A Characterization of the Broadband MIMO PLC Channel in Aircraft

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***Abstract*—The use of Multiple Input Multiple Output (MIMO) techniques for Power Line Communications (PLC) has been proven for the consumer market. As of 2011, MIMO is part of two PLC standards and products are already available for end users. PLC for avionics on the other hand is a niche technology. Fulfilling the high demands for safety-critical components makes the engineering of a PLC solution a challenging task. Many aircraft systems are powered by a three-phase alternating current system and already provide the necessary wiring for adopting MIMO techniques. Our goal is to develop next generation PLC systems for aircraft with MIMO technology.**

The signal propagation on power lines is known to be complex which makes channel modeling a fundamental challenge in the development of PLC systems. Because of the safety-critical nature of avionics applications, the channel models need to be accurate, but more importantly, should represent the actual conditions as realistically as possible.

We present a test bench that emulates the cabin lighting system in an aircraft. The layout of the wire harness is designed such that realistic distances and complexities within the network can be reproduced within a smaller area on the test bench. The original design has been validated with simulations by Bertuol et al. to make sure that the test bench is as close to a real scenario as possible. The design has been modified to provide a three-phase infrastructure and thus allow MIMO communications. The test bench has been used to perform extensive channel measurements, on which we base our channel characterization. We evaluate the channel gain of the different channels, but also MIMO characteristics such as the spatial correlation, and analyze the impact of different topological aspects such as link length or network complexity.

I. Introduction

Today's Power Line Communications (PLC) systems can be found mostly in home networking or smart metering applications. This is reflected by the fact that PLC is already standardized for these domains, such as the ITU-T G.9903 and G.9904 (also known as G3 and PRIME) standard for smart metering, or the HomePlug AV2 standard for in-home multimedia applications [1]. Other domains such as the automotive or aerospace industry also have a high potential for the use of PLC [2], [3], and still, PLC is a niche technology in those domains. These domains have in common that systems may be safety-critical, which puts high demands on the reliability. Since the PLC channel is known to be a difficult one [4], [5], it makes it a challenging task to develop a system that meets the requirements of safety-critical systems.

A fundamental problem in PLC research is the channel characterization and modeling, since the signal propagation is almost as complex as for the wireless channel. Despite being a wired communications technology, the PLC channel is very sensitive to the environment surrounding the wires, which greatly contributes to the modeling difficulties, but more importantly, makes the modeling problem domain specific. Only few models for safety-critical domains, e.g., an aircraft model, exist, while most of the literature provides models for the power grid (at different voltage levels), or in-home networks (c.f. [1], [5] and references therein).

A new development in PLC technology is the adoption of Multiple Input Multiple Output (MIMO) techniques. MIMO techniques are known as multi-antenna techniques, but can be applied to multi-conductor PLC environments as well. An example of such an environment is the use of three-phase alternating current (AC), which has at least three conductors for the phases, and usually has another conductor as neutral. MIMO technology has already been successfully applied to wireless communications such as Long Term Evolution (LTE) or IEEE 802.11n onwards [6]. The use of MIMO for PLC is led by the in-home multimedia domain with the HomePlug Alliance being the first to include this technology in their HomePlug AV2 standard [7], [8].

We aim for adopting MIMO techniques for the use of PLC in avionics systems. In this paper we present a characterization of the broadband MIMO channel in an aircraft. The characterization is based on measurements taken on a test bench that emulates a part of the cabin lighting system (CLS) within the Airbus A380 aircraft. The original test bench design has been presented by Bertuol et al. [9], which we have modified to provide a three-phase infrastructure, and thus enable the use of MIMO.

II. Test Bench

Our test bench is designed to emulate a CLS in an aircraft. It consists of a wire network that connects a secondary power distribution box (SPDB) with several illumination ballast units (IBUs). The wires are aligned in isolated parallel corridors to allow for realistic lengths of the wire harness. The original design has been proposed by Bertuol et al. [9], which we have modified to provide a three-phase infrastructure.

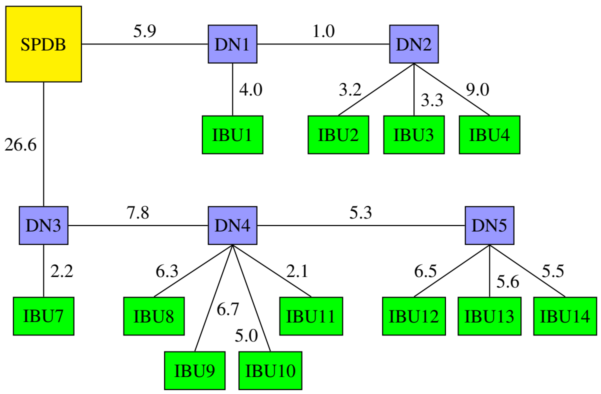


Fig. 1. Tree topology of the CLS network and individual link lengths in Meters

Fig. 2. Test bench design: Isolated copper corridors are used to create long wire lengths

TABLE I
DISTANCES BETWEEN IBUS AND THE SPDB IN METERS

IBU1	IBU2	IBU3	IBU4	IBU7	IBU8
9.9	10.1	10.2	16.0	28.8	40.7
IBU9	IBU10	IBU11	IBU12	IBU13	IBU14
41.1	39.4	36.6	46.2	45.3	45.2

A. Topology

The topology is a tree-like structure as depicted in Fig. 1, with the SPDB as root, intermediary distribution nodes (DNs), and IBUs as leaves. The distances between different DNs, and also to the IBUs have been varied to create a highly irregular topology. Tab. I lists the distances from each IBU to the SPDB. The use of intermediary DNs allows to individually connect and disconnect IBUs to the network and so create arbitrary topologies from straight paths to networks with all branches connected. This variety of topologies allows to analyze for example the impact of the link length (see Sec. IV-A) or the number of branches (see Sec. IV-B) on the channel characteristics.

In order to simulate the long distances on a smaller scale, the cables have been put into parallel corridors that are isolated from each other by copper walls, as shown in Fig. 2. The copper walls are installed to prevent radio frequency (RF) coupling between neighboring corridors. The hull is simulated by a large copper plane at the bottom of the test bench. The wires are mounted on wooden sockets to achieve a constant height of the wires above the ground plane.

B. Electrical Parameters

We have modified the original version of the test bench by replacing the single wires with a three-phase infrastructure. Three-phase systems are typically used either in AC networks with electric motors, or for balancing the loads. We used a single cable consisting of three phases and neutral, thus four wires in total, which supports up to 3×3 MIMO systems in differential mode (DM). The cable parameters are $0.5\,\mathrm{mm}^2$ for the four stranded wires, and an outer diameter of $5.6\,\mathrm{mm}$.

Our PLC system is coupled to the network with a star coupler [7], with a transformer ratio of 1:2 to match the $50\,\Omega$ of the vector network analyzer (VNA) to the line impedance of $100\,\Omega$. The line impedance has been estimated using multi-conductor transmission line theory. The couplers are put in parallel with the loads, the IBUs, which are simulated by a resistive load of $100\,\Omega$ between each phase and neutral.

C. Measurement Setup

The measurements are taken in the frequency domain with a VNA to capture both the magnitude and the phase of the channel response. The frequency range of the measurements captures the region from $1\,\mathrm{MHz}$–$50\,\mathrm{MHz}$, which covers the range of current broadband systems such as the IEEE 1901 standard [10]. Since only a two-port VNA is available, we record only the scattering parameters from one transmit port to one receive port while the other ports are terminated with $50\,\Omega$. Hence, the measurement of a full MIMO channel requires the measurements of all port permutations, which gives 9 measurements for a 3×3 MIMO channel. The channel transfer function (CTF) of each sub-channel $h_{ij}(f)$ is then taken from the S_{21} parameters of the measurement, where i denotes the transmit port and j the receive port.

III. NOTATION AND TERMINOLOGY

A Single Input Single Output (SISO) system can be characterized by a CTF that is given by a scalar, complex-valued, and frequency-dependent channel gain $h(f)$. The MIMO channel, however, is an ensemble of scalar CTFs for each permutation of sub-channels between N_T transmitters and N_R receivers. This is formalized as a frequency dependent $N_R \times N_T$ channel matrix $\mathbf{H}(f)$. The elements $h_{ij}(f)$ of $\mathbf{H}(f)$ denote the CTF between transmitter $j \in [1, N_T]$ and receiver $i \in [1, N_R]$.

The main diagonal elements, $h_{ij}(f)$ for $i = j$, correspond to the CTFs between a pair of transmitter and receiver coupled to the same line, whereas the off-diagonal elements, $h_{ij}(f)$ for $i \neq j$, correspond to a pair of transmitter and receiver coupled to different lines. To the latter we refer to as cross-channels

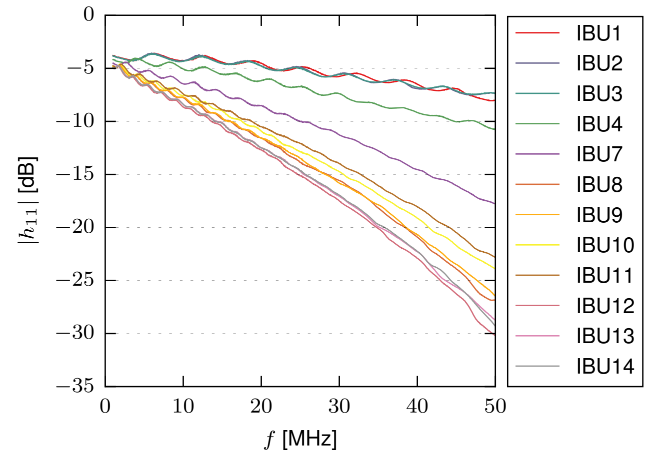


Fig. 3. Impact of the link length: Magnitude response of first co-channel at different IBUs

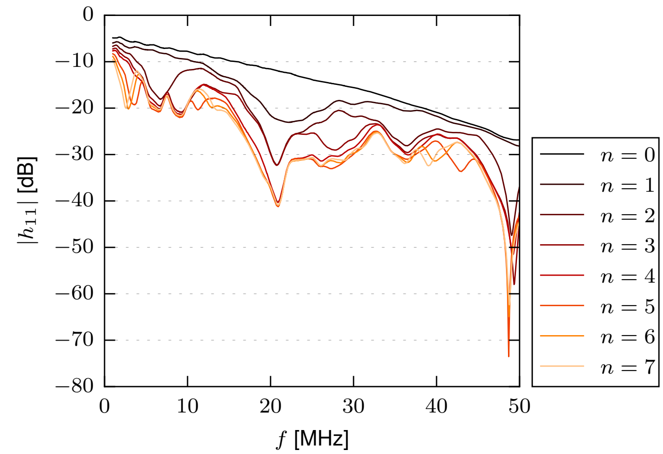


Fig. 4. Impact of branches: Magnitude response of first co-channel at IBU8 with n branches connected

(in accordance to cross-talk in wired communications), while to the former we refer to as co-channels. This terminology and the aforementioned notations will be used throughout this paper.

IV. Channel Transfer Function

The CTF is a very objective measure to characterize the channel as it describes the ratio of the received signal to the sent signal. As detailed in the previous section, the CTF is complex valued, where the magnitude corresponds to the channel gain (or to its inverse, the attenuation), and the angle to the phase shift. In case of single channel systems, the channel gain can be directly interpreted as channel quality, since it reflects the physical losses on the link. In general, this also holds true for the co-channels of a MIMO channel. The values for the cross-channels have to be interpreted with care: Low channel gains correspond to low cross-talk (which is desirable for single channel systems), however, they do not necessarily correspond to the best MIMO performance. Also the opposite, i.e., high channel gains, does not necessarily correspond to good MIMO performance. Sec. V provides more insight into the MIMO channel characteristics.

In the following, the impact of the link length and the number of branches on the CTF is studied separately. The former case corresponds to topologies where all IBUs except one are disconnected from the network, and measuring the channel matrix for the different IBUs. The latter case corresponds to topologies where the channel matrix is measured at the same IBU with different number of IBUs connected to the network.

A. Impact of the link length

Fig. 3 shows the CTFs of the first co-channel for different link lengths and without any branches connected. The network without any branches behaves like a straight line, since we disconnect the branches directly from the DNs. This has been verified by a measurement on a straight line without DNs to make sure that the intermediary DNs do not affect the channel.

The major effect that can be observed is the increase of attenuation with both, distance and frequency. This behavior is consistent with other domains such as the access domain in low voltage (LV) networks (c.f. OPERA reference channels [11]). The other co-channels exhibit the same behavior, which can be seen in the Figs. 5a and 5b.

Specific to the MIMO channel are the periodic ripples in the co-channels, which do not appear for the terminated line of a SISO channel. This is due to the reflections created at the cross-channels, since they are not terminated. The periodicity of the ripples in the co-channels coincides with the periodicity of the notches in the cross-channels, which can be seen in Figs. 5a and 5b.

B. Impact of branches

Fig. 4 shows the CTFs of the first co-channel for the link to IBU8. The number of branches has been varied by subsequently connecting IBU7 to IBU14 to the network and thereby increasing the number of branches from 0 to 7. As expected, the branches introduce additional multipath propagation and therefore add fading notches to the CTF. Since we have static conditions, the locations of the fading notches do not change, instead, additional branches add more notches. Also, the overall attenuation is increased for increasing the number of branches, which makes sense since more loads are connected. From Fig. 5c we can see that both co- and cross-channels are affected by the branches in a similar way.

C. Statistical Analysis

Fig. 6 shows the cumulative distribution function (CDF) for a short link without branches (6a), a long link without branches (6b) and a long link with all branches (6c). A comparison of the two top-most graphs confirms the observation made for the impact of the link length. The median attenuation of the co-channels increases from $5\,\text{dB}$ to $14\,\text{dB}$ and also the higher frequency-dependency is reflected in the change of the slope. The median attenuation of the cross-channels, however, are not significantly affected, and the longer link has even less deep

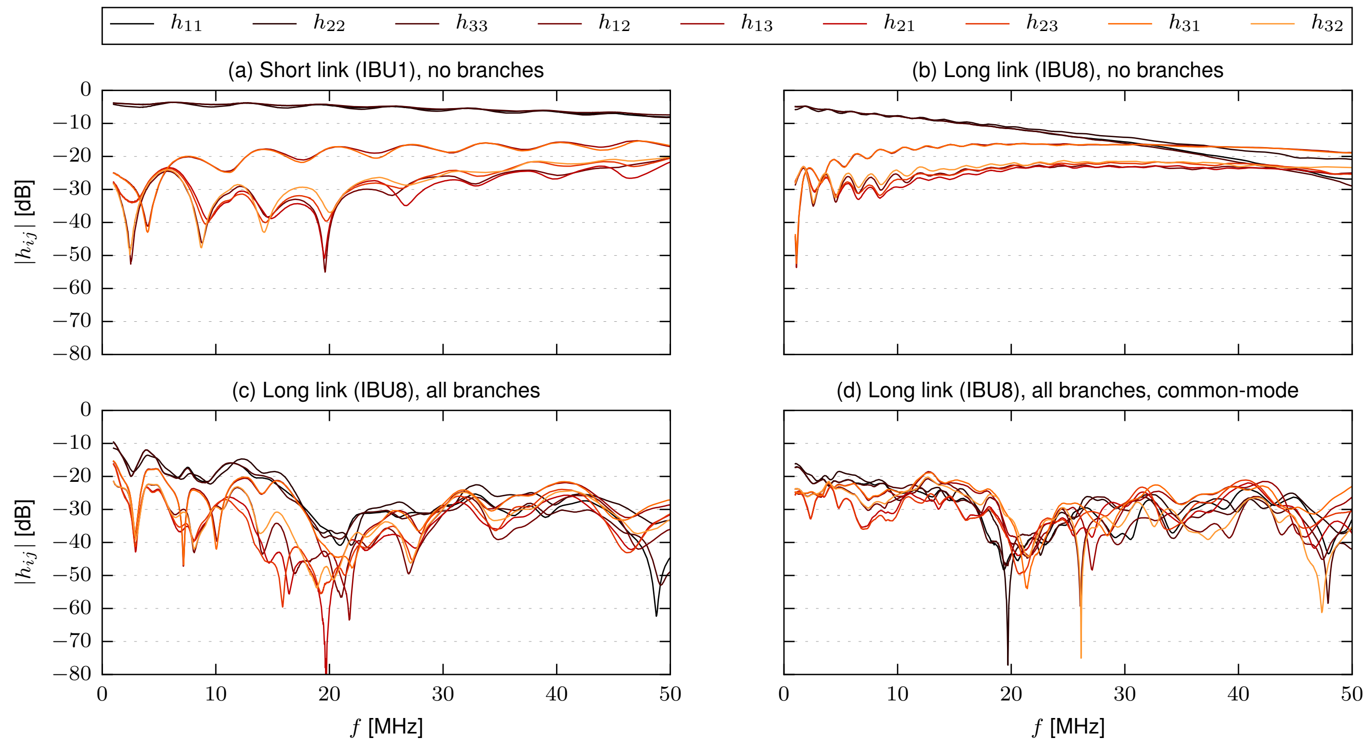


Fig. 5. Magnitude response of all co- and cross-channels for different topologies

notches. As a result, the distance between the co- and cross-channels decreases, which can also be seen from the CTFs themselves in Fig. 5a and 5b.

The third graph Fig. 6c shows the CDF for a long link with all branches connected to the network. We consider this scenario to happen more likely in reality than those without branches. The CDF shows that the distance between the co- and cross-channels further decreases, in fact, roughly 60 % of the co-channels are attenuated as much as the cross-channels.

V. MIMO Characteristics

The channel capacity of a SISO channel is a function of the channel gain, which explains why the channel gain is a good measure to evaluate the channel quality. For a MIMO channel, the singular values are an equivalent measure, since the capacity is a function of the singular values instead of the individual channel gains. In fact, the channel capacity is given by the sum of the capacities of the so-called eigen-channels, where the eigen-channels have a channel gain equal to the singular values of the MIMO channel [12].

Fig. 7a shows the three singular values $\sigma_1, \sigma_2, \sigma_3$ of the channel to IBU8 under different conditions. For the case without branches (black), it can be seen that the eigen-channels are close by and maintain a short distance between each other over the whole frequency range. For the case with all branches connected (blue), we can see significantly more fluctuation due to the multipath propagation. More importantly, the distance between the singular values is now varying over the frequency. A comparison with the singular values of the in-home channel in [8] indicates that the spatial correlation of our avionics harness is comparable to the residential power network.

A. Spatial Correlation

The previously made observation regarding the distance of the singular values can be quantified with the so-called condition number, which can be used as a measure for spatial correlation [7]. The condition number κ of a matrix A is defined as the ratio of the largest singular value to the smallest:

$$\kappa(A) = \frac{\sigma_{\max}(A)}{\sigma_{\min}(A)}. \tag{1}$$

The interpretation of the condition number can be illustrated with two simple examples:

a) All singular values are the same, which gives a condition number of one. In fact, it can be shown that this case yields the highest achievable channel capacity [12].
b) One or more singular values are zero. This yields a condition number approaching infinity.

The latter case has different implications, depending on the utilized MIMO technique. When using beamforming, zero valued singular values mean that less eigen-channels are available and thus the multiplexing gain decreases. However, since beamforming requires channel knowledge at the transmitter, it is capable of using only the available eigen-channels, which makes it more robust to spatially correlated channels [7]. Other MIMO techniques without channel knowledge at the

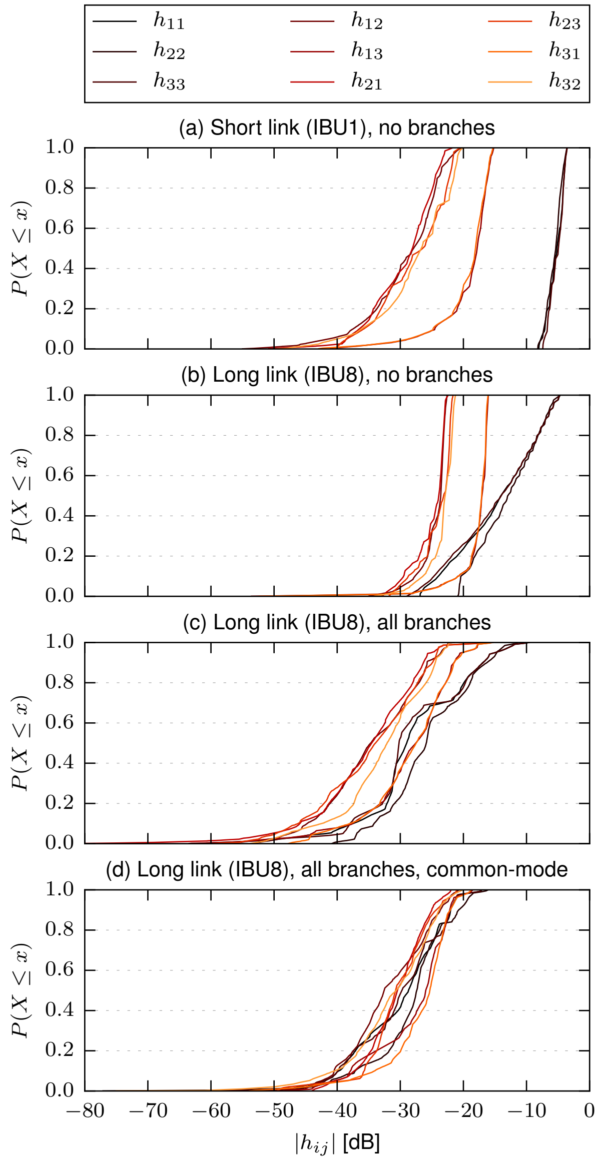


Fig. 6. Cumulative distribution function of magnitude response for 1 MHz to 50 MHz of all co- and cross-channels for different topologies

transmitter, such as V-BLAST, involve matrix inversions of the channel matrix at the receiver. Zero valued singular values imply non-invertible channel matrices, which result in severe performance degradation.

Fig. 7b shows the condition number for the channel to IBU8. It confirms the observation that the link without branches (black) operates close to a condition number of one, which is optimal in terms of MIMO channel capacity. On the other hand, the more realistic scenario with many branches (blue) shows higher condition numbers, which indicates degradation of the MIMO performance.

The spectral distribution of the condition number shown in Fig. 7b can be used similar to the coherence bandwidth for SISO systems. Since we are considering a broadband system, the condition number can be used to determine the bandwidth of the desired broadband MIMO system. For example, a MIMO system of only 10 MHz bandwidth would perform worse in the range of 15 MHz to 25 MHz, compared to a system in the range of 25 MHz to 35 MHz. Since the high condition numbers coincide with the frequencies of the deep notches, it is reasonable to assume that in a realistic scenario, these frequencies are random. Therefore, the bandwidth should be chosen high enough to compensate for the badly conditioned MIMO channel.

VI. Common Mode

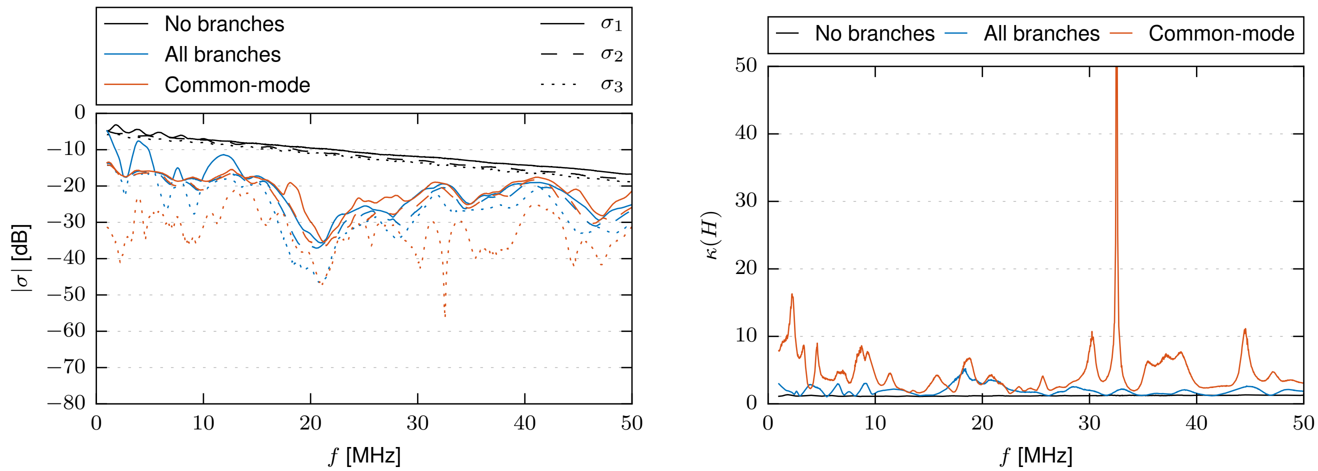
For the common mode (CM) operation we have replaced neutral as common return by the ground plane. This change applies to to the resistive loads that simulate the IBUs and also the coupling of the PLC signal. Since the neutral is bundled together with the phases into a single cable, it remains in the setup, but is disconnected (open loop). We limit our analysis to the realistic case of a long link with all branches connected.

We analyze the realistic scenario for long link lengths (IBU8) with all branches connected. The magnitude response of the CM channel is shown in Fig. 5d. A comparison with the magnitude response of the DM channel in Fig. 5c shows that the distance between co-channel and cross-channel is reduced due to higher attenuation of the co-channels. This observation is confirmed by the CDF in Fig. 6d, in fact, the co-channels are even higher attenuated than some of the cross-channels.

A second observation is an increase of the amount of notches in the CTF. However, when examining the CDF of the DM and CM channel, only the co-channels show a significant change. This means that the impression of more notches is only created by the overlay of all sub-channels in Fig. 5d, whereas, in fact, the locations of the notches are more distributed. From that we can conclude that the CM channel has more randomness than the DM channel.

An evaluation of the singular values and the condition number also shows that the CM channel has worse properties than the DM channel. Fig. 7a shows that the highest singular value of the CM channel (red) ranges at the level of the second singular value of the DM channel (blue). The smallest singular value of the CM channel is significantly smaller than the smallest singular value of the DM channel. The latter observation has an impact on the spatial correlation and is confirmed by Fig. 7b. It shows that the condition number of the CM channel is larger than the corresponding value for the DM channel for almost the entire frequency range.

The observations made for the CM channel suggest that the performance will be degraded compared to DM injection. Since CM is often motivated by the lack of a second return wire, this argument looses validity for MIMO systems. Since CM is also known to have worse electromagnetic compatibility (EMC) characteristics, we conclude that CM injection is not recommended for MIMO since it does not seem to have advantages over DM.



(a) Singular values

(b) Condition number

Fig. 7. MIMO characteristics for different topologies: No branches, all branches and common-mode

VII. Conclusion

In this paper we have presented an avionics test bench that emulates the CLS in the Airbus A380 aircraft. The layout of the network is chosen to mimic as realistically as possible both the distances and the topologies within the real system. We have installed a three-phase infrastructure to provide a wiring for a 3×3 MIMO PLC system. Finally, we present results from measurements of the MIMO channel that have been performed on this test bench.

An analysis of the CTF shows that the co-channel attenuation increases linearly with frequency, while the slope increases with the link length. Due to the lack of terminations at the cross-channels, the co-channels exhibit frequency-selective behavior shown as ripples, whereas the cross-channels exhibit deep notches. In a more realistic scenario with a more complex topology, both co- and cross-channels suffer from multipath propagation, while the relative distance between co-channel and cross-channel gain decreases.

An evaluation of the MIMO channel characteristics with respect to singular value and condition number shows that the topology without branches is close to the theoretical maximum capacity of the channel. However, an analysis of the condition number shows that the more realistic scenario with a more complex topology will suffer from multipath propagation. The spectral distribution of the condition number can be used, similar to the coherence bandwidth, to determine the bandwidth of a broadband system to meet a minimum performance.

Finally, we have analyzed the MIMO channel in CM. Under realistic conditions, the CM channel has shown worse performance over the whole frequency range. Since MIMO in CM operation requires in any case at least two wires, the use of CM loses its legitimacy. Together with the fact that CM is known to have worse EMC properties, we conclude that MIMO PLC in CM operation is not recommended.

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