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Investigation of Allowed Channel Spacing for Differently Modulated Optical Signals in Combined HDWDM Systems

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Introduction

In recent years the dramatic increase of demand for transmission capacity is observed and to secure an appropriate quality of service (QoS) level telecommunications services providers must constantly and continuously develop their transmission systems in use [1–4]. Currently, as a study object of many works have been chosen and focused directly on the fibre total transmission capacity increases, and this can happen in a three different ways. The first one, the existing 10 Gbit/s DWDM system upgrade, but in fact it is the substitution of existing system with 40 Gbit/s DWDM system or faster, because the only 10 Gbit/s system components, which can be used in new 40 Gbit/s system, are fibre, boosters and some external modulated lasers, but all transmitter and receiver electrical parts with bandpass filters must be changed to a new one. The second one, channels compaction by location them closer to each other using smaller channel spacing between them, in that way increasing the number of channel in available transmission frequency spectrum [2]. In this case, the total transmission capacity increment is achieved only because of increasing the number of channels, as the individual transmission rate in each channel remains unchanged. And the third way, total transmission capacity increment, using channel compaction with simultaneous increment of individual channel's transmission bit rate.

It is clear, that none of the proposed fibre's transmission capacity increment solution can be realized immediately, but it requires a certain amount of time and work, as any solution should be implemented gradually in several stages to avoid unnecessary problems.

Our issue in a combined system solution is offered as a part of common transmission system development, during the transition from traditional use of NRZ – OOK modulation format to alternative modulation formats, such as NRZ – DPSK and 2 – POLSK. Such hybrid solution can be topical in the case of combination or even in the case of different transmission systems merger, which results in the necessity to make a different modulated optical signal transmission over a single optical bus. As well as, such need may occur in the future, switching traffic from a variety of WDM systems with the help of reconfigurable optical add – drop multiplexers (ROADM) and transmitting it further over common fibre to its destination or to the next ROADM [8]. The shift towards alternative optical signal modulation formats is necessary, because one of the major problem need to be overcome, in order to increase the total transmission capacity of core networks and a single fibre, are the reduction of transmission impairments and signal modulation format capability to resist against such impairments.

In high density WDM systems with a large fibre span length between two optical amplifiers, signal form distortion causes such effects as linear chromatic dispersion, polarization mode dispersion, fibre non-linear effects or thereof combinations. In WDM system channel spacing reduction limiting factor is interchannel crosstalk, which originate due to optical fibre nonlinearities, such as crossphase modulation (XPM), selfphase modulation (SPM) and four – wave mixing (FWM) [2]. In order to reduce the impact of those effects, various optical modulation formats are increasingly being studied and offered, which could serve as an alternative to currently used traditional on – off keying. In this way manipulated signals are significantly distorted at high speed and high spectral density transmission conditions [4].

Our study object is the allowed channel spacing in combined HDWDM systems, where for optical signal modulation in different channels intensity, phase and polarization shift keying are used. This research provides future WDM solutions with necessary recommendations.

Simulation models

As a simulation model for our transmission system, 10 Gbit/s three – channel WDM system was chosen. In this system optical signal modulation formats applied in each system's channel are different. Per channel transmission bit rate is chosen equal to 10 Gbit/s, because our research is focused on ultra – long haul combined HDWDM transmission system development, which expecting existing 10 Gbit/s system's infrastructure use and further it's development.

In the system's first channel optical signal is transmitted for which modulation differential phase shift keying with non – return – to – zero encoding technique is used (NRZ – DPSK). For the system's second channel on – off keying method and NRZ encoding is used, despite the fact, that NRZ – OOK modulation format is not well situated for high density WDM systems with a large number of transmission channels and high transmission rate and, as consequence of that, a high total transmission capacity. This modulation format can be used as a good foundation and reference point for comparison of different modulation formats, because it's traditionally used modulation format in optical transmission systems, due to its relatively simple realization and historical domination [1]. As modulation format for the system's third channel binary polarization shift keying (2 – POLSK) was chosen. It's the newest modulation format and in the same times the most promising [5].

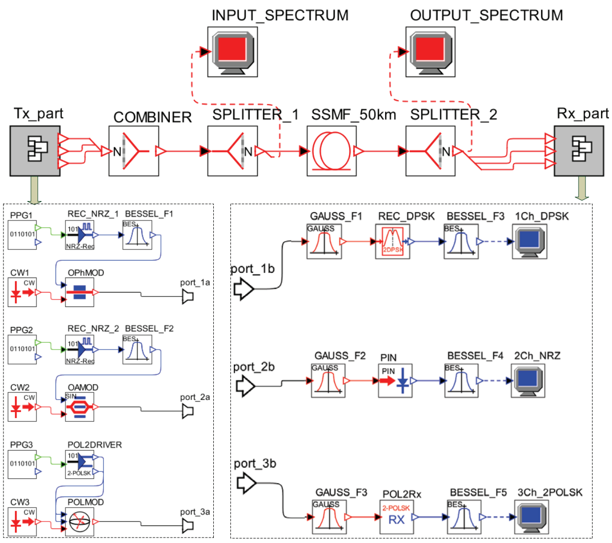

Fig. 1. Simulation model of 3 – channel combined WDM system

Then all three differently modulated optical signals are combined and transmitted through 50 km long standard single mode fibre (SSMF), without using optical amplifiers. On the other fibre end optical signals are filtered with optical Gaussian filters, converted to electrical signals and then electrically filtered using Bessel electrical filters (see Fig. 1).

SSMF length was chosen equal to 50 km, because it's maximal permissible length between two EDFA in an ultra – long haul transmission system, if fibre attenuation coefficient is 0.2 dB/km. Large amplifier spacing in such system would result in a prohibitive increase in amplified spontaneous emission (ASE) noise and in order to achieve the greater range and information capacity, the amplifiers must be located close together with gain no greater than about 10 dB and preferably less [7]. Amplifier spacing further increment will lead to increase of ASE noise influence and as a result BER grow for each system channel. As well as, we must take into account system's accumulated dispersion level, because 10 Gbit/s network, where for optical signal modulation NRZ format is used, operates error free only if residual system dispersion is below 1000 ps/nm. SSMF has 17 ps/nm dispersion and this mean that mentioned above dispersion level threshold won't be exceeded if length of the used fibre is below 58 km. In our case, we studied optical signal transmission over only one span of ultra – long haul transmission system and that's why fibre length was taken from its possible optimal configuration.

For assessment of system performance measurement of various system parameters, such as eye diagram, system's optical spectrum in the beginning and in the end of optical link and BER quantity, were made.

Measurement technique

To evaluate performance of created WDM system, such parameter as bit – error – ratio (BER) was assessed. In order to obtain such characteristic for comparison of different WDM systems configuration we've created for analyse, we had to use a mathematical tool, that would describe and take in a account various linear and nonlinear effects influence to optical signals of combined WDM system. Such mathematical apparatus is successfully realized in OptSim software that numerically solves the nonlinear Schredinger equation (NLSE). As known, it describes the signal propagation constraints in a fibre, and its analytical solution is possible only in specific cases. NLSE is being solved using Split Step Fourier Method (SSFM). This method is based on individual impact assessment of the linear and nonlinear effects in a single optical line segment Δz. This means that in the first Δz segment is taken in account only linear effects, but in the second Δz segment is taken in account only non – linear effects, and so on until the end of optical line. In this case it is assumed, that the Δz length is sufficiently small and linear, as well as nonlinear, effects operating independently of one another in each individual segment. For method basics better understanding, let's look to the NLSE in a differential form

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\}A(t,z), \qquad (1)$$

where A(T, z) is optical field; L – linear operator, which is responsible for the linear effects, such as dispersion and attenuation; N – non-linear operator, which represents the nonlinear effects influence to an optical signal [3].

A calculation of the linear operator occurs in a time domain, by obtaining the time sample convolutions products. Time Domain Split Step (TDSS) method calculates the convolution in the time domain and accurately calculates the delay between signals with different wavelengths. That is possible, because of frequency dependent group velocity, which could be considered as by – product of dispersion. In OptSim software TDSS is realized using finite impulse response (FIR) filters. TDSS automatically cuts of tails of theoretically infinite L impulse responses h(t) and calculates FIR filter with a sophisticated technique, that provides complete control of the overall mistake level, that may occur in the process of calculating along all fibre line length [5].

By contrast, non-linear operator N is being calculated in frequency domain. And the link between time and frequency domain is provided by discrete Fast Fourier Transformation (FFT) [3]. There is also the second L operator calculating method – FDSS (Frequency Domain Split Step), and as its name tells us, it calculates this operator in frequency domain. This method is easier to implement and it requires less computational time and computer resources, but it using might cause serious errors during calculation.

For assessing the various simulation parameters of simulated systems in this work, as well as in a different configuration cases, in addition optical signal spectrums in a different line locations are being used, and signal eye diagrams are detected, because it's the fastest and the most convenient way to approximately evaluate the system performance under different configuration conditions.

For the example, for the proper functioning of the system eye-diagram opening of the mesh must be sufficiently wide open and spectral diagrams should be without regular sharp multi-peaks. Eye diagram represents an electrical signal pattern after detection. Eye-opening height can be considered as a noise indicator, whereas the eye-opening width in the centre of the eye diagram represents a measure of timing jitter. The simulation software allows to obtain sufficiently accurate preliminary results, which, in fact, making it possible to consider them to be true [1].

Results and discussions

The aim of this work was to investigate one possible realization of combined high-density communications system and compare it with conventional WDM system solutions, where only one of the following modulations formats is used for optical signal modulation. For this purpose, three different (NRZ – OOK, NRZ – DPSK, 2 – POLSK) types of optical signal modulation were studied and created four three-channel WDM systems with 10 Gbit/s per channel bit rate.

In the first system for optical signal modulation in all three channels differential binary phase shift keying (DPSK) was used, in the second – the intensity modulation (IM) and in the third – polarization shift keying were used, while the fourth is a combined transmission system, where for the first channels optical signal modulation NRZ – DPSK was used, for the second channel – NRZ – OOK and third – 2 – POLSK. The configuration type of this system was chosen precisely in order to clarify interchannel crosstalk influence effect to transmission in adjacent channels, if modulation formats applied for each channel are different. Number of channels in systems, where just one modulation format is used for the optical signal modulations, was chosen equal to the number of channels of combined system under study. It was specially done, in order to provide, that a total amount of input optical power coupled into the fibre would be approximately equal. This condition was specially held, in order to provide, that fibre nonlinearities could become apparent to the same extent and transmission would take place under same conditions, to make a comparison of these four different transmission systems for a range of channel spacing values. Each system simulation was performed for five different channels spacing, whose values were chosen based on the establishment principle of ITU – T Recommendation G.694.1. As the result, systems were simulated at following values of channel intervals: 25, 37.5, 50, 75, 100 GHz. Systems channels were grouped around 193.1 THz central frequency value and were located in C – Band (1530 – 1565 nm). The simulation results are summarized below.

Table 1. Simulation results

10 Gbit/s WDM System		**Channel Spacing, GHz**				
		25	**37,5**	**50**	**75**	**100**
		BER				
NRZ - DPSK	1st	$5{,}11\times10^{-12}$	$6{,}49\times10^{-13}$	$1{,}78\times10^{-16}$	$5{,}90\times10^{-17}$	$6{,}27\times10^{-17}$
	2nd	$3{,}25\times10^{-9}$	$6{,}12\times10^{-10}$	$1{,}00\times10^{-15}$	$1{,}98\times10^{-17}$	$4{,}00\times10^{-17}$
	3rd	$3{,}18\times10^{-12}$	$2{,}64\times10^{-13}$	$3{,}07\times10^{-16}$	$1{,}23\times10^{-16}$	$1{,}30\times10^{-16}$
NRZ - OOK	1st	$4{,}19\times10^{-29}$	$9{,}00\times10^{-18}$	$4{,}56\times10^{-22}$	$4{,}54\times10^{-26}$	$3{,}03\times10^{-26}$
	2nd	$1{,}06\times10^{-21}$	$2{,}53\times10^{-13}$	$1{,}04\times10^{-21}$	$4{,}85\times10^{-26}$	$1{,}84\times10^{-26}$
	3rd	$6{,}79\times10^{-31}$	$2{,}60\times10^{-16}$	$1{,}00\times10^{-22}$	$1{,}62\times10^{-25}$	$6{,}82\times10^{-26}$
2POLSK	1st	$1{,}00\times10^{-40}$	$1{,}71\times10^{-29}$	$1{,}00\times10^{-40}$	$1{,}00\times10^{-40}$	$1{,}00\times10^{-40}$
	2nd		$4{,}57\times10^{-18}$			
	3rd		$7{,}12\times10^{-30}$			
Combined	1st (DPSK)	$1{,}88\times10^{-25}$	$9{,}95\times10^{-17}$	$7{,}70\times10^{-17}$	$3{,}49\times10^{-17}$	$2{,}55\times10^{-17}$
	2nd (NRZ)	$3{,}23\times10^{-12}$	$2{,}63\times10^{-10}$	$3{,}68\times10^{-24}$	$3{,}54\times10^{-25}$	$2{,}18\times10^{-26}$
	3rd (2POLSK)	$1{,}00\times10^{-40}$	$5{,}12\times10^{-27}$	$1{,}00\times10^{-40}$	$1{,}00\times10^{-40}$	$1{,}00\times10^{-40}$

Let's also note, that optical bandpass Gaussian filters with -3 dB bandwidth equal to 0.11 nm were used for signal filtering at 25 GHz channel spacing, rather than in the other cases, where -3 dB bandwidth is equal to 0.3 nm. For electrical signal filtering Bessel filters with number of poles equal to 5 and -3 dB bandwidth equal to 10 GHz were used.

At the beginning of the results analysis we will focus on traditionally used NRZ – OOK modulation format. As one can conclude form the simulation results, in the case of small channel spacing values the worst systems bit – error – ratio is for the second system channel. This is explained by the fact, that in this case interchannel crosstalk effects are more quintessential and signal spectrum compaction is maximal affordable (see Fig. 2). As one can see from this figure, further compaction leads to different signal spectrum overlapping and as a consequence imminent grow of BER values. If we increase the value of channel spacing, this difference between BER values of each channel disappears. But if we increase channel spacing up to 37.5 GHz, the worst channel BER is already less than desired 10^{-12} at the same filter characteristics. In the data transmission networks with 10 Gbit/s bitrates and higher, if forward error correction techniques (FEC) are not used, BER value must be $<10^{-12}$.

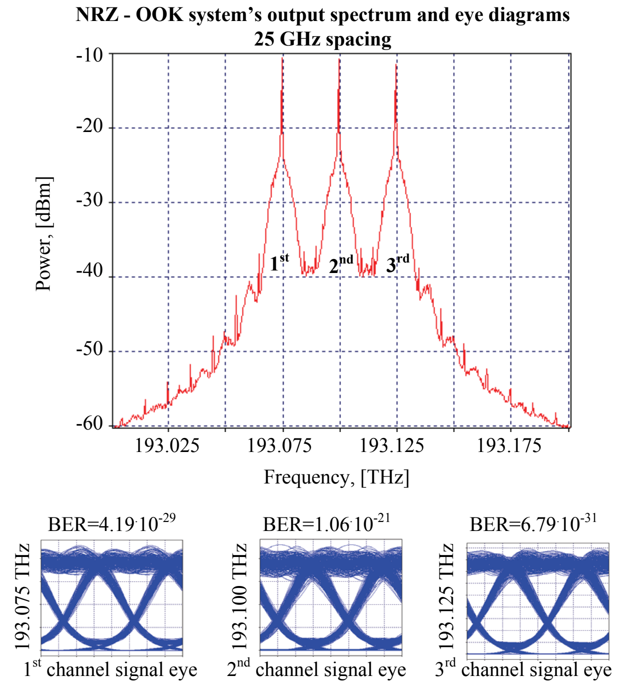

Fig. 2. 3 – channel NRZ - OOK system's output spectrum, signal eye diagrams and BER value in case of 25 GHz channel spacing

If we increase channel spacing value form 37.5 GHz up to 50 GHz, the worst channel BER improves till $1.04{\cdot}10^{-21}$. Further increment of spacing form 50 to 75 GHz or even up to 100 GHz at the given modulation and coding format, as well as bit rate, is not needed, because the BER improvement is not significant (Fig. 3, Fig. 4).

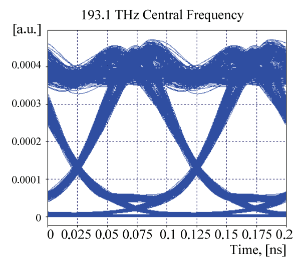

Fig. 3. Eye diagram of the worst (2nd) NRZ – OOK system's channel, 50 GHz channel spacing and BER=$1.04{\cdot}10^{-21}$

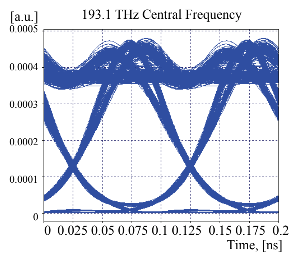

Fig. 4. Eye diagram of the best (2nd) NRZ – OOK system's channel, 100 GHz channel spacing and BER=$1.84{\cdot}10^{-26}$

If we use for optical signal modulation NRZ – DPSK format, the resulting BER values for each simulated channel at certain channel spacing values is several orders worse than it is in the NRZ – OOK format cases (see Fig. 5 – 6). Channel spacing reduction form 100 GHz to 50 GHz, leads to reduction of the worst channel bit – error – rate by one order. This lets make a conclusion about NRZ – DPSK modulation formats suitability to high spectral density transmission conditions. It's non-susceptible to channel spacing decreases or increases, if it happens to specified threshold values, above which a sudden channel degradation process is unavoidable.

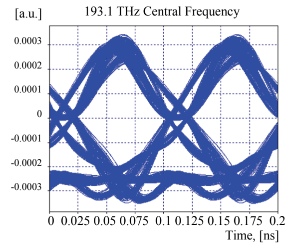

Fig. 5. Eye diagram of the best (2nd) NRZ – DPSK systems channel, Δf=100 GHz and BER=$4.00{\cdot}10^{-17}$

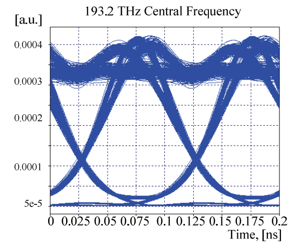

Fig. 6. Eye diagram of the worst (3rd) NRZ – OOK systems channel, Δf=100 GHz and BER=$6.82{\cdot}10^{-26}$

However, if the channel spacing is reduced to 25 GHz, then all three channels BER values are greater than required 10^{-12} but middle channels BER is even greater than ITU – T defined 10^{-9} (see Fig. 7).

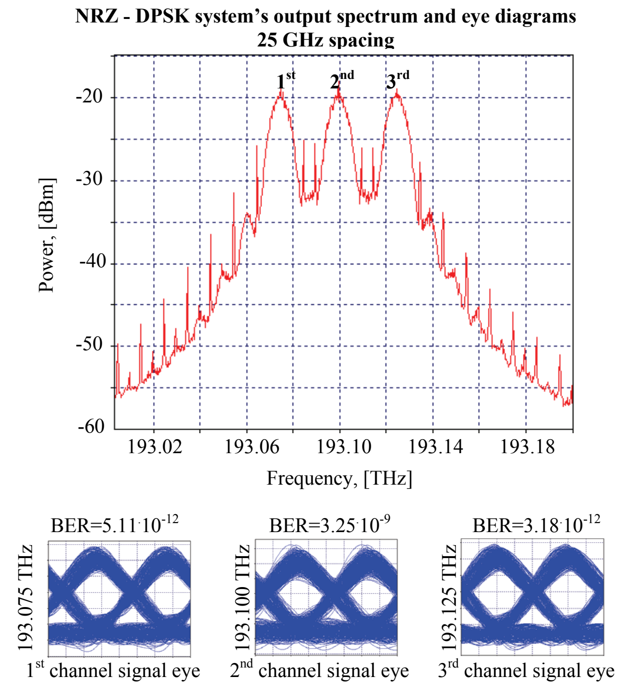

Fig. 7. 3 – channel NRZ – DPSK system's output spectrum, signal eye diagrams and BER value in case of 25 GHz channel spacing

Of course, if special alignment for optical bandpass Gaussian filters and electrical Bessel filters are implemented for 25 GHz channel spacing, it is possible to obtain the desired BER less than 10^{-12}. This aspect was not describe here, because one of this work tasks was to compare the modulation formats with each other at the same signal transmission and reception conditions.

If the modulation format, applied for optical signal in each WDM system transmission channel, is polarization shift keying (2 – POLSK), it is possible to achieve the best possible of channel BER values, irrespective to the channel spacing values as compared to other modulation formats. This is possible due to 2 – POLSK modulated signal spectrum (see Fig. 8). As can been seen, 2 –POLSK modulated optical signal spectrum is narrower than NRZ – DPSK and NRZ – OOK modulated signal spectrum. This property provides to a data signals greater error protection, when it is spread through the optical fibre transmission systems, and WDM signal spectrum lines at the beginning and at the end differ only by the level, spectrum extension and nonlinear effect influence are minimal.

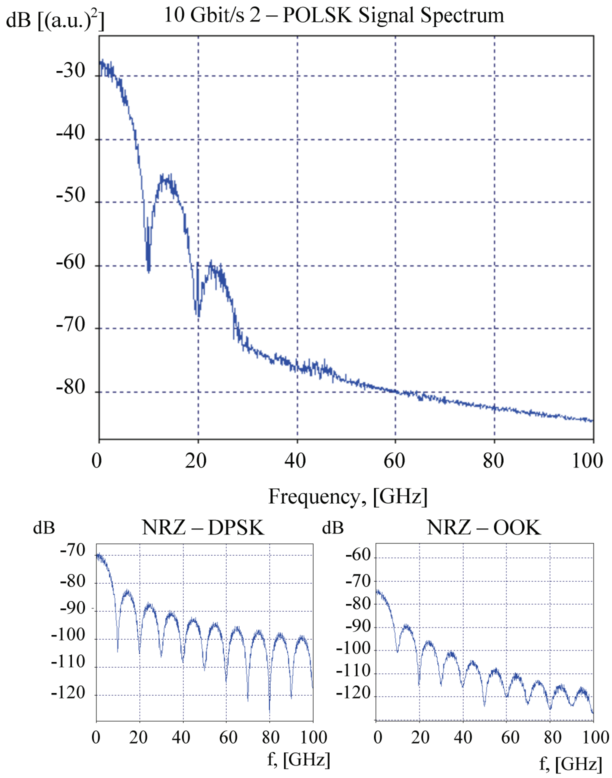

Fig. 8. NRZ – DPSK, NRZ – OOK, 2 – POLSK optical signal spectrums at the transmitter end after electrical conversion

If in multi-channel communication system for optical signal modulations different modulation formats are used, then obtained BER values for each channel will depend not only on the individual modulation format capability to resist from interchannel distortion, but also form that, which modulation format is used in the channel, which is the source of this disorders. This feature gets stronger on small (<50 GHz) channel spacing values, and the obtained simulation results for combined system allow us to conclude this.

If in a combined system 50, 75 or 100 GHz channel spacing are used for channel separation, then the channel BER values corresponding to BER values obtained for systems, where only one modulation format is used for the optical signal modulation. It is approximately 10^{-17} in NRZ – DPSK case, about 10^{-25} in NRZ – OOK and 10^{-40} in 2 – POLSK. Reducing channel spacing to 37.5 GHz, become evident special features of combined transmission and they stand out even more against the background, if 25 GHz interval is used for channel separation. As it can be seen from the obtained results, the first channel, where is used phase modulation, BER level is several orders lower (10^{-25}) than it is for the first channel of 3 – channel NRZ – DPSK system (10^{-12}) (see Fig. 9 and Fig. 7), the same can be applied to the second channel of the combined system (10^{-12}) and 2nd channel (10^{-21}) of 3 – channel NRZ – OOK system (see Fig. 9 and Fig. 2, where 2nd channels signals eye diagrams are pictured).

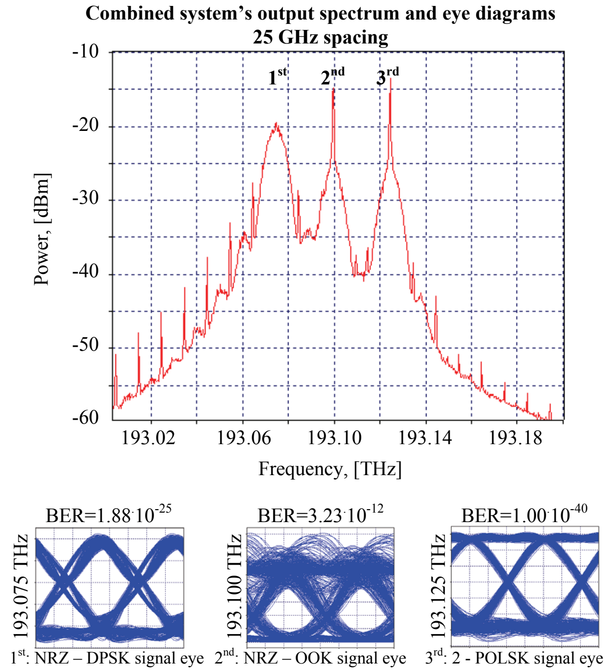

Fig. 9. 3 – Channel combined system's output spectrum, signal eye diagrams and BER value in case of 25 GHz channel spacing

As one can see from these figures, eye opening in both cases are materially different, eye opening for combined system is narrower than for traditional NRZ – OOK system's 2nd channel signal, if 25 GHz interval is used for channel separation.

A reason for such drastic differences in channel performance needs to be seek in modulation format distribution along transmission systems channels, i.e. it's necessary to find out, how and what extent of influence experiences optical signal in transmission channel, which is modulated in one manner, affecting other adjacent channels, in which for optical signal modulation others more different modulation formats are used, but it is already next research goal.

Conclusions

In this article the allowed channel spacing has been studied for three-channel WDM system with 10 Gbit/s transmission rate. Different modulation formats (NRZ – DPSK, NRZ – OOK, 2 – POLSK) are applied for optical signals in each transmission channel. Obtained results are compared with traditional 3 – channel WDM systems where for optical signal modulation only one of mentioned above modulation formats is used.

In summary it can be concluded, that the combined WDM solution allows combining channels with a variety of modulation formats, which are used for optical signal modulation, in one single transmission system, preserving a previously used channel spacing values. We would like to point out one more time, that such combined solution of transmission system is being offered as the transition state form traditionally used NRZ – OOK modulation format to the alternative modulation formats, such as NRZ – DPSK or 2 – POLSK, which use provides a number of superior properties due to their abilities of providing greater protection from interchannel crosstalk, less exposed to expression of non-linear effects and better exposed to channel filtration, as well as less exposed to chromatic dispersion effect. By gradually introducing new system channels, can be increased the total transmission capacity of fibre, thus avoiding of core networks bottleneck effect and in the same time minimize growth of non-linear optical effect influences, because the alternative modulation formats are able to provide the same BER levels as traditionally used NRZ – OOK, but only at lower input power levels.

Acknowledgement

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By the reduction of channel spacing in WDM system, it's possible to add some extra channels to it and in that way to increase the total transmission capacity of the used fibre and postpone bottleneck effect of core networks. But using the alternative modulation formats, such as differential phase shift keying with non – return – to zero coding (NRZ – DPSK) or two – states polarization shift keying (2 – POLSK), instead of traditional on – off keying with NRZ coding (NRZ – OOK), it's possible to achieve the lower bit error ration BER level and channel's tolerance to transmission impairments, such as inter–channel nonlinearities and crosstalk. The study object of this work is the allowed channel spacing in combined HDWDM systems, if modulation format in each system's channel are different. For numerical evaluation of modulation formats simultaneous propagation in WDM system, which consists of three channels with 10 Gbit/s bit rate each, simulation model in OptSim software were introduced. The obtained BER values of each channel were compared with the results of traditional systems, which are using only one of mentioned above optical signal modulation formats. These results will allow choosing development strategy in construction of new optical network and improving already existing network infrastructure. Ill. 9, bibl. 8, tabl. 1 (in English; abstracts in English and Lithuanian).

A. Udalcovs, V. Bobrovs, G. Ivanovs. Gretimų kanalų tyrimas skirtingai moduliuotose kombinuotose optinių signalų HDWDM sistemose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 6(112). – P. 19–24.

WDM sistemas galima papildyti keletu kanalų sumažinus atstumus tarp gretimų kanalų. Padidinus kanalų skaičių, padidėja duomenų perdavimo sparta. Tačiau, naudojant alternatyvių tipų moduliacijas, galima sumažinti bitų klaidų laipsnį ir toleranciją sutrikimo metu. Analizuojamas leidžiamas atstumas tarp gretimų kanalų HDWDM sistemose. Moduliacijos kiekviename kanale yra skirtingo tipo. Tyrimas atliekamas su trimis kanalais, kurių perdavimo sparta 10 Gbit/s. Pateiktas modeliavimo pagal „OptSim" programą modelis. Gautas bitų klaidų laipsnis palygintas su įprastinėmis sistemomis, kuriose taikoma tik vieno tipo moduliacija. Gauti rezultatai gali būti pritaikyti projektuojant naujas optinių tinklų sistemas. Il. 9, bibl. 8, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).