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A Simplified Deterministic Approach to accurate Modeling of Transfer Function for the Broadband Power Line Communication

Abdelali Rennane, Christophe Konaté and Mohamed Machmoum
Nantes of University (Nantes)
France

1. Introduction

With the deregulation of the telecommunication and electricity markets, great deals of new operators providing some innovative services have appeared. In the telecommunications field, the promise of broad-band internet access with easy installation procedure at low cost may help to gain new customers. The Power Line Communication (PLC) technology is a way to fulfill this function. PLC uses the low voltage (LV) and the medium voltage (MV) networks as communication support (Roka & Urminsky, 2008; Meng & Chen, 2004). It consists in an additional signal carrying data information which is superimposed to the 50/60 Hz power wave. As PLC is easy to install, it can be used to extend the internet coverage to areas that are still badly covered by the other broadband technologies, or to provide high speed internet access to every power socket of building. The modeling of the PLC channel is of fundamental importance, since the quality of the transmission is highly influenced by the characteristics of the channel itself. Principally, channel attenuation depends on the characteristics of the cables (length, per-unit-length parameters, and frequency dependence) and of the loads (Roblot, 2007; Barmada et al., 2006). Several techniques have been proposed to properly simulate the PLC channel. A common practice is to consider the transmission path as a black box and to describe the transmission line by a transfer function (Moreno, 2008 ; Philips, 1999). The system parameters are obtained either from measurements and experimental data or from theoretical derivation (Konaté et al. 2007; Anastasiadou & Antonakoupoulos, 2005). The objective of this chapter is to develop a transfer function model for the LV power line based on the transmission line theory. This model will help the PLC system designer to better understand the channel behavior and to engineer the channel performances under different network configurations and load conditions.

This chapter is organized as follows. We start with a representation of the transmission line as two conductors in section 2. We describe the set up experimental in section 3. The next section deals with experimental determination of channel impedance and propagation constant. In section 5, the power channel model is established. In section 6 the proposed deterministic method is generalized to network with N nodes and M branches. Section 7

gives simulation results. The influence of branched line, number of branches and impedance matching are discussed. In section 8, we realized experimental measurements for verification of the parametric model for reference channels in the real PLC environment. A concluding recapitulation closes the chapter in the last section.

2. Transmission Line Parameters of the Cable

The transmission line model represents the transmission line as an infinite series of two-port elementary components, each representing an infinitesimally short segment of the transmission line. The distributed resistance R of the conductors is represented by a series resistor (expressed in Ohm per unit length). The distributed inductance L is represented by a series inductor (Henrie per unit length). The capacitance C between the two conductors is represented by a shunt capacitor C (Farad per unit length). The conductance G of the dielectric material separating the two conductors is represented by a conductance G shunted between the signal wire and the return wire (Siemens per unit length). The model consists of an infinite series of the elements shown in Fig. 1. The values of the components are specified per unit length so the picture of the component can be derived. The parameters R , L , C , and G may also be functions of frequency. An alternative notation is to use R' , L' , C' and G' to emphasize that the values are derivatives with respect to length.

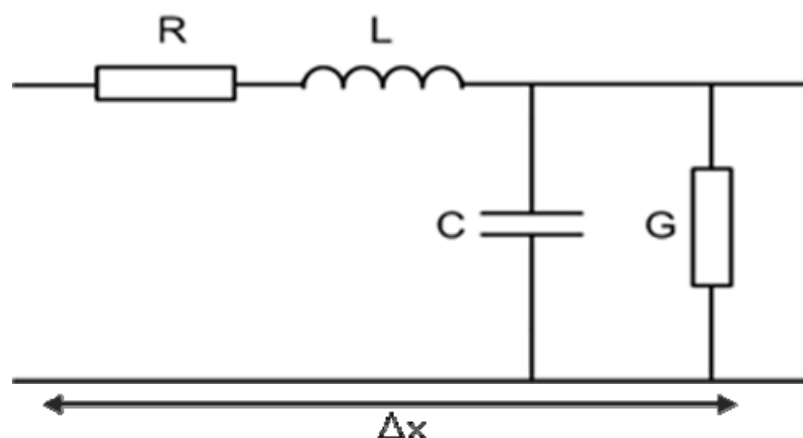


Fig. 1. Distribution network model of a transmission line

The parameters to describe a transmission line are the characteristic impedance Z_C and the propagation constant γ . These parameters are defined as:

$$\bar{Z}_C = \sqrt{\frac{\bar{Z}}{\bar{Y}}} = \sqrt{\frac{R'+jL'\omega}{G'+jC'\omega}} \quad (1)$$

$$\gamma = \sqrt{(R'+jL'\omega)(G'+jC'\omega)} = \alpha + j\beta \quad (2)$$

Where, $\omega = 2\pi f$ is the angular frequency, α is the attenuation constant and β is the phase constant. In our case, considering frequencies in the MHz-range, the resistance per unit length is dominated by the skin effect and the conductance per unit length is mainly

influenced by the dissipation factor of the dielectric material usually Polyvinyl Chloride (PVC). The result of using geometry and material properties in the above equations results in $R' \ll L'$ and $G' \ll C'$ in the frequency range of interest. Hence the cables can be regarded as weakly loss and the characteristic impedance Z_C and the propagation constant γ can be determined using the following simplified expressions:

$$\bar{Z}_C = \sqrt{\frac{L'}{C'}} \quad (3)$$

$$\gamma = \alpha + j\beta = \frac{1}{2} \left(\frac{R'}{Z_C} + G' Z_C \right) + j\omega \sqrt{L' C'} \quad (4)$$

3. Experimental Set up

The PLC test environment (Fig. 2) available in the DAL (Digital Applications Laboratory) is realized with a cable type RO2V 3G of section 2.5 mm² and powered with three-phase network. It is isolated upstream with a three-phase filter; each phase is also isolated with a single-phase filter. The PLC test environment can simulate various power network topologies like “star” or “trees” topologies. This is enabled by multiple circuits and dedicated switches implemented and drawn from a distribution board which is typical of a real home installation. PLC modems can be tested to check their conformance with the HomePlug AV standard and Interoperability (C&I). Performance, robustness and digital application tests (Data/Audio/Video flows) tests can also be carried out on this test environment. The PLC test environment represents also a configurable electrical network that can emulate the propagation medium of PLC signals in real home environment. It can be used for S parameters measurements and power line channel measurement, tests of IP services in reproducible electrical propagation conditions, but also for measurements of electrical impedance and noise.



Fig. 2. PLC test environment available in DAL

When measuring the S parameters as a function of frequency in the range 1-30 MHz, a measurement setup as described in Fig. 3 is used. It consists of the network analyzer (NA) HP4394A (10 Hz-500 MHz), of an Agilent 87513A transmission/reflection set DC-2GHz and of two PLC couplers. These Couplers are designed to reject a 50 Hz signal and allows to perform measurements in the differential mode. They are connected to the NA HP4395A with two coaxial cables "RG58" and plugged on the electric outlets on their electrical interface.

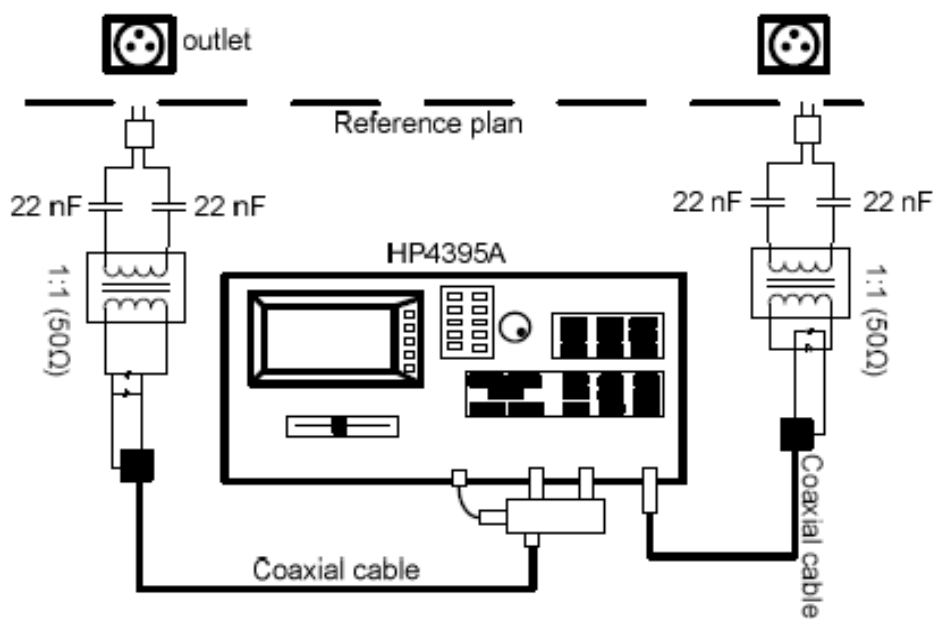


Fig. 3. Transfer function measurement setup

4. Experimental Determination of Z_C and γ

A transmission line of the length l is kept open at one end, and the impedance at its other end is measured using an impedance bridge. In this chapter the experimental results (Z_{open} and Z_{short}) are measured by a network analyzer 4395A using in the Impedance analyzer mode. Assume that it is Z_{open} , the process is repeated after placing a short circuit at its open end, and this impedance is recorded as Z_{short} . Using transmission line theory, the impedance at the input of this transmission line, Z_{in} ($l = 0$) can be determined by:

$$Z_{in} = Z_C \frac{Z_L + Z_C \tanh(\gamma.l)}{Z_C + Z_L \tanh(\gamma.l)} \quad (5)$$

Where

$$Z_{in,open} = Z_C \cdot \cot \tanh(\gamma.l) \quad (6)$$

And

$$Z_{in,short} = Z_C \cdot \tanh(\gamma.l) \quad (7)$$

Combining equations 6 and 7, the characteristic impedance and the propagation constant can be deduced:

$$Z_C = \sqrt{Z_{in,open} \cdot Z_{in,short}} \quad (8)$$

$$\gamma = \frac{1}{l} \arg \tanh \left(\sqrt{\frac{Z_{in,short}}{Z_{in,open}}} \right) \quad (9)$$

The parameters of the cable used (RO2V 3×2.5mm²) are, $R' = 0.31 \Omega/m$, $G' = 64.7 \text{ mS/m}$, $L' = 0.327 \mu\text{H/m}$ and $C' = 66.9 \text{ pF/m}$. The mean value of the characteristic impedance Z_C is 69.9Ω. The attenuation constant α regarding this cable as well as its attenuation in the examined frequency range 1 – 30 MHz (for a length of 40 m) is shown in Fig. 4. The attenuation constant is modeled by the following relation

$$\alpha = a_0 + a_1 f^k \quad (10)$$

Where a_0 , a_1 and k (exponent of the attenuation factor) are obtained from measurements (Zimmermann & Dostert, 2002). Their values are determined using a least-squares fitting method. The obtained attenuation parameters values are $k = 0.75$, $a_0 = 3.11 \cdot 10^{-4} \text{ m}^{-1}$, $a_1 = 1.76 \cdot 10^{-8} \text{ s/m}$ and the phase is easily deduced based on L' and C' values.

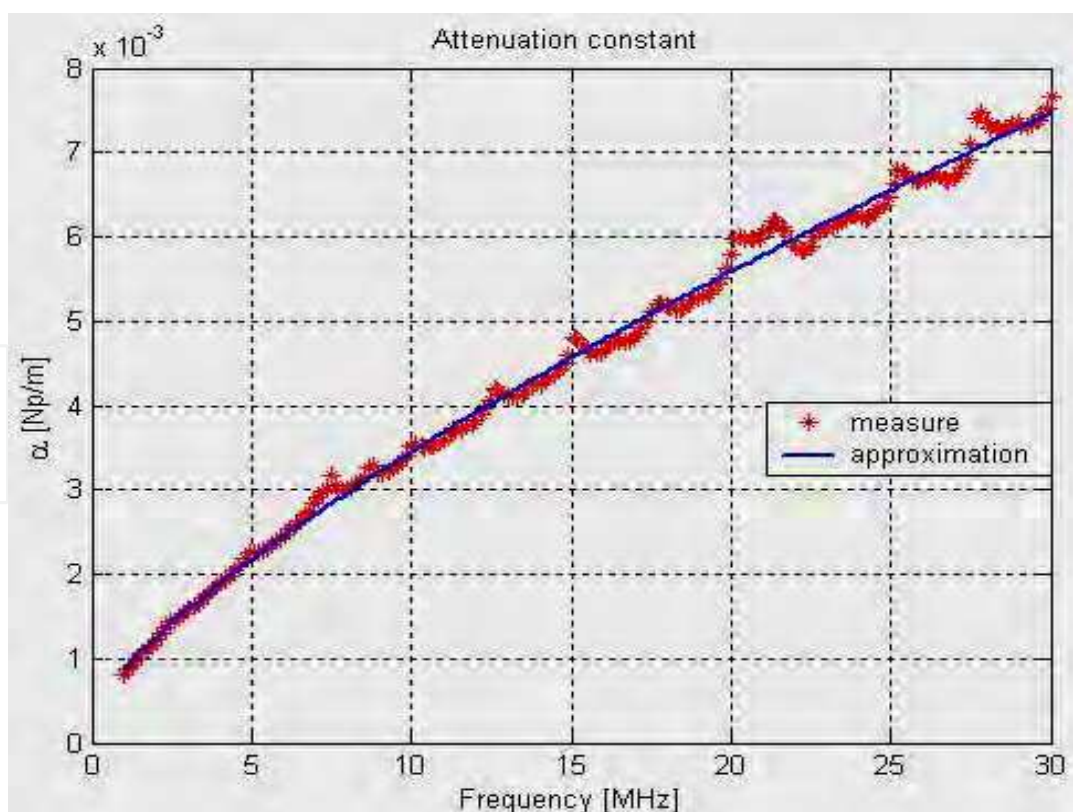


Fig. 4. Attenuation constant of a 40 m RO2V 3*2.5 mm² cable

5. Power Line Channel Model

It has been said that optimization of a transmission system is realizable only when a reasonably accurate channel model is available for investigating the power line network performance in detail (Biglieri et al., 2003). The model proposed by Hensen was straight forward. The attenuation was increasing with frequency and do not take into consideration the multiple phenomenon (Hensen & Schulz, 2000).

Dostert and Zimmermann say that the only way to model the LV power line network for high frequencies is empirically as like their model. We investigated some deterministic models and implemented simulations using MATLAB software package. This software is readily available and it combines mathematical functions as well as the capability to handle long iterations of complex variables. It allows also graphing and comparing results in a simple manner. The execution time of all simulations (see section 7) does not exceed two minutes. Deterministic model basically means finding the transfer function theoretically without taking actual measurements of the transmission line. These usual models are implemented using consistent techniques based on matriciel calculation to present the complex multi-path network. The model that was followed uses chain matrix theory which is used to compute the transfer function of transmission lines.

In Fig.5, the relation between V_1 , V_2 , I_1 and I_2 (the input and output voltages and currents of a two port network in the frequency-domain) is represented by:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (11)$$

Where, the $ABCD$ coefficients are generally complex functions of frequency, and fully characterize the electrical properties of a two port network.

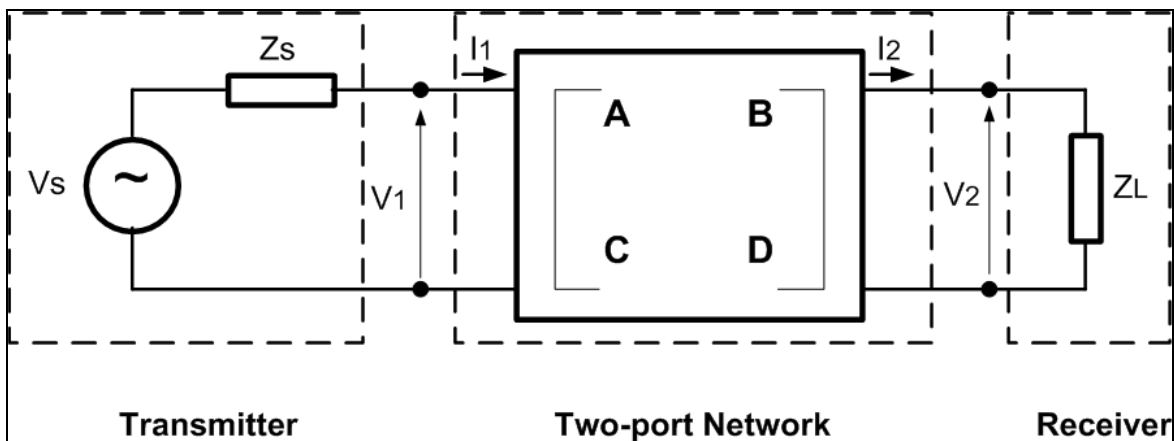


Fig. 5. Block diagram of two port network connected to a Transmitter and Receiver

The $ABCD$ parameters allow us to calculate two important quantities: the transfer function as ratio of the voltage on the load to the source voltage and the input impedance of the network.

$$H(f) = \frac{V_L}{V_s} = \frac{Z_L}{AZ_L + B + CZ_S Z_L + DZ_S} \quad (12)$$

With

$$Z_{in} = \frac{AZ_L + B}{CZ_L + D} \quad (13)$$

Where, Z_S and Z_L are respectively the source and the load impedance. In the case of a two conductor Transmission Line, the $ABCD$ coefficients and the corresponding transmission matrix T take on the following expression:

$$T_i = \begin{pmatrix} \cosh(\gamma.l) & Z_C \cdot \sinh(\gamma.l) \\ Z_C^{-1} \cdot \sinh(\gamma.l) & \cosh(\gamma.l) \end{pmatrix} \quad (14)$$

Where l , γ and Z_C are the length, the propagation constant and characteristic impedance of the cable, respectively. These quantities can be either estimated from measurement as done in section 3.

For information, all parameters Z_{in} , γ , Z_C and the quantities V_L , V_s , A , B , C and D are complex values.

6. Generalized Determination Method for the Low Voltage PLC Channel

This deterministic based model has been implemented and tested on the indoor LV PLC network presented by P sections, N derivations and M nodes (see Fig. 6).

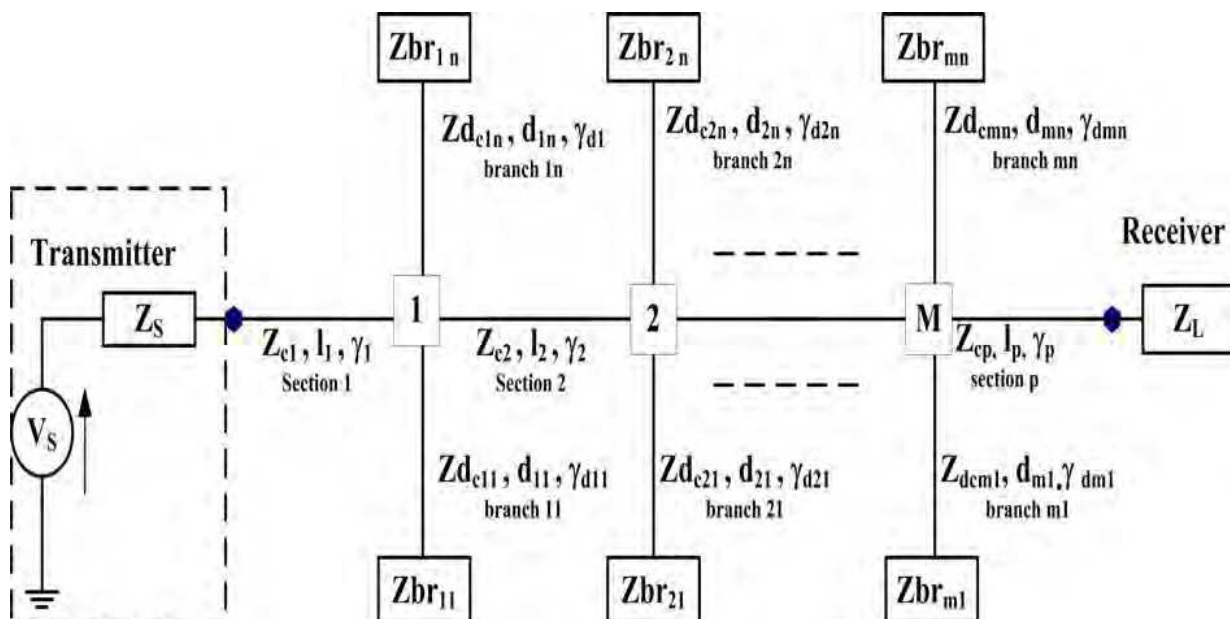


Fig. 6. Power line network with disturbed branches (M nodes and N derivations)

The circuit has been partitioned into $2P$ cascade two-port sub-circuits as shown in Fig. 7. For each sub-circuit it is possible to calculate an A_i , B_i , C_i and D_i coefficients. The total matrix T is defined as:

$$T = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = T_0 \cdot \prod_{i=1}^{P-1} T_i \cdot T_{di} \cdot T_P \quad (15)$$

Where,

$$T_0 = \begin{pmatrix} 1 & Z_s \\ 0 & 1 \end{pmatrix} \quad (16)$$

The parameters of matrix T_i corresponding to the section i are given as:

$$T_i = \begin{pmatrix} \cosh(\gamma_i l_i) & Z_{Ci} \cdot \sinh(\gamma_i l_i) \\ Z_{Ci}^{-1} \cdot \sinh(\gamma_i l_i) & \cosh(\gamma_i l_i) \end{pmatrix} \quad (17)$$

In our study, we have P sections of transmission lines with lengths l_p is connected to a node m , $Z_{br_{ij}}$ is the load at the terminal of each branch and $Z_{cd_{ij}}$ is the characteristic impedance for the node i of the j transmission line branch. T_p is the transmission matrix of the last section P . T_{di} is the equivalent transmission matrix of branches connected at node i given by:

$$T_{di} = \begin{pmatrix} 1 & 0 \\ \sum_{j=1}^N \frac{1}{Z_{d_{eq_{ij}}}} & 1 \end{pmatrix} \quad (18)$$

Where, N represents the number of derivations at node i , and $Z_{d_{eq_{ij}}}$ is defined as:

$$\bar{Z}_{d_{eq_{ij}}} = \bar{Z}_{cd_{ij}} \frac{\bar{Z}_{br_{ij}} + \bar{Z}_{cd_{ij}} \cdot \tanh(\bar{\gamma}_{d_{ij}} \cdot d_{ij})}{\bar{Z}_{cd_{ij}} + \bar{Z}_{br_{ij}} \cdot \tanh(\bar{\gamma}_{d_{ij}} \cdot d_{ij})} \quad (19)$$

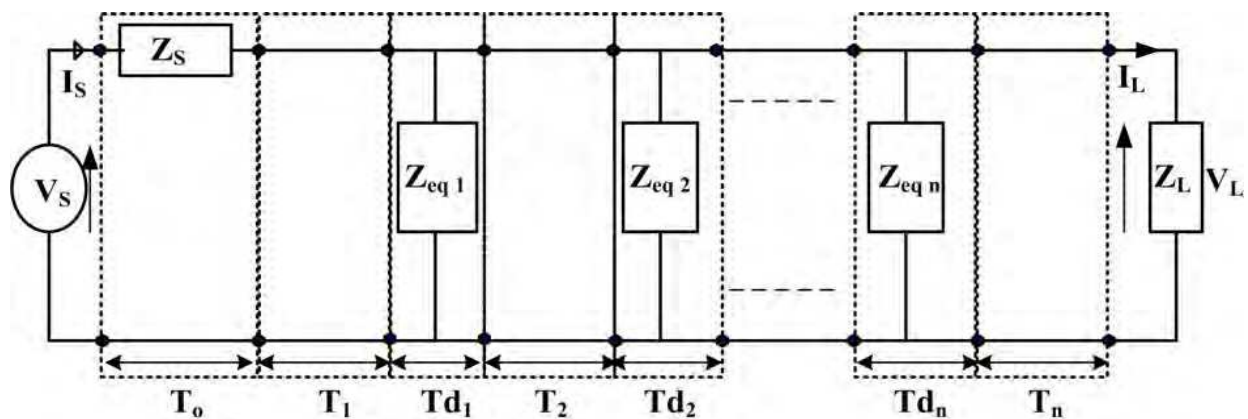


Fig. 7. Basic voltage and current definitions for Two-Port Network with distributed branches

After analyzing the single-branch network in section 5, the remaining task is the determination of the scattering matrix for a cascade of several single-branch networks. Using the microwave theory, there are generally two methods that can be used. The first method is to use the chain scattering matrix (or T-matrix), and the second is to use signal flow graph. For the sake of easier computation, the first method is used in this paper. The relation between the S-matrix parameters (usually measured by a network analyzer) and T-matrix parameters is given by (Misra, 2004).

$$T = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} \frac{1}{S_{21}} & -\frac{S_{22}}{S_{21}} \\ \frac{S_{11}}{S_{21}} & S_{12} - \frac{S_{11} \cdot S_{22}}{S_{21}} \end{pmatrix} \quad (20)$$

The S-matrix for the whole network can be obtained by using the following conversion equation:

$$S = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} \frac{T_{21}}{T_{11}} & T_{22} - \frac{T_{21} \cdot T_{12}}{T_{11}} \\ \frac{1}{T_{11}} & -\frac{T_{12}}{T_{11}} \end{pmatrix} \quad (21)$$

Finally, the $(T_{11}, T_{12}, T_{21}$ and $T_{22})$ parameters allow us to calculate two important quantities: the generalized transfer function can be represented as ratio of V_L to V_S , and the input impedance of the network with distributed branches.

$$H(f) = \frac{Z_L}{T_{11}Z_L + T_{12} + T_{21}Z_S Z_L + T_{22}Z_S} \quad (22)$$

$$Z_{in}(f) = \frac{T_{11}Z_L + T_{12}}{T_{21}Z_L + T_{22}} \quad (23)$$

7. Simulation Results

To explore the range of possible PLC, we now consider a typical low voltage line power network. We present the results of our analysis applied to a variety of wire configurations. In all studies, we consider $Z_L = Z_S = 50 \Omega$ and all the lines per unit length parameters are $L' = 0.327 \mu\text{H}/\text{m}$ and $C' = 66.9 \text{ pF}/\text{m}$.

7.1 Influence of branch length

As an example we start study using a channel with one bridge taps. The corresponding configuration is given in Fig. 8. In this figure, $l_1 = l_2 = 15 \text{ m}$ (l_1 and l_2 are the lengths of two channel sections), d_{11} is the length of distributed branch which is varied as 5 m, 10 m, 15 m and 20 m. The load Z_{br11} was terminated in open circuit, while Z_{C1} , Z_{C2} and Z_{dC11} are the line characteristic impedance ($Z_{C1} = Z_{C2} = Z_{dC11} = 69.9 \Omega$).

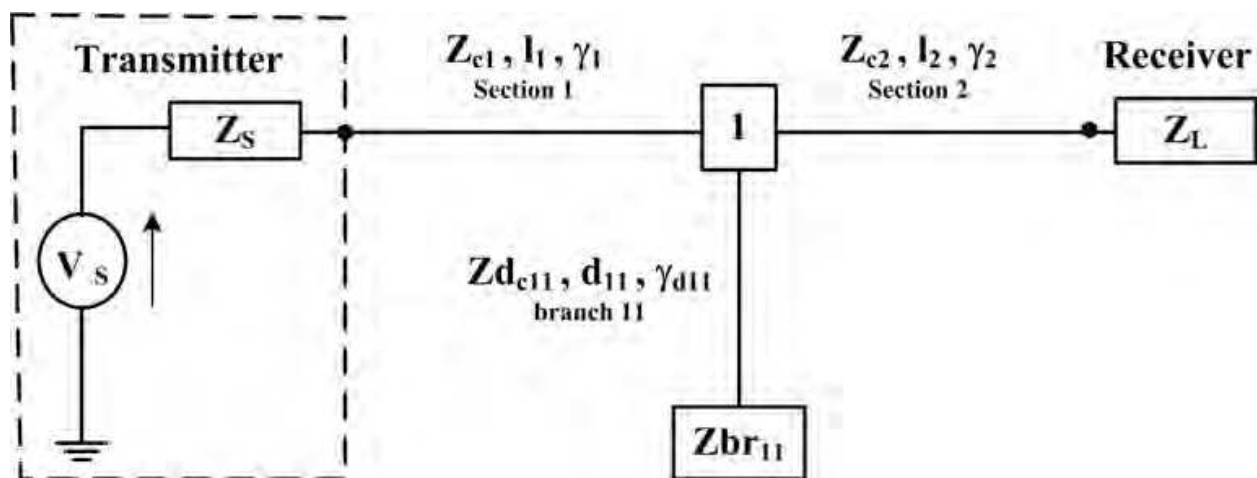


Fig. 8. Configuration of simulated network with a branch

In this case of a two conductor transmission line with two sections, the transmission matrix T takes on the following expression:

$$T = T_0 \cdot T_1 \cdot \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{d_{eq11}}} & 1 \end{pmatrix} \cdot T_2 \quad (24)$$

Fig. 9 (a, b and c) show the corresponding frequency responses for various branch line lengths. We observed that in three cases the peaks of frequency responses was not either attenuating with frequencies. As the length of branched line increases the number of notches increases proportionally.

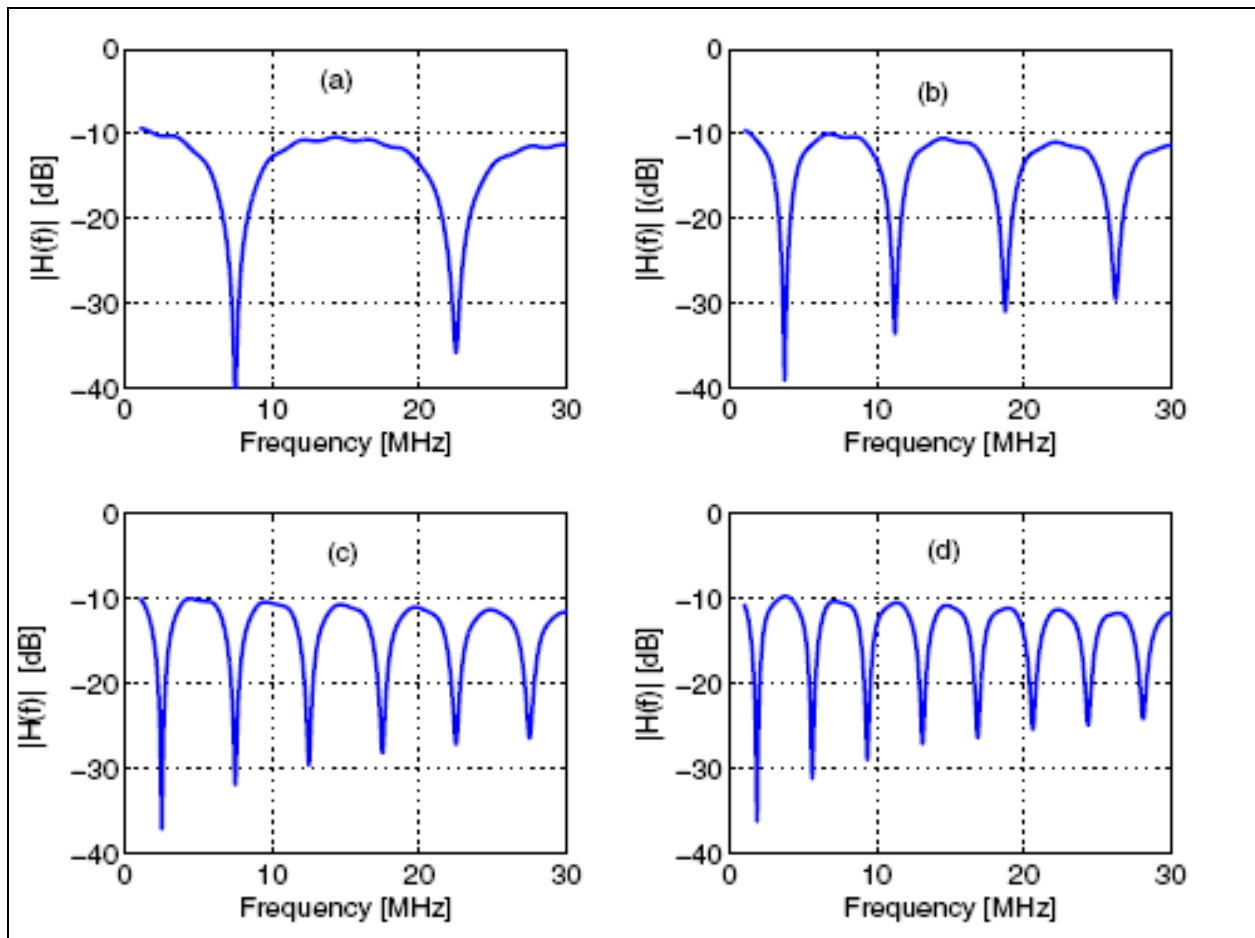


Fig. 9. Simulation results for low channel of power line with one branch of length (a) 5 m, (b) 10 m, (c) 15 m and (d) 20 m

7.2 Influence of number of branches

To analyze the effect of number of branches, we consider the configuration shown in Fig. 10. The line length Transmitter- Receiver (Tx-Rx) was kept constant at 60 m; i.e. $l_1 = l_2 = l_3 = l_4 = 15$ m, with one, two and three disturbed branches. All branches were 5 m long ($d_{11} = d_{21} = d_{31} = 5$ m) and load $Z_{br_{11}}, Z_{br_{21}}$ and $Z_{br_{31}}$ were terminated in open circuit, while $Z_{d_{C11}}, Z_{d_{C21}}$ and $Z_{d_{C31}}$ are the line characteristic impedances. We repeat the same test as before simulating the transfer function with respect the number of branches.

In this case of a two conductor Transmission Line with four sections, the transmission matrix T takes on the following expression:

$$T = T_0 \cdot \prod_{i=1}^3 T_i \cdot T_4 \quad (25)$$

$$\begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{d_{eqi1}}} & 1 \end{pmatrix}$$

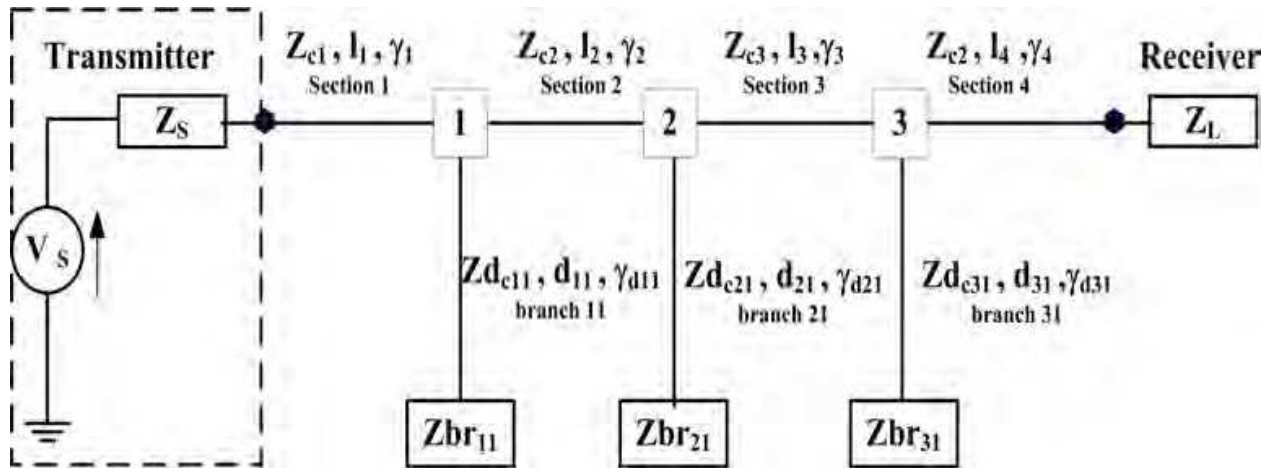


Fig. 10. Power line network with one branch at each node

Fig. 11 shows the transfer function for different number of branches. We noted that the positions of notches are not changed but as the number of branches increases the attenuations of notched point tends to increase.

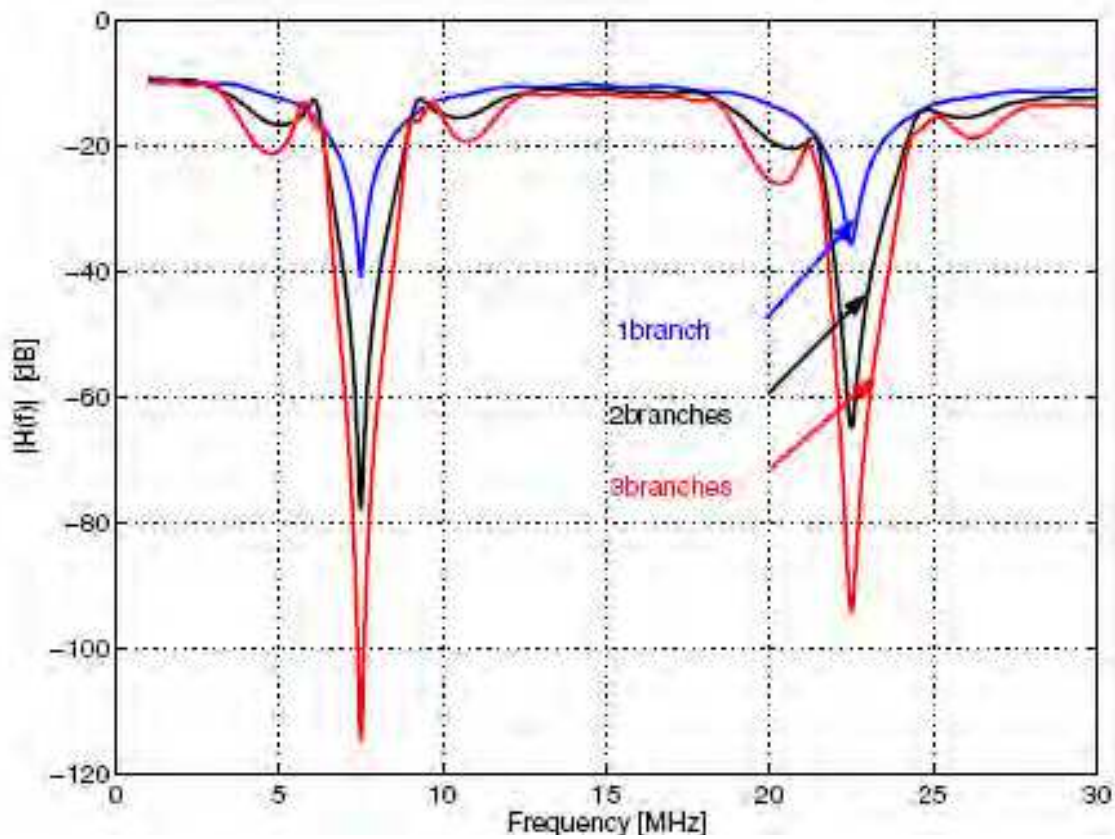


Fig. 11. Simulation results with distributed branches, 1 branch, 2 branches and 3 branches

We have observed the same result of the power line network with multiple branches at a single node. In fact, the positions of notches are not changed and the number of branches increase allows increasing the amplitude response of notched points.

7.3 Influence of impedance matching

This study is accentuated here because it is common that the loads at the termination of branched lines are not only opened circuit. For discussions below we consider the configuration as in Fig. 8. The line length Transmitter-Receiver (Tx-Rx) was kept constant at 30m ($l_1 = l_2 = 15\text{ m}$) while the branch of length 10m is connected to the middle of line (Tx-Rx). The termination Z_{br11} was varied according to given load impedance under our investigation. Firstly, we consider the following load impedances with values $69.9\ \Omega$, shorted circuit ($Z_{br11} = C.C$) and opened circuit ($Z_{br11} = C.O$). Remember that $69.9\ \Omega$ is the characteristic impedance of the branch. For the load impedance shorted and opened, the position of notches and peaks are shifted in the frequency positions with same attenuation. However for the load characteristic impedance the peeks and notches are disappeared (see Fig. 12).

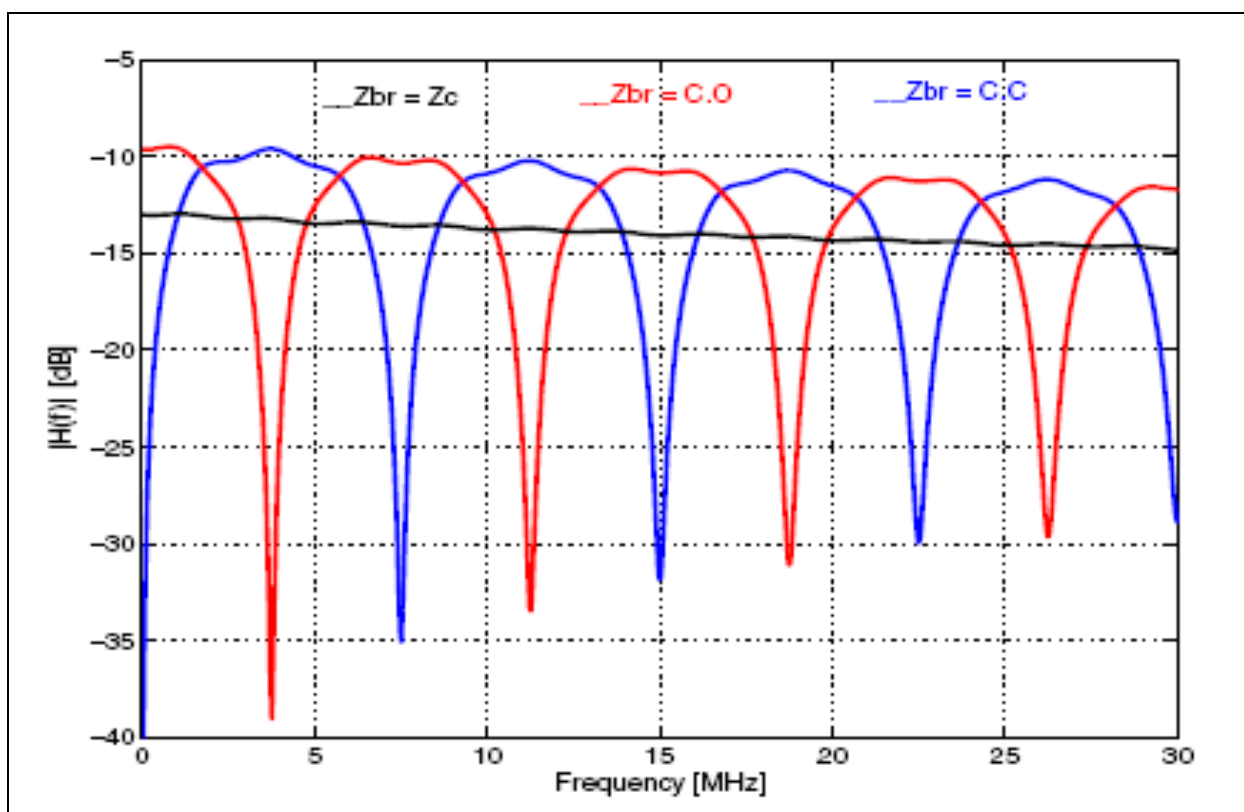


Fig. 12. Simulation results for a LV channel with a branch terminated in open circuit, short circuit and characteristic impedance.

Secondly we propose to analyze the behavior of the characteristic impedance when realistic loads are used. The impedance of proposed realistic loads (TV and microwave) is measured by using the method proposed in (Tang, 2001). The impedance of the power network Z_{ref} is first measured through a socket when the appliance is not connected to the network. After,

the appliance is connected near the socket and the network impedance Z_{tot} is again measured. Therefore, the impedance of the appliance Z_{app} can be deduced by:

$$Z_{tot} = Z_{app} // Z_{ref} \quad (26)$$

After rearranging, we get

$$Z_{app} = \frac{Z_{ref} \cdot Z_{tot}}{Z_{ref} - Z_{tot}} \quad (27)$$

Fig. 13 illustrates the measured impedance of the TV and microwave, always in the frequency range of 1 – 30 MHz. These impedances were used in the derivation of the transfer function of the network under test in Fig. 8.

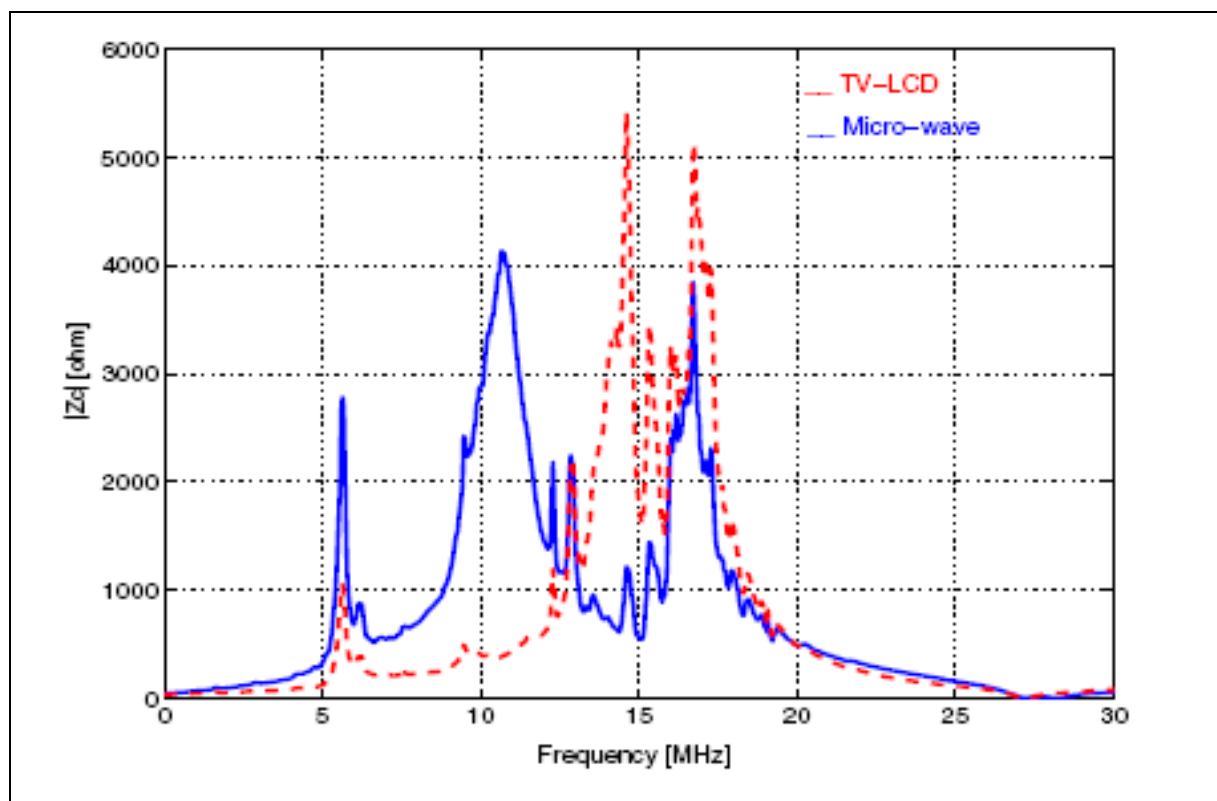


Fig. 13. Impedance of loads TV and Microwave

In this subsection, we have evaluated the response of the magnitude of the derived transfer function for two loads TV and the microwave (see Fig. 14). A strong attenuation notch at about 18 MHz, for both cases is mainly caused by the impedances of the branched loads. For TV, the strength of the attenuation at two notches near 10 MHz and 20 MHz is about 40 and 50 dB. For the microwave, we noted an additional notch near 3 MHz attenuated about 40dB.

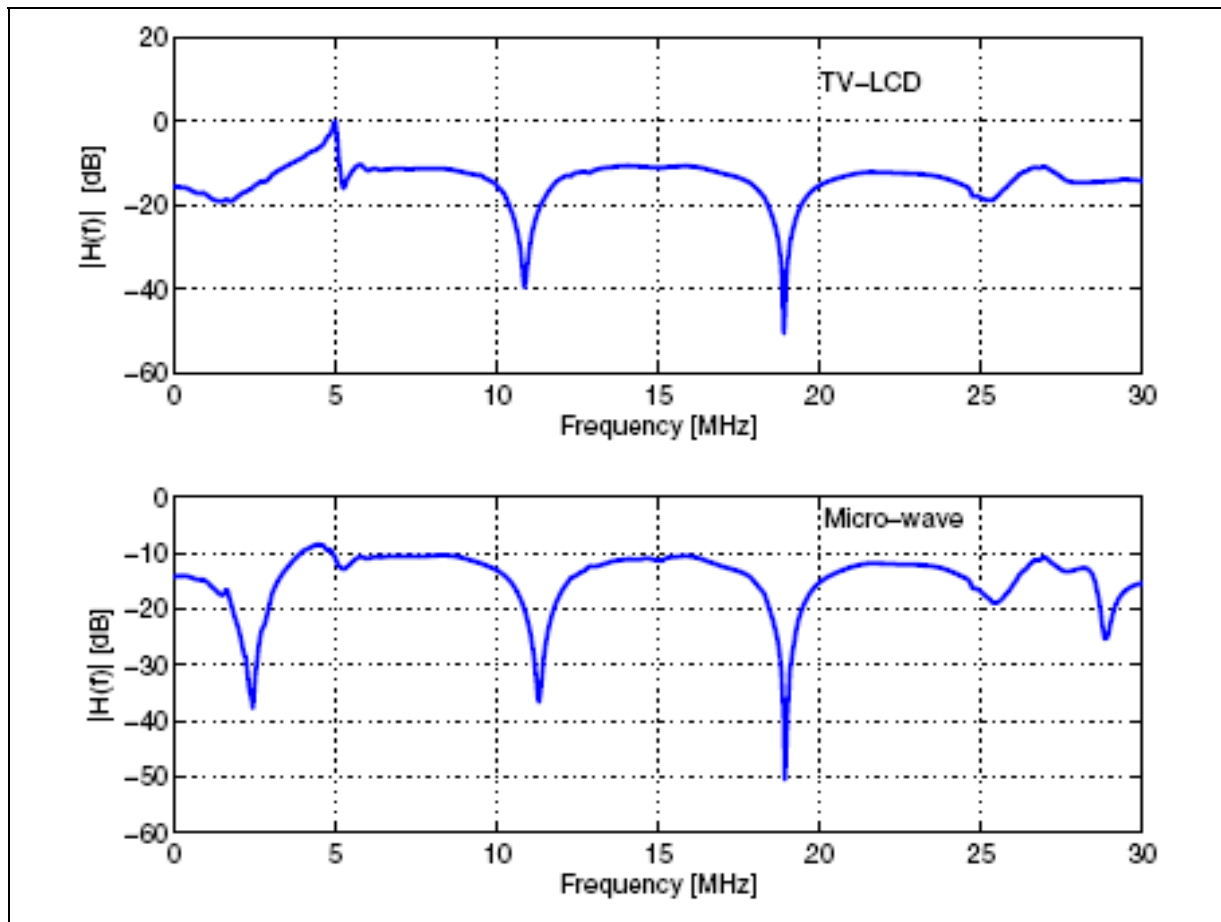


Fig. 14. Simulation results for power line LV network with a branch terminated in TV and Microwave.

8. Validation of the Model by measurements

For Validation the results of simulations based on the proposed model are compared with measurements. This was done on the one hand with a sample network with well known topology and geometric dimensions and on the other hand with a real in-home network. We realized a measurements of the transmission channel characteristics. At the transmitting and the receiving side, an Agilent 4395A network analyzer was located. In addition to this measuring accuracy device, a balun was used to segregate devices from the power distribution network. Data was collected using a network analyzer. The unit was interfaced to a laptop PC, which provided automated control and data archiving. The spectrum analyzer was used in lieu of the regular electronics so that we could continue to work on the while this lengthy measurement (3 full days) was underway. The total transfer function including the active balun used in this testing, results shown above are presented in the following.

8.1. Power line with one branch

As an example, we start study using a channel with one bridge taps. The corresponding configuration is given in Fig. 8. In this figure, $l_1 = l_2 = 15\text{m}$ (l_1 and l_2 are the lengths of two channel sections), d_{11} is the length of distributed branch which is 15 m. The load Z_{br11} was terminated in open circuit, while Z_{C1} , Z_{C2} and Z_{dC11} are the line characteristic impedance ($Z_{C1} = Z_{C2} = Z_{dC11} = 69.9 \Omega$). The measurement points are referred by (Tx) and (Rx).

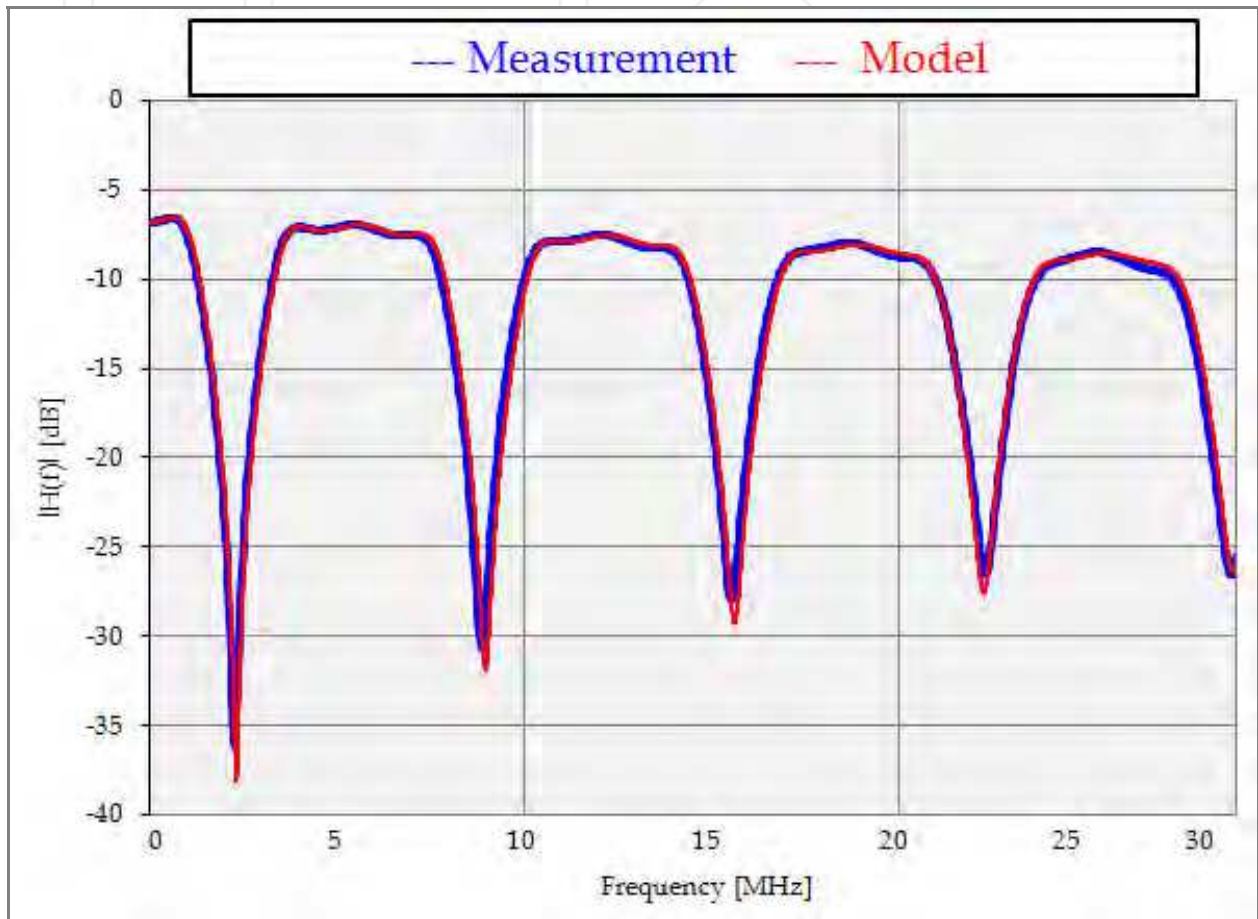


Fig. 15. Comparison between measurement and model of the response of power line channel with one branch

The plots in Fig. 15 illustrate the frequency behavior of transfer function obtained by simulations and measurements. This figure demonstrates that measured transfer function is perfectly close to that simulated by the model.

8.2. Power line network with two branches

To analyze the effect of number of branch, we consider the configuration as given in Fig. 8 with two disturbed branches, both branches were 15m long ($d_1 = d_2 = 15\text{m}$), Z_{br11} and Z_{br12} were terminated in open circuit, while Z_{dc1} and Z_{dc2} are the line characteristic impedances. Measurements with correct results are presented in Fig. 16. Again, the measurements confirm assumptions that the signal attenuation is directly proportional to the number of

branches. The measured transfer function is very close to that modeled, also the positions of notches are not changed (compared to the previous case, see Fig.15).

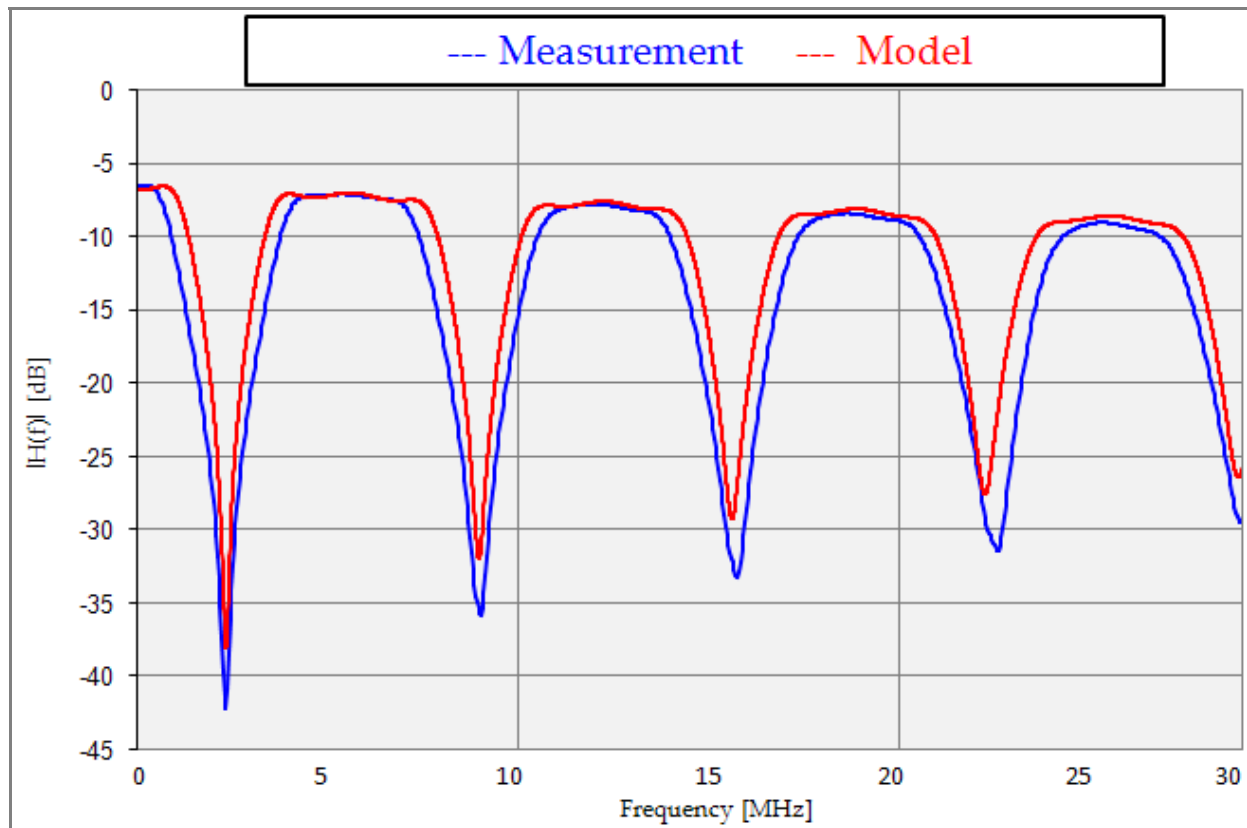


Fig. 16. Comparison between measurement and model of the response of power line channel with two branches

We repeat this test with three branches at each node, we observed that the number of distributed branches increases the amplitude of notched points tends to increase. However, but the position of notches in frequency response depends on the length of branched line, the number of notches increase proportionally with the line length.

9. Conclusion

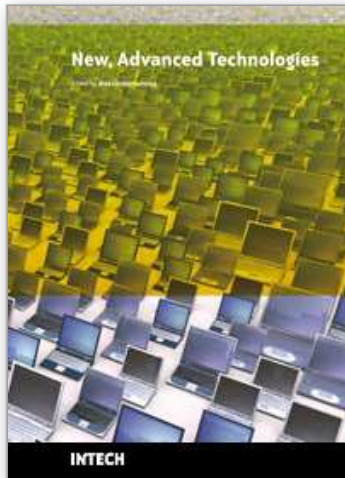
In this chapter, the modeling procedures of power line channel have been presented. The deterministic method uses basic network parameters to derive a transfer function of the channel. The investigated deterministic models were determined from an indoor PLC channel. They are specifically topology dependent. For separate network channels, only the cable parameters, the load impedances and the topology of the network are absolutely needed. The LV network is considered as an M nodes and N branches, which is subdivided into several cascaded two-port of small networks. The transfer function of the channel is later obtained by combining easily the T-matrices of the cascades sub networks. The position of notches in frequency response depends on the length of the branched lines. The increase in branched line length tends to limit the available bandwidth in LV channel, but the

position of deep notches does not change with a number of distributed branches. As the number of distributed branches increases the amplitude of notched points tends to increase. The impedance of realistic household's loads is also measured and their influence on the transfer function of indoor channel is analyzed. In power line network, the variation of these impedances with the frequency at the terminations causes a few distortions. The model used has indicated to come up with good results, hence can be used satisfactorily to characterize power line network.

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10. References

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