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EXPERIMENTAL MEASUREMENTS FOR VERIFICATION OF THE PARAMETRIC MODEL FOR REFERENCE CHANNELS IN THE REAL PLC ENVIRONMENT

Rastislav Róka — Juraj Urminský *

For the expansion of power line communication (PLC) systems, it is necessary to have a detailed knowledge of the PLC transmission channel properties. Their understanding represents the basics in a way of searching for the most powerful PLC data transmission systems. Then, power lines would be able to provide popular services such as an Internet access or in-home/office networking at minimal costs. This contribution briefly discusses the PLC environment and a classification of PLC transmission channels. Also, characteristics of the parametric model for reference channels are described. A main part of our contribution is focused on the presentation of experimental measurements for verification of the parametric model for PLC reference channels in the real PLC environment. Presented information represents a reach enough knowledge base for the design of the PLC modem that can be used for practical deployment of the PLC data transmission.

K e y w o r d s: PLC environment, parametric model of the PLC transfer function, PLC reference channels

1 INTRODUCTION

In foregone years, an interest of telecommunication operators and various research groups led to different solutions in the area of access technologies. Basically, a solution with low costs and fast economic return of investment is looked for. An idea to utilize power distribution lines for data signal transmission is not at all new. Electrical lines of energy companies have been using for management information transmission between a control center and an electric power station for nearly 100 years. But this information exchange never reached over tens of kilobits per second. Data transmission systems can be divided into two large groups. The first group is established by systems used by energy companies (CTP, RCS). The second group incorporates equipment utilized in households for home automation (X10, CEBus, LonWorks). One of these solutions called the power line communication (PLC) is very interesting for operators. Its main advantage is an almost establishing access network, therefore only equipments and measurements on power distribution lines create initial costs. Because power distribution lines were proposed for high frequency signal transmission, there are many problems to be solved. One of the solutions for overcoming problems related to various noise types is to propose such a PLC modem that is able to resist negative environmental influences.

2 THEORY

2.1 The PLC environment and classification of PLC transmission channels

The PLC transmission environment is precisely presented in [1]. As mentioned above, the noise scenario in this PLC environment is very complicated since five general types of noise can be distinguished in power distribution line channels [2, 3]. These five types are (Fig. 1):

1. Coloured background noise — caused by summation of numerous noise sources with low powers. Its PSD varies with frequency in the range up to 30 MHz (significantly increases toward to lower frequencies) and also with the time in terms of minutes or even hours.
2. Narrow-band noise — caused by ingress of broadcasting stations. It is generally varying with daytimes and con-

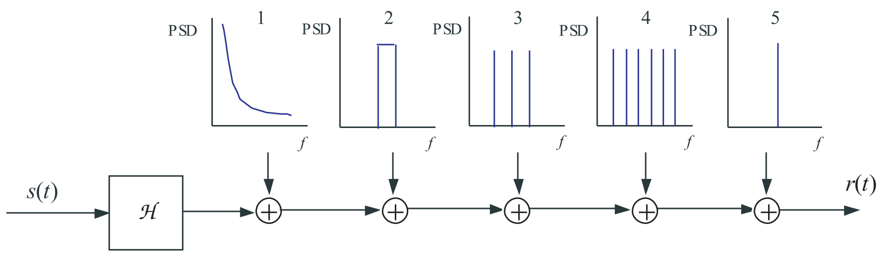

Fig. 1. The noise types in the PLC environment

* Department of Telecommunications, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia; rastislav.roka@stuba.sk, juraju@hotmail.com

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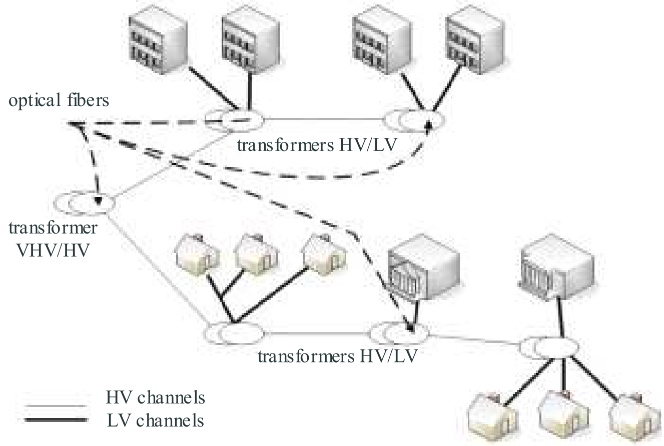

Fig. 2. The noise types in the PLC environment

sists mostly of sinusoidal signals with modulated amplitudes.

3. Periodic impulsive noise asynchronous with the main frequency — caused by switched power supplies and AC/DC power converters. Its spectrum is a discrete line spectrum with a repetition rate in the range between 50 and 200 kHz.
4. Periodic impulsive noise synchronous with the main frequency - caused by rectifiers located in the power supplies operating synchronously with the main cycle. Its PSD is decreasing with frequency and the repetition rate is 50 Hz or 100 Hz.
5. Asynchronous impulsive noise - caused by impulses generated by the switching transients events in the network. It is considered as the worst noise in the PLC environment because of its magnitude that can easily reach several dB over other noise types.

The noise types 1, 2 and 3 can be summarized as background noises because they remain stationary over periods of seconds and minutes, sometimes even of hours. On the contrary, the noise types 4 and 5 are time-variant in terms of microseconds or milliseconds and their impact on useful signals is much stronger and may cause single-bit and/or burst errors in data transmission. Time and domain analyses of impulse noises can be found in [2].

Characteristics of the PLC transmission channel are dependent on the features of the power distribution line network and on the line type. The PLC channel can be classified according to available voltage as follows:

- Channel with a very high voltage (VHV) — this PLC channel has good transmission facilities thank to low noise levels and no-frequent failures on the line. Low noise levels are given mainly by a low number of connections that can cause reflections on the line due to imperfect matching of impedance. (Therefore, the multi-path effect can be neglected.) However, the VHV channel is not used as a data signal transmission line, only as a supporting line for bundles of optical fibers.
- Channel with a high voltage (HV) — this PLC channel is used for data signal distribution in the point-to-point topology. The HV channel is not good as the VHV channel but its transmission facilities are almost maintained along the whole line length.
- Channel with a low voltage (LV) — this PLC channel is used for data signal distribution in the point-to-multipoint topology. The LV channel is utilized for power distribution in houses, flats, buildings, *etc.* In these locations, there are usually many points with imperfect matching of impedance. Therefore, the noise level can be increased and the information signal could be damaged. Also, the multi-path effect is self-evident. In Fig. 2, an example of the power distribution line network with the HV and LV channels is presented

On the basis of the above-mentioned characteristics of PLC channels, it is possible to observe a specific similarity between PLC and radio channels that is included in Tab. 1.

Table 1. An analogy between PLC and radio channels

	The radio channel	The PLC channel
A multi-path signal propagation	Reflections from barriers	Points with imperfect matching of impedance
A temporal variability of the transmission channel	User movement — Dopplers dispersion	Impedance is alternating with alocation

Table 2. Parameters of the RC1 reference channel, $k = 1$, $a_0 = 0$, $a_1 = 1.5 \times 10^{-9}$ (m/s)

N	1	2	3	4	5
g_i	0.6	−0.08	0.08	−0.08	0.15
l_i [m]	100	130	160	190	300

Table 3. Parameters of the RC2 reference channel, $k = 1$, $a_0 = 0$, $a_1 = 2.5 \times 10^{-9}$ (m/s)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
g_i	0.103	0.029	0.043	−0.058	−0.045	−0.040	0.038	−0.038	0.071	−0.035	0.065	−0.055	0.042	−0.059	0.049
l_i [m]	113.2	90.1	101.8	143	148	200	260	322	411	490	567	740	960	1130	1250

Table 4. Parameters of the RC3 reference channel, $k = 1$, $a_0 = 0$, $a_1 = 4.5 \times 10^{-9}$ (m/s)

N	1	2	3	4	5	6	7	8	9	10	11	12
g_i	0.17	0.25	−0.1	−0.12	0.33	−0.37	0.18	−0.2	0.05	−0.15	0.15	0.15
l_i [m]	211.5	228	243	254	278	306	330	360	390	420	540	740

2.2 Characteristics of the parametric model for reference channels

Characteristics of the PLC transmission environment focused on the multi-path signal propagation, the signal attenuation, the noise scenario and the electromagnetic compatibility are introduced in [1]. The main part of this contribution is experimental measurements for verification of the parametric model for various reference channels in a real topology of power distribution networks. First, we present a basic parametric model for the PLC channel with appropriate characteristics for each reference channel.

The frequency response (the transfer function $\mathfrak{H}(f)$) of a transmission line length l can be expressed as follows ($\mathfrak{U}(x)$ is the voltage phasor at the distance x):

$$\mathfrak{H}(f) = \frac{\mathfrak{U}|_{(x=l)}}{\mathfrak{U}_{(x=0)}} \propto \left[e^{-\gamma(f)l} + \mathfrak{r}(f)e^{\gamma(f)l}\right] \qquad \text{where} \quad e^{\pm\gamma(f)l} = e^{\pm\alpha(f)l} + e^{\pm j\beta(f)l}. \tag{1}$$

Here the frequency dependent complex parameter $\mathfrak{r}(f)$ is the so called reflection coefficient determined by the line-load impedance matching conditions. [8] Considering frequencies in the megahertz range, the resistance R per length unit is dominated by the skin effect and thus is proportional to $\sqrt{f}$. The conductance G per length unit is mainly influenced by the dissipation factor of the dielectric material (usually PVC) and therefore proportional to f. With typical geometry and material properties, we can suppose $R \ll \omega L$ and $G \ll \omega C$ in the frequency range of interest. Then, cables can be regarded as low lossy with real valued characteristic impedances and a simplified expression for the complex propagation constant γ can be introduced

$$\gamma(f) = k_1\sqrt{f} + k_2 f + j\,k_3 f = \alpha(f) + j\,\beta(f) \tag{2}$$

where constants k_1, k_2 and k_3 are parameters summarizing material and geometry properties. Based on these derivations and an extensive investigation of measured frequency responses, an approximating formula for the attenuation factor α is found in form

$$\alpha(f) = a_0 + a_1\, f^k \tag{3}$$

that is able to characterize the attenuation of typical power distribution lines with only three parameters, being easily derived from the measured transfer function [4]. Parameters a_0, a_1 and k are characterized by measurements of the transfer function $\mathfrak{H}(f)$ that is much easier than the measurement of primary line parameters R, L, C, G. If we now merge signal spreading along all paths together (we can use a superposition — provided the reflection coefficients can be neglected) we will receive an simplified expression for the frequency response $\mathfrak{H}(f)$ in the form

$$\mathfrak{H}(f) = \sum_{i=1}^{N} g_i\, a(l_i, f)\, e^{-j\,2\pi f \tau_i} \tag{4}$$

where $a(l_i, f)$ is the signal attenuation proportioned with the length and the frequency and N is the number of paths in the transmission channel. It can be supposed that the formula for delay τ_i of a transmission line can be expressed, according to [8], by using the dielectric constant ε_r of insulating materials, the light speed c_0 and the line length l_i as follows:

$$\tau_i = \frac{l_i\sqrt{\varepsilon_r}}{c_0}\,. \tag{5}$$

The parametric model for the PLC channel can be adapted for any topology of the power distribution network. Parameters of this model with various coefficients were presented in ETSI Technical Specifications TS 101 761-1 [5] and TS 101 475 [6] and the following set of reference channels for a practical utilization was established:

- *Reference channel* 1 (RC1) — a channel between transformer stations with features of the HV channel. The distance between separate transformer stations is around 1000 m.
- *Reference channel* 2 (RC2) — a channel from the transformer station up to the main circuit breaker, the distance is approximately 150 m.
- *Reference channel* 3 (RC3) — a channel from the main circuit breaker up to the counting box of consumed energy in the house, a distance is maximum 250 m.
- *Reference channel* 4 (RC4) — a home scenario.

For the presented parametric model, parameters for various PLC reference channels were assumed from the

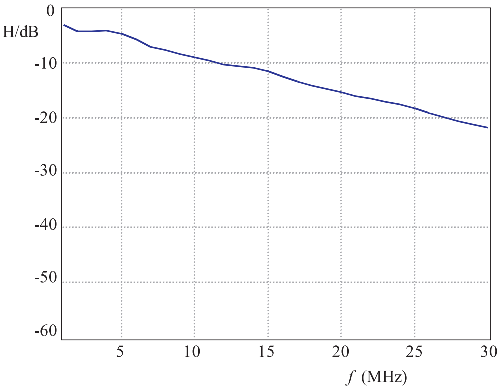

Fig. 3. The frequency response of the RC1 channel

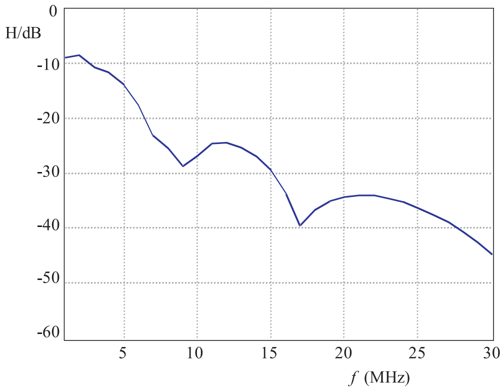

Fig. 4. The frequency response of the RC2 channel

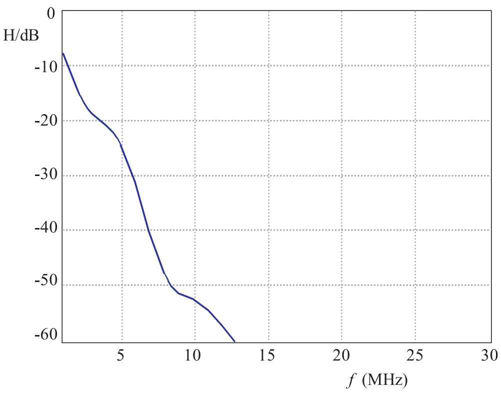

Fig. 5. The frequency response of the RC3 channel

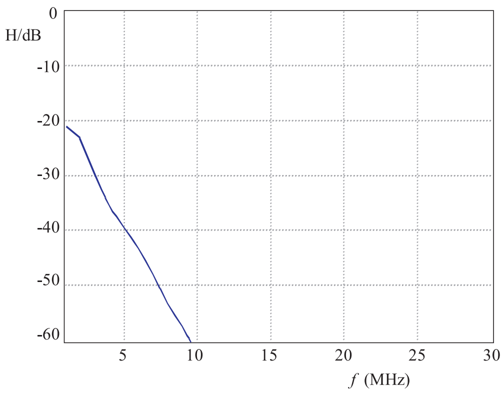

Fig. 6. The frequency response of the RC4 channel

Table 5. Parameters of the RC4 reference channel, $k = 1$, $a_0 = 8 \times 10^{-3}$, $a_1 = 3.5 \times 10^{-9}$ (m/s).

N	1	2	3	4	5
g_i	0.26	0.05	-0.3	0.25	-0.35
l_i [m]	300	350	370	450	510

paper [4]. In spite of their simplification, it is still accurate enough for the PLC system performance analyses. The values of parameters like k, a_0, a_1, g_i, l_i (k, a_0, a_1 are attenuation factors, g_i is weighting factor and finally l_i means the length of i-th line branch) for the multi-path signal propagation in reference channels can be found in Tabs. 2, 3, 4 and 5. Computer simulations at appropriate frequency characteristics of particular reference channels used values from a specific table. These frequency responses are graphically shown in Figs. 3, 4, 5, and 6.

3 EXPERIMENTS

For verification of the defined values for the reference channel parameters, measurements on real PLC channels in the following environments were executed:

1. The 4-floor family house (3 phases)
2. The apartment (1 phase)

We realized a measurement of the transmission channel characteristics and also a measurement of the channel throughput. A detailed scheme of the measurement procedure was introduced in [7]. At the transmitting side, a signal generator SMIQ from Rohde & Schwarz was used to generate signals with a frequency range from 1 MHz up to 35 MHz. At the receiving side, a network analyzer was located. In addition to these measuring accuracy devices, a capacitance coupler was used to segregate devices from the power distribution network. Needfulness for utilization of this coupler is outgoing from the demand to avoid the 50 Hz signal penetration into measuring devices and so to prevent wrong operations. In the following parts, results from measurements are presented in more detail.

3.1 Measurements in the 4-floor family house

In Fig. 7, a detailed scheme of the family house with four floors is presented and 10 measuring points A – J are displayed.

Measurements were realized first between appropriate points on the same floor, then between appropriate floors. In some cases, two various current phases were located on the same floor, so the data signal must be propagated from the contact plug to the main power line distributor and back to the other contact plug. These specific cases were therefore distorted.

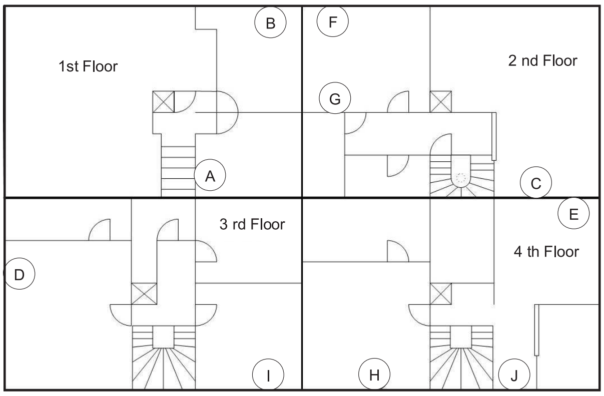

Fig. 7. The 4-floor family house with displayed measuring points

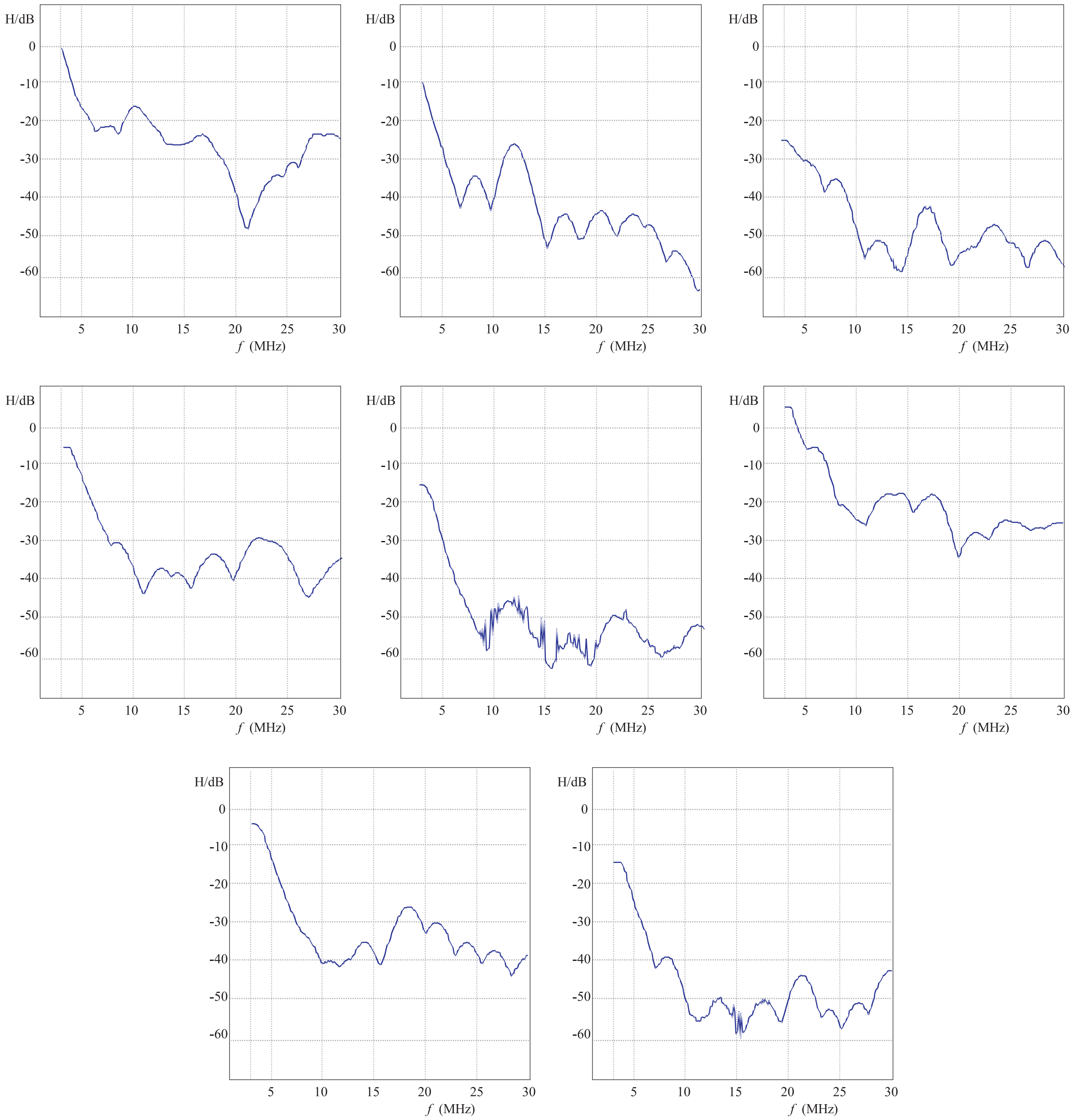

Fig. 8. Frequency responses between particular measuring points in the family house

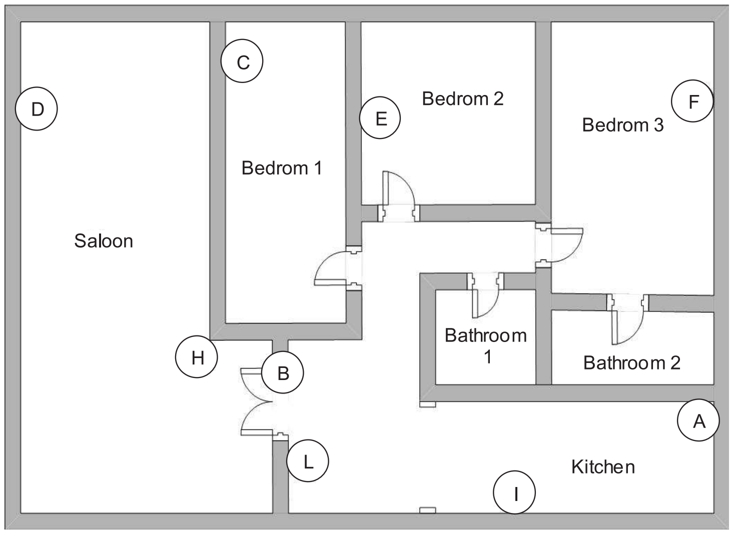

Fig. 9. The apartment with displayed measuring points

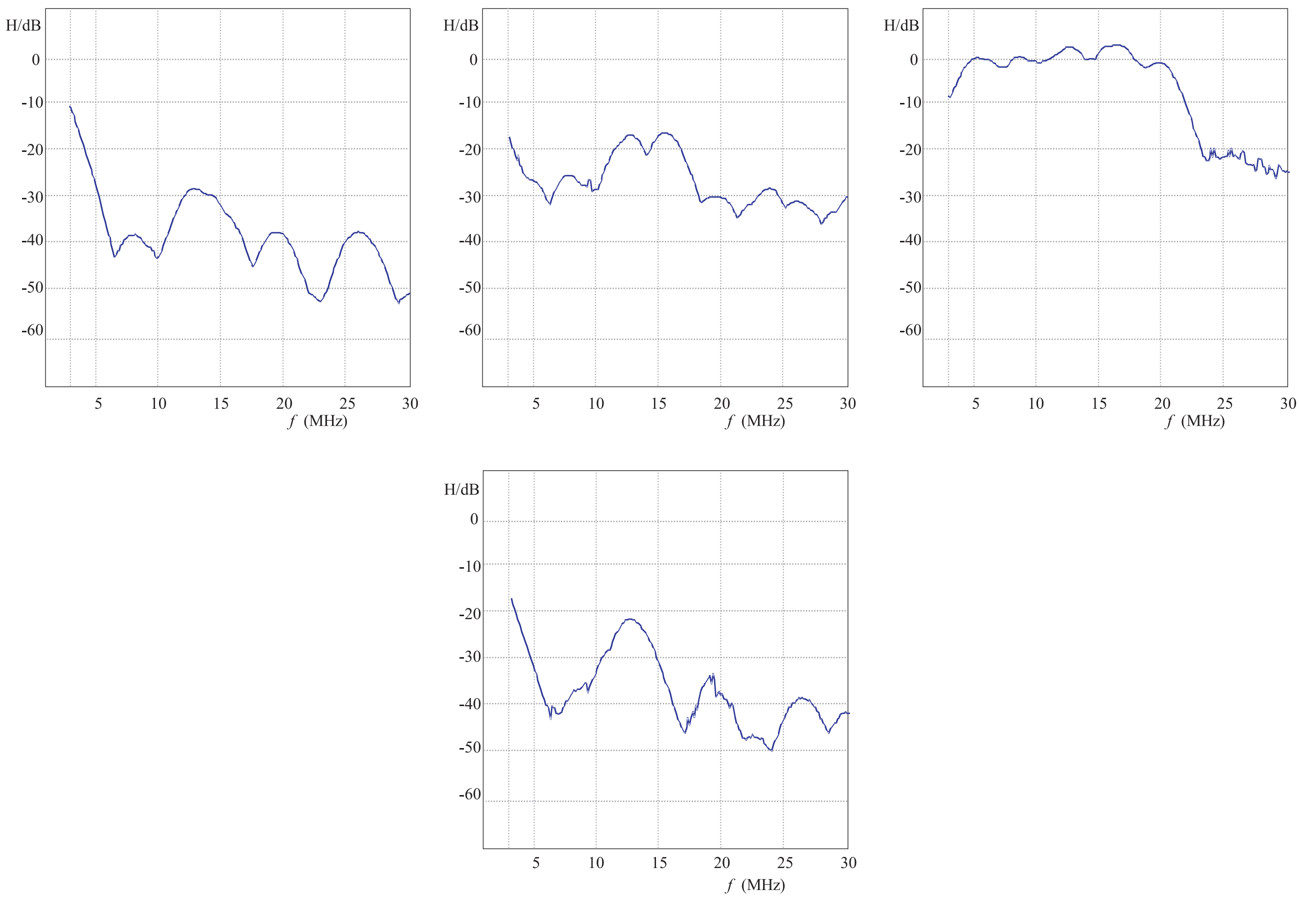

Fig. 10. Frequency responses between particular measuring points in the family house

Measurements with correct results are presented in Fig. 8. As can be seen, the signal attenuation and the multi-path effect are clearly evident in various cases. In cases A–E, E–F, the data signal was propagated twice between the plugs and the main power line distributor. A majority of cases is very similar to those from the RC2 and RC3 reference channels. It means that power distribution lines have too many sections with imperfect matching of impedance that can cause signal reflections. In this way, the level of the signal attenuation at specific frequencies is increased.

3.2 Measurements in the apartment

Measurements with correct results are presented in Fig. 10. Again, our measurements confirm assumptions that the signal attenuation is directly proportional to the distance. In comparison with the 4-floor flat, distances between the measuring points are shorter, therefore the signal attenuation is smaller. As in the first case, a majority of cases is very similar to those from the RC2 and RC3 reference channels.

4 CONCLUSIONS

In spite of problems with high-frequency signal transmission, power distribution lines remain a very interesting transmission medium. Therefore, it is necessary to evolve a technology that is able to overcome various noises and interferences incident in the PLC environment.

We realized experimental measurements for verification of the parametric model for reference channels in the real PLC environment. With respect to the transfer functions decreasing linear performance in the measured frequencies range where the number of imperfect matching points is minimum. Transfer functions have been measured in different electrical paths between the measuring points in a 4-floor family house and an apartment. One can conclude that if the line length path grows, it is more probable that the number of reflections produced by imperfect matching points grows too. Moreover, the transfer function slope increase in the lower frequencies is proportional to the line length.

It is necessary to emphasise the great importance of a correct location planning of the PLC communication networks so as to obtain a better performance of the PLC data transmission system. Results of our measurements can be used for verifying the proposed PLC simulation model. After demonstrating its suitability for searching for the most appropriate digital signal processing techniques, which belongs to critical requirements of the development of the next generation PLC communication systems with higher data rates, it is possible to continue in the design and realization of the extended PLC modem.

Appendix — Abbreviations

AC	Alternating Current
DC	Direct Current
HV	High Voltage
LV	Low Voltage
PLC	Power Line Communication
PSD	Power Spectral Density
RC	Reference Channel
VHV	Very High Voltage

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Rastislav Róka (Ing, PhD) was born in Šaľa, Slovakia on January 27, 1972. He received his MSc and PhD degrees in telecommunications from the Slovak University of Technology, Bratislava, in 1995 and 2002. Since 1997, he has worked as a senior lecturer at the Department of Telecommunications, FEI STU, Bratislava. At present, his research activity is focused on the high-speed signal transport through wirelined access networks by means of xDSL technologies using various techniques of digital signal processing.

Juraj Urminský (Ing) was born in Topoľčany, Slovakia on August 19, 1981. He received his BSc degree in informatics from the Slovak University of Technology, Bratislava, in 2003 and MSc. degree in the telecommunications from the Slovak University of Technology, Bratislava, in 2006.