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An experimental set-up for characterizing the residential power grid variable behaviour

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An Experimental Setup for Characterizing the Residential Power Grid Variable Behavior

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ABSTRACT

The objective of this work is to establish the basic setup and methodology for analyzing the effect of common disturbances on the residential power line channel response regarding time and network topology. Such information is necessary in the process of developing a method of real-time channel sensing used in a multi-carrier communication system that performs dynamical sub-channel bandwidth allocation. Measurements are performed on a controlled experimental power line network, constructed in the image of common residential circuits, but isolated from external sources of disturbance. Transmission line and two-port network theory are used to produce a theoretical model of the network transfer function, which conforms to the experimental results.

I. INTRODUCTION

The idea of utilizing the residential power grid to offer value added digital communication services has been investigated intensively during the last few years. Data transmission over the power grid could be used to extend networking services to every part of today's household based on the existing infrastructure. The interest on high-speed power line communications has increased the need for better understanding of the physical channel properties.

Numerous efforts have been made to measure and characterize the residential power line circuit as a communications medium. The most common approach is based on extensive measurements in various locations and different buildings, attempting to create a statistical model of the intra-building distribution grid [1], [2], [3]. The produced results agree on the channel's variable behavior with respect to time, frequency and network topology. Attenuation and phase shift vary significantly with frequency, while impedance matching is hindered by the frequency dependent characteristic impedance. External sources of noise, such as electrical appliances, switched power supply units or even short wave radio, affect the channel's behavior in different bands, while adding time variance to its characteristics [4].

Most measurements presented in literature are taken on actual residential circuits where physical distances are roughly estimated and the existence of disturbance sources is inferred by their effect on the channel behavior. Taking a different approach, this work aims at measuring and analyzing the effect of various load types using a well-defined and fully characterized power line network. The method is based on measurements performed in a completely controlled environment of an experimental power line network that resembles the topology of common residential circuits, while being totally isolated from external sources of disturbance. Since physical distances and channel characteristics are known, the effect of various noise sources on the channel response can be analyzed with respect to time and network topology.

The work presented here was conducted in a wider framework that can be outlined as the design of a power line communication system that confronts the channel's unfavorable behavior by measuring the underlying conditions 'on the fly' and adapting its transmission technique. The development of a method that enables this kind of real-time channel sensing requires precise knowledge of the expected duration and type of transfer function changes. Although beyond the scope of the work presented in this paper, developing the correct criteria of sub-channel selection in a multi-carrier communication system, would lead to optimal exploitation of the available bandwidth. In this respect, information about the time duration and frequency extent of the channel response variations are of primary importance. Fully understanding how each noise source affects the network can not only indicate which sub-channels are unusable, but can also determine how fast an affected sub-channel will be utilizable again, in a dynamic bandwidth allocation system. Thus, by using the data provided by this work we could model a variety of noise sources, which combined with the theoretical network model presented here, could provide an accurate simulation tool.

The methodology presented here focuses on frequencies between 1 and 10 MHz, but can easily be extended to any frequency band. In Section II, the measurement setup and the experimental network is described. The channel's theoretical model and its simulation results are presented in Section III, while Section IV presents the measurement results on the effect of various load types connected to the network.

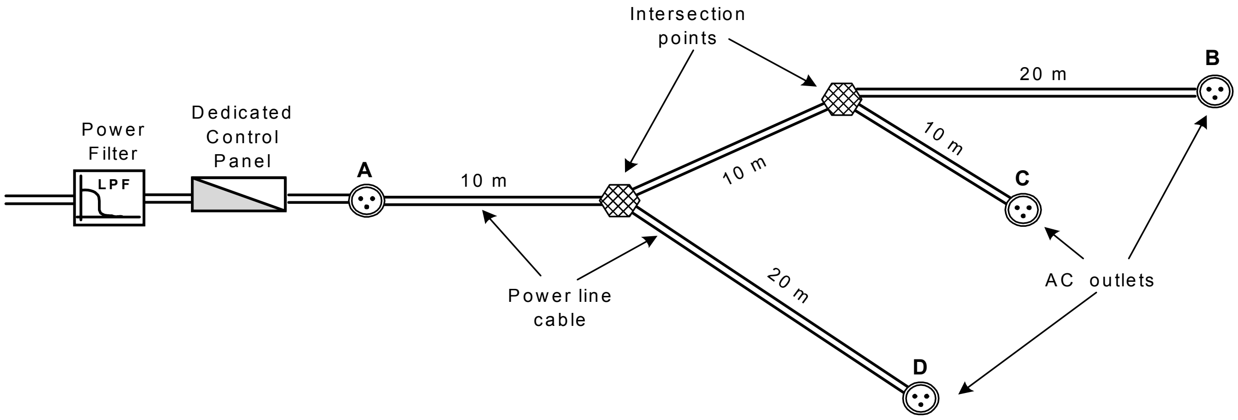

Figure 1.The experimental power line setup

II. Experimental Network Setup

In order to measure and analyze the effect of various load types on the power grid we conducted an extended set of measurements on a well defined experimental power line network. The experimental power grid (Figure 1) was constructed using typical wiring and resembling the topology of the Greek residential distribution grid. The main objective was to create an experimental network with branches similar to those found in a typical residential power grid, terminated at AC outlets and totally isolated from the external environment. In this manner, measurement results can be directly traced back to their source of origin, meaning the network topology or a specific source of disturbance.

The experimental network was loaded with single phase 230V AC through a dedicated single phase control panel. A power filter, responsible for filtering out any external interference, preceded the panel. The cable used for the wiring was H05VVF (3 x 1.5 mm^2), which is typically used in Greek residential buildings. A cross sectional diagram of the cable appears in Figure 2. The cable consists of 3 stranded copper wires, while the insulation is manufactured using PVC.

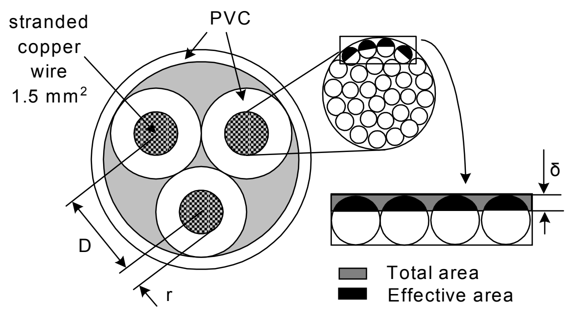

Figure 2. H05VVF cable cross section

Measurements were performed on every AC outlet (points A, B, C, D), giving a complete description of the network behavior regarding the implemented topology. The effect of digital measurement equipment was totally eliminated from the procedure, since their power supply was not provided by the experimental network. The initial measurement setup consisted of a sweep generator and data acquisition devices. All digital equipment were interfaced to the experimental network using properly designed coupling circuits, that prevented the AC voltage from reaching the equipment and provided galvanic isolation through wideband RF transformers.

III. Transmission Line Theory Model

In the process of understanding the behavior of the power grid, we initially produced a theoretical model of the experimental network. Such a task was possible since the topology was well defined and its physical characteristics could be measured. Transmission line theory [5] was used to estimate the behavior of the line, which depended on the cable characteristics. Thus, each cable section was analyzed by modeling its transmission characteristics. Proper integration of all sections into a single model was based on the two-port network theory and their representation by ABCD parameters. The steps taken to generate the theoretical model of the experimental network are described in detail in the following paragraphs. Finally, the theoretical results are compared to those taken by measurements performed on the experimental topology.

A. Transmission line parameters of the cable

Cables are generally analyzed as a form of transmission lines. Assuming balanced conditions, a line of length dz can be represented by an equivalent circuit (Figure 3) consisting of the line's Resistance (R′), Inductance (L′), Capacitance (C′) and Conductance (G′) per unit length.

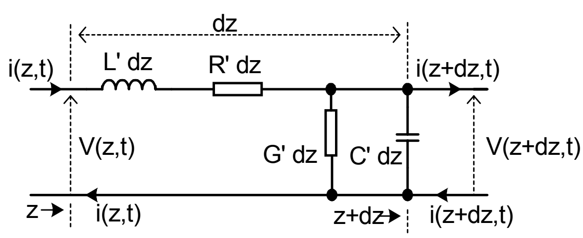

Figure 3. Equivalent circuit of an unloaded power line of length *dz*

Using electromagnetic theory and based on the physical dimensions, structure and cable materials, the R′, L′, C′, G′ primary parameters were calculated. Since we were interested in studying the medium in the 1-10 MHz frequency band, skin effect has to be taken into account, resulting in frequency dependent analytical forms of the primary parameters.

Considering R_{DC} = 0.0121 Ohm/m, measured specifically for this type of cable, we calculated the cable resistivity $\rho = 0.017794$ Ohm.mm^2/m, based on equation:

$$R_{solid} = \rho \cdot l / A \tag{1}$$

where l is the length of the wire, A is its cross section and also assuming that the resistance of a stranded wire is about 2% higher than that of a solid wire of the same diameter, for which equation (1) applies directly. Cable Resistance at high frequencies is affected by the skin effect and is given as a function of frequency in equation (2).

$$R_f = \frac{(u/2 \cdot B) \cdot R_{DC}}{AR} \tag{2}$$

where u is a factor related to the skin depth δ, AR is the Area Ratio factor and B is related to the Bessel functions (ber, bei) [5] as follows:

$$u = r \cdot \sqrt{2}/\delta \tag{3}$$

$$\mathrm{B} = \frac{ber(u) \cdot bei'(u) - bei(u) \cdot ber'(u)}{\left(ber'(u)\right)^2 + \left(bei'(u)\right)^2} \tag{4}$$

The Area Ratio factor (AR) takes into consideration the stranded nature of the wire, since in this case the effective conducting area is less than that of a solid wire at equal skin depth (Figure 2). AR was calculated as the Effective / Total area ratio, presented in equation (5), where r is the wire radius :

$$\mathrm{AR} = \frac{\cos^{-1}\left(\frac{r-\delta}{r}\right) \cdot r^2 - (r-\delta) \cdot \sqrt{r^2 - (r-\delta)^2}}{2 \cdot \delta \cdot r} \tag{5}$$

The same factors had to be considered during the evaluation of the cable Inductance. Skin effect is an important factor and the Area Ratio should again be applied to account for the reduced effective area of the wire at skin depth δ. Equations (6), (7), (8) and (9) were used to calculate the Inductance as a function of frequency :

$$L_f = L\mathrm{int} \cdot a_{str} + Lext_{DC} \cdot a_{str} \cdot (u/4) \cdot B \cdot AR \tag{6}$$

$$L\mathrm{int} = \mu_o \mu_r / 8\pi \tag{7}$$

$$Lext_{DC} = \frac{\mu_o \mu_r}{\pi} \cdot \cos^{-1}(D/2 \cdot r) \tag{8}$$

where μ_o is the vacuum magnetic permeability, and D is the distance between the two wire centers. Copper relative permeability μ_r is equal to unity. The α_{str} factor is not linked to the skin effect, but affects the values of the internal ($Lint$) and external ($Lext$) Inductance in DC. It is a correction factor that corresponds to the ratio of cross sectional area of the stranded wire to that of a solid wire of the same radius.

$$a_{str} = \frac{stranded}{solid} = \frac{n_{str} \cdot \pi \cdot r_{str}^2}{\pi \cdot r^2} \tag{9}$$

where n_{str} is the number of stranded conductors in each wire and r_{str} is the conductor radius.

The cable Capacitance, however, is not affected by skin effect and can be calculated in the same manner as the external Inductance of the cable:

$$C_f = \frac{\pi \cdot \varepsilon_o \cdot \varepsilon_r}{\cos^{-1}(D/2 \cdot r)} \cdot (1/a_{str}) \tag{10}$$

where ε_o is the dielectric permittivity constant of the vacuum and ε_r is the relative permittivity of PVC.

Cable Conductivity is estimated using measured values of the loss factor tanδ:

$$G_f = 2 \cdot \pi \cdot f \cdot C_f \cdot \tan\delta \tag{11}$$

Having calculated the primary parameters of the line, the secondary parameters, namely the characteristic impedance Zo and the transmission factor γ can easily be extracted using equations (12) and (13).

$$Z_o = \sqrt{(R + j2\pi fL)/(G + j2\pi fC)} \tag{12}$$

$$\gamma = \sqrt{(R + j2\pi fL) \cdot (G + j2\pi fC)} \tag{13}$$

B. ABCD parameters model of the topology

Since the primary parameters have been calculated, each section of the experimental network can be represented by an equivalent circuit of appropriate length. Two-port network theory [6] suggests that every part of a network can be modeled by a suitable two-port network, and the complete network model can be formed by the interconnection of the partial two-port networks.

ABCD parameters are useful in characterizing two-port networks. The ABCD matrix for any line section is calculated through transformation of its secondary parameters according to:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma \cdot L) & \sinh(\gamma \cdot L) \cdot Z_o \\ \sinh(\gamma \cdot L)/Z_o & \cosh(\gamma \cdot L) \end{bmatrix} \tag{14}$$

where L is the length of the line. Cascading two such networks equals to the multiplication of their ABCD matrices. Any network connected at some intermediate point of a path can be treated as a lumped network, whose ABCD matrix is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{lmp} = \begin{bmatrix} 1 & 0 \\ 1/Z_{o,lmp} \cdot \coth(\gamma_{lmp} \cdot L_{lmp}) & 1 \end{bmatrix} \tag{15}$$

where Z_L is the path termination impedance of. The network transfer function TF, for a certain path, is given by equation (16).

$$TF = Z_L / (A \cdot Z_L + B) \qquad (16)$$

Based on this theory, we were able to calculate the transfer function for each path of the experimental network, by multiplying the matrices of all the partial two-port networks comprising the path.

C. Theoretical and experimental results

The figures presented in this section compare the results produced by the theoretical model and the measurements performed on the experimental network. Using the model, a transfer function was derived for each path of the topology. Results were also produced for the Characteristic Impedance of the line as a function of frequency.

Measurements were originally conducted without 230V AC supply on the network, so that the setup would represent the conditions that the model was based on. The AC outlets were not terminated. Nevertheless, measurements taken at a later stage with AC power on the network, showed that the existence of AC voltage does not affect the network behavior.

Figure 3 presents results for the magnitude of the transfer function for three paths of the experimental network. The measurement results were found to be in satisfactory agreement with those produced by the model. Small variations are attributed to the cable's stranded nature, which was only approximated by the analytical forms and also to the non-ideal intersection points.

Comparison of measurement and theoretical results verified the validity of the measurement procedure. At the same time, the produced model can be used further to examine the experimental network behavior.

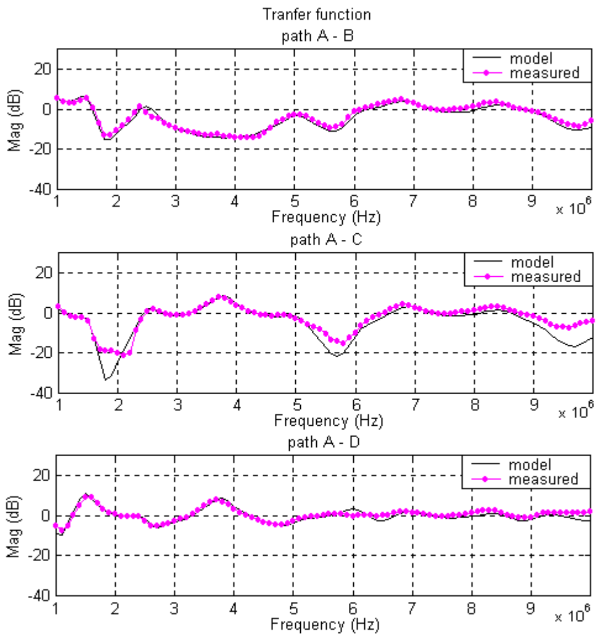

Figure 3. Theoretical and measurement results for paths A-B, A-C and A-D.

D. Experimental network loaded with 230V AC.

In order to perform measurements on the network with 230V AC supply, input and output coupling circuits were used. These circuits are practically high pass filters that prevent the AC power supply at the input to reach the internal circuits. Moreover, a suitable wideband RF transformer was used to provide galvanic isolation from the power line. The coupling circuit used is presented in Figure 4.

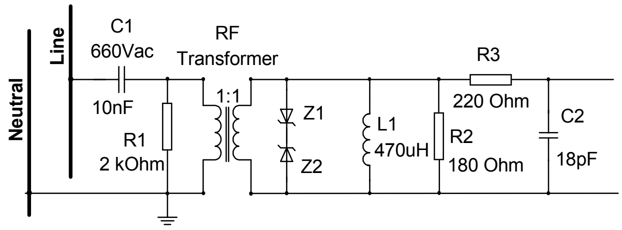

Figure 4. Input coupling circuit

Connecting the coupling circuits at the AC outlets affected the network impedance and thus its response, by changing the termination load seen at the outlets. Measurements taken with the coupling circuits connected to the network produced the same results with and without AC supply, which was anticipated, since the experimental network was constructed in complete isolation from the external power line grid so that no external disturbance could affect its response. The above is demonstrated in Figure 5.

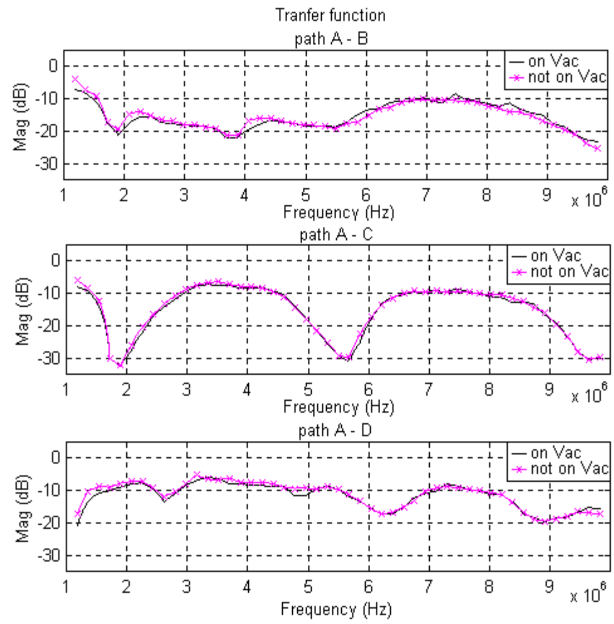

Figure 5. Measurement results for path A- D with and without AC power.

IV. LOAD EFFECT ON NETWORK TRANSFER FUNCTION

During our study of the residential power grid, it became evident that the factors that determine its behavior as a communications medium can be categorized as follows:

- *Unloaded network transfer response*,
  being the network response depending on the wiring topology and the cable physical characteristics,

- *End points impedance*,
  defined by the loads (appliances etc.), permanently or temporarily connected at the AC outlets which alter the network termination impedance and thus its response,

- *Noise introduced in the network*,
  originating from any operating appliance supplied by the network.

The goal of this ongoing work is to study and analyze each one of the factors mentioned above. Thus, an automatic procedure can be formed that enables a power line communications system to adapt its functionality to the underlying network conditions by performing proper measurements, from which the channel response changes can be evaluated.

Measurements conducted on the experimental network included various end-point loads of capacitive and inductive character, as well as a variety of noise sources, mainly home appliances, such as an electrical drill, a hair dryer, an air conditioner, a fan, a fluorescent lamp and more. Data on the effect of each noise source on the channel response are still being gathered and can be used to create models of each source of disturbance. These models can be added to the theoretical network model to produce a complete estimate of the channel behavior. Some of these measurements are presented here.

The first set of measurements involved an analysis of the effect of end-point loads on the network transfer function. Figure 6 presents the effect of a load connected at point B on the transfer function of path A–C. The impedance of this load is $Z_L(f) = 5 - j10^7/2\pi f$. The first graph, exhibits the results produced by the theoretical model. The transfer function characterized as 'open' is produced when all outlets are left open, while 'loaded' refers to the case when the load is connected to the network. The same analysis was done on the measurement results, presented in the second graph of Figure 6. The difference observed between the form of the theoretical and the measured transfer function is due to the fact that the latter includes the response of the two coupling circuits.

The second set of measurements focused on an analysis of the effect that a variety of common household appliances have on the network transfer function. These loads can be characterized as active, since they not only alter the network transfer function by changing the termination impedance, but also increase the channel noise level. Thus, by measuring the network response when a connected noise source is operating and when it is switched off, we derive its complete effect on the network transfer function. The above is depicted in Figure 7, where the attenuation effect on the network transfer function is caused by a hair dryer and a switched power supply connected at point A.

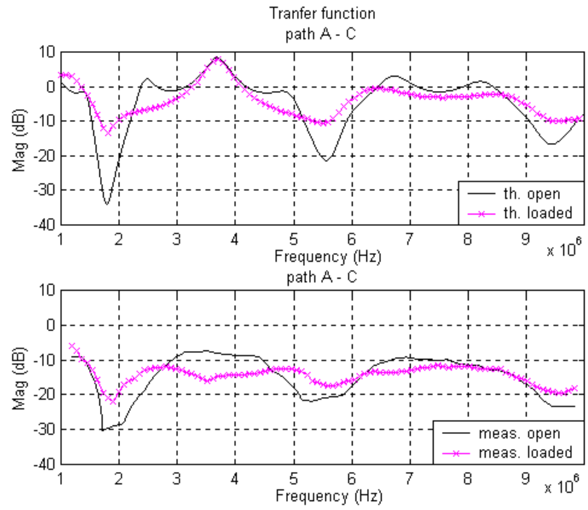

Figure 6. Theoretical and measurement effect of connected load on transfer function

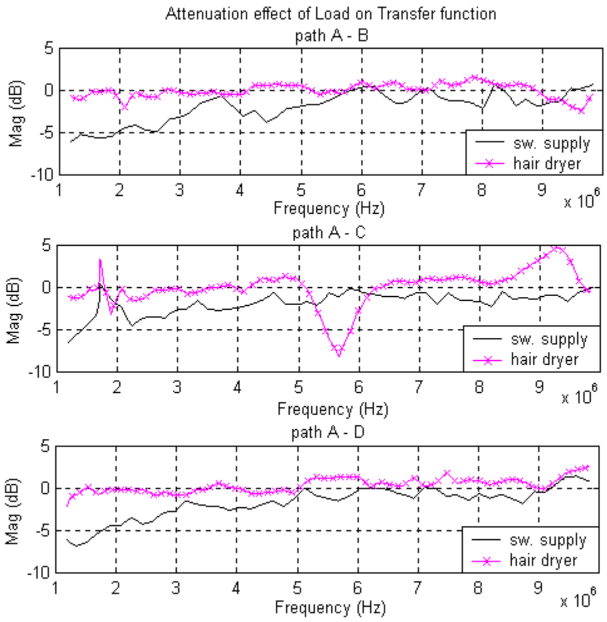

Figure 7. Attenuation effect on the transfer function due to loads connected to the network

The attenuation caused by each of these two loads produces useful information that could be used to determine which bands are heavily affected or which sub-channels are completely unusable during their operation.

A third set of measurements, currently in progress, aims at estimating the effect of loads on the network transfer function regarding time, distinguishing between two major categories of noise sources. The first consists of sources that affect the network during their entire time of operation, e.g. an air-conditioning system, while the second refers to those that have a temporary effect, usually when being switched on and off, such as a fluorescent lamp.

V. Conclusions

The work presented in this paper aims at establishing a measurement method based on an experimental power line network, which resembles the topology of the residential grid, but is isolated from external disturbances. This well defined and controlled network was theoretically modeled with satisfactory precision. The model can easily be extended to simulate any topology by adding branches of variable length, as long as distances and wiring characteristics are known. A variety of measurements was performed on the experimental network, analyzing the effect that different types of loads have on its transfer function. Further analysis is intended to provide information on the attenuation caused by such loads on the channel response and the type of noise they inflict on it. Their behavior can be estimated regardless of network topology, by deriving their effect from the measured transfer function using digital signal processing. As a result of this procedure, a number of noise sources can be modeled and combined with the network model to form a simulation tool, useful in the process of developing a power line communication system that utilizes dynamic transmission techniques.

Acknowledgments

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