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Indoor Channel Modelling for PLC Network in MIMO Context

Abdelmounim HMAMOU*
Faculty of science and technology, Moulay Ismail University of Meknes, Morocco
E-mail : hmamou0512@gmail.com
ORCID iD: https://orcid.org/0009-0001-1816-6338
*Correspondging author

Mohammed EL GHZAOUI
Faculty of Science Dhar Almahraz, Sidi Mohamed ben Abdelleh University, Fez, Morocco
E-mail: elghzaoui.mohammed@gmail.com
ORCID iD: https://orcid.org/0000-0003-3416-2246

Jaouad FOSHI
Faculty of science and technology, Moulay Ismail University of Meknes, Morocco
E-mail: j.foshi@yahoo.fr
ORCID iD: http://orcid.org/0000-0001-7982-8633

Serghini Elaage
Faculty of Science, Moulay Ismail University, Meknes, Morocco
E-mail: kate7smith12@gmail.com
ORCID iD: https://orcid.org/0009-0006-6930-5023

Said Elkhaldi
National School of Applied Sciences Al Hoceima, Abdelmalek Essaadi University, Morocco
E-mail: s.elkhaldi@uae.ac.ma

Sudipta Das
Department of Electronics and Communication Engineering, IMPS College of Engineering and Technology, W.B., India
E-mail: sudipta.das1985@gmail.com
ORCID iD: https://orcid.org/0000-0002-8644-7342

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Abstract: This paper presents a comprehensive study on the modeling of power line communication (PLC) channels in a MIMO (Multiple Input Multiple Output) environment. PLC systems utilize existing electrical infrastructure to transmit data, but the complexity of these channels, characterized by multipath propagation and inter-symbol interference (ISI), poses significant challenges for designing robust and efficient systems. In this study, we rigorously compare two approaches to PLC channel modelling, which are as follows: the empirical approach and the deterministic approach. The empirical approach relies on the analysis of experimental data to derive statistical models of the channel, offering a realistic representation based on concrete observations. In contrast, the deterministic approach employs theoretical principles and electromagnetic equations to model the channel behavior, providing a detailed description of propagation phenomena. The obtained results demonstrate the significant impact of multipath propagation on the performance of PLC communication systems, highlighting the limitations of empirical models in various scenarios and the increased accuracy of deterministic models. This comparative study conducted in this work highlights the advantages and limitations of each approach and proposes solutions to optimize the performance of power line communication networks.

Index Terms: Transmission Channel, Channel Modeling, Power Line Communication, MIMO-PLC, 'Top-Down' and 'Bottom-Up' Approaches, Hybrid Models.

1. Introduction

Power Line Communication (PLC) systems represent an innovative and promising solution for high-speed data transmission, leveraging the existing electrical infrastructure. By utilizing power lines for data transmission, these systems can potentially reduce installation and maintenance costs while providing extensive coverage without the need for new cabling infrastructure. However, the inherent complexity of PLC transmission channels presents significant challenges for the modeling and design of robust and efficient communication systems.

PLC channels are characterized by signal propagation influenced by multipath effects, where signals reflected off various obstacles reach the receiver with different delays and amplitudes, resulting in inter-symbol interference (ISI). This multipath nature of the channel complicates the task of maintaining the integrity and quality of the transmitted signal. Additionally, the temporal variability of PLC channels, due to constant changes in the electrical loads connected to the network adds an extra layer of complexity. Furthermore, PLC channels are affected by several disruptive phenomena, including crosstalk, which is the interference between adjacent transmission lines, attenuation, which decreases the signal power as it propagates along the line, and impulsive noise, which is produced by household appliances and other devices connected to the power grid [1]. Accurate modelling of PLC channels is essential in order to predict and enhance the effectiveness of communication networks, given these combined factors.

A PLC channel model is defined using the 'top-down' approach. Extensive research has been conducted on different power grid topologies and frequency bands. Zimmermann and Dostert [2, 3] proposed the first contribution that defined a model describing the propagation of the PLC signal frequency along the power grid. This model is one of the most well-known in the literature. Using the analytical formulas presented in [4], average attenuation models of the PLC channel as a function of frequency were obtained. Notably, Tonello’s improvement in [5,6] is essentially a statistical extension of Zimmermann's "Top-Down" model, extending the frequency band up to 100 MHz with model parameters considered as random variables. In this extension, and based on the experimental analysis presented in [7], two algorithms can be exploited: the Frequency Domain Maximum Likelihood (FDML) algorithm or the Matrix Pencil (MP) algorithm. More details on the application of these techniques can be found in [7,8].

Conversely, the second approach follows a bottom-up strategy. Therefore, it is commonly called "Bottom-Up." It involves developing an overall model view from the fundamental elements forming the main characteristics of the studied channel. The Multiconductor Transmission Line (MTL) theory is the main basis for this family of models, which allows for accurately describing all phenomena associated with signal propagation from the transmitter to the receiver. Adopting this technique requires a thorough knowledge of the studied network details, especially the electrical cables' properties (section, length, linear and physical parameters), network architecture, connected load impedances, etc. Consequently, this knowledge allows establishment a precise expression of the channel's transfer function, enabling a highly accurate determination of its behavior [4,9].

Since both modeling approaches have strengths and weaknesses, a promising direction would be to develop a hybrid channel modeling method that leverages the advantages of each, in order to achieve a more comprehensive and accurate model. This so-called hybrid approach relies on deterministic algorithms to accurately estimate statistical parameters while considering the propagation channel's specific characteristics. Hybrid models generally rely on the complementarity of two techniques: deterministic and empirical.

The importance of accurate modeling lies in its ability to provide a detailed understanding of signal propagation behaviors and complex interactions within the channel. Effective modeling enables the design of optimized modulation and coding strategies, the development of advanced signal processing techniques, and the implementation of Multiple Input Multiple Output (MIMO) configurations that can significantly enhance the robustness and capacity of PLC systems. Therefore, addressing the challenges of PLC channel modeling is crucial to realize the full potential of this technology and ensure reliable high-speed communications in various residential and industrial applications.

This article aims to explore robust models for PLC communications in MIMO (Multiple Input Multiple Output) environments. In order to increase the capacity and reliability of the communication channel, multiple-input multiple-output (MIMO) systems use several antennas at the transmitter and receiver [10-12]. To ensure an accurate model of the PLC channel in MIMO environments, we focus on two main approaches: empirical and deterministic. By combining these two approaches, the objective is to develop hybrid models that use the advantages of each to enhance the robustness and efficacy of PLC communication systems in MIMO environments. This comparative study highlights the advantages and limitations of each approach and proposes solutions to optimize the performance of power line communication networks.

We begin this article by highlighting the MIMO transmission technique and its significant applications, particularly those related to PLC communications in residential environments. After providing a general overview of channel characteristics, we then present a range of existing approaches for modeling PLC channels. We then extend the single-antenna PLC transmission (or SISO) to the multi-antenna case by introducing the MIMO technique. Thus, in order to choose the approach that will serve as the basis for our MIMO-PLC channel modeling, models developed for PLC channels in the MIMO context are presented and analyzed. In the final paragraph of this article, we provide a frequency-domain and time-domain description of electromagnetic noise observed in the domestic electrical network as a MIMO-PLC channel.

2. Methodology

2.1. Empirical Modeling of MIMO-PLC Channels

Empirical modeling corresponds to a bottom-up strategy, meaning that before defining the model parameters more precisely, one first considers the overall channel statistics obtained from experimental measurements. The analytical study of these measurements allows determining a model represented by a mathematical expression composed of several parameters. This expression represents the transmission channel behavior either as a transfer function in terms of frequency or as an impulse response in terms of time. One of the main advantages of this approach is that it generates simple models that are easy to use and provide realistic results. However, the lack of adaptability to all topologies is a major challenge of this technique, meaning that the model derived from measurements only applies to the measured network and within the measured frequency range. A significant issue is the requirement for a substantial amount of experimental data.

Extensive research has been conducted on different electrical network topologies and frequency bands to define a PLC channel model with the 'top-down' approach. Relying on the multipath phenomenon occurring in the propagation channel, this model is represented by the transfer function $\Psi(\nu)$ given as a function of frequency ν by the equation:

$$\Psi(\upsilon) = \sum_{n=1}^{\Lambda} \delta_n(\nu).\chi(\upsilon, l_n).e^{-j2\pi\upsilon\frac{l_n}{V}} \quad (1)$$

Where:

- Λ is the number of propagation paths,
- δ_n and l_n respectively represent the weighting and length of the n-th propagation path,
- V represents the propagation velocity in transmission lines,
- $\chi(\upsilon, l_n)$ defines the attenuation coefficient on a PLC channel in the frequency domain. This attenuation is characterized by the expression: $\chi(\upsilon, l_n) = e^{-(\alpha+\beta\upsilon^{\Phi})l_n}$, where α, β, and Φ are constants representing attenuation factors derived from transfer function measurements.

Indeed, signals transmitted from a transmitter reach a receiver after following numerous paths, both direct and indirect. To implement the behavior of the PLC channel based on this multi-path model, it is necessary to take into account a precise understanding of the propagation properties of each reflection and transmission in this channel. Note that it will be challenging to evaluate and apply this approach as the network becomes larger and more complex. Several other suggestions have contributed to the development of the PLC channel model described above. Therefore, the expression of the transfer function for this new model is given by:

$$\Psi(\upsilon) = \Gamma \sum_{n=1}^{\Lambda}(\delta_n + \theta_n\upsilon^{\rho}).\ e^{-(\alpha+\beta\upsilon^{\Phi})l_n}.e^{-j2\pi\upsilon\frac{l_n}{V}} \quad (2)$$

In this extension, the parameter values Γ, α, β, ρ, and Φ are considered constant and are used to fit the model to the measured frequency responses. The path length l_n is generated according to a Poisson arrival process with an intensity Φ=0.2 per meter. The path gain factors δ_n and θ_n are generated randomly using a log-normal distribution within the interval [1, -1].

Given the enhancements derived from the use of MIMO technology for PLC communications, numerous studies have been conducted on existing MIMO-PLC channels in the literature. The initial applications of MIMO technique for domestic PLC transmission were conducted in [13,14]. The use of a 2×2 MIMO-PLC channel configuration increased the average capacity by 1.9 compared to SISO-PLC channels, and this gain increases with the number of ports at the receiver level, such that 2.6 can be achieved by leveraging the 2×4 MIMO-PLC channel.

The empirical method was also applied by Canova et al. in [15] to propose a model of a PLC channel in the MIMO context. The principle of this model considers the residential electrical network as a 2×4 MIMO-PLC channel, where 2 ports at the transmitter and 4 ports at the receiver are used, including the common mode. Thus, the approach consisted in introducing a random phase shift into the impulse response, generating eight distinct variations in order to construct the MIMO-PLC channel matrix. Note that each of these variations have the same number of multipath components. The amplitude of certain paths is amplified by a random phase factor to establish a spatial correlation across MIMO sub-channels akin to that observed empirically.

Building on the same approach, Hachmat et al. proposed a 3×3 MIMO-PLC channel model in [16] by adding an arbitrary phase is assigned to each trajectory within the specified interval $\left[-\frac{\Delta\varphi}{2}, \frac{\Delta\varphi}{2}\right]$. We base the recommended model is primarily based on Zimmermann's SISO channel model, which was published in [3], as described in the preceding paragraphs. The idea is to replicate all necessary parameters to generate an accurate model, such as path frequency attenuation parameters, multipath fading, median channel attenuation, and spatial correlation of MIMO channels. By evaluating the experimental properties of the MIMO channel matrix, the SISO sub-channel model can be extended to the MIMO-PLC channel model through the following procedures:

- The first step involves simulating the SISO sub-channels independently so that each sub-channel is generated based on the model proposed in [3,5], using parameters (Γ, α, β, ρ and Φ) obtained according to the statistical laws observed in experimental measurements. In this step, the median propagation channel gain $G_{med} = median(|\Psi(\upsilon)|)$, representing the overall channel attenuation, must be equal to 1 to achieve proper application of the correlation matrix at transmission and reception.
- One of the main characteristics affecting channel capacity in a MIMO communication system is the correlation between the different available sub-channels. As the correlation between sub-channels increases, the maximum capacity of MIMO systems is not reached. Therefore, when modelling the MIMO-PLC channel, it is necessary to consider the observed correlation between different sub-channels. Thus, in order to obtain correlation between the MIMO sub-channels observed in experimental measurements, and extend the SISO channel model to the MIMO-PLC channel model, it is necessary to study the correlation between the different MIMO sub-channels. Specifically, the amplitudes of correlation coefficients are chosen from normal distributions, and the phases of these coefficients are uniformly distributed within the interval [0, 2π].
- Finally, the correlated MIMO-PLC channel matrix is generated using the same approach as that used to model the multiple paths of the PN-PN path, as described by equation (2).

The modified transfer function can be used to model other spatial links if a random phase $\varphi_n \epsilon \left[-\frac{\Delta\varphi}{2}, \frac{\Delta\varphi}{2}\right]$ is added to each path.

$$\Psi(\upsilon) = \Gamma \sum_{n=1}^{\Lambda} \delta_n e^{-j\varphi_n}.\ e^{-(\alpha+\beta\upsilon^{\Phi})l_n}.\ e^{-j2\pi\upsilon\frac{l_n}{V}} \tag{3}$$

The appropriate values of Δφ are:

- The PT-PT channel is obtained from the PN-PN channel by selecting a phase difference Δφ = 2π;
- The NT-NT channel is obtained from the PT-PT channel by selecting a phase difference Δφ = π;
- All other channels are derived from the PN-PN channel by selecting a phase difference Δφ = π.

Another model based on the empirical stochastic approach was improved by Tomasoni et al. in [17]. The parameters of this model are obtained through the statistical analysis of a series of experimental measurements carried out up to a maximum frequency of 100 MHz, in the electrical networks of five different residences in North America. The first step is to use the statistics that have been obtained through experiments to describe each link of the MIMO-PLC channel. Then, the development of the MIMO-PLC channel model involved the introduction of a statistical correlation using an approach similar to that adopted in reference [18]. The correlation between the different MIMO sub-channels is analyzed through a measurement campaign conducted in [17]. Thus, the frequency-dependent MIMO-PLC channel matrix is given by:

$$\Psi(\upsilon) = \Upsilon(\upsilon).R_r^{\frac{1}{2}}(\upsilon).\Psi'(\upsilon).R_t^{\frac{1}{2}}(\upsilon) \tag{4}$$

Where Y represents the overall channel attenuation, which is well represented by the channel gain, R_t and R_r respectively represent the correlation matrices at the transmitter and receiver, and Ψ' is a channel matrix composed of independently and identically distributed Gaussian variables.

2.2. Deterministic Modeling of MIMO-PLC Channels

The approach used by deterministic modeling is a bottom-up one, based on the electrical properties of transmission lines (MTL). This approach provides an accurate description of propagation phenomena but requires a detailed understanding of the channel characteristics. The deterministic approach uses the fundamental equations of transmission line theory to model the PLC channel's behavior The deterministic approach relies on the fundamental equations of transmission line theory to model the behavior of the PLC channel. The approach involves the division of cables into an infinite number of elementary cells, as illustrated in Figure 1. Each cell of length dx is characterized either by the primary RLGC parameters of the cable or by the secondary parameters ZC (characteristic impedance) and γ (propagation coefficient).

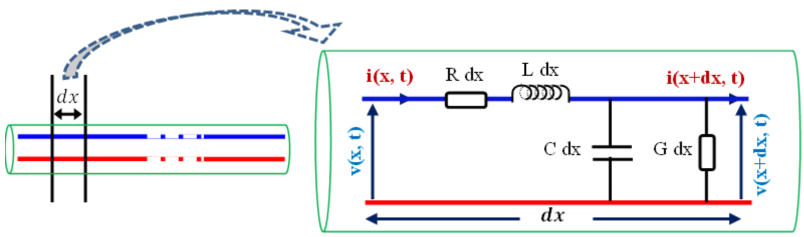

Fig.1. Elementary cell of a PLC line with length dx

These latter parameters are given respectively as a function of the primary parameters by the following expressions:

$$Z_C = \sqrt{\frac{R+i2\pi\upsilon L}{G+i2\pi\upsilon C}} \quad (5)$$

$$\gamma = \sqrt{(R + i2\pi\upsilon L)(G + i2\pi\upsilon C)} \quad (6)$$

Where υ is the frequency, and the parameters R, L, G, and C represent the longitudinal linear resistance, longitudinal linear inductance, transverse linear conductance, and transverse linear capacitance, respectively. Various techniques can be used to extract the values of these parameters. They can be calculated from analytical formulas based on the geometric and physical characteristics of the cable [19], as well as using simulation software. It is also possible to derive them from measurements (from S-parameters using a network analyzer [4], or from the cable impedance using an impedance analyzer [19]). This approach enables precise and detailed modeling of PLC channels by taking into account the physical and geometric parameters of the transmission lines.

Regarding the chain matrix approach, the modeling of such a transmission configuration relies on segmenting this structure into several sections (lines and branches). The lines correspond to the sections placed along the main path, while the branches correspond to the sections connected to it (derivations). Thus, the structure of the entire PLC network is modeled by a succession of elementary two-port networks, which can be represented by an ABCD matrix. The overall transfer function Ψ(υ) is then calculated from the total matrix, resulting from the multiplication of the matrices of the different segments. To illustrate the chain matrix approach, we consider the topology of a simple electrical network with a single derivation. Based on this approach, the configuration can be represented by a sequence of two-port networks as shown in Fig.2.

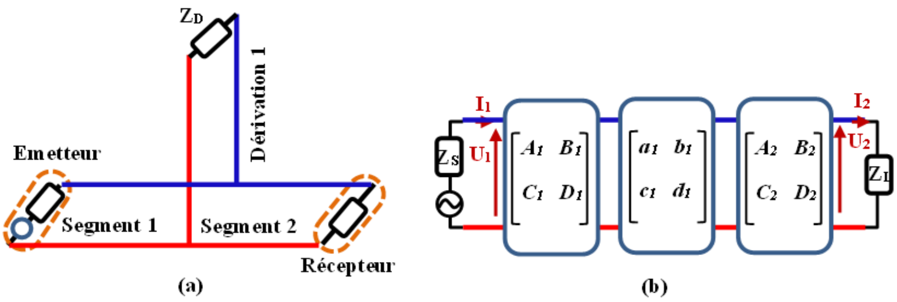

Fig.2. (a) Simple topology, (b) its equivalent chain matrix representation

In this example, the total ABCD matrix is constructed as follows:

$$\begin{pmatrix} A_T & B_T \\ C_T & D_T \end{pmatrix} = \begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \times \begin{pmatrix} a_1 & b_1 \\ c_1 & d_1 \end{pmatrix} \times \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix}$$

The parameters A, B, C, and D can be calculated from the secondary parameters as follows: $A = D = cosh\,(\gamma l)$; $B = Z_C sinh\,(\gamma l)$; $D = {Z_C}^{-1} sinh\,(\gamma l)$

And for the parameters a, b, c and d, they are expressed as follows: $a = d = 1$; $b = 0$; $d = {Z_C}^{-1}\, \frac{Z_C + Z_D tanh\,(\gamma l)}{Z_D + Z_C tanh\,(\gamma l)}$

With l being the length of the line of a section (segment or branch). The network's transfer function is derived from the total chain matrix using the following equation:

$$\Psi(\upsilon) = \frac{Z_L}{A_T Z_L + B_T + C_T Z_S Z_L + D_T Z_S} \quad (7)$$

The deterministic approach has been used to propose several MIMO-PLC channel models in the literature, as detailed in [9,20-23]. In this form of modeling, the MTL (Multi-Conductor Transmission Line) theory has been used to exploit the plurality of conductors in domestic electrical networks to establish a MIMO-PLC channel. However, in the initial applications of this type of modeling, the third available conductor in the domestic network was not considered for transmitting a high-frequency signal via power networks.

Thus, to enhance the performance and efficiency of PLC communication systems in terms of data rate, it is possible to exploit the three wires of the electrical network by adopting MIMO transmission technology as a promising solution. The first studies using MTL theory to model the domestic electrical network as a MIMO-PLC propagation channel were proposed in references [20,24]. The data from these studies enabled the definition of a 2x2 MIMO-PLC transmission system that takes into account the coupling between the conductors within a three-wire cable. The obtained model was validated by comparing the frequency attenuation of the measured and modeled channel.

Another example of deterministic modeling is provided in [22], where the channel model is defined according to the simple MTL (Multi-conductor Transmission Line) theory-based model by adding three modifications (connected electrical devices, branches, and wiring). This aims to improve the channel behavior up to a frequency of 100 MHz. In addition to these enhancements in channel modeling in a residential environment, another contribution related to the influence of common-mode and differential-mode radiation was presented in [23]. The results of this study on the MIMO-PLC channel transfer function verified that differential modes would not cause additional radiation and can therefore be ignored. MIMO-PLC systems are affected by radiation in several ways, but the main source of this radiation is the common-mode signal.

Based on the MIMO-PLC channel transfer function [25] We obtained a new calculation within the same framework and based on MTL theory. This calculation enabled us to observe how devices connected to different outlets in our PLC network influence the channel capacity. This enabled us to demonstrate that the data rate on the MIMO-PLC network is affected by a number of factors, including the type of plug of the device connected to the network outlets. My main contributions are detailed in the work [1]. We selected this model because of its representation through a straightforward mathematical formulation and its special suitability for the characteristics of the home PLC channel. This modelling approach does not demand field measurements; it solely requires comprehensive information of the transmission environment, including network topology, cable properties, and the impedance of each network node.

In MIMO communication inside PLC systems, the signal is simultaneously injected across many ports. To define the three-conductor cable, we can employ the per-unit-length (p.u.l.) equivalent model of an electrical network. As shown in Fig.3, Kirchhoff's laws are used to derive the vector form of the equations expressing voltage and current in the elementary cell of the line. Further information on the general solution of these differential equations can be found in references [1,26].

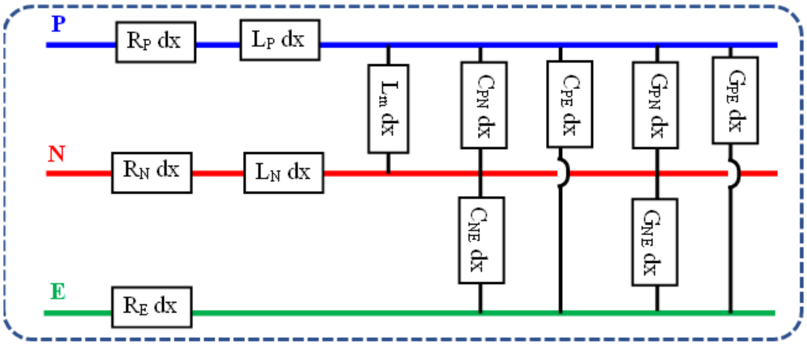

Fig.3. A three-wire electrical line's equivalent per-unit-length circuit

From the matrices obtained for each section, the entire network is given by:

$$M_{Total} = \prod_{n=0}^{N} M_n = M_0 \times M_1 \times \dots M_{N-1} \times M_N \tag{8}$$

M_k is the transmission matrix of segment k, which has a length of l_k. Consequently, the 4×4 matrix can be expressed as follows:

$$M_{Total}^{pq} = \begin{bmatrix} M_{11}^{pq} & M_{12}^{pq} \\ M_{21}^{pq} & M_{22}^{pq} \end{bmatrix}$$

Combine the transmitter/receiver voltages U_{in} and U_{out}. Substitute for at the end of the network, we can then write:

$$U_{out} = \Theta_{11} U_{in} + \Theta_{12} I_{in} \tag{9}$$

and,

$$Z_{out} I_{out} = Z_{out} \Theta_{21} U_{in} + Z_{out} \Theta_{22} I_{in} \tag{10}$$

Subsequent to modification:

$$V_{out} = \Theta_{11} V_{in} + \Theta_{12} I_{in} \tag{11}$$

$$(Z_{out}\Theta_{22})^{-1}(U_{out} - Z_{out}\Theta_{21}U_{in}) = I_{in} \tag{12}$$

Substituting the current I_{in} into the relationship for U_{out}, gives us the expression:

$$V_{out} = \Theta_{11} V_{in} + \Theta_{12} {\Theta_{22}}^{-1} {Z_{out}}^{-1} U_{out} - \Theta_{12} {\Theta_{22}}^{-1} \Theta_{21} U_{in} \tag{13}$$

After modification, we can write:

$$\left(I - \Theta_{12} {\Theta_{22}}^{-1} {Z_{out}}^{-1}\right) U_{out} = \left(\Theta_{11} - \Theta_{12} {\Theta_{22}}^{-1} \Theta_{21}\right) U_{in} \tag{14}$$

This expression can be simplified to:

$$U_{out} {U_{in}}^{-1} = \left(I - \Theta_{12} {\Theta_{22}}^{-1} {Z_{out}}^{-1}\right)^{-1} \left(\Theta_{11} - \Theta_{12} {\Theta_{22}}^{-1} \Theta_{21}\right) \tag{15}$$

Finally, we can give the transfer function of the MIMO-PLC channel with three wires as follows:

$$\Psi^{ij} = \left(I - \Theta_{12}^{pq} \left(\Theta_{22}^{pq}\right)^{-1} \left(Z_{out}^{pq}\right)^{-1}\right)^{-1} \left(\Theta_{11}^{pq} - \Theta_{12}^{pq} \left(\Theta_{22}^{pq}\right)^{-1} \Theta_{21}^{pq}\right) \tag{16}$$

Where, $\Theta_{11}^{pq} = \left(M_{Total}^{pq}\right)^{-1}(1,1)$; $\Theta_{12}^{pq} = \left(M_{Total}^{pq}\right)^{-1}(1,2)$;

$$\Theta_{21}^{pq} = \left(M_{Total}^{pq}\right)^{-1}(2,1)\,; \quad \Theta_{22}^{pq} = \left(M_{Total}^{pq}\right)^{-1}(2,2)$$

I is the 2×2 identity matrix, and $\begin{pmatrix} V_{out} \\ I_{out} \end{pmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \begin{pmatrix} V_{in} \\ I_{in} \end{pmatrix} = \begin{bmatrix} \Theta_{11} & \Theta_{12} \\ \Theta_{21} & \Theta_{22} \end{bmatrix} \begin{pmatrix} V_{in} \\ I_{in} \end{pmatrix}$ The inverse matrix of the chain matrix for a transmission line segment that has a length of L.

2.3. Hybrid Modeling of MIMO-PLC Channels

In order to choose the technique that can be used as a tool in our modeling, the approaches we previously described will be analyzed and compared based on criteria related to: ease of implementation, accuracy, robustness, and adaptability.

In terms of simplicity, the empirical method appears simpler than the deterministic method, as the empirical approach requires only a few measurements from which the parameters of the model can be derived. However, this technique presents various challenges, such as the difficulty in selecting significant paths, especially when the number of paths increases significantly, particularly in the presence of numerous branches in the network. In contrast, the deterministic approach only requires knowledge of the network architecture to develop the model.

Indeed, the most suitable method depends primarily on its accuracy in obtaining a transfer function that precisely matches its measured counterpart. Based on comparisons with measurements of transfer functions from different techniques highlighted in Fig.4, it can generally be concluded that empirical models are less accurate than deterministic models despite their simplicity advantage.

The empirical behavior of the channel is closely linked to a set of measurements characterizing various propagation scenarios. Each configuration is therefore associated with a statistical law that better describes propagation parameters. Thus, it is not easy to apply this model to other structures. However, the deterministic method produces a channel model based on adequate theoretical foundations. Consequently, a channel model that is based on a deterministic method is versatile and can be applied to a wider range of networks.

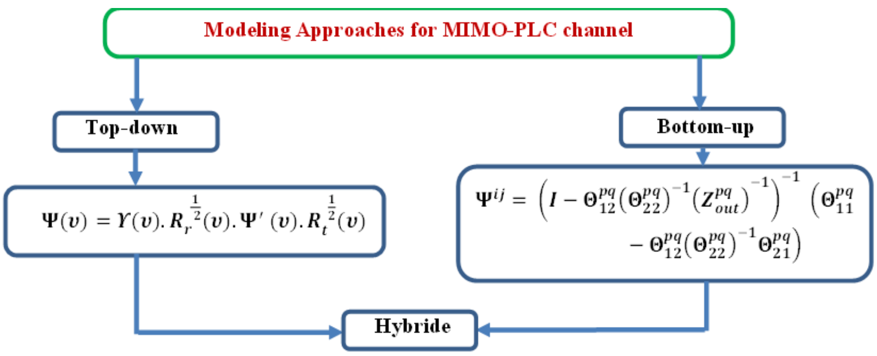

Fig.4. Different Approaches to PLC Channel Modeling

Given that both modeling approaches have strengths and weaknesses, a promising direction consists in designing a hybrid channel model that leverages the advantages of both methods, aiming at a more comprehensive understanding of the channel. This hybrid approach relies on deterministic algorithms to accurately estimate statistical parameters, taking into account the specificities of the propagation channel. Hybrid models typically leverage the complementarity of two techniques. Fig.4 illustrates these types of PLC channel modeling.

3. Results and Discussion

3.1. Network Topology Description

In this study, the PLC channel under consideration, depicted in Fig.5, utilizes a 2.5 mm² cross-sectional area cable, characterized by several branches connected to various household appliances such as lamps, PC chargers, mobile phone chargers, and electric heaters. The cross-section of the cable may vary depending on the connected load or type of power outlet. The twisted-pair cable is assumed to exhibit uniform physical dimensions and homogeneous electrical characteristics across the network, thereby ensuring consistent transmission performance.

The transmitter and receiver are both modeled as impedances, as shown in Fig.6, with all impedance values being equal: $Z^{11}_{in/out} = Z^{22}_{in/out} = Z^{12}_{in/out} = Z^{12}_{in/out} = 50\ \Omega$.

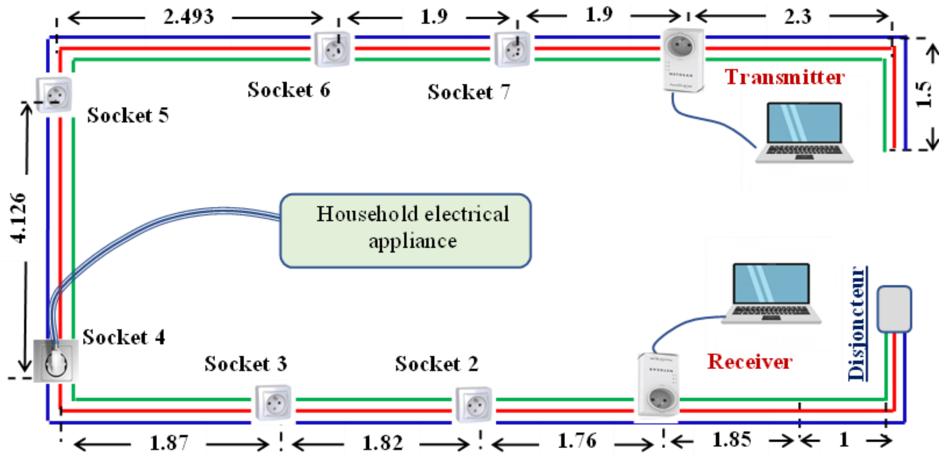

Fig.5. Experimental MIMO-PLC Network

Household appliances are categorized into five distinct classes based on their input impedance characteristics. The input impedances of these appliances are effectively modeled as series connections of parallel RLC circuits, given that their impedance values remain relatively constant in both operational and non-operational states. Consequently, an accurate modeling approach for the input impedances of household appliances should incorporate the methodology adopted in previous studies on series-parallel RLC circuit configurations [9,19,27,28]. Two of the devices include a grounding conductor, while the other two lack this feature. The impedances were strategically selected to assess their influence on the transfer characteristics of the transmission channel within a MIMO architecture.

The fundamental electrical parameters of the cables in the experimental setup are summarized as follows:

- Power lines radius: r = 0.89 mm;
- Distance between the power lines: d = 2.5 mm;
- The conductors' electrical conductivity: σ = 5,575 × 107 S/m;
- Magnetic permeability: μ = 4π10-7 H/m;
- Dielectric permittivity: $\varepsilon = \varepsilon_0 \varepsilon_r$ where, $\varepsilon_0 = (1/36\pi).10^{-9}\ F/m$, is the permittivity of free space.
- Relative permittivity [24]: $\varepsilon_r = \frac{1.6661.10^{-6}}{f} + 2.9701$ F/m.

The simulation was conducted based on the following parameters:

- Frequency band: 1–100 MHz;
- Total number of frequency carriers employed: 4125;
- Carrier frequency: Δf = 24 KHz;

Extensive investigations have been documented in the literature regarding the noise impacting PLC channels in a MIMO setting. Reference [7] provides an extensive examination of the noise characteristics throughout the 1–100 MHz frequency range for MIMO-PLC systems. This study demonstrates that the noise measurements from SISO-PLC models developed by Esmailian and the OMEGA project are well-suited to the noise received on each MIMO transmission port, based on a measurement campaign conducted in North America and Europe, with statistical parameters obtained independently for each port. A separate study in [30] examines the association among several transmission ports, indicating that the most robust correlation is found between the P-T and N-T ports. Figure 6 depicts an instance of MIMO-PLC noise: (a) recorded during the ETSI-STF-410 measurement program [31], and (b) simulated ambient noise employing the model by Haschmat et al. [32].

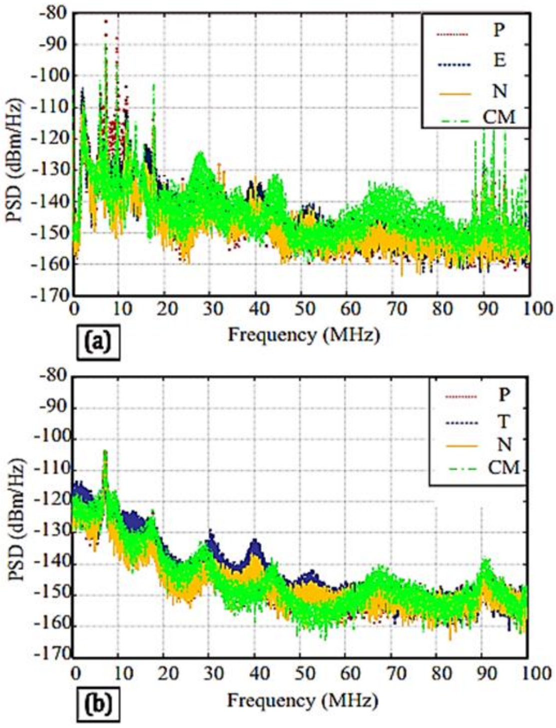

Fig.6. Typical types of background noise observed in MIMO-PLC communication systems

This noise model provides a simple representation of the noise detected in the domestic MIMO-PLC channel. Therefore, it is essential to discuss the noise model using time-domain modelling techniques, which will be presented in the following paragraph.

3.2. Analysis of MIMO-PLC Channel Transfer Function

To assess the impact of household electrical appliances on the channel transfer function, the PLC network configuration illustrated in Fig.5 is considered. In this configuration, all outlets remain open except for outlet 4, which is connected to a household appliance characterized by a specific input impedance Z_{bi}. This setup enables the evaluation of how the presence of the appliance influences the PLC channel's behavior, particularly regarding signal propagation and potential electromagnetic interference.

Fig.7 illustrates the transfer function results of the MIMO-PLC network. These results were obtained with only the four sockets connected to the network, whether they were left open or connected to a device. Regarding household appliances, there are two main types of electrical supply depending on the socket used: with or without the protective conductor T. Therefore, in this analysis, we considered two electrical appliances for each category: an electric heater and a laptop battery charger for the socket type with T, and a lamp and a mobile phone charger for the type without T (the N-T and P-T ports remain open).

The simulation results are presented in Fig.8, Fig.10, Fig.11, and Fig.12. These simulations provide two distinct channel responses: co-channel and inter-channel.

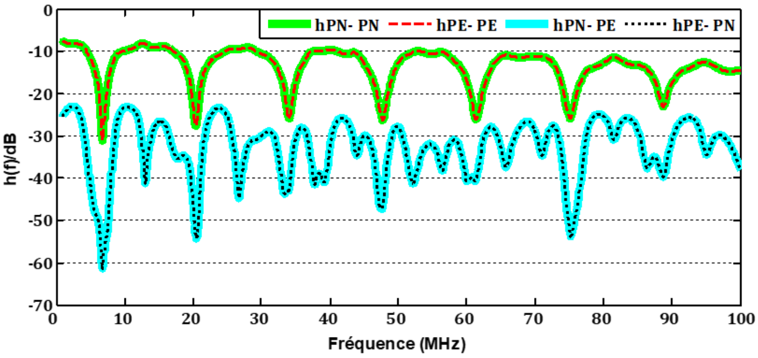

Fig.7. Frequency response of the MIMO-PLC system with fully open socket terminations

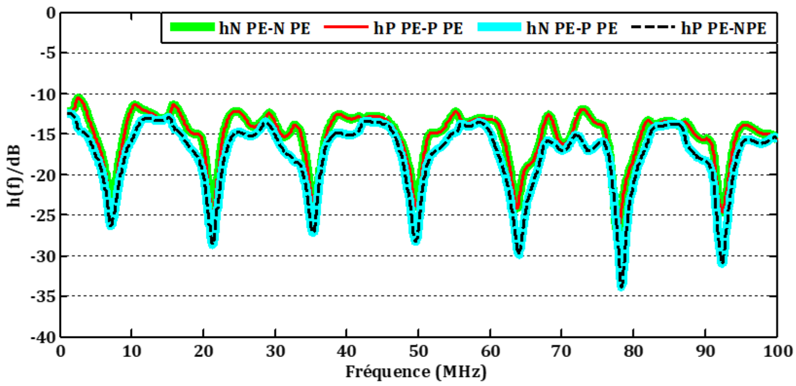

Fig.8. Frequency response of the MIMO-PLC channel with a plugged-in lamp

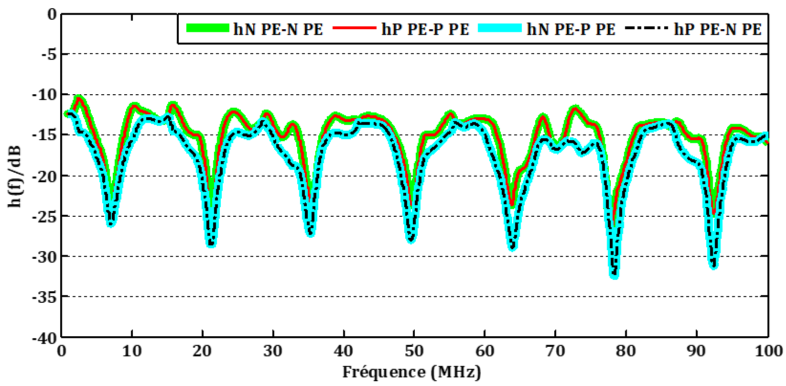

Fig.9. Frequency response of the MIMO-PLC channel with a plugged-in Mobile Phone charger

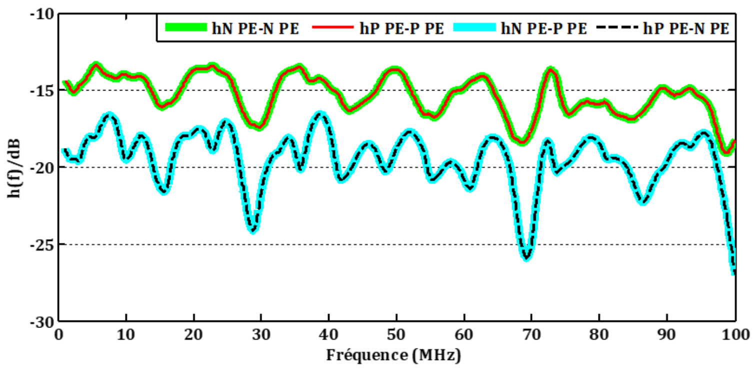

Fig.10. Frequency response of the MIMO-PLC channel with a plugged-in Electric Heating

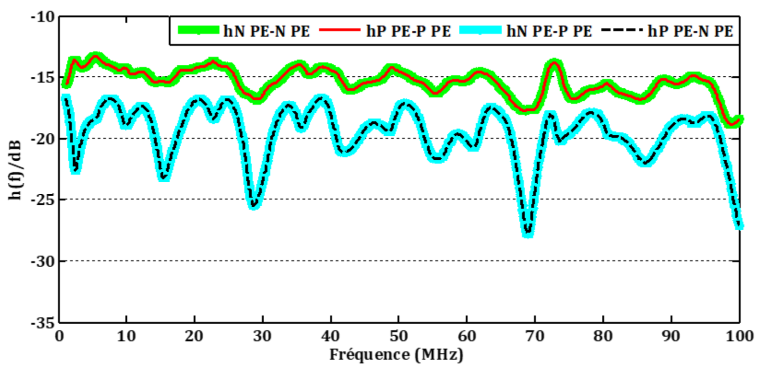

Fig.11. Frequency response of the MIMO-PLC channel with a plugged-in micro-computer charger

The simulation results show that the deterministic approach, especially when utilizing multi-conductor transmission line modeling techniques, provides superior modeling accuracy compared to the empirical method, particularly in environments with highly variable channel conditions. Deterministic models exhibit enhanced robustness to channel variations. However, the empirical approach remains valuable for applications with sufficient experimental data. Consequently, these findings suggest that integrating both approaches could yield an optimal solution for Power Line Communication (PLC) systems, combining the robustness of deterministic models with the practical applicability of empirical methods.

Simulations have shown that empirical models are effective for specific scenarios but lack flexibility for various network topologies. In contrast, deterministic models, although more complex, offer better accuracy for different configurations.

The results of this study have significant practical implications for the design of robust and efficient PLC communication systems. By combining empirical and deterministic approaches, researchers and engineers can develop more accurate and adaptable channel models, thereby enhancing the overall performance of PLC communication systems.

4. Conclusions

This study conducted a comprehensive comparison of two predominant approaches to Power Line Communication (PLC) channel modeling within a MIMO (Multiple Input Multiple Output) context, elucidating the distinct advantages and inherent limitations of each method. The empirical approach, with its reliance on experimental data, provides a practical perspective grounded in real-world observations, while the deterministic approach, grounded in theoretical principles, offers robust predictions based on the physical properties of the communication channel. The comparative analysis underscores the potential benefits of adopting a hybrid approach that synergistically integrates the strengths of both empirical and deterministic methods. Such a hybrid model could significantly enhance the robustness, flexibility, and overall performance of PLC communication systems by leveraging the practical insights of empirical data alongside the predictive power of deterministic models.

Looking forward, future research should focus on the development and refinement of these hybrid models. This entails incorporating critical elements from both empirical and deterministic approaches to create a more comprehensive and versatile modeling framework. Additionally, extensive experimental studies in diverse real-world environments are essential to validate and fine-tune these hybrid models, ensuring their applicability and reliability in practical scenarios. Moreover, exploring the dynamic interactions between various channel conditions and their impact on PLC systems will be crucial in further enhancing the accuracy and efficacy of the models. By addressing these aspects, future work can contribute to the optimization of modulation and coding strategies, the advancement of signal processing techniques, and the effective implementation of MIMO configurations. These efforts will ultimately drive the evolution of PLC technologies, paving the way for reliable, high-speed communication systems capable of meeting the demands of both domestic and industrial applications.

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Authors' Profiles

Dr. Abdelmounim Hmamou received his Ph.D. in Electronics and Telecommunications from Moulay Ismail University, Morocco, in 2022. He is currently a physics and electronics educator and researcher. His research interests include wireless communications, radio propagation, digital signal processing, antennas and electromagnetic wave propagation, and electronics and communication engineering. His recent work focuses on hybrid modeling techniques for communication channels and signal optimization strategies.

Dr. Mohammed EL GHZAOUI received the PhD degree in Transmission and Data Processing from Sidi Mohammed Ben Abdellah University, Morocco, in 2012. From 2013 to 2020, he was a Professor at Moulay Ismail University, where he contributed to teaching and research in wireless communication and signal processing. Since 2021, he has been a Professor at Sidi Mohammed Ben Abdellah University, actively engaged in both undergraduate and postgraduate education, supervising numerous master's and PhD students. His current research interests encompass a broad range of topics in modern communication systems, including Multiple Input Multiple Output (MIMO) systems, Orthogonal Frequency Division Multiplexing (OFDM) modulation, Radio Frequency Identification (RFID), antennas, and power line communication (PLC). He has a strong focus on space–time coding techniques for improving spectral efficiency and robustness in wireless communication. In addition, he has been actively involved in the field of Terahertz (THz) communications, working on the design of THz sources, pulse shaping techniques, and pulse modulation schemes such as Multi-Band On-Off Keying. His research extends to THz channel modeling, which is critical for the development of next-generation high-speed wireless networks. His work also explores the integration of THz communication into emerging 5G and beyond-5G (6G) applications. He has published extensively in peer-reviewed journals and international conferences and has collaborated on various research projects in wireless communication and signal processing. His contributions to academia include reviewing scientific papers for high-impact journals and serving on technical committees for international conferences. He has published more than 80 research articles and several book chapters and also he has edited two books which were Published by Springer in 2022 and 2024.

Dr. Jaouad FOSHI is a professor of higher education at the Faculty of Sciences and Techniques, Errachidia, Morocco. His teaching and research focus on microstrip antennas, microwave engineering, electromagnetic wave theory, antenna design, and MIMO systems. He has extensive expertise in numerical modeling and simulation using tools such as HFSS for advanced electromagnetic structures. His current research explores innovative antenna configurations for next-generation wireless communication systems.

Mr. Serghini Elaage is a secondary school teacher and a current Ph.D. candidate at Moulay Ismail University, Morocco. His research focuses on electronics and communication engineering, with specific interests in information and communication technology, radio communication, wireless networks, and communication systems. He combines practical teaching experience with academic research in emerging communication technologies.

Dr. Said Elkhaldi is a Doctor of Engineering and currently serves as an Assistant Professor at the École Nationale des Sciences Appliquées d'Al Hoceima (ENSAH), Morocco. His academic and research interests focus on Electronics and Communication Engineering, with expertise in wireless communications, microwave engineering, radio frequency (RF) systems, and RF circuit simulation. He has solid experience in RF electronics and uses advanced simulation tools such as Advanced Design System (ADS) for high-frequency circuit analysis and design. Dr. Elkhaldi actively contributes to research in the fields of RF and microwave technologies for modern communication systems.

Dr. Sudipta Das is currently working as a Professor in the Department of Electronics and Communication Engineering at IMPS College of Engineering. & Technology, West Bengal, India. He has 15 years of teaching and 13 years of research experience. His research interests are Microstrip Antennas for microwave, mm-wave, and THz communication systems, Flexible antenna design, Filter design, FSS, Polarizer, Absorber, RFID, microwave components, THz systems, metamaterials, graphene-based photonic structures, micro and nano-scaled antenna design and development for next generation communication systems. He has contributed 275 research articles in various peer-reviewed international journals, conferences of repute, and edited books. He has authored one book on ‘Microstrip Filter Design’, and Edited 6 books working with Springer entitled “Advances in Terahertz Technology and its Applications”, “Terahertz Wireless Communication Components and System Technologies”, Terahertz Devices, Circuits, and Systems, “Recent Advances in Graphene Nanophitonics”, “Next Generation Wireless Communication” and Millimeter Wave and Terahertz Devices for 5G and 6G Systems”, and also contributed several book chapters. He is associated with different international journals as an Editorial Board member and reviewer. His Biography is listed in Marquis Who’s Who in the World 2016. He has been conferred with the “Outstanding teacher in Electronics & Communication Engineering” award by the Global Outreach Research and Education Summit Awards in the year 2019.

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