Precoded Spatial Multiplexing 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 wires to mains-powered devices. Multiple Input Multiple Output (MIMO) methods can significantly increase the PLC channel throughput and the link reliability. In this paper precoded spatial multiplexing is considered in more detail since it offers the best possible data throughput in the PLC channel. Precoded spatial multiplexing requires channel state information (CSI) at the transmitter. CSI feedback possibilities as well as appropriate quantization methods to reduce the amount of feedback data are investigated. We also present a new power allocation algorithm in conjunction with adaptive modulation.**

***Index Terms*—Powerline communications, MIMO, precoded spatial multiplexing, adaptive OFDM**

I. INTRODUCTION

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, which is the precondition to apply Multiple Input Multiple Output (MIMO) methods. In [1] the suitability of MIMO for inhome PLC has been investigated. It has been shown that MIMO can significantly increase the bitrate: Typically it is more than doubled compared to today's single input single output (SISO) systems. Different MIMO schemes like spatial multiplexing (SMX), precoded spatial multiplexing (also referred to as Eigenbeamforming) and the Alamouti scheme in conjunction with adaptive modulation have been compared in PLC system simulations. Eigenbeamforming is considered to be the best choice in the PLC environment for several reasons: It offers the highest bitrate of all investigated schemes. Especially in correlated channels the precoding still allows high bitrates while SMX without precoding faces strong throughput degradations. However, precoded SMX requires channel state information (CSI) at the transmitter (TX). Since the time variation of the PLC channel is rather low, the overall amount of feedback data can be kept low, too. Moreover, CSI feedback data can be appended to an already existing tonemap feedback path that is needed for adaptive OFDM systems.

Precoded SMX uses linear precoding, i.e. the signal to be transmitted is multiplied by a precoder matrix which is a function of the channel matrix. In the case of orthogonal frequency division multiplexing (OFDM), the transmitter requires precoder knowledge for all subcarriers. Generally there are two different options to obtain CSI on transmitter side: In time division duplex (TDD) systems, [2] showed that the SISO PLC channel transfer function is reciprocal. To some extent this reciprocity is also true for PLC MIMO systems, which allows to estimate CSI on transmitter side. The other possibility is to determine CSI on receiver side and to feedback the precoder information back to the transmitter. To keep the amount of feedback information low, an appropriate quantization of the precoder matrices is essential. Both options are discussed in this paper for MIMO-PLC.

The paper is organized as follows: The channel and system model for MIMO-PLC is explained in Section II. Section III deals with precoded SMX: Reciprocity of the PLC-MIMO channel transfer function, the quantization of the feedback information and power allocation algorithms are discussed. Finally simulation results are presented (Section IV).

II. PLC-MIMO CHANNEL AND SYSTEM

A. PLC-MIMO Channel

Figure 1 shows the PLC-MIMO channel for 3-wire installations (P (Phase or Live), N (Neutral) and PE (Protective Earth)). Signals are fed and received differentially between pairs of wires. Therefore there exist 3 different feeding possibilities: 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 0, 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 4th 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 TX.

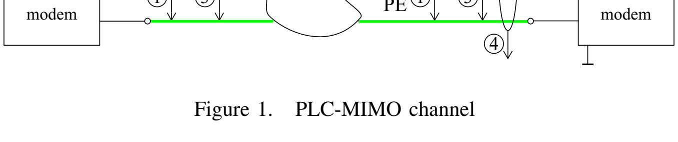

Figure 1. PLC-MIMO channel

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. Measurements in private flats and houses and for different outlet combinations have shown a significant level of crosstalk. The resulting additional transmission paths provide a large channel capacity gain [1]. 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 ν and receiving port μ can be described by a transmission coefficient $h^i_{\mu\nu}$. This leads to the MIMO channel matrix $\mathbf{H}_i$ for each subband i ($\nu = 1, 2$; $\mu = 1, \ldots, 4$):

$$\mathbf{H}_i = \begin{pmatrix} h^i_{11} & h^i_{12} \\ h^i_{21} & h^i_{22} \\ h^i_{31} & h^i_{32} \\ h^i_{41} & h^i_{42} \end{pmatrix} \tag{1}$$

B. PLC-MIMO System

The first stage of the raw physical layer of an OFDM based PLC-MIMO system comprises the multiplexing of the incoming bits into 2 separate streams. The bits of these 2 streams are mapped to complex symbols in the following quadrature amplitude modulation (QAM) stage. The proposed scheme employs adaptive modulation, i.e. each of the N subcarriers uses a QAM constellation according to the instantaneous SNR of the related frequency (also referred to as adaptive OFDM). The lower the SNR, the smaller the chosen QAM constellation. Moreover, if the SNR at a specific frequency is very low, the corresponding subcarrier can also be notched. Figure 2 illustrates the following MIMO specific part of the system: For each subcarrier i the two complex output symbols from the adaptive QAM modulator are pairwise assigned to a vector $\mathbf{s}_i$ ($1 \leq i \leq N$). $\mathbf{s}_i$ is afterwards multiplied by a precoder matrix $\mathbf{F}_i$. The construction of the precoding matrices is discussed later in more detail.

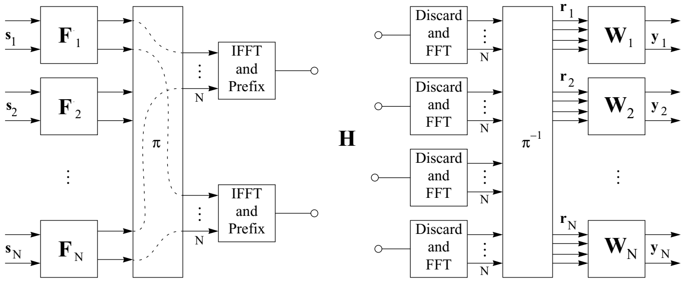

Figure 2. Precoded spatial multiplexing for MIMO-OFDM

The N complex symbols of each transmit path are then OFDM modulated and sent via the 2 transmit ports over the PLC-MIMO channel $\mathbf{H}$. On receiving side, the signals of the 4 receiving ports are in a first step OFDM demodulated. The resulting 4×1 vector $\mathbf{r}_i$ is obtained for each subcarrier i. In the following stage, the 4 received symbols of each subcarrier ($\mathbf{r}_i$) are detected with a linear receiver, which is described by the detection matrix $\mathbf{W}_i$. Finally, the adaptive QAM demodulator and the stream demultiplexer deliver the output signal of the raw phy decoder (not depicted in Figure 2). Basically there are 2 types of linear receivers: Zero-forcing (ZF) and minimum mean squared error (MMSE). This paper is restricted to ZF since MMSE in conjunction with adaptive OFDM provides only marginal performance improvements: Main reason is that the SNR range for each subcarrier is already adjusted by the use of adaptive modulation. The detection matrix $\mathbf{W}_i$ for ZF is the pseudo inverse of the channel matrix $\mathbf{H}_i$ (where ^{H} denotes the hermitian operator):

$$\mathbf{W}_i = \mathbf{H}^p_i = (\mathbf{H}^H_i \mathbf{H}_i)^{-1} \mathbf{H}^H_i \tag{2}$$

If we assume SMX without precoding, i.e. $\mathbf{F}_i = \mathbf{I}$ (where $\mathbf{I}$ is the identity matrix), we obtain for the output symbols:

$$\begin{aligned} \mathbf{y}_i &= \mathbf{W}_i \mathbf{r}_i = \mathbf{W}_i (\mathbf{H}_i \mathbf{s}_i + \mathbf{n}_i) = \mathbf{H}^p_i \mathbf{H}_i \mathbf{s}_i + \mathbf{H}^p_i \mathbf{n}_i \\ &= (\mathbf{H}^H_i \mathbf{H}_i)^{-1} \mathbf{H}^H_i \mathbf{H}_i \mathbf{s}_i + \mathbf{H}^p_i \mathbf{n}_i = \mathbf{s}_i + \mathbf{H}^p_i \mathbf{n}_i \end{aligned} \tag{3}$$

where $\mathbf{n}_i$ is a vector of noise samples of the receiving ports. (3) illustrates the drawbacks of SMX without precoding: Depending on the detection matrix $\mathbf{W}_i = \mathbf{H}^p_i$, the noise term may be amplified in a way that influences the decoding output in a negative way: If the channel matrix $\mathbf{H}_i$ is very correlated, the elements of $\mathbf{H}^p_i$ become very big. As a result, SMX fails for these channels (see also [1]).

III. PRECODED SPATIAL MULTIPLEXING FOR MIMO-PLC

The optimal linear precoder for precoded SMX systems is defined as follows [3] (the subcarrier index i is omitted in the following for convenience):

$$\mathbf{F} = \mathbf{V}\mathbf{P} \tag{4}$$

The precoding matrix $\mathbf{F}$ can be factored into 2 matrices $\mathbf{V}$ and $\mathbf{P}$. $\mathbf{P}$ is a diagonal matrix which describes a power allocation of the total transmit power to each of the transmit streams. The power allocation is considered in section III-C in more detail. $\mathbf{V}$ is retrieved from the channel matrix $\mathbf{H}$ via a singular value decomposition (SVD):

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^H \tag{5}$$

where $\mathbf{D}$ is a diagonal matrix with the singular values of $\mathbf{H}$ as diagonal elements and $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices, i.e. $\mathbf{U}^{-1} = \mathbf{U}^H$ and $\mathbf{V}^{-1} = \mathbf{V}^H$, respectively. Since $\mathbf{V}$ is an unitary matrix, the average signal energy is not affected by the precoding matrix. Precoding with the unitary matrix $\mathbf{V}$ is often referred to as unitary precoding or Eigenbeamforming.

Next, we discuss the effect of the precoding matrix on the detection. Assume that the transmitter uses the precoding matrix $\tilde{\mathbf{V}}$ ($\tilde{\mathbf{V}}$ might be e.g. a quantized version of the perfect precoding matrix $\mathbf{V}$). The receiver "sees" the equivalent channel matrix

$$\tilde{\mathbf{H}} = \mathbf{H}\tilde{\mathbf{V}} \tag{6}$$

and applies the pseudo inverse for ZF detection of the equivalent channel matrix. By setting (6) into (2) it can be easily shown that:

$$\tilde{\mathbf{H}}^p = \tilde{\mathbf{V}}^{-1}\mathbf{H}^p \tag{7}$$

If $\tilde{\mathbf{V}}$ is an unitary matrix, (7) simplifies to

$$\tilde{\mathbf{H}}^p = \tilde{\mathbf{V}}^{H}\mathbf{H}^p \tag{8}$$

Basically, there are two possibilities for the transmitter to obtain knowledge about the precoding matrix:

A. The MIMO channel is reciprocal and TDD is applied

B. The receiver informs the transmitter about the current channel conditions (CSI feedback)

A. Reciprocal MIMO Channel Transfer Function

As shown before, the unitary precoding matrices $\mathbf{V}_i$ depend on the channel matrices $\mathbf{H}_i$ which are build from the path specific channel transfer functions. [2] explains the necessary differentiation between channel transfer function and SNR for the PLC-SISO channel: While the channel transfer function is found to be reciprocal, this behavior does not hold for the SNR of both communication directions. Figure 3 illustrates the basic relation: The upper horizontal line illustrates the transmit power level, the middle line depicts the channel transfer function. The bottom curve shows the noise level, which depends strongly on the distance between noise sources and PLC modem. SNR is defined as the difference between channel transfer function and noise level. On the one hand, both communication directions of a PLC modem face different noise levels and therefore different SNR conditions, resulting in different adaptive OFDM patterns. On the other hand, the channel transfer functions remain the same in both directions.

The next question is whether the PLC channel transfer function is still reciprocal for MIMO systems? As long as we omit the common mode path and consider only the differential MIMO paths (N to PE, P to N, and P to PE), reciprocity still holds for the MIMO case. This allows an important conclusion for our precoded SMX PLC-MIMO system: If the communication system uses the same frequencies for transmitting and receiving (TDD), each modem can use its receiving channel estimation to calculate the precoding matrices that are needed for transmitter operation.

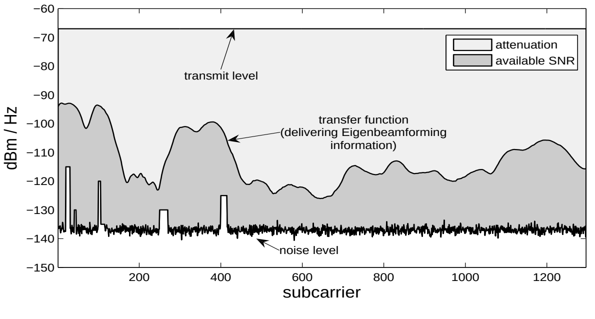

Figure 3. SNR definition and reciprocal channel transfer function

Unfortunately, the reciprocal behavior is not true for the CM path: The distance of devices with unbalanced capacities (i.e. causing CM currents) is different for each PLC modem. Moreover, the reception level on the CM port depends on the modem specific impedance ground for HF signals (e.g. an integrated PLC modem of a TV display with its huge ground plane gets more CM signal level than a small standalone modem). Exploiting the reciprocity of the PLC channel to avoid CSI feedback is only possible as long as the CM path is not used as additional receiving port. Since the CM path often offers a notable increase of the MIMO channel capacity [1], we investigate in the following feedback and quantization possibilities of the precoding matrices.

B. Quantization of the Precoding Matrix

To minimize the feedback overhead, the precoding matrices $\mathbf{V}_i$ have to be quantized in a proper way. Special properties of the precoding matrix $\mathbf{V}$ can be exploited to achieve an efficient quantization. The basic idea of quantization is that the receiver as well as the transmitter have the same set of precoding matrices with a finite number of entries. This set or codebook is called $\mathcal{F} = \{\mathbf{V}_n\},\ 1 \leq n \leq 2^b$ (where b is the number of feedback bits and 2^b is the number of codebook entries). Correlated, neighbored subcarriers can be used to further reduce the amount of feedback data.

1) Properties of the Precoding Matrix: Since for inhome MIMO-PLC the number of transmit ports is limited to 2, the paper focuses on 2×2 $\mathbf{V}$ matrices and highlights some special properties of unitary 2×2 matrices. The 2 columns of $\mathbf{V}$, $\mathbf{v_1}$ and $\mathbf{v_2}$ are orthonormal, i.e. $\mathbf{v_1}$ and $\mathbf{v_2}$ are orthogonal and the norm of these 2 vectors is equal to 1 [4]. This property allows to limit the quantization to the first eigenvector, since $\mathbf{v}_2$ can be derived from $\mathbf{v}_1$ on TX side. $\mathbf{v_1}$ and $\mathbf{v_2}$ are phase-invariant, i.e. each column vector can be multiplied by an arbitrary phase rotation and still remains a valid precoding matrix [5]. Therefore a special distance criterion is needed to find the best codebook entry. We use here the chordal subspace distance (cd) criterion between 2 vectors [6]:

$$d_c^2(\mathbf{v}, \mathbf{v}_n) = 1 - \|\mathbf{v}^H \mathbf{v}_n\|^2 \tag{9}$$

where $\mathbf{v}$ might be the first column of the optimal precoding matrix and $\mathbf{v}_n$ might be the different codebook entries. The receiver calculates first the optimal precoding matrix $\mathbf{V}$ out of $\mathbf{H}$ with the help of the SVD and compares then the first column vector with all codebook entries according to (9) and finally selects the entry with the minimum distance. The related codebook index is then sent back to the transmitter.

2) SNR Optimized Selection Criterion: In addition, this paper proposes another and new selection criterion that does not need the extensive calculation of the SVD. It chooses that codebook entry that maximizes the post-detection SNR. From (8) follows that the detection matrix depends on the precoding matrix, i.e. for each precoding matrix in the codebook we get a different detection matrix $\mathbf{W}_n = \mathbf{V}_n^H \mathbf{H}^p,\ 1 \leq n \leq 2^b$. The detection matrix influences the SNR after detection. The SNR of ZF for both paths after detection is:

$$\mathrm{SNR_j} = \frac{E_s}{\|\mathbf{w}_{jn}\|^2\sigma^2}, \qquad j = 1, 2 \tag{10}$$

where E_s is the average energy of the transmitted symbols, σ^2 is the variance of the noise (assumed to be the same for all receiving ports) and $\mathbf{w}_{jn}$ is the jth row of the detection matrix $\mathbf{W}_n$. From (10) follows that the smaller the norm of $\mathbf{w}_{jn}$, the higher the SNR of path j. We observed that in conjunction with adaptive OFDM it is not necessary to consider an overall measure of all $\mathrm{SNR_j}$ of all path j, but it is sufficient to maximize the SNR of the strongest path. Therefore it is sufficient to calculate $\mathbf{w}_{jn}$ for all j and n and to choose the codebook entry with the minimum $\|\mathbf{w}_{jn}\|^2$.

3) Precoding for OFDM: There are two different approaches to exploit the correlation between neighbored subcarriers of OFDM systems: Clustering and interpolation [5]. The interpolation approach calculates and quantizes only the precoding matrices for certain subcarriers on receiving side. The transmitter interpolates between these subcarriers to obtain the precoding matrices of the other subcarriers. The clustering approach quantizes groups of subcarriers with one precoding matrix and sends back the index for each cluster to the transmitter. The paper focuses on the clustering approach to show that quantization across OFDM subcarriers can further reduce the feedback effort.

The goal is to find for each cluster k, $k = 0, \ldots, K-1$ (K is the number of clusters) one codebook entry that is closest to all subcarrier precoding matrices within the cluster. In [5] the following approach is proposed:

$$\mathbf{V}_k = \arg\min_{\mathbf{V}_n \in \mathcal{F}} \sum_{m=1}^{N/K} d\left(\mathbf{V}_n, \mathbf{V}_{k\cdot N/K+m}\right) \tag{11}$$

where $\mathcal{F}$ is the codebook (with the entries $\mathbf{V}_n$) and d is the distance criterion according to (9) or (10). (11) is accomplished by a brute force search.

4) Codebook Generation: The codebook generation is part of the system design. The codebook $\mathcal{F}$ is constructed with the generalized Lloyd algorithm [7]. The algorithm uses a set of training vectors (which were assumed to be uniformly distributed), starts with an initial codebook and carries out the following steps iteratively until no improvement is observed (for details refer to [7] and the given references):

1) Assign each training vector to one codebook entry according to (9) (nearest neighbor rule)
2) For each region of the assigned training vectors find a new codebook according to a centroid condition

C. Power Allocation

MIMO offers another throughput optimization method which is the allocation of the total transmit power to the two transmit streams. This power allocation can be described by a power allocation matrix $\mathbf{P}$ (see also (4)):

$$\mathbf{P} = \begin{pmatrix} \sqrt{a_1} & 0 \\ 0 & \sqrt{a_2} \end{pmatrix} \tag{12}$$

where a_1 and a_2 describe the power allocation to transmit port 1 and 2, respectively under the constraint $a_1 + a_2 = 1$, i.e. the total transmit power remains the same. It is well known from MIMO theory [8] that the channel capacity optimizing power allocation is obtained by the water filling (WF) algorithm, where a_1 and a_2 are related to the singular values of the channel matrix $\mathbf{H}_i$. However, WF combined with adaptive OFDM is less effective since adaptive modulation already exploits channel SNR differences. Therefore we propose another simple but effective algorithm for adaptive modulation in combination with MIMO. If the SNR of one path and subcarrier i is very low and this subcarrier is notched, the power of this path and subcarrier is assigned completely to the other transmit port (i.e. 3dB SNR increase on the non notched path).

IV. SIMULATION RESULTS

To compare the performance of precoded SMX, we performed simulations with a system according to Figure 2. An OFDM system with 1296 subcarriers ranging from 4 to 30 MHz is used [1]. The symbol duration is 54.4μs, including a guard interval of at least 3.2μs (1/16). The range of QAM constellations of adaptive modulation starts at QPSK and goes up to 1024 QAM, subcarriers can also be notched. The adaptive modulation was adjusted to a target BER of 10^{-3} for the uncoded channel. This value is chosen since additional forward error correction (not considered here) can easily decrease the BER to fulfill the quality requirements of all typical applications. We also assume perfect CSI at the receiver. The noise is assumed to be additive white Gaussian noise (AWGN), the variance of the noise is the same for all receiving ports. For the channel we reuse a large number of measured frequency selective 2×4 MIMO-PLC channels (i.e. including the CM path) [1]. The represantative behavior of the MIMO channels is additionally backed by the fact that the characteristics of the extracted SISO path (P-N to P-N) are very similar to the results found in extensive PLC SISO channel measurements [9]. Figure 4 shows the bitrate depending on the ratio of the transmit power level to the noise power level for different channels. Note the ratio between transmit and the noise power level is not equal to the received SNR since the channels comprise frequency specific attenuation. Perfect precoded SMX is compared to SMX 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 the figure) is less correlated and less attenuated, the second channel (ch2) is very correlated and also highly attenuated. The lower the channel correlation the closer the curves of perfect precoding and SMX without precoding (and vice versa). The correlation of the channel influences the performance of the quantization of the precoding matrix: The curves are “spread” between the curves of perfect precoding and SMX without precoding.

Figure 5 shows the results of the quantization across clustered subcarriers for a typical PLC-MIMO channel when the SNR criterion is applied. The cd criterion delivers very similar

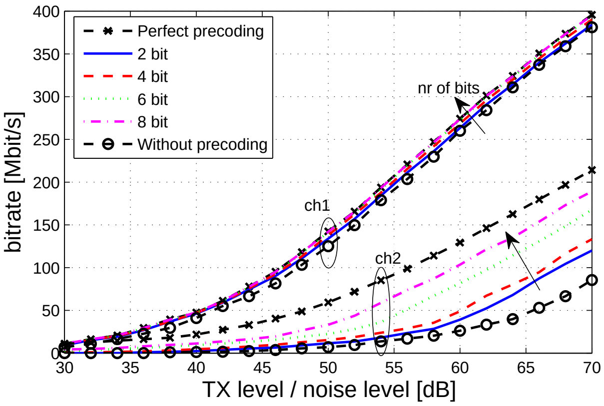

Figure 4. Quantized precoded spatial multiplexing, each subcarrier quantized separately, 2 different PLC channels

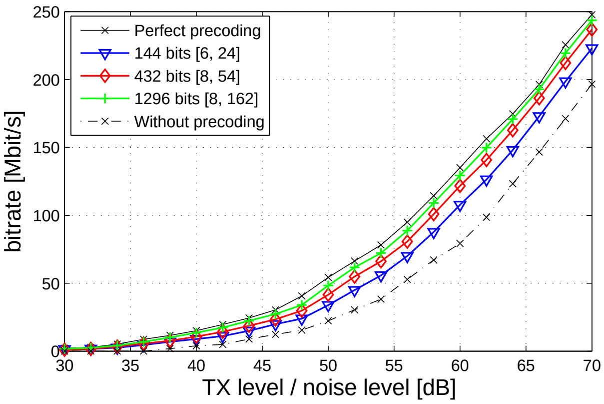

Figure 5. Clustering for a typical PLC-MIMO channel, SNR criterion

results and is ommitted in Figure 5 for better legibility. The total number of feedback bits N_T can be divided into the number of clusters N_C and the number of quantization bits N_B for each cluster: $N_T = N_C \cdot N_B$ (denoted in squared brackets $[N_B, N_C]$ in Figure 5). We examine different numbers of total bits, resulting from different combinations of quantization bits and number of clusters. With an increasing number of total bits the results converge towards perfect precoding. For example, a moderate number of total 1296 bits is already close to the optimum. Initially it is intuitive to derive the cluster size from the coherence bandwidth of an OFDM system (e.g. 81 clusters of 16 subcarriers for the proposed system with 1296 active subcarriers and GI $= 1/16$). However, Figure 5 shows that slightly larger cluster sizes degrade the overall performance not dramatically (e.g. 54 clusters of 24 subcarriers). It is interesting to compare this precoding overhead with the 2nd block of the overall feedback data (OFDM tonemap): If the modulation of every subcarrier is signaled with a resolution of $3\,$bits, $3 \cdot 1296\,$bits are needed for the OFDM tonemap.

Figure 6 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 no power allocation (equal PA), water filling (WF) shows almost no additional throughput gain, while the new proposed PA (new PA) significantly increases the bitrate.

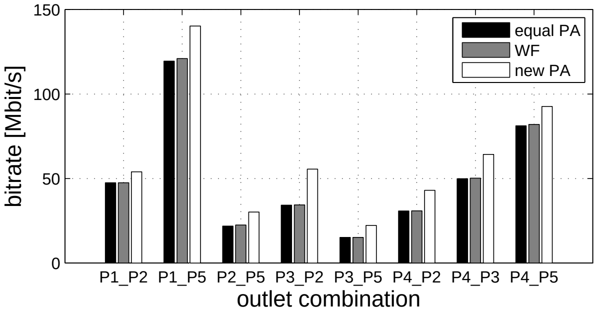

Figure 6. Power allocation, TX level/noise level = 44dB

V. CONCLUSIONS

We investigated precoded spatial multiplexing MIMO combined with adaptive OFDM for inhome PLC. Different options to obtain the necessary channel state information (CSI) of precoded spatial multiplexing on transmitter side are discussed. No feedback is needed for TDD based communication since the PLC channel transfer function is reciprocal as long as the common mode (CM) path is not used. If the CM path is additionally used, the reciprocal property does not hold and feedback of the precoding information is needed. The special properties of the precoding matrices and the correlation between neighbored OFDM subcarriers allows an efficient quantization which significantly reduces the amount of feedback data. Since the time variation of the PLC channel is low, the update rate of the feedback information can be kept low, too. In addition, a new and simple power allocation algorithm for multiplexing MIMO and adaptive OFDM further increases the bitrate of precoded spatial multiplexing.

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