MIMO PLC: Theory, Measurements and System Setup

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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 significantly improve the coverage of guaranteed data throughputs in private homes. This paper gives an overview on MIMO PLC. The results from the channel measurements motivate to implement a MIMO PLC feasibility study in hardware. The system demonstrates HD video streaming over a 2x4 MIMO channel using Beamforming. A MIMO artificial mains network allows testing of the system in the laboratory.**

Keywords- Power line communication; MIMO

I. INTRODUCTION

Multiple Input Multiple Output (MIMO) method for domestic Power Line Communications (PLC) is gaining more and more momentum. After first contributions to research conferences [1-5] HomePlug Powerline Alliance launched a press release [6] that MIMO is one of the major techniques selected by their Technical Working Group for Next Generation PLC networks. The additional communications paths supported by MIMO – in comparison to Single Input Single Output (SISO) – provide significantly higher data throughput rates. The increase of transmission rate is particularly high for channels with inadequate characteristics. An increase of up to factor 5 might be expected [1]. Furthermore most added value of MIMO-PLC is given by the increased coverage to transport for example a HD video stream reliably between all outlet combinations in a private home.

MIMO is well known in wireless transmissions like LTE, WiMAX or 802.11n. However, in the world of wired communications PLC is the 1st application utilizing MIMO technologies with more than one spatial transmission path. Especially the triangle or star style termination at feeding and receiving ports creates new, interesting constellations. Various MIMO schemes like Alamouti, Spatial Multiplexing or Beamforming are applicable for MIMO PLC. Reference [1] identified Eigenbeamforming to provide maximum throughput rates.

The paper is structured in the following way: Section II explains the MIMO PLC channel model. After discussing channel and electro magnetic interferences (EMI) measurements (Section III) the system theory of MIMO Beamforming is explained in Section IV. An up to 2x4 MIMO channel matrix combined with Beamforming provides signal to noise ratio (SNR) gain of up to 20 dB (Fig. 6). Such a high gain increases the motivation to realize a MIMO PLC study in hardware. Section V describes the implementation of a MIMO artificial mains (MAM) which is necessary to reproduce strong fading channels in the laboratory. An outlook on future work and conclusions wrap up the paper.

II. PLC MIMO CHANNEL MODEL

Today's PLC SISO systems use only the path symmetrically between phase (P) and neutral (N) of each outlet. As depicted in Fig. 1 the protective earth (PE) expands the MIMO PLC up to a maximum of 12 paths. For EMI reasons the Common Mode (CM) path is used for receiving only. Fig. 2 shows an implementation of the MIMO PLC probes [7]. There is a triangle-style (transversal) or a star-style (longitudinal) configuration of the probes possible. Fig. 2 presents the triangle probe on the left side and the star probe on the right side. In addition the star-style probe allows the reception of CM signals. The triangle probe has the benefit of providing galvanic isolation between the mains wiring and signal processing hardware. Of course a Schuko prong has to be used for MIMO PLC implementations. According to Kirchhoff's law, the sum of the three voltages (blue arrows) depicted in the triangle probe as well the sum of the three currents (red arrows) in the star probe has to be zero.

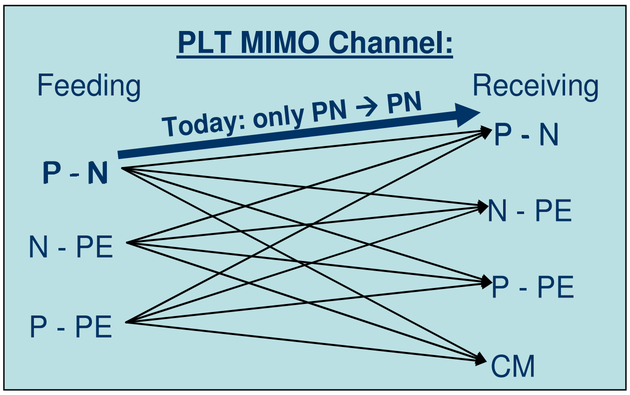

Figure 1. MIMO PLC paths

Due to Kirchhoff's law only 2 out of the 3 feeding possibilities can be used simultaneously. On the reception side all 3 differential paths show some diversity. Parasitic components inside the probes enable various signal paths and gain additional capacity for the MIMO system. Furthermore the common mode reception path could be used at devices equipped with a large metal plate like the backplane of today's HD-TV screens.

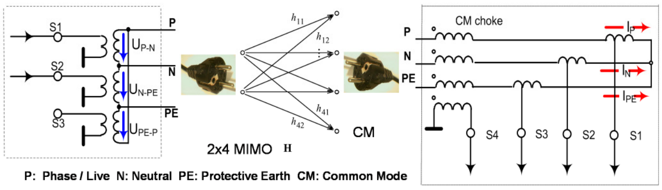

Figure 2. MIMO PLC probes

Fig. 3 provides a high frequency (HF) equivalent circuit of a MIMO PLC channel explaining the creation and reception of CM signals. PLC modems are highly symmetrical implementations. Differential mode (DM) signals U_{DM} only are fed into the main grid. Open light switches or asymmetrical implementations in other appliances convert DM signals into a Common Mode (CM) current. I_{CM} flows via the unwanted parasitic components C_{Para_U}, ground and any other asymmetry back to the location where it was converted. If a PLC modem has to receive U_{CM} it needs a local ground plane providing a low impedance HF connection to ground. The capacitance C_{Para_W} has to be maximized to allow the voltage divider of R_{term} and C_{Para_W} to provide a significant signal level via the internal termination impedance R_{term}. In a private home a HDTV consumes most of the transmitted PLC data. Luckily this device has a big backplane acting as counterpoise. As CM signals are less attenuated than DM signals [7] CM reception significantly improves the data rates at long, highly attenuated links.

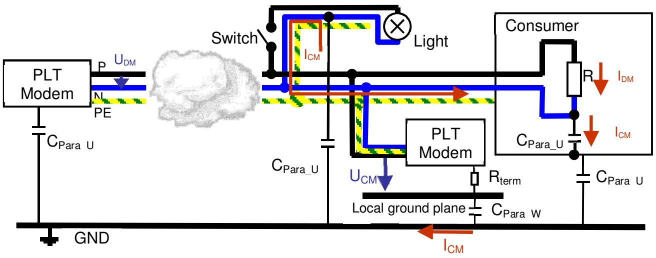

Figure 3. HF equivalent circuit of a PLC MIMO channel

III. MIMO CHANNEL AND EMI MEASUREMENTS

The ETSI special task force STF 410 [8] performs channel and EMI measurements on MIMO PLC. The target of this work is to assist the future MIMO PLC standardization process with suitable channel models and to support the upcoming MIMO regulatory discussions with a large statistics of interference measurements.

CM signals are most relevant for radiations from the power lines as can easily be shown by application of the Biot-Savart rule. As seen above, asymmetries in the mains network are responsible for CM signal conversions. A rough comparison between SISO and MIMO channels helps to investigate potential interferences. E.g. open light switches disconnect only the P wire. Signals fed between N and PE face less asymmetries causing CM conversions. On the other side housing of refrigerators and washing machines are connected to PE which causes asymmetry. Without having measured such effects in multiple buildings it is difficult to predict which effect is dominant. Conducted interferences to a HF radio receiver as done in [9] to specify the coexistence to radio broadcast [10] will also be verified.

Furthermore ETSI STF 410 will record transfer functions of all 12 paths between a pair of outlets, all combinations of impedances (P-N, N-PE, P-PE, CM) and the noise on all paths up to 100MHz. Investigations about the presence of the PE in several countries will also be undertaken.

The attenuations (|S21|) of all individual paths from a typical MIMO PLC channel are presented in Fig. 4. The sweeps had been recorded using the setup shown in Fig. 2. Feeding was done on plug 2 (P2) and receiving on P3 in this flat. The numbers in the legend indicate at P2 the feeding port number (1 to 3) of the triangle probe and at P3 the receiving port number (1 to 4) of the star probe. The variance between the top line and the bottom line is usually more than 30dB. The diversity between the individual paths provides the high gain of the MIMO system compared to SISO. The dashed lines in Fig. 4 are the reception of CM signals. It is obvious that a CM receiver significantly enhances the coverage of the transmission to achieve a high guarantee of minimal throughput.

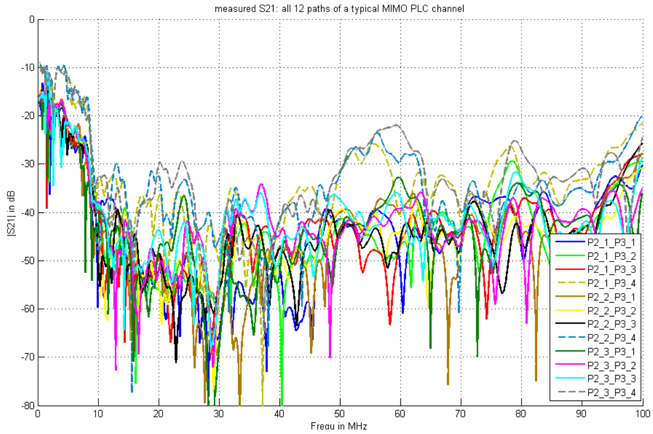

Figure 4. Attenuation of MIMO PLC channel: all 12 paths

IV. MIMO BEAMFORMING SYSTEM THEORY

Fig. 5 presents a block schematic of a MIMO PLC system with two transmit and four receive ports. The incoming data on the top left side is sourced from the forward error correction (FEC). The 1st new block of a MIMO PLC system is the demultiplexer separating the serial data stream into two parallel ones. Depending on the available SNR of each logical transmission path the adaptive quadrature amplitude modulation (QAM) assigns carrier individually a complex symbol to the incoming bits in the frequency domain. In cases of low SNR no communication data might be transported to the receiver. Here, power allocation (PA) is applied between the two logical paths. One of the QAMs doubles the signal amplitude to the constellation while the other QAM assigns no power to this carrier if this stream does not carry any information. Power allocation provides another 3dB gain for these subcarriers. The block MIMO encoding is a matrix multiplication enabling Beamforming. If spatial multiplexing without precoding is applied the block MIMO encoding is not needed. Precoding at the receiver is called Beamforming in the following. The OFDM modulation is implemented by an inverse fast Fourier transform (IFFT) and is identical to the one in a SISO system except the fact that in this case it is used twice. Two signals are transmitted simultaneously. The PLC channels are derived out of individual path field measurements and compiled into a 2x4 transmission matrix.

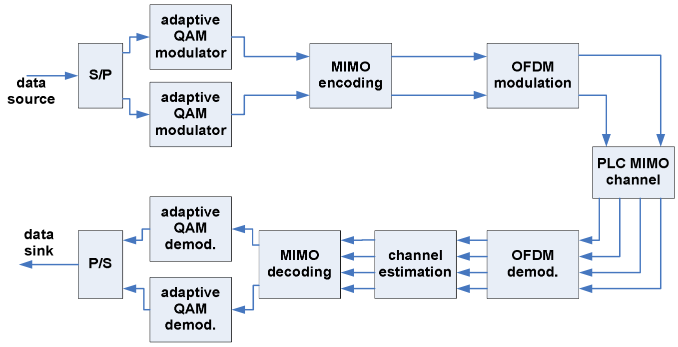

Figure 5. Basic PLC MIMO simulation setup

The lower row in Fig. 5 shows from right to left the steps to be performed at the receiving modem. The FFT (OFDM demodulation) is implemented four times. Then, the channel estimation and equalization reverse the influence from the PLC channel. The optimum unitary precoding matrix **V** depends on the channel matrix **H** and is obtained by a singular value decomposition (SVD) of the channel matrix **H**

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^{H} \tag{1}$$

V and **U** are unitary matrices, $\mathbf{H}^{\mathbf{H}}$ is the hermitian of **H** and **D** is a diagonal matrix containing the singular values. SVD (not shown in Fig. 5) decomposes the two logical paths out of the channel estimation results. Beamforming at receiver side is done in the MIMO decoding block outputting the logical streams to the adaptive QAM demodulators. A parallel to serial converter multiplexes the two logical streams into one for the FEC decoding. To keep backward compatibility with legacy SISO modems the FEC might be identical as the one used previously.

Thanks to the SVD, the algorithm delivers always the best Beamforming vectors independent if Eigen- or Spotbeamforming provides better throughputs. For connections with low SNR the Spot- (or look-direction) Beamforming is advantageous. Here only one logical data stream is multiplied by the **V**-matrix to the 2 physical transmit ports. In contrast to this 1-stream Beamforming, 2-stream or Eigenbeamforming uses both MIMO streams. As described above, a carrier individual power allocation (Water filling) can be applied when a carrier of the 2nd logical stream is not allocated. The additional power level on the 1st stream enhances the system's coverage. When Eigenbeamforming is applied the two logical streams are precoded in a way to achieve maximum orthogonality between the two streams. This allows transmitting two independent data streams simultaneously at identical frequencies with minimal crosstalk.

The MIMO equalizer is based on zero-forcing (ZF) detection. In case of Beamforming more sophisticated receivers do not gain additional performance. The detection matrix

$$\mathbf{W} = \mathbf{H}^{p} = \left(\mathbf{H}^{H}\mathbf{H}\right)^{-1}\mathbf{H}^{H} \tag{2}$$

of ZF detection is the pseudo inverse $\mathbf{H}^{\mathrm{P}}$ of the channel matrix **H**. In case of Beamforming with the precoding matrix **V** the detection matrix can be expressed by

$$\mathbf{W} = \mathbf{V}^{H}\mathbf{H}^{p} = \mathbf{D}^{-1}\mathbf{U}^{H}\,. \tag{3}$$

The SNR of the MIMO streams after detection is

$$\mathrm{SNR}_1 = \rho\frac{1}{\left\|\mathbf{w}_1\right\|^2} \text{ and } SNR_2 = \rho\frac{1}{\left\|\mathbf{w}_2\right\|^2} \tag{4}$$

with ρ the ratio of transmit power to noise power and $\left\|\mathbf{w}_i\right\|$ the norm of the ith row of the detection matrix **W**.

Fig. 6 shows the SNR of the 1st logical decomposed stream from an example measured in a German private home. The median attenuation of this link is 42 dB. The transmit to noise power ratio is ρ=65 dB. The blue line represents the SNR of spatial multiplexing without Beamforming and the green line Beamforming (spatial multiplexing with precoding). The optimum selection of the Beamforming matrix is achieved when SNR_1 is maximized. The SNR of the 2nd logical path is displayed in Fig. 7.

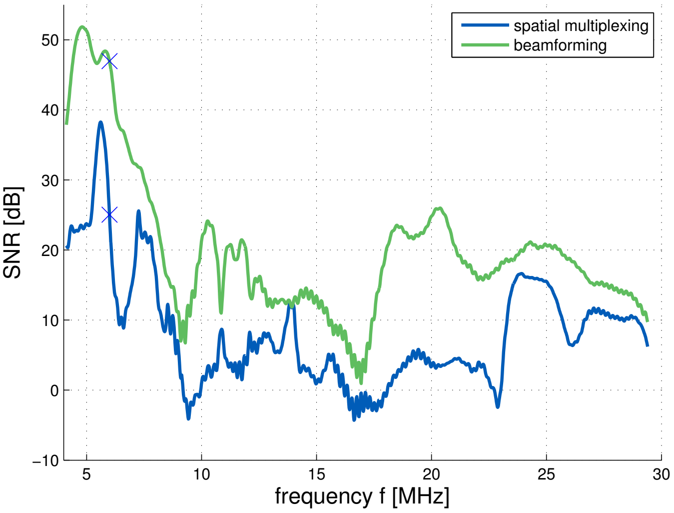

Figure 6. SNR depending on precoding on logical path 1

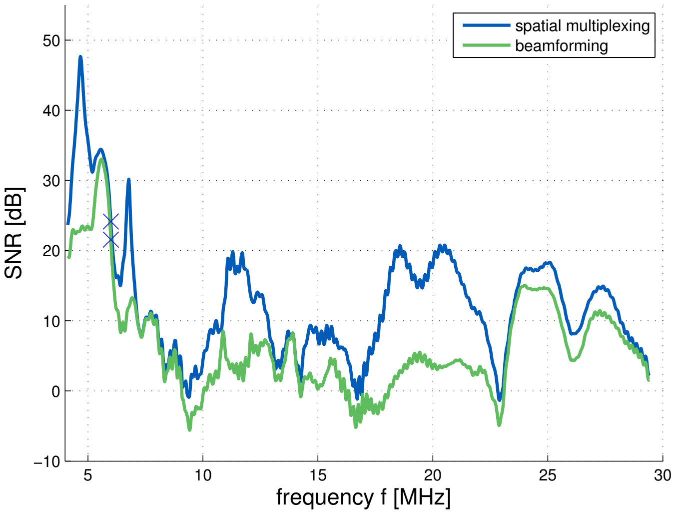

Figure 7. SNR depending on precoding on logical path 2

The two markers X in Fig. 6 and 7 mark a frequency where good Beamforming conditions are found. The unitary property of the 2x2 precoding matrix **V** allows us the description by the two independent parameters v_1 and φ_2. Note: v_1 is real.

$$\mathbf{V} = \begin{bmatrix} v_1 & -v_2^* \\ v_2 & v_1 \end{bmatrix} \text{ with } v_2 = \sqrt{1-v_1^2}\, e^{j\phi_2}\,. \tag{5}$$

Different precoding matrices influence the SNR of the two MIMO paths according to (3) and (4).

Fig. 8 and 9 show the level of the gain or signal elimination due to Beamforming for the frequency marked by X in Fig. 6 and 7. The color lines in Fig. 8 and 9 indicate the SNR. Depending on Beamforming the SNR varies between 25 dB and 47 dB. No Beamforming (v_1=1 and φ_2=0) would result in a SNR of 25 dB. As seen in one of the figures above there is one SNR maximum in the area spanned by v_1 and φ_2. Due both paths being orthogonal one shows a SNR minimum at the location where the others one has its maximum.

Beamforming has to be applied at the transmitter as well the receiver. Fig. 8 and 9 show the accumulation of both beamformings. Transmitter spot beamforming using two physical Tx paths doubles the Rx level compared to a SISO transmission in optimum case. Receiver only technologies like successive interference cancelation (SUC) [5] can not gain back the SNR lost at transmitter if Tx Beamforming is not applied. Not using Beamforming at the transmitter – implementing just spatial multiplexing – is a kind of Beamforming as well, but with an unknown beam direction (like the v_1=1 and φ_2=0 point in Fig. 8 and 9). This is why the authors of [1] found spatial multiplexing to provide less throughput performance at some channels than even SISO transmissions. Here signal elimination was achieved at receiver locations due to unlucky or uncontrolled beam direction.

Alternatively, Beamforming might be optimized to achieve signal elimination at some locations of the PLC network. Further research studies will verify if Beamforming may avoid coexistence problems inter PLC systems or to solve even EMI problems to radio applications.

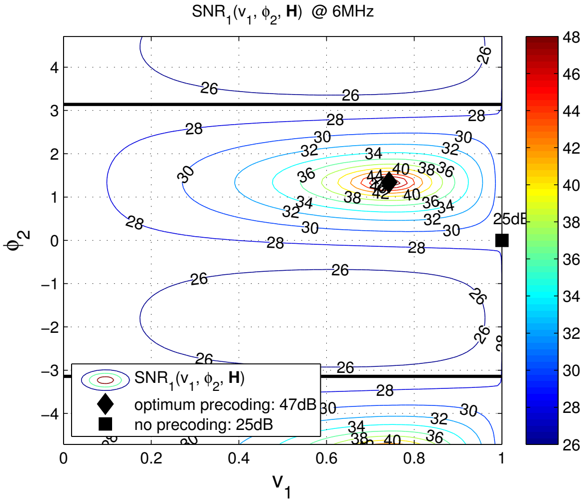

Figure 8. Beamforming gain at a channel for path 1

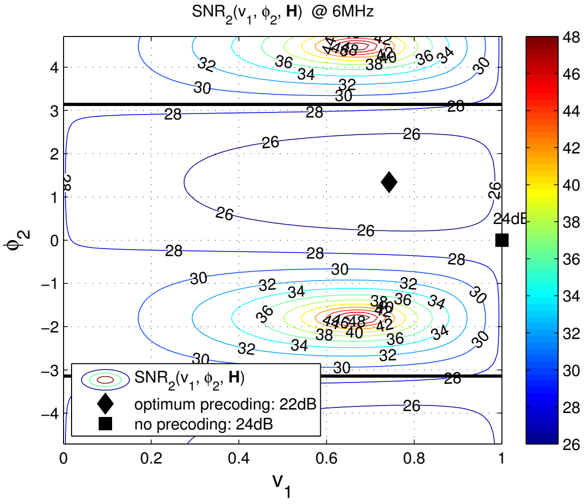

Figure 9. Beamforming gain at a channel for path 2

Not only the data symbols benefit in SNR when Beamforming is applied. The preamble of a multi-node communication network might also be beamformed. Initially the preamble is a broadcast signal that should be received by all nodes. However, channel conditions are never identical to more than one node. If multiple nodes have to listen the preamble the Beamforming shall be optimized on the link providing the worst SNR.

Beamforming requires knowledge about the precoding matrix **V** at the transmitter. This information is obtained via feedback from the receiver to the transmitter. In PLC, this feedback path already exists to transmit the constellations of adaptive modulation. [2] showed that an appropriate quantization of the precoding matrices keep the information about the Beamforming information in the same order of magnitude as the overhead required for the constellations.

V. MIMO ARTIFICIAL MAINS

The MIMO artificial mains (MAM) allows testing and debugging of MIMO PLC implementations. It is a passive channel emulator providing the possibility to adjust characteristics of the 12 paths (from Fig. 1) separately. The objective of the MAM is to provide a three conductor channel between two MIMO-modems with defined transmission parameters. The three conductors represent the phase (P), the neutral line (N) and the protection earth (PE or E).

MIMO PLC modems drive the transversal mode. Due to mode conversion in the mains (as shown in Fig. 3), there are also common mode signals at the receiving end of the network. Thus, MAM must also be able to provide common mode signals generated by defined asymmetries.

There are a great number of equivalent circuits for a three conductor plus earth network. Fig. 10 and 11 show the triple pi form. This appears to be the most natural circuit, because the admittances represent physical parameters of the modems as well as in the network. The circuits are also easy to realize. The signal may be described with three voltages between the conductors and the ground and by the three currents thru the conductors P, N and PE.

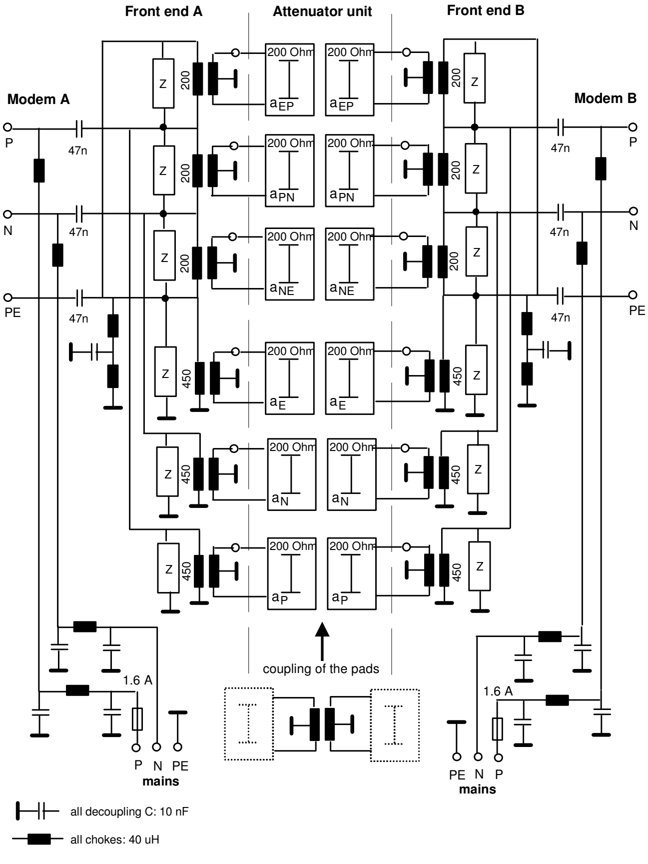

Figure 10. MIMO Artificial Mains (MAM)

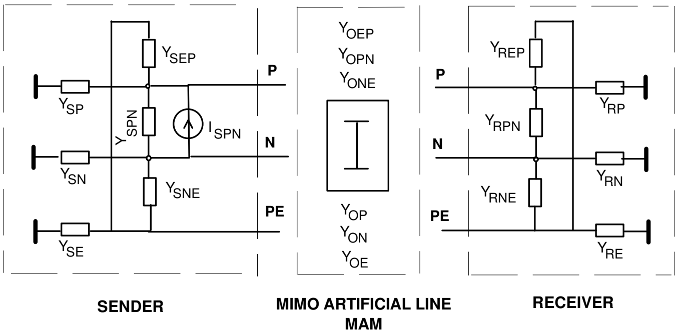

Figure 11. Triple pi equivalent circuits

A. *Impedance considerations*

The admittances of the MAM add to those of the sender and of the receiver. In the test circuit they are all taken as real (ohmic). One should always keep in mind that this is only a rough approximation to reality, nevertheless probably the best possible.

If all transverse admittances (Y_{PN}; Y_{NE}; Y_{EP}) are equal and all admittances to ground (Y_E; Y_N; Y_P) are also equal, then the system is symmetric. In this case no mode conversion takes place, i.e. if a transversal signal is injected no common mode current results. The reverse of this statement is not true. There are many possible compensations, but these have not much practical relevance.

The results of two pole impedance measurements, e.g. ETSI STF 222 [11], were used to determine the values of the admittances of the MAM circuit. With the third conductors left open, an average DM impedance of 100 Ω and an average CM impedance of 150 Ω were found. This corresponds to transverse impedances of 170 Ω and impedances to ground of 425 Ω. To simplify the construction of the MAM 200 Ω (= 4 * 50 Ω), respectively 450 Ω (= 9 * 50 Ω) were chosen. Since the spread of the impedances of the mains is extremely high, this approximation seems perfectly acceptable.

B. *Transmission loss considerations*

For the complete description of the transmission characteristics the three voltages between the conductors and earth and the three currents in the conductors are required. Thus, in principle only three attenuators are required. As the schematic diagram in Fig. 11 shows, the MAM has two times six attenuators. The split in two pads in tandem prevents leakages which may occur if the attenuation of a pad would be more than 40 dB. The transformers between the pads prevent common mode leakages.

There are three paths for the transversal signal components and three paths for the longitudinal signal components. We choose this configuration for the following reasons:

a) The three conductor voltages to ground could be set with the longitudinal paths only (a_E; a_N; a_P). Unfortunately the minimum attenuation for the transversal signals would be fairly high and the calculation of the attenuation of the transversal component rather troublesome.

b) The transversal components (set by a_{PN}; a_{NE}; a_{EP}) are of most interest, because in general the modems are connected as transversal senders. Thus it is of interest to be able to test with transversal attenuations only.

c) Modem receivers may also receive the common mode signal. With the longitudinal attenuations (a_E; a_N; a_P) the common mode component may be easily set.

The pads don't operate with matched terminations. If their attenuation is low, the precise calculation of the transmission loss becomes complex as there is interaction between input and output. If the attenuation in each path is 10 dB or more this effect may be neglected.

C. Frequency dependent transmission loss

The transmission loss of the mains is highly frequency dependent. MAM PLC makes use of the fact that the frequency responses of the three paths are divergent. The reception and analysis of all three signals results in a higher performance compared to the traditional reception of one path only. For the tests one needs such divergent frequency responses. There are two ways to realize this with the MAM:

a) Frequency dependent attenuators (a_{PN}, a_{NE}, a_{EP}, a_E, a_N, a_P)

b) Shunt two poles in the transversal paths (Z in the schematic of Fig. 10).

The MIMO PLC system implemented here utilizes the frequency range from 4 MHz to 30 MHz. The MAM is optimized for these frequencies, as well. Channel properties like attenuation, impedances or diversity are very similar to the ones found in buildings. Of course the number of fades in frequency domain depends on the number of resonance circuits connected to the pads.

VI. FUTURE WORK

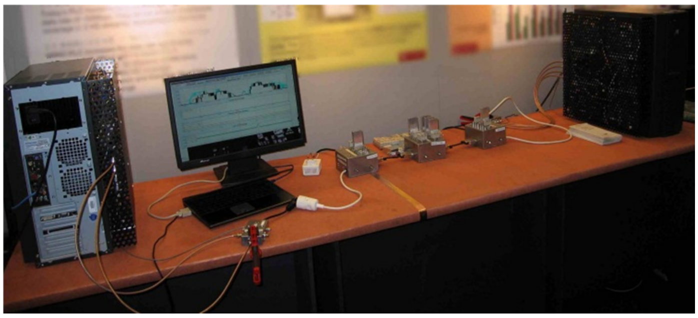

Figure 12. Hardware setup of the MIMO PLC feasibility study

A feasibility study was implemented to verify the gain of MIMO PLC compared to SISO transmissions. Fig. 12 shows the hardware setup of the study. The PC on the left side is the transmitter where two coaxial cables are connected to the PLC probe. The Tx probe is connected to the outlet of the MAM which consists of the three boxes Front End A, Attenuator Unit and Front End B. To the top of the MAM units are various filter and attenuator elements connected causing a high diversity MIMO PLC channel. From the receiving probe four coaxial cables lead to the receiving MIMO PLC modem which is implemented in the 2nd PC on the right side of Fig. 12.

Results of the feasibility study implemented at Sony will be presented in [12].

MIMO PLC inspires standardization committees today. Homeplug, ETSI and ITU-T have it on their agenda. IEEE 1901 has the freedom to enhance their physical layers with MIMO.

VII. CONCLUSIONS

The additional capacity of MIMO PLC is shown by various authors of research publications. This paper delivers the principles of the channel model including the reception of common mode signals. It gives an outlook on the upcoming regulatory discussion, shows the gain in SNR due to Beamforming and provides details about the implementation of a MIMO artificial mains. All the promising measures motivate the implementation of a MIMO PLC feasibility study which is described in [12]. This feasibility study proves an increase of transmission rate of factor 2 from SISO to MIMO.

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