# The Environment of Fixed Transmission Media and Their Negative Influences in the Simulation

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***Abstract:*** *This paper is devoted to the environment of fixed transmission media and their negative influences in the simulation. There are two basic areas of fixed transmission environments – metallic and optical. An attention is focused on main features and characteristics of environmental negative influences at the signal transmission. Consequently, simulation models for appropriate transmission paths are introduced with functional blocks representing main negative influences existing in the specific environment. The created Simulink models for technologies and communications are verified for real environmental conditions. Then, they can allow executing different analyses for advanced digital signal processing techniques at the signal transmission.*

***Keywords:*** *metallic homogeneous lines, power distribution cables, optical single-mode fibers, simulation models*

## I. INTRODUCTION

FOR successful understanding of the signal transmission in access networks that utilized fixed transmission media, it is necessary exactly to recognize essential negative influences in the real environment of metallic homogeneous symmetric lines, power distribution cables and optical fibers. This paper discusses features, frequency and time characteristics of negative influences on signals transmitted by means of the VDSL technology, the PLC technology and PON networks. For the expansion of communication systems on fixed transmission media, it is necessary to have a detailed knowledge not only about specific primary and/or secondary parameters of different cable types. These parameters can be used for calculating of the appropriate transfer function and the channel frequency response by various methods. However, as important as this knowledge, characteristics of transmission environments with considered negative influences in the real developing for customer installations are essential. Above all, a way for eliminating their impacts on the signal transmission is crucial for performance improving by means of advanced signal processing techniques. For this purpose, modelling and simulations are very effective accelerators.

A main attention of the metallic transmission environment is focused on the explanation of substantial negative influences and on the description of proposed VDSL and PLC simulation models. Presented simulation models represent a reach enough knowledgebase for the extended digital signal processing techniques of VDSL and PLC signal transmissions that can be extremely helpful for various analyses, testing and performance comparisons.

A main attention of the optical transmission environment is focused on the explanation of its substantial linear and nonlinear effects and on the description of the proposed optical communication path's simulation model. The presented simulation model represents a reach enough knowledgebase that can be helpful for various tests and performance comparisons of various advanced modulation and encoding techniques or their combinations suggested and intended to be used at signal transmissions in the transmission environment of optical fibers.

## II. RELATED WORKS

In telecommunication applications, there are many various signal processing techniques used to improve the data transmission reliability over noisy channels. In [15], the performance of the TCM system using convolution codes and various phase-shift keying modulations was evaluated by simulations in Matlab Simulink environment. In proposed Simulink model, characteristics of the transmission medium are presented by just simple AWGN channel.

Diversity techniques are used to provide effective and establish efficient communication links between earth station terminals and satellites. For this wireless transmission media, negative influences must be also analyzed. In [3], illustrations of rain fades and their effects in satellite communications as well as relevant techniques to reduce these effects using various simulation tools such as Matlab, OPNET and Celplanner were presented.

Adjacent systems within a cable binder that transmit or receive data signals in the same frequency range can create crosstalk interferences. Therefore, crosstalk cancellers play a key role in achieving very high bit rates in wire line xDSL systems. In [26], transmitter, receiver, channel and noise characteristics in the environment of homogeneous symmetric lines have been modeled. However, the noise model is dedicated only to the

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NEXT crosstalk and no other noise types are considered. Also, very simple block implementation of the ADSL environment is realized using Matlab where some simulation results are showed.

The communication infrastructures exploited by a transport management system and between elements of the intelligent transport system are extremely important. In [25], the use of communication technologies considered for the smart grid including the PLC system was proposed in this context. Considered initiatives were evaluated in the laboratory using appropriate measurements focused on environmental characteristics and their comparison with the transfer function.

In [16], a new technique of data transmission through power distribution lines was studied for utilization in industrial unites. A network development without exact goals and increasing roots can impose different noise types that may result in a signal delay and other negative interactions. Network noises differ with time and loads connected to the power distribution line. Evaluating problems and preparing a conformation with international conditions can provide a suitable situation for developing technologies in the industry.

For testing broadband PLC communications, a basic power line communication model should be proposed and realized. The main advantage of modelling is a possibility to track specific problems and the network behavior can be monitored by change of various parameters, which would be impossible in real terms. On the other hand, the simulation does not work with real elements. Therefore, it may be just as accurate as accurate models of the elements are. In [12], different levels of mapping carrier frequencies in the OFDM modulation were simulated on the simple AWGN channel used as a transmission channel where the white noise is added to a useful signal with the normal distribution. The modelling of transmission channels will be the biggest priority in the future. In [13], an overview of two possible approaches for modeling power lines was brought. Multipath and two-port network models were theoretically described and compared with measurements on the simplified model of power distribution lines.

The optical fiber provides a transmission medium in which microwave signals that modulate optical carriers can be transmitted and distributed with high bandwidth and very low losses. In [1], an optical link simulator was designed like a platform on which the transmission and optimization of communication systems could be carried out. The simulator has been developed under the Simulink environment in the form of modules to minimize confusion, errors and to facilitate the design. A block was constructed for reproducing the behavior of a laser diode. For single-mode optical fibers, linear and non-linear models of the transfer function were used. However, impacts of different effects on the optical signal were inadequately simulated.

In [7], a software tool developed for simulating of optical communication systems was presented. In the same way, the optical system is divided into three parts – a transmitter, an optical fiber and a receiver. The simulation allows determination of the spectral and frequency responses of particular blocks and the whole system. Main features of optical generations are shortly introduced. Then, optical transmitter and receiver responses and a fiber optic modelling are presented in a simplified manner. For the signal transmission, options for the WDM multiplexing and optical amplification are allowed with elementary and partial characteristics. Non-linear effects are not considered absolutely. The tool has been developed using the Matlab programming environment. It is very suitable for educational purposes, therefore it is also utilized in our simulation model for the optical communications.

The accurate determination of fiber non-linearities is an important issue in the design of optical communication systems. Besides analyzing their impact on optical waves at the signal transmission using an appropriate simulation model, acquired results should be verified and compared with results from measurements. In [2], the need of knowing fiber non-linear coefficients in global optical networks was presented. Except characteristics of basic Kerr non-linearities in silica-based optical fibers, their implications for optical communication systems together with measurement techniques are reviewed. Non-linear coefficient measurement methods divided into two groups – interferometric and non-interferometric methods – are focused on the self-phase modulation, the modulation instability, the cross-phase modulation and the four-wave mixing effect.

## III. THE ENVIRONMENT OF METALLIC HOMOGENEOUS LINES

### A. *Linear negative influences on transmitted signals*

Propagation loss and linear distortions (distortions of the module and the phase characteristics and the group delay characteristic) are linear negative influences dependent on physical and constructional parameters, such as a line length, a core diameter of the wire, a mismatch of impedances in cross-connecting points of sections, a frequency bandwidth and so forth [21].

We first discuss the propagation loss $L_{dB}$ in a perfectly terminated line. If $R$, $L$, $G$ and $C$ are primary constants of the line and $\omega = 2.\pi.f$, where $f$ is the frequency, then

$$\gamma(\omega)=\alpha(\omega)+j.\beta(\omega)=\sqrt{(R+j.\omega.L).(G+j.\omega.C)} \tag{1}$$

and

$$\mathcal{Z}(\omega)=\sqrt{\frac{(R+j.\omega.L)}{(G+j.\omega.C)}} \tag{2}$$

where $\gamma(\omega)$ denotes the propagation constant, $\alpha(\omega)$ is the specific attenuation constant, $\beta(\omega)$ is the specific phase-shift constant and $\mathcal{Z}(\omega)$ is the characteristic impedance. For a perfectly terminated homogeneous line with the length $l$, the transfer function $\mathcal{H}(l, f)$ of metallic homogeneous symmetric lines is given by

$$\mathcal{H}(l,f) = e^{-l.\gamma(f)} = e^{-l.\alpha(f)}.e^{-j.l.\beta(f)} \tag{3}$$

and the propagation loss $L_{dB}$ is given as

$$L_{dB}(l,f) = -20.\log_{10}\left|\mathcal{H}(l,f)\right| = \frac{20}{\ln 10}.l.\alpha(f) = a_{line}(l,f)\ [dB] \tag{4}$$

We must place emphasis on the interchangeable use of terms - the line attenuation $a_{line}(l, f)$ and the propagation loss $L_{dB}(l, f)$ to designate the quantity in (4) only for the case of a perfectly terminated line. We can see that a dependency of the propagation loss $L_{dB}$ on the line length $l$ is linear and is also an increasing function of the frequency $f$ as should be apparent from the expression for the propagation constant $\gamma(\omega)$ in (1). A power level of transmitted signals is also influenced by other important parameters - a diameter and constructional material of the core.

## B. *Near-end and Far-end crosstalk signals*

The term “crosstalk” generally refers to the interference that enters a communication channel through some coupling paths. If either single or multiple interferers generate a crosstalk signal, we can define a gain of the NEXT crosstalk path using a following relation

$$\left|\mathcal{H}_{NEXT}(l,f)\right|^2 = \frac{\pi^2.f^2.k_{NEXT}}{\alpha(f)}\left[1-e^{-4.\alpha(f).l}\right] \approx K_{NEXT}.f^{3/2} \tag{5}$$

where variables are given as $K_{NEXT} = 0{,}882.10^{-14}.N_d^{0{,}6}$, $N_d$ is the number of disturbing pairs (disturbers), $f$ is the frequency in Hz. An approximation on the right in (5) is valid when the line length $l$ is large and for frequency regions where the real part $\alpha(\omega)$ of the propagation constant is proportional to $\sqrt{f}$. We can also derive a gain of the FEXT crosstalk path in a similar manner using a following relation

$$\left|\mathcal{H}_{FEXT}(l,f)\right|^2 = 4.\pi^2.f^2.k_{FEXT}.l.e^{-2.\alpha(f).l} \approx K_{FEXT}.l.3280.f^2.\left|\mathcal{H}(l,f)\right|^2 \tag{6}$$

where variables are given as $K_{FEXT} = 3{,}083.10^{-20}$, $l$ is the line length in km, $f$ is the frequency in Hz and $\mathcal{H}(l, f)$ expresses the transfer function of a metallic homogeneous symmetric line.

From a data communication point of view, the NEXT crosstalk is generally more damaging than the FEXT crosstalk, because the NEXT does not necessarily propagate through the line length and thus does not experience a propagation loss of the signal [17], [21], [27].

## C. *Impulse noise signal*

In unshielded twisted pairs, various equipment and environmental disturbances such as signaling circuits, transmission and switching gear, electrostatic discharges, lightning surges and so forth can generate an impulse noise. The impulse noise has some reasonably well-defined characteristics. Features of the typical impulse noise can be summarized as follows:

- occurs about 1-5 times per minute (on an average 4 times per minute),
- peak values in the range 2 - 33 mV,
- most of energy concentrated below 40 kHz,
- time duration in the range 30 - 150 μs.

Of course, mentioned features don’t characterize all possible impulse noise signals. In the simulation model, therefore, characteristics of the impulse noise signal can be randomly varied.

## IV. THE ENVIRONMENT OF POWER DISTRIBUTION CABLES

## A. *The multipath signal propagation*

The PLC transmission 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 a range from a few ohms to some kiloohms, That’s why the PLC signal propagation does not only take place along a direct line-of-sight path between a transmitter and a receiver but also additional paths are used for a signal spreading. This multipath scenario must be seriously considered. The simulation model can be simplified if we approximate 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 [8], [28].

## B. *The signal attenuation*

Characteristics of the PLC transmission environment focused on the multipath signal propagation, the signal attenuation, the noise scenario and the electromagnetic compatibility are introduced in [20]. First, we can present basic characteristics of the PLC channel.

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

$$\gamma(\omega) = \sqrt{(R + j.\omega.L)\cdot(G + j.\omega.C)} = \alpha(\omega) + j.\beta(\omega) \tag{7}$$

depending on the primary cable parameters $R, L, G, C$.

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

$$\mathcal{H}(f)=\frac{\mathcal{U}(x=l)}{\mathcal{U}(x=0)}=e^{-\gamma(f)\cdot l}=e^{-\alpha(f)\cdot l}e^{-j\cdot\beta(f)\cdot l} \tag{8}$$

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 a dissipation factor of the dielectric material (usually PVC) and therefore proportional to $f$. With typical geometry and material properties, we can suppose $G << \omega.C$ and $R << \omega.L$ in the frequency range of interest. Then, cables can be regarded as low loss ones with real valued characteristic impedances and a simplified expression for the complex propagation constant $\gamma$ can be introduced

$$\gamma(f)=k_1\cdot\sqrt{f}+k_2\cdot f+j\cdot k_3\cdot f=\alpha(f)+j.\beta(f) \tag{9}$$

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 $\alpha(f)$ is found in a form

$$\alpha(f)=a_0+a_1\cdot f^k \tag{10}$$

that is able to characterize the attenuation of typical power distribution lines with only three parameters, being easily derived from the measured transfer function [28]. Now the propagation loss $L_{dB}$ is given at the length $l$ and the frequency $f$ as

$$\begin{aligned} L_{dB}(l,f)&=-20.\log_{10}\left|\mathcal{H}(l,f)\right|=\frac{20}{\ln 10}.l.\alpha(f)=\frac{20}{\ln 10}.l.(a_0+a_1.f^k) \qquad [Np]\\ &\approx 8{,}686.l.(a_0+a_1.f^k) \qquad [dB]\end{aligned} \tag{11}$$

We can see a linear dependence of the propagation loss $L_{dB}$ on the line length $l$. Parameters $a_0$, $a_1$ and $k$ are characterized by measurements of the transfer function $\mathcal{H}(f)$ that is much easier then the measurement of primary line parameters $R$, $L$, $C$, $G$. If we now merge a signal spreading on all paths together (we can use a superposition), we can receive an expression for the frequency response $\mathcal{H}(f)$ in a form

$$\mathcal{H}(f)=\sum_{i=1}^{N} g_i\cdot a(l_i,f)\cdot e^{-j.2.\pi.f.\tau_i} \tag{12}$$

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. The delay $\tau_i$ of the transmission line can be calculated from the dielectric constant $\varepsilon_r$ of insulating materials, the light speed $c$ and the line length $l_i$ as follows

$$\tau_i=\frac{l_i\cdot\sqrt{\varepsilon_r}}{c} \tag{13}$$

### C. *The noise scenario*

Unfortunately, in a case of the PLC environment, we can't stay only with the additive white Gaussian noise. The noise scenario is much more complicated, since five general classes of noise can be distinguished in power distribution line channels. These five classes are:

1. *Colored background noise* – caused by a summation of numerous noise sources with low powers. Its PSD varies with the frequency in a range up to 30 MHz (significantly increases toward to lower frequencies) and also with the time in terms of minutes or even hours.
2. *Narrowband noise* – caused by ingress of broadcasting stations. It is generally varying with daytimes and consists mostly of sinusoidal signals with modulated amplitudes.
3. *Periodic impulsive noise asynchronous with the main frequency* – caused by rectifiers within DC power supplies. Its spectrum is a discrete line spectrum with a repetition rate in a range between 50 and 200 kHz.
4. *Periodic impulsive noise synchronous with the main frequency* – caused by power supplies operating synchronously with the main cycle. Its PSD is decreasing with the frequency and a 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. Fortunately, the average disturbance ratio is well below 1 percent, meaning that 99 percent of the time is absolutely free of the asynchronous impulsive noise.

The noise types 1, 2 and 3 can be summarized as background noises because they are remaining 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 more stronger and may cause single-bit or burst errors in a data transmission [9], [10].

## V. THE SIMULATION MODEL FOR THE VDSL AND PLC TECHNOLOGIES

For considering of the signal transmission on metallic homogeneous lines by means of the VDSL and PLC technologies, it is necessary comprehensively to know characteristics of negative environmental influences and features of applied modulation techniques. It is difficult to realize of the exact analytical description of complex systems such as the VDSL and PLC systems in the real environment of local access networks. In addition, due to dynamical natures of some processes, it is not suitable. For analyzing of various signal processing techniques used by the VDSL and PLC technologies, a suitable and flexible enough tool are computer simulations and modeling schemes of real environmental conditions at the signal transmission.

For modeling of the VDSL and PLC transmission paths, we used the software program *Matlab* together with additional libraries like *Signal Processing Toolbox* and *Communication Toolbox*. The realized model (Fig. 1) represents the high-speed data signal transmission in both downstream and upstream directions for the VDSL environment utilizing metallic homogenous lines and for the PLC environment utilizing power distribution lines. This VDSL environment model is the enhanced version of the ADSL environment model introduced [17]. New features of this simulation model are VDSL transmission characteristics and applications of pre-coding techniques and trellis coded modulations. The realized model also represents a high-speed signal transmission in the PLC system utilizing outdoor power distribution lines in downstream and upstream directions [20]. The signal transmission over outdoor power distribution lines represents the transmission between a transmitter in the transformer substation and a receiver in the customer premises.

The requested analysis can be based on computer simulations that cover the most important features and characteristics of the real transmission environment for the VDSL and PLC technologies and result in searching for the optimal combination of advanced modulation, encoding and pre-coding techniques. On Fig. 2, a structure of the VDSL environment block is introduced. Courses of particular PSD noises in this environment realized in the appropriate simulation model are graphically presented on Fig. 3. On Fig. 4, a structure of the PLC environment block is introduced. Courses of particular PSD noises in this environment realized in the appropriate simulation model are graphically presented on Fig. 5.

Basic functional blocks realized in the simulation model are shown on Fig. 1. The VDSL simulation model can be divided into the three main parts:

1. A transmitting part - it is responsible for encoding (using various techniques), for interleaving and for modulating (using various approaches) of signals into a form suitable for the transmission channel.
2. A transmission channel (metallic homogenous lines, power distribution lines) - this part of the model realized appropriate negative influences on the transmitted signal. Above all, it goes about a propagation loss, a signal distortion, crosstalk noises, white and impulse noises, the radio interference for the VDSL environment. For the PLC environment, it goes about the propagation loss, the signal distortion, impulsive, coloured and narrow-band noises. Because these negative influences expressively interfere into the communication path and represent its main limiting factors, they present a critical part of the model and, therefore, it is necessary exactly to recognize and express their characteristics by correct parameters.
3. A receiving part - it is conceptually inverted in a comparison with the transmitter. Its main functions are the signal amplification, demodulation, de-interleaving, removing of the inter-symbol interference and the correction of errored information bits.

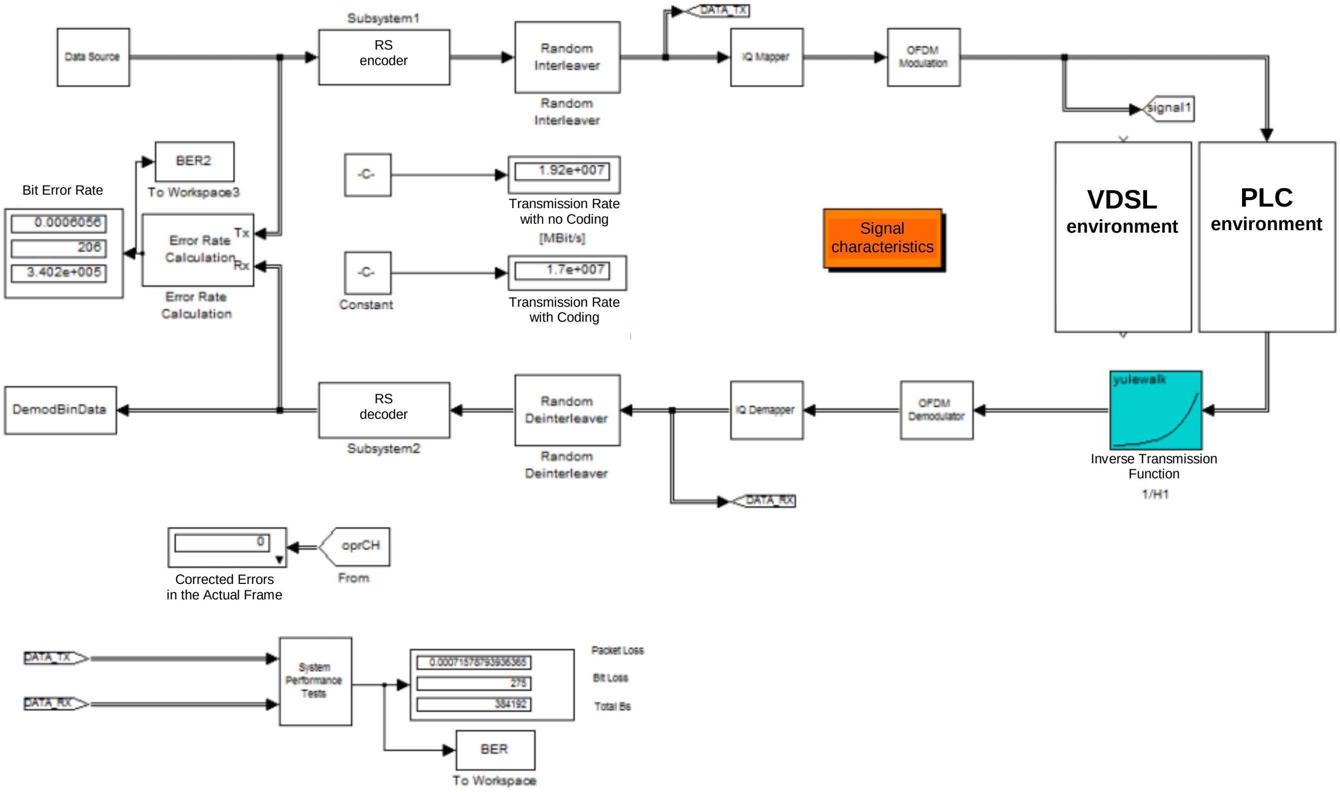

Fig. 1 The Simulink model of VDSL and PLC transmission paths

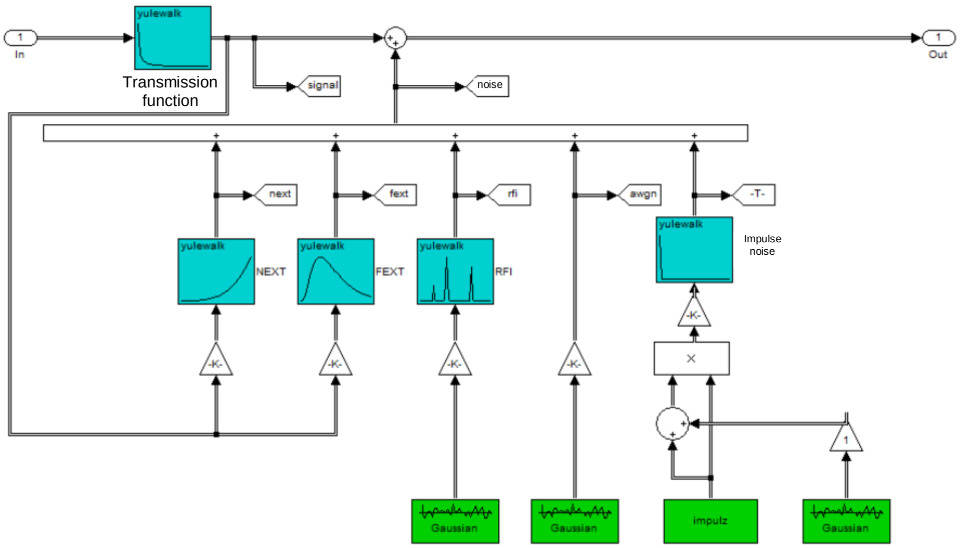

Fig. 2 The VDSL environment block

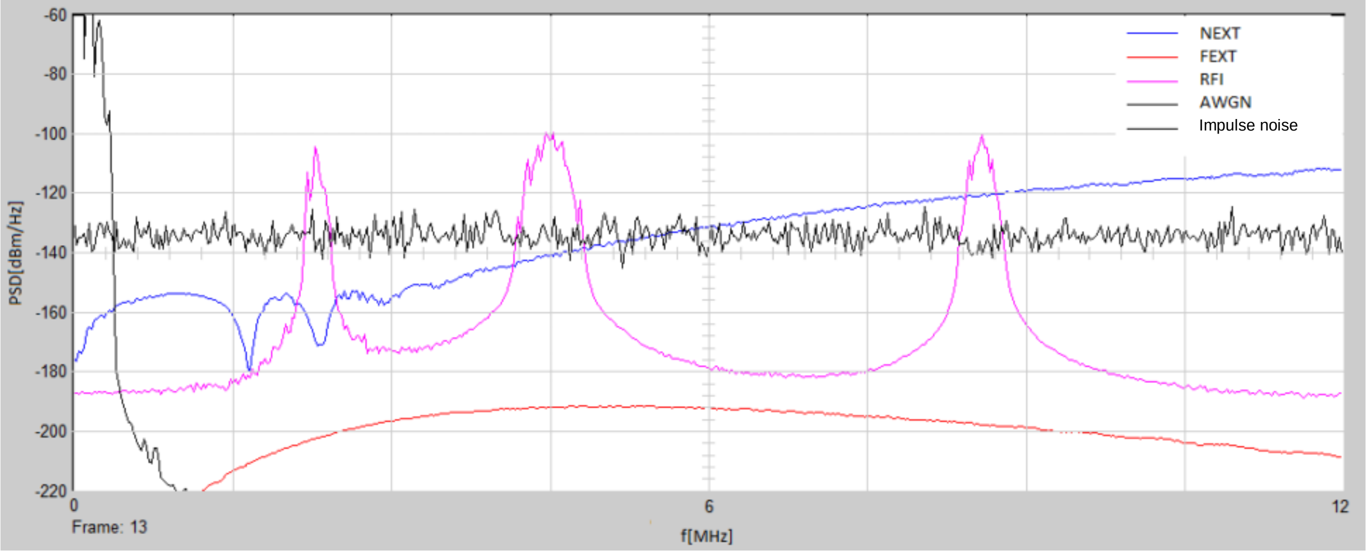

Fig. 3 Particular PSD noises in the VDSL environment

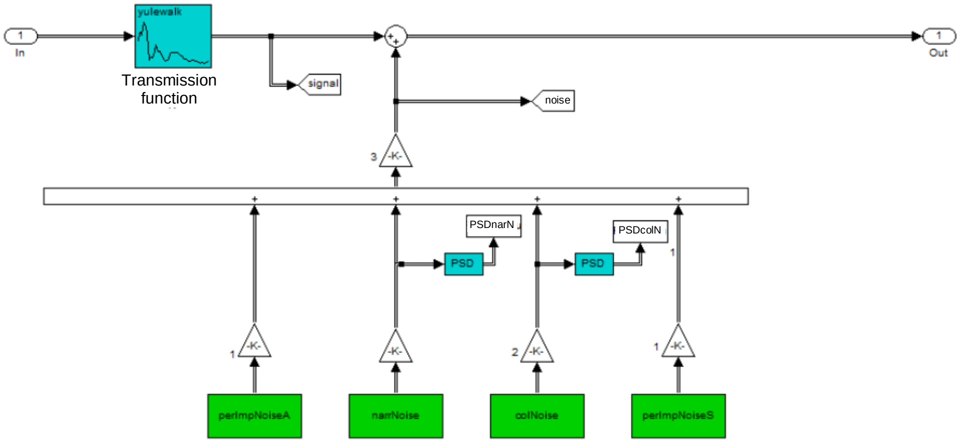

Fig. 4 The PLC environment block

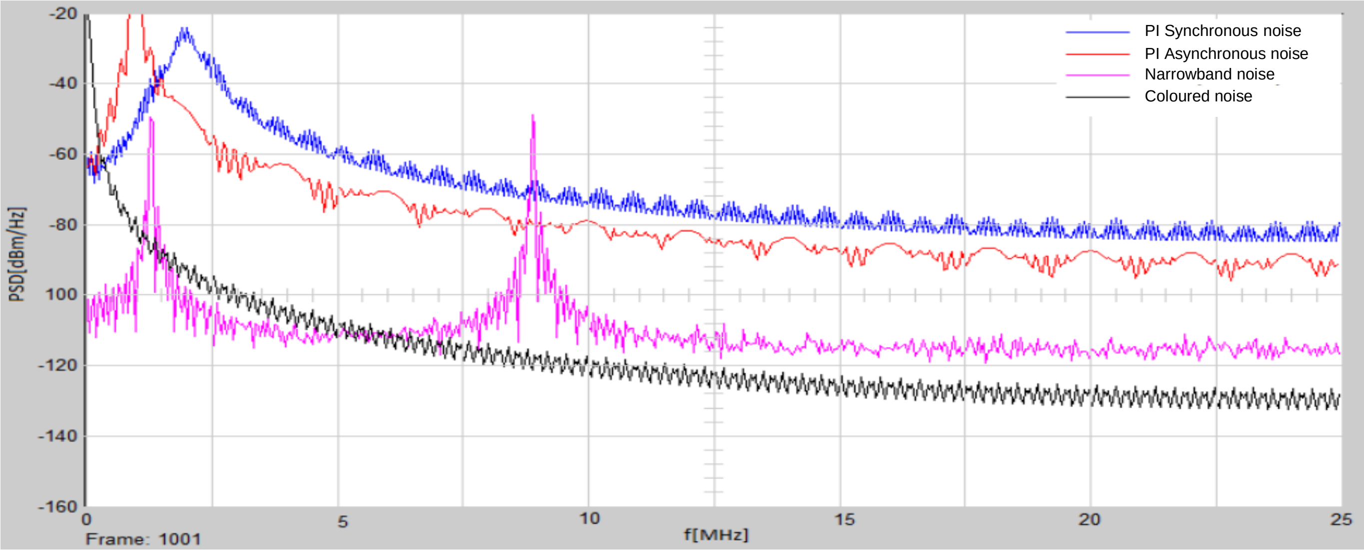

Fig. 5 Particular PSD noises in the PLC environment

## VI. Examples of Analytical results

For particular simulation models presented in [24], specific parameters and power levels of concrete noise types are setting equally for both environments and stay fixed for all executed simulations. The average noise power varies between 20 - 40 μW in the PLC environment and between 10 - 15 μW in the VDSL environment. A fact that the noise power is not absolutely constant is caused by repeating of the noise generation before each simulation and by stochastic amplitude and position from a central frequency of the narrowband noise. Similarly, the FEXT and NEXT noise powers are depending on the input signal power. This input signal power is limited due to conditions of the spectral compatibility in the VDSL environment. The PSD input signals doesn't exceed a value of - 50 dBm/Hz. The bandwidth of transmission environments is setting with respect to norms and recommendations. The bandwidth of particular subchannels is changing according to a number of utilized modulation states (Table I) so that the total VDSL bandwidth is equal to 12,8 MHz, the total PLC bandwidth is 25,6 MHz.

Table I

Features of the Sub-channel Bandwidth

| Number of subchannels | 64 | 128 | 256 | 512 | 1024 |
|---|---|---|---|---|---|
| *VDSL subband [kHz]* | 200 | 100 | 50 | 25 | 12,5 |
| *PLC subband [kHz]* | 400 | 200 | 100 | 50 | - |

For given environments, DMT and OFDM modulation techniques were compared.

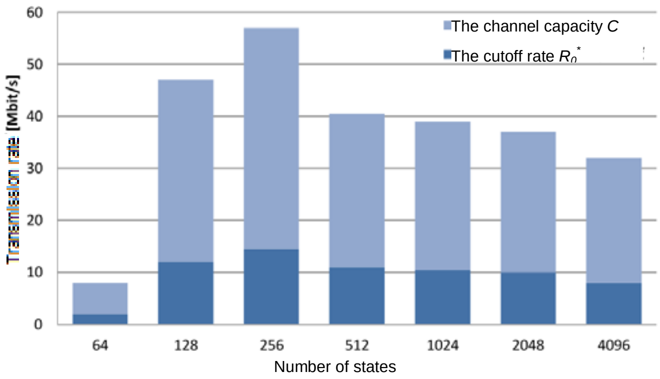

Fig. 6 A dependency of transmission rates on the number of DMT states – the PLC environment, the line length 100 m

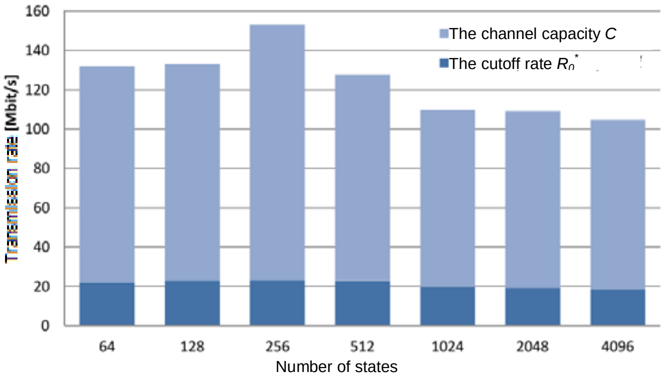

Fig. 7 A dependency of transmission rates on the number of DMT states – the VDSL environment, the line length 100 m

The first target of simulations is determining an optimal number of DMT states with the most effective utilization. As we can see (Fig. 6 and 7), an optimal number of states is the 256-DMT for both environments. For lower number of subchannels, more bits must be allocated for maintaining transmission rates at same frame size as in a case of higher modulation schemes. More bits in the subchannel bring a worse resistance against bit error rates. Due to this reciprocal relation, lower transmission rates can be achieved at the 64- and 128-DMT modulation schemes. This effect is more expressive in the PLC environment with much more noise influences primarily from impulses. At higher modulation schemes, a bandwidth of the subchannel is divided by 2, however a number of bits in the frame size is decreasing. The reason is caused by the bit loading technique based on the SNR value in a specific subband. For narrower subbands, the SNR ratio can be decreased under the minimum possible number of allocated bits. In this case, some subchannels fall out from information bit transmitting and the total transmission rate rapidly goes down. This behavior can be found for both – the channel capacity and the cut-off rate.

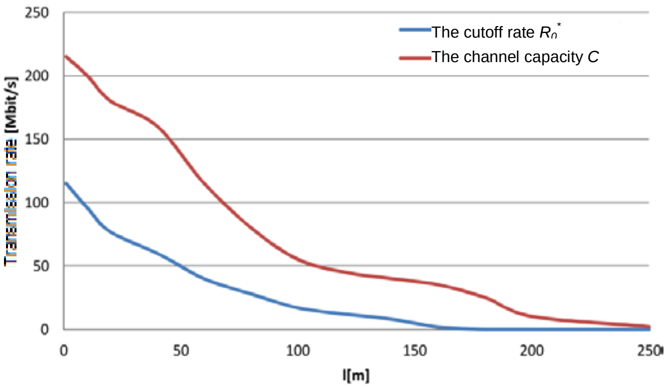

Fig. 8 A dependency of transmission rates on the line length – the PLC environment, the OFDM modulation

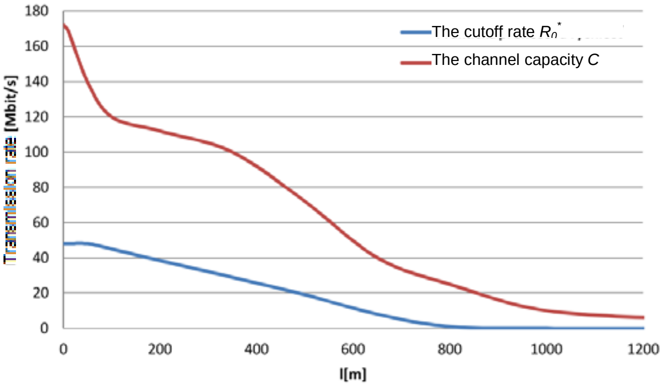

Fig. 9 A dependency of transmission rates on the line length – the VDSL environment, the OFDM modulation

After selecting the optimal number of states for the OFDM modulation technique, a line length is changed for both VDSL and PLC environments for determining its influence on transmission rates (Fig. 8 and 9). Results clearly declare that the OFDM reaches much better values of transmission rates especially for the PLC environment, where the cut-off rate exceeds 50 Mbit/s at the 50 m line length. It's more than double increase to the DMT.

## VII. THE ENVIRONMENT OF OPTICAL FIBERS

### A. *Transmission parameters of the optical fiber*

Basic transmission factors of the standard optical single-mode fiber utilized in telecommunications are following:

- linear effects - the attenuation,
  - dispersions (CD, PMD).
- nonlinear effects - Kerr nonlinearities (FWM, SPM, XPM, XPolM),
  - Scattering nonlinearities (SRS, SBS).

Linear effects represent a majority of losses at the optical signal transmission signal through the optical fiber. These linear effects are mainly caused by the attenuation and the dispersion. The attenuation limits a distance of the optical signal transmission and the dispersion influences transmission rates of optical signals.

Nonlinear effects in the optical fiber may potentially have a significant impact on the performance of WDM optical communication systems. In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels and they limit the maximum power per channel, the maximum bit rate and the system reach [14].

These effects play an important role in a transmission of optical pulses through the optical fiber. We can classify nonlinear effects:

a) *Kerr nonlinearities*, which is a self-induced effect in that the phase velocity of waves depends on the wave's own intensity. The Kerr effect describes a change in the refractive index of the optical fiber due to an electrical perturbation. Due to the Kerr effect, we are able to describe following effects :
   - Four Wave Mixing FWM - the effect, in which mixing of optical waves rise the fourth wave that, can occur in the same wavelength as one of mixed waves.
   - Self-Phase Modulation SPM - the effect that changes the refractive index of the transmission media caused by an intensity of the pulse.
   - Cross-Phase Modulation XPM - the effect where a wave of the light can be changed by the phase of another wave of the light with different wavelengths. This effect causes a spectral broadening.

b) *Scattering nonlinearities*, which occur due to an inelastic photon scattering to the lower energy photon. We can say that energy of the light wave is transferred to another wave with different wavelengths. Two effects appear in the optical fiber:
   - Stimulated Brillouin and Raman scattering - effects that change a variance of the light wave into different waves when intensity reaches certain limit.

Knowing which fundamental linear and nonlinear interactions dominate is helpful to conceive techniques that improve a transmission of optical signals, including advanced modulation formats, a digital signal processing and a distributed optical nonlinearity management.

### *B. The attenuation*

The most important parameter of optical fibers is the attenuation that represents a transmission loss. In practical way, it is a power loss that depends on a length of the transmission path. The attenuation leads to a reduction of the signal power as the signal propagates over some distance. When determining the maximum distance that a signal propagate for a given transmitter power and receiver sensitivity, the attenuation must be considered. The total signal attenuation $a$ [dB] defined for a particular wavelength can be expressed as

$$a[dB] = 10\log_{10}\frac{P_i}{P_0} \tag{14}$$

where $P_i$ is the input power and $P_0$ is the output. The attenuation coefficient $\alpha$ [dB/km] of the optical fiber can be obtained by measuring the input and the output optical power levels. The specific attenuation of the optical fiber along the fiber length $L$ [km] can be expressed as

$$\alpha[dB/km] = \frac{10\log_{10}\frac{P_i}{P_0}}{L} = \frac{a}{L} \tag{15}$$

where $L$ is the optical fiber's length in [km]. For the link length $L$, the $P(L)$ must be greater than or equal to the receiver sensitivity $Pr$.

The attenuation of optical fibers is mainly caused by material absorption losses, radiation scattering and by bending losses. The fiber loss is not only source of the optical signal attenuation along transmission lines. Fiber splices and fiber connectors also cause the signal attenuation. The number of optical splices and connectors depends on the transmission length and must be taken into account unless the total attenuation due to fiber joints is distributed and added to the optical fiber attenuation.

### *C. Dispersions*

The dispersion is a widening of the pulse duration as it travels through the optical fiber. We distinguished two basic dispersive forms - the intermodal dispersion and the chromatic dispersion. Both cause an optical signal distortion in multimode optical fibers, whereas a chromatic dispersion is the only cause of the optical signal distortion in single-mode fibers.

The chromatic dispersion CD represents a fact that different wavelengths travel at different speeds, even within the same mode. In a dispersive medium, the index of refraction $n(\lambda)$ is a function of the wavelength. Thus, certain wavelengths of the transmitted signal will propagate faster than other wavelengths. The CD dispersion is the result of material dispersion, waveguide dispersion and profile dispersion.

The chromatic dispersion is caused by different time of the spreading wave through fiber for a different wavelength and it depends on the spectral width of the pulse. As mentioned before, optical fiber represents the transmission system. Then the system has transfer function $\mathscr{H}_0(\omega)$given by equation (16). We assume that $|\mathscr{H}_0(\omega)| = 1$ and we can expand phase into the Taylor series as is given by equation (17). If we consider first two coefficients, then we can write transfer function as given by equation (18).

$$\mathscr{H}_0(\omega) = \left|\mathscr{H}_0(\omega)\right|.e^{-j.\varphi(\omega)} \tag{16}$$

$$\varphi(\omega) = -\left[\varphi_0 + \frac{d\varphi}{d\omega}(\omega-\omega_0) + \frac{1}{2}\frac{d^2\varphi}{d\omega^2}(\omega-\omega_0)^2 + \frac{1}{6}\frac{d^3\varphi}{d\omega^3}(\omega-\omega_0)^3 \ldots\right] \tag{17}$$

$$\mathscr{H}_0(\omega) = e^{-j.\varphi_0}.e^{-j.\frac{d\varphi}{d\omega}(\omega-\omega_0)}.e^{-j.\frac{d^2\varphi}{d\omega^2}(\omega-\omega_0)^2} \tag{18}$$

where $\mathscr{H}_0(\omega)$ is a transfer function,$\varphi_0$ is an initial phase of the system and $\omega_0$ is an initial angular frequency

After few operations, we can obtain time $t$ from the transfer function, which represents the travel time of the pulse through the fiber, the signal phase shift $\Delta\varphi$ and the Group Velocity Dispersion GVD coefficient. These parameters are described by two equations:

$$t = \frac{1}{2\pi}\frac{d\varphi}{df_m} \tag{19}$$

$$GVD = \frac{1}{2\pi}\frac{d^2\varphi}{df_m^2} \tag{20}$$

The chromatic dispersion causes broadening and phase changing of the signal. Then pulses at the end of optical fibers may start to overlap and this effect is called as the Inter Symbol Interference ISI.

The polarization mode dispersion PMD is another complex optical effect that can occur in optical single-mode fibers. The SMF support two perpendicular polarizations of the original transmitted signal. If a fiber is not perfect, these polarization modes may travel at different speeds and, consequently, arrive at the end of the fiber at different times. The difference in arrival times between the fast and slow mode axes is the PMD. Like the CD, the PMD causes digitally-transmitted pulses to spread out as the polarization modes arrive at their destination at different times.

$$\Delta\tau = D_{PMD} . \sqrt{L} \tag{21}$$

The main problem with the PMD in optical fiber systems is its stochastic nature, letting the principal state of polarization PSP and the differential group delay DGD vary on timescales between milliseconds and months.

The resulting overall dispersion is composed of chromatic dispersion and polarization mode dispersion path and is given by the resulting relation [18], [19]

$$D = \sqrt{D_{CD}^2 + D_{PMD}^2} \tag{22}$$

### D. *The Four Wave Mixing effect*

The four wave mixing FWM is a parametric interaction among waves satisfying a particular phase relationship called the phase matching. This nonlinear effect occurs only in systems that carry more wavelengths through the optical fiber and it is classified as a third-order distortion phenomenon. In this case, we are assuming that three linearly polarized monochromatic waves with angular frequencies $\omega_j$ (j = 1, 2, 3) are propagating. If we consider third-order polarization vector ***P*** given by equation (23) that characterizes the medium and it is a function of the electrical field, and simplified it, we obtain his components: three components have the frequencies of the input field, the others have frequencies $\omega_k$ given by equation (24)

$$\overline{P} \approx \varepsilon_0 \left\{ \chi^{(1)} \overline{E} + \chi^{(2)} : \overline{E}\,\overline{E} + \chi^{(3)} \vdots \overline{E}\,\overline{E}\,\overline{E} \right\} \tag{23}$$

where $\chi^{(1)}$ is the linear susceptibility, $\chi^{(2)}$, $\chi^{(2)}$ is the second- and the third-order susceptibility and ***E*** represent vector of electrical field of mode.

$$\omega_k = \omega_1 \pm \omega_2 \pm \omega_3 \tag{24}$$

As we can see from the equation (24), nonlinear interaction generates new frequency components of the material polarization vector, which can interfere with input fields if a phase matching condition is obtain. The most frequency components fall away from our original bandwidth or near it. Frequency components that directly overlap with bandwidth will cause an interference with original waves.

The power of new generated waves can be obtain by solving coupled propagation equations of four interacting waves. We assume that the new generated FWM wave is mainly depended on three nearest waves of the light, so the power $A_k^2$ at the frequency $\omega_k = \omega_1 + \omega_2 - \omega_3$ is given by

$$A_k^2 = 4\eta\gamma^2 d_e^2 L_e^2 A_1^2 A_2^2 A_3^2 \, e^{-\alpha l} \tag{25}$$

where factor $\eta$ is the FWM efficiency, $\gamma$ is the nonlinear coefficient, $L_e$ is the effective length, $A_1^2(z)$, $A_2^2(z)$, $A_3^2(z)$ are powers of input waves, $l$ is the fiber length, $\alpha$ is the attenuation and $d_e$ the so-called degeneracy factor (equal to 3 if the degenerative FWM is considered, 6 otherwise).

The power of the FWM represents sum of the partial power from interacting waves, which degenerate the signal. This power of the FWM is different for each channel and change with the parameter of interacting signals.

As we can see from the equation (25), the nonlinear effect FWM is mainly rising with increasing powers of interacting signals and the shape of the FWM effect depends on the modulation and the bit rate of these signals. If input powers of signals are too high, the scattering nonlinearities occur and transmission would not be possible. However, the scattering nonlinearities are not presented. The power also depends on the channel spacing and on the dispersion. If we use negative dispersion fibers, the FWM effect will be more intensive and the SNR will fall to values unsuitable to transmit. If we used standard fibers, we can decrease the FWM effect, but we cannot use high bit rates due the dispersion [5], [18], [19].

### E. *The Self-Phase Modulation effect*

The self-phase modulation SPM has an important impact on high data speed communication systems that use the dense wavelength division multiplexing. The SPM effect occurs due to the Kerr effect in which the refractive index of optical fiber increases with the optical intensity decreasing the propagation speed and thus inducts the nonlinear phase shift. The relation between intensity and refractive index can be described

$$n_r = n_{r0} + \overline{n_2} I(t) \tag{26}$$

where $n_r$ is the refractive index dependent on intensity, $n_{r0}$ is the linear refractive index, $n_2$ is the nonlinear refractive index and $I(t)$ is the intensity.

This varying parameter $n_r$ causes the SPM effect in which the signal phase propagating through the optical fiber changes with the distance and can be described by

$$\phi = \left( n_0 z + \phi_0 \right) + \frac{2\pi}{\lambda} \overline{n_2} I(t) z \tag{27}$$

where $\Phi_0$ represents the initial phase.

The equation (27) shows that the different phase shift occurs during the pulse propagation caused by the intensity dependence of phase fluctuations. This variation in phase with time is responsible for changes in frequency spectrum by following equation

$$\omega = \frac{d\phi}{dt} \tag{28}$$

If we assume the variation of phase with intensity pulse then we can write following equation

$$\omega' = \omega_0 + \frac{d\phi}{dt} \tag{29}$$

where $\omega'$ is the signal frequency affected with the SPM effect, $\omega_0$ is the initial signal frequency. This variation in signal frequency is called the frequency chirp.

The SPM effect impact becomes more significant with increasing an optical fiber length, especially when optical amplifiers such as EDFA and RAMAN are used [6], [18], [19].

### *F. The Cross-Phase Modulation Effect XPM*

The cross-phase modulation XPM is very similar to the SPM in which the intensity from different wavelength channels changes the signal phase and thus the XPM occurs only in WDM systems. In fact, the XPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels. The XPM effect results to spectral broadening and distortion of the pulse shape.

If we assume *N* signal having different carrier frequencies propagating in an optical fiber, the nonlinear signal phase depends on signal intensities at different frequencies. This phase shift can be described by expression

$$\Delta\phi_i = \frac{2\pi \overline{n_2} z}{\lambda}\left[ I_i(t) + 2\sum_{i \neq j} I_j(t) \right] \tag{30}$$

where the first term in bracket represents the SPM effect and the second term represents XPM effect.

In the equation (30), the factor 2 has its origin in a form of the nonlinear susceptibility and represents the XPM twice as effective as the SPM for the same power amount. The XPM effect affects the signal only the interacting signals superimpose in time. The XPM effect can decrease a system performance even greater than the XPM effect, especially in case of 100 channels systems [6], [18], [19].

## VIII. THE SIMULATION MODEL FOR THE OPTICAL COMMUNICATIONS

For modeling of the optical transmission path, we used the software program *Matlab 2014a Simulink* together with additional libraries like *Communication Blockset* and *Communication Toolbox*. The realized model (Fig. 10) represents the signal transmission in the environment utilizing optical fibers for very high-speed data signals in both directions. Optical communication technologies will always be facing the limits of high-speed signal processing and modulation, which is an important factor to take into account when discussing advanced optical modulation formats. The main task of the simulation model is an analysis of various modulation and encoding techniques.

Basic functional blocks realized in the optocommunication simulation model can be divided into the three main parts:

1. A transmitting part - it is responsible for the generating and for modulating of generated signals according to required information inputs into a form suitable for the transmission channel. The modulation block contains a basic set OOK modulation and other variations of modulation techniques.
2. A transmission channel (the optical fiber) - this part of the model realizes negative influences on the transmitted signal. Because these negative influences expressively interfere into the communication and represent its main limiting factors, they present a critical part of the model and, therefore, it is necessary exactly to recognize and express their characteristics by correct parameters. At the present time, the CD and the PMD dispersion blocks are realized, where the group velocity dispersion GVD and differential group delay DGD parameters are used to characterize and simulate the linear CD and PMD effects. From Kerr nonlinearities, the FWM block realizes this effect that mainly depends on the power of adjacent-channel neighbors, the wavelength channel spacing and the dispersion only in WDM systems. The SPM block changes a signal phase and frequency depending on signal intensity changes. The XPM block is similar to the SPM and depends on signal intensity changes of adjacent-channel neighbors. For scattering nonlinearities, an influence of the signal intensity caused by these effects realized in the SBS and SRS blocks change the signal envelope and impact on the optical signal-to-noise ratio OSNR.
3. A receiving part - it is conceptually inverted in a comparison with the transmitter. At the receiver side, a signal is demodulated by appropriate demodulator and the BER ratio is calculated. Also, blocks for graphical presenting of transmitted optical signals can be utilized.

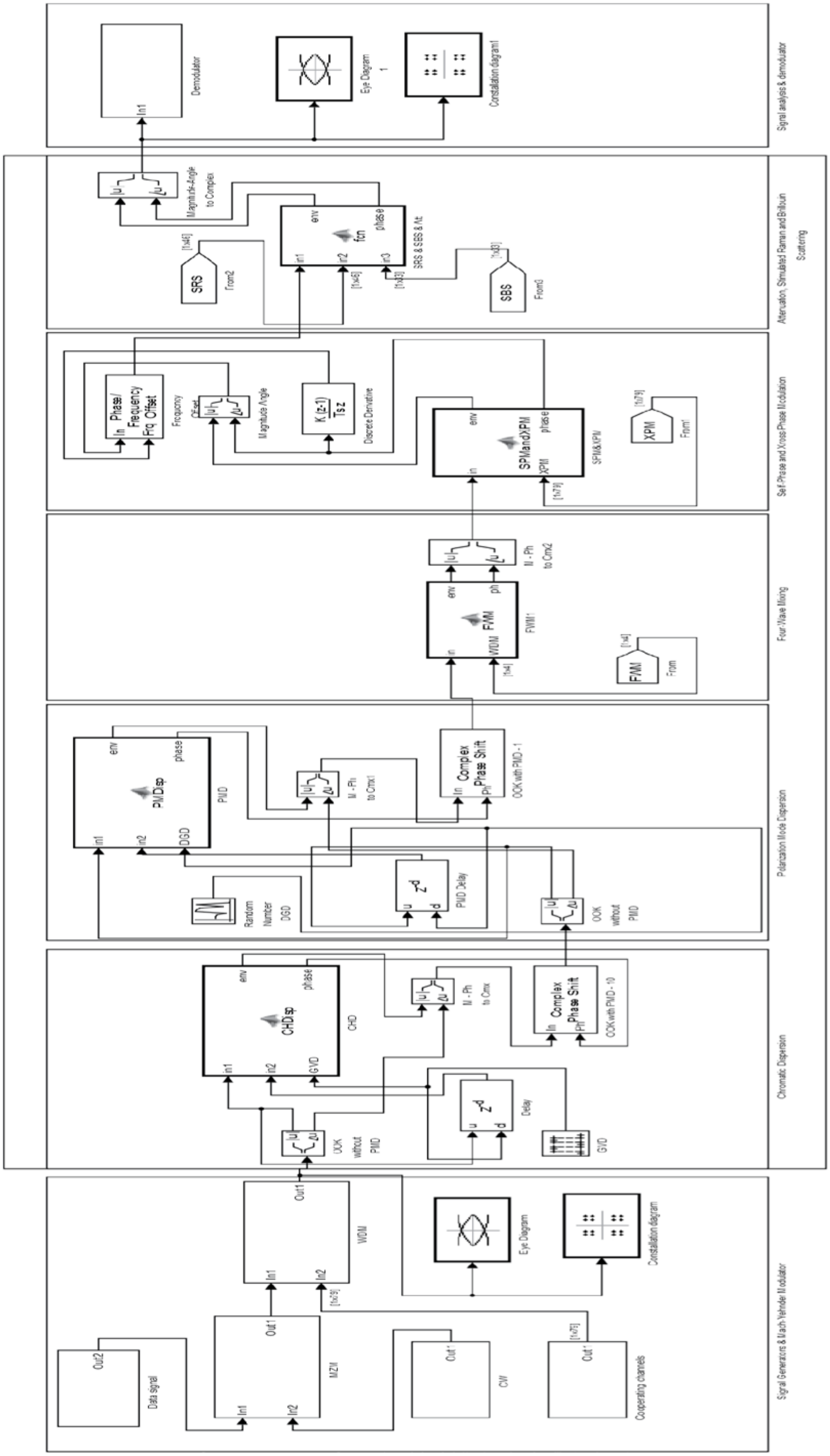

Fig. 10 The Simulink model of the optical transmission path

## IX. EXAMPLES OF RESULTS

For this simulation model, specific parameters and power levels of concrete linear and nonlinear effects are setting suitable for analyzing their influences on optical signals in WDM transmission systems [5], [6]. The simulation model is realized for the single mode non-zero dispersion-shifted optical fiber with parameters satisfying the ITU-T G.652 specification. Overall, partial contributions of environmental influences are relatively very small comparing to the total signal degradation. For presenting functionalities of the optical transmission path, a graphical representation called the eye diagram can be successfully utilized. The eye diagram is an oscilloscope displaying a received signal repetitively sampled with the bit interval. The simulation of the signal transmission in the optical transmission medium will be demonstrated using the initial on/off keying OOK. Assuming the OOK modulation is noncoherent, the demodulation process changes the intensity of optical signals into the electric domain directly.

On Fig. 11, eye diagrams corresponding to OOK optical signals at the 10 Gbit/s transmission rate before transmitting into the optical path (left) and after transmitting in the 60 km optical fiber length influenced by all mentioned environmental effects (right) are presented. Signals are received in the Demodulator block by the direct detection. For modeling a noise in this block, the AWGN channel with the 20 dB SNR level is assumed. For this case, the demodulated BER value is more than $10^{-12}$.

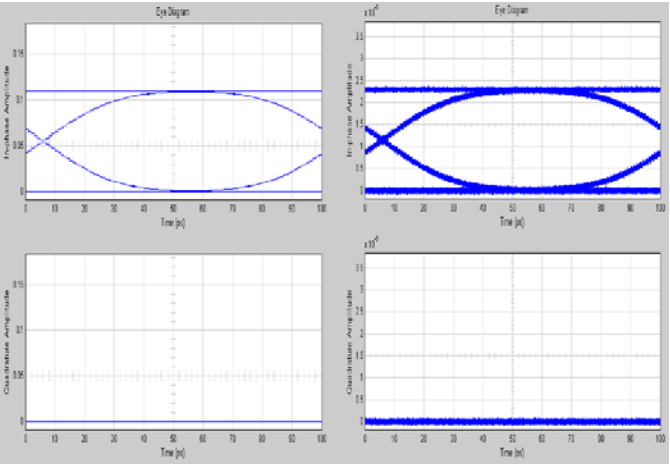

Fig. 11 Eye diagrams for OOK optical signals before (left) and after (right) transmitting in the 60 km the optical transmission path

On Fig. 12, eye diagrams corresponding to optical signals at the 10 Gbit/s transmission rate after transmitting in the 90 km optical fiber length (left) and after transmitting in the 160 km optical fiber length (right) influenced by all mentioned environmental effects are presented. Again, signals are received in the Demodulator block by the direct detection and the assumed 20 dB SNR noise level is the same as in the previous case. However, received signals are more attenuated and noisy. For these cases, the demodulated BER values with more than $10^{-9}$ are insufficient.

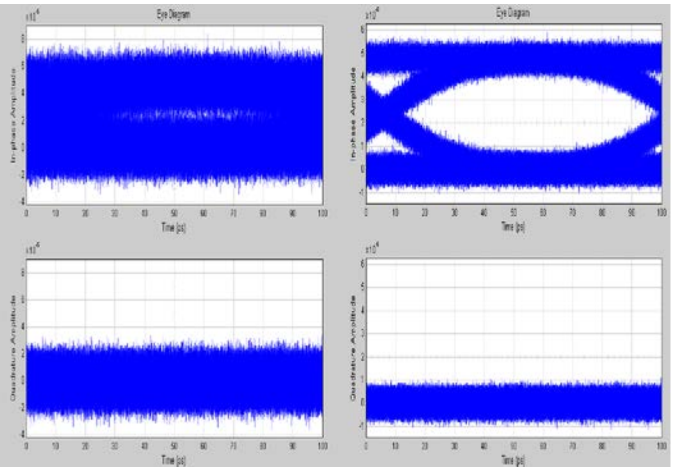

Fig. 12 Eye diagrams for OOK optical signals after transmitting in the 90 km (left) and 160 km (right) the optical transmission path

On Fig. 13, constellation diagrams related to the OOK modulation technique for optical signals at the 10 Gbit/s transmission rate before (left up) and after transmitting in the 60 km (right down), 90 km (right up) and 160 km (left down) optical fiber lengths influenced by all linear and nonlinear effects are presented. As can be seen, a spreading of constellation points is more expressive with increasing fiber lengths.

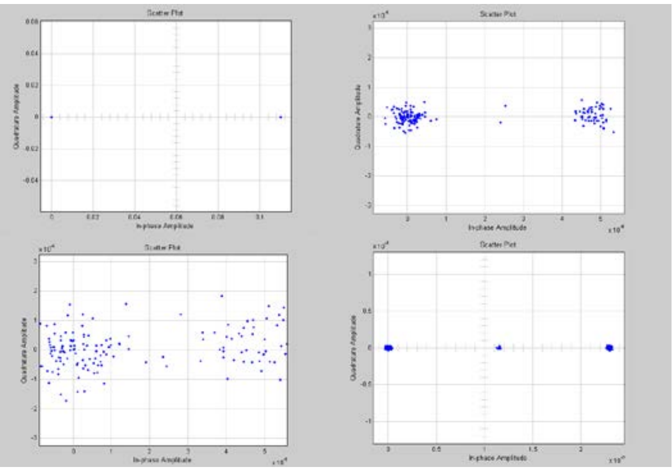

Fig. 13 Constellation diagrams for OOK optical signals before (left up) and after transmitting in the 60 km (right down), 90 km (right up) and 160 km (left down) the optical transmission path

On Fig. 14, a complete frequency spectrum of 80 optical transmission channels (red) in the simulation model is presented together with the analyzed channel at the 193,4 THz frequency (blue).

Using this simulation model, a possible utilization of advanced signal processing techniques in optical transmission systems can be simulated. There can be different modulation and/or encoding techniques independently or in combinations analyzed.

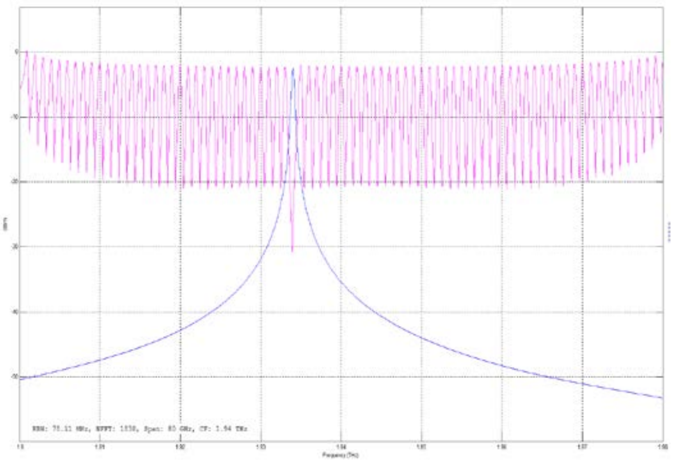

Fig. 14 The frequency spectrum of 80 optical transmission channels (red) and the analyzed 193,4 THz frequency channel (blue)

## X. CONCLUSION

The first, this paper analyzes basic features of the real transmission environment for metallic homogeneous lines and presents possibilities for modeling and simulating of the information signal transport in this environment by means of the VDSL technology. We focused on the determination and the analysis of concrete characteristic features for substantial negative influences of internal and external environments and on the representation of frequency dependencies of transmitted VDSL signals.

The second, this paper analyzes basic features of the real transmission environment for the outdoor power distribution lines and presents possibilities for modeling and simulation of the information signal transmission in this environment by means of the PLC technology. We focused on transmission characteristics of the PLC channel, namely the multipath signal propagation, the signal attenuation and the interference scenario revealing different classes of the impulsive noise. We created a model of the complex frequency response in a range from 500 kHz up to 30 MHz. Moreover, we realized experimental measurements for verification of the parametric model for reference channels.

For given environments, examples of analytical results from a comparison of DMT and OFDM modulation techniques were presented. It is obvious from presented results that using of concrete modulation technique is depending on many factors, for example the access line length. The PLC environment has more expressive negative influences from numerous reflections and impulse noise occurrences with high amplitudes. If we want to offer real transmission rates at least 10 Mbit/s for subscribers, then the line length in the PLC environment is limited up to 150 m. In the VDSL environment, this transmission rate can be reached also at the 800 m line length of homogeneous symmetric lines. Indeed, the PLC technology reaches higher real transmission rates at line lengths up to 50 m caused by the influence of FEXT crosstalk on short VDSL lines.

Basic features and characteristics of negative environmental influences at the signal transmission in VDSL and PLC environments can be used for modeling spectral characteristics of signals on the transmission path. The VDSL and PLC simulation models allow determining main problems that can arise at the VDSL or PLC signal transmission. For realizing of individual model blocks, we concentrated on the choice of appropriate parameters so that these blocks could be adjusted and modified for future demands. The PLC simulation model is verified by measurements in the real PLC transmission environment that confirmed its satisfactory conformity with real transmission conditions.

The third, this paper analyzes transmission parameters for the optical transmission medium and presents possibilities for modeling and simulation of the information signal transmission in the environment of optical single-mode fibers. We focused on linear transmission factors – the attenuation and the dispersion - and on nonlinear effects – the four wave mixing, the self-phase modulation and the cross-phase modulation. Nonlinear effects in the optical fiber may potentially have a significant impact on the performance of WDM optical communication systems.

For given environment, beginning with only the OOK modulation using the 10 Gbit/s transmission rate can be considered without any encoding techniques. The demodulated BER value is kept in expected transmission boundaries for less than 50 km. Then, encoding techniques can be used to improve the range of the optical transmission system. Expected codes can provide the improvement of optical transmission system ranges up to 80 - 90 km. Besides, phase modulations with better performance than the OOK can be considered. The coherent system is capable by suppressing dispersion effects to increase optical transmission system ranges to around 100 km.

The simulation model for the optical communication path represents the signal transmission in the optical environment for very high-speed data signals in both directions. Knowing which fundamental linear and nonlinear interactions dominate in the optical transmission medium is helpful to conceive techniques that improve a transmission of optical signals, including advanced modulation formats, encoding techniques, digital signal processing and a distributed optical nonlinearity management.

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## ABBREVIATIONS

| | |
|---|---|
| ADSL | Asymmetric DSL |
| AWGN | Additive White Gaussian Noise |
| CD | Chromatic Dispersion |
| DC | Direct Current |
| DGD | Differential Group Delay |
| DMT | Discrete Multi Tone |
| FEXT | Far-End Crosstalk |
| FWM | Four Wave Mixing |
| GVD | Group Velocity Dispersion |
| HPON | Hybrid Passive Optical Network |
| ISI | Inter-Symbol Interference |
| NEXT | Near-End Crosstalk |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OSNR | Optical Signal-to-Noise Ratio |
| PLC | Power Line Communication |
| PMD | Polarization Mode Dispersion |
| PON | Passive Optical Network |
| PSD | Power Spectral Density |
| SBS | Stimulated Brillouin Scattering |
| SPM | Self-Phase Modulation |
| SRS | Stimulated Raman Scattering |
| TCM | Trellis-Coded Modulation |
| VDSL | Very high bit rate DSL |
| WDM | Wavelength Division Multiplexing |
| XPM | Cross-Phase Modulation |
| XPolM | Cross-Polarization Modulation |

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Rastislav Róka (Assoc. Prof.) 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 been working as a senior lecturer at the Institute of Telecommunications, FEI STU, Bratislava. Since 2009, he is working as an associated professor at this institute. His teaching and educational activities are realized in areas of fixed transmission media, digital and optocommunication transmission systems and network. At present, his research activity is focused on the signal transmission through optical transport, metropolitan and access networks by means of new WDM and TDM technologies using advanced optical signal processing included various modulation and encoding techniques and through metallic access networks by means of xDSL, HFC and PLC technologies. His main effort is dedicated to effective utilization of the optical fiber's transmission capacity of the broadband passive optical networks by means of DBA and DWA algorithms applied in various advanced HPON hybrid optical network infrastructures.