that is fed back from the Rx modem to the Tx modem with b bits by using b bits. The pre-processing is performed by

$$x = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} s, \quad (2)$$

where $G_1 = \sin(\theta)$ and $G_2 = \cos(\theta)$ and $\theta \in [0, 2\pi)$. Before each symbol transmission takes place, the Rx modem analyzes the 2^b possible instantaneous SNR values obtained by using the 2^b pairs of values associated with θ. After identified the pair of phases that maximizes the instantaneous SNR, the Rx modem sends b bits to the Tx modem informing the phases of G_1 and G_2.

We can rewrite (1) as

$$y = \tilde{y} + v_y \quad (3)$$

where

$$\begin{aligned} \tilde{y} &= h_G s \\ &= (G_1 h_1 + G_2 h_2 + G_1 h_{12} + G_2 h_{21}) s \\ &= (\sin(\theta) h_1 + \cos(\theta) h_2 + \sin(\theta) h_{12} + \cos(\theta) h_{21}) s. \end{aligned} \quad (4)$$

and

$$v_y = v_1 + v_2. \quad (5)$$

Considering the received signal in (3), the input of the receive detector is given by

$$\begin{aligned} \tilde{s} &= y h_G^* \\ &= (|h_1|^2 + |h_{12}|^2 + \beta_s) \sin^2(\theta) \\ &+ (|h_2|^2 + |h_{21}|^2 + \beta_c) \cos^2(\theta) \\ &+ \beta_{sc} \sin(\theta) \cos(\theta) + v_y h_G^* \end{aligned} \quad (6)$$

in which $\{\cdot\}^*$ is the the complex conjugate operator, $\beta_s = 2\Re\{h_1 h_{12}^*\}$, $\beta_c = 2\Re\{h_2 h_{21}^*\}$ and $\beta_{sc} = 2\Re\{h_1 h_2^*\} + 2\Re\{h_1 h_{21}^*\} + 2\Re\{h_2 h_{12}^*\} + 2\Re\{h_{12} h_{21}^*\}$. The symbol detection can be performed as

$$\hat{s} = \arg \min_{s' \in S} \{|s' - \tilde{s}|^2\}, \quad (7)$$

where $|\cdot|^2$ and $\Re\{\cdot\}$ denote the square modulus of a complex number and the real part of a complex number, respectively. As we can note, the detection can be performed with low computational burden. Additional, we can easily determine the power contribution associated with signal s, which is expressed by

$$P_{\tilde{y}}(\theta) = \alpha_s \sin^2(\theta) + \alpha_c \cos^2(\theta) + \beta_{sc} \sin(\theta) \cos(\theta) \quad (8)$$

where $\alpha_s = |h_1|^2 + |h_{12}|^2 + \beta_s$ and $\alpha_c = |h_2|^2 + |h_{21}|^2 + \beta_c$, is the power of the received symbol.

In order to obtain the optimum θ phase which maximizes the instantaneous SNR, (8) needs to be differentiated with respect to θ. Hence, the first and second derivative of $P_{\tilde{y}}(\theta)$ are given by

$$P'_{\tilde{y}}(\theta) = 2\alpha_{sc}\sin^2(\theta)\cos^2(\theta) + \beta_{sc}[\sin^2(\theta) - \cos^2(\theta)], \quad (9)$$

and

$$P''_{\tilde{y}}(\theta) = 2\alpha_{sc}[\cos^2(\theta) - \sin^2(\theta)] - 8\beta_{sc}[\sin(\theta)\cos(\theta)], \quad (10)$$

respectively, where $\alpha_{sc} = \alpha_s - \alpha_c$.

Solving (9) and (10) with the following conditions

$$P'_{\tilde{y}}(\theta) = 0 \quad \text{and} \quad P''_{\tilde{y}}(\theta) < 0 \ ,$$

we find

$$\theta^* = \arctan\left(\frac{\alpha_{sc} + \sqrt{\alpha_{sc}^2 + 4\beta_{sc}}}{\beta_{sc}}\right) \quad (11)$$

which is the θ optimum that maximizes the instantaneous SNR.

Since we are interested in working with a quantized feedback channel, we need to find good sets of phases to be considered for θ for different number of b. The sets used in this paper are $\{\pi/4, -pi/4\}$ and $\{3\pi/8, \pi/8, -pi/8, -3\pi/8\}$ for $b = 1$ and $b = 2$ bits, respectively, and it is based on [8]. Table I presents the selection criteria adopted to choose the appropriated phases accordingly to the quantization level.

TABELA I

SELECTION RULE FOR THE QUANTIZED FEEDBACK CHANNEL.

Number of feedback bits (b)	$\beta_{sc} > 0$		$\beta_{sc} < 0$	
	$\alpha_{sc} > 0$	$\alpha_{sc} < 0$	$\alpha_{sc} > 0$	$\alpha_{sc} < 0$
1 bit	$\pi/4$		$-\pi/4$	
2 bits	$3\pi/8$	$\pi/8$	$-\pi/8$	$-3\pi/8$

Finally, it is important to highlight that the idea behind this technique is to distribute the transmission power to both channels in a more efficient way, instead of dealing with the delay between the signals at the channel outputs.

III. SIMULATION RESULTS

In this section, we present the simulation results to assess the performance gain obtained by using the proposed technique.

The performance is analyzed through Monte Carlo simulations in terms of bit error rate (BER) *versus* SNR. We assumed that the symbols are mapped into a binary PSK (BPSK) constellation, the additive noises are white Gaussian and perfect CSI is available at the Rx modem. Also, the Rx modem sends b bits through an error-free and zero-delay feedback channel. Considering the single-carrier modulation, we used 67160 samples of h_1 and h_2 channels in the simulations. These samples were obtained from data set yielded by a measurement campaign to characterize Brazilian low-voltage and indoor PLC channels by deploying the measurement methodology discussed in [9]. Figs. 2 and 3 show real and imaginary amplitudes of these channels whose the chosen center frequencies are 244.14 kHz and 1.81 MHz, respectively. For this channels, we assume that the frequency bandwidth is equal to 48.8 kHz. We can see that the channels present distinctive characteristics (i.e., mean and variance are quite different). Additionally, for channels h_{12} and h_{21}, we assume an attenuation of 20 dB of power with respect to the gains of channels h_1 and h_2 and their phases are modeled as uniform random variables.

Fig. 4 shows the BER performance of single-carrier scheme transmitting BPSK symbols through the aforementioned channels, where we can note that the performance difference between the data communication system without feedback (no feedback) and with ideal feedback (Rx modem sends to the Tx modem the phase, θ^*, obtained in (11)) grows up to about 7 dB, after that the performance related to system with ideal feedback begins to approximate to that one without feedback. On the other hand, Fig. 5 reveals that the performances of both systems present irrelevant difference. Based on the plots in Fig. 2 and 3, we note that feedback can offer improvement, in term of BER, if the spreads of real and imaginary components of channels is low. By evaluation the diversity associated with both channels for both center frequencies, we have noted that only the channels with low spread (center frequency equal to 244.14 kHz) show low diversity and, as a consequence, feedback is useful to improve the performance. Regarding the use of the proposed technique, we noted in Fig. 4 and 5 that the performance, when the number of feedback bits are $b = 1$ bit and $b = 2$ bits, is almost the same for the ideal feedback case. Again, due to the diversity reason, the performance gains can only be achieved when the data communication system operates in the center frequency equal to 244.14 kHz.

In section III-A we extend the analysis of proposed scheme to a PLC system based on a multi-carrier, which makes use of the hermitian-symmetric orthogonal frequency-division multiplexing (HS-OFDM) modulation [10].

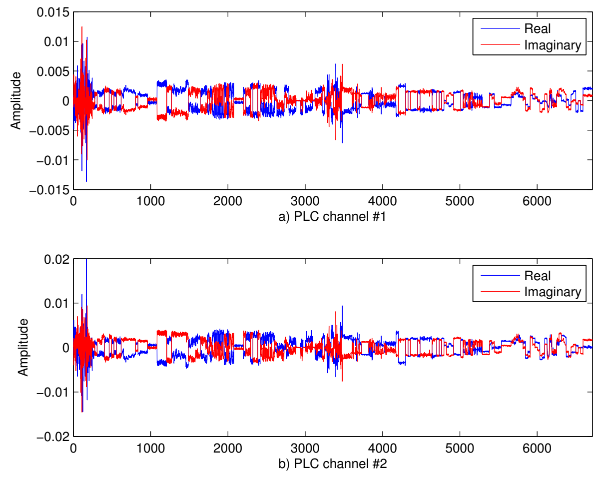

Fig. 2. Amplitudes of real and imaginary components of channels h_1 and h_2 for center frequency equal to 244.14 kHz.

A. *Performance Analysis for HS-OFDM Scheme*

In order to analyze the improvements that the proposed technique can offer for HS-OFDM scheme [10], we carried out some simulations in which we had assumed that the number

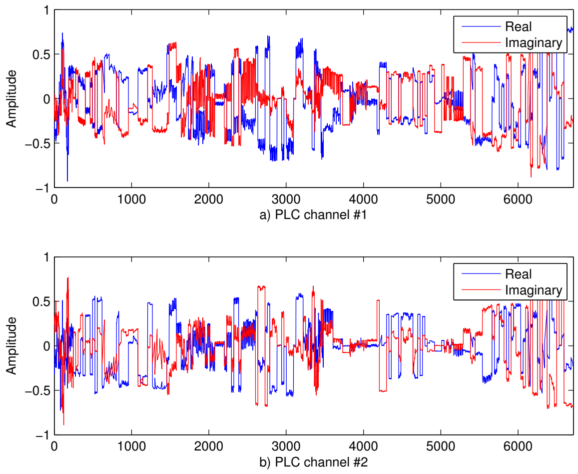

Fig. 3. Amplitudes of real and imaginary components of channels h_1 and h_2 for center frequency equal to 1.81 MHz.

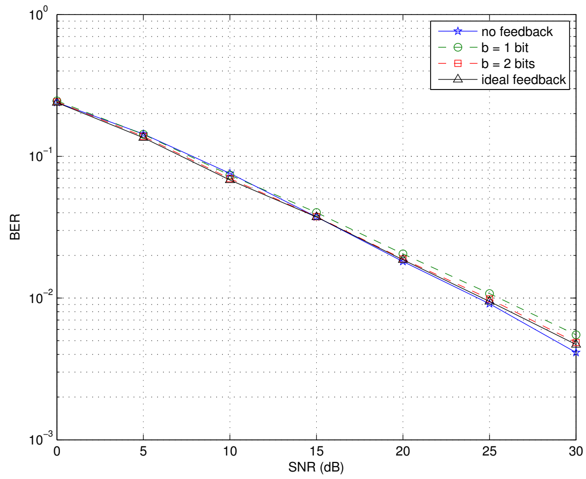

Fig. 5. BER performance results when center frequency is equal to 1.81 MHz.

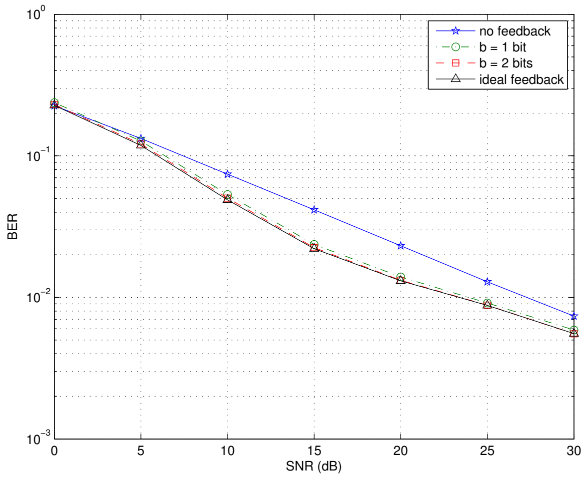

Fig. 4. BER performance results when center frequency is equal to 244.14 kHz.

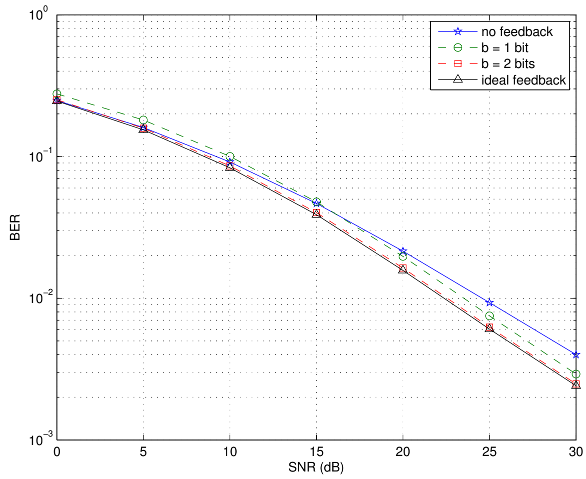

Fig. 6. BER performance results for HS-OFDM scheme.

of sub-carriers is $N = 2048$, the length of cyclic prefix is $L_{cp} = 512$, the frequency band is between 1.7 and 100 MHz; BPSK modulation is adopted; 6716 channels frequency responses obtained in the measurement campaign previously discussed are used.

Fig. 6 shows BER performance results for the HS-OFDM scheme without feedback, with ideal feedback, and with quantized feedback ($b = 1$ bit and $b = 2$ bits). We can see that performance losses introduced by the quantized feedback is small. For instance, if $b = 1$ bit, the HS-OFDM scheme performs within 0.5 dB of the ideal feedback, while $b = 2$ bits yields results very similar to ideal feedback.

IV. Conclusions and Final Remarks

In this paper, we analyzed the performance of the proposed technique that makes use of quantized CSI feedback information to improve the performance of a MIMO PLC system, which deploys two power cables to transmit data from the Tx modem to the Rx modem and one error-free and zero-delay feedback channel to send b bits to the Tx modem. Additionally, we presented samples of time-varying in-home PLC channels, which were obtained from a measurement campaign to analyze the performance of the proposed technique. Based on simulations results, we noted that the proposed technique shows, when single-carrier modulation scheme is adopted, disparate performances because there is a dependence between the performance and the spread of the channel coefficient associated with a given center frequency. On the other hand, when we consider a HS-OFDM scheme, the use of feedback channel shows a gain of BER in relation to without feedback channel. Finally, based on simulation results, we stated that a BER lower bound performance is practically achieved by using only two bits of feedback.

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REFERÊNCIAS

[1] L. T. Berger, A. Schwager, P. Pagani, MIMO Power Line Communications: Narrow and Broadband Standards, EMC, and Advanced Processing (Devices, Circuits, and Systems), *CRC Press*, 2014.

[2] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451-1458, Oct. 1998.

[3] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time Codes for High Data Rate Wireless Communications: Performance Criterion and Code Construction," *IEEE Trans. Inform. Theory*, vol. 44, no. 2, pp. 744-765, Mar. 1998.

[4] L. Hao and J. Guo, "A MIMO-OFDM scheme over coupled multi-conductor power-line communication channel," in Proc. *IEEE International Symposium on Power line Communications and Its Applications*, Pisa, Italy, Mar. 2007, pp. 198-203.

[5] C. L. Giovaneli, J. Yazdani, P. Farrell, and B. Honary, "Application of space-time diversity/coding for power line channels," in Proc. *IEEE International Symposium on Power line Communications and Its Applications*, Athens, Greece, Mar. 2002, pp. 101-105.

[6] A. Schwager, D. Schneider, W. Bäschlin, A. Dilly, and J. Speidel, "MIMO PLC: Theory, measurements and system setup," in Proc. *IEEE International Symposium on Power Line Communications and Its Applications*, Udine, Italy, 3-6 Apr. 2011, pp. 48-53.

[7] R. Machado and B. F. Uchôa-Filho, "Extended techniques for transmitted antenna selection with STBCs," *IEEE Journal of Communication and Information Systems*, vol. 21, no. 3, pp. 188-195, Dec. 2006.

[8] I. Choi, J. K. Kim, H. Lee, and I. Lee, "Alamouti-codes based four-antenna transmission schemes with phase feedback," *IEEE Communications Letters*, vol. 13, no. 10, pp. 749-751, Oct. 2009.

[9] T. R. Oliveira, C. A. G. Marques, W. A. Finamore, S. L. Netto and M. V. Ribeiro, "A methodology for estimation frequency responses of electric power grids,"*Jounal of Control, Automation and Electrical Systems*, vol. 25, no. 6, pp. 720-731, Set. 2014

[10] M. V. Ribeiro, G. R. Colen, F. P. V. Campos, Z. Quan, "Poor HV. clustered-orthogonal frequency division multiplexing for power line communication: when is it beneficial?," *IET Communications*, vol. 8, no. 13, pp. 2336-2347, Set. 2014.