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State-of-art Power Line Communications Channel Modelling

Wenfei Zhu[a,b,*], Xu Zhu[b], Enggee Lim[a], Yi Huang[b]

[a]Department of Electrical and Electronic Engineering, Xian JiaoTong Liverpool University, Suzhou, 215123, P.R.C
[b]Department of Electrical Engineering and Electronics, The University of Liverpool, Brownlow Hill, Liverpool, L69 3GJ, U.K.

Abstract

Power line communication (PLC) is an emerging technology for multimedia, broadband Internet access and smart grid applications. However, the development of PLC has been slowed down by the absence of a generally applicable channel model. The modelling of PLC channel is very challenge due to a number of reasons such as the harshness and diversity of power networks, and the difficulties in measurement. Two channel modelling approaches can be found in literature, namely the top-down approach and the bottom-up approach. These two approaches are summarised and analysed in this paper. Some representative works are also presented. Several future works, including random channel generation, channel model generalisation and smart grid channel modelling are suggested.

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Keywords: power line communication; channel modelling; top-down approach; bottom-up approach; transmission line theory; smart grid

1. Introduction

Power line communication (PLC) has attracted a lot of attention in applications like multimedia, broadband Internet access and smart grid. Because of the existence of power grid all over the world, PLC has a deployment cost that is comparable to that of wireless communication [1]. This makes it a potential competitor of wireless communication in the aforementioned applications. However, the development of PLC technologies is not as fast as that of wireless communication technologies mainly due to the difficulties in channel modelling.

One of the most significant challenge of PLC channel modelling is the harshness of power networks. First, it is frequency selective due to reflections and transmissions caused by impedance mismatches at discontinuities. Second, it exhibits high attenuation and strong low-pass behaviour which limits not only the coverage of the network but also the bandwidth that can be used for communication. Moreover, it is time-varying due to change of topology, load impedances and cable parameters. Apart from these, PLC systems are further impaired by coloured background noise and complex impulsive noise. Therefore, extensive studies on these channel characterizations are necessary for reliable channel models.

The global diversity of power grids and PLC applications further increases the difficulty of PLC channel modelling. On one hand, the structure of power grid varies from country to country. For example, two-phase configuration is common in the United States but not in Europe while three-phase configuration is common in Europe [2]. Additionally, the power grid may have several variations within a country. On the other hand, different

*Corresponding author. Tel.: +86-512-88161671 .
E-mail address: wzhu@liverpool.ac.uk.

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applications target different network layers and frequency bands. The power grid is usually divided into four layers, namely high voltage (HV) transmission network, medium voltage (MV) distribution network, low-voltage (LV) distribution network and the indoor power distribution network in residential and commercial buildings. Most of the researches focus on the last two layers. The Automatic Metering Infrastructure (AMI) of smart grid also operates in these two layers as is recommended by many commercial and non-commercial standards, such as PRIME, G3-PLC, ITU-T G.hnem and IEEE 1901.2. The smart meter collects power consumption data from appliances through indoor power networks and communicates with utility's central office via outdoor power networks. Regarding operating frequency bands, the CENELEC bands (3-500kHz) are recommended by the aforementioned standards for smart grid applications. Nevertheless, as will be described in this paper, most of the existing channel models target broadband (1-100MHz) PLC applications. As a result, it is hard to develop a generally applicable model and there is no such model that can be directly applied to smart grid PLC yet.

Measurement is another challenge aspect of PLC channel modelling. Measurement of PLC channel is usually dangerous because of the high voltage. Critical isolation of the mains voltage is required for not only protection but also signal extraction. Apart from safety reasons, the measurement of outdoor distribution network is still challenge as it is hard to get access to it. Due to this reason, most of the individual researches [3–16] on PLC channel modelling were based on indoor measurements. In addition, there is a limited number of measurement campaigns around the world. Some examples are those held by ETSI (the European Telecommunications Standards Institute), OPERA (the Open PLC European Research Alliance) and OMEGA (Home Gigabit Access) project.

Multiple-input-multiple-output (MIMO) PLC channel modelling is even more complicated than single-input-single-output (SISO) PLC. On one hand, expensive multi-port equipments and complex coupling circuits have to be employed for the measurement of MIMO channels. One the other hand, the coupling between different ports makes the analysis of MIMO channels very challenge.

Two kinds of PLC channel modelling approaches can be found in literature, namely the top-down approach [3, 12, 14, 15, 17–19] and the bottom-up approach [5–11, 20–25]. A top-down approach attempts to find the most fitted model from measurements (either impulse responses or frequency responses) by means of data fitting, while in a bottom-up approach the channel model is derived from transmission line theory without relying on any measurement. Although various channel models can be found in the literature, a widely accepted channel model that is generally applicable is still absent since existing models target different network layers and frequency bands, or they are based on specific measurement results, network topologies and assumptions.

This paper is organised as follows. Section 2 summarises the basic ideas of the two PLC channel modelling approaches and presents some representative works. Section 3 suggests some future works of PLC channel modelling. Section 4 concludes this paper.

2. PLC Channel Modelling Approaches

2.1. Top-down Approach

Similar to wireless channel modelling, this approach treats the PLC channel as a black box and a large number of measurements are collected by exciting the channel with a reference signal in either time domain or frequency domain. Complex fitting algorithms are then applied in order to find a model that fits the measurements well. The fitting process includes identification of proper parameters and estimation of those parameters. The objective is to use a few parameters to approximate the channel with high accuracy.

This approach is advantageous in that the developed models are usually easy to use and they allow fast channel generation. This makes them suitable for running Monte Carlo simulation, where a large number of channel realisations are required. With the help of the statistical results derived from measurements, the channel and even system performance may be studied analytically. The most significant disadvantage of this approach is its low flexibility. The model and its parameters derived for a specific network and frequency band may not be applied to other networks and frequency bands. Therefore, in order to develop a generalised top-down model, extensive channel measurements must be done globally. Another disadvantage is that it lacks physical connection with reality. For example, it is hard to use this model to describe the spatial correlation presented in power networks. Since power network is a bus system, it is possible that the received channel responses of two neighbouring nodes have high correlation. Consequently, this approach may not be applied to network-related system modelling.

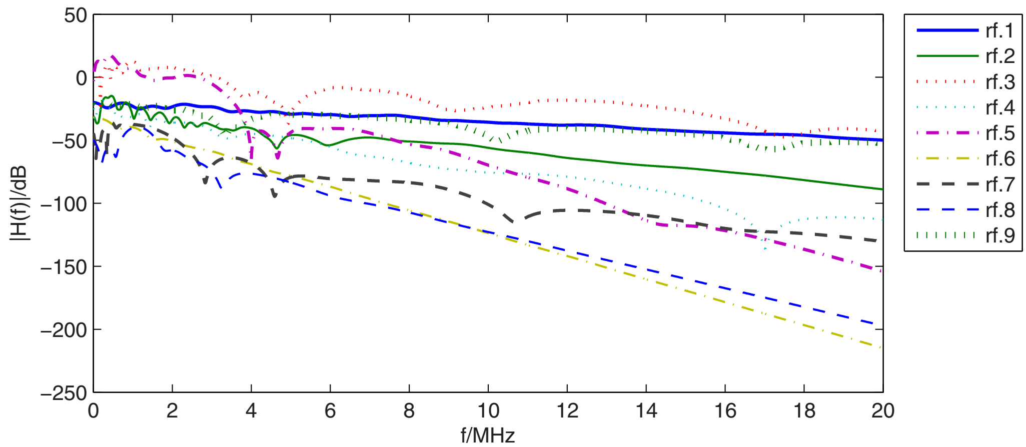

Fig. 1. Frequency responses of OPERA reference channels [26]

Many researchers have contributed to this approach with different network locations, topologies, frequency bands, etc. A well-known top-down model proposed by Zimmermann and Dostert [18] describes the channel (0.5-20 MHz) based on multipath phenomenon. The multipath nature of PLC channel is due to the presence of branches and impedance mismatches which cause multiple reflections. The transfer function of the channel can be expressed as:

$$H(f) = \sum_{i=1}^{N} g_i e^{-(a_0+a_1 f^k)d_i} e^{-j2\pi f(d_i/v_p)} \tag{1}$$

where N is the number of dominant paths, g_i is the weight of the ith path determined by reflections and transmissions, a_0 and a_1 represents the attenuation of cable, k determines the dependency of attenuation on frequency f, d_i is the length of the ith path, and v_p is the phase velocity of the cable.

The model is completed by assigning proper values to the above parameters. Based on their own measurements, Zimmermann and Dostert defined several reference channels in terms of link distances. A set of parameters were then determined for each channel. Additionally, OPERA project [26] proposed 9 reference channels for LV and MV networks based on this model. Figure 1 shows the channel transfer function of these reference channels.

A major drawback of this model is that the computational cost for determining the dominant paths and the corresponding parameters grows with the number of dominant paths. In indoor environments, there are usually a large number of paths and the attenuation is low due to short path length. As a result, many strong paths may present, causing a high computational cost.

Many other top-down channel model proposals can be found in literature. Based on extensive measurements, Tlich et. al. [15] proposed a random channel model (1-100 MHz) in frequency domain by analysing statistical properties of the magnitude and phase of the measured channel transfer function. On the contrary, the channel model (1.8-30 MHz) proposed by Galli [17] is based on time domain statistical analysis, such as average channel gain and RMS delay spread. Galli also compared the statistical results of power lines with other wires such as twisted-pair and coaxial cable, and found that these wires have similar statistical properties. In [27], Tonello developed a random channel generator based on Zimmermann's model and he further refined his model (2-100 MHz) recently [12] by including more statistical results.

There are very few MIMO top-down channel modelling methods in the literature. Some pioneers can be found in [3, 14]. In [14], measurement and analysis of MIMO inhome PLC channel were performed. A MIMO channel model was then proposed. This model first generates a SISO channel realisation and then other correlated channels are generated by assigning a random phase to each path of the SISO channel. However, no theoretical support was provided for this correlation generation method. Measurement on MIMO inhome channel was also conducted in [3] and a channel model was developed by statistical analysis, including correlation, of the measurements.

2.2. Bottom-up Approach

The bottom-up approach is usually based on transmission line theory [28]. This approach requires perfect knowledge of the targeting power network, including its topology, the used power line cable and load impedances of terminals. These network elements are modelled mathematically so that they can be incorporated to generate the channel.

Transmission line theory was originally developed to describe electromagnetic (EM) wave propagation in a piece of transmission line with a bunch of partial differential equations (PDEs). Voltages along the transmission line were derived by solving these PDEs and incorporating reflections at line ends. The theory must be modified so that it can be applied to model signal propagation in a network. Voltage ratio approach [5–9, 20–22, 28], ABCD matrix [10, 28] and s-parameters [23–25] are three popular methods in literature. Voltage ratio approach and ABCD matrix are basically the same method in different forms because they all focus on voltages and currents at network nodes. S-parameters approach is different. It describes wave propagation in a network by utilizing transmission and reflection coefficients. Although this approach is complicated, it is directly related to signal propagation in a network. Therefore, it can be easily extended to the situation where different kinds of cables with different number of conductors are connected together. It is hard for a voltage ratio approach or an ABCD matrix approach to be applied to this situation. We refer readers to [23] for a good demonstration of this approach. An exception of bottom-up approach can be found in [11]. This model is basically a multipath model partly cooperated with transmission line theory.

The advantage of bottom-up approach is that it can be applied to various situations flexibly as long as the network information is perfectly known. In addition, this approach is closely related to the physics of power networks since it is derived from the physical interpretation of EM wave propagation in transmission line networks. Therefore, this approach can be used for network-related system modelling such as multiuser systems and relay systems. This approach also has several disadvantages. First, this approach is usually computational complex and the complexity grows with the complexity of the network. Second, this approach may not be practical since it only considers several key elements of a power network. A practical model should consider many other natural and artificial interference sources such as weather and radio. Finally, the collection of the aforementioned network elements (topology, cable, load) is challenge due to a large number of variations of them.

2.2.1. Two-conductor Transmission Line Model

Two-conductor transmission line (2TL) theory [5, 6, 10, 11, 22] is used for power networks connected with two-conductor transmission lines, such as twisted-pair and coaxial cable. In this section, we are going to briefly introduce the voltage ratio approach proposed by Tonello and Versolatto [6] and demonstrate a supplement to his approach.

By solving the wave equations and incorporating reflections at line ends (see chapter 5 of [28]), we can obtain the voltage at any point along a cable:

$$V(z) = \frac{1 + \Gamma_{Load} e^{-2\gamma L} e^{2\gamma z}}{1 - \Gamma_{Source}\Gamma_{Load} e^{-2\gamma L}} \frac{Z_C}{Z_C + Z_S} V_S \, e^{-\gamma z} \tag{2}$$

where L is the length of cable, z is the position along the cable with $z = 0$ at source and $z = L$ at load, Z_C and Z_S are characteristic impedance and source impedance, V_S is the voltage source, $\gamma = \sqrt{ZY}$ is the propagation constant with $Z = r + j\omega l$ and $Y = g + j\omega c$, Z, Y, r, l, g and c are per-unit-length impedance, admittance, resistance, inductance, conductance and capacitance respectively, Γ_{Load} and Γ_{Source} are reflection coefficients at load and source with $\Gamma_{Load} = (Z_L - Z_C)/(Z_L + Z_C)$ and $\Gamma_{Source} = (Z_S - Z_C)/(Z_S + Z_C)$ and Z_L is the load impedance. It is easy to get the voltage ratio between source and load from Eq. 2.

$$\frac{V(L)}{V(0)} = \frac{1 + \Gamma_{Load}}{e^{\gamma L} + \Gamma_{Load} e^{-\gamma L}} \tag{3}$$

Eq. 3 is the key to channel modelling of a network. Chain rule is adopted in Tonello's model for calculating the overall channel transfer function between any two nodes of a network. The network is first divided into sections along the direct path between two nodes and then transfer function of each section is calculated using Eq. 3. In this equation, the load reflection coefficient is calculated with the input impedance of the next section since the

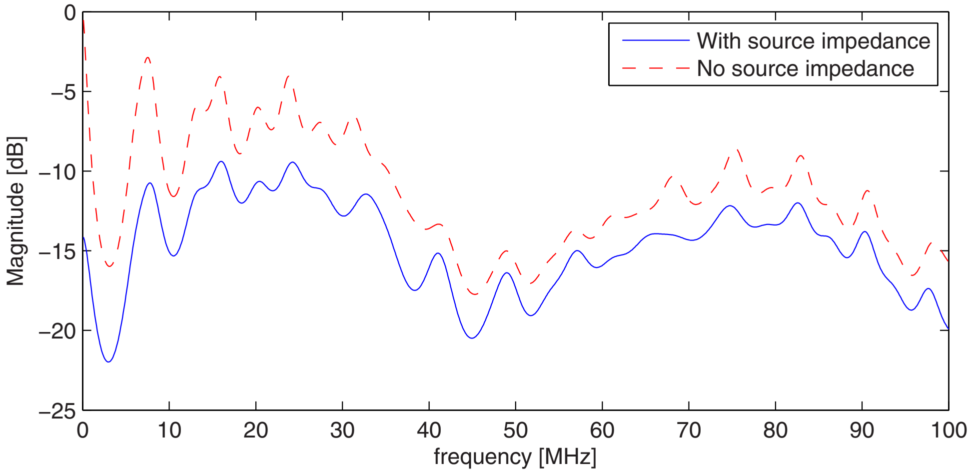

Fig. 2. Sample frequency responses generated with Tonello's model and the modified one

load impedance of one section is equivalent to the input impedance of its next section. By doing so, the terminal impedance is carried back to the desired node. The input impedance of a cable is calculated by

$$Z_{in}(0) = Z_C \frac{1 + \Gamma_{Load} e^{-2\gamma L}}{1 - \Gamma_{Load} e^{-2\gamma L}} \tag{4}$$

In terms of branch, this model treats the branches depart from the same node as parallel circuits represented by their input impedances. Therefore, it is straightforward to calculate the total input impedance at that node with Ohm's law. Finally, all the transfer functions are multiplied together according to the chain rule to obtain the overall transfer function.

This method has a drawback in that it does not consider the reflection at source. The term $Z_C/(Z_C + Z_S)$ in Eq. 2 represents voltage division caused by the source impedance. However, this division was eliminated in Eq. 3 because Eq. 3 is actually the voltage ratio between the voltages at two line ends but not the voltage ratio between load voltage and source input voltage. Therefore, we modified this method by using Eq. 2 (set V_S to unity) instead of Eq. 3 for the transfer function of the section that is directly connected to the source. No other changes were made. Figure 2 shows two sample frequency responses generated with Tonello's model and the modified one based on the topology in figure 6 of [29] with all load impedances (including source impedance) equal to 50 Ohms. Comparing the two frequency responses, it is easy to see that further attenuation is introduced by source impedance.

As in Eq. 2, the propagation constant includes the attenuation and phase shift of a cable. This is determined by the so-called per-unit-length parameters, including resistance, conductance, inductance and capacitance. The determination of these parameters are very challenge and usually assumptions, such as homogeneous dielectric and uniform cable, are made to simplify the calculation. Analytical results can be provided for some symmetric cables such as coaxial cable. The determination of these parameters for asymmetric cables is much more complex. Further details can be found in [6, 28].

2.2.2. Multi-conductor Transmission Line Model

Multi-conductor transmission line (MTL) theory [7–9, 20, 21, 23–25] is a generalisation of 2TL theory for more than two conductors. Similar to 2TL theory, a set of PDEs are formulated for voltages and currents on all conductors. Since more than one voltage and current are presented, all the variables, including voltages, currents and per-unit-length parameters, are represented in compact matrix forms. The PDEs cannot be solved directly since coupling between conductors are naturally included in per-unit-length parameters. In chapter 7 of [28], eigenvalue decomposition is adopted to decouple the PDEs. Because of this coupling, the solution to those PDEs is more complex than that to two-conductor transmission lines. In addition, analysis of this kind model is challenge due to the non-communicative property of matrix and the presence of coupling.

We are not going to present the details of this theory due to space limitation. The derivation can be found in chapter 7 of [28]. Instead, we will review some good researches here. As an extension of the work in [6], Versolatto and Tonello proposed a channel modelling method based on MTL theory [20]. The method is almost the same as the one in [6]. An equation was derived for the voltage ratio between two line ends and chain rule was adopted for the calculation of the overall transfer function. Source reflection is neither considered in this method.

As mentioned above, the model in [23] is a good MTL model based on s-parameters. The s-parameters models of cable segments, sources, loads and derivation points are presented. One advantages of this work is that it allows the connection of different kinds of cables with different number of conductors. However, the complexity of this model is very high. In [25], Bakhoum proposed an s-parameters based model that is specifically designed for three-phase systems.

A common problem of the above models is that they are all theoretical models which only consider the cable structure and network topology, while the practical wiring practices are not considered. For instance, as stated by Galli [1], grounding has significant influence on channel transfer functions. In [7–9], Galli et.al. proposed a practical MTL modelling approach that is based on US indoor wiring practices. Similar models can be studied for other wiring practices in different countries.

Determination of per-unit-length parameters for MTL approach is much more complex than that for 2TL approach. Analytical solutions can only be provided for cables with certain symmetry (see chapter 6 of [28]). The solutions for other cables can be very complex and for some asymmetric cables, numerical methods, such as the one used by Sartenaer in [23], have to be adopted.

3. Future Works

PLC channel modelling is still an open and challenge research topic. There are several good channel modelling approaches [6, 7, 12, 17, 18, 20, 23] in literature. The focus is now on random channel generation and channel model generalisation. In addition, channel modelling for Narrowband PLC (NB-PLC) in CENELEC bands (3-500 kHz) will be of paramount importance for the study of smart grid communication systems.

3.1. Random Channel Generation

Random channel generation of a top-down approach is usually directly related to the statistics of channel responses. In time-domain, statistics of amplitude and time information of a impulse response, such as amplitude distribution, power delay profile and root mean square (RMS) delay spread, are usually required. In frequency domain, there is no standard way of random channel generation. Different kinds of statistics are possible depending on the parameters defined for the model.

Several works were mentioned in section 2.1. Galli provided a good example of a time domain approach in [17]. As presented in [15], the statistics of peaks and notches of channel frequency responses were analysed. This is a possible approach but it has no physical connection with reality. The model of Tonello et.al. [12] is a good attempt that is based on the physics of signal propagation in a network.

Time variation and spatial correlation are other two important factors that could be included in a top-down random channel generator. However, there are few researches on these two factors. A good example on measurement based time variation study can be found in [16]. Two kinds of spatial correlation can be found in a PLC network, namely the spatial correlation between conductors and the spatial correlation between users. A study on spatial correlation between conductors can be found in [13] while no research on spatial correlation between users was found.

Random channel generation of bottom-up approaches is usually realised by varying network topology and load impedances. The power line cable can also be changed but usually the same power line cables are used in an area or a country. Other aspects such as weather and tolerance of a cable can also be included. In addition, different wiring practices should be considered for more practical channel models.

Few papers regarding the generation of random topology can be found in literature. Tonello and Versolatto [6] proposed a random topology generator based on in-home European wiring practices and norms. Based on some standard power grid system of the US, Wang proposed a novel random topology generator by using graph theory. This generator also allows looped network.

There is also little information about the distribution of load impedance. Some measurements on the load impedance variation of indoor devices were done in [16]. It was found load impedances vary periodically with the mains frequency. A good analysis on the influence of load impedances on channel transfer function can be found in [30]. However, no statistics of load impedance was provided in both works.

As a conclusion, many aspects regarding random channel generation can be studied, including faster and more accurate top-down channel generators, more information and analysis on time variation and spatial correlation of PLC channel, simple random topology generators for the power network of other countries and practical load impedance generation.

3.2. Channel Model Generalisation

Most of the researches on PLC channel modelling are individual and discrete. These researches are specific to particular network topologies and frequency bands. In order to develop a top-down channel model that is generalised to different kinds of network and is valid for a wide frequency band, extensive measurements are necessary. New top-down channel models may have to be developed for different networks and frequency bands. The generalisation of a bottom-up approach usually doesn't require change of the model, but the generality should be reflected in the generation of network topology, load impedances and power cables.

3.3. Channel Modelling for Smart Grid Communications

The most significant problem of channel modelling for smart grid communications is the lack of narrowband channel models. As mentioned above, most of the channel models, especially top-down ones, are broadband channel models in the frequency band of 1-100 MHz. Very few of them focus on or cover the CENELEC bands (3-500 kHz).

It is very likely that a broadband top-down approach cannot be applied to generate narrowband channel realisations. However, a bottom-up approach is able to generate the frequency response of channel in all frequencies as long as the frequency dependent parameters such as load impedances and per-unit-length parameters are available in all frequencies. Nevertheless, measurements are still required for the validation of the model.

The study of outdoor LV distribution network channel modelling is of paramount importance for smart grid because LV distribution networks will support the communication between smart meters and central offices with very high reliability.

Spatial correlation can also be a very interesting research direction because a large number of smart meters and sensors will share the same network. If correlation information between meters and sensors can be utilised, communication system design may be simplified. In addition, this may also help the design of relay systems.

4. Conclusion

Two PLC channel modelling approaches, namely the top-down approach and the bottom-up approach, are introduced in this paper. The top-down approach requires extensive channel measurements while the bottom-up approach is based on transmission line theory. A top-down model proposed by Zimmermann was explained and several reference channels were illustrated. The bottom-up approach is divided into 2TL and MTL approaches in terms of the number of conductors in the considered power cable. A 2TL model proposed by Tonello was described in details. We also pointed out a drawback of this model and provided a modification of it.

Several future works, including random channel generation, channel model generalisation and smart grid channel modelling, were suggested in this paper. Random channel generation requires extensive study on channel parameters such as amplitude, delay, time variation, spatial correlation, network topology, load impedances, per-unit-length parameters, etc. Channel modelling generalisation requires thorough study of power grid across the world. We also pointed out that the study of narrowband and outdoor channel models are of paramount importance for smart grid applications.

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