# An IEEE 1901 Based PHY Simulator for MIMO PLC in Safety-Critical Applications

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***Abstract*—The More Electric Aircraft (MEA) opens up opportunities for new and innovative solutions, but also poses challenges. Electrical components require not only power, but also data communication, whereas the wiring contributes a significant amount to the weight of an aircraft. Power Line Communications (PLC) has proven its potential for reducing the wiring for communications as it uses the power lines instead.**

**The safety-critical application domain, however, makes it a challenging task to bring PLC to the aircraft. Commercially available products are not suitable and the relatively small market segment provides not enough incentives for the necessary adaptations by the technology providers. Furthermore, the development of safety-critical components is a costly process, not only because the components have to fulfill high standards, but also because the development process itself has to fulfill certain criteria.**

**A recent development in PLC technology is the adoption of Multiple Input Multiple Output (MIMO) techniques to the PLC domain. MIMO communications has already proven its benefits in wireless communications, and as of 2011, has also been specified in first PLC standards. Most aircraft are equipped with power systems based on three-phase alternating current (AC) which already provides the necessary wiring to enable the adoption of MIMO techniques. The use of MIMO techniques for PLC in aircraft, however, has to be evaluated under the aspects of the safety-critical environment, and may not necessarily come to the same conclusions like existing MIMO PLC solutions.**

**Based on an earlier developed model-based design approach, we have built a PHY simulator based on the IEEE 1901 standard. After evaluating MIMO concepts in literature, but also in existing standards, we have decided for the V-BLAST structure and integrated it into our PHY simulator. Our practical approach has revealed a number of challenges with respect to the frame synchronization and channel estimation, which required a complete re-design of the preamble format. The simulation results contribute to our technology assessment process of potential benefits of MIMO technology for safety-critical applications.**

## I. Introduction

With the trend towards the More Electric Aircraft (MEA), electrical components more and more replace hydraulic, mechanical, and pneumatic systems in aircraft, which opens up opportunities, but also poses challenges. One of these challenges is the increase of wiring, and as a consequence an increase of weight, to provide power and data communication to the electrical components. In fact, communications may contribute as much as $40\,\%$ to the aircraft wiring [1]. Power Line Communications (PLC) technology might be one possible approach to cope with this problem, which has already been shown in earlier studies [2], [3].

The use of commercially available PLC technology is limited due to other performance objectives and operating conditions. Safety-critical applications put high priority on reliability and worst-case performance, while consumer technology optimizes for the average-case. The relatively small market segment provided by aeronautics (or other safety-critical domains) provide only little incentives for adaptations by the technology providers. In addition, the development of components for safety-critical application is a costly process, as not only functional and performance requirements have to be fulfilled, but also certain aspects of design assurance guidelines [4].

A recent development in PLC research is the adoption of Multiple Input Multiple Output (MIMO) techniques to PLC. MIMO communications is well known in the Wireless domain and has already successfully been implemented in standards such as Long Term Evolution (LTE) or IEEE 802.11 [5]. Its potential to PLC has been studied for in-home multimedia applications, which resulted in the specification of MIMO in the latest HomePlug standard AV2 [6]. Many aircraft systems have a power supply based on three-phase alternating current and so provide the necessary infrastructure for adopting MIMO techniques.

In this paper we present a MIMO PHY simulator based on the IEEE 1901 standard and use this simulator to assess the benefits of MIMO technology for safety-critical PLC applications. The choice of our implemented MIMO method has been obtained from an evaluation of different MIMO techniques in literature [5], [7] and standards [6], [8] under the relevant aspects of safety-critical applications. Our approach has the advantage that practical challenges of the implementation are taken into account at an early stage in the technology assessment phase, which is important considering the costly development process.

## II. MIMO for Safety-Critical Environments

The term MIMO covers a number of multi-antenna techniques whose mechanisms are fundamentally different and thus have different objectives, and also work under different conditions. Also, many MIMO techniques that exist in literature have high complexities and thus make them not suitable

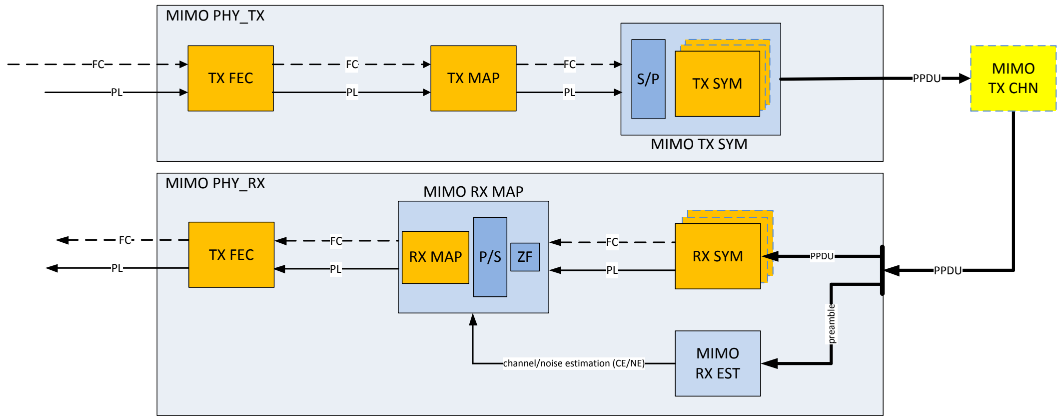


Fig. 1: Architecture of PHY transceiver with MIMO extension

for practical considerations. This narrows down the set of applicable MIMO techniques to:

i) The BLAST[1] techniques, which exist in three variants, the vertical (V-BLAST), horizontal (H-BLAST) and diagonal (D-BLAST) method. The BLAST techniques fall into the category of spatial multiplexing methods.
ii) Orthogonal space-time block codes (STBCs), with the Alamouti code being the most prominent [9]. STBCs fall into the category of spatial diversity methods.
iii) Beamforming. In the context of MIMO, beamforming refers to eigen-beamforming and should not be confused with beam steering, which is a smart antenna technique [5]. Eigen-beamforming can be seen as a spatial multiplexing technique, although it can also be operated with only one spatial stream. Some standards do specify this mode of operation known as single-mode eigen-beamforming [5] or spot-beamforming [6].

Beamforming is one of the most widely used MIMO techniques in current standards. Among the wireless standards the most prominent might be LTE and the IEEE 802.11 standard, but also the PLC standard HomePlug AV2 specifies the use of beamforming. One of the biggest advantages of beamforming is its versatility as it can provide spatial multiplexing and spatial diversity with the same technology. A major drawback of beamforming is that it requires channel knowledge at the transmitter. This has several disadvantages such as increased connection setup times or performance degradation in case of abrupt changes in the channel [4]. It is also not suitable for one-to-many or broadcast communications, which all together makes beamforming less favorable for safety-critical applications.

STBCs provide spatial diversity, which in general is a favorable property for safety-critical applications. STBCs have the limitation that the the Alamouti code is the only full rate orthogonal STBC and that it is restricted to two transmit antennas. Other orthogonal STBCs exist for a higher number of transmit antennas, but have a code rate less than one.

We have decided for the V-BLAST architecture in our implementation, although STBCs would also be a candidate for future considerations. This approach has several advantages, although in our application domain we do not primarily aim for increasing the throughput. The increase of the throughput can be used for more robust channel coding, which gives a higher flexibility and reuse of existing components. Also, convolutional codes offers a coding gain [10], which STBCs are not able to provide [5]. Furthermore, including a MIMO technique into our system also comes at the expense of higher protocol overhead (see Sec. III-C), where the increased capacity allows to maintain the data rates of the Single Input Single Output (SISO) system.

## III. PHY Simulator

The development of PLC systems for safety-critical applications is a challenging task. Compared to other application domains, safety-critical applications demand high standards in their functional and performance requirements. In addition, certain aspects of so-called design assurance guidelines have to be fulfilled which further complicates the development process [4]. We have developed a model-based design approach to fulfill the abovementioned requirements, whose core comprises a physical (PHY) layer simulator. We have based our physical simulator on the IEEE 1901 standard, as this has the benefit of being interoperable with other potential technology suppliers. The original PHY simulator has been designed for a SISO system, since IEEE 1901 does not yet specify the use of MIMO communications.

### *A. IEEE 1901 Components*

Fig. 1 depicts our transceiver architecture that consists of a PHY transmitter, a PHY receiver and a channel emulator. The original version of the platform is shown in yellow that has been implemented against the IEEE 1901 standard. The

[1]Bell Laboratories Layered Space-Time

four main functional blocks of the physical transceiver are the forward error correction (FEC) blocks (TX and RX FEC), the mapper and de-mapper blocks (TX and RX MAP), the orthogonal frequency division multiplexing blocks (TX and RX SYM) and the RX EST block. The first three blocks exist in both the transmitter and receiver, while the last component is specific to the receiver.

The TX FEC block is the first block in the processing chain and implements the FEC. It is responsible for adding redundant bits to mitigate the negative effect of channel impairments. The IEEE 1901 standard specifies the use of Convolutional Turbo Codes (CTC) together with a scrambler and an interleaver, which provides performance close to the Shannon capacity [11].

The TX MAP block implements the symbol mapper. It performs the digital modulation according to a given constellation such as BSPK, QPSK or QAM modulation. IEEE 1901 specifies the use of orthogonal frequency division multiplexing (OFDM), which has the advantage that each sub-carrier may be modulated differently. This includes the possibility to attenuate or even deactivate certain sub-carriers in order to be compliant with electromagnetic compatibility (EMC) regulations. The TX MAP block provides all these functionalities.

The last block in the transmit chain is given by the TX SYM block, which implements the OFDM mechanism. OFDM is a well-known technique to cope with the channel impairments that arise from multipath propagation. The OFDM functionality is realized with an Inverse Fast Fourier Transform (IFFT) in the TX SYM block.

The RX FEC, RX MAP and RX SYM blocks in the receiver essentially perform the reverse operations to their counterparts in the transmitter, and are arranged in the reverse order. The TX CHN block implements the channel emulator, which is explained in Sec. IV in more detail.

The component specific to the receiver is the RX EST block. The RX EST block performs several operations whose performance are critical for providing robust demodulation of the data: the frame synchronization (FS), channel estimation (CE) and noise estimation (NE). The FS compensates the unknown channel delay and synchronizes the receiver with the beginning of the OFDM symbol. The CE provides the necessary channel information for the equalization that compensates for the channel attenuation. The NE is used in the de-mapper to compute soft-values, which allows for better FEC. All the abovementioned operations are performed based on a known preamble that is sent at the beginning of each OFDM frame.

### B. V-BLAST Structure

As previously outlined, we have decided for the V-BLAST structure as a candidate MIMO technique for safety-critical applications. The parts in Fig. 1 highlighted in blue depict our modifications to implement this MIMO functionality. These modifications affect the following blocks:

- TX SYM: A serial-to-parallel converter has been added to create the MIMO streams. Each transmit stream has its own OFDM symbol generator, which is indicated by the dashed blocks.

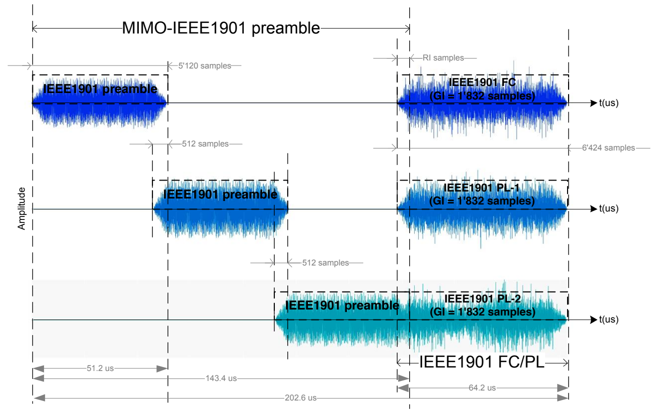


Fig. 2: MIMO PPDU frame format

- RX SYM: Symmetric to the transmitter, each receive antenna has its own OFDM demodulator.
- RX MAP: The channel equalization has been replaced by a zero forcing (ZF) receiver, which performs the equalization and the demultiplexing of the MIMO streams. A parallel-to-serial converter sequentializes the stream and thus provides transparency to the following Demapper and FEC blocks.
- RX EST: The RX EST block has been adjusted to the new MIMO preamble format (see Sec. III-C).
- TX CHN: The channel emulator has been extended to a MIMO channel.

### C. MIMO Preamble

As stated earlier, the RX EST operations are a critical part of the receiver, as errors in these operations will have a great impact in the receiver performance. For the MIMO implementation, it is not possible to simply replicate the preamble to each transmit antenna as they would interfere with each other at the receiver.

This problem can be illustrated as follows. Let us denote the MIMO channel by its channel matrix $\mathbf{H}(f)$. The use of OFDM allows us to consider the sub-carriers independently, thus we can omit the frequency-dependent notation and keep in mind that the following considerations apply on a per sub-carrier basis. The channel model can now be expressed as

$$\mathbf{r} = \mathbf{H} \cdot \mathbf{s} + \mathbf{z}, \tag{1}$$

where $\mathbf{s}$ denotes the sent symbols, $\mathbf{r}$ the received symbols and $\mathbf{z}$ some additive noise. The dimensions of the involved quantities are $\mathbf{r}, \mathbf{z} \in \mathbb{R}^{N_R \times 1}$, $\mathbf{s} \in \mathbb{R}^{N_T \times 1}$ and $\mathbf{H} \in \mathbb{R}^{N_R \times N_T}$, where $N_T$ and $N_R$ denote the number of transmit and receive antennas, respectively.

The channel estimation problem can be expressed as finding the channel matrix $\mathbf{H}$ in Eq. (1), where the sent signal $\mathbf{s}$ is the preamble and thus known to the receiver. If the preamble is a replicate of the same signal on all transmit antennas, the elements of s are all equal, hence, Eq. (1) becomes

$$\begin{bmatrix} r_1 \\ \vdots \\ r_{N_R} \end{bmatrix} = \begin{bmatrix} h_{11} & \dots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R 1} & \dots & h_{N_R N_T} \end{bmatrix} \cdot \begin{bmatrix} s \\ \vdots \\ s \end{bmatrix} + \begin{bmatrix} z_1 \\ \vdots \\ z_{N_R} \end{bmatrix}, \quad (2)$$

which has not enough equations to find $\mathbf{H}$. A possible approach to cope with this problem is to apply time division multiplexing (TDM) to the preamble. The preamble is shifted in time at the different transmit antennas, i.e., we can write

$$\mathbf{S} = \begin{bmatrix} s & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & s \end{bmatrix} \quad (3)$$

with $\mathbf{S} \in \mathbb{R}^{N_T \times N_T}$, which eliminates the interference problem. Inserting this preamble scheme into Eq. (1) yields

$$\mathbf{R} = \mathbf{H} \cdot \mathbf{S} + \mathbf{Z}, \quad (4)$$

where the columns of $\mathbf{R}$ and $\mathbf{Z}$ correspond to consecutive time instances. Eq. (4) provides now enough equations to solve for $\mathbf{H}$ and thus CE can be performed.

An advantage of this approach is the possibility to reuse the components of the SISO system at the expense of increasing the preamble length by a factor of $N_T$. Other mechanism analogously to frequency or code division multiplexing exist to allow for simultaneously transmitting the preambles from all antennas, but have other trade-offs to make such as worse frequency resolution or sensitivity to channel distortions. Fig. 2 depicts the time domain representation of our MIMO physical layer protocol data unit (PPDU) frame format.

## IV. Channel Emulator

The channel emulator block TX CHN performs a convolution in the time domain of the signal and the channel impulse response. Since the original version implements a SISO system, the TX CHN block performs only a single convolution. We have implemented four impulse responses according to the reference models from the OPERA project, which we call *Ref-1* to *Ref-4* [12]. Fig. 3 shows the frequency response $h_{\text{Ref-1}}$ of the first reference model.

For the MIMO implementation we had to modify the TX CHN block as it computes for each receive antenna the superposition of the convolutions between each transmit signal and the corresponding sub-channel. We have implemented a $3 \times 3$ MIMO system which gives a $3 \times 3$ channel matrix according to Eq. (1). For the simulations we considered two different channel models: A crosstalk-free channel and a more realistic channel with crosstalk.

The crosstalk-free channel has been constructed by assuming the same SISO channel on all phases, i.e., $h_{ij} = h_{\text{Ref-1}}$ for $i = j$, and zero otherwise:

$$\mathbf{H}_{\text{Ref-1-no-xtalk}} = \begin{pmatrix} h_{\text{Ref-1}} & 0 & 0 \\ 0 & h_{\text{Ref-1}} & 0 \\ 0 & 0 & h_{\text{Ref-1}} \end{pmatrix}. \quad (5)$$

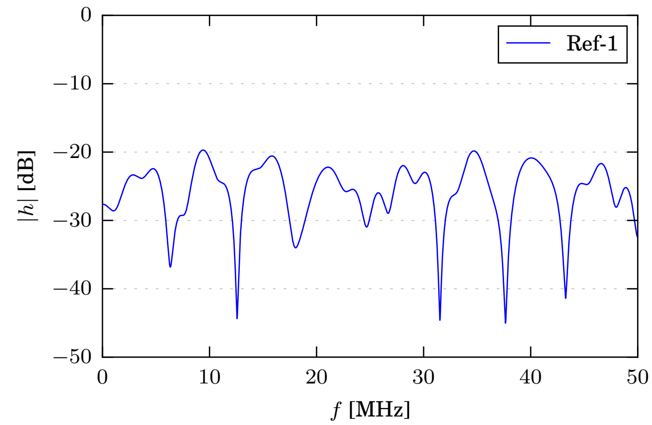


Fig. 3: Magnitude response of reference channel model *Ref-1*

TABLE I: Parameters of our IEEE 1901 Based MIMO PLC System with Different Configurations

| Configuration | 1 | 2 | 3 |
|---|---|---|---|
| Antenna configuration | | | |
| $N_T \times N_R$ | $1 \times 1$ (SISO) | $3 \times 3$ | $3 \times 3$ |
| OFDM parameters | | | |
| Bandwidth | 1.8 MHz to 30 MHz | | |
| Usable carriers | 1968 | | |
| Modulation parameters | | | |
| Modulation | QPSK | | |
| Tone mask | 1666 active carriers | | |
| FEC parameters | | | |
| Code rate | 16/21 | 1/2 | 1/2 |
| Channel parameters | | | |
| Channel model | Ref-1 | Ref-1-no-xtalk | Mixed-Ref |
| Noise model | AWGN | | |
| PHY metrics | | | |
| PPDU duration | 169.8 µs | 202.6 µs | 202.6 µs |
| $n_{\text{PL}}$ per PPDU | 1 | 2 | 2 |
| Data rate (approx.) | 15 Mbit/s | 16 Mbit/s | 16 Mbit/s |

For the full MIMO channel, we have combined different reference models to form a channel matrix that has the structure:

$$\mathbf{H}_{\text{Mixed-Ref}} = \begin{pmatrix} h_{\text{Ref-1}} & h_{\text{Ref-4*}} & h_{\text{Ref-4*}} \\ h_{\text{Ref-4*}} & h_{\text{Ref-2}} & h_{\text{Ref-4*}} \\ h_{\text{Ref-4*}} & h_{\text{Ref-4*}} & h_{\text{Ref-3}} \end{pmatrix}, \quad (6)$$

where *Ref-4** denotes shifted versions of reference model 4. The shift is performed as a ciclic shift in the time domain, which results in a lower spatial correlation and thus ensures a full rank channel matrix. We refer to this channel model as the *Mixed-Ref* model.

## V. Simulations

We have conducted several simulations in order to verify our implementation and to evaluate the performance of the

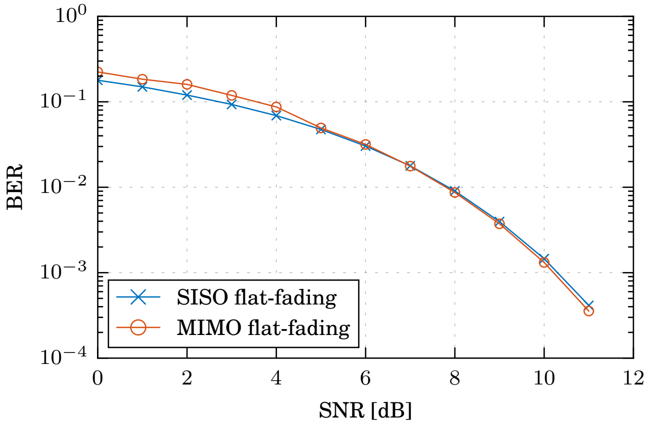


Fig. 4: Bit error rate comparison for flat-fading channels without crosstalk

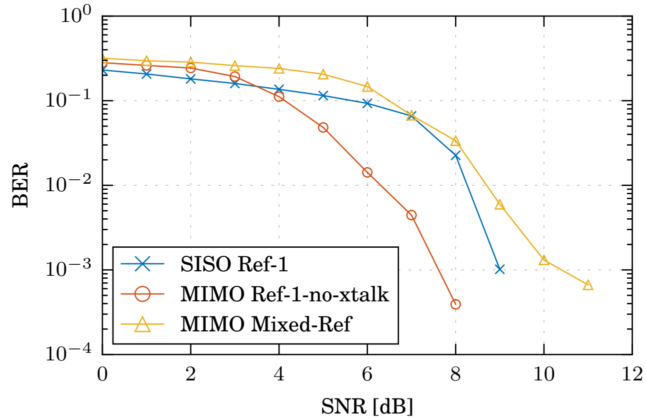


Fig. 5: Bit error rate for fading fading channels: SISO (blue) and MIMO (red) without crosstalk, and MIMO with crosstalk (yellow).

MIMO implementation. A summary of the system parameters are listed in Tab. I. The physical data rates are calculated from the amount of information bits per PPDU duration according to the formula:

$$R_b = \frac{n_{\text{info}}}{T_{\text{PPDU}}} = \frac{n_{\text{PL}} \cdot n_{\text{mod}} \cdot n_{\text{carrier}} \cdot R_{\text{code}}}{T_{\text{PPDU}}}, \quad (7)$$

where $n_{\text{PL}}$ denotes the number of payloads per PPDU, $n_{\text{mod}}$ the number of bits per symbol, $n_{\text{carrier}}$ the number of used carriers and $R_{\text{code}}$ the code rate. For the SISO system, we send only one payload per PPDU. The MIMO system is able to send two payloads, as depicted in Fig. 2. The number of bits per symbol are given by the modulation type, i.e., $2\,\text{bits/symbol}$ in case of QPSK. The parameters $n_{\text{carrier}}$ and $R_{\text{code}}$ are specified in Tab. I. As indicated in Sec. III-C, the preamble duration of the MIMO system is $N_T$ times longer that the original IEEE 1901 preamble, which gives a longer PPDU duration for the MIMO system. Fig. 2 shows the lengths of the preamble and payload section of a PPDU.

### A. Verification of MIMO Implementation

In order to verify our MIMO implementation, we have deactivated the FEC and used a flat-fading channel without crosstalk. Without crosstalk, the MIMO channel together with the ZF receiver have the same behavior like parallel SISO systems with conventional channel equalization. The bit error rate (BER) shown in Fig. 4 confirms that both implementations perform equally, except for the low signal-to-noise ratio (SNR) region.

One drawback of our CE implementation is that once the preamble has been detected, the CE for the cross-channels performs badly (although they are zero), which leads to a noise amplification by the ZF receiver.

### B. Performance of the MIMO System

Fig. 5 shows the BER curves for the simulations with the configurations listed in Tab. I. The blue curve shows the performance of the SISO system (configuration 1), which we will use as a base line to compare with. The red curve shows the performance of the MIMO system with configuration 2, where we used the higher channel capacity for a more robust channel coding (code rate 1/2 instead of 16/21). As shown in Tab. I the PHY data rates are about the same. The BER curve shows that the better channel coding is paying off so the MIMO technique is able to provide a higher robustness. However, this channel has no crosstalk which is usually not the case in reality.

The third curve shows the performance of the MIMO system with configuration 3, which has a more realistic channel with crosstalk. In this scenario, the MIMO system performs worse than the SISO system so even the more robust channel coding is not able to compensate for the noise amplification introduced by the ZF receiver.

It should be noted that the SISO system would also suffer from the crosstalk in a realistic setting, whereas in our SISO simulation, no crosstalk is considered. Also the *Mixed-Ref* channel is only an artificially generated MIMO channel, so an actual MIMO channel might not be as bad. However, this paper focuses on the challenges regarding the implementation of a MIMO while a discussion about realistic channel modeling would be out of scope. It should be highlighted though that an assessment of the benefits of MIMO technologies have to be considered under a wholistic view, which includes the channel conditions, the different MIMO techniques and, their implementation.

## VI. Limitations and Future Work

On an abstract level, the V-BLAST structure is a rather simple MIMO technique, since it only involves a parallelization of the streams at the transmitter and a demultiplexing at the receiver. Literature already provides numerous approaches for the receiver implementation with their advantages and disadvantages [5]. For a realistic system, however, we have learnt that a well-designed preamble together with the respective FS, CE and NE algorithms, pose a significant challenge to the MIMO system design. Our system can be improved in this respect as we have decided for an approach that is simple to implement, but has a negative impact on the symbol duration.

For similar reasons, we have implemented the ZF receiver, which has known disadvantages regarding the noise amplification. We therefore plan to replace the ZF by an minimum mean square error (MMSE) estimator, which requires a more sophisticated NE method.

Finally, we aim at implementing STBCs as an alternative to V-BLAST. This should give more conclusive results in order to find a MIMO technique that serves best the requirements of safety-critical applications.

## VII. Conclusion

MIMO techniques are already well established in wireless communications and its adoption to PLC is gaining momentum. The use of three-phase alternating current (AC) already provides the necessary infrastructure for adopting MIMO techniques, which is common in aircraft, but also in other domains. The potential of MIMO communications for such PLC systems, however, has to be evaluated under different aspects because of the safety-critical nature.

To do so, we discuss different MIMO techniques with respect to requirements posed by safety-critical applications. We select V-BLAST as a candidate MIMO technique for an implementation in our physical simulator. We have reused our IEEE 1901 physical simulator for integrating the V-BLAST structure. This allows the evaluation of the system performance under more realistic conditions, as practical challenges of the implementation are taken into account.

The performance evaluation has verified our initial assessment, that the V-BLAST method is able to provide more robustness, if the increased throughput is used for more robust channel coding. Our study has also revealed challenges in the design of a MIMO system regarding robust but efficient methods for channel estimation and frame synchronization. This leaves further questions that have to be answered before finding conclusive evidence for finding the most suitable MIMO technology for safety-critical PLC systems.

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