Simulation of impedance and propagation in PLC networks

Dubravko Sabolić, Member, IEEE, Alen Bažant, Member, IEEE, and Dinko Begušić, Member, IEEE

Abstract — *Here we present a propagation model for Power-Line Communication (PLC) networks, based on a frequency domain analysis. First we set a simple two-port model of a network and calculate complex attenuation factor from the z-parameters, which are expressed in terms of impedances easily calculable/measurable from the network's ports. We provide all the elements for a simple end efficient propagation model, including propagation by crosstalk between different circuits in e.g. three phase networks, as well as influence of the loads connected to the ports of different circuits on such networks. We conclude that the model shown is suitable for PLC channels simulations, giving very accurate results and enabling modeling of wide band channel characteristics. Since the propagation model relies on impedance calculations, we can also use it for the calculations of impedances seen from network termination ports. With the developed tool we have been able to predict channel propagation factors in both real and imaginary part, as well as port impedances, in very complex networks, which could not be achieved with usual time domain approach in an economic way*[1].

Index Terms — **Power-Line Communications Network, Propagation, Impedance.**

I. Introduction

In this article we present an accurate and straightforward model for propagation analysis in complex Power-Line Communication (PLC) networks. The model is based on the simulations of input impedances of network's ports. We also mention a parallel measurement method, grounded on the same principles.

Models which first evaluate an impulse response of the network, then switch to frequency domain by means of inverse fast Fourier transform, and finally introduce correction for material losses in cables, are today widely spread, rather well developed, and thoroughly displayed in the literature, e.g. [1, 2, 3]. We shall take here an alternative approach to the same problem, starting our analysis from the frequency domain. Therefore, because of the unique relationship between time- and frequency domain representations of the channel responses, we expect to achieve equally valid results.

D. Sabolić is with HEP PrP Zagreb, Ulica grada Vukovara 37, 10000 Zagreb, Croatia, (e-mail: sabolic@ieee.org).

A. Bažant is with University of Zagreb, Faculty of electrical engineering and computing, Unska 3, 10000 Zagreb, Croatia (e-mail: alen.bazant@fer.hr).

D. Begušić is with Univeristy of Split, Faculty of electrical engineering, R. Boškovića bb, 21000 Split, Croatia (e-mail: begusic@fesb.hr).

Since distribution networks generally have very complex topologies and many ports, multipath propagation phenomena occur. However, tracing of all possible impulse paths in ultibranched networks, i.e. pure calculation of delays and amplitudes of all possible modes of impulse propagation, turns out to be very complex task, even for relatively simple networks.

Here we shall present another modeling method, completely based in frequency domain. While developing this method, we were led by several firm principles:

- The propagation model should be as simple as possible, and it may require as input data only the network topology and a few cable properties for each cable type used.
- In parallel with the calculation tool, we should also develop a measuring method based on the same principles, enabling analyses of the totally unknown networks, i.e. black boxes.
- The model and the measuring method must be experimentally verified against each other, as well as against another independent direct channel attenuation measurement, all performed on a model network designed for this purpose.
- Both model and measurement method must be based on easily calculable/measurable quantities, which must be related only to network terminals, and not to inner (hidden) quantities within the network.
- The model must define all the elements needed to make a software tool for propagation analysis. Besides pure complex transfer function, this tool should also be able to perform calculations and analyses of other quantities important for wide-band communication channel characterization.

Since our complete analysis relies on impedance calculations, the software tool we developed for the demonstration purpose was also used for port impedances simulations. One could view impedance calculation as a by-product of complex transmission function determination procedure, although in fact the impedance simulation routines are in the very core of the propagation model software.

II. Basic analysis

Fig. 1. shows the basic two-port network model with z-parameters. From the elementary analysis of this circuit, the input/output voltage ratio, which we call attenuation, Γ, is:

$$\Gamma = \frac{V_1}{V_2} = \frac{(z_{22} + Z_L)\cdot z_{11} - z_{12}^2}{z_{12} Z_L}. \quad (1)$$

Other attenuation factors could also be easily specified, e.g. E/V_2, I_1/I_2, $[(V_1 I_1)/(V_2 I_2)]$, but throughout this article we

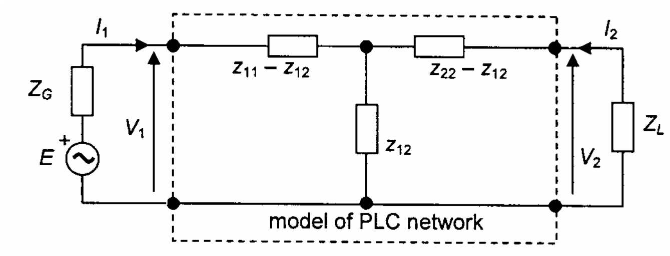

Fig. 1. Two-port model of PLC network.

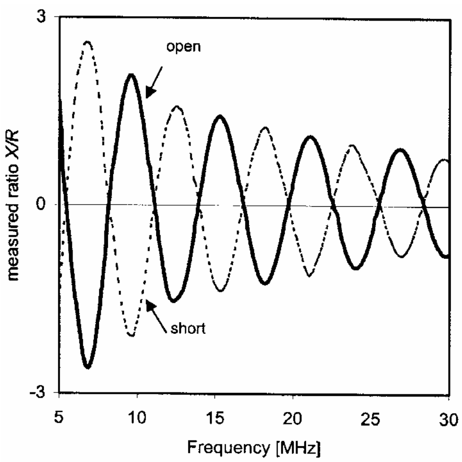

Fig. 2. Measured ratios of imaginary and real part of the impedances of 15-meter cable (one pair in a 3-wire cable), when the other end is open, or shorted.

assume attenuation is defined as port voltages ratio, (1). Next, we introduce the following quantities:

- Z_{1O} – impedance seen at port 1, when port 2 is open;
- Z_{1S} – impedance seen at port 1, when port 2 is short circuited;
- Z_{2O} – impedance seen at port 2, when port 1 is open;
- Z_{2S} – impedance seen at port 2, when port 1 is short circuited.

Since *z*-parameters can be expressed in terms of three of the four of those impedances, (1) can be transformed to:

$$\Gamma = \frac{Z_L Z_{1O} + Z_{1S} Z_{2O}}{Z_L \sqrt{Z_{2O}(Z_{1O} - Z_{1S})}}, \qquad (2)$$

or to:

$$\Gamma = \frac{Z_{1O}(Z_L + Z_{2S})}{Z_L \sqrt{Z_{1O}(Z_{2O} - Z_{2S})}}. \qquad (3)$$

Now we have two equivalent formulas expressed in terms of port impedances rather than *z*-parameters. All of those impedances can easily be calculated or measured in PLC networks. Both propagation model is based on (2), or (3). For the two port network, at least three of four impedances defined above, seen from the two ports under defined conditions, are required. Of course, *z*-parameters can also be calculated by performing three measurements/simulations only from one port, requiring that the other can be loaded by three different precise terminations. We choose the approach with formulas (2) or (3) because it gives the simplest expressions, thus reducing error accumulation when measurements based on the same principle as the simulation method are involved. From purely computational (modeling) point of view, all the approaches mentioned above are equivalent.

Let us emphasize that along with the simulation method treated here we can also define a measurement method involving measurements of port impedances, and then calculation of the attenuation factor from them by (2) or (3). So, when ever we address impedance measurements, we also address impedance calculations, and vice versa.

We shall not present here an extension of the model to multi-port networks, which is rather straightforward from the basic *z*-parameter network analysis. One can find this topic described in [5]. In general, the multi-port approach may not be very practical because in real networks load impedances are in most cases not known, or at least not sufficiently precisely known. So, we can only simulate load influences in the theoretic context, which we also find usable. However, for the development of the simulation software tool, or the measurement method, we shall apply the two-port model. Load variations are modeled by stochastic termination of all the network nodes according to appropriate distributions which simulate realistic situations.

III. Cable Parameters

The model described in short above was experimentally tested on a test network. The cable used for tests was three-wire 0.75 mm^2, PVC isolated. It was the cable with highest specific attenuation available on market, which is an advantage for demonstration of material attenuation modeling. We have calculated parameters α (attenuation constant) and β (phase constant) from the ratio between real and imaginary part of a piece of cable with the length *l:*

$$X_O / R_O = \pm \sin(2\beta l) / \sinh(2\alpha l). \qquad (4)$$

The sign is + when the line section is shorted, and – when it is open. Measured ratios for a 15-meter peace of cable are given on Fig. 2. Attenuation constant can be calculated from envelope decay. Since $\beta = 2\pi f/v$, where *f* is frequency, and *v* is wave velocity in the medium, for our model is important to determine value of *v*. The suitable model for α is [1]:

$$\alpha = \alpha_0 + \alpha_1 f^K. \qquad (5)$$

Here we shall not describe in details methods of calculations of the parameters by applying least squares to the measured

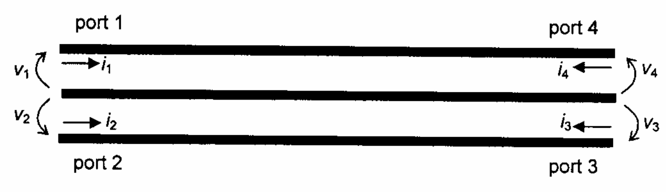

Fig. 3. Three-wire cable as a four-port network.

data. Thorough description of procedures can be found in [5]. For α we obtained, according to (5):

For our cable we obtained: $K = 0.709$;
$\alpha_1 = 0.00095\ \mathrm{m^{-1}\,MHz^{-1}}$
$\alpha_0 = 0.00307\ \mathrm{m^{-1}}$.

These figures are in agreement with values found in literature, see e.g. [1], and they also enabled very accurate simulations. For wave velocity we obtained: $v = 1.652 \times 10^8$ m/s, i.e. 0.55 times light speed in vacuum. It is constant within the frequency band of our interest (here from 5 to 30 MHz) Finally,
$\beta = (2\pi/v)f = 0.038 \times (f/\mathrm{MHz})\ \mathrm{m}^{-1}$.

The wave impedance, Z_0, was found from the data as the geometrical mean between short- and open line impedances:

$$Z_0 = \sqrt{Z_S Z_O}\,. \tag{6}$$

This was calculated for all measured points at 259 different frequencies, and then all results were averaged. The statistical processing showed very small frequency dependence of the resulting best linear fit throughout the frequency band from 5 to 30 MHz. Real part of Z_0 was never different from the absolute value of it more than 1.5%, and in 96% of total frequency band the difference was less than 0.5%. Resulting Z_0 was 90.442 Ω.

IV. Propagation by Crosstalk

In polyphase distribution networks propagation by crosstalk between different circuits at high frequencies normally occurs. Such mode of propagation should be avoided as much as possible because of generally higher attenuations. Still, in some practical cases this may not be possible. Furthermore, network loads connected to wire pairs different than those which are used for communication signals influence propagation properties in a signal path. Their impact can be also modeled with crosstalk propagation concept. We have performed analysis of crosstalk based on the coupled lines theory [4]. Without details, which can be found in [5], we shall state here only main conclusions.

Observe Fig. 3. Let $Z_{(1,4)O}$ denote the impedance seen from the port 1, when the port 4 (and all the others) is open, and let $Z_{(1,4)S}$ denote the impedance seen from port 1 when port 4 is shorted, and all the other ports are open. Let $Z_{(1,3)S}$ be the impedance seen from port 1, when port 3 is shorted, and let Z_0 denote the wave impedance for the transmission line between ports 1 and 4, which can be measured as the geometrical mean between the latter two impedances, when the ports 2 and 3 are open. We have proven that the following equation holds:

$$Z_{(1,3)S} = a \cdot Z_{(1,4)O} + (1-a) \cdot Z_{(1,4)S}\,. \tag{7}$$

The impedance $Z_{(1,3)S}$ is a *linear combination* of $Z_{(1,4)O}$ and $Z_{(1,4)S}$. Here $a = 4Z_{0e}Z_{0o}/(Z_{0e} + Z_{0o})^2$, Z_{0e} is the even-mode wave impedance, and Z_{0o} is the odd-mode wave impedance, which is always smaller or equal to Z_{0e} [4].

Note that the factor a can be viewed as another cable parameter and thus added to the set of parameters discussed in Chapter III. In fact, the propagation model would not be complete without this parameter. Knowledge of Z_0 and a is equivalent to the knowledge of the pair of wave impedances Z_{0e} and Z_{0o}. From our previous considerations one can easily derive the connection between those two sets of parameters:

$$Z_{0e} = Z_0\left(1+\sqrt{1-a}\right); \qquad Z_{0o} = Z_0\left(1-\sqrt{1-a}\right). \tag{8}$$

This is a relation with general validity. We found the set (Z_0,a) much more practical than (Z_{0e},Z_{0o}) because both Z_0 and a are in fact very easy to measure on a single peace of cable. Since the impedance seen from port 1 when the port 3 (and all the others) is open equals z_{11}, as well as to z_{33}, which is also equal to $Z_{(1,4)O}$, we have managed to express all the impedances needed to fully describe the crosstalk behavior in a structure from Fig. 3. with the impedances $Z_{(1,4)O}$ and $Z_{(1,4)S}$ only. The latter two are very easy to simulate, because they are simply: $Z_{(1,4)O} = Z_0 \coth(\gamma l)$ and $Z_{(1,4)S} = Z_0 \tanh(\gamma l)$. This is essential if one wants to make a *practical* simulation tool. Now, z_{13} parameter for two-port network with ports 1 and 3, while others are open (see Fig. 3.), is simply:

$$z_{13} = \sqrt{Z_{(1,4)O}\left(Z_{(1,4)O} - Z_{(1,3)S}\right)}\,. \tag{9}$$

In such a network, parameters z_{11} and z_{33} are obviously equal to $Z_{(1,4)O}$.

V. Propagation and Impedance Analysis Tool

Having all the elements explained, we may describe how the analysis tool works. It is grounded on impedance calculations. The complex Γ factor, which is reciprocal to the complex transfer function, is calculated according to (2) or (3). Assume one wants to calculate Γ for the propagation between ports A and B in a network. The program must calculate at least three impedances, for example: impedance seen from A when B is open; impedance seen from A when B is short; and impedance seen from B when A is open. In a distribution network of any complexity those calculations are easy to perform because we have explicit formulas for impedance transformations available. On Fig. 4. one can see a typical junction where four

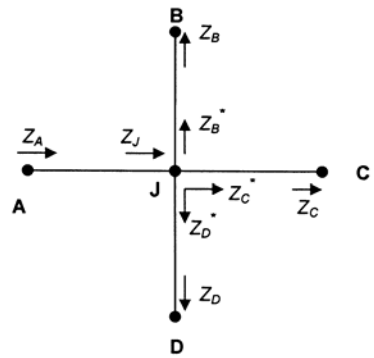

Fig. 4. A typical element of a complex network's structure for explanation of the algorithm used in the simulation software tool.

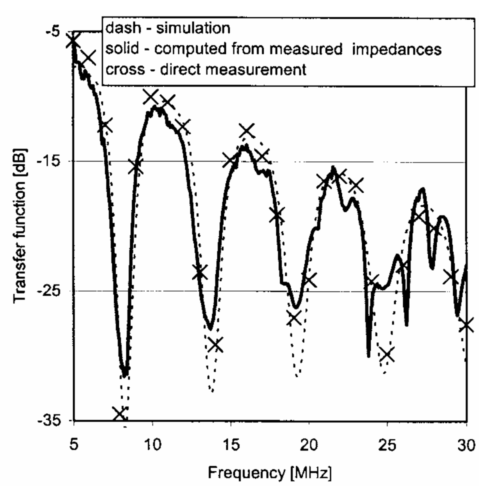

Fig. 5. On the experimental verification of the propagation model.

lines meet. Say we want to calculate the impedance seen from the port A, when ports B, C, and D are loaded by impedances Z_B, Z_C and Z_D. Those loads can be anything, for example another line sections or parallel combinations of line sections. Let all four sections have the length l and the complex propagation constant γ. One can make calculations with following series of straightforward equations:

$$Z_X^* = Z_0 \frac{Z_X + Z_0 \tanh(\gamma l)}{Z_0 + Z_X \tanh(\gamma l)}. \tag{10}$$

$$Z_J = Z_B^* \parallel Z_C^* \parallel Z_D^*. \tag{11}$$

$$Z_A = Z_0 \frac{Z_J + Z_0 \tanh(\gamma l)}{Z_0 + Z_J \tanh(\gamma l)}. \tag{12}$$

Letter X in (10) stands for any of the port designations, B, C, or D, from Fig. 4. This algorithm can obviously be performed easily over arbitrary complex distribution network containing such line branches. Another situation can occur if we have to model the crosstalk propagation. Then the program must calculate the z-parameters of such a section (z_{11}, z_{33} and z_{13}, see Chapter IV.). Impedance transformation by a two-port loaded with certain Z_L is simply:

$$Z_L^* = z_{11} - \frac{z_{13}^2}{z_{33} + Z_L}. \tag{13}$$

Note that the program has to calculate nothing else, but impedance transformations, using explicit formulas. In this way, program generates data on complex transfer function, which is equal to $1/\Gamma$, and on complex impedances seen from any port or inner node.

We have tested the model against direct attenuation measurements, and against attenuation calculated from impedances measured from network ports. One can see details in [5]. Here we can only state that the model produced very good results in both amplitude and phase parts. An example of testing is given on Fig. 5.

As regards simulation software tool, we made for demonstration a program that operated over a distribution network of an imagined office building with 150 termination ports. It is self-understood that the network of such complexity cannot be modeled with time-domain approach in an economic way, unless some channel impulse response measurements are taken. Our program needed fractions of a second to simulate the complex transfer function of a single channel. Since this function can depend heavily on the loads connected to network ports, especially if they are placed in the vicinity of the transmitter or the receiver, we developed another interesting feature.

Our program was generating loads for every termination port stochastically, according to a given distribution. Such a procedure can be performed a number of times. We used to have 1,000 simulations for each channel, meaning that the set of terminating impedances were stochastically changed 1,000 times. In such numerical experiment it is possible to generate a waste of data on various physical quantities important for PLC channel properties, enabling statistical analysis of them. We found this approach very useful because PLC network are in real life conditions hardly predictable. With this feature we have been able to analyze:

- transfer function (amplitude, phase; real and imaginary part, various representations and visualizations);
- group delay versus frequency;
- delay spread according to various definitions;
- network impulse response by means of appropriately adjusted fast inverse Fourier transform;
- delay and delay spread for ultra wideband excitation of the channel;
- full impedance analysis (module, phase, real and imaginary part, Smith chart representation);
- thorough analysis of the channel's Shannon capacity (here the noise scenarios were needed, too).

A full statistical analysis for each quantity mentioned above in a desired frequency band was carried out. Due to a limited scope and volume of this paper, we shall not present the simulation results in any further detail here.

VI. EXAMPLES OF SIMULATION RESULTS

On the following figures we give a short excerpt from the whole set of propagation and impedance data calculated for

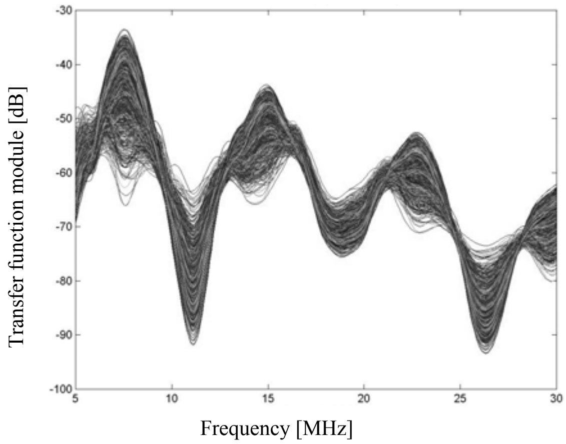

Fig. 6. Transfer function module.

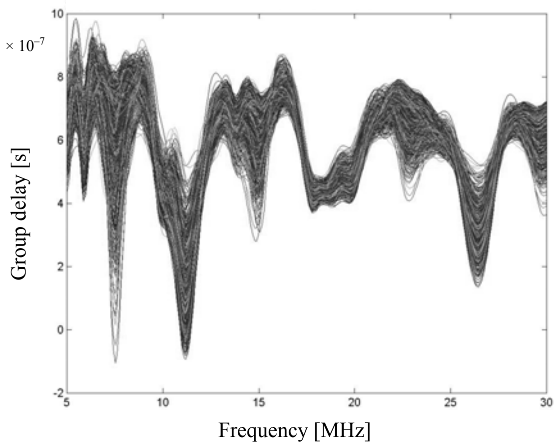

Fig. 7. Group delay.

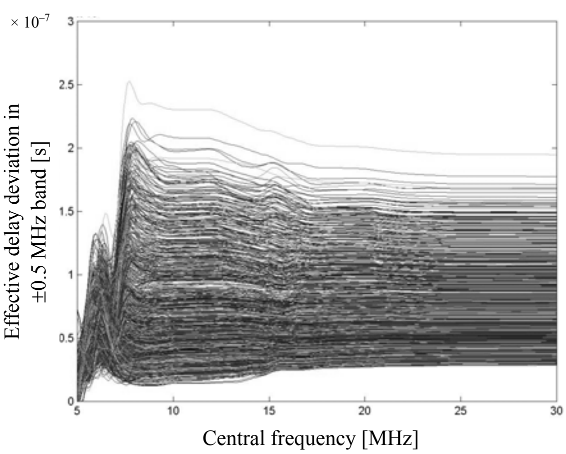

Fig. 8. Effective deviation of group delay within a bandwidth of ±0.5 MHz about central frequency.

an imagined office building described above, with stochastic termination of all 150 ports with resistances randomly chosen from the interval [0, 500 Ω]. Fig. 6. – Fig. 10. illustrate some propagation related properties of the simulated channel (between ports about 65 meters away in a described multiport 5-story building network), while Fig. 11. and Fig. 12. give basic calculation of real and imaginary parts of the impedance seen from one network port. All of the following figures, except Fig. 10, contain thousand curves, one for each randomly generated state of network ports termination.

VII. Conclusions

In this article we have presented a propagation model in frequency domain suitable for PLC channel transfer function simulations and port impedance calculations. In both model and measurement method the transfer function is calculated from the impedances that can be calculated/measured on network ports. We have briefly explained simple methods for cable parameters extraction, as well as necessary building blocks for the adequate software tool. We have experimentally verified the proposed model. The simulation tool can be used for extensive channel and impedance analyses.

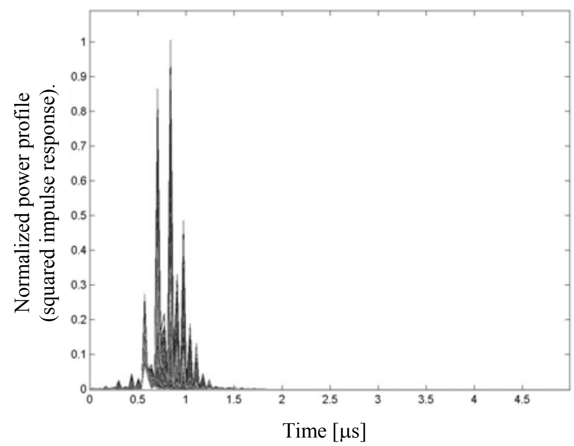

Fig. 9. Normalized squared impulse response of the channel.

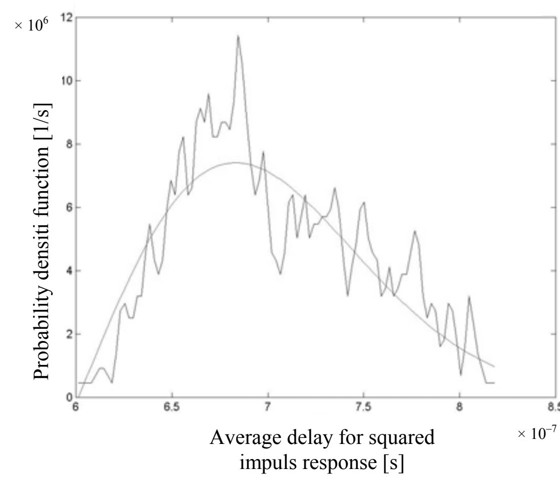

Fig. 10. Probability density function of squared impulse response average delay in 1000-run numeric experiment. Smooth curve on the picture is best-fit Rayleigh approximation.

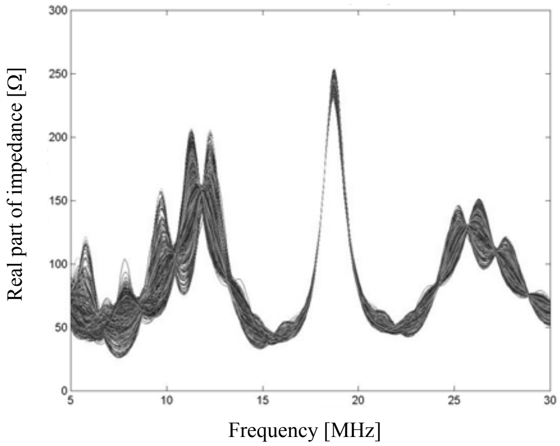

Fig. 11. Real part of impedance seen from one of the network's ports.

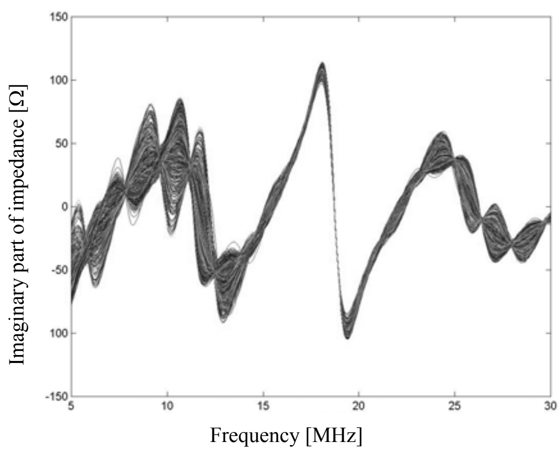

Fig. 12. Imaginary part of impedance seen from one of the network's ports.

REFERENCES

[1] K. Dostert, *Powerline Communications*, Prentice Hall PTR, 2001.

[2] M. Zimmermann, K. Dostert, "An Analysis of the Broadband Noise Scenario in Powerline Networks", *Proc. 4th International Symposium on Powerline Communications and its Applications*, Limerick, Ireland, April 5th-7th, 2000, available online at URL (June 2004): http://www-iiit.etec.uni-karlsruhe.de/~plc/

[3] M. Zimmermann, K. Dostert, "Analysis and Modeling of Impulsive Noise in Broad – Band Powerline Communications", *IEEE Trans. on Electromagnetic Compatibility,*vol. 44, no. 1, pp. 249-258, 2002.

[4] D. M. Pozar, *Microwave engineering,* 2nd ed, John Wiley and Sons, Inc, 1998.

[5] D. Sabolic, V. Varda, A. Bazant, "PLC Signal Propagation Modeling", *Proc. The 4th IASTED International Conference on Power and Energy Systems EuroPES 2004,* Rhodes, Greece, Jun. 2004.

[6] M. Zimmermann, K. Dostert, "A Multi-Path Signal Propagation Model for the Power Line Channel in the High Frequency Range", *Proc. 3rd International Symposium on Power-Line Communications*, Lancaster, UK, 1999, available online at URL (June 2004): http://www-iiit.etec.uni-karlsruhe.de/~plc/

[7] M. Zimmermann, K. Dostert, "A Multipath Model for the Powerline Channel", *IEEE Trans. on Communications*, vol. 50, no. 4, pp. 553-559, 2002.

[8] K. Dostert, "High Speed Data Transmission over Power Lines Using Multi-Carrier (OFDM) Techniques", *Frequenz,* vol. 54, no. 11-12, pp. 271-276, 2000.

[9] D. Liu *et al*, "Wide Band AC Power Line Characterization", *IEEE Trans. on Consumer Electronics*, vol. 45, no. 4, pp. 1087-1097, 1999.

[10] R. Cortina *et al*, "Telecommunication Systems on Power Distribution Networks: High Frequency Performances of Carrier Channels", *IEEE Trans. on Power Delivery*, vol. 9, no.2, pp. 654-660, 1994.

[11] F.J. Canete, *et al*, "Broadband Modelling of Indoor Power-Line Channels", *IEEE Trans. on Consumer Electronics,* vol. 48, no. 1, pp. 175-183, 2002.

Dubravko Sabolić (S'95–M'04) was born in 1969, in Zagreb, Croatia. He received the M.Sc. degree from the University of Zagreb, Croatia, in 1996. He is working towards the PhD degree in electrical engineering, as well as the M.Sc. degree in economics, all at the same university. In 1994 he joined the National Power Company, HEP, first as a telecommunications engineer, and from 1999 as a chief of Telecommunications department in Transmission region Zagreb. From 2001 he is serving as commissioner at the Telecommunications Council, the national regulatory authority for telecommunications. The areas of his professional interests are telecommunications for power systems, especially PLC communications, telecommunications legislation, and regulation of telecommunications industry.

Alen Bažant (M'00) received the B.S., M. S. and Ph.D. degrees in electrical engineering in 1985, 1990 and 1998, respectively, from the Faculty of electrical Engineering and Computing, University of Zagreb at Zagreb, Croatia. He began to work on the Faculty of Electrical Engineering and Computing (FER) at January 1987 as a departmental assistant on the department of Telecommunications. In 1989 he began to work in a company Nikola Tesla (present Ericsson Nikola Tesla) in Zagreb. Upon receiving masters degree he was shortly with Croatian Telecomm (former HPT), and got back to FERwhere he has been employed as an assistant involved in teaching and research. In 1993 he was with two companies in Zagreb, Optima O.S.N. and TIS d.d. His primary occupation in these companies was related to software engineering. In 1994 he had returned to FER and began a Ph.D. study. During 1995 and 1996 he spent six months in Ericsson New Zealand in Wellington working on problems related to mobile telephony. In May 1996 he returned to FER. Since 2000 he has been assistant professor. He is a coauthor of one textbook. His research interests are in transmission media characteristics and analyses, modulations and line coding, in multiple access technologies used in local area networks and in technologies related to lowest two layers of OSI reference model.

Dinko Begušić was born in Split, Croatia, in 1960. He received M.Sc.E.E. degree from University of Zagreb in 1988, and Ph.D. degree from the same university in 1992. He is a full professor of the University of Split, Faculty of electrical engineering, where he was carrying several duties as vice-dean, or head of department. From 2001 he is serving as commissioner at the Telecommunications Council, the national regulatory authority for telecommunications.