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# MODELLING OF TRANSMISSION CHANNELS OVER THE LOW–VOLTAGE POWER DISTRIBUTION NETWORK

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For the expansion of power line communication (PLC) systems, it is necessary to have detailed knowledge of the transmission channel properties, such as the transfer function, interference scenario and channel capacity. Their understanding represents the basics in a way of searching for the most powerful coding and modulation techniques. Then, power lines would be able to provide popular services such as Internet access or in-home/office networking at minimal costs. This contribution briefly discusses possible ways for modelling the transmission channels over the low-voltage power distribution network together with various modulation and coding techniques. A result of this discussion is a proposition of a simulation model for the PLC environment. The main part of our contribution is focused on the description of the proposed simulation model and on the explanation of simulation methods for principal impairments in PLC channels, such as time-varying channel attenuation, multiple access interference, background and impulse noises. Presented information represents a knowledge base reach enough for the design of the PLC channel model that can be extremely helpful for various tests and performance comparisons.

Keywords: PLC environment, PLC transmission channel, PLC simulation model

## 1 INTRODUCTION

One of the most important features of present data communication is its orientation on broadband services. At this time, the fast Internet access seems to be the most popular service but also other services — such as Video on demand, Conferencing or Teleworking — are gradually expanding. From a technical viewpoint, the transmission capacity of the access network is the main condition for service deployment. To fulfil this condition, it can be chosen from several solutions — utilizing the existing telephone lines through digital subscriber lines (xDSL) or cable distributions via cable modems (CATV), installing new optic fibres (PON), using wireless technologies (WLL, WLAN) or utilizing electrical power lines (PDSL, PLC).

Exactly, the electrical power distribution grid offers, due to its omnipresence, a tremendous potential for extended fast and reliable communication services. Since the exploitation has just started, the PLC technology is far behind recent leading access methods (xDSL, CATV) regarding transmission rates, services and deployments. In spite of this delay, the PLC has still a big chance to break through on the market with communication technologies in the access network. The main reason is that electrical power lines can be found in essentially all buildings and residences, which cannot be said about other access methods. For example, in rural areas, where transmission media from telephone companies or cable companies do not reach and where radio coverage is either poor or very expensive through the one-way satellite access, communication through power lines may be the only feasible solution. This solution is usable not only for Internet access but in the future also for high-speed networking that includes the fast Internet access, the Voice over IP or the Home Entertainment.

This paper brings an overview of the basic properties of transmission channels in the power distribution network focusing mainly on multipath signal propagation, signal attenuation, noise scenario and electromagnetic compatibility. Several modulation and coding approaches are briefly discussed. Finally, the simulation model is created concerning all major negative influences of the PLC environment. Moreover, single blocks of the PLC simulation model with concrete parameters are mentioned.

## 2 THEORETICAL PART

### 2.1 The PLC transmission environment

Long time ago, the electrical power distribution grid started being used not only for power supply purposes but also for data transmission. However, this was, more or less, the management, control and supervision of power plants and distribution [1]. All these are tasks that require only low data rates in the range of kbit/s. In current PLC systems, demands are stronger (services requiring data rates higher than 1 Mbit/s). To achieve these demands, it is necessary to have a model of the PLC environment reflecting real conditions and influences of the power distribution grid. Adequate models have not been standardized yet and there is also no available universally recognized PLC transmission model. More or less, only the basic PLC scenario is clear [2]. It is depicted in

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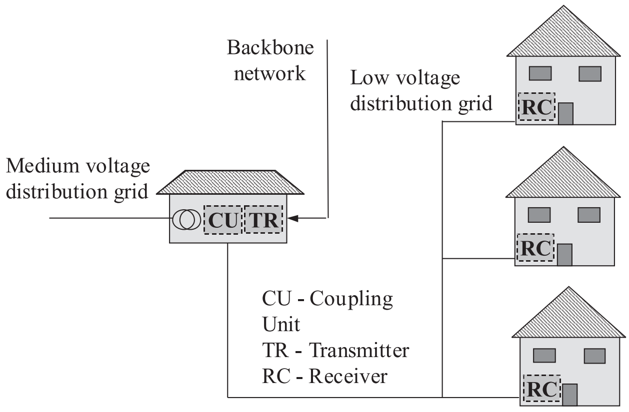

**Fig. 1.** The structure of the typical European low-voltage power distribution network.

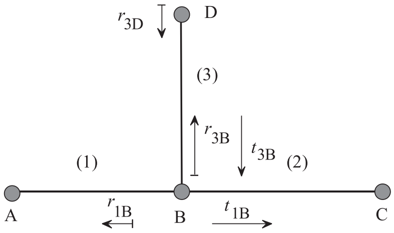

**Fig. 2.** The multipath signal propagation — cable with one tap.

Fig. 1. Data transmitters are placed in the transformer substation and may be connected to the Internet. Then, the whole PLC channel can be characterized as a star-shaped bus structure with branches going to every supplied building. A single low-voltage line consists of four wires — three phases and the neutral. Each building is attached to the grid through cable-boxes. Data receivers can be located in any of the buildings. Such a scenario exhibits a strong level of branching (that means a great number of reflections), hence strong cross-coupling effects between wires in a cable and also a nonstationary topology caused by plugging different household appliances into the network.

These are the reasons of many problems that the PLC channel suffers from. The most important ones are:

- Frequency-varying and time-varying attenuation of the medium.
- Dependence of the PLC model on locations, network topologies and terminated loads.
- High interference due to noisy loads.
- High, non-white background noise.
- Various forms of impulse noise.
- Issues of electromagnetic compatibility (EMC) that limit the available transmitted powers.

In the following subsection we will look closer at the single negative features of PLC channels and analyse their properties.

### 2.1.1 The multipath signal propagation

As mentioned before, the PLC channel has a tree-like topology with branches formed by additional wires tapered from the main path and having various lengths and terminated loads with highly frequency-varying impedances in the range from a few ohms to some kiloohms. That is why signal propagation does not only take place along the direct line-of-sight path between the transmitter and receiver but also additional paths are used for signal spreading. This multipath scenario can be easily explained by the example of a cable with one tap (Fig. 2) [3].

The line consists of three segments (1), (2) and (3) with lengths $l_1$, $l_2$ and $l_3$ and characteristic impedances $Z_{L1}$, $Z_{L2}$, and $Z_{L3}$. To simplify considerations, points A and C are assumed to be matched, which means $Z_A = Z_{L1}$ and $Z_C = Z_{L2}$. Then, points B and D are reflection points whose reflection factors are denoted as $r_{1B}$, $r_{3D}$, $r_{3B}$, and the transmission factors are denoted as $t_{1B}$, $t_{3B}$. Because of multiple reflections, the number of propagation paths is infinitive (*ie*, A $\rightarrow$ B $\rightarrow$ C, A $\rightarrow$ B $\rightarrow$ D $\rightarrow$ B $\rightarrow$ C, and so on). The affect of all reflections and transmissions can be expressed for each propagation path i in the form of the weighting factor gi that is mathematically equal to the product of reflection and transmission factors along the path. The value of $g_i$ is always less or equal to one because all reflection and transmission factors can be only less or equal to one. Our model can be simplified if we approximate the infinite number of paths by only N dominant paths and make $N$ as small as possible. When more transmissions and reflections occur along the path, then the weighting factor will be smaller. When the longer path will be considered, then the signal contribution from this part to the overall signal spreading will be small due to the higher signal attenuation.

The delay $\tau_i$ of the path can be calculated from the dielectric constant $\varepsilon_r$ of insulating materials, the light speed $c_0$ and the length $l_i$ of cables as follows:

$$\tau_i = \frac{l_i\sqrt{\varepsilon_r}}{c_0} = \frac{l_i}{\nu_p}\,. \tag{1}$$

If we now merge signal spreadings on all paths together (we can use superposition), we will receive an expression for the frequency response in the form

$$H(f) = \sum_{i=1}^{N} g_i\, A(l_i, f)\, e^{-j2\pi f\tau_i} \tag{2}$$

where $A(l, f)$ is the signal attenuation proportioned with the length and frequency.

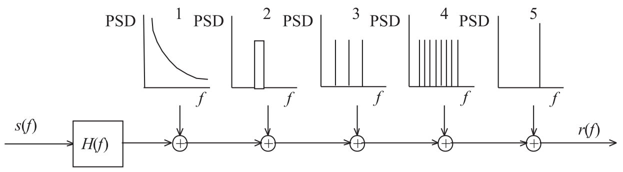

**Fig. 3.** The noise scenario in the PLC environment.

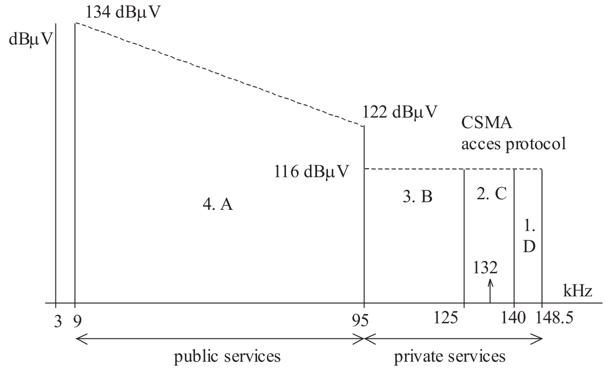

**Fig. 4.** The CENELEC bandwidth allocation.

### 2.1.2 Signal attenuation

The total signal attenuation on the PLC channel consists of two parts: coupling losses (depending on the transmitter design) and line losses (very high and can range from 40 to 100 dB/km) [3]. To find a mathematical formulation for signal attenuation, we have to start with the complex propagation constant

$$\gamma(\omega) = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha(\omega) + j\beta(\omega) \qquad (3)$$

depending on the primary cable parameters $R$, $L$, $G$, $C$. Then the frequency response $H(f)$ (the same as in expression 2 but now from a different point of view) of the transmission line with length can be expressed as follows ($U(x)$ is the voltage at distance $x$):

$$H(f) = \frac{U(x = l)}{U(x = 0)} = e^{-\gamma l} = e^{-\alpha l} e^{-j\beta l}\,. \qquad (4)$$

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 suppose $R \ll \omega L$ and $G \ll \omega C$ in the frequency range of interest. Then, cables can be regarded as weakly lossy with real valued characteristic impedances and a simplified expression for the complex propagation constant $\gamma$ can be introduced

$$\gamma = k_1 \sqrt{f} + k_2 f + j\, k_3 f \qquad (5)$$

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

$$\alpha(f) = a_0 + a_1 f^k \qquad (6)$$

that is able to characterize the attenuation of typical electrical power distribution lines with only three parameters, being easily derived from the measured transfer function [3]. Now the propagation loss $L_{dB}$ is given at the length $l$ and the frequency $f$ as

$$\begin{aligned} L_{dB}(l,f) &= -20\log_{10}|H(l,f)| = \frac{20}{\ln 10} l\alpha(f) \\ &= \frac{20}{\ln 10} l(a_0 + a_1 f^k) \approx 8.686\, l(a_0 + a_1 f^k) \ \ (\mathrm{dB})\,. \qquad (7) \end{aligned}$$

We can see a linear dependence of the propagation loss $L_{dB}$ on the line length $l$.

### 2.1.3 The noise scenario

Unfortunately, in the case of the PLC, we cannot stay only with the additive white Gaussian noise (AWGN). The noise scenario is much more complicated since five general classes of noise can be distinguished in power distribution line channels [4, 5]. These five classes are (Fig. 3):

1. *Coloured background noise* — caused by summation of numerous noise sources with low powers. Its PSD varies with the frequency in a range up to 30 MHz (significantly increases towards 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 consists mostly of sinusoidal signals with modulated amplitudes.
3. *Periodic impulse 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 impulse 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 the frequency and the repetition rate is 50 Hz or 100 Hz.
5. *Asynchronous impulse noise* — caused by impulses generated by the switching transients in the network. It is considered to be the worst noise in the PLC environment because of its magnitude that can easily reach several dB over other noise types. Fortunately, the average disturbance ratio is well bellow 1 percent, meaning that 99 percent of the time is absolutely free of asynchronous impulsive noise [4].

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 or burst errors in data transmission. Time and domain analyses of impulse noises can be found in [4]. We will just mention a few expressions regarding the mathematical description of the impulse noise model and the impulse energy and power.

The time behaviour of the impulse noise can be described by three basic figures, *ie* the impulse width $t_w$, the arrival time $t_{arr}$ and the interarrival time $t_{iat}$ or the impulse distance $t_d$. The interarrival time (the impulse distance) means the distance between two impulse events that can be described by

$$t_{iat} = t_w + t_d = t_{arr,i+1} - t_{arr,i} \,. \tag{8}$$

Then, a train of impulses $n_{imp}(t)$ can be described as

$$n_{imp}(t) = \sum_{i=1}^{N} A_i \, imp\Big(\frac{t - t_{arr,i}}{t_{w,i}}\Big) \tag{9}$$

where $A_i$ means the impulse amplitude and $imp(t)$ is the generalized impulse function. Parameters $A_i$, $t_w$ and $t_{arr}$ are random variables, whose statistical properties may be investigated by measurements. More information can be found in [4].

The best way how to characterize the extent of the impact of impulses on data transmission are the values of impulse energy and impulse power. The impulse energy $E_{imp}$ can be calculated from the time-domain representation $n_{imp}(t)$ as

$$E_{imp} = \int_{t_{arr}}^{t_{arr}+t_w} n_{imp}(t)^2 \mathrm{d}t \,. \tag{10}$$

As we can see from (10), the impulse energy is influenced by the impulse shape and width. Finally, the impulse power can be determined by

$$\psi_{imp} = \frac{1}{t_w} \int_{t_{arr}}^{t_{arr}+t_w} n_{imp}(t)^2 \mathrm{d}t \,. \tag{11}$$

and can be used for a comparison of impulse and background noises.

### 2.1.4 Electromagnetic compatibility

Considering today's international status, a traditional PLC standard exists only for systems used for simple control, supervision and switching purposes. It deals with the systems occupying a frequency range up to 525 kHz, whereby the standard implicitly limits unwanted radiation by restricting the maximum signal amplitude in the power distribution lines grid. In Europe, there is such a standard CENELEC EN-50065-1 [6]. The standard provides a frequency spectrum from 9 to 140 kHz for powerline communications. This frequency range is separated into A, B, C, D bands with detailed transmission signal amplitude limitations and service provisioning. The band allocations are illustrated in Fig. 4.

The designed CENELEC frequency bands clearly do not support viable high data rate communication through the PLC. Therefore, the European Commission issued a mandate to CENELEC and ETSI for elaborating a new standard for emissions from telecommunication networks. It can be expected that the new standard will specify the limits of magnetic field levels at a distance of 3 m from the network under test. The outcome of this mandate will represent a harmonized European standard applying to each member of the European Union.

Since the PLC standardization process is still underway and not completed, the national regulatory authorities started a national legislation process under the risk of contradicting to the outcomes of the European harmonization process.

In the United States, using of PLC is regulated by the FCC Part 15, which distinguishes between low-speed applications for signalling and switching purposes and high-speed data transmission applications. More information about the standardization issue can be found in [2, 6].

## 2.2 Modulation techniques for the PLC system design

From the characteristics of the PLC channel mentioned above we can summarize three major factors that play an important role in the selection of appropriate modulation techniques for the optimal PLC system: the presence of noise and impulse disturbances; a time-varying frequency-selective nature of the channel and regulatory constraints with regard to the electromagnetic compatibility. There are two basic choices - either a robust enough solution or an adaptive solution. Experience from wireless systems or xDSL technologies is calling for the latter solution although this choice is not ideal because of necessity of an initial channel phase estimation and constant updating of parameters during a session.

We can choose from three different types of modulation schemes - namely the single-carrier modulation, the spread spectrum technique and the multi-carrier modulation. In the following text we briefly describe the advantages and drawbacks of each of these methods in the PLC transmission environment.

### 2.2.1 Single-carrier modulation

Those basic and not very complex schemes belong to single-carrier modulation (SCM) schemes in which information is encoded in amplitude, phase or frequency changes of the carrier frequency $f_0$. Then, the wideband signal of this type has its frequency spectrum placed around $f_0$.

From this point of view the SCM modulation is cheap and easy to implement but its basic versions are not robust enough against such disturbing effects like the strong intersymbol interference ISI or the impulse noise. They need additional improvements that make applications more expensive and therefore less prospective. Notches in the transfer function of the channel and their low-pass nature cause very strong ISI. Powerful detection and equalization techniques can be used to eliminate this but less complex linear equalizers cannot be used. Instead of them, the decision feedback equalizer (DFE) [7] seems to be quite a good solution since it also minimizes the impact of the coloured noise. The only problem can be with the impulse noise that could cause catastrophic error propagation. To avoid this, the impulse noise detector could be used to stop an adaptation of the equalizer at that moment [8]. Also, the nonlinear symbol or sequence (Viterbi) detectors exhibit a computational complexity that increases exponentially with the length of the impulse response that is considerable in the power line channels. Thus, reduced-state versions of these detectors are necessary for practical implementations.

To summarize, the necessity of using additional complex techniques in connection with the SCM modulation to provide satisfactory transmission rates eliminate the main advantage — simplicity. Therefore, the SCM is not a very promising modulation technique for use in the PLC systems.

### 2.2.2 The spread spectrum technique

The basic idea of spread spectrum (SS) systems is the use of the code sequence that spreads narrowband signals over wider bandwidths [5]. This approach is much more suitable for the PLC environment because of the following reasons: robustness to narrowband interferences and selective attenuations, low power density spectrum that reduces interference problems and thus complies regulatory issues limiting the transmitted power of PLC modems. On the other hand, if we want to use the full advantage of these positive features, we need a large bandwidth expansion that may severely limit the maximum data rate. In the PLC transmission environment, code synchronization circuits can be simplified by using zero crossings of the power frequency for a rapid synchronization of code, data and carrier signals by choosing data rates to be integer multiples of 50 Hz.

SS systems have also a feature which has a great importance in the PLC communication. Using of the special spreading code leads to a multiple access technique [8] called the code-division multiple access (CDMA) that allows several users, possibly with different rate demands, to access the PLC channel simultaneously. There are basically three methods how the variable-rate CDMA can be implemented:

1. *Multimodulation*, where different users use different modulation schemes;
2. *Multicode*, where the so-called virtual users are defined. These virtual users are transmitting at the same rate and are detected by different receivers. Each physical user can have assigned one or more virtual users according to its transmission rate;
3. *Variable spreading* means that high-rate users transmit shorter modulated signals with a reduced spreading length.

With the CDMA, an available bandwidth is open for each participant, so the access need not be coordinated. On the other hand, if more participants become active, then higher mutual disturbances will arise. Therefore, a trade-off between the quality of service and the number of active customers is essential. In the search for it, a parameter called the processing gain (PG) can be used. It represents the ratio of the transmitted signal bandwidth and the message bandwidth after conventional modulation. For evaluation, a simple rule must be fulfilled: The number of participants must always remain smaller than the PG, otherwise the robustness against interference is completely lost.

For the reasons mentioned above, the spread spectrum technique is quite an interesting solution for the PLC environment and has a potential to be used in the real PLC scenario.

### 2.2.3 Multi-carrier modulation

The multi-carrier modulation represents a group of very popular (especially on DSL lines) and promising modulations whose basic feature is the parallel transmission of symbol's blocks on different subcarriers occupying a subband which is so narrow that the associated subchannel has a flat frequency response. Probably the best-known representative is DMT modulation used in ADSL and partially also in VDSL technology. In the field of PLC technologies this kind of modulations is included in the form of OFDM modulation.

The orthogonal frequency division multiplexing (OFDM) transmission scheme is suitable for frequency-selective channels because of its ability to cope with this feature by dividing the available bandwidth into $N$ equally spaced narrowband subchannels [9]. A data stream is distributed to subcarriers (each subcarrier is centred in one subchannel) and transmitted in parallel. To obtain a high spectral efficiency, the frequency responses of subcarriers are overlapping and orthogonal, hence the name OFDM. Each narrowband subcarrier can be modulated using various modulation formats; BPSK, QPSK and QAM (or the differential equivalents) are commonly used. Due to a subchannels' narrowband property, the attenuation and group delay are constant within each channel. Thus, the ISI is cancelled and coherent equalization simply amounts to normalization by a complex scalar, while an incoherent equalization does not require any further equalization.

A substantial advantage of the OFDM is its adaptability, since it is possible to choose the optimum modulation scheme individually for each subchannel. It is also possible to fade out the signal on some frequencies because of very bad conditions for transmission or regulatory restrictions [10]. To suppress the intersymbol interference, a cyclic prefix must be inserted in each block of symbols. Its duration depends on the channel memory that is quite long in PLC channels and in this way the cyclic prefix reduces the bandwidth efficiency. Although time synchronization can be achieved relatively easily, carrier synchronization is crucial since it affects the OFDM in a way that is analogous to the effect of the time-varying channel and results in intercarrier interference ICI. All these mentioned effects are getting more crucial with the length of the OFDM symbol. To overcome this problem, a shorter cyclic prefix in connection with partial equalization can be used. This technique is called channel shortening. The multicarrier techniques have a large dynamic range of their transmitted signals, which calls for amplifiers with wide linear regions.

The overall complexity of the OFDM system is comparable to single-carrier solutions including wideband equalization. Because of the high spectral efficiency, robustness against channel distortion, high flexibility and adaptability, it is expected that the OFDM will become the most favourable modulation scheme in all PLC application fields.

### 2.3 Coding techniques for the PLC system design

In the field of coding techniques, there is no general channel model that has been standardized. That is why the coding techniques are chosen on the basis of similarities between the PLC transmission environment and other well-known transmission environments. Thus a lot of different coding schemes look suitable for the PLC depending on the choice of the channel model. In the following text, we will mention just some of them [10]. We will focus only on forward encoding techniques (FEC) since they represent the main way to effectively cope with unfriendly transmission environment on power lines.

The spatial effect in the form of three different phases of the power distribution line can be used in space- time codes. It is possible to design space-time block codes using the 4-pulse amplitude modulation 4-PAM as a modulation scheme with rate 1 and diversity order 3. For the case of perfect isolation between phases, it is assumed the rate 3/2 and diversity order of 2. Simulations present that the latter code achieves a coding gain of about 10 dB at a bit error rate of $10^{-3}$.

Other coding schemes are based on the assumption that the multipath signal propagation model can be used to describe the PLC channel. It is possible to use this assumption because the channel transfer function depends on the superposition of many independent random variables representing the effects of mismatched lines. Therefore, the PLC channel can be roughly modelled as the Rayleigh fading channel [7]. A special feature for code words used over this type of channel is that they should have large Hamming distances as well as large Euclidean distances.

Also, it is possible to adapt the existing coding schemes demonstrating good performance on similar kinds of channels such as metallic homogeneous lines used by xDSL technologies. But, also particularities of the PLC must always be considered.

Since the impulse noise is present in the PLC channel, we can expect a strong burst of errors during transmission. Therefore, the coding schemes have to be integrated with the interleaving technique that disperses errors and allows code capabilities designed to control independent errors to be fully exploited. On the contrary, interleaving would introduce a delay proportional to the code block length and to the channel coherence time of the channel. For this reason, delay constraints can be used at the cost of leaving some residual channel memory. In this case, concatenation of the convolutional code (corrects isolated errors) with the Read-Solomon code (corrects short bursts of errors) represents a classical and very efficient solution.

Finally, it must be mentioned that interleaving may result in significant performance degradation if there are residual errors after decoding. At this time, integrated solutions are also known. One of them is the bit-interleaved coded modulation (BICM) [11, 12, 13], where its performance in combination with the Grey mapping of bits onto signals comes very close to the optimum for the AWGN channel. Under the word BICM we can imagine serial concatenation of the convolutional encoder, random bit interleaver and memoryless modulator. The information sequence is encoded by the convolutional encoder before being bitwise interleaved. The purpose of the random bit interleaver is to break the sequential fading correlation and to increase the diversity order to the minimum code Hamming distance. Following, consecutive bits of the interleaved coded sequence are grouped to form the channel symbol according to a labelling map. Different types of labelling maps can be used — Gray, mixed, set-partitioning, modified set-partitioning or random. More information can be found in [12, 13].

## 3 EXPERIMENTAL PART

### 3.1 Basic model conception and simulation of the PLC environment

As we pointed above, the choice of the most suitable modulation and coding techniques in the PCM system depends on the selected transmission channel model. That is why it is important that the selected model be identical with the real environment with all its features. Since an adequate model has not been standardized yet, the question of its choice is still remaining open.

All simulations were made in the software program *Matlab v6.1* together with additional libraries like *Signal Processing Toolbox 4.2* and *Communication Toolbox 1.4*. The model (Fig. 5) represents high-speed signal transmission in the PLC environment utilizing outdoor power distribution lines in downstream and upstream directions. The signal transmission over outdoor power distribution

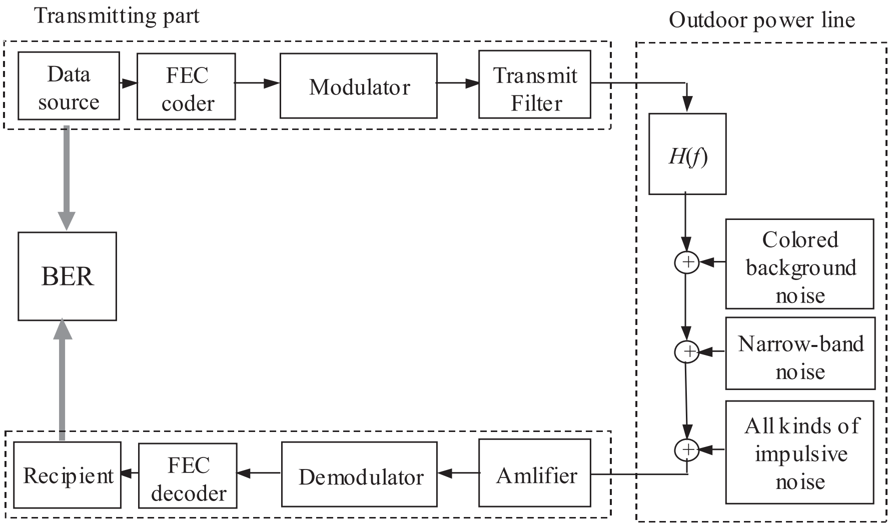

**Fig. 5.** The block scheme of the PLC simulation model.

**Table 1.** Parameters of the 15-path PLC simulation model, $k = 1$, $a_0 = 0$, $a_1 = 7.8 \times 10^{-10}$ m/s

| $N$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $g_i$ | 0.029 | 0.043 | 0.103 | −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) | 90 | 102 | 113 | 143 | 148 | 200 | 260 | 322 | 411 | 490 | 567 | 740 | 960 | 1130 | 1250 |

lines represents the transmission between the transmitter in the transformer substation and the receiver on the customer premises.

Our simulation model of the PLC environment is an enhanced version of the PLC transmission path model introduced in [14]. Changes are in a considering real data transmission and applications of particular coding and modulation techniques.

Our simulation model (Fig. 5) can be divided into three main parts:

1. The transmitting part — it is responsible for encoding (because of using the FEC technique) and for modulation of signals into a form suitable for the transmission channel. .
2. The transmission channel (the outdoor power lines) — this part of the model accounts for the negative influences of the PLC environment on the transmitted signal. Above all, these are the propagation loss, signal distortion, impulse, coloured and narrow-band noises.
3. The receiving part — it is conceptually inverse in comparison with the transmitter. Its main functions are signal amplification, demodulation and correction of error information bits.

### 3.2 The transmitting part of the model

The transmitted message carried to the receiving part is generated as a random binary chain with a given length. This message is also saved (for BER calculation), encoded by a particular type of FEC codes and modulated. From the coding and modulation techniques, we are intending to implement several different ones to be able to compare them and find the most appropriate one.

### 3.3 The outdoor power distribution line

The negative influences of the PLC environment upon the signal transmission depend on the parameters of power distribution lines (core material, cable insulation, cable length, core diameter, the number, position and properties of additional wires tapered from the main path) as well as on the number and properties of points of nonhomogeneity (instrument panels, PLC signal coupling units, regenerator units, points of wire interconnections). If we want to achieve exact results from simulations, all these factors must be accepted. Of course, this acceptance leads to a complicated and complex PLC simulation model. Because of this fact we have to choose a trade-off between the model complexity and the accuracy of reality representations. For modelling of the PLC transmission channel, we chose a generalized multipath model because of its accuracy, easy implementation and understandability [3].

Mathematically, it can be described in the form of the Eqn. (12) that we get by combining expressions (1), (2), (4) and (6) from sections 2.1.1 and 2.1.2 together.

$$\begin{aligned} H(f) &= \sum_{i=1}^{N} g_i A(l_I, f) e^{-j2\pi f \tau_i} \\ &= \sum_{i=1}^{N} |g_i(f)|\, e^{\phi_{g_i}(f)}\, e^{-(a_0 + a_1 f^k) l_i}\, e^{-j2\pi f \tau}\,. \end{aligned} \qquad (12)$$

In general, the weighting factor $g_i$ is complex and frequency-dependent because the reflection points may have complex and frequency-dependent values. According to extended measurements, it is possible to consider $g_i$ as a complex but not frequency-dependent value or as a real value. In many practical models it can be considered in this way [3].

For the presented model, the parameters were assumed from paper [3]. In spite of its simplification, it is still accurate enough for the PLC system performance analyses. It is a model of a 110 m link supposing $N = 15$ main paths. The values of other 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 length of $i$-th branch) can be found in Table 1.

In the PLC transmission environment, not only signal distortion expressed by the channel transfer function $H(f)$ is present. Also different types of noise have a very negative influence on the transmitted signals in the form of a time-invariant behaviour of the SNR on powerline channels. The first type of noise, the coloured background noise, is modelled by filtering the AWGN noise through a filter with an exponentially decreasing transfer function for increasing the frequencies with an average of 35 dB/decade in the low frequency range up to 10 kHz and a low rate in the high frequency range [15]. The narrowband noise is generated in a similar way only with a difference in band-pass filters with a random selection of the lower passband edge frequency. The power of these narrow spikes is varying around $-80$ dBW/Hz. The impulse noise can be described by expression (9) from section 2.1.3. From [4], the parameters of periodic impulse noises (type 3 and 4 from section 2.1.3) are more and less deterministic. Namely, the width of noise impulse is about 200 $\mu$s, the impulse amplitude is concentrated around two values; about 0.4 V and then between 0.7 and 1 V. The interarrival time values are 10 ms, 6 ms, and 12 ms.

The biggest problem for modelling represents the asynchronous impulse noise because of its random occurrence and random durations from some microseconds up to a few milliseconds. It cannot be ignored since its influence with the PSD more than 50 dB is particularly devastating the transmitted signal. As this is a random process whose future behaviour only depends on the present state or on limited periods in the past, it may be described by the so-called portioned Markov chain. In this model, all states are partitioned into two groups, where the first represents a case where no impulse event occurs and the second represents the occurrence of an impulse event. Transitions between states from the first group to the second and vice versa are described by two independent probability matrices $U$ for impulse-free states and $G$ for impulse states. The values of these matrices can be found in paper [4]. Each impulse noise state corresponds to an exponential distribution of the impulse width, while each impulse-free state corresponds to an exponential distribution of the impulse distance. Thus, this kind of modelling represents a superposition of several exponential distributions that approximate real scenarios very well.

### 3.4 The receiving part of the model

At the receiver side, the distorted and attenuated signal is first amplified and then demodulated. Part of the demodulation is also a demapping block as part of the modulator responsible for converting the constellation points sequence into a binary data sequence corrupted by transmission errors. They are consequently removed in the FEC decoder. Finally, the corrected sequence is compared with the original transmitted message and the bit error rate is calculated.

## 4 CONCLUSIONS

This paper analyses the basic features of the real transmission environment of outdoor power distribution lines and presents possibilities for modelling and simulation of information signal transmission in this environment by means of the PLC technology. Together with the PLC transmission environment, possible modulation and coding techniques are introduced in order to create a complete picture of the PLC transmission path.

The basic block scheme of our proposed model is composed from 3 parts — transmitter, receiver and transmission channel. We focused partly on transmission characteristics of the PLC channel and partly on the interference scenario revealing narrow-band interferences and different kinds of impulse noise. We analysed both of these areas from the global perspective, it means that we did not focus on every single component of the PLC transmission path but we analysed it as a whole. We created a model of the complex frequency response in the range from 500 kHz to 20 MHz. Because of the high complexity and computational demands, we did not model every single component but we focused on a model derived from the physical effects of these elements, namely the multipath signal propagation and typical signal attenuation. This model has a good applicability to real power distribution line networks and is easy mathematically described. Besides the transmission channel, transmitter and receiver parts were also implemented.

The simulation model is partly based on the model from [3], where its authenticity was verified by measurements in the real PLC transmission environment. Also our complete model has been verified by measurements and they confirmed its satisfactory conformity with real transmission conditions. More information about the process of verification and also the results of simulation will be the main topic of the next contribution.

Using our PLC simulation model, it is possible to verify the correctness of the proposed model, to compare it with other ones and to demonstrate its suitability for searching for the most appropriate coding and modulation techniques, which belongs to critical requirements of the development of the next generation PLC communication systems with higher data rates.

## Appendix — abbreviations

| | |
|---|---|
| ADSL | Asymmetric Digital Subscriber Line |
| AWGN | Additive White Gaussian Noise |
| BER | Bit Error Rate |
| BICM | Bit-interleaved Coded Modulation |
| BPSK | Binary Phase Shift Keying |
| CATV | Cable Television |
| CDMA | Code Division Multiple Access |
| DFE | Decision FeedBack Equalizer |
| DC | Direct Current |
| ICI | Inter-Channel Interference |
| ISI | Inter-Symbol Interference |
| MCM | Multi Carrier Modulation |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PLC | Power Line Communication |
| PSD | Power Spectral Density |
| RS | Reed-Solomon |
| QAM | Quadrature Amplitude Modulation |
| QPSK | Quadrature Phase Shift Keying |
| SER | Symbol Error Rate |
| SCM | Single Carrier Modulation |
| SNR | Signal-to-Noise Ratio |
| SS | Spread Spectrum |
| TCM | Trellis-Coded Modulation |
| xDSL | x Digital Subscriber Line |

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