An HF Multipath-Propagation Analysing Method for Power Delay Profile estimations of Indoor Single-Phase Low Voltage PLC Channels

Ioannis C.PAPALEONIDOPOULOS[1], Constantinos G.KARAGIANNOPOULOS[2], Ioannis E. ANAGNOSTOPOULOS[3], Nickolas J.THEODOROU[4]

[1] National Technical University of Athens, Faculty of Electrical and Computer Engineering, High Voltages and Electric Measurements Laboratory, 9 Heroon Polytechniou Str., GR 157-80 Athens, Greece.
Phone: +30-210-7723607, Fax: +30-210-7722581, E-mail: Jpap@central.ntua.gr.

[2] National Technical University of Athens, Faculty of Electrical and Computer Engineering, High Voltages and Electric Measurements Laboratory, 9 Heroon Polytechniou Str., GR 157-80 Athens, Greece.
Phone: +30-210-7723545, Fax: +30-210-7722581, E-mail: ckarag@central.ntua.gr.

[3] National Technical University of Athens, Faculty of Electrical and Computer Engineering, Multimedia Laboratory, 9 Heroon Polytechniou Str., GR 157-80 Athens, Greece.
Phone: +30-210-7722538, Fax: +30-210-7722538, E-mail: Janag@telecom.ece.ntua.gr.

[4] National Technical University of Athens, Faculty of Electrical and Computer Engineering, High Voltages and Electric Measurements Laboratory, 9 Heroon Polytechniou Str., GR 157-80 Athens, Greece.
Phone: +30-210-7723558, Fax: +30-210-7723559, E-mail: ntheodor@central.ntua.gr.

Abstract

Focalised on the statistical characterisation of fading indoor PLC channels, a method providing the High Frequency transfer properties of such channels on account of multipath propagation is introduced. Taking into account a finite set of paths, channel's transfer function is calculated in terms of cable's type and the vicinal network topology. Accuracy of the method has been justified by transfer-function measurements of sample channels in the 2-30MHz band, whereas applicability stands wherever cabling meets the two-conductor transmission-line model. Preliminary power-delay-profile simulations are also demonstrated, indicating utility of the method for channel capacity estimations.

1. Introduction

Electric grid turns out particularly hostile as transfer medium in the area of MHz. The principal constraints are imposed due to intersymbol interference generated by multipath propagation effects and the resulting delay spread. That is to say, not only the desired signal, but also one or more delayed and attenuated copies of it being hereafter referred to as "paths" arrive at reception as a result of several reflections caused at points where impedance mismatches occur. Multipath fading channels are grouped and designated in terms of the path amplitude and arrival-time probability distributions, as the power delay profile is requisite for link capacity estimations. Several channel analysing techniques stemming from multipath-propagation principles have up to now been suggested (e.g. [1]-[3], [6]). The work presented in [2] and [3] lies in fact very close to the approach introduced herein; the same notation is therefore maintained to certain extent.

In this paper, a completely analytical method is proposed, so that no experimental feedback is required to define the model parameters. Having cables' distributed constants and electric network's topology in the vicinity of the channel, transfer function is estimated as the superposition of a finite path multitude. Tracing along path propagation routes is comprised, and limiting the analysis within the set of paths that lie no lower than two orders of magnitude below the line-of-sight-equivalent path makes up the main approximative step.

In Section 2, analytical formulation of the method is deployed. Measurement results and relevant evaluation are given in Section 3. Power-delay-profile simulations that have been performed are presented in Section 4. A concluding discussion on the utility of the work presented closes this paper in Section 5.

2. Multipath Propagation Model

Let a positively travelling sinusoidal voltage wave component be assumed, towards a point of discontinuity. Such could be either an open-circuited end, or a point of which the aggregate characteristic impedance to the right is different from the one to the left, i.e. a load termination, a serial connection of different cables, or a cable junction. Denoting transmission coefficient by t and reflection coefficient by ρ, it is obtained

$$1+\rho = t\,, \quad (1)$$

$$\rho = \frac{Z_{0t} - Z_0}{Z_{0t} + Z_0}\,, \quad (2)$$

where Z_{0t} the resultant characteristic impedance right after the mismatch point. If impedance mismatch is caused by a load termination, Z_{0t} equals load's impedance Z_L, whereas in the case of a junction, aggregate characteristic impedance right after the cable intersection is the resultant of the several characteristic impedances in parallel

A signal transmitted over a PLC channel suffers numerous reflections at network's points of discontinuity, giving thus rise to the multipath propagation effect, which results in a multitude of discrete paths arriving at reception. A path is in fact the result of a distinct component that arrives at reception via a unique route along the grid, after being reflected a specific number of times at specific discontinuity points of its route. Assuming the existence of N different paths, channel's partial transfer function with regard to a single path i, with d_i the corresponding aggregate route propagation distance, is thereby

$$H_i(f) = g_i e^{-ad_i} e^{-j\beta d_i}\,, \quad (3)$$

where a is propagation constant and β the phase constant, and the overall transfer function is given as

$$H(f) = \sum_{i=0}^{N} H_i(f) = \sum_{i=0}^{N} g_i e^{-ad_i} e^{-j\beta d_i}\,, \quad (4)$$

where

$$g_i = |g_i| e^{j\phi_i} \quad (5)$$

is a weighting factor carrying the effect of transmission and reflection coefficients along the route i, defined as

$$g_i = \left(\prod_{m_t=1}^{M_{t,i}} t_{i,m_t}\right) \cdot \left(\prod_{m_r=1}^{M_{r,i}} \rho_{i,m_r}\right), \quad (6)$$

where the path i is supposed to have come $M_{t,i}$ times across points of discontinuity and been $M_{r,i}$ times reflected. The amplitude of path i is

$$|H_i(f)| = |g_i| e^{-ad_i} \quad (7)$$

Respective path arrival times are

$$\tau_i = \frac{d_i}{c}\,, \quad (8)$$

where c the propagation velocity over the power lines considered, which usually remains constant, despite the utilization of different dimensional cable types. Phase constant is related to propagation velocity as

$$\beta = \frac{2\pi f}{c}\,. \quad (9)$$

For convenience, the term "path" is also used herein to describe every partial transfer function that corresponds to a path. The direct component, of which the route involves no reflections, is characterised by the value $i = 0$. Strictly, the path number is infinite, but in practice only a finite multitude of paths are of non-negligible value. The sequence of paths ranging within two orders of magnitude below the direct one is hereby suggested as adequately describing channel's transfer properties.

The analysis developed so far stands wherever single-phase LV cables conforming to the two-conductor uniform transmission line model are utilized. Several indoor single-phase cable types fall under this category [2], [6] [7].

3. Applicability and Experimental Evaluation

3.1. Experimental Grids

Topology of the network paradigms measured is that of a backbone bus with transverse branches connected in parallel, as illustrated in Fig. 1, of which the multitude is hereafter denoted by n. The branches are numbered consecutively from transmission to reception, i.e. index (1) is assigned to transmitter branch and index (n) to the receiver one. Three sample grids have totally been investigated. Let $x[i_b]$ be the distance of the i_b-branch junction from the bus origin, $y[i_b]$ the length of branch i_b and S bus's length. Assembly of the experimental power-line circuitries has been as follows:

1st bus: $n = 4,\ S = 32.7m,\ X = \begin{bmatrix} 1.9m \\ 3.8m \\ 28.8m \\ 30.7m \end{bmatrix},\ Y = \begin{bmatrix} 1.7m \\ 1.6m \\ 2.2m \\ 2m \end{bmatrix}$

2nd bus: $n = 5,\ S = 36.4m,\ X = \begin{bmatrix} 26.9m \\ 29.1m \\ 30.7m \\ 32.7m \\ 34.4m \end{bmatrix},\ Y = \begin{bmatrix} 2m \\ 1.9m \\ 1.6m \\ 1.6m \\ 2m \end{bmatrix}$

$$3^{d}\text{ bus: } n = 6, S = 59.2m, X = \begin{bmatrix} 1.9m \\ 26.9m \\ 28.5m \\ 30.6m \\ 32.3m \\ 57.3m \end{bmatrix}, Y = \begin{bmatrix} 2m \\ 2.2m \\ 1.7m \\ 1.6m \\ 2m \\ 1.9m \end{bmatrix}.$$

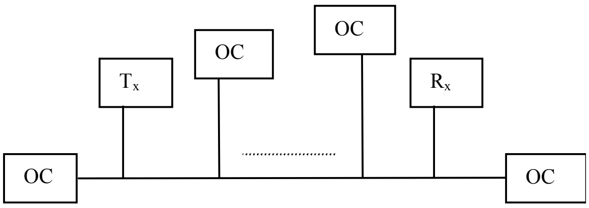


Fig. 1. Topology of the measured grid paradigms.

As indicated in fig. 1, transmitter and receiver have been set matched, whereas all other branches as well as the bus ends have been kept open circuited. A signal/function generator has been used to transmit, and a digital real-time oscilloscope to capture input and output sinusoidal signals. Having all over the same cable type, reflection coefficients at terminations and junctions get respectively $\rho_L = 1$ and $\rho_J = -1/3$, and transmission coefficient comes out as $t = 2/3$. The cable type NYM 3x2.5mm^2 per VDE-0250 has all over been employed, fabricated by copper and PVC. Conductivity and relative dielectric constant have been therefore assumed $\sigma = 5.76 \cdot 10^7 \, S/m$ and $\varepsilon_r = 3.6$, and cable's distributed parameters and transmission constants have been estimated according to [7].

3.2. Results and Discussion

For evaluation purposes, a program in Pascal has been compiled that calculates transfer function executing the superposing process described in Section 2 above. Input information includes the bus topology, i.e. parameters n and S as well as X and Y vectors, cable's material constants (ε_r, μ_r and σ), and dimensional parameters. Comparison between theoretical and experimental results is set out in fig. 2-4. At the computational process, all paths having $|g_i| \geq 0.01$ have been counted in, of which the multitude N for every sample grid tested is indicated on respective diagram.

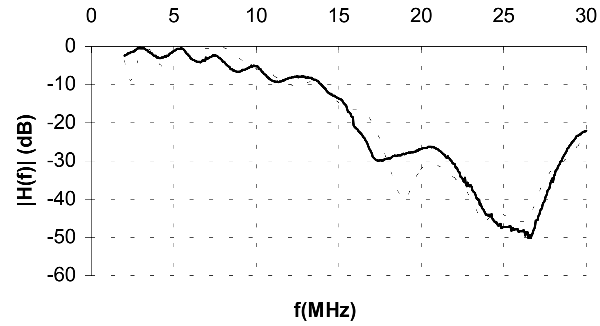


Fig. 2. Amplitude response of the 1st bus ($N = 2691$)

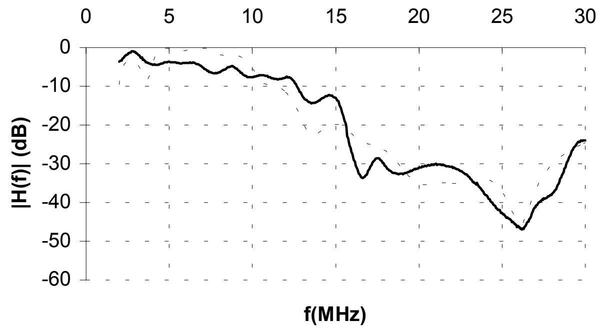


Fig. 3. Amplitude response of the 2nd bus ($N = 6431$)

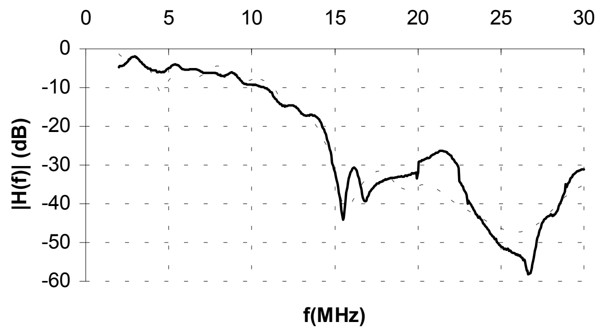


Fig. 4. Amplitude response of the 4th bus ($N = 13447$)

Inspection of the graphs set above appears indeed confirmative of the model proposed. Theoretical curves remain in all three cases close to the measured ones. No deviation above 10dB is observed. Variation of 10dB corresponds of course to an absolute-value ratio around (3.2), but when considering quantities that fluctuate across two or more orders of magnitude, like the amplitude of HF signals propagating over power-line networks, such differences are acceptable and considered of minor range. Most of the divergence accrued should come from imperfections of the experimental set-up, and especially due to impedance mismatches between connectors, cables and the equipment. Although termination at reception has been well matched, reflection up to 30% has been noted at transmission, but not taken into account during calculations.

From a scientific point of view, the discrepancies could in the first place be attributed to variation of the relative dielectric constant along the band tested, which has been taken constant all over the computational procedure. In addition, a slight matter concerning sound application of the path-selection criterion arises at here. Deciding incorporation of a component i or not to the multipath analysis by virtue of the weighting factor modulus $|g_i|$ in relation to a preset threshold does not preserve absolutely equal treatment of all paths. Impact of longer echoes is more intensely taken into account, as two paths with the same weighting factor may in fact have considerably unequal magnitudes due to long difference between respective route runs.

Amending the above two flaws of the method is easily attained and incorporated to the computational procedure. In any case, the model seems wide suitable for approximative PLC channel simulations, not demanding any experimental feedback.

4. Power-Delay-Profile Aspects

4.1. Simulation

Indoor cabling is in general installed at tree topology, formed of replicated star and bus structures. The star centre is normally a distribution panel, from which load-feeding lines originate configured like a bus, forming the branches of the tree, of which panels are the nodes. Load-feeding branches also serve sometimes as secondary buses. Such tree topologies usually comprise two branch layers, as the panels are commonly installed at two-level interconnection architecture along the grid. The main electric panel to which power supply from distribution LV network is coupled feeds distribution sub-panels where the load lines originate from, although more sub-panel levels may be found in huge buildings. Hence, bus structure constitutes the primary element of indoor grids' topology. In fact, power-line networks are assembled of adjoining bus topologies, so that statistical characteristics of a branched backbone line should inherently be assigned to indoor PLC channels. Having open-circuited terminations, the worst-case scenario is taken into account, as by the resultant unitary reflection coefficient at the branch ends multipath delay spread effect gets maximized.

On the basis of the study introduced above, preliminary power-delay-profile estimations have been attempted. To this effect, an additional program in Pascal has been compiled that calculates and records in appropriate data files the path amplitudes and arrival times. For the measured grid paradigms No 1 to No 3 defined above, path inventory of all components having the weighting factor g_i within two orders of magnitude below the weighting factor g_0 of direct path has been performed. Simulation at 15MHz has been conducted for each of the three buses, and the results are depicted in fig. 5-7. Symbol μ denotes the mean parameter and σ the standard deviation. The theoretical Normal and Lognormal dashed curves are in each diagram drawn with the mean and standard-deviation parameters of corresponding path set.

4.2 Discussion

Resulting channel power-delay profiles originate from a single-frequency simulation process, but are still indicative of the multipath-propagation effect in the HF band, and lead to concepts of considerable practical and theoretical value. To begin with, only bus No 2 has given a single path set in the sense of uninterrupted path-arrival sequence. Cumulative arrival-time and amplitude distributions are therefore plotted in fig. 6, where respective compliance with the Normal and Lognormal distributions is apparent. Simulation over the other two sample grids reveals that the aggregate multitude of paths arrives at reception at well-defined groups in the time domain; the probability density function (pdf) curves displayed in fig. 5 and 7 refer thus to the individual dominant path subsets that have in each case been observed. Good conformance to the Normal and Lognormal distributions respectively for the arrival-time and amplitude sequences is also obvious within a path group.

Clear indication on the effect of network's spatial configuration upon the generation of dominant path groups and incident statistical behaviours is in addition obtained. Along the grid No 2, whereat path multitude arrives as a single group, the transverse branches are coupled at similar distances in between, along a section 7.5m long some 27m from transmission and 2m from reception. Considering bus No 1, two distant branched sections exist, and two path sets have indeed arisen. Three distant branched sections are configured along bus No 3, and three path groups are observed. It is therefore deduced that any grid section assembled at equable allocation of scattering points (junctions and terminations) gives rise to an individual path group displaying the Normal arrival-time distribution and the Lognormal amplitude one. The latter is also vaguely interpreted in theory, as multipath propagation, characterised as a multiplicative process due to multiple reflections, could be expected to yield Lognormal distribution in the same way that an additive process results in Normal distribution as described by the Central Limit Theorem.

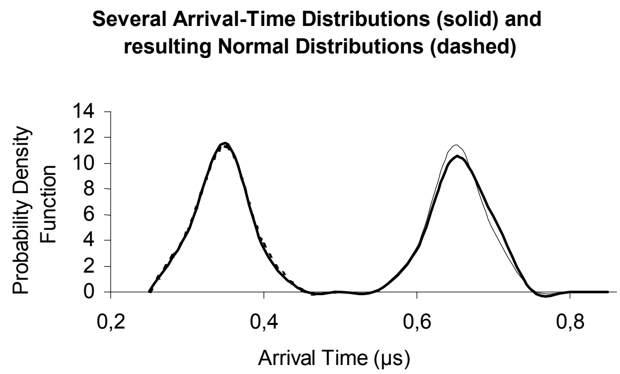
From the reasoning deployed heretofore it comes up that fading behaviour of indoor single-phase PLC channels should be characterised by a path set of a Normal arrival-time sequence and a Lognormal amplitude fluctuation, as uniform spatial distribution of junctions and terminations therein more or less prevails. However, several dominant path groups as defined above would probably exist at PLC links along the access LV network, as each consumer (house, premises etc.) could be considered a distant, isolated branched section. The rationale developed so far is of course not generalized, but indicant and based on the preliminary study described above. A valid aspect concerning statistical fading properties of PLC channels is though profoundly suggested. Further investigation is hereby encouraged, concentrating on the grouping and characterisation of indoor PLC installations on multipath-fading principles.

The analysis and statistical simulation that have been presented concern propagation of distinct sinusoidal signals, being thus directly applicable to the narrowband or multi-carrier (e.g. OFDM) case, where the bandwidth occupied is small compared to carrier frequency. Equivalent wideband analysis of the power delay profile would though be feasible through a very similar procedure to the one carried out above. In that case, channel's transfer properties would be treated in the time domain by use of the impulse response instead of transfer function. Estimating transfer function by the multipath analysing method introduced, an inverse Fourier transformation would give the impulse response, so that all suitable formulism and computational procedures should be thereon developed.

5. Conclusion

In this paper, a method providing HF transfer properties of indoor PLC channels has been proposed based on multipath-propagation principles, applicable wherever cables fall into the two-conductor uniform transmission-line model. Employing the generalized multipath propagation model, estimation of the channel response by inclusion of the path set within two orders of magnitude below the direct path has been suggested. A completely analytical/computational process has been proposed, so that no experimental feedback or parameter calibration is incorporated. The cable distributed parameters and the grid network in the vicinity of the link need only be provided. Collation with measured amplitude-response curves has verified the method to be well adequate for the approximate channel evaluations required in practice. Preliminary power-delay-profile estimations that have been performed indicate in relation to indoor PLC channels the Normal distribution for path arrival times and the Lognormal for path amplitudes. Further exploration is hereby strongly encouraged, in order for network topology and range to be quantitatively interrelated with the channel power-delay-profile.

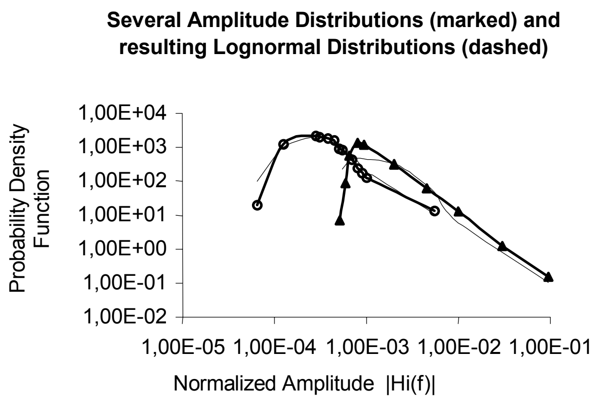
(a) Arrival-Time Distribution of the several path-sets.



1^{st} subset: 1104 paths, $\mu = 0.32\mu s$, $\sigma = 0.03\mu s$

2^{d} subset: 1587 paths, $\mu = 0.63\mu s$, $\sigma = 0.031\mu s$

(b) Amplitude Distribution of the several path-sets.

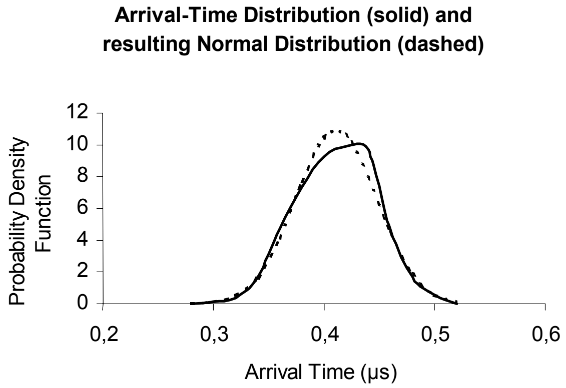


1^{st} subset: 1104 paths, $\mu[\ln|H_i(f)|] = -6.55$, $\sigma = 0.82$

2^{d} subset: 1587 paths, $\mu[\ln|H_i(f)|] = -8.0$, $\sigma = 0.66$

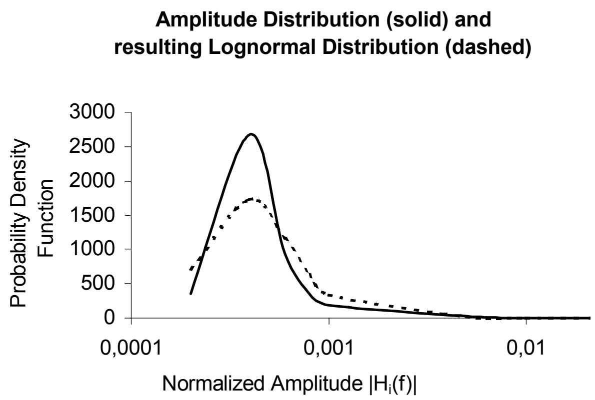
Fig. 5. Power-Delay-Profile of the 1^{st} bus $(N = 2691)$

(a) Cumulative Arrival-Time Distribution



$\mu = 0.40\mu s$, $\sigma = 0.036\mu s$

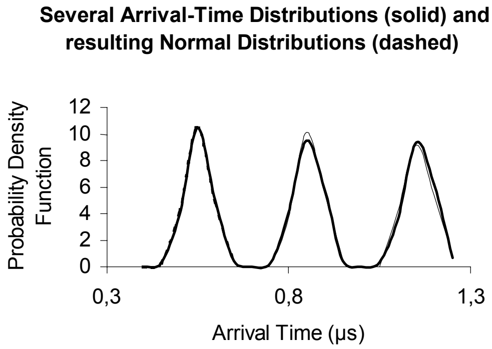
(b) Cumulative Amplitude Distribution



$\mu\left[\ln\left|H_i(f)\right|\right] = -7.81$, $\sigma = 0.667$

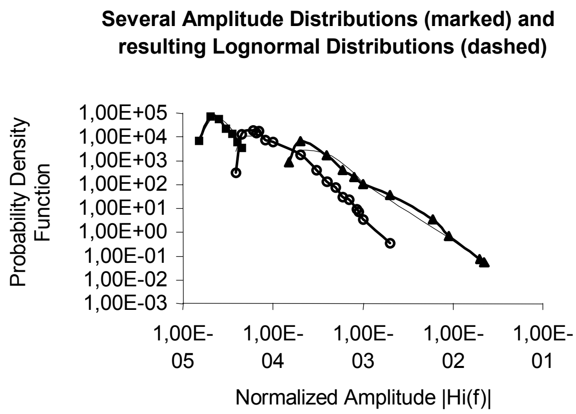
Fig. 6. Power-Delay-Profile of the 2nd bus $(N = 6431)$

(a) Arrival-Time Distribution of the several path-sets



1st subset: 7152 paths, $\mu = 0.53\mu s$, $\sigma = 0.035\mu s$
2d subset: 5602 paths, $\mu = 0.83\mu s$, $\sigma = 0.036\mu s$
3d subset: 693 paths, $\mu = 1.13\mu s$, $\sigma = 0.041\mu s$

(b) Amplitude Distribution of the several path-sets



1st subset: 7152 paths, $\mu\left[\ln\left|H_i(f)\right|\right] = -8.25$, $\sigma = 0.677$
2d subset: 5602 paths, $\mu\left[\ln\left|H_i(f)\right|\right] = -9.45$, $\sigma = 0.531$
3d subset: 693 paths, $\mu\left[\ln\left|H_i(f)\right|\right] = -10.7$, $\sigma = 0.3$

Fig. 7. Power-Delay-Profile of the 4th bus $(N = 13447)$

References

[1] H. Philips, "Modelling of Powerline Communication Channels" in *Proc. ISPLC'99*, 1999, pp.14-21.

[2] M. Zimmermann and K. Dostert, "A Multi-Path Propagation Model for the Power-Line Channel in the High Frequency Range," in *Proc. ISPLC'99*, 1999, pp.45-61.

[3] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel", IEEE Transactions on Communications, vol. 50, No. 4, April 2002, pp.553-539.

[4] T. Esmailian, F.R. Kschischang, and P.G. Gulak, "An In-building Power Line Channel Simulator", in *Proc. ISPLC2002*, 2002, pp. 31-35.

[5] D. Anastasiadou and T. Antonakopoulos, "An experimental set-up for characterizing the residential power grid variable behavior", in *Proc. ISPLC2002*, 2002, pp. 65-70.

[6] A. Matov, "A Planning Tool for High Bit Rate Transmission over Power Line Communication Channels ", in *Proc. ISPLC2001*, 2001, pp. 15-20.

[7] I.C. Papaleonidopoulos, C.G. Karagiannopoulos, N.J. Theodorou, C.E. Anagnostopoulos and I.E. Anagnostopoulos, "Modelling of Indoor Low-Voltage Cables in the High Frequency range," in *Proc. ISPLC2002*, 2002, pp. 267-271.