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APPLICATION OF THE KOHONEN NEURAL NETWORK IN ANALYSIS OF THE MEASUREMENT RESULTS OF THE POLARIZATION MODE DISPERSION

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Summary: This paper presents a subject of the Polarization Mode Dispersion (PMD). PMD is characteristic for a single mode optical fiber transmission. Several aspects have been presented in the paper, such as the interferometric method for measuring the PMD, as well as the statistical analysis of the measurement results contrasted with the analysis of the same results by use of the Kohonen neural network (KNN).

Keywords: Polarization Mode Dispersion, interferometric method for measuring the PMD, statistical analysis, Kohonen neural network

1. INTRODUCTION

Polarization Mode Dispersion (PMD) is characteristic only for a single mode optical fiber (telecommunication fiber) transmission. It results from the fact that only one mode, LP_{01}, is provided in the telecommunication fiber. It is called the fundamental mode. It is double generated, as it is a combination of two orthogonal modes, which are in two different polarization states.

One can distinguish two axes: **the fast axis** which is the vertical axis responsible for the faster polarization and the **slow axis** which is the horizontal axis responsible for the slower polarization of the optical fiber [1]. When the optical fiber is ideal then both modes are propagated with the same speed. In practice there is no such case and the PMD phenomenon occurs, which results from the fallowing factors:

- **intrinsic factors (fiber imperfections):** noncircular geometry, asymmetrical distribution of refraction factor between the fiber core and the cladding, mechanical stresses and local deformations in the the border between the core and the cladding;
- **external factors (physical stresses):** inflexion, compression, twist, influence of electric and magnetic field and temperature.

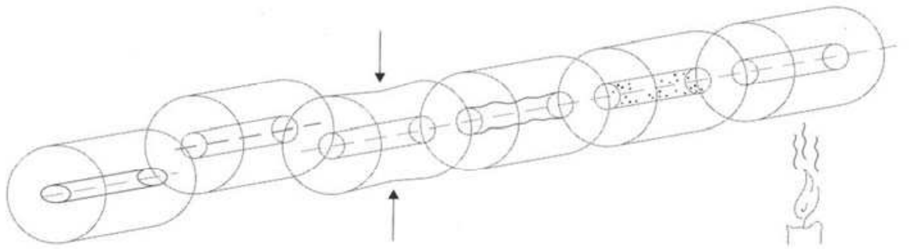

Fig. 1. Graphic presentation of factors influence of PMD

Changes of the speed that are caused by the PMD are quasi-random (probably-random), so the PMD is called statistic or stochastic, because it fluctuates in time (e.g. with the age of optical fiber). Statistic character of this phenomenon causes, that it should be measured when the bitrate in the optical network is bigger than 2.5 Gbps.

Differential Group Delay – DGD between two orthogonal polarization modes has the Maxwell's solution in time, which has been proved both empirically and analytically. The middle result of the DGD is called a delay of the PMD and is shown as the PMD factor [1]. For long optical fibers with the length to exceed one or two kilometers, the PMD factor is defined as PMD_{LLcoeff} and is expressed in $\left[\mathrm{ps}/\sqrt{\mathrm{km}}\right]$.

The unit of the PMD shows that this factor does not increase linearly with the length of the fiber but is proportional to the square root of this length, as follows [1]:

$$PMD_{\mathrm{LLcoeff}} = \frac{\Delta\tau}{\sqrt{L}} \tag{1}$$

where:

$\Delta\tau$ – a differential group delay $[\mathrm{ps}]$;

L – the length of the optical fiber $[\mathrm{km}]$.

The consequence of the PMD effect is wider optical impulse ($\Delta\tau$). It lowers power of optical signal. To mark (fix) the length of optical fiber in which the PMD effect occurs it is necessary to use some dependents [1]:

- admissible decreasing the sensitivity of the receiver usually settled for 1 dB, so if it is needed to keep loose of power down 1 dB, is fixed that DGD – $\Delta\tau$ should be 0,1 bitperiod – T_{bit}:

$$\Delta\tau_{\mathrm{max}} \le \frac{T_{\mathrm{bit}}}{10} \tag{2}$$

where:

$\Delta\tau_{\mathrm{max}}$ – maximum value of differential group delay $[\mathrm{ps}]$;

T_{bit} – bitperiod $[\mathrm{ps}]$.

- if $T_{\mathrm{bit}} = \frac{1}{B}$, where B is the bitrate, then considering equation (1) the length of optical fiber that depends of the PMD_{LLcoeff} factor can be expressed as follows:

$$L \leq \frac{1}{100 \cdot B^2 \cdot (PMD_{\text{LLcoeff}})^2} \tag{3}$$

where: L is the length of optical fiber $[\text{km}]$, B is the bitrate $[\text{Gbps}]$, PMD_{LLcoeff} is the PMD factor for a long optical fiber $\left[\text{ps}/\sqrt{\text{km}}\right]$.

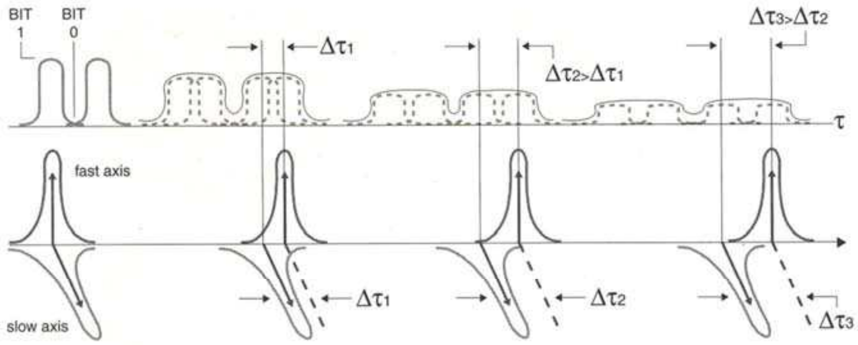

Fig. 2. The PMD effect in the optical signal

Currently used single mode optical fibers that have been described in the Recommendation G.652 [2], should have the PMD_{LLcoeff} factor smaller than 0.5 $\left[\text{ps}/\sqrt{\text{km}}\right]$ [1, 2]. Most of the optical fibers, that are currently produced, have the PMD_{LLcoeff} factor less than 0.5 $\left[\text{ps}/\sqrt{\text{km}}\right]$, sometimes even ten times less. For the bitrate of 2.5 Gbps, 10 Gbps and 40 Gbps the maximum value of the DGD ($\Delta\tau$) should be equal to 40 ps, 10 ps and 2.5 ps respectively. Theoretically, for $PMD_{\text{LLcoeff}} = 0.5$ $\left[\text{ps}/\sqrt{\text{km}}\right]$, the length of the optical fiber is limited to 6400 km for STM-16, to 400 km for STM-64, and to 25 km for STM-128 [1].

2. EXPERIMENTAL RESULTS AND CHARACTERISTICS OF THE INTERFEROMETRIC METHOD

A 54 kilometers long optical telecommunication line, composed of two optical fibers, has been used to perform described measurements. This line is rented from PKP (Polish Railways) by a Polish company that offers the access the fast Internet and data transmission. This line has been rebuilt to enable transmission of signals with the bitrate in-between 30 and 40 Gbps. On this optical way were some different events like: macrobendings, mechanical weld, electrical welt, connectors. This line has been verified to be in the accordance with the Instruction T – 01 TP S.A. and Recommendation ZN – 96 TP S.A. – 002. This means that: attenuation of the line, attenuation of events and the factor of Chromatic Dispersion (all for two wavelength: 1550 nm and 1625 nm) with OTDR Anritsu model MW9076, was made. The PMD_{LLcoeff} factor has been measured using the PMD analyzer offerd by Nexus.

The measurements of the PMD effect have been performed by interferometric method, which takes advantage of the function of autocorrelation of the electromagnetic field (the characteristic of power fluctuation in time). A widthband source of the light (electroluminescence diode – LED or the halogen lamp, which emits the white light) is connected with one end of the optical fiber, while the second end of this fiber is connected to the Interferometer. This method is used to measure the DGD parameter in-between 0.1 ps and 100 ps for the wave length ranging from 60 to 80 nm [3]. To perform the measurements for larger lengths the PMD analyzer was used instead of the Interferometer.

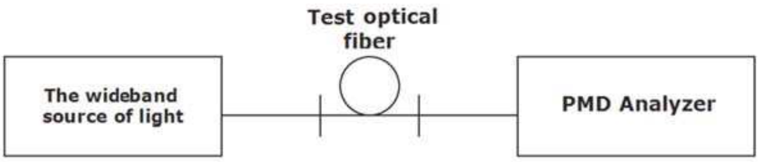

Fig. 3. Schematic diagram of the measurement experiment of the PMD factor

DGD between two orthogonal modes can be marked using the function of autocorrelation. Two examples can be mentioned:

- **the optical fiber with a weakly coupled mode:** a distant between the main and the side peaks is large. In this case the DGD parameter is as follows [3]:

$$\Delta\tau_{g,r} = \frac{2 \cdot dk}{c} \tag{4}$$

where:

dk – is the length of a movable mirror from the position in which distances between the interferometer's mirrors were equal [m], while *c* is the speed of light in the vacuum equal to $2.998 \cdot 10^8$ [m/s];

- **the optical fiber with the strongly coupled mode**: a distance between the main and the side peaks is small. The DGD parameter can be described using the Gauss resolution for approximation of the characteristic of the autocorrelation function [3]:

$$\Delta\tau_{g,r} = \sigma_{X(t)} \cdot \sqrt{\frac{3}{4}} \tag{5}$$

where:

$\sigma_{X(t)}$ – is the standard deviation of the normal resolution approximating characteristic of the autocorrelation function in the optical fiber with the strong couple mode $[\text{ps}]$.

The length of the optical fiber was measured using OTDR, before measurement of the PMD by use of the PMD analyzer. The obtained values were put into the PMD analyzer. The PMD_{LLcoeff} factor will be estimated by use of the length of the line according to equations (1) and (5).

The PMD parameter has static properties that enabled repeating the measurements for ninety times, with the intervals of 16 minutes (ninety results for a single optical fiber). The measurements have been performed for each of the two optical fibers, to obtain correct results. The transmission will be provided in the III optical window (λ = 1550 nm), so the measurements were done only for the wavelength of 1550 nm. The PMD factor is measured only in one way such as the Chromatic Dispersion factor.

3. STATISTICAL ANALYSIS OF THE MEASUREMENT RESULTS

Analysis of measurement results the factor PMD for optical fiber is presented in the following order:

- checking the type of the distribution which is formed by gathered measurement results using the harmony test of Pearson or Kolmogorow – Smirnow;
- marking the trust section for the measured PMD factor and ascertainment which of the results don't belong to this section;
- marking the range of bitrate using the trust section for the measured PMD factor for two significance levels α ;
- final conclusions concerning presented statistical analysis of the presented measurement results and expertise of the whole optical telecommunication line.

The measurements of the PMD effect have been performed in two samples of optical fibers A and B with 16 minutes intervals. The statistical analysis is performed only for the A optical fiber. The fallowing results for the A fiber have been achieved. It should be determined which solution is the source of the PMD effect and then this section should be marked to eliminate the incorrect results. Using equations (2) and (3) it should be verified which of the acceptable factors of the PMD can appear in a given optical network that use the bitrates of 30 and 40 Gbps.

Two different significance levels have been selected in the presented analysis, namely $\alpha = 0.05$ and $\alpha = 0.1$.

Firstly, the null hypothesis should be formulated. It is supposed that the resolution of the PMD factor is normal: $H_0 : F(x) \sim N(m,\sigma)$.

Secondly, the normal resolution parameters have to be marked by basing on the data obtained from measurements. To perform this task, the fallowing patterns and calculations have been used:

$$m = \frac{\sum_{i=1}^{90} x_i}{90} = 0.378 \left[\frac{\text{ps}}{\sqrt{\text{km}}}\right] \tag{6}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{90} (x_i - m)^2}{90}} = 0.136 \left[\frac{\text{ps}}{\sqrt{\text{km}}}\right] \tag{7}$$

where:

m – expected value (mean, the first moment of the normal);

x_i – measurement result (factor PMD);

σ – standard deviation.

Thirdly, the measured data need to be grouped into some distribution series and presented in the table that simplifies the analysis which is required to verify the authenticity of the null hypothesis.

Table 1. The help table for the harmony test of Pearson

I	Section of distributing series	p_i	$n_\Sigma \cdot p_i$	l_{n_i}	$\left(l_{n_i} - n \cdot p_i\right)^2$	$\frac{\left(l_{n_i} - n \cdot p_i\right)^2}{n \cdot p_i}$
1 ⋮ 32	$(-\infty; 0.3)$	0.281	9.549	32	504.063	52.789
33 ⋮ 54	$\langle 0.3; 0.4)$	0.279	9.481	22	156.733	16.532
55 ⋮ 77	$\langle 0.4; 0.5)$	0.277	9.413	23	184.614	19.613
78 ⋮ 90	$\langle 0.5; +\infty)$	0.187	5.539	13	44.163	6.950
$\sum_i$	$n = 33.981$	≈ 1		90		$\chi^2 = 95.884$

where:

n_Σ – sum of the measurement results;

l_{n_i} – size range in a number of distributive.

The probability p_i of findings that the PMD value was estimated using the table of the distribution function for the normal resolution in the analyzed section of the distributing series. It has been performed in the following way:

$$P\left(x \in (-\infty;\ 0.3)\right) = P(-\infty < x < 0.3) = \\ = P\left(\frac{-\infty - m}{\sigma} < u < \frac{0.3 - m}{\sigma}\right) = P\left(\frac{-\infty - 0.378}{0.136} < u < \frac{0.3 - 0.378}{0.136}\right) = 0.281 \tag{8}$$

$$P\left(x \in \langle 0.3; 0.4)\right) = P(0.3 \le x < 0.4) = \\ = P\left(\frac{0.3 - m}{\sigma} \le u < \frac{0.4 - m}{\sigma}\right) = P\left(\frac{0.3 - 0.378}{0.136} \le u < \frac{0.4 - 0.378}{0.135}\right) = 0.279 \tag{9}$$

$$P\left(x \in \langle 0.4;\ 0.5)\right) = P(0.4 \le x < 0.5) = \\ = P\left(\frac{0.4 - m}{\sigma} \le u < \frac{0.5 - m}{\sigma}\right) = P\left(\frac{0.4 - 0.378}{0.136} \le u < \frac{0.5 - 0.378}{0.135}\right) = 0.277 \tag{10}$$

$$P\left(x \in \langle 0.5;\ +\infty)\right) = P(0.5 \le x < +\infty) = \\ = P\left(\frac{0.5 - m}{\sigma} \le x < \frac{+\infty - m}{\sigma}\right) = P\left(\frac{0.5 - 0.378}{0.136} \le x < \frac{+\infty - 0.378}{0.136}\right) = 0.187 \tag{11}$$

Using the χ^2 – Pearson resolution's table for two different significance levels: $\alpha = 0.05$ and $\alpha = 0.1$, and 89 degrees of freedom we receive:

$$\left.\begin{matrix}\alpha = 0.05 \\ i-1 = 89\end{matrix}\right\} \chi_\alpha^2 = \chi_{0.05}^2 = 112.022$$

$$\left.\begin{matrix}\alpha = 0.1 \\ i-1 = 89\end{matrix}\right\} \chi_\alpha^2 = \chi_{0.1}^2 = 106.469$$

The following equation has to be used to verify the correctness of the null hypothesis [5]:

$$P\left(\chi^2 > \chi_\alpha^2\right) = \alpha \tag{12}$$

The null hypothesis can not be rejected, considering the obtained results. It results form the fact that the inequality in equation (12) is not true, as $\chi^2 = 95.884$.

If the resolution of the measured PMD factor is known, the trust section can be marked in order to verify given results during the experiment. For this purpose, Table 1 and a positive number of t_α have been used. The positive number characterizes the accuracy of the estimation and it can be obtained from the normal resolution Tables:

$$\left.\begin{matrix}\alpha = 0.05 \\ i-1 = 5\end{matrix}\right\} t_\alpha = t_{0.05} = 1.987$$

$$\left.\begin{matrix}\alpha = 0.1 \\ i-1 = 5\end{matrix}\right\} t_\alpha = t_{0.1} = 1.662$$

The trust section for the normal resolution is described as follows [5]:

$$\left(m - t_\alpha \cdot \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - m)^2}{n}}}{\sqrt{n-1}} ; m + t_\alpha \cdot \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - m)^2}{n}}}{\sqrt{n-1}} \right) \tag{13}$$

where:

n – number of the measurement results.

Using equation (13), the trust section can be found for a specified significance level α, while using equation (3) and the length of the optical fiber (L) the range of the bitrate can be determined as follows:

- for $\alpha = 0.05$: $\left(0.378 - 1.987 \cdot \frac{0.136}{\sqrt{89}};\ 0.378 + 1.987 \cdot \frac{0.136}{\sqrt{89}}\right) \Rightarrow (0.349;\ 0.406) \left[\frac{\text{ps}}{\sqrt{\text{km}}}\right]$

  $B \in (33.515;\ 38.981)\ [\text{Gbps}]$

- for $\alpha = 0.1 \left(0.378 - 1.662 \cdot \frac{0.136}{\sqrt{89}};\ 0.378 + 1.662 \cdot \frac{0.136}{\sqrt{89}} \right) \Rightarrow (0.354;\ 0.401) \left[\frac{\text{ps}}{\sqrt{\text{km}}} \right]$

  $B \in (33.904;\ 38.468)\ [\text{Gbps}]$

In the conclusion, it can be noticed that the assumed by the system administrator transmission bitrate in-between 30 and 40 Gbps, does not fall within the range which was based on the statistical analysis of the measurement results. This means, that the tested fiber optic should not be used in the transmission system, with a maximum bitrate of 40 Gbps. Accordingly, the transmission can't be realized using SDH (STM – 256), because the maximum bitrate in this system is 40 Gbps. The transmission system will operate correctly for the maximum bitrate of 38 Gbps, or by using a different optical fiber, with a lower value of the PMD factor.

4. KOHONEN NEURAL NETWORKS ALGORITHM

Teuvo Kohonen proposed a new class of neural networks in 1975, that use competitive, unsupervised learning algorithms [6]. The Kohonen neural networks (KNNs) in their classical approach, also called self organized maps (SOM), contain one layer of neurons. This layer is organized as a map. The number of the outputs of the network equals to a total number of neurons. All neurons have common inputs, whose number depending on the application varies in-between two and even several dozen. The SOMs are used in data visualization and analysis [7, 8, 9].

The competitive unsupervised learning in KNNs relies on presenting the network with the learning vectors X in order to make the neurons' weight vectors W resemble presented data. For each training vector X both KNNs determine Euclidean distances (d_{EUC}) between this vector and the weights vectors W in each neuron, which for n network's inputs are calculated using the following formula:

$$d_{\text{EUC}}(X, W_i) = \| X - W_i \| = \sqrt{\sum_{l=1}^{n} (x_l - w_{il})^2} \tag{14}$$

The neuron, whose weights are the most similar to the training vector X becomes a winner and is allowed to adapt own weights. Two general types of such networks can be distinguished. In the Winner Takes All (WTA) approach only the winning neuron can adapt the weight, while in the Winner Takes Most (WTM) algorithm also neurons that belong to the winner's neighborhood are allowed to adapt the weights, according to:

$$W_j(l+1) = W_j(l) + \eta(k) G(i, j, R, d)[X(l) - W_j(l)] \tag{15}$$

where:

$\eta(k)$ – learning rate in the k^{th} training epoch;
$G(i, j, R, d)$ – neighborhood function.

These neurons that belong to the winner's neighborhood are trained with different intensities that depend on the neighborhood function $G()$. In the classical approach a simple rectangular function is used which is defined as [6, 9]:

$$G(i,j,R,d)=\begin{cases}1 & \text{for } d(i,j)\le R\\ 0 & \text{for } d(i,j)>R\end{cases} \tag{16}$$

where:

- $d(i, j)$ – topological distance between the winning, i^{th}, neuron and any other, j^{th}, neuron in the map;
- R – range of the neighborhood that is decreased after each epoch.

The common opinion is that much better results can be achieved if the Gaussian function is used instead of the rectangular one [8]. The Gaussian function is defined as follows:

$$G(i,j,R,d)=\exp\left(-\frac{d^2(i,j)}{2R^2}\right) \tag{17}$$

This is important to distinguish the map topology from the neighborhood function. Topology means the grid of neurons i.e. determines which neurons belong to the neighborhood of any neuron in the map [9, 11]. Typical topologies described in literature are rectangular with four of eight neighbors or the hexagonal [6-9].

5. MEASURED DATA ANALYSIS BY KNN SOM

The KNN has been used to analyze the measurement results of the PMD parameter. The number of the inputs has been selected to be equal to 2. The input vectors consist of the following parameters: PMD and *B*. The number of the training patterns was equal to 90. The simulations have been performed for the Gaussian neighborhood function and the rectangular grid with four neighbors. The map size is 2x2 neurons.

Training the WTM network has been divided into two phases i.e. the *ordering phase* at the beginning of the learning process and the *tuning phase* at the end. In particular phases, the learning rate η, as well as the value of the radius *R,* have different values. The learning rate η decreases along the learning process starting from a relatively large value $\eta_{max} = 0.9$ to very small values, on the level of $\eta_{min} = 0.02$ in this particular case. In the tuning phase the η parameter remains constant and equal to the lower value. The radius *R,* in the ordering phase, decreases from its maximum value, for which it covers the entire map to zero. In the tuning phase, the value of this parameter remains constant and equals 0. This means that only the winning neuron is allowed to adapt the weights i.e. the SOM works as the WTA network. All these parameters mentioned above have the influence on both the speed and the quality of the learning process, which can be evaluated using the so called quantization error. This error is defined as follows:

$$Q_{err}=\frac{\sum_{j=1}^{m}\sqrt{\sum_{l=1}^{n}(x_{j_l}-w_{wl})^2}}{m} \tag{18}$$

where:

- m – number of the learning patterns in the input data set;
- n – number of the network inputs.

The measured data have been divided into four distinct classes in the statistical method described above. The number of four results from the real areas. The last class i.e. for (PMD $\in \langle 0.5;\ +\infty)$) represents these values of the PMD coefficient, which exceed the values in the ITU-T order. The range of values for PMD $\in (-\infty;\ 0.5)$, or in the real case for PMD $\in \langle 0;\ 0.5)$, have been divided into three classes with a similar numerical value. Data from particular classes generate similar results. To demonstrate the statistical character of the PMD coefficient, it is necessary to divide data at least into three classes. Division of data into larger number of classes will have no influence on the confidence interval described by (13). On the other hand, increasing the number of classes will increase the time required for analysis, and therefore the number of four is treated as an optimal value.

The statistical method has one important drawback, that is not present in the method based on the Kohonen SOM. The statistical method does not allow for an automatic division of the measured data into classes. Moreover, the user must also perform oneself all required calculations as described in Section 3. The application of the neural network with a given number of neurons allows achieving the same results as in the statistical method without any action from the user. The user does not need to be a specialist in the area of the mathematical statistics.

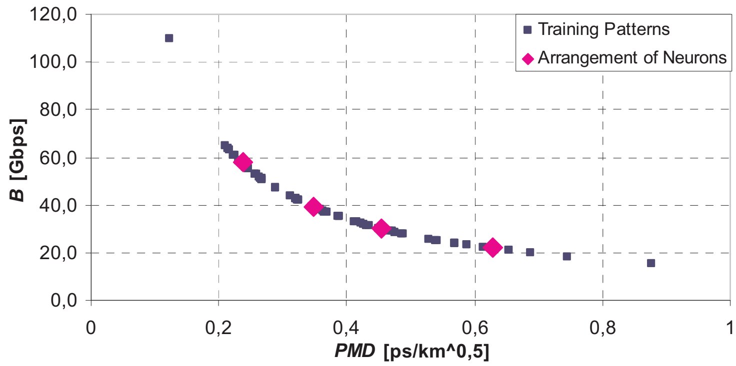

Fig. 4. Training patterns and the final arrangement of neurons after completing the learning process

Software model simulation results, illustrating both training patterns and the final arrangement of neurons after completing the learning process, are shown in Fig. 4. Input data are divided into 4 classes i.e. the number of neurons in the SOM. Each class is represented by a different number of the learning patterns. Particular classes consist of 30, 24, 23, 13 input patterns, respectively. The first class is for PMD $\in (-\infty;\ 0.286\rangle$, the second for PMD $\in (0.278;\ 0.392\rangle$, the third for PMD $\in (0.392;\ 0.523\rangle$, while the fourth for PMD $\in (0.523;\ \infty)$. The classes obtained using the analysis based on the SOM approximately overlap with the results obtained by use of the statistical method.

Kohonen SOM can be realized in various ways. The authors present the software model simulation results in this paper, but different hardware solutions, based on the application specific integrated circuits (ASIC) have been proposed by the authors earlier [10-14]. Hardware implemented networks offer a fully parallel operation of all neurons in the map and therefore can become much faster than their software counterparts, while consuming much less energy [12-14]. This opens quite new possibilities of applications of such networks e.g. in low power portable devices. Hardware implemented network of this type will allow for a constant control monitoring of the optic fiber tracts.

Hardware implemented KNN will enable an automatic choice of the optimal fiber optic line. This will enable data transmission to be performed on the constant basis with the bit rate assumed by the operator. An additional advantage of this solution is the possibility of its application in particular nodes of the digital broadcasting networks, in which different transmission paths converge. After determining the bit rate for each of the input paths, assuming the knowledge of the PMD coefficient values for these paths, one can use the proposed solution to make the allocation of the input data streams to the respective output paths. This solution will ensure preservation of the established top bit rate between the boundary (terminal) nodes in the network. In case when the broadcast is performed in one of the four fibers represented by particular classes of the Kohonen map, the remaining fibers can be analyzed using the KNN in real time. After detecting a more favorable transmission path, the network can automatically select this path. This will ensure more reliable operation of the entire transmission system. Sample Flowchart of the proposed solution is shown in Figure 5.

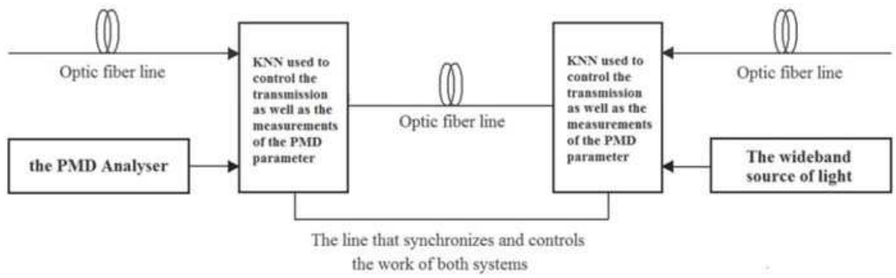

Fig. 5. Block diagram of control – measuring realized based on the KNN

6. CONCLUSIONS

In his paper the Kohonen SOM has been used to analyze the measurement results of the PMD parameter. Obtained results are very similar to the results obtained in the statistical analysis. Using artificial neural network allows for saving the time required for execution of the statistical analysis, as the network perform this analysis and data classification in the real time. In case of the statistical method, this type of analysis can be performed only before opening the fiber-optic highway or in the situation when a reconfiguration has been performed. This opens quite new application possibilities of such networks.

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ZASTOSOWANIE SIECI NEURONOWEJ KOHONENA DO ANALIZY WNIKÓW POMIARU DYSPERSJI POLARYZACYJNEJ

Streszczenie

W pracy omówiono zagadnienie dyspersji polaryzacyjnej – PMD (ang. Polarization Mode Dispersion), która jest charakterystyczna dla transmisji z wykorzystaniem jednomodowego włókna światłowodowego. Przedstawiono również interferometryczną metodę pomiaru współczynnika dyspersji polaryzacyjnej, statystyczną analizę rzeczywistych wyników pomiaru oraz analizę tych samych wyników pomiaru za pomocą sieci neuronowej Kohonena.

Słowa kluczowe: dyspersja polaryzacyjna, metoda interferometryczna pomiaru PMD, analiza statystyczna wyników pomiarów, sieć neuronowa Kohonena