MIMO for Inhome Power Line Communications

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Abstract

Inhome Power Line Communications (PLC) enables new and highly convenient networking functions without any additional cables to mains-powered devices. Throughput measurements have shown that current PLC technology does not provide sufficient bandwidth for all typical inhome applications in a reliable way. This paper clarifies if Multiple Input Multiple Output (MIMO) methods, being well-known from the wireless world, can significantly increase the PLC channel throughput and the link reliability. After proving the theoretical capacity increase on measured PLC channels, different MIMO schemes are compared regarding their suitability for the PLC channel.

Keywords - Power line communication; MIMO

1 Introduction

Although today's PLC solutions theoretically offer datarates of up to 200 Mbit/s, measurements in private households have shown that in reality only much lower bitrates can be guaranteed due to high attenuation, frequency selective transfer functions, and noise of the powerline channel. Typical inhome applications such as High Definition (HD) video streaming as a key application for the IP centric home network require datarates of around 20 Mbit/s with high reliability.
Today's PLC systems use one transmit and one receive port for their data communication. However, in Europe and in the US 3-wire installations basically allow more feeding and receiving possibilities. Generally, in presence of multiple feeding and receiving ports, MIMO principles can be used [1],[2]. MIMO technology recently has been successfully introduced by wireless standards such as IEEE 802.11n or WiMAX. Compared to their basic SISO (Single Input Single Output) solutions they offer a fundamental increase of datarate. The key question is: Can MIMO schemes increase the PLC channel capacity as well as the connection coverage and reliability in a similar way?
MIMO for PLC has already been touched by a few previous publications: [3] firstly published the potential usage of multi-phase power cables for MIMO communication. [4],[5] assume perfect isolation between different phase wires for space-time encoded access PLC systems. Based on the same channel assumptions, [6] proposes an OFDM based space-time MIMO system for PLC. [7] considers for the first time a coupled access PLC MIMO channel but also restricts itself to space-time and space-frequency codes. This paper is focusing on MIMO schemes for inhome applications where high bitrates are required.
Chapter 2 explains the transition from the SISO to the MIMO channel model for PLC. Based on measured PLC channels of several flats and houses, a capacity calculation is provided in chapter 3. Chapter 4 introduces different MIMO schemes that can be applied to PLC. Chapter 5 compares the performance of these MIMO approaches for the measured PLC channels, as well as in presence of additional impulsive noise sources.

2 PLC MIMO Channel Model

All PLC modems available today use one transmitting and one receiving port for their communication: The signal is symmetrically fed and received between the live and neutral wire. In Europe, the US and many other parts of the world, inhome installations consist of 3 wires, which offers additional feeding and receiving options.
Figure 1 shows the PLC MIMO channel. Differential signalling between any 2 of the 3 wires lead to 3 different feeding possibilities: P (Phase or Live) to N (Neutral), P to PE (Protective Earth), and N to PE.

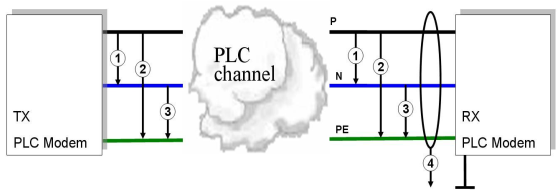

Figure 1: PLC MIMO channel

According to Kirchhoff's rule the sum of the 3 input signals has to be 0. Therefore only 2 out of the 3 independent input ports can be used. On receiving side all 3 differential reception ports are available. Additionally there is a 4^{th} reception path, the so called common mode path (CM). CM signals are created unintentionally in unbalanced networks. Unbalanced parasitic capacities from installations or devices to ground cause a CM current returning to the source. Due to electromagnetic coupling between adjacent wires crosstalk arises, i.e. the transmit signal from any feeding port is visible on all 4 receiving ports. Figure 2 illustrates the transfer functions of all possible receiver ports if P-N is chosen as feeding port. The similarity of the transfer function shapes indicates basically a common multipath environment as well as a strong coupling between the individual paths.

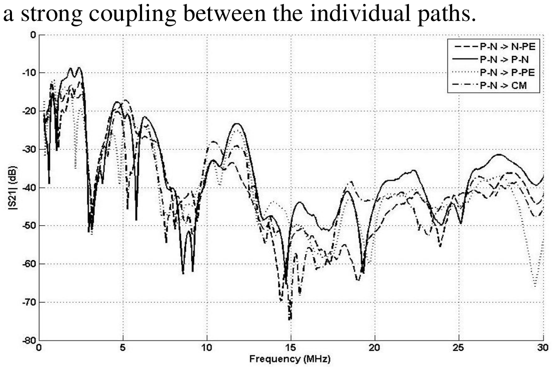

Figure 2: Transfer function $|S_{21}|$ example of all 4 receiving ports, with P-N as feeding port

The MIMO channel between the feeding port ν and the receiving port μ can be written as a channel matrix **H**, with the transmission coefficients $h_{\mu\nu}$ as elements (ν=1,2; μ=1,…,4):

$$\boldsymbol{H} = \begin{pmatrix} \boldsymbol{h}_{11} & \boldsymbol{h}_{12} \\ \boldsymbol{h}_{21} & \boldsymbol{h}_{22} \\ \boldsymbol{h}_{31} & \boldsymbol{h}_{32} \\ \boldsymbol{h}_{41} & \boldsymbol{h}_{42} \end{pmatrix} \qquad (1)$$

For the frequency selective PLC channel, the spectrum can be divided into sufficiently small frequency subbands (i.e. **H** is different for each subband).

3 PLC MIMO Channel Capacity

To verify if the MIMO principle can be successfully applied to PLC, channel capacity calculations based on measurements in private flats and houses are performed: In several flats and houses, the complex frequency response of all 12 feeding / receiving combinations (3 tx and 4 rx ports) of many socket connections have been recorded with a network analyzer.

Theoretically, the channel matrix **H** can be decomposed into 2 parallel and independent SISO branches by a singular value decomposition (SVD) [2]:

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^{\mathbf{H}} \quad \textit{with} \quad \mathbf{D} = \begin{pmatrix} \sqrt{\lambda_1} & 0 \\ 0 & \sqrt{\lambda_2} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad (2)$$

λ_i are the eigenvalues of the 'squared' channel matrix $\mathbf{H}\cdot\mathbf{H}^H$. **U** and **V** are unitary matrices, i.e. $\mathbf{U}^{-1} = \mathbf{U}^H$ and $\mathbf{V}^{-1} = \mathbf{V}^H$. Upper case H indicates the Hermiteian operator as the transposed and conjugate complex (*) of a matrix. The decomposition is shown in Figure 3.

The rank of the measured channel matrices was always found to be 2. Therefore the capacity can be calculated as the sum of two independent SISO channels. As indicated, the overall bandwidth is divided into N equivalent subbands, yielding the channel capacity:

$$\boldsymbol{C} = \boldsymbol{B}\frac{1}{\boldsymbol{N}}\sum_{i=1}^{N}\sum_{j=1}^{2}\log_2\left(1+\frac{\boldsymbol{\lambda}_{i,j}\boldsymbol{E}_S}{\boldsymbol{n}_T\boldsymbol{N}_0}\right)\boldsymbol{bit/s} \qquad (3)$$

with:

B:	channel bandwidth	n_T: nr. of tx paths
E_s:	total average tx energy	N_0: AWGN level

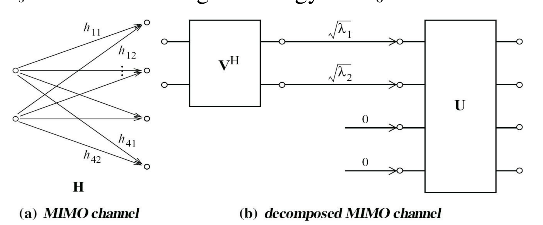

Figure 3: Decomposition of the MIMO channel into 2 parallel SISO channels

Figure 4 compares the transfer functions of a typical PLC channel with the decomposed 2 SISO paths of the PLC MIMO channel.

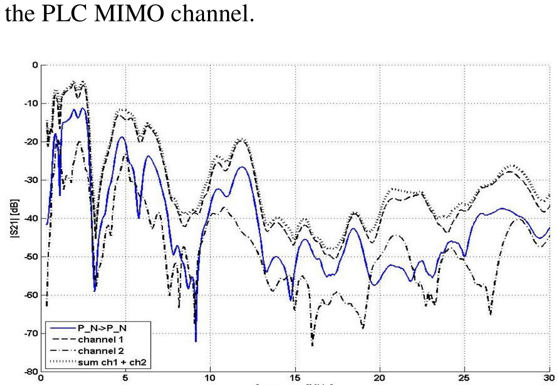

Figure 4: Transfer function $|S_{21}|$ example of live to neutral as tx and rx port, compared to the 2 decomposed SISO channels and their sum

The sum of the two decomposed SISO paths in Figure 4 shows generally much less attenuation than the transfer function of the current PLC channel, indicating a channel capacity gain.
Channel capacity calculations are made for 2 transmit power levels: -93*dBm/Hz* as a lower and -67*dBm/Hz* as a higher feeding power level. The noise spectral density NSD is set to -136*dBm/Hz*, i.e. the receiver noise floor is considered to be flat [8]. One key parameter is the optimum number of feeding and receiving ports, which delivers the best trade-off between system complexity and throughput: Basically there are several MIMO arrangements, which differ by their number of transmit and receive ports (see Table 1).

MIMO mode	Tx ports	Rx ports
1 x 2	P-N	P-N, CM
1 x 3	P-N	P-N, P-PE, N-PE
1 x 4	P-N	P-N, P-PE, N-PE, CM
2 x 3	2 best of: P-N, P-PE, N-PE	P-N, P-PE, N-PE
2 x 4	2 best of: P-N, P-PE, N-PE	P-N, P-PE, N-PE, CM

Table 1: PLC MIMO arrangements. (P)–Live; (N)–Neutral; (PE)–Protective Earth; (CM)–Common Mode

1x2 MIMO can be used if there is no protective earth, e.g. in Japan. 1x4 is feasible if there is a low impedance ground for HF signals, otherwise 1x3 is applied. A second transmit port is available if the feeding modem uses a three-pin plug. In Figure 5, the MIMO gain relative to SISO mode is shown as a function of various outlet connections. Parameter is the n_T x n_R MIMO arrangement. While a single feeding port and up to 4 receiving ports (1 x n_R) offers only a small gain in channel capacity, the addition of a 2nd feeding port provides a significant increase, which typically results in more than twice of today's channel capacity. Compared to 2x3 MIMO, 2x4 MIMO with the inclusion of the common mode as the 4th reception path exhibits a significant additional gain.

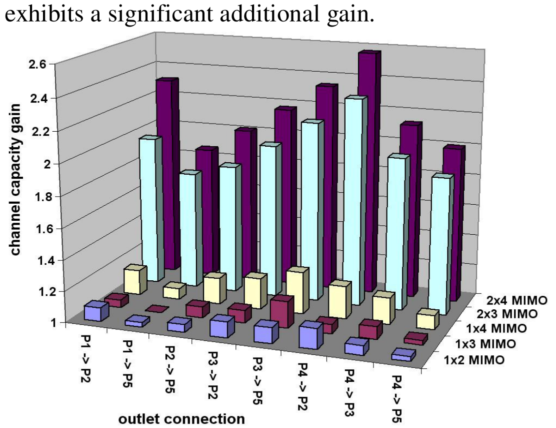

Figure 5: MIMO capacity gain for various PLC outlet connections

Table 2 summarizes the channel capacity gain calculated for 2x3 and 2x4 MIMO, as a result of all measured PLC MIMO channels.

	Low transmit level (*-93 dBm/Hz*)			High transmit level (*-67 dBm/Hz*)		
	Average gain	Min gain	Max gain	Average gain	Min gain	Max gain
2x3 MIMO	2.2	1.3	4.9	1.8	1.2	2.9
2x4 MIMO (incl. CM)	2.6	1.5	5.2	2.1	1.3	2.9

Table 2: MIMO for PLC – channel capacity gain

In all cases there is a significant increase of the capacity compared to today's SISO channels. The MIMO gain varies for different outlet combinations, depending on the path specific attenuation and the correlation between the different MIMO paths: The lower the channels correlation, the higher the MIMO gain.
Although 2x3 MIMO already improves the average capacity of the PLC channel in the range from factor 1.8 to 2.2, the 2x4 MIMO with the common mode path inclusion offers the best result, providing an average capacity gain between 2.1 and 2.6. The capacity gain is most effective for low transmit levels as well as for difficult channels, which exhibit high attenuation and frequency selectivity.
If channel state information (CSI) is available at transmitter side, waterfilling can be applied as an additional method to increase the PLC MIMO channel capacity [1],[2]. In this case, the total transmit power is allocated in an optimized way to the 2 feeding ports. While waterfilling shows almost no effect for high transmit power levels (high signal to noise ratio (SNR) at the receiver), it offers up to 10% additional channel capacity gain for low transmit power levels.
Based on the results shown above, MIMO technique is promising to increase the PLC channel capacity. Calculations have shown that throughput and link reliability can be improved significantly. In the next chapters different MIMO encoding and decoding schemes are introduced and benchmarked in the PLC environment.

4 MIMO Schemes for PLC

In this section different state of the art basic MIMO schemes are applied to an OFDM based PLC system. Different goals can be achieved: On the one hand MIMO method can provide a capacity gain by sending different streams over the different transmit ports (spatial multiplexing). For this class, spatial multiplexing and eigenbeamforming (with channel state information at the transmitter) are investigated. On the other hand, a diversity gain can be achieved to combat fading by sending replicas of each symbol over different transmit ports (space-time or space-frequency coding). For this application the Alamouti scheme is investigated. The different MIMO schemes are introduced briefly in this chapter, a more detailed description is given for example in [1],[2].

4.1 Spatial Multiplexing

For spatial multiplexing, 2 different symbols are sent from the two transmit ports. Let $\mathbf{s}_i$ be the vector of the 2 symbols sent on the i-th subcarrier, then the vector of the symbols on each of the 4 receiving ports and i-th subcarrier is ($\mathbf{H}_i$ is channel matrix of subcarrier i):

$$\mathbf{r_i} = \mathbf{H_i}\,\mathbf{s_i} \tag{4}$$

The transmit symbol vector $\mathbf{s}_i$ can be detected with a matrix $\mathbf{W}_i$, which can be realized by different receiver architectures, such as zero forcing (ZF) or minimum mean squared error (MMSE). For example, the detection matrix of the ZF receiver is the Moore-Penrose-Inverse of the channel matrix:

$$\mathbf{W}_i = \left(\mathbf{H}_i^H\,\mathbf{H}_i\right)^{-1}\,\mathbf{H}_i^H \tag{5}$$

The output symbols are:

$$\mathbf{y}_i = \mathbf{W}_i\,\mathbf{H}_i\,\mathbf{s}_i \;= \mathbf{s}_i \tag{6}$$

If CSI is available at the transmitter, eigenbeamforming can be applied. The transmit symbol vector for each subcarrier is multiplied with the matrix $\mathbf{V}_i$, which is derived from the SVD of the channel matrix $\mathbf{H}_i$ (similar to (2)). If we take $\mathbf{W}_i = \mathbf{U}_i^H$, we obtain the decoded symbols as follows:

$$\mathbf{y_i} = \mathbf{U_i^H H_i V_i s_i} = \mathbf{U_i^H U_i D_i V_i^H V_i s_i} = \mathbf{D_i s_i} \tag{7}$$

Since $\mathbf{D}_i$ is a diagonal matrix, the channel is decomposed into two parallel and independent paths.
Figure 6 shows the principle of spatial multiplexing for MIMO-OFDM. Each QAM symbol vector $\mathbf{s}_i$ that is associated to the i-th subcarrier is multiplied by the corresponding matrix $\mathbf{F}_i$, then OFDM modulated and sent via the two transmit ports over the PLC MIMO channel. At the receiver each signal is OFDM demodulated and all 4 symbols of each subcarrier are detected with $\mathbf{W_i}$. In case of eigenbeamforming the matrices $\mathbf{F_i}$ are equal to $\mathbf{V_i}$. For spatial multiplexing without CSI at the transmitter $\mathbf{F_i}$ is an identity matrix. The spatial code rate is $r_s = 2$.

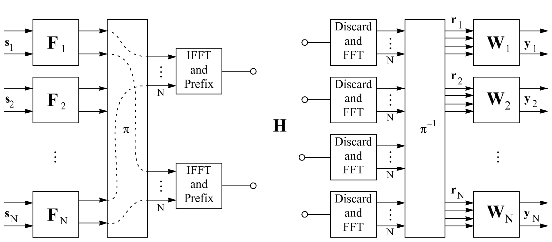

Figure 6: Spatial multiplexing for MIMO-OFDM

4.2 Alamouti Scheme

The Alamouti scheme is a simple but very effective space-time or space-frequency coding scheme for MIMO systems with 2 transmit ports. The encoding can be described by the encoding matrix:

$$\begin{array}{c} \text{time, (frequency)} \longrightarrow \\ S = \begin{pmatrix} s_1(k) & -s_2^*(k+1) \\ s_2(k) & s_1^*(k+1) \end{pmatrix} \; \text{space} \downarrow \end{array} \tag{8}$$

The original Alamouti scheme transmits the symbols s_1 and s_2 at the first time instant k over transmit port 1 and 2. At the next time instant $k+1$ $-s_2*$ and s_1* are transmitted via transmit port 1 and 2, respectively. Combined with OFDM, Alamouti encoding can be applied in two different ways: Space-frequency encoding indicates that k and $k+1$ are assigned to two adjacent subcarriers of the same OFDM symbol, while for space-time coding k and $k+1$ maps onto the same subcarrier of two consecutive OFDM symbols.
Since the columns of **S** are orthogonal, the Alamouti scheme belongs to the class of orthogonal codes, which allows a simple decoding [1],[2]. For decoding it is assumed that successive OFDM symbols face the same channel conditions (space-time coding), which is fulfilled for a quasistatic PLC channel. On the other hand, the space-frequency Alamouti scheme requires that the channel matrices of adjacent subcarriers are equal (typically true for a sufficiently large number of subcarriers).

5 MIMO Performance for PLC

To compare the performance of the different MIMO schemes, the same 2x4 MIMO channels as used for the channel capacity calculations are embedded into the system simulations. Figure 7 shows the basic setup:

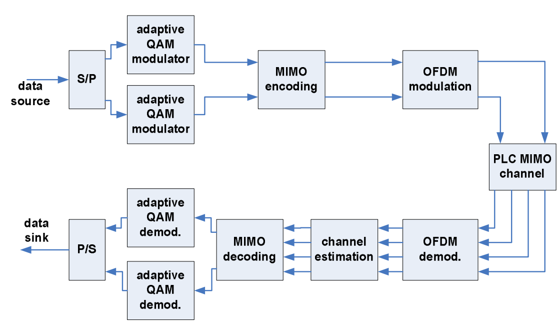

Figure 7: Basic PLC MIMO simulation setup

On the physical layer, an OFDM based scheme with 1296 subcarriers ranging from 4 to 30 MHz is used. The symbol duration is $54.4\mu s$, including an adaptive guard interval of at least $3.2\mu s$. The proposed scheme employs adaptive modulation, i.e. each subcarrier uses a QAM constellation according to the instantaneous SNR of the related frequency. The lower the

SNR, the smaller the chosen QAM constellation. The range of QAM constellations starts at QPSK and goes up to 1024 QAM. Moreover, if the SNR at a specific frequency is very low, the corresponding subcarrier can also be notched. Note, adaptive OFDM requires feedback from the receiver to the transmitter, containing the information of the chosen constellation for each subcarrier. On the different subcarriers of one received OFDM symbol, we often observed SNR differences of more than 40 dB, which makes adaptive OFDM very effective (see also frequency response curves in Figure 4).

5.1 Throughput Comparison of Different MIMO Schemes

To benchmark the different MIMO schemes, the algorithm of the adaptive QAM was adjusted to a target bit error rate (BER) of 10^{-3} for the uncoded channel. This value is chosen since additional forward error correction (FEC) like turbo coding or low density parity check coding (LDPC) can easily decrease the BER to fulfil the quality requirements of all typical applications. To avoid negative impact from channel estimation and quantization effects, perfect channel state information is assumed for the transmitter and the receiver. According to the channel capacity calculations in chapter 3, two different transmit power levels are selected for benchmarking, namely -93*dBm/Hz* and -67*dBm/Hz*.

Figure 8 shows the achieved bitrate for several outlet combinations of one measurement site at the higher transmission level.

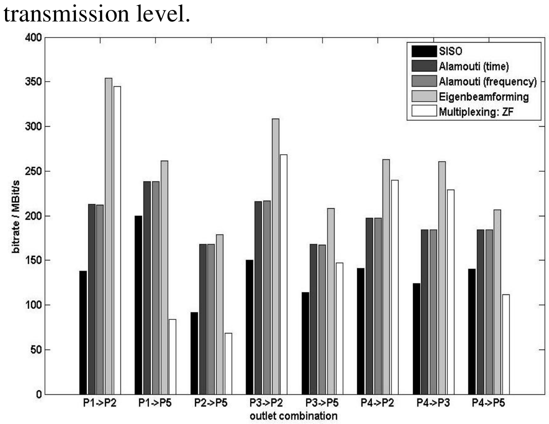

Figure 8: Throughput comparison of different MIMO schemes for different outlet combinations, transmit power level = -67*dBm/Hz*

Table 3 summarizes the average throughput of the different MIMO schemes for all measurement sites.

Tx power level	SISO	Alamouti		Beamforming		Multiplexing	
	MBit/s	MBit/s	Gain	MBit/s	Gain	MBit/s	Gain
-93dBm/Hz	**10.1**	**41.0**	**4.05**	**42.6**	**4.21**	**16.0**	**1.58**
-67dBm/Hz	**122.0**	**191.7**	**1.57**	**285.8**	**2.34**	**245.3**	**2.01**

Table 3: Average bitrate at different transmit power levels

Generally, there is a significant increase in the throughput for all MIMO schemes compared to SISO transmission. Beamforming MIMO offers generally the best result. For the high transmit power level, the Alamouti scheme exhibits the lowest MIMO bitrate in almost all examined PLC channels but still exceeds the SISO bitrate by far. Spatial multiplexing achieves the second highest bitrate in most of the PLC channels but is faced by a strong decrease in some channels: The bitrate can be even smaller than for SISO. The reason is the enhancement of noise by the detection matrix $\mathbf{W}$: The Frobenius norm of $\mathbf{W}_i$ can be rather large for PLC channels where the spatial multiplexing fails. For adaptive OFDM, MMSE instead of ZF detection does not improve the performance significantly: In general there's almost no performance difference between MMSE and ZF for subcarriers with high SNR. Low SNR subcarriers basically benefit from MMSE detection, but are notched in most cases anyway.

For low SNR, the performance of the Alamouti and the eigenbeamforming MIMO scheme is similar. It is interesting to note that the throughput gain for these two MIMO schemes exceeds the gain that is reached for channels with higher SNR. Spatial multiplexing often fails in low SNR channels: High noise levels in low SNR channels are further increased by the detection matrix in the receiver. The gain compared to SISO is sometimes even below one.

Figure 9 summarizes the results as the cumulative probability to achieve a certain bitrate for all measured channels: For high transmit power levels, eigenbeamforming is superior to all other MIMO schemes. The rather flat curve for spatial multiplexing with ZF decoding visualizes the drawbacks of this MIMO scheme in some channels. For the low transmit power level, the Alamouti scheme is almost as good as eigenbeamforming, while multiplexing with ZF decoding can't exceed substantially the SISO performance.

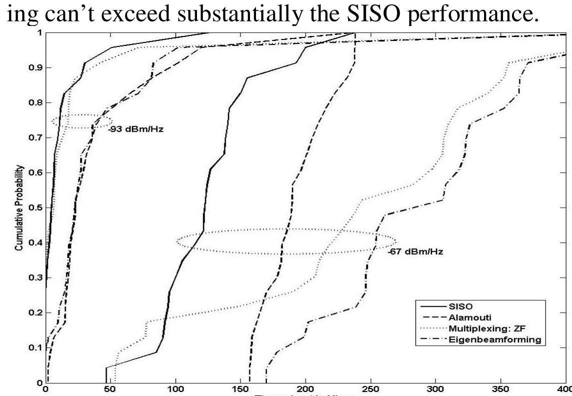

Figure 9: Cumulative probability of the simulated bitrate for different MIMO schemes

5.2 MIMO Scheme Comparison in Presence of Noise Generating Devices

Powerline modems are faced with additional noise that is generated by devices being plugged to the mains network. The performance of the different MIMO schemes in presence of these noise devices is crucial.

Class A noise is widely used to model the impulsive noise of the powerline channel. It is a combination of AWGN and additional impulsive noise, and its probability density function (PDF) is [9]:

$$p_Z(z) = \sum_{m=0}^{\infty} \frac{\alpha_m}{\sqrt{2\pi\sigma_m^2}} \exp\left(-\frac{z^2}{2\sigma_m^2}\right) \qquad (9)$$

with $\alpha_m = e^{-A}\frac{A^m}{m!}$ and $\sigma_m^2 = \frac{(m/A)+T}{1+T}$. σ^2 is the total variance of the class A noise, $T = \frac{\sigma_G^2}{\sigma_I^2}$ is the Gaussian-to-impulsive noise power ratio (with σ_G^2 as the variance of the AWGN component and σ_I^2 as the variance of the impulsive component). The parameter A is the impulsive index, where a small A indicates a highly impulsive noise, whereas for $A \to \infty$ the class A noise PDF becomes Gaussian.

In [10], characteristics of several different noise sources are examined. In addition to the class A noise model, the most severe impulsive noise sources have been embedded into simulations, as a noise add-on to the powerline channel of the previous chapters. Besides two mobile phone chargers, a light dimmer and a PC power supply have been examined with respect to their distortion impact. The devices are characterized by an AWGN noise source with variance σ_G^2 and an additional level of impulsive noise. The same impulsive noise is assumed for every receiving path. These simulations confirm the superior performance of eigenbeamforming. Figure 10 depicts the results of eigenbeamforming in a typical PLC channel with different additional noise generating devices.

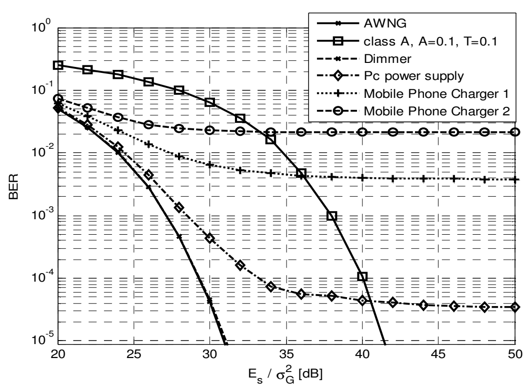

Figure 10: BER of eigenbeamforming MIMO in presence of a PLC channel and additional noise generating devices

Additional class A noise shows the typical waterfall curve, but results in a degradation of several dB. While the dimmer has almost no negative impact on the BER, the mobile phone chargers with their high number of noise pulses may cause a considerable BER floor of up to 0.1. Obviously, these worst case noise scenarios can't be handled completely by current raw physical MIMO schemes. Although these scenarios are not representative for the overall performance, PLC specific improvements for the MIMO coding schemes have to be studied further. Placing the data bursts in time slots without strong noise pulses may be a solution. Since this is part of the MAC (Medium Access Control) layer, it is not considered here in detail.

As is well known, eigenbeamforming requires CSI at the transmitter, resulting in an additional amount of feedback data. Reducing this feedback information to a minimum is also an important future issue. Sophisticated quantization and data compression methods are required that take advantage of the special PLC channel characteristics.

6 Conclusions

We have shown that MIMO becomes technically feasible for inhome PLC by using all available wires and the common mode path. MIMO schemes offer a significant increase in bitrate, which is typically more than doubled compared to today's SISO systems. Our simulations confirm the theoretical capacity gain: Different state of the art MIMO schemes are considered and benchmarked. The Alamouti scheme offers an attractive throughput increase. The proposed scheme, which combines MIMO eigenbeamforming with OFDM using adaptive modulation is superior, even if additional impulsive noise sources are present. The bitrate gain exceeds a factor of 2.5 for almost all considered PLC channels. Two kinds of feedback data from receiver to transmitter are required, namely subcarrier constellation signalling and for eigenbeamforming channel state information. However, the update rate for these messages can be kept low since the time variation of the PLC channel is rather slow.

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