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Application of Multiple Input Multiple Output Power Line Communication (MIMO-PLC) to Power Systems

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Multiple input multiple output power line communication is presented with its major characteristics and models. Orthogonal frequency division multiplexing modulation scheme applied to power line channel model is presented, also, combination of orthogonal frequency division multiplexing with MIMO Alamouti space time block codes to improve reliability and data rate performance of the system is done. The evaluation of the orthogonal frequency division multiplexing-PLC system over power line communication channel is performed. The comparison between simple PLC and MIMO-PLC systems based upon achieved data rates and reliability in terms of bit error rate is presented.

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1. Introduction

Due to concerns about the worldwide energy crisis, rising fuel costs and global warming, utility companies are trying to explore new markets to find new business opportunities. Currently, they are placing much emphasis on the concept of the "Smart Grid" where the digital communications is the backbone [1–3]. Utilities prefer to have a fixed connection and full control over their own communications infrastructure, for economic and strategic reasons. The advantage of this technology is in transmitting information to selected users, broadcast simultaneously to all users; turn off parts of the network in the event of danger and to gather user statistics [4–11].

The widespread of the powerline infrastructure influences the idea of it being used as a communication medium, known as powerline communications, and seems to be a cost effective solution that raises the possibility that every household would be connected at any time and services would be provided at real-time. Power line communications (PLC) basically means any technology that enables data transfer at low or high speeds through power lines by using advanced modulation technology [12–20].

High data rates required for modern uses, PLC networks have to operate in a frequency spectrum of up to 30 MHz, very strong limits regarding the electromagnetic emission from the PLC networks were specified, which results in reduction of network distances and data rates and increases sensitivity of the PLC system to disturbances [3].

This work is mainly concerned with the models and techniques that are used in maintaining communication over powerlines, with relatively high data rates and acceptable reliability. A (2×2) MIMO orthogonal frequency division multiplexing (OFDM) PLC system is simulated, it offers a clear understanding of its high data rates performance, it reaches error free transmission level for typical value of the signal-to-noise ratio (SNR = 13 dB).

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2. Problem description

Broadband PLC systems operate at frequencies above 1.8 MHz with which the power line produces electromagnetic radiation that may interfere with the other radio services operating at that frequency, leads to limitations in electromagnetic emission (EM). These EM limitations imply the use of small values of the power signal to be transmitted through the channel, hence, a relatively high level of minimum value of SNR which can be detected at the receiver [21–24].

The power line is a frequency selective channel that provides different levels of attenuation at different frequencies, result in different SNRs for different subcarriers. In addition to multipath fading that causes intersymbol interference (ISI) between the transmitted symbols [25, 26].

2.1. Single input single output (SISO) PLC-OFDM

2.1.1. Model description

A Bernoulli binary generator is used as the data source in the proposed model. It is a generator which generates random binary numbers according the Bernoulli distribution. Channel coding, realized by the Reed–Solomon code (RS (48; 8)), was used to ensure data transfer in the communication channel.

From the channel coding block we obtain a serial flow of data. This flow enters the mapping block. The bit sequences are converted to a symbol sequence in the block mapping. The distribution of symbols is the result of mapping. This symbols distribution is dependent on the selected modulation. The type of carrier modulation is adaptive to the SNR as shown in Table I.

TABLE I
The SNRs associated carrier modulation.

Range of SNR [dB]	Carrier modulation	Coding rate
[1–9.4]	BPSK	1/2
[9.4–11.2]	QPSK	1/2
[11.2–16.4]	QPSK	3/4
[16.4–18.2]	16-QAM	1/2
[18.2–22.7]	16-QAM	3/4
[22.7–24.4]	64-QAM	2/3
[24.4≤SNR]	64-QAM	3/4

The sub-band separation of the useful signal is realized in the select rows block. It is necessary to insert the pilot signals and implement an estimate of transmission channel in the case of coherent system detection. This is realized by the help of the pseudo-number (PN) sequence generator. Block complex (0, 0) is used to generate the middle carrier frequency. Block concatenate is used to add up all the carrier frequencies, which enter this block.

The size of the framework is then adjusted for inverse fast Fourier transform (IFFT) in the pad block and the signal is adjusted for IFFT in the shift block. After that the signal undergoes the IFFT, where data are converted from the frequency domain to the time domain. To avoid ISI, the OFDM protective interval is used. It is realized by the add cyclic prefix block. The final model has been created from OFDM model and power lines model together with noises models.

2.1.2. SISO-PLC simulations

A parametric study of the effects of adjusting different system specifications was carried out. The following remark was applied:

- The data rates provided for different SNRs show direct proportionality (Table II). Indeed, the higher the SNR, the larger is the data transfer rate.

TABLE II
Variation of the data rates for different SNRs.

SNR [dB]	7	10	14	17	20	23
R [kb/s]	2.75	5.75	8.75	11.75	17.75	23.75

TABLE III
Variation of the data transfer rate vs. bandwidth.

SNR [dB]	7	23
9 kHz	2.75	23.75
92 kHz	35.77	308

Another parameter that may affect the performance of the system is the operational bandwidth. A comparison of data rates R [kb/s] was provided using 9 kHz, and 92 kHz bands for two values of SNR (Table III) show again proportional relationship between the data rate and the bandwidth. Narrow band PLCs provides low data rates which limit their use only for related applications.

2.2. MIMO broadband PLC-OFDM model

2.2.1. Model description

This model simulates data transmission over 2 powerlines, hence, 2 ports in each of the transmitter and the receiver side, using the same OFDM scheme as the precedent, in addition to assumption that the two cables are separated by distance greater than the carrier wavelength ($\frac{\lambda}{2}$), channel fades are independent.

a. MIMO-OFDM PLC system

Consider the given 2×2 MIMO-OFDM PLC:

$$H[kn] = \begin{bmatrix} h_{1,1}[k,n] & 0 \\ 0 & h_{2,2}[k,n] \end{bmatrix}, \quad (1)$$

where h_{11} and h_{22} are the channel transfer functions that correspond to the two power lines, note that the lines are assumed uncorrelated, no EM interference between them. At time slot k an input data block is mapped into 2 complex constellation sequences $S_1(k,1), S_2(k,2)$, N is the number of subcarriers. The received signal after FFT processing at receiving port j is

$$R_j\,[k,n] = \sum_{i=1}^{2} H_{ij}\,[k,n]\,S_i\,[k,n] + N_j[k,n]|_{j=1,2}, \quad (2)$$

where $H_{ij}[kn]$ is the channel frequency response from transmitting port i to receiving port j at the n-th tone of the OFDM block. N_j is the noise received at port j.

b. Alamouti STBC

During the first time slot, the two symbols $[s_1\ s_2]$ are transmitted in the two cables simultaneously. In the second time slot, the symbols $[-s_2^* s_1^*]$ are transmitted. Combined with OFDM Alamouti-space-time encoding processes every OFDM symbol at each subcarrier of the same OFDM, Alamouti code is an orthogonal code, which allows a simple decoding. For space-time Alamouti decoding, it is assumed that the channel is static during two successive time slots. At receiver, maximum likelihood (ML) detection is described by

$$\hat{s} = \arg_{\boldsymbol{s}(l)\in C} \max\left(p[\boldsymbol{r}(l)|\boldsymbol{s}(l)]\right), \quad (3)$$

where $\boldsymbol{s}(l)$ is the transmitted signal, $p[\boldsymbol{r}\,(l)\,|\boldsymbol{s}\,(l)]$ is the conditional probability density function (PDF) of the received vector $\boldsymbol{r}(l)$, C represents all possible transmitted vectors.

The ML receiver searches all possible transmitted vectors and selects the one with the maximum value of conditional PDF for the output. The conditional PDF of the received vector $\boldsymbol{r}(l)$ can be further described as

$$p[\boldsymbol{r}\,(l)\,|\boldsymbol{s}\,(l)] = f[\boldsymbol{r}\,(l) - \boldsymbol{H}\,(l)\,s\,(l)], \quad (4)$$

where $f\,(x)$ is the noise PDF, $\boldsymbol{H}\,(l)$ is channel transfer matrix

$$\hat{s} = \arg_{\boldsymbol{s}(l)\in C} \max\left(f[\boldsymbol{r} - \boldsymbol{H}\,(l)\,\boldsymbol{s}\,(l)]\right). \quad (5)$$

If the noise has Gaussian distribution

$$\hat{s} = \arg_{\boldsymbol{s}(l)\in C} \max\left(\|\boldsymbol{r}\,(l) - \boldsymbol{H}(l)\boldsymbol{s}\,(l)\|^2\right). \quad (6)$$

2.2.2. Simulation and results

Once again, the same parametric study done on the SISO-PLC case is reconducted for the MIMO PLC system. The following results are obtained:

- The simulation consists in varying SNRs at 10 MHz bandwidth and observe the data rates (Table IV). Again, the data transfer rates show proportional dependence on the SNR. However, the values recoreded for the same SNR are higher for the MIMO-PLC than the SISO-PLC.

- The other parameter that affects the performance of the system is the operational bandwidth. A comparison of data rates R [kb/s] provided using 5 MHz, and 10 MHz bands for two values of SNR (Table V) show again proportional relationship between the data rate and the bandwidth. The bandwidth levels here are large which suggests the employment of MIMO-PLC for wideband applications. Narrow band MIMO-PLCs provides low data rates (even less than the SISO-PLC at lower bandwidth (see Table III)).

TABLE IV

Variations of the data rates vs. SNR.

SNR [dB]	7	10	14	17	20	23
R [kb/s]	3.92	8.19	12.45	16.63	25.28	33.81

TABLE V

Comparison of data rates R [kb/s] provided using 5 MHz, and 10 MHz band.

SNR [dB]	7	23
5 MHz	1.98	17.09
10 MHz	3.92	33.81

2.3. Comparison between SISO-PLC and MIMO-PLC

2.3.1. From reliability point of view

Clearly, due to time diversity gained through introducing Alamouti-STBC scheme to the OFDM-PLC system, results in a high reliability offered by MIMO-PLC compared to SISO-PLC.

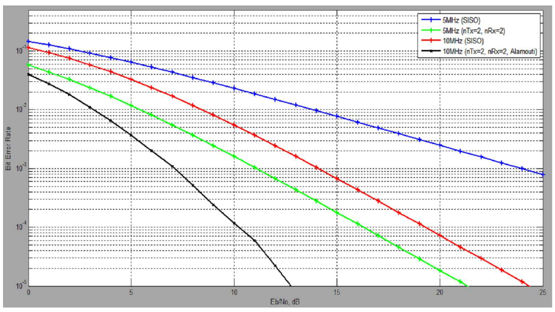

Fig. 1. MIMO and SISO ($B = 5$ MHz, $B = 10$ MHz) bit error rate (BER) vs. SNR.

The channel bandwidth has a remarkable impact on the reliability, since it represents the degree of conversion of the channel from a frequency selective fading channel into a flat fading channel.

For small SNR values, MIMO-OFDM system outperforms SISO-OFDM. It provides less than 10% error rate, that decreases to 0.01% for (SNR = 10 dB). At that rate, SISO systems exceeds 10% (Fig. 1).

OFDM-PLC system that uses the broadband 10 MHz shows a great performance in providing high data rates compared to narrow bands ($B = 92$ kHz).

So to obtain as high data rates as possible, it is preferable to enlarge the bandwidth. Using several powerlines provides a capacity gain that is linearly proportional to the number of the lines.

2.3.2. From data-rate point of view

Table VI summarizes the results already obtained in the parametric studies in the previous section. Clearly, one would notice that the MIMO-PLC system provides better performance in terms of data transfer rate.

TABLE VI

Summary of the data rate relation R [Mb/s] to SNR for two systems.

SNR [dB]	7	10	14	17	20	23
MIMO	3.92	8.19	12.45	16.63	25.28	33.81
SISO	2.75	5.75	8.75	11.75	17.75	23.75

SISO-OFDM-PLC system does not offer diversity, which is the main concern of systems that tend to literally guarantee the transmission when dealing with highly important data such as control signals. However, regardless of which system is better, the error rate is inversely proportional to the bandwidth over which the subcarriers of the OFDM depend. The higher is the number of subcarriers in addition to the bandwidth, the lower is the probability of errors to occur.

3. Conclusion

The work presented two types for which communication over powerlines is performed, mainly SISO-OFDM PLC and (2 × 2) MIMO Alamouti-OFDM PLC. A complete description of the SISO-OFDM PLC has been made, passing from data generation and bits loading through the multipath fading PLC channel model, ending at the receiver. The simulation of the two systems that are presented allows the comparison of the achieved data rates provided. Characteristics set carefully in order to provoke the real world problems that are preventing PLC from not being seen as a prime interest. The two systems seem to perform the same task when high data communication over broadband powerlines is needed, one can conclude:

- The relatively low complexity of the SISO-OFDM as compared to MIMO-OFDM systems, making it a better choice due to its multicarrier modulation that is intended to combat the multipath fading nature of the channel.

- MIMO-OFDM system performs better in terms of reliability and high data rates.

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