Potential of 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 show that today's PLC technology is not providing sufficient bandwidth for high speed inhome applications in a reliable way. This paper shows the potential of Multiple Input Multiple Output (MIMO) methods, being well-known from the wireless world, to increase the PLC channel throughput and the link reliability significantly. After proving the theoretical capacity increase on measured PLC channels, different MIMO schemes are compared regarding their suitability for the PLC channel. Further, a MIMO-PLC system using precoded spatial multiplexing, OFDM and adaptive QAM-modulation is proposed and discussed.

1. Introduction

The goal of home networking is connecting all digital electronic devices within a private house or flat. As shown in Fig. 1, a typical application of home networking is e. g. the streaming of high definition (HD) video content from a PC or home server to a HD-TV in the living room. Various wired (e.g. Ethernet, Coax) and wireless networks (e.g. WiFi) exist to establish these home networking functions. However, there might be some drawbacks of these solutions, especially for 'room to room' connectivity and long distances within the house. The data throughput of wireless connections decreases if the signal is attenuated by walls or ceilings. Wired networks may require inconvenient installation efforts. For mains-powered devices Powerline Communications (PLC) enables new and highly convenient networking functions without any additional cables. An inhome backbone connecting all devices or clusters in the house is provided by PLC, as can be seen in Fig. 1. Wireless devices communicate via an access point to the PLC network.

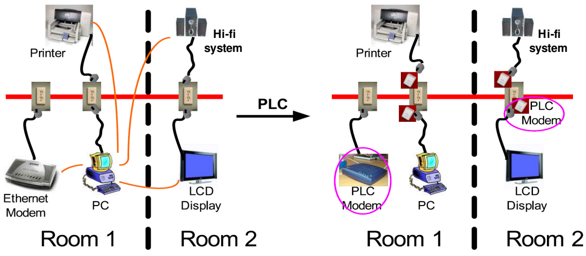

Figure 1 PLC application scenarios

Today's PLC solutions promise data rates up to 200 Mbit/s on physical layer. This throughput can be achieved on excellent PLC channels, only. Measurements in buildings show significant lower bitrates due to high attenuation, frequency selective transfer functions and noise in many cases. Today's PLC systems use one transmit and one receive port for data communication. However, in most parts of the world 3-wire installations allow more feeding and receiving options. In presence of multiple feeding and receiving ports, MIMO principles are applicable. Recently MIMO technologies were successfully introduced by wireless standards such as IEEE 802.11n or WiMAX. Compared to basic Single Input Single Output (SISO) solutions MIMO can offer a fundamental increase of data rate. The key question is: Does MIMO increase channel capacity and improve coverage as well as reliability also of PLC links?

In order to investigate the potential of MIMO for PLC we investigate PLC-MIMO channels by measurement in Section 2, compute the channel (system) capacity in Section 3 and compare different MIMO schemes (Section 4). A detailed discussion of the proposed MIMO scheme is done in Section 5.

2. PLC-MIMO Channel

Today's PLC modems are SISO based: The signal is symmetrically fed and received between the live, also called phase (P) and the neutral (N) wire. If there is an additional wire, i.e. protective earth (PE) more feeding and receiving options are available.

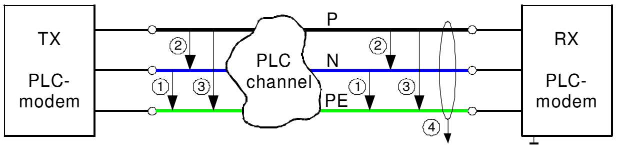

Figure 2 PLC-MIMO channel

Fig. 2 shows the PLC-MIMO channel for 3-wire installations with differential signal feeding between the wires.

There are three different feeding options: N to PE, P to N and P to PE. According to Kirchhoff's rule the sum of the 3 input signals has to be zero. Thus, only 2 out of the 3 input ports can be used independently. On receiving side, all 3 differential receiving ports are available. Additionally the common mode path (CM) could be used as a 4th reception option. 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. The CM receive signal is especially interesting for e.g. flat panel TVs equipped with a backplane as good capacity towards ground. In summary, up to 2 transmit and up to 4 receive ports are available, i.e. 2x4 MIMO.

Measurements in several private flats and houses were performed: The complex frequency responses of all 12 feeding/receiving combinations (3 TX and 4 RX ports) of many socket connections were recorded with a network analyzer. The measurements show a significant crosstalk between adjacent wires due to electromagnetic coupling, i.e. the transmit signal from any feeding port is visible on all 4 receiving ports. Fig. 3 illustrates the transfer functions (magnitude) of all possible receiving ports, if P-N is chosen as feeding port. The similarity of the transfer function shapes indicates a strong coupling between the individual paths.

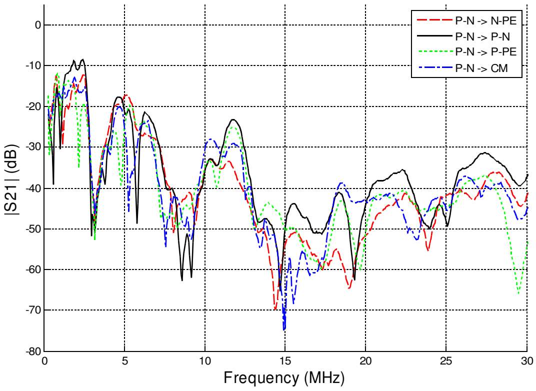

Figure 3 Measured magnitude of transfer function |S21| of all 4 receiving ports, with P-N as feeding port

The very frequency selective PLC channel can be divided into *N* subbands that are sufficiently flat in the frequency domain (mapping later to *N* OFDM subcarriers). For each subband *i* the MIMO channel path between feeding port *v* and receiving port μ can be described by a transfer coefficient $h^i_{\mu\nu}$. This leads to the MIMO channel matrix $\mathbf{H}_i$ for each subband *i* ($\nu = 1,2$; $\mu = 1,\ldots,4$; $i = 1,\ldots,N$):

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

3. Channel Capacity

Based on these channel measurements the channel capacity is investigated. Theoretically, the channel matrix $\mathbf{H}_i$ can be decomposed into 2 parallel SISO branches by a singular value decomposition (SVD) [1]:

$$\boldsymbol{H}_i = \boldsymbol{U}_i \boldsymbol{D}_i \boldsymbol{V}_i^H \quad \text{with} \quad \boldsymbol{D}_i = \begin{pmatrix} \sqrt{\lambda_{i,1}} & 0 \\ 0 & \sqrt{\lambda_{i,2}} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad (2)$$

$\lambda_{i,j}$ are the eigenvalues of the 'squared' channel matrix $\mathbf{H}_i \cdot \mathbf{H}_i^H$. $\mathbf{U}_i$ and $\mathbf{V}_i$ are unitary matrices, i.e. $\mathbf{U}_i^{-1} = \mathbf{U}_i^H$ and $\mathbf{V}_i^{-1} = \mathbf{V}_i^H$. Upper case H indicates the Hermiteian operator as the transposed and conjugate complex (*) of a matrix.

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:

$$C = B \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{2} \log_2\left(1 + \frac{\lambda_{i,j} E_S}{n_T N_0}\right) \quad \left[\frac{bit}{s}\right] \qquad (3)$$

with:

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

Channel capacity calculations are made for 2 transmit power levels: -93dBm/Hz as a lower and -67dBm/Hz as a higher feeding power level. The noise spectral density NSD is set to -136dBm/Hz, i.e. the receiver noise floor is considered to be flat [2].

In [3] different MIMO arrangements (different number of transmit ports and receiving ports) are investigated. One transmit port and different number of receiving ports offer a small gain compared to SISO, only. If two transmit ports are used the channel capacity is doubled compared to SISO, in average.

Tab. 1 summarizes the channel capacity gain compared to SISO for a 2x3 MIMO arrangement (the 3 differential receiving ports are used). Next, the results of the 2x4 MIMO arrangement (including the common mode) are presented for the two different transmit power levels.

	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 1: MIMO for PLC – channel capacity gain

Fig. 4 shows the relationship between the cumulative probability and the channel capacity for the parameters given in Tab. 1.

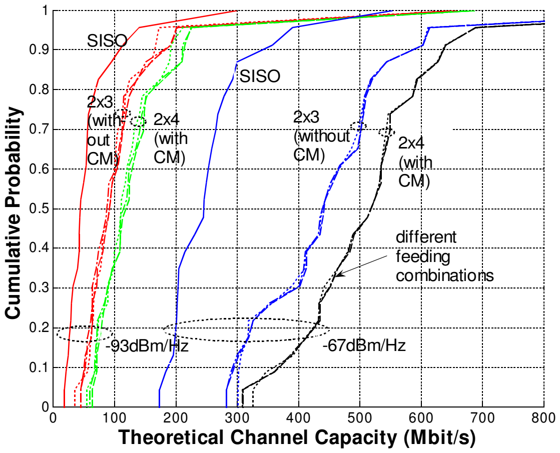

Figure 4 Cumulative probability of the channel capacity

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 is.

2x3 MIMO already improves the average capacity of a PLC channel by about factor 1.8 to 2.2. 2x4 MIMO with the common mode path 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.

4. MIMO Schemes for PLC

The investigation of the channel capacity shows promising gain. Different state of the art basic MIMO schemes are applied to an OFDM based PLC system and examined regarding their suitability for PLC.

To handle the very frequency selective transfer function of the channel our system employs adaptive modulation, i.e. each subcarrier uses a QAM constellation according to the actual SNR of the related subchannel. The different MIMO schemes can be classified by the goals to achieve. On the one hand MIMO can provide throughput gain by sending different streams over the different transmit ports (spatial multiplexing). For this class, spatial multiplexing with and without precoding (with and without channel state information at the transmitter) are investigated. On the other hand a diversity gain can be achieved using the MIMO principle 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. Thanks to adaptive modulation the higher SNR achieved by the Alamouti scheme can be turned into higher throughput. In the next section a brief description of the different schemes is given.

4.1. Alamouti Scheme

The Alamouti scheme [4] is a simple but very effective space-time or space-frequency coding arrangement for MIMO systems with 2 transmit ports. The encoding can be described by the encoding matrix:

$$\xrightarrow{\text{time, (frequency)}}$$
$$S=\begin{pmatrix} s_1(k) & -s_2^*(k+1) \\ s_2(k) & s_1^*(k+1) \end{pmatrix} \Big\downarrow \text{space} \qquad (4)$$

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 is applied in two different ways: Space-frequency encoding indicates k and $k+1$ 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 [4]. For decoding successive OFDM symbols facing the same channel conditions (space-time coding) is assumed. This is fulfilled for a quasistatic PLC channel. On the other hand, the space-frequency Alamouti scheme requires the channel matrices of adjacent subcarriers to be equal (typically true for a sufficiently large number of subcarriers).

4.2. (Precoded) Spatial Multiplexing

Fig. 5 illustrates the MIMO specific parts of the OFDM based spatial multiplexing system on QAM symbols level. For each subcarrier i the two complex output symbols from the adaptive QAM modulator are assigned to a vector $\mathbf{s}_i$ ($i = 1,\dots,N$). Afterwards $\mathbf{s}_i$ is optionally multiplied by a precoder matrix $\mathbf{F}_i$. This matrix is discussed later in more detail.

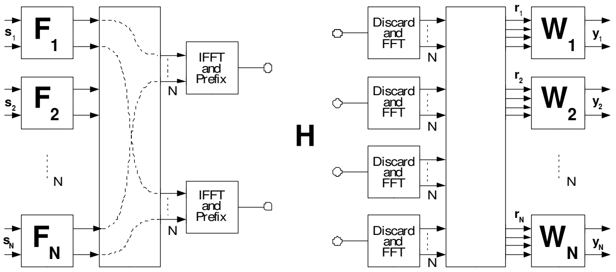

Figure 5 Precoded spatial multiplexing for MIMO-OFDM

The *N* complex symbols of each transmit path are OFDM modulated and sent via the 2 transmit ports over the PLC-MIMO channel **H**. At the receiving side the signals of the 4 receiving ports are first OFDM demodulated. A 4x1 vector $\mathbf{r}_i$ is obtained for each subcarrier *i*:

$$\boldsymbol{r_i} = \boldsymbol{H_i} \boldsymbol{s_i} + \boldsymbol{n_i} \tag{5}$$

where $\mathbf{n}_i$ is a vector of noise samples of the receiving ports. In the following stage, the 4 received symbols ($\mathbf{r}_i$) of each subcarrier are detected with a linear receiver, which is described by the detection matrix $\mathbf{W}_i$. Basically there are 2 types of linear receivers, namely the zero-forcing (ZF) and minimum mean squared error (MMSE) receiver. Due to only marginal performance improvements by the MMSE receiver in combination with adaptive OFDM [3] we focus on a ZF receiver. To simplify notation the subcarrier index *i* is dropped in the following. The operations have to be performed for each subcarrier. The detection matrix **W** for ZF is the pseudo inverse of the channel matrix **H**:

$$\boldsymbol{W} = \boldsymbol{H}^{\boldsymbol{p}} = \left(\boldsymbol{H}^{\boldsymbol{H}} \boldsymbol{H}\right)^{-1} \boldsymbol{H}^{\boldsymbol{H}} \tag{6}$$

Assuming spatial multiplexing without precoding, i.e. $\boldsymbol{F} = \boldsymbol{I}$ (where $\boldsymbol{I}$ is the identity matrix), the output symbols are obtained:

$$\boldsymbol{y} = \boldsymbol{W} \boldsymbol{r} = \boldsymbol{W}(\boldsymbol{H} \boldsymbol{s} + \boldsymbol{n}) = \boldsymbol{s} + \boldsymbol{H}^{\boldsymbol{p}} \boldsymbol{n} \tag{7}$$

The performance of spatial multiplexing is improved by using precoding at the transmitter. The optimal linear precoder is given by [5]:

$$\boldsymbol{F} = \boldsymbol{V} \tag{8}$$

where **V** is the matrix calculated by the SVD (2). Since **V** is an unitary matrix, the average signal energy is not affected by the precoding matrix. Precoding with the unitary matrix **V** is often referred to as unitary precoding or Eigenbeamforming. Considering $\boldsymbol{W} = \boldsymbol{U}^{\boldsymbol{H}}$ the decoded symbols are:

$$\boldsymbol{y} = \boldsymbol{U}^{\boldsymbol{H}} \Big(\underbrace{\boldsymbol{H}}_{\boldsymbol{U} \boldsymbol{D} \boldsymbol{V}^{\boldsymbol{H}}} \boldsymbol{V} \boldsymbol{s} + \boldsymbol{n} \Big) = \boldsymbol{D} \boldsymbol{s} + \boldsymbol{U}^{\boldsymbol{H}} \boldsymbol{n} \tag{9}$$

Since **D** is a diagonal matrix, the channel is decomposed into two parallel and independent paths. The final estimation of the transmit symbol vector **s** is obtained by scaling **y** by $\mathbf{D}^{-1}$. The transmitter may not use the perfect precoding matrix but the precoding matrix $\tilde{\boldsymbol{V}}$ ($\tilde{\boldsymbol{V}}$ might be also a quantized version of the perfect precoding matrix **V**). The receiver operates on the equivalent channel matrix

$$\tilde{\boldsymbol{H}} = \boldsymbol{H} \tilde{\boldsymbol{V}} \tag{10}$$

and applies the pseudo inverse for ZF detection of the equivalent channel matrix. Substituting (10) into (6) leads to:

$$\tilde{\boldsymbol{H}}^{\boldsymbol{p}} = \tilde{\boldsymbol{V}}^{-1} \boldsymbol{H}^{\boldsymbol{p}} \tag{11}$$

If $\tilde{\boldsymbol{V}}$ is an unitary matrix, (11) simplifies to

$$\tilde{\boldsymbol{H}}^{\boldsymbol{p}} = \tilde{\boldsymbol{V}}^{H} \boldsymbol{H}^{\boldsymbol{p}} \tag{12}$$

4.3. Comparison of MIMO Schemes

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. An OFDM system with 1296 subcarriers ranging from 4 to 30MHz is used. The symbol duration is 54.4µs, including a guard interval of at least 3.2µs (1/16). The range of QAM constellations for adaptive modulation starts with QPSK and goes up to 1024 QAM. Subcarriers may be notched, i.e. if the SNR at a specific frequency is very low, no information is allocated to this subcarrier. The adaptive modulation was adjusted to a target bit error ratio (BER) of 10^{-3} for the uncoded channel. This value is chosen since additional forward error correction (not described here) easily decreases the BER to fulfil the quality requirements of all typical applications. Perfect channel state information (CSI) is assumed at the receiver and transmitter. The receive signal is corrupted by additive white Gaussian noise (AWGN) with zero mean. The variance of the noise is the same for all receiving ports. According to the channel capacity calculations in Section 3, two different transmit power levels are selected for benchmarking, namely -93dBm/Hz and -67dBm/Hz.

Fig. 6 shows the achieved bitrate for several outlet combinations of one measurement site at the higher transmission level.

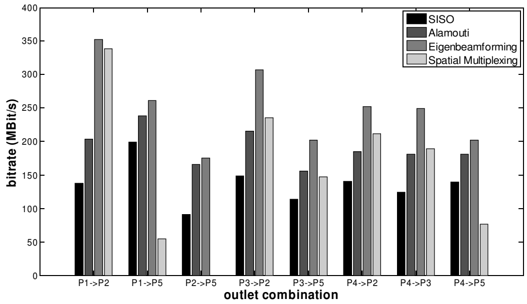

Figure 6 : Throughput comparison of different MIMO schemes for different outlet combinations, transmit power level = -67dBm/Hz

Tab. 2 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 2: Average bitrate at different transmit power levels

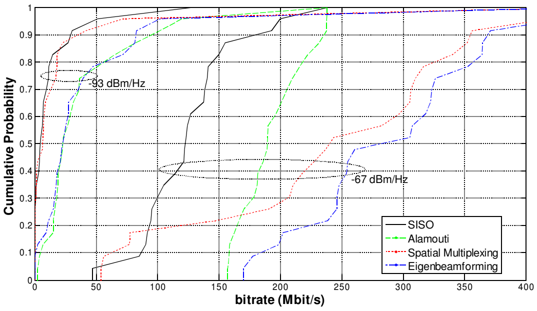

Figure 7 Cumulative probability of the simulated bitrate for different MIMO schemes

Generally, there is a significant increase in the throughput for all MIMO schemes compared to SISO transmission. Eigenbeamforming 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 may even be smaller than for SISO. The reason is the enhancement of noise by the detection matrix **W** (see also equation (7)): The Frobenius norm of **W** may be rather large for high correlated PLC channels.

For low SNR, the performance of the Alamouti and the Eigenbeamforming MIMO scheme is similar. The throughput gain in the low SNR regime of these two methods exceeds the gain reached by the SISO scheme for channels with higher SNR. Fig. 7 summarizes the results of 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 with some channels. For the low transmit power level, the Alamouti scheme is almost as good as Eigenbeamforming, while spatial multiplexing with ZF decoding does not substantially exceed the SISO performance. Another special characteristic of power line communications is the presence of additional impulsive noise generated by devices being plugged to the mains network. In [3] the influence of these noise sources is discussed for the different MIMO schemes described above and the investigations confirm the superior performance of Eigenbeamforming.

5. Precoded Spatial Multiplexing

Based on the MIMO scheme comparisons precoded spatial multiplexing (Eigenbeamforming) turns out to be the best choice for PLC since it offers the highest bitrate. However, this scheme requires channel state information at the transmitter. Basically, there are two options for the transmitter to obtain knowledge about the precoding matrices. If the MIMO channel is reciprocal and the system uses time division duplex (TDD), both the transmit and the receive modem have channel state information and can determine the precoding matrices. In [6] this option is discussed in detail and it is shown that the MIMO-PLC channel is reciprocal if the common mode is not used. On the other hand CM can provide a significant gain as showed in the previous section. As the reciprocity is not fulfilled in this case, the receiver needs to inform the transmitter about the required channel state information, i.e. the receiver has to feed back the precoding matrices to the transmitter.

5.1. Quantization of the Precoding Matrix

To keep the feedback overhead small, the precoding matrices have to be quantized in an appropriate way. This can be done by exploiting the unitary property of this matrix. Both the receiver and the transmitter are equipped with the same set of quantized precoding matrices (also called codebook). If the codebook comprises 2^b entries b bits are needed for the feedback. [6] addresses this quantization of the precoding matrices for MIMO-PLC in detail:

- Selection criterion for the choice of the precoding matrix out of the codebook where the special properties of the precoding matrix have to be considered
- Precoding for OFDM: By exploiting the correlation between neighbouring subcarriers the feedback overhead can be further reduced
- Generation of the codebook

Fig. 8 shows the bitrate depending on the ratio of the transmit power level and the noise power level for two different channels. Note, this ratio is not equal to the SNR at the receiver, since the channels comprise frequency specific attenuation. Perfectly precoded spatial multiplexing is compared to spatial multiplexing without precoding and quantization of the precoding matrix with 2, 4, 6 and 8 bit for each subcarrier separately. Two different channels are considered. The first channel (ch1 in Fig. 8) exhibits smaller correlation and attenuation compared to the second channel (ch2). The lower the channel correlation the closer the curves for perfect precoding and spatial multiplexing without precoding are (and vice versa). The correlation impacts the performance of the quantization of the precoding matrix: The curves are “spread” between perfect precoding and spatial multiplexing without precoding.

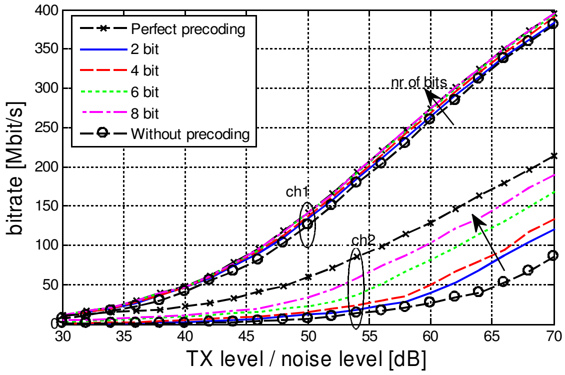

Figure 8 Quantized precoded spatial multiplexing, each subcarrier quantized separately, 2 different PLC channels

Further results, especially for the quantization across subcarriers can be found in [6].

The quantization significantly reduces the feedback overhead with marginal performance degradations, only. The transmission of feedback information for precoded spatial multiplexing is not an additional burden for two reasons. The applied adaptive modulation needs a feedback path anyhow and the update rate can be kept low since the time variation of the PLC channel is rather slow.

5.2. Power allocation

The MIMO principle offers another degree of freedom to optimize the throughput which is the allocation of the total transmit power to the two transmit streams. In combination with adaptive modulation the waterfilling algorithm [1] shows almost no performance gain since adaptive modulation already exploits channel SNR differences. Therefore another simple but effective algorithm for adaptive modulation is proposed [6]. If the SNR of one path and subcarrier is too low for the most robust constellation this subcarrier is notched. The power for this path and subcarrier is assigned completely to the other transmit port. This increases the SNR of the remaining path by 3dB. Fig. 9 illustrates the results of power allocation (PA) for different outlet combinations of one building. A rather low TX level is chosen to highlight the effect of PA. Compared to equal PA, water filling (WF) shows almost no additional throughput gain, while the proposed PA (new PA) significantly increases the bitrate.

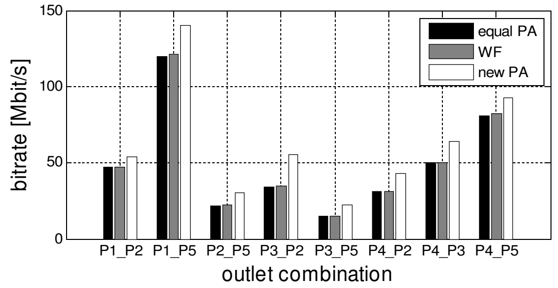

Figure 9 Power allocation, TX level/noise level = 44dB

6. Conclusions

The MIMO principle becomes technically feasible for inhome PLC by using all available wires and the common mode reception path. Channel capacity calculations based on measurements of PLC-MIMO channels show a significant increase in bitrate, which is typically more than doubled compared to today's SISO systems. A comparison of different MIMO schemes confirms the theoretical capacity gain. As a result precoded spatial multiplexing combined with OFDM and adaptive modulation turns out to be the best choice for PLC since it offers the highest bitrate. Two kinds of channel state information from receiver to transmitter are required, namely for adaptive subcarrier modulation and for precoded spatial multiplexing. The special properties of the precoding matrices and the correlation between neighbouring OFDM subcarriers allow an efficient quantization which significantly reduces the amount of feedback data to an acceptable level. Since the time variation of the PLC channel is low, the update rate of the feedback information can be kept small as well.

A further possibility to enhance the throughput rate of PLC is using the frequency range above 30MHz as described in [2] which has the drawback of challenging a new regulatory situation for PLC.

Finally, EMC mitigation techniques [7] may be applied to PLC independent of the MIMO coding scheme.

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