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Abstract

Estimation of network loading conditions can assist the prediction of channel behavior between any two communicating devices on a power line network, thus making the use of more efficient adaptable transmission techniques feasible. This paper presents a method for performing impedance estimation of termination loads connected to a power line network by utilizing channel training data sequences. The network is considered as a set of multiple point-to-point links, whose characteristics are affected by the loads connected to its termination points. Their transfer functions can be used to determine the reflection and transmission coefficients at all points of discontinuity on the network and finally, to estimate the connected impedances. The limitations of the proposed method are analysed and an example that demonstrates the method's effectiveness is presented.

1. Introduction

Achieving high-speed data transmission and improved performance in power line networks requires the use of a flexible transmission technique that adapts its characteristics to the underlying channel conditions [1]. Such a communications system depends on the development of an efficient, real-time channel estimation method [2], [3]. Loads connected or disconnected from the network and loads that change their characteristics as time progresses, introduce noise and affect the channel's response, resulting to its time-varying behavior. Thus, unlike other communications systems, such as xDSL, channel training in power-line networks should be performed both during system initialization and periodically during normal data transmission [4]. The process of *initial channel training* estimates the transmission conditions and requires a long duration in time, since it is performed only once, before the devices start their actual data transmission. However, periodic channel estimation, referred to as *inbound channel training*, could be performed using training sequences injected into the user data and should be implemented in a manner that avoids the addition of substantial overhead. Efficient *inbound channel training* should enable detection of the changes in the channel's response, relative to the previous estimates, and restrict the added overhead to the minimum possible.

This work focuses on the *initial channel training* and presents a method that determines the original loading conditions of the network, using the measured channel response, which depends on the network topology, the physical medium characteristics and the termination impedances. *Initial channel training* is performed either during network power-up or during normal operation, in case the communicating devices need to recalculate the channel's frequency response. The method is applied to all devices that are active during the *initial channel training* process and can be extended to any new device that is activated during data transmission. It is based on the exchange of predefined training sequences between any transmitter-receiver pair. The received sequences are collected and processed to determine the response of every point-to-point connection on the network. This information is then used as the input to an algorithm that analytically relates the channels' responses to the network topology, its physical characteristics and its loading conditions.

Section 2 presents the channel training method used during network initialization and the representation of each point-to-point link as a set of FIR filters. The network topology is described in Section 3. Section 4 presents the method used for network loading estimation, based on its topology and FIR filter coefficients, as well as an analysis on the method's accuracy. Finally, Section 5 demonstrates the use of the proposed method on a small-scale network and gives analytical results.

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2. Channel Training

In every communications system, it is always necessary to use some start-up procedures in order to adapt the receiver's circuits to the channel conditions. These procedures include gain control, channel identification, equalization etc. Channel identification is required in order to measure the channel's impulse response and the power spectral density of existing noise. In cases where multiple subchannels are used simultaneously, multitone channel identification is used to directly estimate the conditions on each subchannel. In order to perform channel identification, a known training sequence, x, is transmitted and the sequence of received symbols, y, is assembled at the receiver side.

The power line network can be considered as a SIMO (single input multiple output) system, since in a network with m connected devices, channel training is performed according to the following procedure: All communication devices coordinate their operation using a low speed channel, called the *control channel*, which is not included in the data transmission frequency range. All devices temporarily seize their actual data transmission (if channel retraining has to be performed) and sequentially transmit the predefined training sequence. This sequence, transmitted by one device, is received by the remaining $m-1$ devices. At the end of the training process, each device has acquired $m-1$ sequences of received symbols, representing the $m-1$ possible sources of information during normal network operation. Device i uses the received $y_{j,i}$ ($1 \leq j \leq m$ and $j \neq i$) data sequences from all other devices and the training sequence x, to estimate the coefficients of an order-N FIR filter that describes the respective point-to-point link. Then, the filter coefficients collected at each termination point are either transmitted to a central processing unit or distributed to all communicating devices, using the *control channel*. In any case, using the information gathered by every device, the termination impedance estimation method, described in the next section, is performed and all communicating devices are informed about the load impedances and the respective reflection coefficients. Using this information and *inbound channel training*, each device updates its estimate of the network termination loading and adapts its receiver circuits accordingly. Noise estimation, in terms of noise variance of each subchannel, can also be performed during channel training, but is not discussed in this work.

In order to perform synchronization, channel identification and timing verification, the training sequence used consists of three consecutive sub-sequences. Each one has suitable characteristics for performing the respective task. Channel identification is implemented using a sequence with white noise spectral characteristics (at least in the frequency band of interest) and is generated by repeating a PN sequence of length $L > N$ [2]. The analysis divides the frequency band into several subchannels, each one of which is considered to have a constant frequency response during channel training. An LMS adaptive algorithm is used at each receiver for estimating the FIR filter coefficients.

3. Indoor Power Distribution Network Description

We study the indoor power line network as a multipath environment, where delayed replicas of the transmitted signal reach the receiver with different amplitude and phase characteristics. These multipath signal components are caused by reflections on channel discontinuities, such as termination loads and line junctions. Analytical calculation of the multipath effect in the indoor power grid is feasible due to its loop-free topology and its bounded complexity. Thus, the multipath effect can be traced back to the channel's physical characteristics by calculating cable loss, reflection and transmission coefficients. Considering L different propagation paths between any two communicating devices, the channel impulse response can be calculated as the summation of the received signal components, according to:

$$h(\tau, t) = \sum_{i=1}^{L} \{r_i . e^{j\theta_i} . e^{-\gamma l_i} . \delta\left(t - \tau_i\right)\} \tag{1}$$

where $re^{j\theta_i}$ is the complex reflection factor of path i, $e^{-\gamma l_i}$ is the propagation factor, which depends on the path's length l_i and the propagation constant γ, and $\tau = l_i/v$ is the path's delay, based on the group velocity of propagation v. The reflection factor is the product of all reflection/transmission coefficients of path i.

The indoor power grid can be described using the following parameters: termination impedances, line section types and lengths. For each type of cable, the characteristic impedance Z_0 and the propagation factor γ of the line can be calculated through transmission line theory equations, using the cable primary parameters (R', L', C', G') [5]. Network description matrices comprise information such as the number of termination points and nodes (where branches begin), their connectivity, line section lengths and cable characteristics (Z_0 and γ) [6].

Consider a network with m termination points T_i and n nodes C_j, which is described by the matrices $\mathbf{TC}$[mxn], $\mathbf{CC}$[nxn], $\mathbf{LT}$[mxn] and $\mathbf{LC}$[nxn]. The matrix $\mathbf{TC}$[mxn] describes the interconnections between termination points and nodes. Each line corresponds to a termination point T_i and each column to a node C_j. Element $TC(i,j)$ is equal to one when a connection between T_i and C_j exists, or zero otherwise. The matrix $\mathbf{CC}$[nxn] describes the interconnections between the internal network nodes. Each line and each column correspond to a certain node C_i. Non-zero elements $CC(i,j)$ imply a connection between the corresponding nodes, whereas zero elements imply no direct connection. Since nodes cannot be connected to themselves and

$C_iC_j = C_jC_i$, the matrix has zero diagonal, and exhibits symmetry around it. The $\mathbf{LT}$[mxn] matrix is generated by replacing the non-zero elements of $\mathbf{TC}$ matrix with the corresponding lengths $l_{T_iC_j}$. The $\mathbf{LC}$[nxn] matrix is generated by replacing the non-zero elements of $\mathbf{CC}$ matrix with the corresponding lengths $l_{C_iC_j}$. The $\mathbf{LC}$ matrix is also symmetric around its diagonal. The above network description matrices are used by the termination impedance estimation method, presented in the following section.

4. Termination Impedance Estimation Method

The proposed method relates the channel impulse response, between any pair of communicating devices, to the impedances connected at every network termination point. Estimation of network loading is based on the estimation of the reflection and transmission coefficients at every point on the network (both termination points and internal nodes), which are related to the network termination impedances. The method estimates the first L paths of every point-to-point connection on the network, based on the anticipated order of arrival of the corresponding signal components. This process uses the network description matrices presented in the previous section to forecast the possible signal iterations and calculate their propagation delay and loss. Overlapping paths, that correspond to the same transmission delay, give a response equal to the summation of their complex factors. The method proceeds with the estimation of the channel (point-to-point connection) frequency response using an a priori known training sequence as input and the corresponding measured output sequence. Although the power line suffers from frequency selective fading, its response can be divided into several subchannels, with a fairly constant frequency response. Based on (1), the theoretical frequency response for subchannel k is:

$$H_k = \sum_{i=1}^{L} r_{ik}.e^{j\theta_{ik}}.e^{-\gamma_k l_i}.e^{-j2\pi f \tau_{ik}} \quad (2)$$

The channel response can be modeled using multiple FIR filters of order L, as shown in Figure 1. In that case, the response of subchannel k is given by the following equation:

$$H_{k,filter} = \sum_{i=0}^{L-1} b_{ik}.z^{-i} \quad (3)$$

where each FIR filter corresponds to a subchannel of constant response. The presented method utilizes a general equation error method to identify the best model from the frequency response data, for every subchannel. The general expression used for this purpose is given by:

$$\min_{b,a} \sum_{i=1}^{N} w(i).[H(f(i)).A(f(i)) - B(f(i))]^2 \quad (4)$$

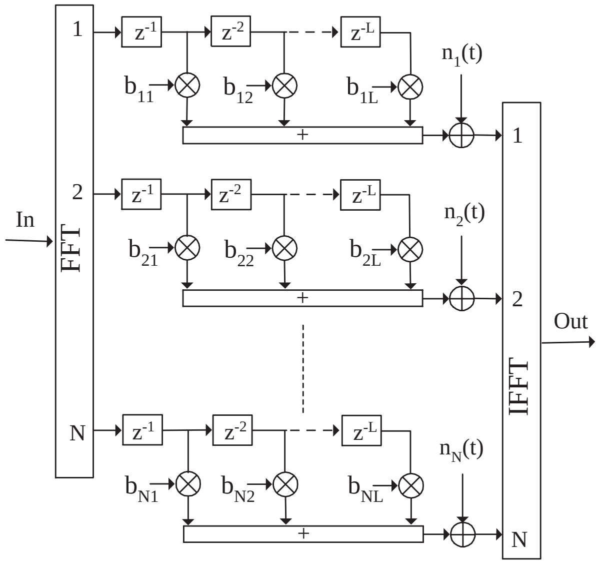

Figure 1: Multipath channel model using multiple FIR filters. Each FIR filter represents a single subchannel.

where $f(i)$ is the N point frequency vector, $w(i)$ is a weight function, while $A(f(i))$ and $B(f(i))$ are the Fourier transforms of the polynomials a and b respectively. Details for the equation error method are given in [7]. Given the requested filter order L and that $a = 1$, since an FIR filter is considered, the polynomial coefficients b_i are estimated.

The estimated filter coefficient b_{ik} corresponds to the i^{th} path complex weighing factor of subchannel k, which equals to the product of the path's reflection factor $r_{ik}.e^{j\theta_k}$, its propagation loss $e^{-\gamma_k l_i}$ and its propagation delay $e^{-j2\pi f_k \tau_{ik}}$. Thus, a system of L equations is formed, from which the network reflection/transmission coefficients can be derived. The method repeats the above process for every frequency subchannel and for every point-to-point connection. In order to expedite the process of network coefficient estimation, an efficient system of equations can be formed using only the first arriving path of each channel, thus forming a system of $m(m-1)$ linear equations. These equations are supplemented by the equations formed when the next s arriving paths of one of the estimated channels are used, where s is the number of internal nodes that are directly connected to one or more termination points.

Having estimated the network reflection coefficients at every network point, those that correspond to the network termination loads are used to calculate the respective impedances. Therefore, each termination impedance can be calculated by combining the results of training from all possible transmission channels.

Estimation of the initial network loading conditions along with periodic *inbound channel training* facilitate the detection of new loading conditions. In the previously described method, it was assumed that all termination points of the network contain, at least, a communications transceiver.

4.1. Analysis of the Method's Accuracy

The load impedance is estimated using the following relation:

$$Z_L = Z_0 \frac{1+\rho}{1-\rho} \tag{5}$$

where ρ is the reflection coefficient at the respective termination point, and Z_0 is the characteristic impedance of the transmission line.

If $\Delta\rho$ is the error on the estimation of the reflection coefficient, ΔZ_0 is the estimation error of the characteristic impedance and $\hat{\rho}$ is the estimated reflection coefficient ($\hat{\rho} = \rho + \Delta\rho$), then the estimation error of Z_L is given by:

$$\frac{\Delta Z_L}{Z_L} = \rho_{e1} + \frac{\Delta Z_0}{Z_0}\rho_{e2} \tag{6}$$

where

$$\rho_{e1} = \frac{2\Delta\rho}{(1-\rho-\Delta\rho).(1+\rho)}$$

and

$$\rho_{e2} = \frac{(1+\rho+\Delta\rho).(1-\rho)}{(1-\rho-\Delta\rho).(1+\rho)}$$

The method's accuracy depends not only on the reflection coefficient estimation error, but also on the value of the reflection coefficient itself and the estimation error of the characteristic impedance. Factor ρ_{e1} is independent of Z_0 and determines the estimation error when an accurate estimate/measurement of the characteristic impedance exists, while factor ρ_{e2} determines how the error on the characteristic impedance affects the estimation accuracy of the termination impedance.

If $\Delta Z_0 = 0$, the estimation error of Z_L is equal to the estimation error of ρ when:

$$\Delta\rho = \frac{2-(1+\rho)^2}{1+\rho} \tag{7}$$

For each value of ρ, which corresponds to specific values of Z_L and Z_0, there is a specific value of $\Delta\rho$ that satisfies (7). As long as $\Delta\rho$ remains smaller than this value, the relative estimation error of Z_L (6) is also smaller than the relative estimation error of ρ. However, when $\Delta\rho$ exceeds this value, the relative estimation error of Z_L becomes greater than the relative estimation error of ρ. Figure 2 presents the above two cases. The unshaded area corresponds to the first case, while the shaded corresponds to the second one. It can also be stated that as $\rho \to 1$, the method's accuracy decreases rapidly. This however, is an impossible condition, since it has been assumed that each termination point has, at least, a communication device attached to it and therefore, all termination impedances are equal or smaller than the transceiver impedance.

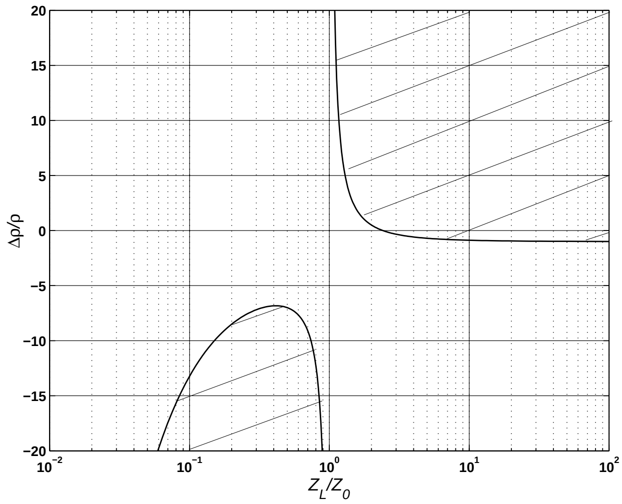

Figure 2: The method's accuracy.

5. Simulation Results

In this section we consider a rather simple network, shown in Figure 3, in order to give a detailed description of the proposed method.

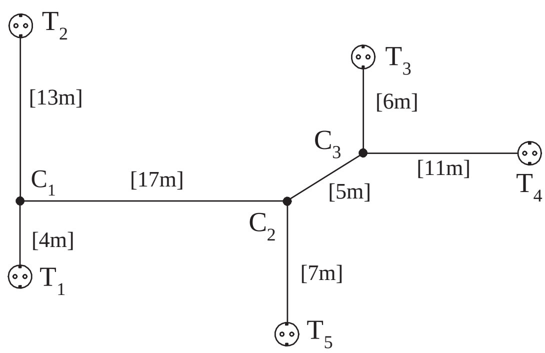

Figure 3: The experimental network.

The network under consideration comprises type H05VVF (3 x 1.5 mm^2) cables [5], which, in the frequency range of 1 to 5 MHz, have the characteristic impedance Z_0 that is shown in Figure 4. The network has $m = 5$ termination points and $n = 3$ nodes and it can be described using the following matrices, as defined in Section 3:

$$\mathbf{TC} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad \mathbf{LT} = \begin{bmatrix} 4 & 0 & 0 \\ 13 & 0 & 0 \\ 0 & 0 & 6 \\ 0 & 0 & 11 \\ 0 & 7 & 0 \end{bmatrix}$$

$$\mathbf{CC} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad \mathbf{LC} = \begin{bmatrix} 0 & 17 & 0 \\ 17 & 0 & 5 \\ 0 & 5 & 0 \end{bmatrix}$$

Based on the channel training results, each communicating device, located at the network termination points, uses the received y_k data from all other devices and the training sequence x to estimate the coefficients of an order-N FIR filter that describes the respective point-to-point link in a certain frequency subchannel. The estimated magnitude and phase of the first coefficients of all FIR filters at 2.75 MHz are presented respectively in the following matrices:

$$\mathbf{M} = \begin{bmatrix} 0 & 0.854 & 1.196 & 0.982 & 0.829 \\ 2.680 & 0 & 2.921 & 2.400 & 2.025 \\ 0.350 & 0.272 & 0 & 0.547 & 0.512 \\ 0.367 & 0.285 & 0.702 & 0 & 0.537 \\ 0.581 & 0.452 & 1.230 & 1.007 & 0 \end{bmatrix}$$

$$\mathbf{P} = \begin{bmatrix} 0 & 0.106 & -1.011 & -0.689 & -0.393 \\ -0.187 & 0 & -1.545 & -1.223 & -0.930 \\ -0.321 & -0.561 & 0 & 0.619 & -0.409 \\ -0.267 & -0.506 & 0.352 & 0 & -0.353 \\ -0.429 & -0.668 & -1.131 & -0.809 & 0 \end{bmatrix}$$

Each line corresponds to the termination point where the data sequences are injected into the network, while each column corresponds to the termination point where the data sequences are received from the network.

Therefore, based on the analysis described in [6], the reflection coefficients at every termination point are estimated for each subchannel and using the respective values of Z_0, the load impedances are calculated. The reflection coefficients are estimated using the first coefficients of all FIR filters and the next 3 coefficients of only one of the point-to-point channels. The values of the reflection coefficients at all termination points at 2.75 MHz and for $Z_0 = 6.3269 + j0.1246$ are given by:

Theoretical	Estimated	Error(%)
$0.8735 + j0.1535$	$0.8758 + j0.1545$	0.6515
$0.4452 - j0.2312$	$0.4484 - j0.2290$	0.9516
$0.8569 + j0.0851$	$0.8578 + j0.0913$	7.2855
$0.4204 + j0.5473$	$0.4231 + j0.5538$	1.1876
$0.7103 + j0.2385$	$0.7028 + j0.2555$	7.1279

Figure 5 demonstrates the simulation results of the previously described network for various termination impedances. For each termination point, the two subfigures correspond to the impedance magnitude and phase respectively. The solid line represents the theoretical values, while the circular symbol (^{o}) corresponds to the estimated value at the specific frequency point.

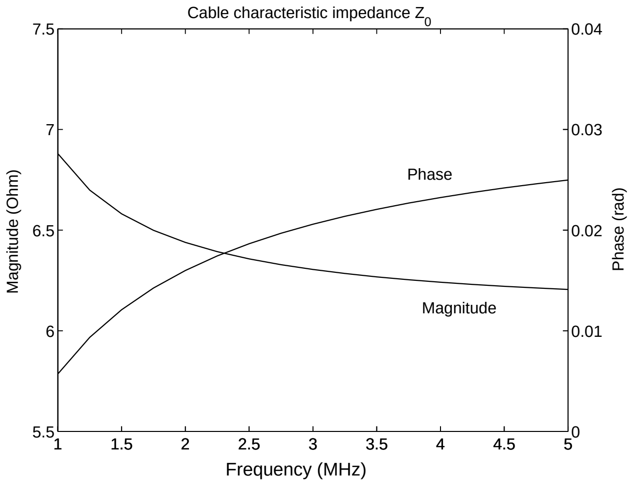

Figure 4: The Z_0 in the frequency range of 1 to 5 MHz

These results indicate that the proposed method can estimate the network impedances very accurately, in magnitude and phase, as long as the conditions described in subsection 4.1 are satisfied. Comparing the results of Figure 5 with the estimations of the reflection coefficients for loads at T_3 and T_5, we conclude that even though the coefficients estimation error is about 7%, the respective impedance estimations present a much smaller error, which is in agreement with the analysis in subsection 4.1.

6. Conclusions

In this paper, we presented an analytical method for estimating the impedance of loads connected to a power line network. The method, which is based on channel response measurements taken during channel training, estimates the reflection coefficients at every network termination point and finally calculates the connected load impedances.

During normal network operation, the channel behavior between any two communicating devices can be continuously determined, using the proposed method and new network loading estimates, extracted during *inbound channel training*. Therefore, the use of adaptable transmission techniques becomes applicable.

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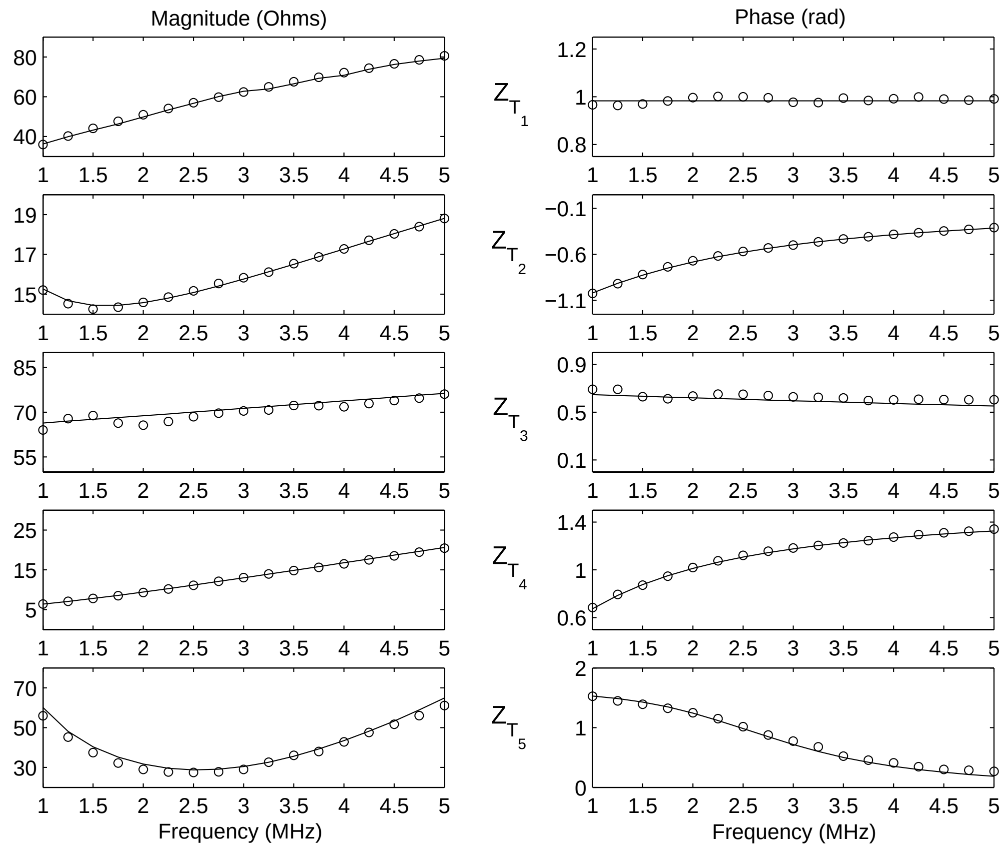

Figure 5: Theoretical and estimated termination impedances in the frequency range of 1 to 5 MHz

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