Theoretical postulation of PLC channel model

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Abstract

The objective of this document is to supply a theoretical basis for modelling the communication links over powerlines. A comprehensive summary of transmission properties and the noise scenario on public mains supply when used for data transmission are given.

Different PLC models - PLC channel, noise in PLC channel, coupling units, filters and conditioning devices – will be created and they will be used to simulate the PLC channel.

PLC applications will have to work at very unusual channels, solely designed for optimal electrical power transportation, completely disregarding signal transmission at high frequencies.

It is shown that the typical properties are described by transfer functions and noise scenarios typical for access and inhouse networks. The general transfer function for different channel types is derived and, since an emulation system should reproduce typical classes of channels rather than single measurements, the transfer function is concretised with reference channels. These are later serving as basis for development of channel simulators and channel emulators. Special attention is paid to modelling of aperiodic impulsive noise since PLC systems are reacting very sensitive to them and this class of noise has been insufficiently considered so far.

Keywords: ***Powerline communication, PLC channel, inhouse, high frequency, low and medium voltage***

I. INTRODUCTION

A. *What is PLC?*

The Powerline Communication Technology provides broadband Data and Voice transmission on existing Power Networks.

B. *Powerline Communications can provide:*

-Fast and secure surfing on the Internet, e-commerce, e-mail and e-banking

-Powerful telephone connection using the internet that offers security and good speech quality. Send and receive fax messages is also possible.

-Smart Home Applications with remote maintenance and in-house control of internet enabled household appliances like refrigerators, heating systems, smoke and fire alarm systems.

-Surveillance systems with both visual and motion detectors that can be monitored by you and a security service.

-Health Care Services

-Online reading of utility meters for flexible and easy up-to-date billing.

C. *Structure of a inhouse network*

As illustrated in Fig. 1, the substation supplies the bus bar. If used for Power-Line-Communications, the PLC-signal will also be applied to bus bar. The physical connection from the substation to the backbone network can be realized by conventional communication links as fibre optics, radio relay links or broadband cables. The advantage is that in access networks with its distinct low pass characteristic, lower frequencies may be used, and in inhouse networks not having those characteristic higher frequencies may be used.

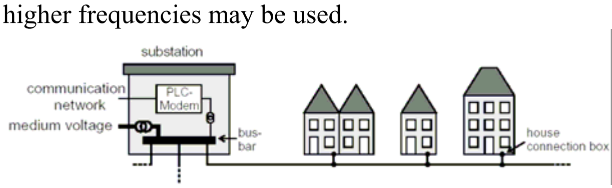

Fig. 1 Topology of the low voltage distribution grid

Cables of the mains network are usually laid into earth. These are built for energy transfer with little losses, but are not optimal for data transfer. Multiple measurements showed that these cables have a strong low pass characteristic depending on the type of cable, the length of the cable and the frequencies of the signal. Figure 2 shows the attenuation depending on frequency and length for different types of cables.

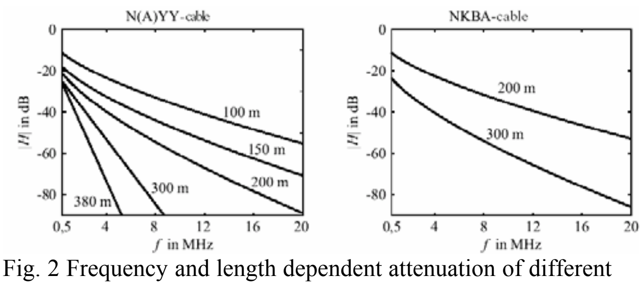

Fig. 2 Frequency and length dependent attenuation of different types of cable

The low pass characteristic is caused by dielectric losses in the insulation of the cable. This also explains why overhead lines do not show this low pass characteristic. Fig. 2 illustrates that the N(A)YY-cable with its PVC insulation exhibits more attenuation than the NBKA-cable with paper insulation. Inhouse cables show few low pass characteristic, caused by short distances. On the one hand, the low pass characteristic of access networks limits the maximum distance to be overcome by PLC, on the other hand, it limits the maximum usable frequency. It has proven to be sensible, to split up the available frequency range in that way, that lower frequencies (below 10 MHz) are used for access network, and the higher frequencies between 10 MHz and 30 MHz are used for inhouse networks.

The low voltage “local loop access network” between the substation and the customer premises are often operated in a star shaped structure. In opposite to the telephone copper loop the power line “local loop access network” does not consist of point-to-point connections between substations and customer premises but represents a line bus with the distributor cables and the house service cables. A typical access network link between a substation and a customer (Fig. 3) consists of the distributor cable or a series connection of distributor cables with the characteristic impedance Z_{Li} and the branching house connection cables with the characteristic impedance $Z_{L,H}$.

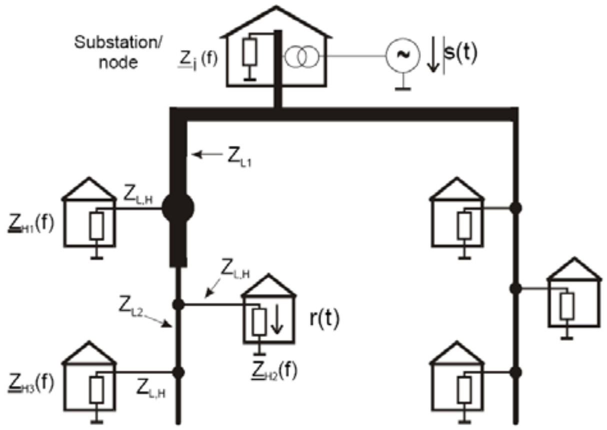

Fig. 3 Signal propagation over the power line local loop access network

The house service cable ends at a house connection box. The inhouse cabling follows, which is modelled by a termination impedance $Z_H(f)$.

II. SPECIFICATION OF THE PLC-CHANNEL

A. *Physical effects on signal propagation*

A.1.Attenuation caused by cable losses

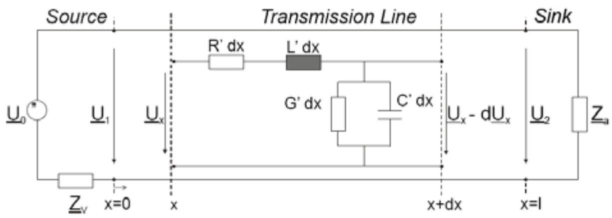

Fig. 4 Signal propagation over a transmission line

Transmission line theory describes the voltage and current along a line (Figure 4) as follows [1]:

$$\underline{U}(x) = \underline{U}_2 \cosh(\underline{\gamma} x) + \underline{I}_2 \underline{Z}_L \sinh(\underline{\gamma} x) \tag{1}$$

$$\underline{I}(x) = \underline{I}_2 \cosh(\underline{\gamma} x) + \frac{\underline{U}_2}{\underline{Z}_L} \sinh(\underline{\gamma} x) \tag{2}$$

The Parameters to describe a transmission line are the characteristic impedance $\underline{Z}_L$ and the propagation constant γ.

$$\underline{Z}_L = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \tag{3}$$

$$\underline{\gamma} = \sqrt{(R' + j\omega L')(G' + j\omega C')} = \alpha + j\beta \tag{4}$$

Considering a matched transmission line, which is equivalent to regarding only the wave propagating from source to destination, the transfer function of a line of the length *l* can be expressed as follows:

$$H(f) = \frac{\underline{U}(x=1)}{\underline{U}(x=0)} = e^{-\underline{\gamma} \cdot l} = e^{-\alpha(f) \cdot l} e^{-j\beta(f) \cdot l} \tag{5}$$

Fig. 5 shows a cross section of a typical power line cable with four conductors, widely used in German power distribution systems. When feeding signals into two adjacent conductors, most of the electric field is concentrated between these two conductors. For a first estimate the electric and magnetic field can be approximated by equations describing a micro strip line.

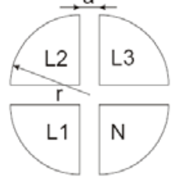

Fig. 5 Cross section of a typical power line cable (4 conductors)

The inductance per unit length and capacity per unit length can be expressed as follows:

$$L' = \mu_0 \mu_r \frac{a}{r} \tag{6}$$

$$C' = \varepsilon_0 \varepsilon_r \frac{r}{a} \tag{7}$$

Resistance per unit length is dominated by the skin-effect:

$$R' = \sqrt{\frac{\pi\mu_0}{kr^2} f} \rightarrow R' \sim \sqrt{f} \qquad (8)$$

The conductance per unit length:

$$G' = 2\pi f C' \tan\delta \rightarrow G' \sim f \qquad (9)$$

is mainly influenced by the dissipation factor of the dielectric material (usually PVC). Using geometry and material properties in the above equations results in $R' << \omega L'$ and $G' << \omega C'$ in the frequency range of interest.

Hence, the cables can be regarded as weakly lossy and the characteristic impedance $\underline{Z}_L$ as well as the propagation constant γ can be determined using the following simplified expressions:

$$\underline{Z}_L = \sqrt{\frac{L'}{C'}} \qquad (10)$$

$$\underline{\gamma} = \underbrace{\frac{1}{2}\frac{R'}{\underline{Z}_L} + \frac{1}{2} G' \underline{Z}_L}_{\mathrm{Re}(\underline{\gamma}) = \alpha} + j \underbrace{\omega\sqrt{L'C'}}_{\mathrm{Im}(\underline{\gamma}) = \beta} \qquad (11)$$

$$\underline{\gamma} = \underbrace{k_1\sqrt{f} + k_2 f}_{\mathrm{Re}(\underline{\gamma}) = \alpha} + j \underbrace{k_3 f}_{\mathrm{Im}(\underline{\gamma}) = \beta} \qquad (12)$$

$$\alpha(f) = a_0 + a_1 \cdot f^k \qquad (13)$$

$$A(f,d) = e^{-\alpha(f)d} = e^{-(a_0 + a_{11} \cdot f^k)d} \qquad (14)$$

A.2. Multi-Path-Signal-Propagation

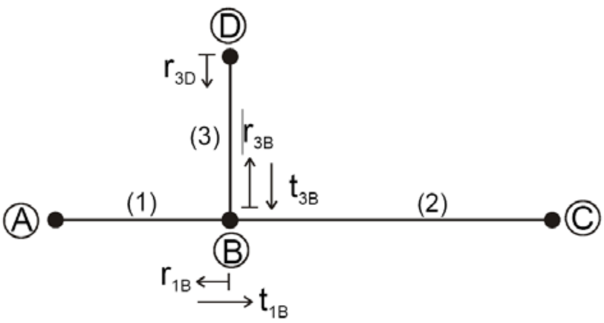

Fig. 6 Multi-path propagation along a line with one branch

Path No	Way of the signal path	weighting factor g_i	length of path d_i
1	A→B→C	t1B	l1 + l2
2	A→B→D→B→C	t1B·r3D·t3B	l1+2l3 +l2
:	:	:	:
N	A→B (→ D→B)$^{N-1}$ →C	t1B·r3D·(r3B·r3D)$^{(N-1)}$ t3B	l1 + 2(N-1)·l3 + l3

Table 1 Signal Propagation paths of the examined sample network

For a simplified consideration A and C are matched, which means $Z_A = Z_{L1}$ and $Z_C = Z_{L2}$. The remaining points for reflections are (B) and (D) with the reflection factors.

Each path *i* has a weighting factor g_i, representing the product of the reflection and transmission factors along the path. The time-delay τ_i of a path

$$\tau_i = \frac{d_i}{v_p} \qquad (15)$$

can be calculated from the length d_i and the phase velocity v_P. The losses of real cables cause an attenuation $A(f,d)$ increasing with cable length and frequency.

The signal components of the paths have to be added due to superposition and the transfer function from A to C can be expressed as:

$$H(f) = \sum_{i=1}^{N} \underbrace{|g_i(f)|^{\varphi_{g_i}(f)}}_{\substack{\text{weighting}\\ \text{factor}}} \cdot \underbrace{e^{-(a_0 + a_1 f^k)d_i}}_{\substack{\text{attenuation}\\ \text{term}}} \cdot \underbrace{e^{-j2\pi f \tau_i}}_{\substack{\text{delay}\\ \text{term}}} \qquad (16)$$

B. Theoretical channel model

B1. A general multi-path-signal propagation model of the transfer function

Combining the multi-path-propagation and the frequency and length depending attenuation finally leads to:

$$H(f) = \sum_{i=1}^{N} \underbrace{g_i}_{\substack{\text{weighting}\\ \text{factor}}} \cdot \underbrace{e^{-(a_0 + a_1 f^k)d_i}}_{\substack{\text{attenuation}\\ \text{term}}} \cdot \underbrace{e^{-j2\pi f \frac{d_i}{v_p}}}_{\substack{\text{delay}\\ \text{term}}} \qquad (17)$$

Equation (17) represents the basis of models describing the complex transfer function of typical power line channels. Using this model all the substantial effects of the transfer characteristics of power line channels in the frequency range from 500 kHz to 40 MHz can be modelled by a small set of parameters. Increasing the number of paths N allows easy control of the precision of the model.

C. Channel reference models

For implementation of a channel transfer function into a channel emulator, several steps are necessary. First, we need a suitable channel model which is capable of imitating all measured effects. Based on channel measurements, those channels are selected who seem to be a good representative of real channels.

In the following, a selection is made which should cover the majority of important power line channel in practice. We will present the characteristic properties and the practical-oriented procedure of modelling first for channels of access network and then for inhouse networks.[2]

C.1. Reference channels for access and medium voltage networks

Attenuation parameters can be easily determined from an attenuation measurement using estimation routines like Least-Square-Estimation (LS-Estimation).

The left part of Fig. 7 shows a measured attenuation characteristics and the result of modelling.

The middle part of Fig. 7 shows the measured and modelled impulse response. In this case, modelling is quite easy because time position follows directly from impulse response. In general, this is not that visible when multiple following impulses are overlapping partly with contrary polarity. With the limitation of paths, echoes reaching their maximum of amplitude after 2.5 µs or later have not been considered. Finally, the right part of Fig. 7 shows six single impulses used for modelling. Scaling does not match the figure in the middle part. Thus, this graph shows the result of modelling (that means the sum of all single impulses) for comparing purposes.

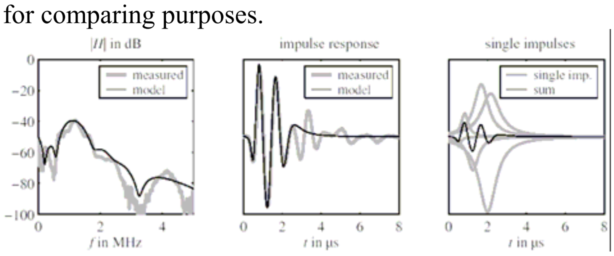

Fig. 7 Reproduction of a channel measurement

We encounter several issues/problems which occur during path parameter estimation:

- Amplitudes of single impulses (corresponding to the weighting parameters of the model) are much greater than the maxima and minima of impulse response.
- Amplitudes of single impulses are getting greater with increasing length of path, although maxima and minima of impulse response are decreasing. In this example, the fifth impulse has the greatest weighting factor, although the impulse response has a maximum at the second impulse.
- Single impulses are wider than maxima and minima of impulse responses to be modelled. This means that every newly added impulse influences the preceding impulses.

The following classes of length are defined for reference channels:

- Short distances, about 150m
- Medium distances, about 250m
- Long distances, about 350m.

In the following, we deal with some examples of reference channels using frequencies up to 20 MHz as our measurements showed that other measurement ranges make no sense. For bad channels this maximum frequency is even lower.

Signal propagation speed in media for all channels will be v_p = 1,53 · 108 m/s.

Class of length 150 m

- The first channel of this class (Fig. 8) represents a channel without branches, so that five paths should be enough for modelling. The channel only provides a low attenuation and only has little low-pass characteristic. Frequency-selective notches seem not to exist. Impulse response is dominated by a main echo and decayed after about 1.5 µs. Thus, we deal with an almost ideal channel.

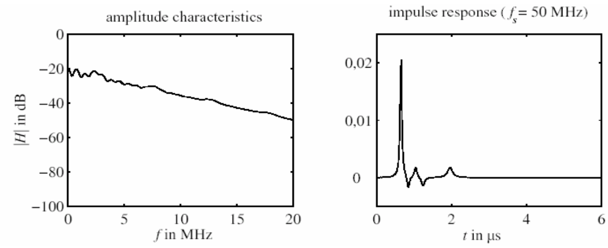

Fig. 8 Reference channel 1 (class "150m, good")

Attenuation parameters:	$a_0 = 0$	$a_1 = 1{,}65 \cdot 10^{-9}$ s/m		$k = 1$		
Path parameters:						
i	g_i	d_i/m		i	g_i	d_i/m
1	0,09	100		4	–0,012	190
2	–0,012	130		5	0,022	300
3	0,012	160				

Table 2 Parameters of reference channel 1 (class "150m, good")

- The second channel of this class shows a more distinct low-pass characteristic and high frequency dependent notches seem to be non-existent again. Impulse response shows a very complex developing, thus 17 paths are required for modelling. The duration of channel response is about 8 µs.

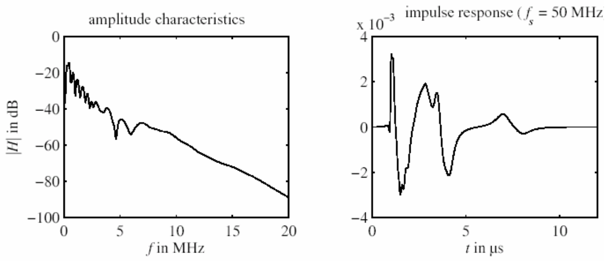

Fig. 9 Reference channel 2 (class "150m, medium")

Attenuation parameters:	$a_0 = 0$	$a_1 = 2{,}8 \cdot 10^{-9}$ s/m		$k = 1$		
Path parameters:						
i	g_i	d_i/m		i	g_i	d_i/m
1	–0,15	150,8		10	0,04	435
2	0,165	152,3		11	0,02	468
3	0,032	172		12	–0,015	494
4	–0,014	210,4		13	0,0865	534
5	–0,035	230		14	–0,062	581
6	–0,035	258		15	–0,083	632
7	–0,03	294		16	0,05	1070
8	0,015	370		17	–0,035	1224
9	0,022	400				

Table 3 Parameters of reference channel 2 (class "150m, medium")

- The third reference channel has a similar basic attenuation as the second channel, but additionally shows frequency selective notches. The base was a measurement in a row house estate with a distinct regular network structure. This can be recognized at the great number of echoes. The model deals with 15 paths.

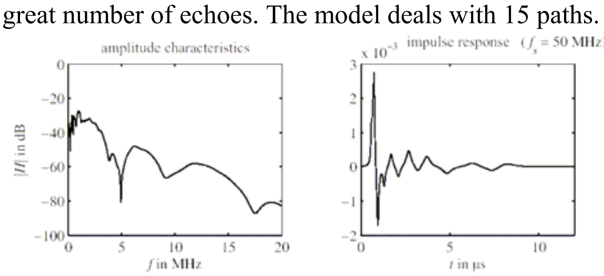

Fig. 10 Reference channel 3 (class "150m, bad")

Attenuation parameters:	$a_0 = 0$		$a_1 = 2{,}5 \cdot 10^{-9}$ s/m		$k = 1$	
Path parameters:						
i	$g_i \cdot 10^2$	d_i/m		i	$g_i \cdot 10^2$	d_i/m
1	1,832	113,2		9	1,263	411
2	0,516	90,1		10	–0,622	490
3	0,765	101,8		11	1,156	567
4	–1,031	143		12	–0,978	740
5	–0,800	148		13	0,747	960
6	–0,711	200		14	–1,049	1130
7	0,676	261		15	0,871	1250
8	–0,676	322				

Table 4 Parameters of reference channel 3 (class "150m, bad")

C.2. Reference channels for inhouse networks

For modelling inhouse networks the simple echo model without low-pass attenuation is used. The usage of the simplified model is justifiable, as inhouse cable length is relatively short. That’s why attenuation can be neglected.

For inhouse networks much higher signal frequencies are used. Thus, sampling frequency for reference channel modelling is set to 100 MHz. At this frequency we are capable of reproducing channels up to 50 MHz. However, this is sufficient for reproduction of inhouse channels for both available and future PLC-systems.

Modelling of channel measurements

Using a channel model without low-pass attenuation, simplifies modelling of channel measurement as the impulse response is reduced to a sum of weighted Dirac-impulses. Fig. 11 shows the result of a channel measurement as a grey line. The modelling of the channel is represented by the black line.

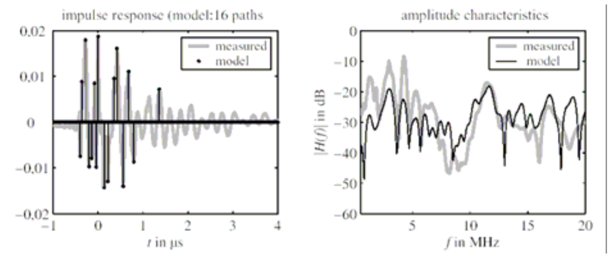

Fig. 11 Measurement and modelling of an inhouse channel

For modelling, all relevant echoes have been extracted from impulse response. Only those echoes have been considered, whose absolute amplitude does not under-run the absolute maximum of impulse response with more than 10 dB. Depending on threshold value, a different number of echoes results for the model. This leads to 16 considered paths in this example. The higher the number of considered paths, the longer is the modelled impulse response and the wavier is the developing of attenuation. Searching for a significant echo is a simple method comparatively for channel modelling. The absolute value of transfer function in the right part of Fig. 11 illustrates, that this method does not provide an exact matching of measurement and model but typical effects of multi-path propagation are already reproduced very well. Thus, proceeding this way is very appropriate for setting up reference channels.[3]

Model	Number of paths	Impulse response delay	Initial delay	Maximum amplitude	Minimum amplitude
1	5	0,5 µs	0,2 µs	0,05	0,005
2	10	1,0 µs	0,2 µs	0,01	0,002
3	15	1,5 µs	0,5 µs	0,003	0,0003
4	20	2,0 µs	0,5 µs	0,0005	0,0001

Table 5 Default values for in-house reference channels

General procedure for creating inhouse channel models

Generation of a reference channel impulse response is done as follows:

• The impulse response starts with a positive impulse response of maximum amplitude. The amplitudes are decaying exponentially until the last impulse reaches the minimum amplitude.

• Starting from the second impulse, polarities of single impulses are randomly chosen.

• Time positions of the single impulses (from second to last) are randomly chosen with respect to variance of bandwidth of distance variation

Fig. 12 illustrates the single steps of the procedure using a channel with *N*P = 5 paths.

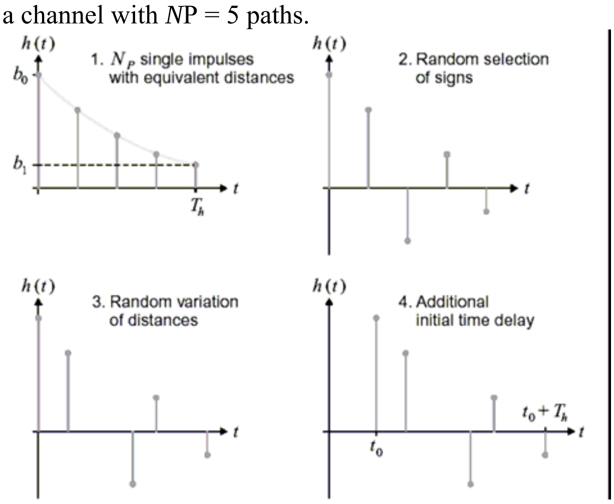

Fig. 12 Design of a inhouse reference channel

In a final step, the generated impulse response is shifted to the right by the desired initial time delay. Fig. 13 shows the results for four model channels, generated with the given values of Table 5.

Besides simulation of transfer properties, it is very important to reproduce a realistic noise scenario. Again, it is necessary to adapt theoretical noise models for implementation in hardware and software.

We deal with four different types of noise which additively and independently overlay each other:[4]

• Coloured background noise
• Narrow-band noise
• Periodic impulsive noise
  • net-synchronous
  • net-asynchronous
• Aperiodic impulsive noise.

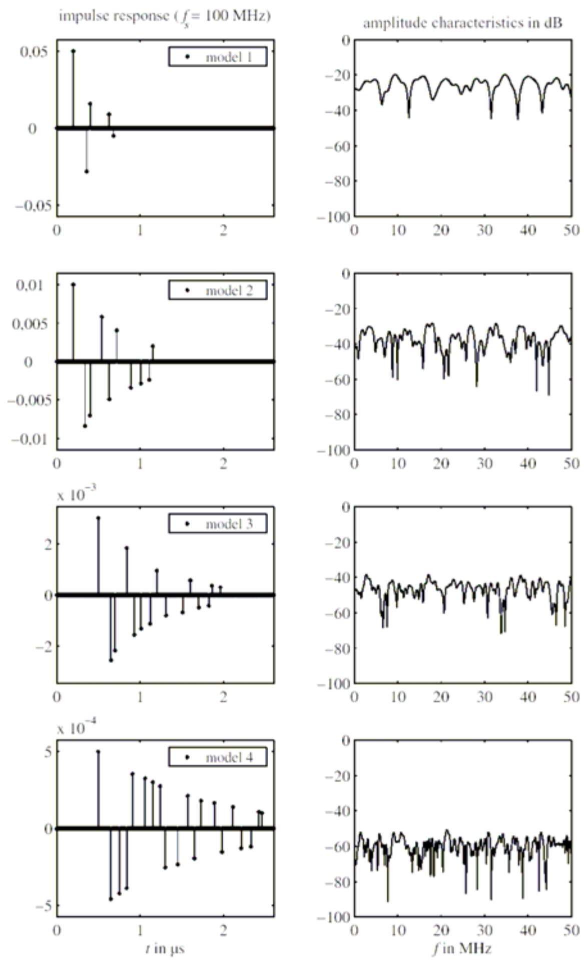

Fig. 13 Reference models for inhouse channels

III. CONCLUSIONS

- PLC will contribute to the fast development of the European broadband market as a result of the increase of competition in access network (ADSL, cable modem, satellite, fixed wireless, fibre optic, 3G mobile and power line) especially in populated areas.
- The attenuation effects functionality of PLC-systems as, because of EMC-compatibility, transmitter power cannot be increased infinitely. If attenuation exceeds a certain value, the signal cannot be received at all.

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