The Effects of Interconnections in the Broadband Power Line Communications

Saad DOSSE BENNANI*, Jamal BELKADID**, Ali BENBASSOU*** et Mouhime EL BEKKALI****

*ENSA de Fès, BP 2626 Route d’Immouzer Fès - MAROC
bennani_saad@yahoo.com

**EST de Fès, BP 2427 Route d’Immouzer Fès - MAROC
belkadid@hotmail.com
ali.benbassou@caramail.com
mouhime.el.bekkali@caramail.com

Abstract: In-building power lines have often been considered as attractive media for high-speed data transmission, particularly for applications like home networking. This paper presents the influencing of load impedance on the performance of medium voltage power line communication (PLC) network. The assuming channel consists of two wires which are widely used for indoor power-line.

From the frequency response of the transfer function (ratio of the received and transmitted signal), it is seen that the position of notches and peaks in the magnitude responses are largely affected in terms of attenuation by the above said network configuration. The observations presented in the paper could be helpful in suitable design of the PLC systems for a better data transfer and system performance.

Key words: Power Line Communications, channel modelling, transfer function, peaks, notches, impedance matching.

INTRODUCTION

In recent years, the power line channel, which only performs as a pure energy distribution network, is being changed to a medium for multi-purpose, such as data, voice transmission, home automation products control, and Internet.

However, it has been observed that, there are a number of challenges associated with data transfer through such network. Existing power line topology (geometry and transmission voltage levels) varies from region to region and country to country.

The design of an appropriate communication system, the choice of modulation and coding schemes, and the evaluation of performance, require the knowledge of the end-to-end PLC channel responses in a wide range of frequencies.

The most widely used model for the power line channel transfer function $H(f)$ is the multipath model proposed by Philipps [PHI 99] and Zimmermann [ZIM 02].

Actually, the proposed model is the result of a top-down approach: the various parameters need to be determined through measurements. As such, it is not suitable for the computation a priori of the actual transfer function of a given link. Alternative models, based on the multiconductor transmission line theory (MTL), have been proposed in the case of indoor channels [ESM 03], [PES 01] and [SAR 01].

In this paper, an estimation method of the transfer function of branched power line channel (PLC) based on the Multiconductor Transmission Line (MTL) is discussed.

As an application of the proposed method, the effect of the impedance matching at the end of branched cables.
1. Power line cable transfer function

1.1. Qualitative specification

A typical power line cable (figure 1) consists of two conductors: one connected to the neutral, and the other connected to the phase. Each of the phase and neutral conductors is covered by an insulator and the set of two conductors is placed inside another insulator (figure 2). Both of two conductors have the equal radii.

Such a configuration is described by distributed parameters $R$, $L$, $C$ and $G$, denoting respectively per-unit-length series resistance, series inductance, shunts capacitance and shunt conductance of the line, define as in (figure 3).

![Figure 1 - Typical Power Line Modem Applications Scenario](image1)

![Figure 2 - Cable cross-section](image2)

![Figure 3 - Lumped element model](image3)

1.2. Distributed parameters of a PLC cable

The transmission-line approach specified above-two uniform conductors inside homogeneous dielectric-results in the following distributed parameters [ESM 03]:

$$R = \frac{l}{r} \sqrt{\frac{\mu f}{\pi \sigma}} \epsilon \mu (\Omega / m)$$  \hspace{1cm} (1)

$$L = \frac{\mu_0}{\pi} \cosh^{-1} \frac{d}{2r} \epsilon \mu (H / m)$$  \hspace{1cm} (2)

$$C = \frac{\pi \epsilon}{\cosh^{-1} \frac{d}{2r}} \epsilon \mu (F / m)$$  \hspace{1cm} (3)

$$G = \omega C \tan \delta \epsilon \mu (S / m)$$  \hspace{1cm} (4)

$$\varepsilon_r = \begin{cases} -0.8802 & \text{for } 1.6 \text{ MHz} \leq f \leq 5 \text{ MHz} \\ -3.3335 \times 10^{-9} & f + 3.1167 \\ \text{otherwise} \end{cases}$$  \hspace{1cm} (5)

$$\tan \delta = -5.7257 \times 10^{-10} f + 0.06$$  \hspace{1cm} (6)

$$\gamma = \alpha + j \beta = \sqrt{(R + j \omega L), (G + j \omega C)}$$  \hspace{1cm} (7)

$$Z = \sqrt{ \frac{Z}{Y} } = \sqrt{ \frac{R + j \omega L}{G + j \omega C} }$$  \hspace{1cm} (8)

Where, $r$ is the radius of the conductors (=0.8 mm), $D$ is the distance between the conductors (=3.2mm), $\sigma$ is the electric conductivity of the conductors(=5.5758x10^7), $\mu$ is the magnetic permeability(= $\mu_0$), $\epsilon_r$ is the dielectric constant(=8.8542x10^-12). $\tan \delta$ is the dielectric loss tangent.

The results of the different parameters intervening in the calculation of distributed parameters of a PLC cable are shown in (figure 4).
1.3. Modelling

In this section, we will assume that the exact structure and type of wires as well as loads that are connected to the channel are known perfectly.

1.3.1. ABCD matrix and channel transfer function.

The ABCD representation for a two-port circuit is very convenient for the calculation of channel transfer functions [3]. In (figure 5), the relation between \( V_1, I_1, V_2 \) and \( I_2 \) (the input voltage and current and output voltage and current of a two port network) can in general be represented as:

\[
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_2 \\
I_2
\end{bmatrix}
\tag{9}
\]

Where \( A, B, C \) and \( D \) are appropriately chosen constants. It is easy to show that if we have a cascade of two-port circuits, the ABCD representation of this circuit is the product of the ABCD matrices for the individual two-port circuits.

Now consider the circuit of (figure 5), in which all voltages and currents are presented by their phasors. Using the ABCD model for the two-port box in this figure it is easy to calculate the transfer function of the circuit (\( V_L / e_r \)) as:

\[
H(f) = \frac{V_2}{V_s} = \frac{Z_L}{A Z_L + B + C Z_L Z_e + D Z_L}
\tag{10}
\]

Also it is easy to calculate input impedance of the two-port circuit (\( Z_i \)) as:

\[
Z_i = Z_{in} = \frac{V_L}{I_1} = \frac{AZ_L + B}{C Z_L + D}
\tag{11}
\]

Two parallel cables (for example power line phase and neutral cables) can be modelled as a transmission line. A transmission line can be characterized by its characteristic impedance \( Z_c \) and its propagation constant \( \gamma \).

\[
Tx = \begin{bmatrix} Zb_1 & Zb_2 & Zb_3 & Zb_4 & Zb_5 & Zb_6 \end{bmatrix}
\]

\[
Z_{eq} = \frac{Z_c}{\tanh(\gamma d)} \tag{13}
\]

1.3.2. Transfer function of a transmission line with bridge tap.

The transfer function of the two-port circuit of (figure 5) is given by (10), and the ABCD parameters of a transmission line can be computed using (12). Therefore, the calculation of the transfer function for a simple transmission line is straightforward. Consider, for example, (figure 6a), which shows a transmission line with one bridge tap.

If we replace the bridge tap with the equivalent impedance (\( Z_{eq} \)), which can be seen from terminals \( A \) and \( B \), the circuit can be simplified to that of (figure 6b). In this figure, \( Z_{eq} \) can be calculated as:

\[
Z_{eq} = Z_c - \frac{Z_{br} \tanh(\gamma d_{br})}{Z_c + Z_{br} \tanh(\gamma d_{br})}
\]

In (figure 6b) the circuit has been partitioned into three cascade two-port sub-circuits. For each sub-circuit it is possible to calculate an ABCD matrix (\( \phi_i \), \( i=1, 2, 3 \)) and the ABCD matrix for the total circuit (\( \phi \)) is:

\[
\phi = \prod_{i=1}^{n} \phi_i
\tag{14}
\]

Where
\[
\phi_1 = \begin{bmatrix} \cosh(\gamma d_1) & Z_c \sinh(\gamma d_1) \\ \sinh(\gamma d_1)/Z_c & \cosh(\gamma d_1) \end{bmatrix}
\]
(15)

\[
\phi_2 = \begin{bmatrix} 1 & 0 \\ 1/Z_{eq} & 1 \end{bmatrix}
\]
(16)

\[
\phi_3 = \begin{bmatrix} \cosh(\gamma d_3) & Z_c \sinh(\gamma d_3) \\ \sinh(\gamma d_3)/Z_c & \cosh(\gamma d_3) \end{bmatrix}
\]
(17)

Figure 6 - (a) A transmission line with one bridge tap connection. (b) Equivalent of the left-hand circuit

2. Influence of load impedance

The influence of load impedance is an important study. It is common that the loads at the termination of branched lines are not always characteristic impedance or resistive, rather it could be a case dependant arbitrary load, like, low or high impedance (R type) compared to line characteristic impedance and practical load impedance (RL type) representing transformers, machines, etc. For discussions below we considered the configuration as in (figure 7).

The length of the PLC cable (not included the lengths of bridges taps connections) was kept constant and equal to 22m, while six branches of length 10m\(d_b\) are connected to the PLC cable. The termination of point E was varied according to the given load impedance under investigation. Note that \(Z_c\) and \(Z_L\) are the characteristic impedance of line and the load impedance of the transmitter.

Figure 7 - A two port network connected to a voltage source and a load

2.1. Resistive Load

We consider the following load impedances with values 2Ω, 20Ω, 50Ω, 78Ω, 1kΩ and open circuit terminated at all branches. Note 78Ω is the characteristic impedance of the PLC cable. Figure 8 shows the frequency response for medium voltage channel for various termination impedances.

We note that the software used is Matlab.

Figure 8 - Transfer function magnitude of the sample channel with six branches all terminated in various resistive loads 2Ω, 20Ω, 50Ω, Zc, 1KΩ & Open Circuit

For the load impedances less than channel characteristic impedance the position of notches is unchanged with no attenuation (figures. 8). It is interesting to observe that when the load impedance lower the peaks vary between -10dB until -38dB whereas the notches vary between -100dB until -60dB. As the load increase the peaks are increase and the notches decrease. As the load is characteristic impedance peaks and notches disappear.

When the load impedance increase beyond the characteristic impedance the peaks and notches behave in the same way as if it were approaching lower impedances, but with a shift in their frequency position.

2.2. Inductive Loads

The effect of inductive terminal loads is also worth investigating. For this an RL load termination at branched line \((Z_b)\) of (figure 5) was considered, where the inductance varies as 0.1mH, 1mH, 10mH and 100mH (figure 9), with constant resistance of 50Ω.

The frequency response has the same behaviour as in (figure 8). This indicates that the behaviour of inductive load is like open circuit at high frequency as expected.
3. Input Impedance of an Electric Motor

Some devices plugged on the PLC network have input impedance which varies the following manner [CAN 07] (figure 10):

\[
Z(j\omega) = \frac{R_0}{1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}
\]

(18)

With \(\omega \in [2.28] 2\pi \text{ Mrad} / s\)
\(R_0 \in [200,1800] \Omega \quad Q \in [5,25]\)

Figure 10 - Magnitude of the complex impedance for an electric motor

Figure 11 shows frequency response of transfer function for the PLC cable described before. The length of the PLC cable was kept constant and equal to 22m (from emitter to receiver without adding lengths of branches), while all branches have the same length (10m). We discuss two cases: first case: \(Z_{bi}=CO\) for \(i=1:6\), second case \(Z_{b3}=Z_{electric\ motor}\), \(Z_{bi}=CO\) for \(i=1:2:4:5:6\).

In low frequencies, we attend an appearance of new notches which disappear beyond 25MHz. In addition, we attend an attenuation of notches along the frequency band.

Figure 11 - Transfer function magnitude of the sample channel terminated in the third branch with a complex impedance of an electric motor

4. Conclusion

In this paper, the influencing of load impedance on the performance of medium voltage power line communication (PLC) network was discussed.

We showed that when the load impedance increases towards the line characteristic impedance the peaks attenuations tend to increase and notches tends to improve. As the termination impedance tends to an open circuit signals are less attenuated.

The position of notches in frequency response tends to shift from one region to another region as the termination impedance changes.

In the case of the complex loads presented by the motors, we attend along the strip of frequency [1.6MHz, 100MHz] to the birth of the new peaks little important and to the attenuation of the other peaks.

The sensitivity analysis presented here has important implication for the possible design considerations of PLC equipment.

ACKNOWLEDGMENT

This paper has been done in the setting of the R&D project – MAROC TELECOM CONTRACT N° 10510007556.06/PI

4.1. References


