

Bottom-Up Transfer Function Generator for Broadband PLC Statistical Channel Modeling

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Abstract—We follow a bottom-up approach for modelling the channel transfer function aiming at realizing a fast statistical channel simulator. The simulator is derived from transmission line theory. It computes the transfer function via a fast procedure that calculates the voltage ratio between the receiver port and the transmitter port given a real or randomly generated network topology. The approach allows not only taking into account the cable characteristics, the number and length of branches, but also the effect of loads. In particular the effect of time-variant loads that cause the channel transfer function to be time-variant.

Keywords—Power line communications, Channel modeling.

I. INTRODUCTION

Power line communications are becoming an attractive solution to deliver broad band services both in indoor and outdoor scenarios since they allow exploiting the existing infrastructure without the need of new wires. To design reliable communication systems, the knowledge of the channel characteristics is a very important aspect. It is widely recognized that a realistic channel model is fundamental to perform algorithm design and performance analysis. This paper proposes an approach to generate the channel transfer function using a bottom-up approach that starts from the physics of propagation in a power network. In particular, we focus on the indoor scenario with a transmission band from 1 to 100 MHz.

The wide literature on PLC channel modeling essentially follows two approaches: a top-down or a bottom-up approach. The former approach, considers the PLC channel as a black box, and describes the multipath propagation via an echo model in the time domain [1]-[2], or in the frequency domain [3]-[4] using a parametric model whose parameters can be obtained with fitting the results from measurements. Such models are simple and easy to be implemented with a computer simulation. One limit is that they depend on the measurement accuracy, the data fitting algorithm used, and the number of parameters used. Further, they are not capable to describe the physics of propagation, the topology, and the effect of the loads.

The bottom-up approach allows obtaining the frequency response of the channel starting from the properties of the components in the power network, such as lines, branches and loads. It clearly describes the relationship between the channel behavior and the model parameters. The transfer function can be obtained by either using the network matrix [5]-[9] approach, or with the theory of transmission lines that considers the

effects of multiple transmissions and reflections [10]-[11]. Although the network matrices accurately represent the properties of the channel, the parameter computation of each two-port network can be a prohibitively difficult task in complex networks. The multiple transmission/reflection approach may be limited in practice by the difficulty of taking into account all paths. A simplification is described in [11] where it is proposed to consider the most significant ones according to a certain metric.

In this paper we follow a bottom-up approach for modelling the channel transfer function aiming at realizing a fast statistical channel simulator. The transfer function is obtained by the computation of the voltage ratio between the receiver and transmitter ports. This approach does not require finding all possible signal propagation paths as in [11]. A similar idea was presented in [12] although for a simple topology made by a single wire with no branches, i.e., not for realistic multiple branches topologies as found in real indoor scenarios. We, instead, deal with the complex indoor power network where the procedure in [12] cannot be straightforwardly applied. In this scenario the branch effect and computational order of the transfer function becomes important.

The choice of using a bottom-up approach is motivated by the goal of obtaining an accurate model starting from the knowledge of the topology, cables, and loads. We also propose some simplification for complex topologies for easy and efficient computation without loss of accuracy. The idea is based on dividing the network into simpler sections where the evaluation of the voltage ratio is simplified. Compared with the two-port network matrix approach, this method greatly saves calculation time when the PLC network is complex. Furthermore, it poses the basis for the development of a statistical channel model that can be obtained from a statistical model of the topology, the cables, and the loads. Further, it allows to include modeling of the time-variant behavior of the channel.

This paper is organized as follows. In Section II we describe the approach used to model the transmission properties. In Section III, we present the method used for the computation of the transfer function using the voltage ratio approach. In Section IV, the relationship between the transfer function and the path loss is discussed. In Section V, we discuss the application of the method to realize a statistical channel simulator and we report several numerical examples. Finally, the conclusions follow.

II. MODELLING THE PLC NETWORK PROPERTIES

The transmission line theory allows us to determine the transfer function (frequency response) of the PLC channel following a bottom-up approach. To do this we first need to describe the network topology. Then, we need to take into account the properties of the network components as cables and loads. In particular, the approach that we follow is based on the calculation of the transfer function via the evaluation of the voltage ratio between two nodes (transmitter and receiver under consideration). The approach is described in the following.

A. Typical Power Network Topology

The transmission properties depend on the components of the power network and corresponding topology. A typical indoor power network with radial topology is shown in Fig. 1. Since, the topology can be rather complex, we divide it into small parts that we refer to as units. As it will be clear in the following, this allows computing the transfer function between two nodes as the product of the transfer function of each unit. The shortest signal path between the two nodes under consideration is referred to as backbone path. It is depicted with a bold line in Fig. 1, while the N branches are depicted with slim lines. They are relatively long and may be connected with many other branches.

The units are obtained by dividing the network along the backbone. Each unit may represent either the unique backbone portion, or a portion of the backbone together with multiple branches. For convenience, we select the units such that they comprise a portion of the backbone link and a branch. Each branch may comprise several sub-branch connections that we divide into levels. Each level consists of several cables terminated by loads or connections to the next level.

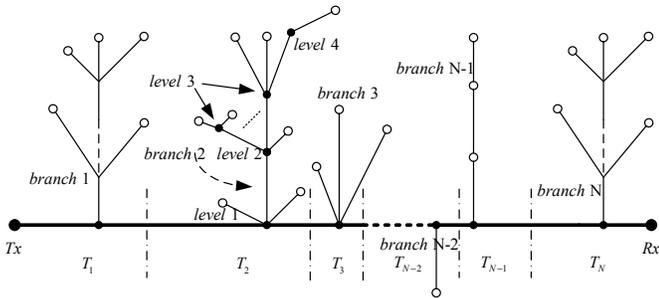


Fig. 1. Typical topology of power line network

B. Line Parameters and Cable Models

The calculation of the transfer function via the bottom-up approach requires the knowledge of the line characteristic impedance and transmission constant. We implicitly assume the two-conductor uniform transmission line model. To determine these line parameters we can follow two approaches. One is based on the determination of such parameters via measurements of cables with various structures. The other derives the parameters from theoretical models that use the distributed constants, i.e., resistance, inductance, admittance

and capacitance (R , L , G and C) per unit length. The resistance R mainly depends on the skin effect which becomes significant at high frequency. The inductance L includes the self-inductance and mutual inductance between pair of wires. The capacitance C is composed of the capacitive coupling between the wires and that between the wires and the jacket. The conductance G is related to the conductivity of the dielectric material and capacitance C . The calculation procedure of the line parameters is described in [9]-[10],[17]. With the knowledge of the line parameters, the corresponding characteristic impedance Z_c and transmission constant γ can be derived as

$$Z_c = \sqrt{\frac{R + j2\pi fL}{G + j2\pi fC}} \quad (1)$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j2\pi fL)(G + j2\pi fC)} \quad (2)$$

It should be noted that the cables deployed in a given network may be of different type. For instance, the backbone cable may differ from the cables used in the other branches. The cables can be single wire or multiple-wire with plastic coating. Shielding is typically not used in residential power networks. Each wire may use a one-ply conductor, or more often it uses strand conductors that are self-twisted and enclosed in an insulating sheath. The wires cross-section can also differ. Typical cross-section geometries in residential power networks are shown in Fig. 2 [13],[16]. Often, as for instance in the Italian indoor layouts, a number of single-conductor wires are used and randomly twisted and laid out in plastic hoses. Theoretically, the line parameters of such cables may be obtained by using multi-conductor transmission line theory. Although the uniform transmission line model does not strictly apply in this case, the division of the network into sections could be done such that in each arbitrarily small unit the uniform transmission line model can be assumed. Further, a large number of power relay conjunction boxes and home appliances are connected to the power network via three-conductor wires with triangularly symmetric cross section. The transmission line theory can be applied directly to such kind of wire since we can consider it as the conventional parallel two-conductor line [13].

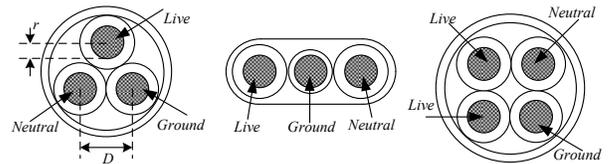


Fig. 2. Cross-section of several power cables.

III. TRANSFER FUNCTION OF THE POWER NETWORK

The transfer function between two nodes is given by

$$H(f) = \frac{V_{Rx}(f)}{V_{Tx}(f)} \quad (3)$$

where $V_{Rx}(f)$ is the voltage measured at the receiver input port, while $V_{Tx}(f)$ is the voltage measured at the input port of the transmitter. To use transmission line theory, the TEM or quasi-TEM wave propagation is herein assumed. Strictly speaking, the TEM or quasi-TEM field requires lossless or weakly lossy conductors lying in parallel with each other in a homogeneous dielectric. As mentioned above, in many situations this assumption holds true, or it is a good assumption for simulation purposes.

To ease the task of computing the transfer function, we propose to divide the network topology into units as described in Section II.A. Then, we first compute the transfer function of each unit by dividing the unit itself into three sections as depicted in Fig. 3 for the n -th unit. The three sections are characterized by the characteristic impedances $Z_{c_1}^{(n)}$, $Z_{c_2}^{(n)}$ and $Z_{c_b}^{(n)}$, the transmission constants $\gamma_1^{(n)}$, $\gamma_2^{(n)}$ and $\gamma_b^{(n)}$, and the lengths $l_1^{(n)}$, $l_2^{(n)}$ and $l_b^{(n)}$. The section with sub-index b is associated to the branch that belongs to the unit itself.

For simplification, we assume a branch having a single level. However, the procedure can be generalized to include multi level branches. The section with sub-index 1 is referred to as the transmitter side section while that with sub-index 2 is referred to as the section of the receiver side. $Z_{el}^{(n)}$ represents the impedance of the receiving side. $E_g^{(n)}$ and $Z_g^{(n)}$ are the equivalent source and inner impedance at the transmitting side.

For the first unit, $E_g^{(1)}$ and $Z_g^{(1)}$ are the equivalent source and inner impedance of the transmitter, while $Z_{el}^{(1)}$ represents the equivalent impedance at the receiving side of the transmitter; $Z_b^{(n)}$ is the load impedance connected to the branch terminal.

Now, the input impedance of section 1 can be computed as

$$Z_{in}^{(n)} = Z_{c_1}^{(n)} \frac{Z_p^{(n)} + Z_{c_1}^{(n)} \tanh(\gamma_1^{(n)} l_1^{(n)})}{Z_{c_1}^{(n)} + Z_p^{(n)} \tanh(\gamma_1^{(n)} l_1^{(n)})} \quad (4)$$

where

$$Z_p^{(n)} = \frac{Z_{in_i}^{(n)} \cdot Z_{in_b}^{(n)}}{Z_{in_i}^{(n)} + Z_{in_b}^{(n)}} \quad (5)$$

and $Z_{in_i}^{(n)}$, $Z_{in_b}^{(n)}$ are respectively the input impedances of section 2 and of the branch section. They are respectively equal to

$$Z_{in_i}^{(n)} = Z_{c_2}^{(n)} \frac{Z_{el}^{(n)} + Z_{c_2}^{(n)} \tanh(\gamma_2^{(n)} l_2^{(n)})}{Z_{c_2}^{(n)} + Z_{el}^{(n)} \tanh(\gamma_2^{(n)} l_2^{(n)})} \quad (6)$$

$$Z_{in_b}^{(n)} = Z_{c_b}^{(n)} \frac{Z_b^{(n)} + Z_{c_b}^{(n)} \tanh(\gamma_b^{(n)} l_b^{(n)})}{Z_{c_b}^{(n)} + Z_b^{(n)} \tanh(\gamma_b^{(n)} l_b^{(n)})}. \quad (7)$$

To obtain the transfer function of the n -th unit which is the voltage ratio between $V_{el}^{(n)}$ and $V_1^{(n)}$, the reference plane

shifting

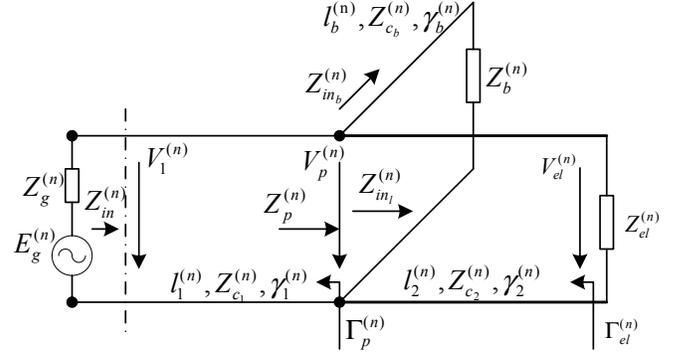


Fig. 3. Detailed topology of a unit of index n .

scheme should be applied [14], yielding

$$H^{(n)}(f) = \frac{V_{el}^{(n)}}{V_1^{(n)}} = \frac{V_{el}^{(n)}}{V_p^{(n)}} \frac{V_p^{(n)}}{V_1^{(n)}} \quad (8)$$

$$\frac{V_{el}^{(n)}}{V_p^{(n)}} = \frac{1 + \Gamma_{el}^{(n)}}{e^{j\gamma_2^{(n)} l_2^{(n)}} + \Gamma_{el}^{(n)} e^{-j\gamma_2^{(n)} l_2^{(n)}}} \quad (9)$$

$$\frac{V_p^{(n)}}{V_1^{(n)}} = \frac{1 + \Gamma_p^{(n)}}{e^{j\gamma_1^{(n)} l_1^{(n)}} + \Gamma_p^{(n)} e^{-j\gamma_1^{(n)} l_1^{(n)}}} \quad (10)$$

where

$$\Gamma_{el}^{(n)} = \frac{Z_{el}^{(n)} - Z_{c_2}^{(n)}}{Z_{el}^{(n)} + Z_{c_2}^{(n)}} \quad (11) \quad \Gamma_p^{(n)} = \frac{Z_b^{(n)} - Z_{c_1}^{(n)}}{Z_b^{(n)} + Z_{c_1}^{(n)}} \quad (12)$$

Finally, the total transfer function is simply obtained as

$$H(f) = \prod_{n=1}^N H^{(n)}(f) = \prod_{n=1}^N A^{(n)}(f) e^{j\Phi^{(n)}(f)} \quad (13)$$

where n denotes the unit index, and $A^{(n)}(f)$ and $\Phi^{(n)}(f)$ are the fading portion and delay portion of the transfer function of each unit. N is the total number of units used in the calculation.

The relation (13) holds true when the load impedance $Z_{el}^{(n-1)}$ of unit $n-1$ equals the input impedance $Z_{in}^{(n-1)}$ of section n .

In particular for the unit N , the load impedance $Z_{el}^{(N)}$ equals that of the receiver. The simple proof of such a result is not reported for space limitations. This suggests to compute the unit transfer function starting from the last unit, i.e., the one associated to the receiver.

A. Multi-Level Branches

The branches in the power network introduce most of the discontinuities which lead to signal reflections and cause multipath fading. As depicted in Fig. 1, the branches can be classified into four types:

- 1) single branch, as for instance the branch of index $N-2$;
- 2) star branch with several cables connected at the same

level, as the branch of index 3;

3) multi-level single branch, as the branch of index $N-1$;

4) the combination of type 2) and 3), as the branch of index 2.

As explained in the previous section, the computation of the transfer function of a given unit requires the knowledge of the input impedance of the branch associated to that unit. If the branch is a single branch, then the input impedance can be easily computed using the relation (7). The case of a star branch can also be evaluated since it is just the parallel of input impedances. More complex is the case of multilevel branches of different types. However, the problem can be solved by computing the sub-branches impedances starting from the outermost level, e.g., from level 4 in the branch of index 2 in Fig.1.

In order to simplify the computation and speed up the procedure we can also consider some simplification based on the branches length. That is, if we consider a single branch as in Fig. 3, its input impedance (7) can also be written as

$$Z_{in}^{(n)} = Z_{c_l} \frac{1 + \Gamma_b e^{-2\gamma l}}{1 - \Gamma_b e^{-2\gamma l}} \quad (14)$$

where Γ_b is the reflection coefficient at the load. If the length of the branch is sufficiently large, the input impedance approximates the characteristic impedance of that branch. This approximation can be made in the band 1-100 MHz for branches that are longer than 20 m. This is numerically shown in Fig. 4, assuming a branch with a characteristic impedance of 50 Ohm, with a load equal to $150 + j2\pi f \times 3 \times 10^{-9}$.

As a result, if we consider a portion of the backbone with length relatively long compared with the wavelength, as one unit, the computation of the transfer function may be greatly reduced since the circuits connected to the line toward the receiving side give a negligible contribution such that the equivalent load impedance of the upper unit is equal to the characteristic impedance of the line.

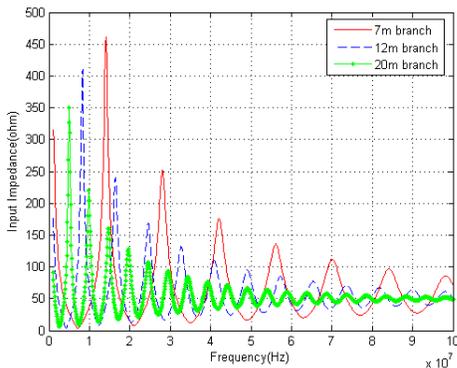


Fig. 4. Input impedance with different branch lengths.

IV. PATH LOSS

The path loss represents the power attenuation from the transmitter to the receiver and it is defined as

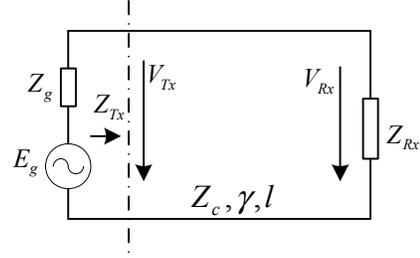


Fig. 5. Equivalent circuit for path loss and transfer function calculation.

$$P(f) = \frac{P_{Rx}(f)}{P_{Tx}(f)} \quad (15)$$

In order to derive the path loss from the transfer function, the equivalent circuit in Fig. 5 can be used. $P_{Rx}(f)$ and $P_{Tx}(f)$ can be derived from the voltage and impedance at Z_{Rx} and Z_{Tx} respectively. Subsequently, the path loss is obtained as follows

$$P(f) = |H(f)|^2 \frac{R_{Rx}(f) |Z_{Tx}(f)|^2}{R_{Tx}(f) |Z_{Rx}(f)|^2} \quad (16)$$

Therefore, the path loss is easily derived from the total transfer function as depicted above depending on the input impedance at the transmitter and load impedance at the receiver.

V. STATISTICAL TRANSFER FUNCTION GENERATOR

The voltage ratio approach that we have described allows the accurate computation of the transfer function between two nodes when an accurate knowledge of the PLC network in terms of topology, cables, and loads is available. For the purpose of communication systems design and analysis it is of great importance to use a statistical channel model that captures the ensemble of PLC networks. The bottom-up approach allows accomplishing this goal by using a statistical description of the parameters needed. It also differs from the statistical top-down approach that was proposed in [18] and that directly draws transfer functions from a certain distribution of the parameters used within the multi-path frequency response model. Although, the top-down approach is simple to be realized, it lacks a direct link to the physical transmission behavior.

In the herein described bottom-up approach, transfer functions can be efficiently computed. Therefore, it can be used to generate realization of transfer functions from realization of randomly generated network topologies. The idea is based on dividing the PLC networks into classes corresponding to different environments such as family houses, small offices and industrial buildings. Then, the topologies in each class are drawn from a multivariate distribution that describes the number of nodes, branches, and corresponding lengths. For each node we also draw realizations of loads. The loads are classified into open, and those associated to an appliance. Finally, different cable characteristics can be taken into account.

Another interesting characteristic of this bottom-up approach is that it can be used to take into account the time-variant behavior of the channel response as a result time-variant loads as it has been reported in [15] for certain type of appliances.

Finally, the voltage ratio approach allows obtaining a channel transfer function for each realization of the random parameters with low complexity (and thus within a short time) which is an important aspect when a channel simulator has to be realized.

A. Numerical Examples

In Fig. 6.A and 6.B we report two examples of network topologies that have been randomly generated. We assume the deployment of cables of the same type. Some of the loads are open while others have impedance typical of the home appliances such as PC, monitor and electrical kettle. The resulting frequency and impulse response are shown in Fig. 7.A and 7.B.

Since the topology in Fig. 6.A has a longer backbone and a larger amount of branches compared to that in Fig. 7.B, it leads to a heavier attenuation and more severe multipath fading.

As discussed before, the transfer function computation can be simplified by neglecting the loads attached to long branches. In turn, this implies that the input impedance of the branch corresponds to the characteristic impedance. The effect of such an approximation is shown in Fig. 9 for the sample network in Fig. 8 where we compare the transfer functions with and without load 2. The transfer functions are almost identical in the frequency band of interest whether or not load 2 is considered.

It is worth mentioning that if we include in the model the time-variant impedances of the loads (obtained from measurements) we can easily obtain, via the voltage ratio approach, time-variant transfer functions. For space limitations, we do not report such results.

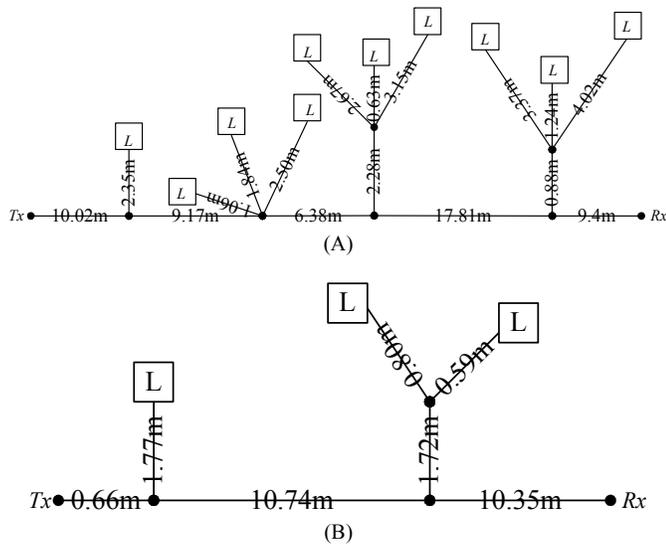


Fig. 6. Sample topologies.

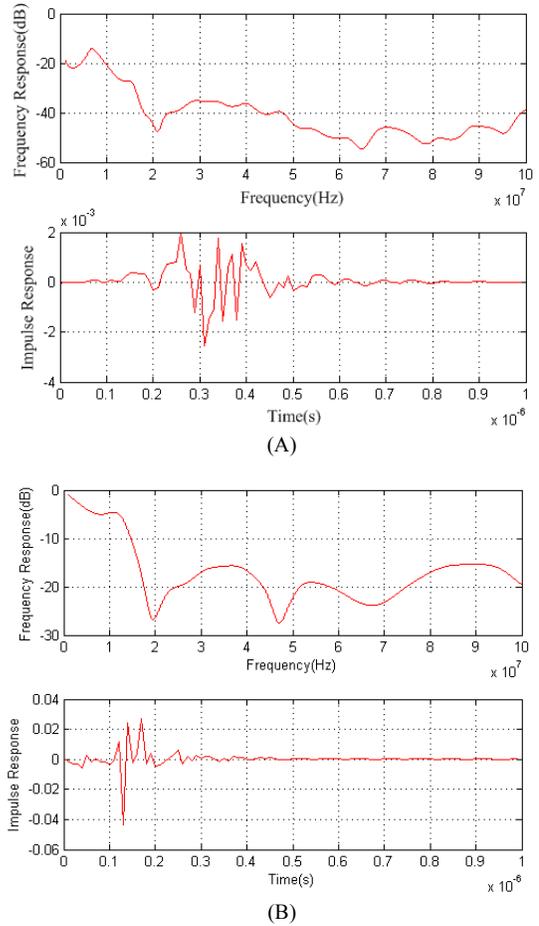


Fig. 7. Frequency and impulse response for the networks in Fig. 6.A-B.

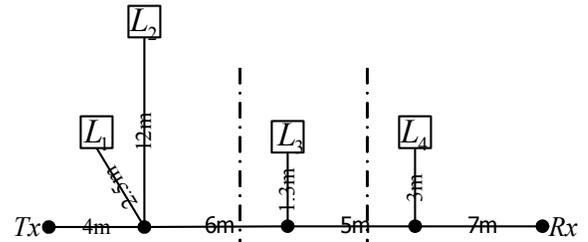


Fig. 8. Sample network with long branch.

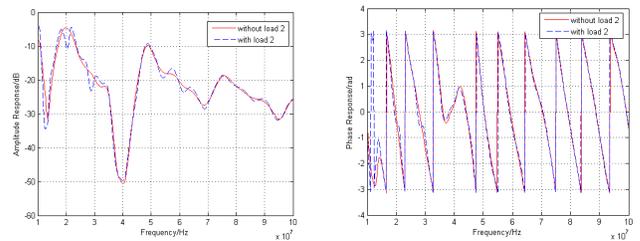


Fig. 9. Comparison of long branch effect in the transfer function. Left plot, amplitude. Right plot, phase.

VI. CONCLUSIONS

This paper discusses an approach to channel modeling and efficient simulation based on transmission line theory. The approach is based on the computation of the voltage ratio via the partitioning of a complex network topology into simpler sub-units. The total transfer function between the transmitter and receiver is efficiently determined as a multiplication of the transfer functions of the component units starting from the receiver side. The cable characteristics as well the effect of time-variant loads can be taken into account. A statistical bottom-up channel simulator is then realized by computing the transfer function according to the voltage ratio method herein described for each realization of the random network topology.

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