MIMO Power Line Communications

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***Abstract*—Despite being a well-established ingredient to many wireless systems, *multiple input multiple output* (MIMO) signal processing has only recently been considered for broadband *power line communications* (PLC). Adapting multiple-antenna transmission and reception techniques to a wired medium such as the electrical grid requires solving a number of issues, both regarding the physics of electromagnetic transmission and the optimization of the signal processing strategies. In the last few years, significant steps were made to demonstrate the benefits of MIMO PLC and to develop the necessary hardware. As a result, MIMO PLC has been adopted in several broadband PLC specifications, precisely as part of ITU-T G.hn in Recommendation G.9963, and as part of the industry specification HomePlug AV2, which is backward compatible to IEEE 1901. This article reviews important aspects of MIMO PLC, highlighting its similarities and main differences with classical wireless MIMO. It focuses first on the peculiarities of the electrical grid, with a survey of PLC channel and noise characterization in a MIMO context. It further estimates MIMO PLC channel capacity adhering to the electromagnetic compatibility regulations currently in force. Besides, MIMO signal processing techniques most suited to PLC environments are discussed, allowing for throughput predictions. It is found that eigenbeamforming is the best choice for MIMO PLC: the full spatial diversity gain is achieved for highly attenuated channels and maximum multiplexing gain is achieved for channels with low attenuation by utilizing all spatial streams. It is shown that upgrading from a conventional *single input single output* (SISO) PLC configuration to a 2 by 2 MIMO configuration the throughput can be more than doubled while coverage is increased. The survey concludes with a review of specific MIMO PLC system implementations in the specifications ITU-T G.9963 and HomePlug AV2.**

***Index Terms*—MIMO, PLC, survey, power line communications, multiple input multiple output, ITU-T G.hn, G.9963, HomePlug, AV2, IEEE 1901.**

I. Introduction

THE target of *home networking* is to connect all digital electronic consumer devices within a home. The consumer should be able to access all services and data at any time and any place in the home, regardless of where the electronic devices are located. Wireless systems work well within a single room. However, their data throughput and reliability decrease dramatically if the wireless signal has to pass through walls or ceilings especially when made of concrete with metal reinforcements [1], [2]. To enable real broadband throughput for 'room-to-room' connectivity, an in-home backbone network that connects individual devices or clusters in the house with minimum installation effort is desirable. PLC fulfills these requirements. However, common place *single input single output* (SISO) PLC systems as treated in detail in [3] might lack in coverage, especially on long links in large homes. Here, the utilization of the third wire in conjunction with *multiple input multiple output* (MIMO) signal processing is capable of boosting coverage and capacity of the PLC transmissions.

MIMO systems have been heavily investigated since the mid nineties, targeting primarily wireless communications [4], [5]. Nowadays, different MIMO processing options, with the aim of increasing data rates and communication reliability, are in operation in major wireless cellular systems such as UMTS, LTE, WiMAX, as well as wireless local area networks (WLANs) based on IEEE 802.11n [6], [7].

Also, *digital subscriber line* (DSL) systems have to deal with near-end and far-end crosstalk between individual modems and recent developments treat the DSL cable binders as MIMO communication channels with the aim of applying multi-user coordination and interference mitigation techniques, also called *vectoring* [8], [9].

Irrespectively, the power line channel has for a long time been regarded as dual conductor SISO channel. In reality, many *in-home* installations make use of three wires, and medium, and high voltage installations often have four or more conductors. Although the theoretical foundation of multiconductor transmission line theory was extensively laid out in the last century [10], first large scale public measurement results on MIMO power line channel and noise characteristics became only available in 2008 [11]. In 2010, ETSI[1] *Specialist Task Force* (STF) 410 was launched to collect all kind of MIMO channel properties in several European countries. The measurement campaign and experimental results are documented in the technical reports [12]–[14].

To make *broadband power line communication* (BB-PLC) systems economically viable on a world wide scale, internationally adopted standards became essential. The *International Telecommunications Union - Telecommunication Standardization Sector* (ITU-T), as well as the *Institute of Electrical and Electronics Engineers* (IEEE) commenced work on such next generation standards, namely *ITU-T G.hn* [15]–[17] and *IEEE 1901* [18], [19]. Although first released as SISO standards, in 2011 the ITU published a MIMO transceiver extension (G.9963, [20]) to its G.hn standard family. Simultaneously, the *HomePlug Powerline Alliance* introduced MIMO signal processing as part of the HomePlug AV2 specification [21], [22], which is fully backward compatible to millions of IEEE

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[1]The *European Telecommunications Standards Institute* (ETSI) is an independent non-profit standardization organization formed by equipment makers, network operators, and other stakeholders from telecommunications industry.

1901 modems already operating in the field.

This survey reviews MIMO channel and noise aspects in Section II, before introducing essentials of *electro magnetic compatibility* (EMC) and MIMO signal processing in Section III and Section IV, respectively. Section IV also presents throughput estimates based on measurements obtained by ETSI STF 410 and addresses hardware implementation aspects with respect to MIMO signal processing. This survey is rounded off by a comparative analysis of MIMO in ITU-T G.hn and HomePlug AV2 in Section V and an overview of MIMO PLC research challenges in Section VI. Also noteworthy is the complementary source of PLC related literature: IEEE ComSoc *Best Readings in Power Line Communications* [23].

II. Channel and Noise Characteristics

Before looking at channel and noise characteristics in particular it is important to have an idea of power line topologies and coupling methods. The very principle of power line communications implies that small-signal, high-frequency technologies are being deployed over power-carrying cables and grids that were designed for electricity transmission at low frequencies. Couplers are used to connect the communications equipment to the power line. Besides, grid topologies are possibly the most important stage-setter for overall channel and noise properties.

A. Topologies

Power lines are frequently characterized according to their voltage levels, as *high voltage* (HV, 110 kV to 380 kV), *medium voltage* (MV, 10 kV to 30 kV) and *low voltage* (LV, 110 V to 400 V) lines [24]. Communication properties of HV and MV installations are assessed in [25]–[28] and [29]–[32], respectively. However, deployment of MIMO signal processing to HV and MV lines has up to the present day been limited. This might be explained by the fact that coupling broadband MIMO signals into and out of these lines is costly, and in many cases alternatives such as fiber optical backbone links or *wide area networks* (WANs) are already in place posing a fierce competition [33], [34]. Turning to LV topologies, they can further be subdivided into a *distribution* or *access* part, running from an MV-LV transformer up to individual buildings [35]–[38], and an *in-home* part [37], [39]–[44], where the LV lines run in a tree or star topology up to the different power sockets in every room. For single phase in-home installations, three wires, namely *live* (L) (also called *phase*), *neutral* (N), and *protective earth* (PE), are common. Exactly how common on a worldwide scale was investigated by ETSI in [12]. It may be concluded that the PE wire is present at all outlets in China and the Commonwealth of Nations, at most outlets in Western countries, and only at very few outlets in Japan and Russia.

B. Coupling Methods

Turning to power line couplers, one may generally distinguish between *inductive* and *capacitive* implementations. Inductive couplers guarantee a balance between the lines whereas capacitive couplers often introduce asymmetries due to component manufacturing tolerances. Couplers especially tailored to MV, and HV can be found in [45]. Further, details on low voltage inductive SISO couplers may, for example, be found in [46] and [47]. The following will focus on LV inductive MIMO coupling options as presented in Figure 1, *i.e.* a *delta-style* coupler [48], a *T-style* coupler [49], and a *star-style* coupler [48].

Coupler designs are tightly related to radiated emission. According to the *Biot-Savart law* the main source of radiated emission is the *common mode* (CM) current. To avoid radiated emission, usually PLC modem manufacturers aim at injecting the signal as symmetrically as possible. This way, 180°out of phase electric fields are generated that neutralize each other resulting in reduced emission. This desired symmetrical way of propagation is also known as *differential mode* (DM). In case of asymmetries, *e.g.* caused by parasitic capacitances on the network, a small part of the differentially injected current turns into CM current. Normally, there are many asymmetries inside a PLC topology. For example, an open light switch causes an asymmetric circuit and, hence, even if only DM is injected, DM to CM conversion may occur [50].

Specifically, to avoid additional CM currents at the source, feeding MIMO PLC signals can be done using the delta or T-style couplers, while it is not recommended using the star-style coupler - also known as *longitudinal coupler*. As shown in Figure 1, the delta-style coupler, also called *transversal probe*, consists of three baluns arranged in a triangle between L, N and PE. The sum of the three voltages injected is zero (following Kirchhoff's law). Hence, only two of the three signals are independent. Turning to the T-style coupler, it feeds a differential mode signal between L and N, plus a second signal between the middle point of L-N to PE. Further details on the pros and cons of each coupler type may be found in [12].

All three types are well suited for reception. However, especially the star-style coupler is interesting, where again Kirchhoff's law forces the sum of all currents arriving at the center point to zero. Thus, only two of the three received signals are independent. Nevertheless, due to parasitic components the signals at the third port may additionally improve the capacity of a MIMO PLC system. A more significant benefit is, however, the possibility to receive CM signals, *i.e.* a forth reception path. The CM transformer is magnetically coupled (Faraday type coupling). On average, CM signals are less attenuated than DM signals which makes their reception interesting especially for highly attenuated channels [48].

As an example configuration, assume that the delta-style coupler is used at the transmitter to feed the input ports D_1 and D_3, and that the star-style coupler is used at the receiver to receive from the output ports S_1, S_2 and S_4. The resulting MIMO PLC channel is shown in Figure 2 with $N_T = 2$ *transmit* (tx) and $N_R = 3$ *receive* (rx) ports, resulting in overall 6 tx-rx paths.

C. Channel Characterization and Modeling

Power line channel characteristics heavily depend on the topologies and coupling strategies used, and, hence, span a

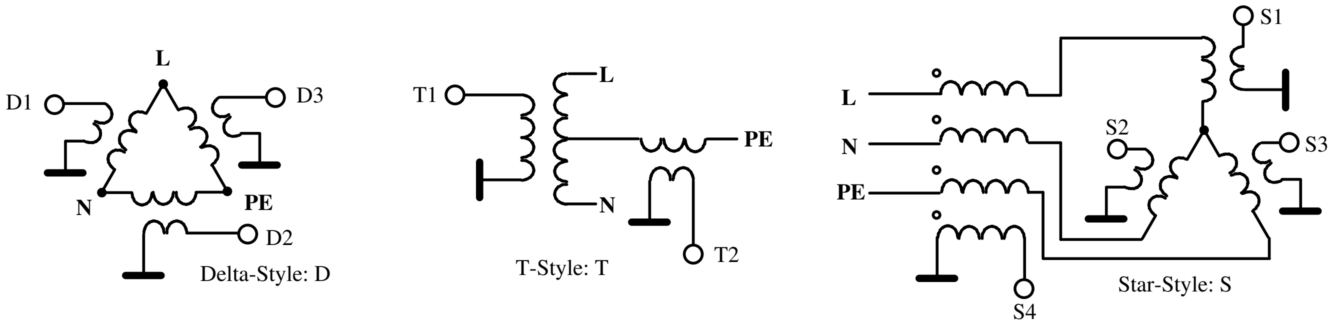

Fig. 1. Inductive MIMO PLC couplers.

very large range. Generally, the PLC channel exhibits *frequency selective multipath fading*, *low-pass behavior*, *cyclic short-term variations*, and *abrupt long-term variations*.

Channel characterization and modeling are tightly interrelated. Characterization through measurements is indispensable to derive, validate and fine-tune the models, while the models themselves often provide valuable understanding and insight that stimulates more advanced characterization. In general, PLC channel models can be grouped into *physical* and *parametric* models (also referred to as *bottom-up* and *top-down* models [51]). While physical models describe the electrical properties of a transmission line, *e.g.* through the specification of the cable type (line parameters), the cable length and the position of branches [49], [52]–[55], parametric models use a much higher level of abstraction from the physical reality, and describe the channel, for example, through its impulse response or transfer function [36], [56], [57]. Further, within each group it can be distinguished between *deterministic* and *stochastic* models. While deterministic models aim at the description of one or a small set of specific reproducible PLC channel realizations, stochastic models aim at reflecting a wide range of channel realizations according to their probability of occurrence.

Turning specifically to MIMO channels, one of the first public *parametric-deterministic* investigations of MIMO signal processing for broadband in-home PLC appears in [11], [58]. Similar field measurements are conducted in [59], [60]. Following this trend, experimental channel characterization have been conducted in [48], [61]–[63]. Among the published results, [59], and [60] conclude that the application of 2×2 MIMO signal processing to in-home PLC provides a capacity gain in the order of 1.9. Further, [11] shows that this gain ranges between 1.8 and 2.2. in a 2×3 MIMO configuration. When adding CM reception, *i.e.* in a 2×4 configuration, average gains between 2.1 and 2.6 are observed. Along these lines, MIMO capacity results can be found in Section III. In [61] and [62] a number of channel parameters are assessed including the average attenuation *versus* frequency, the channel delay spread, the coherence bandwidth and the correlation among tx and rx ports. It is worth noting that the correlation between MIMO subchannels is uniformly distributed in $[0, 1]$ [62]. Hence, some channels exhibit a low degree of diversity when considering different tx and rx ports. However, unlike wireless channels, transmission over electrical networks enjoys high values of *signal to interference plus noise ratio* (SINR). As a result, the application of MIMO to PLC provides significant capacity gain, even in highly correlated channels, as will be seen in Section III-F. So far, the largest published MIMO PLC field measurement campaign is provided by the ETSI STF 410 [12]–[14], gathering measurements from six European countries. Using these measurements, channel attenuation and cable input impedance were statistically characterized [63], [64]. Table I provides a summary of the main MIMO PLC channel characteristics extracted from the aforementioned parametric-deterministic investigations [14], [61], [62].

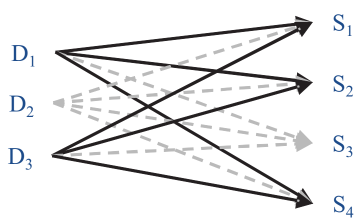

Fig. 2. Tx and rx coupler port connections forming a 2×3 MIMO system.

Only a few proposals for *physical-deterministic* MIMO channel models have been made so far. The most straightforward bottom-up approach is to apply *multi conductor transmission line theory* (MTL) [10], [65]. As reflected in Figure 3, MTL theory can be applied to compute the currents $i_1(x,t)$, $i_2(x,t)$ and $i_3(x,t)$ flowing in a 3-wire transmission line as well as the corresponding differential voltages $v_1(x,t)$, $v_2(x,t)$ and $v_3(x,t)$ for a given line position x and a given time t. To do so, many per-unit length line parameters, as indicated on Figure 3, need to be either measured or theoretically computed. Note that some authors consider a simplified model with three conductors, where the PE wire is assumed to be equivalent to the ground [66]. At high frequencies this assumption is not valid, especially when the reception of CM signals is expected. In such cases, a more complete model with a separate ground potential is necessary to provide accurate results.

The physical-deterministic MTL modeling approach has been used for in-home LV electrical networks in [49], [54], [67], and for overhead MV and HV networks in [68]. However, these studies do not consider the use of three electrical wires for the purpose of MIMO communication.

The first use of the MTL theory to explicitly model a MIMO

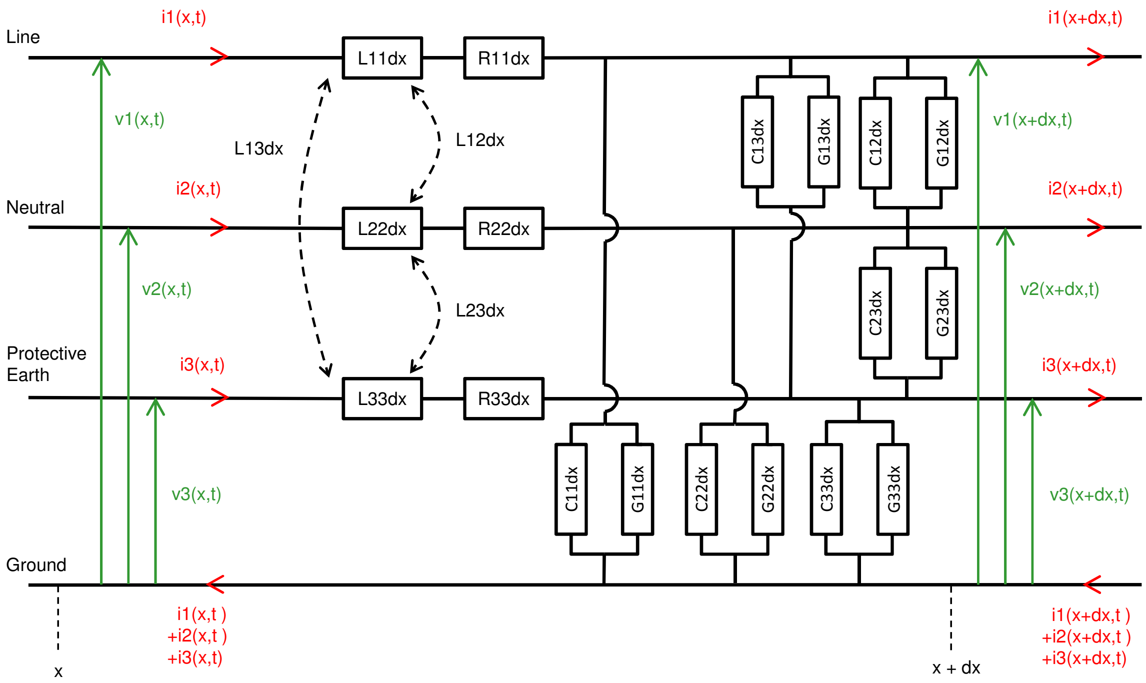

Fig. 3. MTL theory: equivalent circuit of a per-unit length section of a 3-wire transmission line.

PLC channel in a *physical-stochastic* approach appears in [66], [69]. The work therein extends a physical-stochastic SISO channel model presented in [70] by recomputing the MTL equations in the case of three conductors. Using a stochastic topology generator [70], it is then possible to produce MIMO channel realizations of random electrical networks.

On the other hand, a *parametric-stochastic* approach has been applied by several research teams to devise models of the MIMO PLC channel. The first attempt is described in [71]. This study considers a 2×4 MIMO channel, where two differential input ports can be addressed simultaneously, and up to 4 rx ports are considered, including the common mode path. The model first considers a SISO PLC *channel impulse response* (CIR) composed of 5 to 20 taps according to the model defined within the European R&D project OPERA [72]. It then builds the 2×4 MIMO channel by producing 8 variants of this CIR. Each of the variants has the same tap structure, but the amplitudes of some of these taps are multiplied using different random phases uniformly drawn from the interval $[0, 2\pi[$. The more taps are modified the more uncorrelated the channel becomes. The model produces MIMO channels that exhibit similar frequency fading structures as observed in the measurements in [11]. The same approach is further developed in [62], where a 3×3 MIMO channel model has been designed to fit observations from a measurement campaign in France. The proposed MIMO channel model builds on the SISO channel model first defined by Zimmermann [36], and later extended by Tonello by providing complementary channel statistics [73]. An example of measured as well as simulated *channel transfer functions* (CTFs) is given in Figure 4 (a) and (b) respectively, where similarities between measured and parametric-stochastic CTFs become evident.

An alternative *parametric-stochastic* approach based on a mathematical description of the MIMO channel covariance matrices as introduced in [74] is presented in [75]. The study is based on measurements recorded in five North American houses and allows very straight forward reproduction of the MIMO channel's correlation properties.

Table II provides a comparison between the different PLC channel modeling options introduced. Each of the four exists in its own right and bears advantages and disadvantages when it comes to specific applications. Hence, channel model selection has to be carried out on a case by case basis.

D. Noise Characterization and Modeling

Turning to the noise characterization, one should note that in contrast to many other communication channels the noise on a power line cannot be described as *additive white Gaussian*

TABLE I
MAIN CHANNEL CHARACTERISTICS.

Parameter	Value	Source
Attenuation [range] and (median)	[10, 100], (53) dB	[14]
Attenuation vs. frequency slope	0.2 dB/MHz	[14], [61]
Relative attenuation for different reception ports	CM port provides least attenuation for difficult channels	[14]
RMS delay spread	0.2 μs to 2.5 μs	[61]
	0.02 μs to 1.2 μs	[62]
Coherence bandwidth, 90%	$<$ 3 MHz	[62]
Input impedance [range] and (median)	L-N: [10, 190], (86)Ω L-PE: [10, 190], (89)Ω N-PE: [10, 190], (87)Ω	[14]
Correlation	approx. uniform in interval [0, 1]	[62]

Note: Measurement bandwidths differ from 1-100 MHz in [14] to 2-150 MHz in [62] and 0-88 MHz in [61].

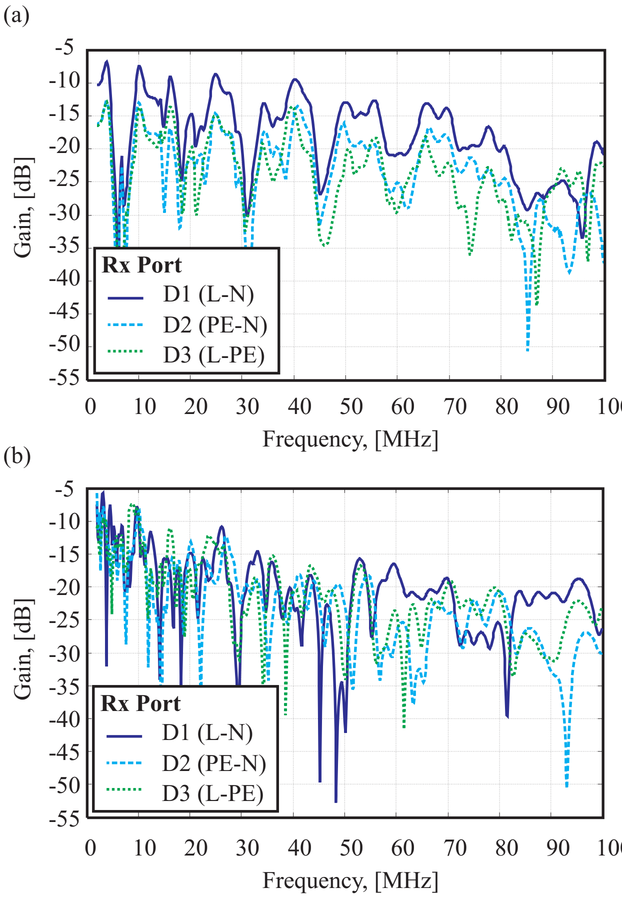

Fig. 4. MIMO PLC CTF examples. (a) CTF measured within an experimental measurement campaign in France [60]. (b) CTF simulated using the MIMO PLC channel model of Hashmat *et al.* [62]. All results are only shown for tx port D1 (L-N).

noise (AWGN). Instead, it can be grouped based on temporal as well as spectral characteristics. Following, for example, [14], [37], [76] one can distinguish *colored background noise*, *narrowband noise*, *periodic impulsive noise* (asynchronous or synchronous to the AC frequency), as well as *aperiodic impulsive noise* [77], [78].

Specifically, with respect to the MIMO noise situation, only a few modeling proposals have been made so far. For example, [79]–[81] are developing models of background noise on the basis of experimental time domain noise measurements in five houses in France, and are mainly targeting a reproduction of the frequency domain noise characteristics. In [80], the measurements are compared against two parametric SISO background noise models, namely the Emsailian model [42], and the OMEGA model [82]. The models are fitted to the noise received on each of the MIMO rx ports, and statistics of the model parameters are derived separately for each rx port. In [81], the MIMO noise is regarded as a *multivariate time series* (MTS), which allows to capture both the intrinsic characteristics of the noise received on each port, but also their cross-correlation. The noise MTS is then modeled using an auto-regressive filtering procedure. The modeled noise *power spectral density* (PSD) presents a high degree of similarity with the experimental observations. However, the model leaves room for improvements, especially considering its ability to reproduce sporadic time domain events, such as impulsive noise. Figure 5 (a) presents an example of measured noise from the ETSI STF 410 measurement campaign, along with the corresponding simulated background noise samples using the MTS model from [81] in Figure 5 (b). Along the same lines, [83] presents MIMO noise measurements and statistical results based on the ETSI STF 410 data. It is observed that the CM (S4) signal is affected on average by 5 dB more noise than the differential mode signals received on any wire combination. This difference can be explained by the higher sensitivity of the CM signal to interference from external sources, such as radio broadcasting. Moreover, it is observed that the S1 (L), S2 (N) and S3 (PE) ports present similar noise statistics. However, when considering large noise records (5% percentile), one can observe that the PE port is more sensitive to noise by approximately 2 dB than the N or L ports. Similarly, for low noise levels (95% percentile), the L port is less sensitive to noise by approximately 1 dB than the N or PE ports.

Alternatively, [84] addresses MIMO noise based on experimental measurements collected in the US. It is shown that the noise is correlated on the D1 (L-N), D2 (PE-N) and D3 (L-PE) receive ports, with the strongest correlation measured between the L-PE and N-PE receiver ports. Moreover, the correlation decreases for increasing frequencies and it is shown that noise correlation helps to increase MIMO channel capacity.

Besides all these initial efforts to characterize and model PLC noise specifically with respect to MIMO systems, a number of properties still need to be investigated and modeled. In particular, the occurrence of impulsive noise, its time domain variations, and the correlation of noise pulses observed on different rx ports requires further analysis. Note that the noise structure is rather specific for power line transmission as compared to classical wireless communication, which re-

TABLE II
COMPARISON OF CHANNEL MODELING OPTIONS.

Feature	**Physical-deterministic**	**Physical-stochastic**	**Parametric-deterministic**	**Parametric-stochastic**
Modeling principle	electromagnetic transmission theory	electromagnetic theory & topology generator	playback of experimental measurement parameters	statistical fit to experimental measurement parameters
Measurement requirements	none	none	large data base	large data base
Topology knowledge	detailed	detailed stochastic models	none	none
Complexity of model design	medium	high	low	medium
Complexity of channel generation	high	high	very low	low
Correlated multi-user studies	straight forward	straight forward	straight forward	difficult
Closeness to experimental data	accurate for considered topology	on a statistical basis	exact	on a statistical basis
Ability to extrapolate	yes	yes	no	no

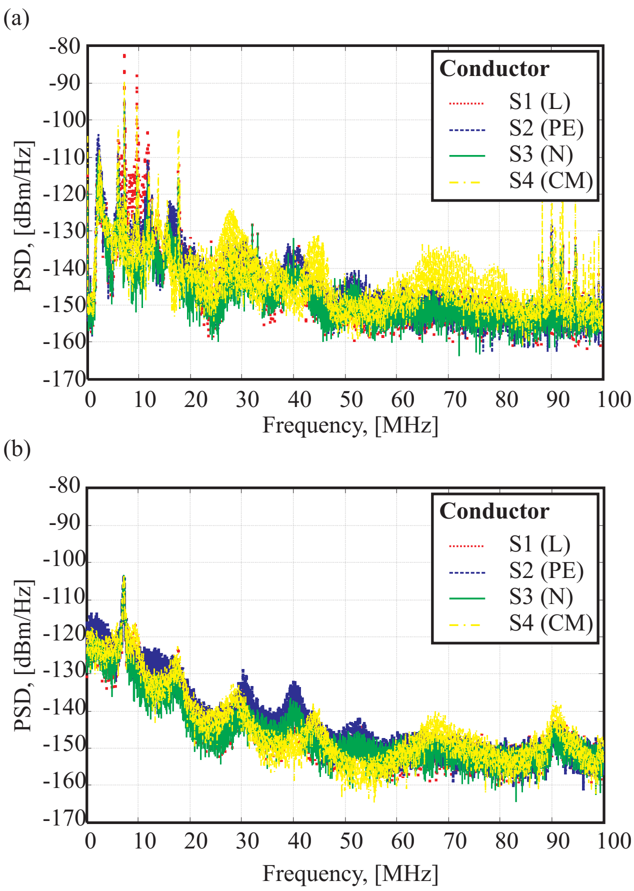

Fig. 5. MIMO PLC background noise examples. (a) Background noise measured within the ETSI STF 410 measurement campaign [14]. (b) Corresponding background noise simulated using the MIMO PLC channel model of Hashmat *et al.* [81].

quires implementing dedicated signal processing strategies. For instance, adaptive modulation is particularly suited to deal with unequal noise power spectral density. Further, the correlated nature of the noise received at different ports is usually mitigated using whitening filters. Finally, coding and retransmission are employed to handle different types of occurring noise. These aspects are further developed in Section IV.

III. EMC REGULATIONS AND MIMO CAPACITY

With respect to broadband EMC regulations, one may distinguish two frequency ranges, *i.e.* 1 MHz to 30 MHz, where according to CISPR 22 [85] conducted emission is at the focus of regulation, and 30 MHz to 100 MHz, where the focus shifts to radiated emission. Regulation is region or country specific, and the following outlines regulations for the important BB-PLC markets *Europe* (EU), *United States of America* (US), and *Japan* (JP).

A. European Regulations

For Europe BB-PLC EMC regulations are laid out by CENELEC[2] in EN 50561-1:2013 [86], which refers to PLC as *powerline telecommunication* (PLT). In particular, the following features are described:

- An EMC emission measurement procedure at the PLT port while no communication takes place.
- A second emission measurement procedure at the PLT port when normal communication takes place.
- A general limitation on the injected PSD of -55 dBm/Hz.
- Permanent notching of certain parts of the radio spectrum, *i.e.* related to amateur radio and aeronautical bands.

[2]Comité Européen de Normalisation Électrotechnique, in English: European Committee for Electrotechnical Standardization

- A procedure for adaptive notching, meaning that the PLC equipment senses the presence of radio services, and notches the affected frequencies for its own operation (also documented in [48] and specified in [87]).
- A procedure of adaptive transmit power management, meaning that the transmitting equipment limits its transmit power as a function of channel attenuation and noise to a level below the allowed maximum, that is just sufficient to achieve the required data rate.

More specifically, [86] limits the maximum PLC transmit signal level between 1.6065 MHz and 30 MHz. Furthermore, CENELEC started drafting an EMC standard for frequencies above 30 MHz, following a decision from the CENELEC TC 210 meeting in December 2012 [88]. The standard is not yet finalized and for the purpose of generating simulation results - presented later in this article - a 30 dB reduction is assumed with respect to the feeding levels below 30 MHz.

B. *US Regulations*

In the US, [89] and [90] specify how emissions from PLC devices are evaluated. The documents refer to PLC as *broadband over power lines* (BPL) and consider it as a *new type of carrier current technology*. The emission limits are given in a radiated field strength depending on the frequency and distance from the exterior wall of the building [91].

Similarly to the European regulations, notches are additionally required to protect *aeronautical mobile* and *radionavigation* services. In some geographical zones extra frequencies have to be excluded, and care must be taken not to disturb public safety services. Adaptive interference mitigation techniques are also described. A wrap up of regulations on RF emissions from power line communication systems in the US may be found in ITU Recommendation SM.1879-1 [92].

C. *Japanese Regulations*

The Japanese regulations for PLC transmissions in the high frequency band apply to the common-mode current measured at the mains port of a PLC modem. The specified measurement methods are similar to the concept of the CISPR 22 telecommunication port measurements [85]. An *impedance stabilization network* (ISN) [92] is defined by the electrical properties measurable from the outside. These are the *symmetry*, the *differential mode impedance*, Z_{DM}, and the *common mode impedance*, Z_{CM}. The modem's communication signals are assessed by measuring the CM current converted by the ISN from the symmetrically fed signals. However, the selected values of the ISN are not typical for Japanese buildings. As a result of the selected measurement procedure, the maximum allowed feeding level is significantly reduced and shows a high uncertainty depending on the size of the modem under test. Furthermore, the limits of the frequencies below and above 15 MHz differ by 10 dB. A typical PLC modem with the size of a human fist may inject -71 dBm/Hz below 15 MHz and -81 dBm/Hz above. In similarity to European and US regulations, Japan omits frequencies of radio amateurs and some Japanese radio broadcast stations. Further, any PLC transmissions above 30 MHz is not envisaged.

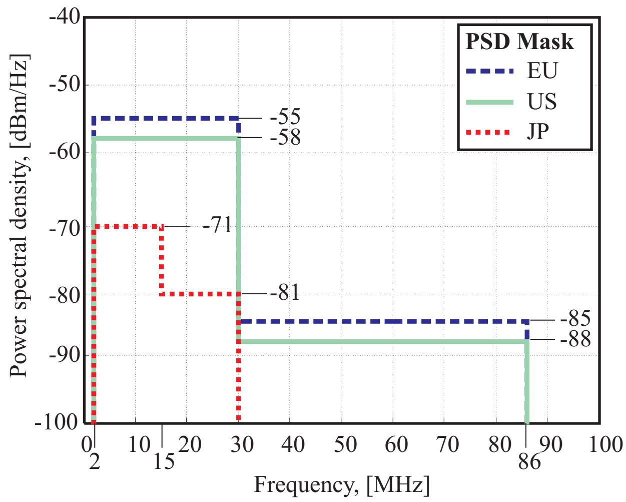

Fig. 6. Transmit PDS masks. Note, the EU limit above 30 MHz is subject to pending regulations.

D. *MIMO Specific Regulations*

EMC regulations available today do not explicitly consider the injection of MIMO signals. In the process of establishing specific regulations for MIMO PLC transmission, the following elements should be considered. Regulatory documents have to be written in a technology neutral way not favoring any feeding style. MIMO PLC modems are not broadly available today and the selected coupler (see Figure 1) affects the radiation potential. In the case of simultaneous injections into multiple wires, accumulation of individual feedings has to be assessed. A radiated emission test may be used for this purpose. However in the frequency range below 100 MHz it is difficult to create a homogeneous field in an anechoic chamber. E-field measurement equipment is not specified to operate below 30 MHz. A conducted test setup has to verify the interference potential of the selected coupler in a fair way.

E. *Average Feeding Level Comparison*

Permissible PLC feeding levels heavily affect achievable throughput rates. In order to compare the potential of the PLC systems installed around the world Figure 6 introduces the US, EU and JP PSD masks. The transmit level is frequently described using a power spectral density in dBm/Hz. Technically a PSD in dBm/Hz cannot be measured (even if many spectrum analyzers provide results using this unit) because the PSD is the *power* (P) in an infinitely small *bandwidth* (BW), *i.e.* the derivation $\delta P/\delta BW$. If the bandwidth becomes infinitely small the question which measurement detector is applied becomes obsolete, as there is no more variance in the signal. However, simultaneously the measurement time goes to infinity. The levels in Figure 6 relate to the *average detector* after converting them to an identical resolution bandwidth. Detailed calculations of the PLC feeding levels may be found in [93].

F. *MIMO Channel Capacity*

Using the feeding levels from Figure 6 together with the ETSI STF 410 measurement data [14], allows to predict

TABLE III
CHANNEL CAPACITY AND CAPACITY GAIN AT HIGH COVERAGE POINT FOR DIFFERENT TRANSMIT POWER MASKS

MIMO configuration	EU mask Mbit/s	EU mask gain	US mask Mbit/s	US mask gain	JP mask Mbit/s	JP mask gain
1×1	82		62		6	
1×2	126	1.55	103	1.65	23	3.63
1×4	173	2.12	143	2.30	34	5.37
2×2	153	1.87	121	1.94	23	3.52
2×4	235	2.88	190	3.05	41	6.35

MIMO PLC channel capacity as summarized in Table III. For better comparison among individual feeding PSDs, country or region specific notches are not applied. The noise is recorded with an average detector using a resolution bandwidth of 9 kHz. The capacity results in Table III take into account noise correlation by calculating an *equivalent channel matrix* with the help of a noise whitening filter [84], [94]. 'Capacity' refers to the ideal maximum Shannon capacity making full use of the equivalent channel eigenmodes [95]. The channel matrix may be decomposed by means of a *singular value decomposition* (SVD) into parallel and independent channels (see also Section IV) where the MIMO capacity is the sum of the capacity of the individual channels. The capacity values can therefore be seen as an upper bound that will not be reached in normal real world implementations. Particularly, Table III shows the channel capacity at the high coverage point of 98%, *i.e.* 98% of the measured channels exceed the bitrate provided. This focus on the high coverage point is motivated by the fact that for PLC applications it is most challenging to achieve a guaranteed minimum bitrate for all links within the home, while a highly reliable network is key to broad user satisfaction.

The *single input multiple output* (SIMO) configurations with only one transmit port already offer a significant gain. The most complex investigated SIMO scheme, 1×4, increases capacity by a factor of 2.12 (EU mask), 2.3 (US mask) and 5.37 (JP mask) compared to SISO. The explanation for the different gains depending on the applied mask is simple: the higher the tx power mask limits, the higher the obtainable SINR. However, at higher SINR an SINR-gain from SIMO processing is mapped less efficiently to capacity due to an implicit logarithmic relationship between SINR and capacity. Hence, using the least stringent EU mask leads to much less SIMO gains than using the most stringent JP mask.

In contrast, the dual stream configuration 2×2 MIMO provides less gain *e.g.* with gain factors of 1.87, 1.94 and 3.52 for the EU, US and JP mask, respectively. The second, weaker stream (exploiting the weaker eigenmode) does not contribute much in low SINR situations. Here it is more important to collect all the available signal energy at the receiver, which is optimized as the number of receive ports increases. Only when turning to the 2×4 MIMO configuration, the use of a second stream also makes sense, where now the combination of a high number of receive ports with dual stream transmissions leads to gains of 2.88, 3.05 and 6.35 for the EU, US and JP mask, respectively. Note that the aforementioned bitrate increases when applying the Japanese power mask are hypothetical, because the 3rd wire rarely exists in Japanese in-home installations. In most Japanese buildings only a 1×2 SIMO configuration is feasible, as, in addition to differential mode reception, the reception of the common mode is possible independently of the existence of a protective earth wire.

Limiting the investigation to EU and US masks only and focusing this time on the median point (50%, not shown in Table III), 2×2 MIMO provides a capacity gain of around 1.71, which is surpassed by a gain of around 2.16 when going to 2×4 MIMO. This demonstrates that the MIMO gain in the high coverage area is even higher than for the median case.

It may be concluded that - with a sufficient number of receive ports - multi-stream transmission improves good as well as difficult links, making MIMO a promising method for meeting ambitious throughput as well as coverage requirements. It should, however, be noted that real world hardware implementation and complexity constraints may significantly limit the achievable gain as outlined in more detail in the following sections.

IV. MIMO PLC SIGNAL PROCESSING

When considering MIMO processing, one generally has to distinguish between *open-loop* and *closed-loop* systems. The earlier do not exploit channel knowledge at the transmitter, the later do. Generally, the benefits to be obtained from MIMO signal processing may be (i) reduction of SINR variance (diversity gain), (ii) increase of SINR mean (in the wireless world know as beamforming gain or antenna gain) and (iii) the increase of simultaneous transmitted data streams, known as spatial multiplexing gain and made possible through co-stream interference suppression and/or cancellation. Dependent on the deployed scheme, different blends of these benefits are realizable. In this respect, a comprehensive MIMO literature review, specifically taking into account the wireless domain, can be found in [5].

Current BB-PLC systems are all using carrier modulation, either based on conventional *orthogonal frequency division multiplexing* (OFDM) [96] or on *Wavelet-OFDM* [97]. These carrier modulation schemes are flexible when it comes to implementing notching requirements as introduced in Section III and allow to deal with a frequency selective broadband channel with colored noise as a set of frequency flat fading narrowband channels/carriers, the condition being that the carrier spacing is small compared to the channel's coherence bandwidth. Compared to conventional OFDM, Wavelet-OFDM has the advantage of lower spectral leakage which alleviates the implementation of notches [98]. On the other hand, the relatively high spectral leakage of conventional OFDM might be improved by Windowed-OFDM [99]. Under both options the data rate is adjusted to the carriers' SINR. This adaptation requires in a broad sense *channel state in-*

formation (CSI) at the transmitter. Hence, all current BB-PLC systems are inherently *closed-loop*. As a consequence, and apart from special situations where CSI cannot be easily exploited, *e.g.* it is not yet obtained, it is too quickly outdated, or in a broadcast/multicast situation, pure open-loop tx diversity schemes make little sense. Hence, the following directly discards popular open-loop space-time and space-frequency diversity schemes like *space-time block codes* (STBCs) [100], and space-time Trellis codes (STTCs) [101], acknowledging, however, that their derivatives have been considered for MIMO PLC in [102]–[110]. A performance comparison of the famous STBC Alamouti scheme [100] and spatial multiplexing applied to MIMO PLC can be found in [11]. It is shown that the Alamouti scheme does not achieve the performance of spatial multiplexing.

Another important aspect - as already pointed out in the capacity evaluation - is that the obtainable SINR per carrier is generally high. This leads to frequent use of higher order modulation (*e.g.* up to 4096 *quadrature amplitude modulation* (QAM)), which are characterized through a less than linear SINR to throughput relation, *e.g.* a 3 dB SINR increase leads to less than twice the throughput. This loss in power efficiency for higher order QAM means however that lots can be gained through the deployment of MIMO signal processing schemes that target benefit (iii) *i.e.* the increase of simultaneous data streams [111]. Schemes that exploit benefit (iii) are generally referred to as *spatial multiplexing* and can be *open-loop*, like the famous *Bell Laboratories Layered Space-Time* (BLAST) scheme [112]. Combining benefit (iii) with *closed-loop* CSI one may additionally exploit benefit (i) and (ii) *i.e.* a reduction of SINR variance and an increase of SINR mean.

While all previous considerations deal with the benefits of MIMO signal processing for a single transmitter-receiver pair, MIMO can also be exploited to simultaneously transmit different data streams to different receivers which in the wireless world is known as *multi-user MIMO*. Multi-user MIMO for PLC systems is for example explored in [113]. It is found that only a marginal total throughput gain is achieved for the scenario of one transmitter sending to several receivers compared to single user MIMO. The main reason is the limited number of transmit ports (2 for the in-home scenario, see Section II) and the spatial correlation. However, a performance gain may be achieved for the distributed scenario of several transmitter-receiver pairs. Further, [114], [115], and [116] consider signal processing to enhance multi-user and multi-hop performance. The following however leaves multi-user aspects at a sideline, with the aim to provide a clear focus on current single user MIMO signal processing.

A. Received Signal Model

The following assumes a conventional OFDM system. Nevertheless, most of the MIMO signal processing considerations are equally applicable to Wavelet-OFDM. For simplicity, a frequency domain signal model is presented, not showing *inverse fast Fourier transform* (IFFT), nor *fast Fourier transform* (FFT) stages that constitute standard elements in any OFDM tx-rx chain. For brevity, the mathematical formulation does not show any carrier index either. Instead, it is presented for an arbitrary individual carrier, bearing in mind that any real system would perform operations on a per carrier basis. Finally, for simplicity it is also assumed that the channel is time invariant during several OFDM symbol periods, this way avoiding specific mentioning of a symbol time index. Nevertheless, it should be noted that in a real world system channel variations, *e.g.* caused by connected loads such as switched power supplies or florescent lamps [117], may cause performance degradations if not accounted for.

The channel matrix $\mathbf{H}$, of dimension $N_R \times N_T$ includes not only the MIMO PLC channel but also the couplers and all band filters in the transmitter and receiver. The entries of the channel matrix $\mathbf{H}$ use the measured MIMO PLC channels as introduced in Subsection II-C. Compared to *e.g.* the wireless channel which is sometimes modeled by independent fading coefficients in the channel matrix $\mathbf{H}$, the MIMO PLC channel matrix shows a rather high spatial correlation as outlined in Subsection II-C. The upper limit of spatial multiplexable and recoverable streams, N_{stream}, is determined by the rank of the channel matrix. For full-rank channels, one obtains $N_{stream} = min(N_T, N_R)$. $\mathbf{s}$ describes the $N_T \times 1$ symbol vector containing the symbols transmitted via the N_T transmit ports. The transmitted symbols, *i.e.* the elements of $\mathbf{s}$, have the average power $\frac{P_T}{N_T}$, where P_T is the total transmit power. $\mathbf{r}$ represents the $N_R \times 1$ received vector observed over the N_R receive ports. Therewith the received signal model writes,

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} , \quad (1)$$

where $\mathbf{n}$ is the $N_R \times 1$ noise vector. Its elements, the noise samples, are assumed to follow a zero mean Gaussian distribution with variance N_0 and are further assumed to be independent over receive ports. This can be achieved using appropriate whitening filters at the receiver. In addition, the transmitter may apply linear precoding, which can be integrated in the received signal model through,

$$\mathbf{s} = \mathbf{F}\mathbf{b} , \quad (2)$$

where $\mathbf{b}$ is an $N_T \times 1$ symbol vector and $\mathbf{F}$ is a $N_T \times N_T$ precoding matrix.

B. Linear Detection and SINR formulation

MIMO detection aims to recover the transmitted streams. Considering linear detection, described by the detection matrix $\mathbf{W}$, the equalized received vector can be written as,

$$\begin{aligned} \mathbf{y} &= \mathbf{W}\mathbf{r} \\ &= \mathbf{W}\mathbf{H}\mathbf{s} + \mathbf{W}\mathbf{n} . \end{aligned} \quad (3)$$

The simplest linear detection algorithm is known as *zero forcing* (ZF) [95], where the detection matrix $\mathbf{W}$ is the pseudo inverse $[\cdot]^\dagger$ of the estimated channel matrix $\hat{\mathbf{H}}$, *i.e.* ,

$$\begin{aligned} \mathbf{W}_{\mathrm{ZF}} &= \left(\hat{\mathbf{H}}^H \hat{\mathbf{H}}\right)^{-1} \hat{\mathbf{H}}^H \\ &= \hat{\mathbf{H}}^\dagger \ . \end{aligned} \tag{4}$$

Assuming perfect channel estimation, *i.e.* $\hat{\mathbf{H}} = \mathbf{H}$, and applying $\mathbf{W}_{\mathrm{ZF}}$ in (3) results in,

$$\begin{aligned} \mathbf{y} &= \mathbf{H}^\dagger \mathbf{H}\mathbf{s} + \mathbf{H}^\dagger \mathbf{n} \\ &= \left(\mathbf{H}^H \mathbf{H}\right)^{-1} \mathbf{H}^H \mathbf{H}\mathbf{s} + \mathbf{H}^\dagger \mathbf{n} \\ &= \mathbf{s} + \mathbf{H}^\dagger \mathbf{n} \ , \end{aligned} \tag{5}$$

which shows the design criterion. If the noise is zero, the transmit symbol vector is recovered and the co-channel interference is removed completely. However, if there is noise, the variance of $\mathbf{H}^\dagger \mathbf{n}$ might increase compared to the original variance of $\mathbf{n}$. The problem is commonly referred to as *noise enhancement*. Linear detection can be improved by the *minimum mean square error* (MMSE) receiver which trades off co-channel interference suppression and noise enhancement. The MMSE detection matrix is [95],

$$\mathbf{W}_{\mathrm{MMSE}} = \left(\hat{\mathbf{H}}^H \hat{\mathbf{H}} + \frac{N_T}{\rho} \mathbf{I}_{N_T}\right)^{-1} \hat{\mathbf{H}}^H \ , \tag{6}$$

with $\mathbf{I}_{N_T}$ an $N_T \times N_T$ identity matrix, and $\rho = \frac{P_T}{N_0}$ the ratio of the total transmit power P_T to the noise power N_0.

Independent of the linear detection matrix realization, the SINR, Λ_p, of the streams $p = 1, \ldots, N_{stream}$ is given by [95],

$$\Lambda_p = \frac{\left|[\mathbf{W}\mathbf{H}]_{pp}\right|^2}{\sum_{i=1, i \neq p}^{N_{stream}} \left|[\mathbf{W}\mathbf{H}]_{pi}\right|^2 + [\mathbf{W}\mathbf{W}^H]_{pp} \frac{N_T}{\rho}} \ , \tag{7}$$

where the notation $[\cdot]_{pi}$ indicates selection of the element in row p and column i.

Other methods like *successive interference cancellation* (SIC) [95], *maximum likelihood* (ML) detection [95], or fractionally spaced equalizers using MIMO biorthogonal partners [118] are not considered due to their increased implementation complexity. However, MIMO PLC using SIC is investigated, for example, in [71], [94].

C. Precoding and Power Allocation

If no precoding is applied, the spatial streams are transmitted directly via the transmit ports, *i.e.* $\mathbf{s} = \mathbf{b}$, in the following referred to as *spatial multiplexing* (SMX) without precoding. In this case no CSI is required for MIMO transmission. On the other hand, precoding at the transmitter is based on CSI. The optimum linear precoding matrix $\mathbf{F}$ minimizes the *mean square error* (MSE) matrix $E\left\{(\mathbf{y}-\mathbf{b})(\mathbf{y}-\mathbf{b})^H\right\}$, where $E\{\cdot\}$ represents the expectation operation. To obtain it $\mathbf{F}$ can be factored into two matrices $\mathbf{V}$ and $\mathbf{P}$ [119],

$$\mathbf{F} = \mathbf{V}\mathbf{P} \ . \tag{8}$$

$\mathbf{P}$ is a diagonal matrix, which describes the power allocation of the total transmit power to each of the transmit streams. $\mathbf{V}$ is the right hand unitary matrix of the SVD of the channel matrix, *i.e.* $\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^H$, $\mathbf{U}$ is the left hand unitary matrix and $\mathbf{D}$ is a diagonal matrix containing the singular values of the channel matrix.

Precoding by just the unitary matrix $\mathbf{F} = \mathbf{V}$ is often referred to as *unitary precoding* or *eigenbeamforming* (EBF) [120]. Since $\mathbf{V}$ is a unitary matrix, the average signal power is not affected by this kind of precoding.

If only one spatial stream carries information, *i.e.* $\mathbf{b} = \begin{bmatrix} b_1 \\ 0 \end{bmatrix}$, the precoding from (2) turns into,

$$\begin{aligned} \mathbf{s} &= \mathbf{V}\mathbf{b} \\ &= \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 \end{bmatrix} \begin{bmatrix} b_1 \\ 0 \end{bmatrix} \\ &= \mathbf{v}_1 b_1 \ , \end{aligned} \tag{9}$$

with $\mathbf{v}_1$ the first column of the precoding matrix $\mathbf{V}$. This one-stream beamforming is also called *spotbeamforming* (SBF). Even though only one logical stream carries information, both transmit ports are used since $\mathbf{s}$ is a 2×1 vector for two transmit ports. Spotbeamforming might be used if only one receive port is available, *i.e.* in a *multiple input single output* (MISO) configuration, or if the receiver supports only the decoding of one stream. Also, in low SINR situations spotbeamforming improves the coverage.

Looking at the schemes making use of power allocation, one may note that there are basically two options: (i) to allocate the total transmit power across carriers and (ii) to allocate across the available MIMO streams. In case of PLC, option (i) is only realizable within the resolution bandwidth used for regulatory assessment, *i.e.* 9 kHz for frequencies below 30 MHz and 120 kHz for frequencies above [121]. Generally, EMC regulations impose a maximum PSD feeding level across the carriers, and shifting energy between carriers is only possible if carrier spacing is smaller than the resolution BW. Looking at option (ii), *waterfilling* delivers the optimum MIMO power allocation to maximize the system capacity for Gaussian distributed input signals [95]. However, if the input signals are taken from a finite set of QAM symbols, like it is the case for current BB-PLC systems (see Section V), waterfilling is not optimum. Instead, [122] derives the optimum power allocation for arbitrary input distributions, and for parallel channels corrupted by AWGN. Details on the algorithm termed *mercury waterfilling* may be found in [122], [123]. In the same line, [58], [94] derive a simplified/approximated mercury waterfilling algorithm, where only three power allocation coefficients, namely 0, 1 and $\sqrt{2}$, are used. If a stream's SINR would be insufficient to support the lowest bitloading, transmission is disabled and its power is used to boost the co-stream, resulting in a 3 dB SINR gain of the remaining stream. If, however, both streams are capable to support at least the lowest bitloading constellation, tx power is equally allocated to both streams. This simplified power allocation scheme does not require any additional feedback as the power allocation decisions may be based on the bitloading requests already obtained from the receiver. Performance of the scheme is analyzed in [94], where it is shown to be close to optimum.

D. Performance Results

To investigate the potential of the different MIMO schemes, linear receiver strategies, and power allocation options, an OFDM MIMO system simulation is set up making use of the ETSI STF 410 channel measurements in a parametric-deterministic approach. The simulator uses 1296 carriers over the frequency range from 4 to 30 MHz. Each carrier is adaptively loaded with QAM symbols of 0 to 12 bit, where bitloading thresholds are adjusted to achieve an uncoded *bit error rate* (BER) of 10^{-3}. An additional *forward error correction* (FEC) code [124] might easily reduce this BER. The achieved raw bitrate is obtained as the sum of the number of bits assigned to all carriers divided by the OFDM symbol length. 'Raw bitrate' indicates that guard interval length, training data or FEC overhead are not considered. For simplicity, noise is modeled as AWGN, uncorrelated over the rx ports and with equal noise power on all ports. The transmit power to noise power level is artificially set to $\rho = 65\,\text{dB}$. This value corresponds to a transmit power spectral density of -55 dBm/Hz and an average noise power spectral density of -120 dBm/Hz. The example of $\rho = 44\,\text{dB}$ (PSD = -72 dBm/Hz) is provided as well to highlight the impact of low SINR channels. Impulsive noise is not considered. In the case of MIMO, the two feeding ports D1 and D3 (*i.e.* L-N and L-PE, see Section II-B) and all four receive ports (S1, S2, S3, S4) are used. In case of SISO the D1 (L-N) port is used at the transmitter and the S1 port (L) at the receiver. It was observed that using the S2 (N) tx port instead yields the same average performance. The corresponding SINR is calculated based on the channel matrix of each subcarrier as indicated in (7) assuming perfect rx channel knowledge. Performance results are displayed in Figure 7.

Looking at Figure 7 (a) it is found that 2×4 SMX without precoding paired with ZF-detection performs about the same or even worse than SISO for most channels and bitrates up to about 40 Mbit/s. The high correlation of the power line channels results in high values of the detection matrix entries, leading to an amplification of the noise. This effect is mitigated using MMSE detection. Further, 2×4 *eigenbeamforming* (EBF) with ZF-detection achieves the highest bitrate of the investigated schemes. Its gain over SISO is highest for the low bitrate region of Figure 7 (a), *i.e.* for channels with high attenuation. Looking at Figure 7 (b), it is found that 2×4 SMX without precoding paired with ZF-detection now outperforms SISO in contrast to the case presented in Figure 7 (a). Since the SINR is higher, the noise enhancement of the ZF-detection is in this case not that severe. For the same reason, the gain of MMSE over ZF becomes smaller. Looking at the low probability values in Figure 7 (b), one can observe

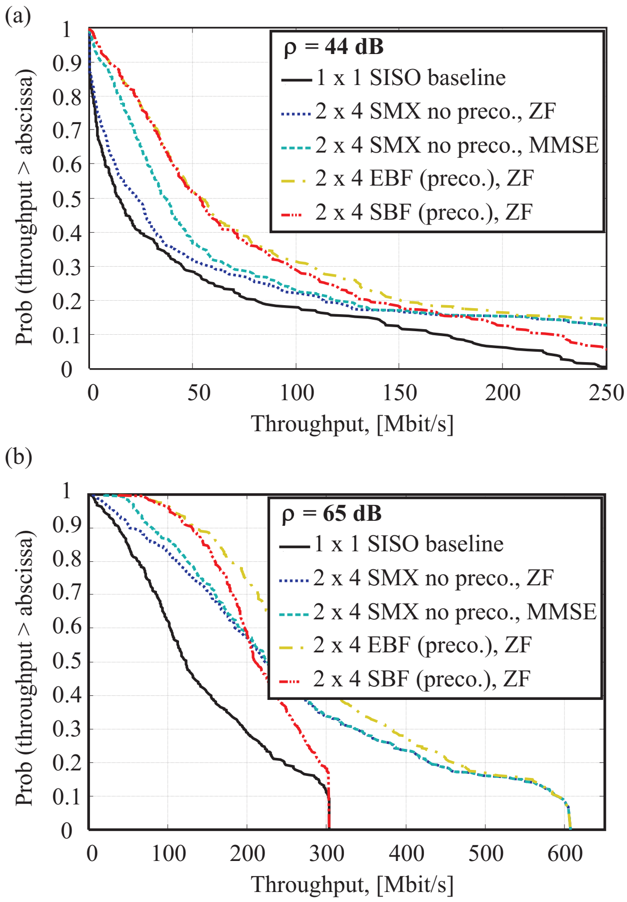

Fig. 7. Complementary cumulative distribution function (C-CDF) of the bitrate for different MIMO schemes. $N_T = 2$, $N_R = 4$ besides in SISO case. (a) $\rho = 44\,\text{dB}$. (b) $\rho = 65\,\text{dB}$. In both cases using mercury waterfilling power allocation.

that 1-stream *spotbeamforming* (SBF) approaches the SISO performance, since no spatial multiplexing gain is achieved with only one spatial stream. Similarly, spatial multiplexing without precoding approaches the same performance as eigenbeamforming for very good channel conditions.

Looking at median values, eigenbeamforming performs best (gain compared to SISO of factor 2.2 for $\rho = 65\,\text{dB}$) followed by the simpler SMX scheme without precoding (gain compared to SISO of factor 1.8 for $\rho = 65\,\text{dB}$).

It may be concluded that eigenbeamforming is the best choice for MIMO PLC since the full spatial diversity gain is achieved for highly attenuated channels and maximum multiplexing gain is achieved for channels with low attenuation by utilizing all spatial streams. Spatial correlation of the transmit signals may cause higher radiated emission of the power lines. However, the unitary precoding matrix of eigenbeamforming does not introduce any correlation of the transmit signals if the two streams before precoding are uncorrelated [94]. Beamforming in general offers flexibility with respect to the receiver configuration. Only one spatial stream may be activated by the transmitter, *i.e.* spotbeamforming, if only one receive port is available. This might be the case if the outlet is not equipped with the 3rd wire or if a simplified receiver implementation is used which supports only one spatial stream.

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Since beamforming aims to exploit the strongest channel eigenmode the performance loss of not utilizing the second stream is relatively small compared to the spatial multiplexing schemes without precoding. This is especially true for highly attenuated and correlated channels, where the second stream could carry only small amounts of information (see the high coverage area in Figure 7).

Again, these results have to be taken with a bit of care, as hardware and real world imperfections have been ignored in these simulations but will be addressed in the following.

E. Hardware Implementation Aspects

Looking at real world implementations, there is a broad variety of steps that become significantly more complicated when going from a SISO to a MIMO system. For example, as building blocks for the detection matrix introduced in (3), a minimum of four channels have to be estimated, which requires modification of preamble and training symbols. At least two adaptive gain control stages have to be settled at the receiver. In addition, extending the operating range towards lower SINRs demands that stages like *preamble detection* or *synchronization* increase their performance with respect to their SISO counterparts. To test real world hardware constraints, a MIMO demonstrator was build, allowing up to 2×4 MIMO systems with on-the-fly control of eigen- and spotbeamforming [94], [125], [126].

One key step is received symbol estimation, which requires rx-filters - potentially based on the columns of the detection matrix from (3) - to be applied to the received signal vector $\mathbf{r}$. In case of precoding at the transmitter, ZF detection may be sufficient since in case of optimum beamforming, ZF and MMSE detection yield the same performance [94]. In case of two transmit ports, the calculation of the ZF detection matrix, as given in (4), involves a 2×2 matrix inversion. Although a closed-form solution exists, the direct calculation may not be the best hardware implementation approach. A fixed-point implementation of the direct approach faces numerical problems. Especially, the calculation of the determinant of $\mathbf{H}^H\mathbf{H}$ may be problematic for correlated channels. Calculations of "square products" of the form $\mathbf{H}^H\mathbf{H}$ should also be avoided as the word width of the multiplication output is doubled compared to the input word width. Additionally, many hardware consuming calculations are required. These drawbacks motivate the use of an alternative implementation based on the *QR decomposition* [127]. Benefits are improved numerical stability and straight forward parallelization [128], [129]. Hence, a QR decomposition based method has been implemented in the hardware demonstrator [94].

Further, in case of beamforming, the transmitter needs knowledge about the precoding matrix $\mathbf{V}$. This may be derived by means of the SVD from the channel matrix $\mathbf{H}$. Typically, only the receiver has knowledge about the channel matrix and therefore the precoding matrix $\mathbf{V}$ has to be fed back to the transmitter. Quantization is applied to reduce feedback overhead. $\mathbf{V}$ is a unitary matrix, *i.e.* $\mathbf{V}^{-1} = \mathbf{V}^H$. Hence, its columns $\mathbf{v}_i$ $(i = 1, \ldots, N_T)$ are orthonormal and phase invariant [127]. This means, multiplying each column vector by an arbitrary phase rotation results in another valid precoding. This allows to represent the complex 2×2 matrix $\mathbf{V}$ by only the two angles ϕ and ψ

$$\mathbf{V} = \begin{bmatrix} \cos\psi & \sin\psi \\ -e^{j\phi}\sin\psi & e^{j\phi}\cos\psi \end{bmatrix}, \tag{10}$$

where the range of ϕ and ψ to represent all possible beamforming matrices is $0 \leq \psi \leq \pi/2$ and $-\pi \leq \phi \leq \pi$. Quantization of $\mathbf{V}$ may be achieved by directly quantizing ϕ and ψ or via a codebook which contains a set of pre-defined precoding matrices. The amount of feedback can be reduced further by exploiting the correlation between neighboring subcarriers [130]–[132]. Here, two main approaches are commonly reported: *clustering* and *interpolation*. For clustering, groups of subcarriers are assigned to the same precoding matrix while for interpolation, the precoding matrix is determined only for certain subcarriers and the precoding matrices for the remaining subcarriers are interpolated. Investigations on precoding quantization may be found in [58], [94].

The hardware demonstrator allows the performance comparisons of different MIMO configurations (spatial multiplexing without precoding, eigenbeamforming, spotbeamforming, SISO) and the influence of system parameters like the number of receive ports. Also, different channel and noise conditions may be examined by monitoring several system parameters, including the bitrate, the BER, adaptive modulation and channel estimation results. The demonstrator was tested under real channel conditions in a variety of buildings. For example, to assess the available throughput, adaptive modulation was adjusted to an error-free transmission. The throughput was then compared for SISO and 2×4 MIMO transmission. One of the main findings was that the performance results indicated in Figure 7, could largely be confirmed. Besides, the demonstrator was used to support the standardization work that lead to the HomePlug AV2 specification.

V. MIMO in Current PLC Systems

A. ITU-T G.hn

The ITU-T G.hn standards belong to the "G" family specifying "Transmission systems and media, digital systems and networks". The acronym "hn" stands for *home networking* and was an intermediate name used in the early stages of standard development. Based on this legacy, the term G.hn is still commonly used to refer to the family of standards G.9960 to G.9964. ITU-T G.hn is not only applicable to power lines but also to phone lines and coaxial cables, therewith for the first time defining a single standard for all major wireline communications media. In 2009, the PHY layer and the overall architecture were approved as ITU-T Recommendation G.9960 [16]. The *Data Link Layer* (DLL) Recommendation G.9961 [17] was approved in June, 2010. Finally, a MIMO transciever extension G.9963 [20] and a power spectral density specification G.9964 [133] were approved in December, 2011. The MIMO extension includes spatial multiplexing without precoding, as well as eigen- and spotbeamforming.

Other related Recommendations are G.9961 Amendment 1 [134], which contains a mechanism for mitigating interferences between neighboring G.hn domains and Recommendation G.9972 [135], which deals with coexistence mechanism for wireline home networking transceivers. Turning to the higher layers, Recommendation G.9970 [136] describing a "generic architecture for home networks and their interfaces to the operators' broadband access networks" deserves to be mentioned.

To promote the ITU-T G.hn standard, and to address certification and interoperability issues, the *HomeGrid Forum* was founded [137]. It certified the first G.hn chipset in December 2012.

B. IEEE 1901 and its HomePlug AV2 Extension

Simultaneous to ITU-T G.hn developments, IEEE P1901 [138] was working on the "*Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications*" [19]. It covers the aspects access, in-home, as well as coexistence of access-in-home and in-home-in-home networks and the official IEEE Std 1901-2010 was published in December 2010. To assure a broad industrial backing, two optional PHY technologies, namely *FFT-PHY* (based on HomePlug AV) and *Wavelet-PHY* (based on HD-PLC) were included. The two resulting PHY layers are not interoperable, but a mandatory *Inter-System Protocol* (ISP) assures their coexistence.

The HomePlug Powerline Alliance [139] serves as the certifying body for IEEE 1901 FFT-PHY compliant products, whereas the HD-PLC Alliance serves as the certifying body for IEEE 1901 Wavelet-PHY compliant products.

While IEEE 1901 Wavelet-PHY/HD-PLC is presently mainly used on the Japanese market, IEEE 1901 FFT-PHY/HomePlug AV is used in many countries around the globe, with products of the HomePlug family currently possibly being the most deployed BB-PLC technology worldwide. In analogy to the introduction of MIMO to ITU-T G.hn, the HomePlug Powerline Alliance introduced the HomePlug AV2 specification in January 2012. It includes features like MIMO with and without precoding, an extended frequency range of up to 86 MHz, efficient notching, several transmit power optimization techniques, 4096-QAM, power save modes, short delimiter and delayed acknowledgement. Together these features are boosting the maximum PHY rate to around 2 Gbit/s. Further, to cover multiple home networking media under one umbrella, IEEE P1905.1 devised a "Standard for a Convergent Digital Home Network for Heterogeneous Technologies" [2], [140]. It defines an abstraction layer for multiple home networking technologies like IEEE 1901, IEEE 802.11 (Wi-Fi), IEEE 802.3 (Ethernet) and MoCA 1.1 (coax cable) and is extendable to work with other home networking technologies.

C. HomePlug AV2 and ITU-T G.hn Comparison

HomePlug AV2 uses the band from 2 MHz up to 86 MHz with services above 30 MHz being optional (the stop frequency can be negotiated between modems). ITU-T G.hn (G.9960/G.9961) operates from 2 MHz up to 100 MHz using bandwidth scalability, with three distinct and interoperable bands defined as 2-25 MHz, 2-50 MHz, and 2-100 MHz. The architectures defined by HomePlug AV2 and ITU-T G.hn (G.9960/G.9961) are similar in several aspects. In ITU-T G.hn one refers to a sub-network as *Domain*. Operation and communication is organized by the *Domain Master* who communicates with various *Nodes*. Similarly, the sub-network in HomePlug AV2 is referred to as *Basic Service Set* (BSS). The equivalent to the domain master is the *BSS Manager*, which connects to so-called *Stations*.

TABLE IV
COMPARISON OF MIMO SCHEMES DEVELOPED IN ITU-T G.9963 AND HOMEPLUG AV2.

Item	**ITU-T G.9963**	**HomePlug AV2**
MIMO modes	Tx selection Spatial multiplexing without precoding Eigenbeamforming Spotbeamforming	Tx selection Spatial multiplexing without precoding Eigenbeamforming Spotbeamforming
Beamforming feedback in bits for ϕ and ψ	4; 4 or 8; 8	7; 5
Beamforming carrier grouping	Clustering with variable cluster size	Interpolation with variable pilot spacing
Stream power allocation	On subcarrier basis, power of non-utilized stream allocated to remaining stream	On subcarrier basis, power of non-utilized stream allocated to remaining stream

Even if many features appear to be individually developed by ITU-T and IEEE/HomePlug, several are actually identical. The fact that ITU-T G.hn and HomePlug AV2 largely agree on channel coherence time, coherence bandwidth, guard interval, roll-off window timings, *etc.* shows that the BB-PLC channel is analyzed similarly and that channel difference for comparable topologies are not very different around the globe. Similarities continue with PHY-frame header settings making use of QPSK, FEC coderate 1/2, and repetition codes. The segmentation process of embedding the application data into PLC convenient packets is similar and data is in both cases encrypted using AES-128 [141]. The MAC cycle or Beacon period is selected to be 2 AC line cycles. The bit-loading of carriers can be line cycle dependent, and immediate, as well as delayed acknowledgments are possible.

Turning specifically to the MIMO processing options, a comparison of the schemes adopted in the specifications ITU.G9963 and HomePlug AV2 is provided in Table IV. Identically to the HomePlug AV2 specification the ITU Recommendation standardizes the format of the feedback information coming from the receiver on how the precoding angles have to be set at the transmitter. One may note that ITU-T G.9963 and HomePlug AV2 support tx selection diversity, spatial multiplexing without precoding, eigenbeamforming (also referred to as spatial multiplexing with precoding) and spotbeamforming. The option of transmitting only one spatial stream ensures compatibility to SISO transmission. Power allocation on a subcarrier basis among MIMO streams is realized by simply adding 3 dB if the other tx stream is not used. Some minor differences may be noted in the quantization of the beamforming matrix as detailed in Table IV. HomePlug AV2 uses the definition of (10) for the precoding matrix quantization, while ITU-T G.hn introduces the concept of *tx port mapping* (TPM) with a 2×2 TPM matrix. The corresponding ITU-T G.hn implementation of (10) is called TPM#5 and is defined as [20], [142],

$$TPM\ \#5 = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{j\varphi}\cos\theta & -e^{j\varphi}\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}, \quad (11)$$

where $0 \leqslant \theta \leqslant \frac{\pi}{2}; \quad 0 \leqslant \varphi < 2\pi$. This precoding matrix is identical to the matrix specified in IEEE 802.11n [7]. Note that on the first sight the definition of the unitary precoding matrix as selected by ITU-T G.hn in (11) appears different from the definition selected by HomePlug AV2 as given in (10). However, there are many possible definitions of unitary 2×2 matrices described by two rotation angles and both can be easily transformed from one to another. Besides, while the normalization factor $\frac{1}{\sqrt{2}}$ is explicitly included in (11), this factor is included via the power allocation and not via the unitary precoding definition of (10) for HomePlug AV2. The carriers' precoding information may be *grouped* in ITU-T G.hn while HomePlug AV2 may interpolate the precoding matrix based on pilot carriers. The group size and pilot spacing are variable in order to balance performance and memory requirements.

With all these communalities, differences are that ITU-T G.hn supports multicast transmissions, *i.e.* transmitting to multiple nodes using a common *bit allocation table* (BAT), while HomePlug AV2 does not. Nevertheless, HomePlug AV2 implements the option of a short delimiter, *i.e.* data and pilot carriers in preamble and frame control, an option not implemented by ITU-T G.hn.

Modulation and FEC coding of both MIMO PLC standards is kept identical to their SISO predecessors in order to maintain backward compatibility. In the case of eigenbeamforming the payload bits are independently quadrature amplitude modulated on both steams in an adaptive manner, where the available SINR per stream and carrier defines the amount of payload for each carrier. The allowed constellations vary from 1 bit per OFDM carrier up to 12 bits. However, two very different FECs, *i.e. low-density parity-check code* (LDPC) in ITU-T G.hn and Turbo Code in HomePlug AV2, are chosen - see [143] for a comparative analysis. This makes it more difficult (or costly) to implement both standards in a single chip, as the FEC part is up to the present day a non-negligible space factor when manufacturing wafers. Nevertheless, dual mode devices have already started to appear on the market.

VI. MIMO PLC Research Challenges

Although many aspects of MIMO PLC, especially those focusing on point-to-point (single user) MIMO, have already been investigated as outlined in the previous sections, challenges remain in order to fully understand the physics of MIMO transmission and optimally exploit this technology for a wide scope of applications. Working the way up from the physical layer, one may categorize MIMO PLC research challenges as:

- Channel and noise characterization and modelling
- Channel and noise emulation
- Multi-user MIMO signal processing and Precoding
- EMC and cognitive methods
- Cooperation, relaying and network coding

Each of these categories is discussed in more detail in the following subsections.

A. Channel and Noise Characterization and Modelling

Apart from the characterization of the propagation channel and noise in Section II-C and Section II-D, further investigation is required to efficiently exploit the physics of MIMO transmission in a plurality of scenarios:

Future research with respect to the *in-home* scenarios should focus on the cyclic temporal variations of the MIMO channel conditions, in order to complement the findings already established for SISO channels [144]. Further, recent research results introduce the correlation of the colored background noise at different ports [145], as well as the occurrence of impulsive perturbations [146]. However, comprehensive multiport noise models are still missing, and an even better understanding of the correlation properties of the noise received at different ports would help designers in developing efficient noise mitigation techniques. Additional system impairments, such as the self-interference caused by undersized guard intervals [147], also need precise modelling to achieve practical throughput computations.

When turning to *outdoor* and *access* scenarios, that play an increasingly important role in emerging *advanced metering infrastructure* (AMI) and Smart Grid applications, modelling the effects of transformers (see for example [148]), re-closers, capacitor banks, and different country specific multi-phase wiring practices are interesting points for further study. Also from a practical point of view, bringing down the equipment and installation costs of especially MV and HV couplers is interesting. Moreover, to treat multi-user MIMO aspects, as well as issues related to cooperation, relaying and network coding (addressed in Subsection VI-E), the correlation (self-similarity) between channels and noise events towards different users within the same PLC network is worth further exploration.

With the desire to make e-mobility a reality, there is also an increased interest to characterize MIMO PLC channels in electric vehicles, so-called *vehicle power line communications* (VPLC). Although measurement results start to be available [149], [150] in some cases even up to cell-wise monitoring of battery states [151], published results aiming specifically at MIMO PLC are still scarce and further work is necessary.

B. Channel and Noise Emulation

Besides characterization, testing PLC modems in realistic yet reproducible conditions is a major issue that requires hardware emulators. The real time constraint of such equipment raises issues related to the analog-to-digital and digital-to-analog conversion capabilities, as well as complexity issues related to the digital implementation of the channel and noise filters. The design of couplers avoiding uncontrolled (parasitic) propagation paths also represents an interesting challenge. In this line [152] presents a SISO narrowband channel emulator and a comprehensive broadband channel emulator including MIMO capabilities and cyclo-stationary behaviour is described in [153].

C. Multi-user Signal Processing and Precoding

In terms of signal processing, current research primarily focuses on increasing the available single user MIMO throughput or coverage. Adding the constraint of minimizing the undesired electromagnetic radiation and potential interference to neighbors or other equipment opens interesting fields of investigation and first insight on *smart beamforming*, *time reversal* and *advanced linar precoding* techniques can, for example, be found in [154]–[156], respectively.

Apart, through multi-user (multipoint) spatial division multiplexing the system throughput might be increased at the cost of higher coordination overhead and complexity. First result can, for example, be found in [113], where it is shown that the limited number of ports and the high spatial correlation are challenging issues. Nevertheless, spatial division multiplexing, and interference suppression to and from neighboring links are interesting research areas especially for densely populated PLC networks.

D. EMC and Cognitive Methods

Cognitive PLC was standardized by EN50561-1 [86] solving the interference issues towards *high frequency* (HF) radio broadcast in the time, frequency, and location domain. With broadband PLC moving to higher frequencies, interferences between power lines and digital subscriber lines (and especially to G.fast, the new digital subscriber line standard developed by ITU-T [157], [158]) becomes more likely and practical interference cancellation implementations are interesting areas of ongoing development.

Generally, cognitive and active EMI mitigation scenarios have the potential to revolutionize today's EMC standardization landscape. Instead of the traditional specification of permanent immunity and emission thresholds, future systems are likely to adapt to their environments and interesting regulation work is ongoing to specify the interference mitigation techniques in order to be reproducible by EMC testing houses.

E. Cooperation, Relaying and Network Coding

Finally, cooperation and relaying have emerged as promising techniques in the wireless world [159], [160]. Moving towards larger PLC networks, *e.g.* outdoor and access networks and distributed PLC systems to support the Smart Grid, cooperative techniques have been specifically addressed in [115], [116], [161]–[163]. Combining these schemes with multi-user MIMO processing bears interesting research challenges, not only from an information theory and algorithmic point of view but also considering implementation complexity where significant problems with respect to pipelining, memory requirements, and processing delays have to be dealt with. It is, hence, expected to see first cost-effective real world implementations to emerge in narrowband PLC systems and standards. Additionally, as processing capabilities increase, cooperative technologies might very well find their way into broadband MIMO PLC mass market.

VII. CONCLUSION

This article presented the application of MIMO processing to power line communication, by investigating many relevant aspects of this technology: network topologies and coupling methods, channel and noise characterization, EMC regulation, MIMO capacity and signal processing, hardware implementation aspects, and current standardization efforts. While various high, medium and low voltage PLC topologies were introduced, the focus was on low voltage in-home power line topologies. Usage of MIMO techniques over in-home topologies is possible because a protective earth wire is present in all outlets in China and the Commonwealth of Nations, at most outlets in Western countries and only at very few outlets in Japan and Russia. A first lesson learned is that the coupling functionality is key to exploit multiple ports in a multi-wire transmission line. At the transmitter, only two simultaneous differential mode signals can be injected, in order to minimize radiated signals, and to comply with Kirchhoff's law. At the receiver, the three available differential mode signals and the common mode signal can improve the overall performance. While the general concept of MIMO transmission is similar in the wireless and in the PLC context, the power line environment bears its own specificity that needs to be taken into account when designing MIMO systems. From the propagation channel perspective, the sub-channels formed by the Line, Neutral and Protective Earth wires can present a high degree of correlation. However, this drawback is compensated by the large values of SINR generally observed in in-home PLC systems. As a result, the application of MIMO processing to in-home PLC provides significant capacity gains in the order of 2 to 2.5.

Broadband propagation characteristics were experimentally investigated in the framework of a large scale MIMO PLC measurement campaign carried out by ETSI Specialist Task Force 410. Additionally, a broad range of relevant literature was reviewed. It was found that the median channel attenuation is 53 dB with a low pass behavior characterized by an attenuation of 0.2 dB/MHz. Investigation of the noise characteristics indicated a complex noise structure, with a non-AWGN background noise and impulsive noise events occurring at different scales requiring, for example, the implementation of a noise whitening filter at the receiver. Other aspects of PLC noise seem interesting, for instance, the generally larger noise correlation over receive ports leading to an increased capacity.

The paper reviewed the current EMC limits in the EU, the US and Japan and provided recommendations regarding future MIMO specific EMC regulations. The allowed tx power along with the channel attenuation and noise characteristics set the scene to develop the digital communication techniques efficiently exploiting the MIMO feature. From the signal processing point of view, PLC MIMO is similar to its wireless counterpart. However, one key difference is noteworthy: PLC systems are essentially closed-loop, as CSI is required at the transmitter to load different constellations on different carriers. Therefore, popular open-loop tx diversity schemes such as Alamouti space-time block coding are sub-optimal and are generally not selected in the PLC context. In addition, because of the generally high SINR operating points, multiplexing schemes and not pure mean gain or diversity oriented schemes are needed to achieve interesting MIMO gains. System simulations revealed that the highest bitrates are achieved using eigenbeamforming techniques also referred to as precoded spatial multipexing.

Further, the paper presents a hardware simulator that was built to test MIMO configurations as well as signal processing options on-the-fly. Overall, a throughput gain by a factor of two is possible. Clearly, permissible receiver cost and complexity might restrict these options in real world commercial implementations. Despite increased implementation complexity, MIMO signal processing has become an integral part of present day broadband PLC systems, namely of international standard ITU-T G.hn (specifically in G.9963) and of specification HomePlug AV2, which is fully backward compatible with IEEE 1901. Both include options for spatial multiplexing with and without precoding. Commercial MIMO hardware solutions are starting to become available and it is expected that the addition of MIMO signal processing will become a key factor to boost user satisfaction when connecting their digital homes.

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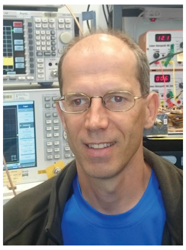

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