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PAPERS

Experimental measurements for evaluation of the network throughput of the RC4 channel in the in-home PLC network

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For the expansion of in-home PLC networks, it is necessary to have a detailed knowledge of the PLC transmission channel properties. This contribution shortly discusses theoretical characteristics of the RC4 reference channel. A main part is focused on the network throughput and on the interphase PLC signal liaising presented in the RC4 reference channel for higher frequencies than 10 MHz. For evaluation of considered transmission parameters, experimental measurements related to various noise sources and to interactions between different phase conductors are realized in the real in-home PLC network.

Keywords: in-home PLC network, RC4 reference channel, network throughput, noise sources, interphase signal liaising

1 Introduction

Characteristics of power line communication (PLC) transmission channel are dependent on features of the power distribution network and on the line type [1], [2], [3]. The PLC channel with a low voltage (LV) is used for a data signal distribution in the point-to-multipoint topology. The LV channel is utilized for a power distribution in houses, flats, buildings, etc. In these locations, there are usually many points with imperfect matching of impedance. Also, the multi-path effect is self-evident. Therefore, an influence of noise sources can be increased and the signal transmission could be disabled. Parametric models for PLC channels are possible to adjust to any topology of the power distribution network [3,4]. For a practical utilization in the in-home PLC network, the reference channel 4 (RC4) representing a link typically found in residential areas without significant regular network structures and with strong branching can be considered [5-7].

2 Theory

We focus on a parametric model for the RC4 reference channel in a real utilization of power distribution lines within the in-home PLC infrastructure. The RC4 reference channel can be represented by a link with shorter lengths and less branches than other 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 [4], [8].

Based on these derivations and extensive investigation of measured frequency responses, the approximating formula with only three parameters was chosen for attenuation factor

$$\alpha(f) = a_0 + a_1 f^k \tag{1}$$

this can be easily derived from the measured transfer function [1-2]. Parameters a_0, a_1 and k are specified by the measurements of transfer function $\mathcal{H}(f)$ rather than by measured primary line parameters R', L', C', G'. If we now superimpose the signals spreading on all paths we receive an expression for the frequency response $\mathcal{H}(f)$

$$\mathcal{H}(f) = \sum_{i=1}^{N} g_i a(l_i, f) \exp\left(-j2\pi f \tau_i\right) \tag{2}$$

where $a(l_i, f)$ - is the signal attenuation proportioned to the length and the frequency and N is the number of paths in the transmission channel.

For a computer simulations of the PLC transmission channels one can utilize the values from specific tables introduced in [1]. The values of parameters k, a_0, a_1, g_i, l_i, (k, a_0, a_1 are attenuation factors, g_i is the weighting factor and finally l_i is the length of i-th line branch) for the multi-path signal propagation in the RC4 reference channel are presented in Tab. 1. The RC4 frequency response is graphically shown in Fig. 1. Because of the numerous branches, this link exhibits a high attenuation, especially in the region over 10 MHz. However, a high attenuation cannot be compensated by the signal power enhancement for reasons of the electromagnetic compatibility (EMC), [8-9]. Therefore, the frequency domain of the RC4 reference channel will be practically utilizable up to 10 MHz without serious problems at the information signal transmission.

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

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

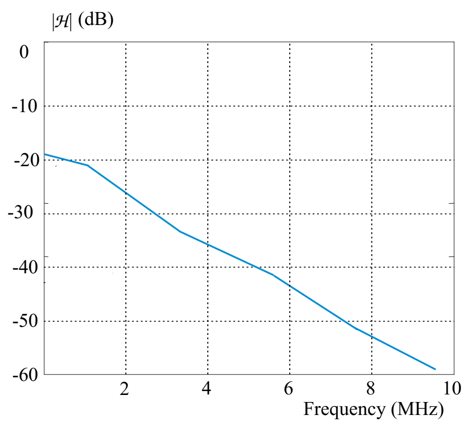

Fig. 1. The frequency response of the RC4 reference channel

Except the frequency response, noise sources and signal liaising can markedly influent the transmission parameters of the RC4 reference channel for higher frequencies than 10 MHz. Therefore, we focused also on a design of a measurements using PLC equipment with regard to the evaluation of theoretical network throughput and functionality of end-user devices in various application conditions in the in-home PLC network. The designed measurement for higher frequency domains were divided into two parts - the network throughput at different noise sources representing various types of the impulse noise and the interphase liaising of PLC signals. In the first measurement, the influence of particular noise sources on the network transmission features is examined. In the second measurement, conditions of the interphase signal liaising between two connections created by PLC modems are determined. Experimental measurements were done in two types of PLC modems - the HD 200 modem (frequency range to 30 MHz) and, the HAV 500 modem (frequency range even up to 68 MHz) [12-13].

Transmission parameters of the in-home PLC network are evaluated by the IxChariot software. IxChariot is the simulation program that can create a virtual traffic in the real network between several network elements with assigned IP addresses and, subsequently, to evaluate network parameters in both real and simulation traffic.

After the program initialization, the traffic type (VoIP, IPTV, ...), IP addresses for end-user equipment, the active network protocol (RTP, TCP, UDP, ...), the measuring period and measured transmission parameters must be selected. Moreover, other settings of advanced parameters can be executed.

1 Measurements of the network throughput

Measurements of the PLC network throughput are realized in the single family house on created the in-home PLC network, Fig. 2. In the course of measurements, all domestic electrical appliances are pulled out power sockets. In this measured network, only PLC modems and noise sources are connected.

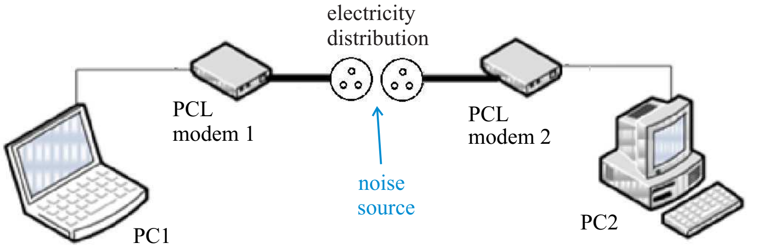

Fig. 2. The basic scheme for measurements of the PLC network throughput

Individual PLC modems have default IP addresses that can be easily changed using an internet browser. The first PLC modem (PLC modem 1) is set up the endpoint, the second one (PLC modem 2) presents the fixed access point. Addresses of end-user equipment and a subnetwork mask are adjusted in Windows using IPv4 settings. By the means of the Power Packet Utility program, more advanced settings of PLC modems can be realized [12-13].

3.1 Measurements without noise sources

These measurements create a reference base for comparing with measured values from other measurements. There are realized two reference measurements.

In the first case, PLC modems are directly connected into a socket of the electricity distribution. For HD 200 modems, the average total throughput of the PLC network is 78.9 Mbit/s. Fig. 3 shows a time behavior of 10 used data streams. TCP streams have multiple less values of the transmission rate than UDP stream due to confirming of UDP packets in contrast to TCP packets.

For HAV 500 modems, transmission rates are rapidly increased. The average total throughput of the PLC network is 222.5 Mbit/s. Fig. 4 shows a time behavior of 10 used data streams.

In the second case, PLC modems are connected to the extension cable that has a negative influence with minimal values due to its intrinsic environment. This extension cable is connected into a socket of the electricity distribution. Figure 5 shows a time behavior of data streams in the PLC network for HD 200 modems, the average total throughput is 69.1 Mbit/s. Figure 6 shows a time behavior of data streams in the PLC network for HAV 500 modems, the average total throughput is 216.2 Mbit/s.

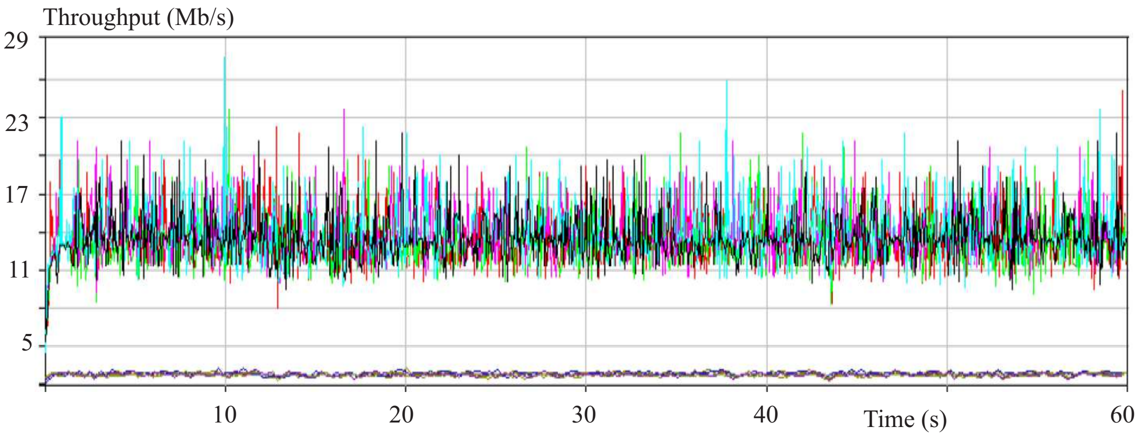

Fig. 3. The network throughput of directly connected HD 200 modems without noise sources

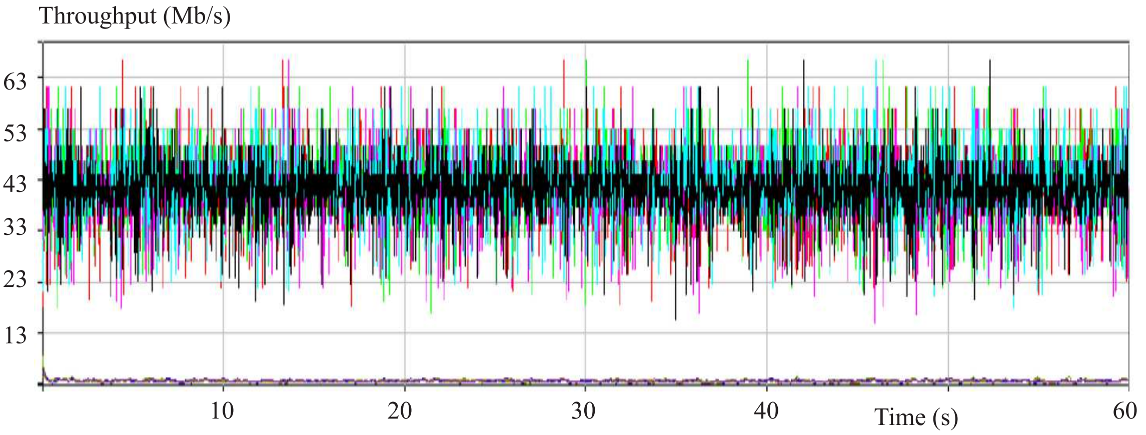

Fig. 4. The network throughput of directly connected HAV 500 modems without noise sources

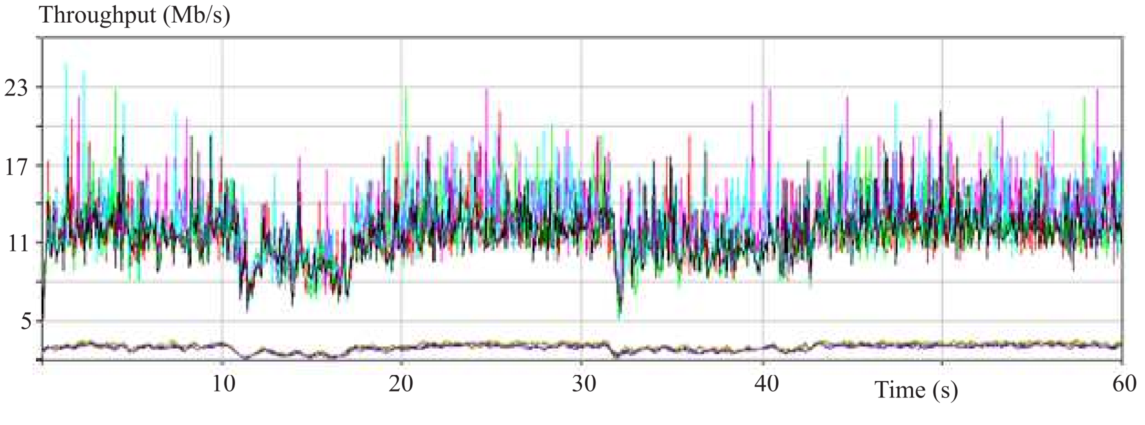

Fig. 5. The network throughput of HD 200 modems connected through the extension cable without noise sources

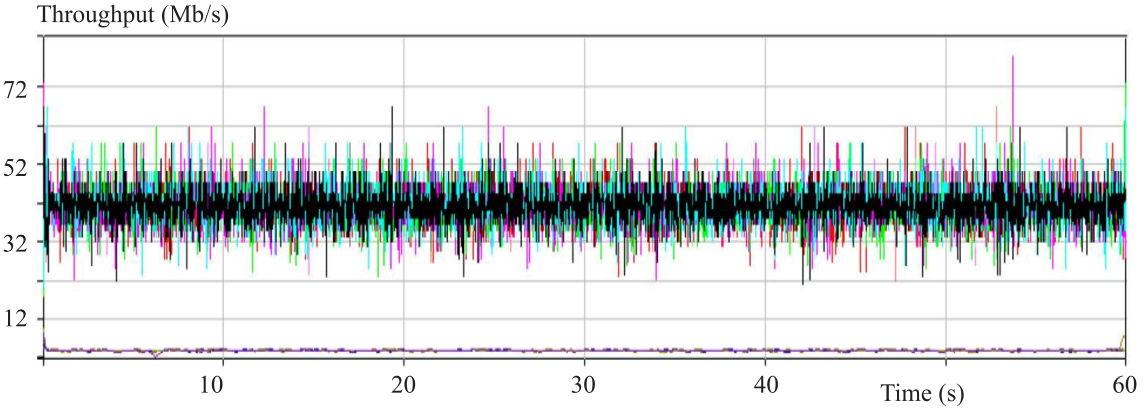

Fig. 6. The network throughput of HAV 500 modems connected through the extension cable without noise sources

Table 2. Values of PLC network throughputs at various noise sources for HD 200 modems

Noise sources	The direct connection to the socket (Mbit/s)	%	The connection through the extension cable (Mbit/s)	%
No load	78.9	100	69.1	100
Cell Phone Charger	48.7	61.7	36.9	53.4
Notebook Adapter	74.2	94.6	61.5	89.0
Vacuum Cleaner	78.4	99.3	65.8	95.2

Table 3. Values of PLC network throughputs at various noise sources for HAV 500 modems

Noise sources	The direct connection to the socket (Mbit/s)	%	The connection through the extension cable (Mbit/s)	%
No load	222.5	100	216.2	100
Cell Phone Charger	148.7	66.8	133.5	61.7
Notebook Adapter	211.1	94.9	201.4	93.2
Vacuum Cleaner	217.4	97.7	211.8	98

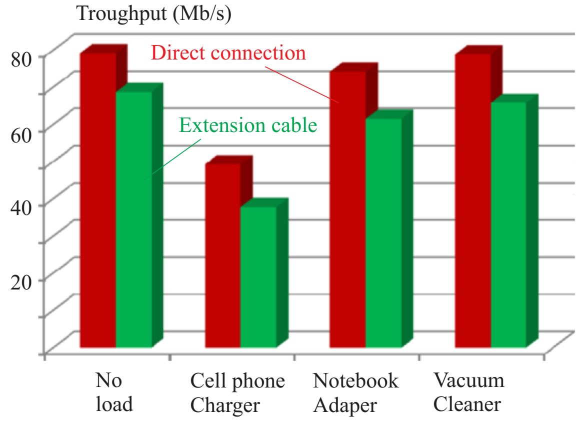

Fig. 7. The PLC network throughput with various noise sources at HD 200

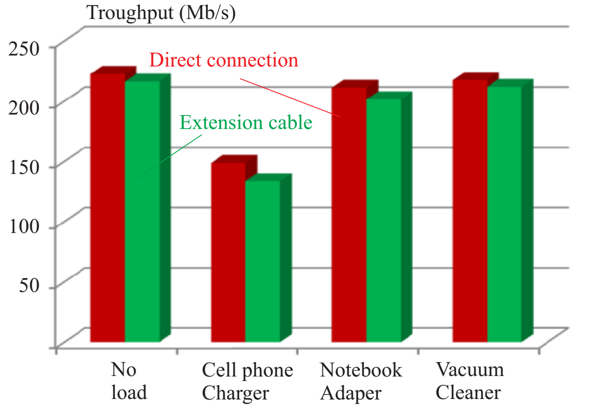

Fig. 8. The PLC network throughput with various noise sources at HAV 500

3.1 Measurements with noise sources

All used noise sources are connected into the electricity distribution through a neighboring socket located between sockets for connecting PLC modems in the in-home network, Fig. 2. All sockets are working on the same phase conductor.

The first noise source, the cell phone charger has an extreme influence on the network throughput realized using HD 200 modems. The average value of this network throughput is 48.7 Mbit/s at the cell phone charger directly connected into the neighboring socket. At the connection to the electricity distribution through the extension cable, the transmission capacity is decreased to the 36.9 Mbit/s. Comparing with reference values, a degradation is around 30 Mbit/s in both cases. This noticeable decrement of transmission rates is due to high-frequency impulses outgoing the charger impulse source. Just the periodical impulse noise asynchronous to the AC frequency presents the biggest barrier for PLC modems.

HAV 500 modems are also predisposed to the impulse noise originating from the cell phone charger. This noise source causes a degradation of the total PLC network throughput nearly about 80 Mbit/s in both connections. In a case of the direct connection to the socket, the actual network throughput is 148.7 Mbit/s. For connection through the extension cable, its value is a little bit lower with the 133.5 Mbit/s value. Based on these data, it is obvious that also newer PLC modems cant absolutely eliminate influences of the periodical impulse noise asynchronous to the AC frequency.

Another noise source, the notebook adapter with the 65 W output power representing the periodical impulse noise synchronous to the AC frequency has a minimal influence on the PLC network throughput. Comparing with reference values, the network throughput decreases only moderate. In a case of the direct connection to the socket, the actual network throughput is 74.2 Mbit/s. For connection through the extension cable, its value is a little bit lower with the value 61.5 Mbit/s. This measurement presents that the notebook adapter has only a very small, almost negligible influence on the throughput in the PLC network realized using HD 200 modems.

At the measurement with HAV 500 modems, results are similar like in a previous case. The used notebook adapter has a minimal influence on the network throughput. Actual values of the network throughput are 211.1 Mbit/s in the first case, respectively 201.4 Mbit/s in the second case.

The last noise source, the vacuum cleaner is used for evaluation of the asynchronous impulse noise outgoing from the induction motor with the 2000 W power. Comparing with reference values, the network throughput remains nearly unchanged. For direct connection to the socket, the actual network throughput is 78.4 Mbit/s. For connection through the extension cable, its value is 65.8 Mbit/s. So, this measurement presents that the vacuum cleaner has only a minimal influence on the throughput in the PLC network realized using HD 200 modems that is incognizable from a viewpoint of the PLC network operation.

At the measurement with HAV 500 modems, the PLC connection is not subject of interferences Actual values of the network throughput are 217.4 Mbit/s in the first case, respectively 211.8 Mbit/s in the second case. Based on these data, it is obvious that also newer PLC modems are in substance resistant to the asynchronous impulse noise.

As can be seen in Tab. 2 and in Fig. 7, the lowest PLC network throughput is reached by influencing the cell phone charger. From other noise sources, the vacuum cleaner has the smallest influence and its values of the network throughput are nearly equal to reference values.

As can be seen in Tab. 3 and in Fig. 8, the highest influence on the PLC network throughput is achieved utilizing the cell phone charger. Values of the network throughput influenced by other noise sources are changing minimally and present negligible variances comparing to reference values without noise sources.

On cue, measurements of the in-home PLC network throughput on connections created using newer HAV 500 modems achieve several higher values than measurements using older HD 200 modems. However, these values dont accomplish values reported by the manufacturer that represent theoretical values of the transmission rate reachable only at ideal conditions. For both PLC modem types, various noise sources have a comparable influence. The highest influence has the cell phone charger as a noise sources representing the periodical impulse noise asynchronous to the AC frequency that can bring a decrease of the network throughput up to 40%. Other noise sources have no expressive influences on the network throughput of the in-home PLC network.

4 Measurements of the interphase signal liaising

In some cases of real in-home PLC network installations, we can meet a specific collateral phenomenon/effect between different PLC connections. This effect is caused by an authentic installation of power distribution lines in a form inadequate for the PLC signal transmission. Due to a physical propinquity of various phase wires in the neighboring area, specific interphase signal liaising can arise.

The interphase signal liaising is due to used high-frequency in RC4 reference channel (tens of MHz) and, the electro-magnetic radiation; signal comes over one conductor to other. The aim of measurements was to determine the conditions for mutual interactions of adjacent in-home PLC networks using modems connected into the electricity distribution through the sockets using different lines.

The scheme for the interline PLC signal liaisings measurement is shown in Fig. 9. The PLC network is created by two PLC modems (M1, M2) that are interconnected with corresponding notebooks (PC1, PC2) using the network cables. Both systems are fed by power lines L1 and L2.

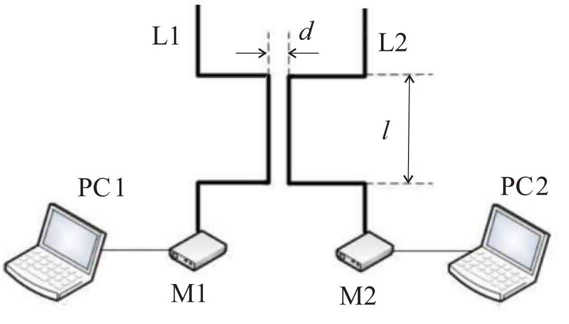

Fig. 9. The measurement scheme for the interphase PLC signal liaising

The aim of the first measurement was to determine a minimum length (l) of closely aligned lines (L1, L2) at equal separation ($d \to 0$ cm) necessary for a possible interline PLC signal interference. The response time for the ping-echo request was measured for both directions of the PC communication.

Acquired average response time with the packet loss and the connection establishment are presented in Tab. 5.

It follows, that with the increasing length of power lines aligned in parallel, the response time is progressively decreasing.

The optimal length of a parallel connection between two power lines at small fixed distance ($d \to 0$ cm) is more than 2 m. Logically, longer the parallel power lines, the better time responses between endpoints. For 5 and more meters, transmission parameters in the in-home PLC network are already changeless.

Table 4. Liaising of the interline signal for different length (l) of parallel lines (with fixed distance, $d \to 0$ cm)

Parallel connection l (m)	HD 200 PC1→PC2 (ms)	HD 200 PC2→PC1 (ms)	HD 200 Packet Loss %	HD 200 Con.	HAV 500 PC1→PC2 (ms)	HAV 500 PC2→PC1 (ms)	HAV 500 Packet Loss %	HAV 500 Con.
0.5	∞	∞	100	N	∞	∞	100	N
1	∞	∞	100	N	2848	3012	24	Y
1.1	1825	1714	29	N	1203	1074	9	Y
1.2	1451	1612	18	Y	1311	817	0	Y
1.3	1078	946	6	Y	822	759	0	Y
1.4	541	498	0	Y	378	376	0	Y
1.5	485	311	0	Y	142	151	0	Y
2.0	14	12	0	Y	7	3	0	Y
3.0	6	5	0	Y	4	3	0	Y
5.0	2	2	0	Y	2	2	0	Y

Table 5. Liaising of the interline signal for different distance (d) of parallel lines (with fixed length $l = 5m$)

Mutual distance d (cm)	HD 200 PC1→PC2 (ms)	HD 200 PC2→PC1 (ms)	HD 200 Packet Loss %	HD 200 Con.	HAV 500 PC1→PC2 (ms)	HAV 500 PC2→PC1 (ms)	HAV 500 Packet Loss %	HAV 500 Con.
0	2	2	0	Y	2	2	0	Y
1	2	2	0	Y	2	2	0	Y
2	4	3	0	Y	2	2	0	Y
3	17	19	0	Y	11	8	0	Y
4	116	101	0	Y	94	107	0	Y
5	742	859	6	Y	524	712	2	Y
6	1814	2427	23	Y	1158	1747	31	Y
7	∞	∞	100	N	∞	∞	100	N

The aim of the second measurement was to determine a maximum distance (d) of two different power line conductors when the PLC signal is capable of liaising. Based on the previous measurements, the length of wires connected in parallel was set to $l = 5$ m. This length is sufficient for PLC signal transition from L1 to L2 phase and backwards. The network element configuration is the same as in a previous measurement.

Acquired average response times with the packet loss and the connection establishment are presented in Tab. 5.

It follows from the results that with the increasing distances between two different power lines conductors, the response time is progressively increasing. For $d > 4$ cm, the delay increases and simultaneously the transmission rate decreases approaching to values impermissible for the PLC signal transmission.

From measurements of the PLC signal liaising between different power lines, it results that PLC modems are able cooperate if fed by connections using different power line. However, some conditions must be fulfilled.

For HD 200 modems, the line wires must be aligned at least at $l = 3$ m while their separation does not exceed $d = 2$ cm, to provide conforming connection at the 50 Mbit/s transmission rate.

For HAV 500 modems, the line wires must be aligned at least at $l = 2$ m while their separation does not exceed $d = 3$ cm, to provide conforming connection at the 150 Mbit/s transmission rate.

For values exceeding considered limits, the interphase PLC signal liaising is not in progress. Based on measurement values, we can determine when different in-home PLC networks working on different phase wires can suffer from the interphase signal liaising.

5 Conclusions

For any communication technology, the most important object is achieving the certain limits for significant transmission parameters, above all the network throughput, the transmission rate, the delay and the packet loss.

All experimental measurements were executed at various diverse conditions in the real in-home PLC network realized with HD 200 and HAV 500 modems. The first measurement is focused on the different noise sources and their influences on PLC signal transmissions. The most negative action presents the periodical impulse noise asynchronous to the AC frequency originating in the cell phone charger that can cause an expressive decrement of the transmission rate. Other noise sources are not affecting transmission parameters of the PLC network in a substantial way.

The second measurement is oriented on condition for the interphase PLC signal liaising in higher frequency domains in real in-home PLC network. The trouble-free connection between two PLC modems connected on different phases can be created at the minimum length of parallel cables at least 3 m with their mutual distance not exceeding 2 cm. These conditions for the interphase PLC signal liaising can be certainly satisfied in every operational electricity distribution of any object. At shortening parallel connections or increasing mutual distances, a quality of communication is rapidly decreasing up to a termination of the signal connection between PLC modems.

We realized experimental measurements on the electricity distribution and its real utilization within in-home PLC network infrastructures. So, the theoretical assumption for practical utilization of the RC4 reference channel for higher frequencies than 10 MHz can be confirmed.

It is necessary to conclude a great importance of the location design and planning of the PLC communication for obtaining a better performance of the in-home PLC network. Results of our realized measurements can be utilized for selecting suitable and appropriate power distribution lines utilized by PLC modems within real in-home applications. There can be suggested an expansion of the PLC topology with variable multi-path models. However, it is obvious that there is a significant effect of connecting on some network transmission characteristics of the electricity distribution within in-home cable infrastructures. This will be a great challenge for future.

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