Analysis of the Spatial Correlation of Indoor MIMO PLC Channels

Julio A. Corchado, José A. Cortés, Francisco J. Cañete, Antonio Arregui and Luis Díez

***Abstract*—In this paper, an analysis of the spatial correlation of multiple-input multiple-output (MIMO) power line communications (PLC) channels in the frequency range 1-80 MHz is provided, where the term spatial correlation refers to the relation between the paths that form the MIMO channel matrix. The study is based on a large set of 2x2 MIMO channels measured in four different countries. The presented statistical analysis of the condition number reveals three important facts. First, that the spatial correlation is almost independent of frequency, which has important implications in the development of top-down MIMO PLC channel models. Second, that the use of an alternative injection method can notably reduce the spatial correlation and, consequently, increase the system bit-rate. Third, that there exist countries whose channels have larger spatial correlation values than others. Since spatial correlation plays a key role in the performance of MIMO PLC systems, a hypothesis relating the type of wiring deployed in the indoor power grid to the spatial correlation is given and supported by simulations.**

***Index Terms*—MIMO, wiring, PLC, spatial correlation**

I. INTRODUCTION

In recent years, PLC has become a valuable solution to provide many services, like the support of local area networks (LAN)s and the transmission of high-speed multimedia content, in a cost-effective manner as it takes advantage of the already deployed power grid. In many countries, the majority of modern indoor power networks have three conductors: phase (P), neutral (N) and protective earth (E). This allows exploiting the MIMO capability of the channel by using differential transmission among conductors. Accordingly, the latest releases of PLC systems specifications include MIMO techniques [1], [2].

Studies carried out in the last years have analyzed characteristics of MIMO PLC channels such as the attenuation, delay spread and spatial correlation [3]–[6]. Channel models derived from measurements, referred to as top-down, and obtained from a model of the physical structure of the power grid, known as bottom-up, have been proposed [3], [5], [7]–[9].

In this context, the present work makes four contributions:

- It verifies that the spatial correlation is frequency independent, which notably simplifies the development of top-down MIMO PLC channel models.
- It shows that the spatial correlation can be reduced by modifying the injection mode. This result suggests a simple way of enhancing the performance of MIMO PLC systems without increasing their complexity.
- It reveals that there are countries whose channels have lower spatial correlation values than others, which implies that MIMO PLC systems might perform better in some countries than in others.
- It demonstrates that differences in the spatial correlation between countries can be largely due to the type of cabling deployed in their respective indoor power grids. This fact provides an *a priori* (without measurements) criterion to compare the performance that a given MIMO PLC system would attain in different indoor networks. It also highlights that top-down channel models should be parametrized differently depending on the type of cabling employed in the power grids under study.

Presented results are based on a measurement campaign carried out in four European countries. Channels were registered in the frequency band 1-100 MHz, but the analysis is restricted to the range 1-80 MHz to avoid the FM broadcast band.

The remainder of the paper is organized as follows. Section II presents the spatial correlation concept along with an analysis, carried out over measured channels, of its dependence on frequency and on the injection mode. Section III firstly shows that there are countries whose MIMO channels exhibit lower correlation values than others. Then, a hypothesis for this behavior is given and supported by means of simulations. Finally, in Section IV, conclusions are drawn.

II. CHANNEL SPATIAL CORRELATION ANALYSIS

A. Definition of Spatial Correlation

In this section, the spatial correlation of MIMO PLC channels is studied. The spatial correlation term has been adopted from the multiple-antenna wireless argot. The idea behind multiple-antenna configurations is that channels between each pair of transmitting and receiving antennas can be considered statistically independent. Thus, theoretically, multiple independent channels can be created, by means of some techniques such as precoding, which can then be exploited to improve link reliability and throughput [10]. In practice, full potential multi-antenna gains are not achievable because channels between each pair of transmitting and receiving antennas are not truly independent, but they are correlated to a certain degree. The closer antennas are deployed, the stronger the (spatial) correlation between channels is.

Spatial correlation can be seen as an indicator of the achievable gain in MIMO channels: the lower the spatial correlation, the higher the potential gain is [10]. In PLC, the

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existing multiple differential ports in each outlet play the role that antennas do in the wireless scenario. Hence, the spatial correlation definition applies since MIMO PLC channels are also described by matrices whose elements keep a certain dependence. In this paper, the analysis is focused on frequency domain 2x2 MIMO channel matrices, $\mathbf{H}(f)$, which are defined as follows

$$\mathbf{H}(f) = \begin{bmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{bmatrix}, \quad (1)$$

where $H_{ij}(f)$ denotes the channel frequency response (CFR) between the j-th transmitting port and the i-th receiving port for a given frequency f. The available ports in the typical three-conductor power-grid scenario with differential injection are PN, NE and EP; which stand for the differential signal between P, N and E conductors. From now on, the index f will be omitted for simplicity when not necessary.

In this work, channel spatial correlation is evaluated by means of the condition number of the MIMO matrix, as in [11], which for a 2x2 channel is defined as,

$$\kappa\ (\text{dB}) = 20 \log_{10}\left(\frac{\sigma_1}{\sigma_2}\right), \quad (2)$$

where σ_i denotes the i-th singular value of the MIMO channel matrix $\mathbf{H}$ and, without loss of generality, $\sigma_1 > \sigma_2$. Note that small values of κ denote lower spatial correlation and, therefore, higher potential gains.

B. Frequency Analysis

In Fig. 1, the cumulative distribution function (CDF) of the condition number of 132 channels measured in 11 locations from Belgium, Germany and the United Kingdom (UK) are split into three bands with the same amount of octaves per band. Measurements have been accomplished in average-size homes using the methodology described in [12]. As seen, obtained results point towards the confirmation that spatial correlation is roughly frequency independent.

This phenomena may turn out surprising as one of the main reasons the signal leaks into adjacent channels in PLC, $H_{ij} \neq 0$ for $i \neq j$, is the crosstalk due to the proximity of the wires. Being this effect extremely dependent on frequency, the higher the frequency the stronger the crosstalk effect, it would appear that spatial correlation should vary with frequency as well. What it may actually be happening is that crosstalk effects are somewhat being masked by other elements, such as impedance mismatches along the network and the effect that plugged-in devices introduce into the system.

Top-down models for MIMO PLC channels are generally built by adding a correlation term to a set of single-input single-output (SISO) responses. Models proposed up to now have implicitly assumed that spatial correlation is frequency independent [3], [8]. This notably simplifies both the model and the fitting process. However, to the authors' knowledge, this hypothesis has not yet been backed with measurements, in contrast to the well documented case of wireless channels [13]. Results shown in Fig. 1 corroborate the validity of the assumption.

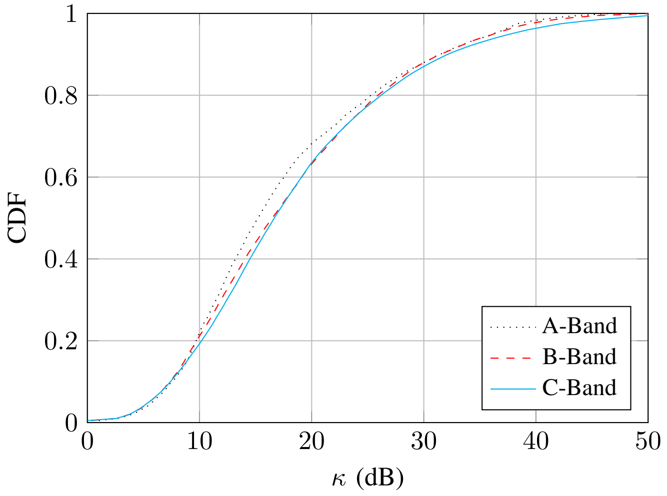

Fig. 1. CDF of the condition number of measured 2x2 MIMO channels (differential injection mode: PN and EP ports) split in three frequency bands. A-Band comprises frequencies between 1 and 5 MHz, B-Band goes from 5 to 20 MHz and C-Band covers the segment between 20 and 80 MHz.

C. Injection Modes

The most popular method for the transmission of electrical signals in both SISO and MIMO wired scenarios is the differential injection. This technique encodes the information in the voltage difference between a couple of wires (two or more couples are used in the MIMO case), in contrast to other techniques as single-ended injection which utilizes the voltage difference between one conductor and ground. However, there are many other injection modes available. As a matter of fact, some of the measurements studied in this work were obtained using a transmission method known as pseudo-differential injection [14]. In this section, some insight on the advantages and the expressions that relate this method to the conventional differential injection will be provided.

From the information in [14], and after some algebra, the pseudo-differential MIMO matrix, $\mathbf{H}^{\text{ps}}$, can be expressed in terms of the differential frequency responses as:

$$\begin{aligned} H_{11}^{\text{ps}} &= H_{\text{PN,PN}} \\ H_{12}^{\text{ps}} &= (H_{\text{EP,EP}} - H_{\text{NE,EP}} - H_{\text{NE,NE}} + H_{\text{EP,NE}}) \cdot \frac{1}{2} \\ H_{21}^{\text{ps}} &= (H_{\text{PN,NE}} - H_{\text{PN,EP}}) \cdot \frac{1}{2} \\ H_{22}^{\text{ps}} &= (H_{\text{EP,EP}} - H_{\text{NE,EP}} + H_{\text{NE,NE}} - H_{\text{EP,NE}}) \cdot \frac{1}{4}. \end{aligned} \quad (3)$$

One of the benefits of this mode with respect to the differential method is that the resultant 2x2 MIMO matrices are better conditioned, thus have lower values of κ, as depicted in Fig. 2. It shows the CDF of the condition number, κ, of the differential and pseudo-differential MIMO matrices of all channels measured in Belgium, Germany and the UK.

The performance of MIMO systems is higher in uncorrelated channels than in correlated ones, under similar noise and attenuation conditions [10]. Hence, results shown in Fig. 2 suggest an inexpensive way of improving the performance of MIMO PLC systems, since the complexity of the coupler

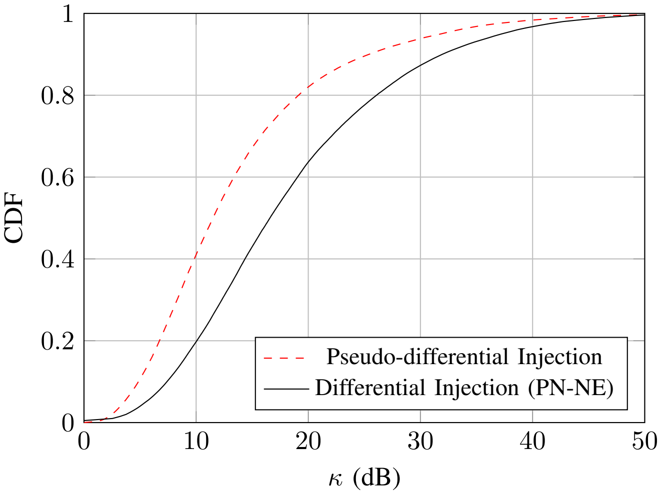

Fig. 2. CDF of the condition number of 132 measured 2x2 MIMO channels for different injection modes. Measurements were taken in 11 locations belonging to Belgium, Germany and the UK.

needed to perform the pseudo-differential injection is similar to the conventional one employed in differential injection [14].

III. Wiring Influence on Spatial Correlation

Wiring practices vary greatly from one country to another. For example, home electrical circuits in UK buildings usually follow a ring-shaped arrangement whereas the use of branched (tree-like) structures is the most common practice everywhere else in Europe. Similarly, while monopolar and flat cables are the *de facto* standards in Spain and in the UK, respectively, both types can be simultaneously found (in different proportions) in other countries. The relative position between conductors inside wires is fixed in UK power grids due to the use of flat cables, as shown in Fig. 3. On the contrary, the loose arrangement of wires inside the conduits typically found in other European countries (including Spain) causes the relative position between conductors to change continuously along the length of the cables. This variable distance modifies the responses of the individual links that form the MIMO channel matrix substantially and, therefore, the relative relation between the links.

The aforementioned fact leads us to consider the hypothesis that there is a strong relation between the type of wiring used in the power grid and the spatial correlation of the MIMO PLC channels. To corroborate it, the spatial correlation of UK and Spanish channels is analyzed. They have been selected because of the greater certainty that measured power grids in these countries are deployed using flat and monopolar cables, respectively. These results are then compared with the ones derived from a set of channels generated using a bottom-up in-home PLC channel generator based on multiconductor transmission line (MTL) theory configured with both types of cables.

A. Measurements

Fig. 4 displays the CDF of the condition number of 93 pseudo-differential MIMO matrices corresponding to channels measured in Spain and the UK. As seen, there is a difference of around 7 to 10 dB in the 20% of the channels with the highest values of κ. Even though the difference is lower for the rest of the channels, it is still a significant one.

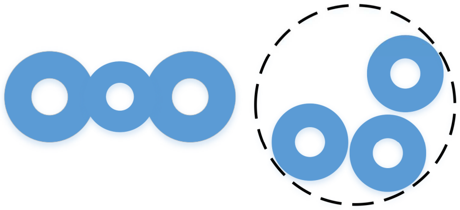

Fig. 3. Cross section of a 3 conductor flat cable (left) and of 3 monopolar cables (right).

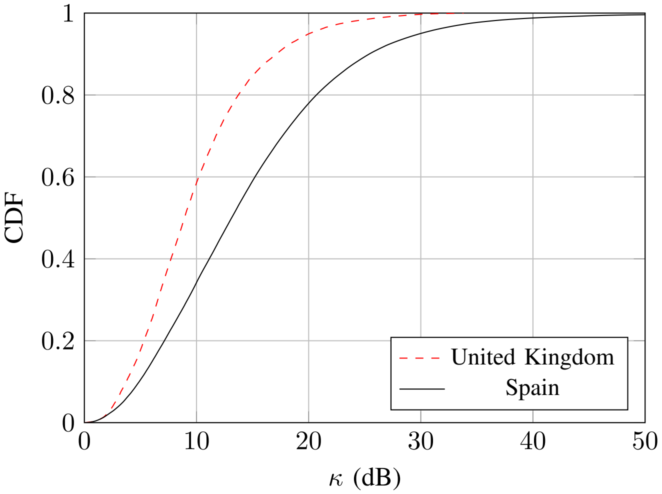

Fig. 4. CDF of the condition number of 93 measured 2x2 MIMO channels (pseudo-differential injection) located in the UK and Spain.

B. Simulations

Fig. 4 shows that MIMO PLC channels measured in Spain exhibit larger spatial correlation values than the ones measured in the UK. However, simulations must be accomplished to confirm that the disparity is due to the type of cabling and not to the topology differences (tree-like vs ring-shaped). To this end, a bottom-up channel generator must be used, since results given by top-down ones are biased by the set of measurements employed to fit their parameters. Accordingly, the study has been carried out using an MTL-based generator like the one described in [9]. Fifty random channels have been generated for both flat and monopolar wiring settings. A tree-shaped topology is used in all cases in order to isolate the effect of the type of wiring on the channel spatial correlation. The generated power grids correspond to average-size dwellings, like the measured ones.

Fig. 5 shows the CDF of the condition number of the generated channels. It can be clearly observed that the type of wire deployed in the underlying power grid has a significant influence on the spatial correlation. As seen, monopolar wires yield MIMO channels with larger correlation values than flat ones, as it happens in the measured channels shown in Fig. 4.

It must be emphasized that the objective of Fig. 5 is just to highlight that the correlation differences shown in Fig. 4 can be largely due to the different type of wiring used in the network. Nevertheless, it can be noticed that there is quite a good match between the values of the channels generated using monopolar wires and the ones measured in Spain, despite the fact that the topology and the number and type of devices connected to the measured networks are completely unknown. The larger differences between curves corresponding to channels generated using flat wires and to channels measured in UK can be due to their significant topology differences. As mentioned, circuits in actual UK homes usually have ring-shape arrangements, while tree-like deployments have been employed in the simulations. Moreover, further simulations (not shown here) have been performed to assess the effect of the indoor grid size in the spatial correlation. Obtained results indicate that its influence is much smaller than the one of the type of cabling. Hence, it is not the main cause of the differences observed in Fig. 4.

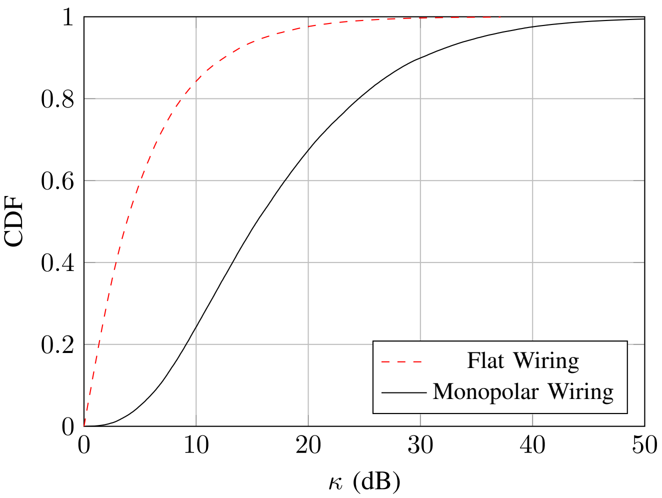

Fig. 5. CDF of the condition number of 50 generated 2x2 MIMO channel matrices (pseudo-differential injection mode) for different grid wiring settings.

There are several characteristics of indoor power grids whose qualitative influence in the performance of PLC systems is well-known. For instance, as the number of devices connected to the grid increases (so does the noise level), performance decreases. Similarly, as the size of the indoor network increases (so does the number of branches and the multipath effect), performance gets lower. When dealing with MIMO systems, results shown in this section add another element to this catalogue: performance will be higher in networks with flat cables than in those with monopolar ones (assuming similar power grid sizes and number of connected devices).

Finally, results shown in this section also confirm that top-down MIMO PLC channel models should be parametrized differently in power grids using monopolar and flat cables.

IV. CONCLUSION

In this work, three main results concerning spatial correlation in MIMO PLC channels have been presented. Firstly, it has been shown, by means of measurements, that spatial correlation in PLC channels does not show a significant dependence with respect to frequency, just like in the typical wireless MIMO scenario. Secondly, it has been shown that there exist alternative injection modes to the usual differential one, like the pseudo-differential injection, which yield lower spatially correlated MIMO channels. Lastly, it has been pointed out that spatial correlation is substantially dependent on the country where the channel is located in. In this regard, a hypothesis that relates this diversity to the type of wiring chosen for the power grid is stated and then supported with simulated results.

ACKNOWLEDGMENT

The authors would like to thank Marvell Hispania S.L. for its support and contribution to this work.

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