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10 Gbps optical line using EDFA for long distance lines

***Abstract**. The aim of this article is to demonstrate change in the BER (Bit Error Rate) and Q-factor in long distance lines. Nowadays it is not possible to create fully optical communication systems without software tools to simulate real optical networks under the given circumstances. There have been two 10 Gbps optical line topologies created: one without EDFA (Erbium Doped Fibre Amplifier) of up to 115 km and another using EDFA on a long distance line up to 3200 km. The article shows the BER worsening with the distance increasing and also the need for the link amplifier.*

Streszczenie.** Celem niniejszego artykułu jest przedstawienie zmian w BER (Bit Error Rate) oraz współczynnika Q na dużych odległościach. Obecnie nie jest możliwe stworzenie w pełni optycznych systemów komunikacyjnych bez użycia narzędzi programowych do symulacji rzeczywistych sieci optycznych w danych okolicznościach. Utworzono dwie 10 Gbps optyczne topologie liniowe: jedna bez EDFA (Erb z domieszką włókien Amplifier) maksymalnie do 115 km, a druga z użyciem EDFA na duże odległości do 3200 km. W artykule przedstawiono BER pogarszającą się wraz z rosnącą odległością.. **(Linia optyczna 10 Gbps na duże odległości wykorzystująca EDFA)

Keywords: BER, EDFA, OptSim, Q-factor.
Słowa kluczowe: BER, EDFA, OptSim, Q-factor.

Introduction

It has been 18 years since the standardisation of the first optical access network OAN (Optical Access Network) of the APON type (ATM Passive Optical Network). During this time the whole new range of technologies and systems were standardised in the area of optical access networks. The pinnacle of which is the technology NG-PON2 (Next-Generation Passive Optical Network 2) using the combination of a run-in technology of the TDM (Time Division Multiplex) and WDM (Wavelength Division Multiplex) [1], [2] and [9]. The entry of optical technologies into the area of access networks is very gradual, mostly because of the high start-up investment needed for building these networks. Although the passive and active elements are relatively financially accessible, the most expensive part of the realisation still remains the trench digging and the laying of the optical fibres.

The introduction of this technology is even slower in the Slovak Republic. Despite the countless benefits of the FTTx (Fibre To The x) network type the technology of VDSL (Very high bit rate Digital Subscriber Line) is used more and more [1], [3] and [8]. The market situation is improved by small providers of ISP (Internet Service Provider) who try to build up networks of the FTTH (Fibre To The Home) and FTTB (Fibre To The Building) types.

Signal wave multiplexing and the usage of EDFA on long distance lines

Within the wavelength field the WDM multiplex is a technology where the optical signals with different wavelengths are joined into one signal, then transferred together and finally separated again [3], [4]. This is mostly used in optical communication for data transfer of several channels with moderately different values of the wavelengths. Thanks to this method the transfer capacity of the optical lines has markedly increased resulting in a more effective use of the optical fibres and also of EDFA fibre amplifiers.

WDM

The WDM system is created by n transmitters and n modulators of different wavelengths connected into the multiplexor (Fig.1). The demultiplexor, separating individual wavelengths for respective n transmitters, is connected on the other side after the signal transfer through the optical fibre. The wavelength spectrum is divided into individual wavelengths which represent respective transfer channels. The number of possible created transfer channels depends on the purity of the spectral line and also on the wavelength differentiation success. Other factors influencing the number of channels are transferred signal degradation due to dispersion and nonlinear effects such as SPM (Self-Phase Modulation), FWM (Four-Wave Mixing), XPM (Cross-Phase Modulation), SRS (Stimulated Raman Scattering) and SBS (Stimulated Brillouin Scattering) [3], [4], [5] and [6]. The number of transfer channels is influenced also by the stability of lasers, channel crosstalk at multiplexing and demultiplexing and also the width of the region of constant gain of optical amplifiers as the channels have to be placed within this region.

The first WDM system used two transfer channels which meant a two directional transfer using one fibre. The transfer channels in this system are of 850 nm and 1300 nm wavelengths because of their superior parameters of optical fibre transferability. At present there exist more WDM systems divided according to the number of channels: WWDM (Wide Wavelength Division Multiplexer), CWDM (Coarse Wavelength Division Multiplexer) and DWDM (Dense Wavelength Division Multiplexer).

The WWDM systems use four channels within the wavelength range of 1310 nm – the ones with multi-mode fibres also use a wavelength range of 850 nm. The distance between the transfer channels is 25 nm. The CWDM system uses from 4 to 16 transfer channels. The transfer channels are within the wavelength range of 1270 nm to 1610 nm [9]. The distance between respective channels is 20 nm. At present the DWDM systems represent the most advanced type of the WDM technology. The distance between the transfer channels is only 0.4 nm and the wavelength range is from 1530 nm to 1565 nm. This results in a relatively high number of transfer channels, from 32 to 160.

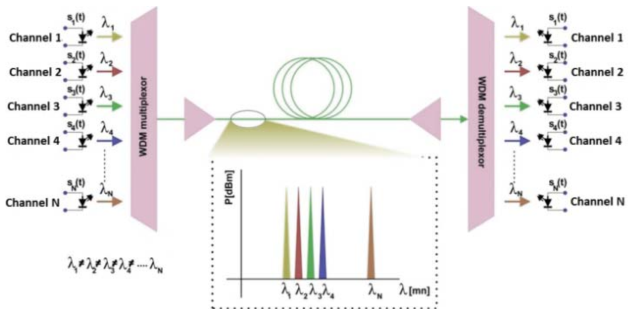

Fig.1. WDM multiplex

EDFA

These amplifiers consist of optical fibre several tens of metres long which is doped with rare earth with Erbium Er^{+3}. The EDFA principle was initially discovered in 1960 but only further progress and economic gains enabled the up until then prohibitively expensive laser lamps to be used commercially in optical networks in the 1990s. The EDFA systems allowed the start of a new generation of optical communication and systems [4]. The benefit of EDFA is to strengthen the optical signal simultaneously at several wavelengths. This increases the system's transferring capacity and uses the technology of WDM optical multiplexing thanks to the option of transferring more wavelengths in one one-mode fibre. EDFA helped to lower the prices of long distance lines and increased their capacity. Instead of one expensive optical amplifier for one wavelength it uses one optical amplifier for a whole range of wavelengths in one fibre [6], [7]. From the 1990's the WDM systems with EDFA support the capacity increase in optical networks and today the capacity of the optical fibre is at the level of tens of Gbps. The admission of EDFA amplifiers ushered in undesirable effects connected with high transfer speed. Today the EDFA amplifiers are most widely used in optical communications [3], [4] and [8]. They also ensure the transatlantic data transfer and elsewhere where there are thousands of optical cables and the signal is considerably absorbed and it needs to be amplified.

The scheme of EDFA connection is pictured in Fig.2. The intake laser diode is of 980 or 1480 nm wavelength and currently available diodes have a power of 450 mW, bound into single-mode fibre. The filter absorbs the spontaneous emission noise and the optical isolator removes the undesirable light reflections. The optical isolator is an opto-fibre component allowing the light flow only in one direction. The optoelectronic feedback node directs the amplifiers gain and the intake power. In optical communication EDFA's are used for the regeneration of the signal absorbed by absorption and the dispersion in the transfer fibre. They are inserted into long distance transfer lines approximately every 70 – 100 km [4].

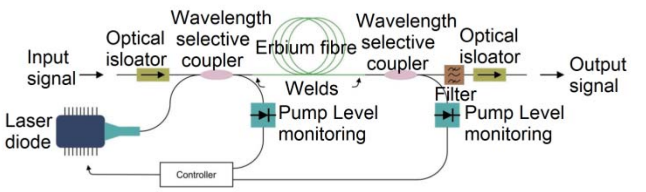

Fig.2. Scheme of EDFA connection

Q-factor and BER

Q-factor expresses the analogue quality of the digital signal considering the gap between the signal and noise. It contains all physical worsening that degrades the signal and cause bit error [3], [4] and [9]. The higher the Q-factor's value, the lower the bit error. The calculation of the Q–factor is given as

(1) $$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0},\ [-]$$

where I_1 is logic level „*1*", I_0 is logic level „*0*", σ_1 is standard variance of logic level „*1*" and σ_0 is standard variance of logic level „*0*" [8]. Bit error bE can be computed as the ratio between received error bits and the overall number of received bits *p* during time *t* [3], [4] and [9].

(2) $$BER = \frac{bE}{vp \cdot t},$$

where *v* is the transfer's speed. Bit error shows quality of the whole optical system. In real digital communication systems there is a nonzero likelihood of error decision whether the patterned value represents the value of the logical "0" or logical "*1*" [8]. The calculation of bit error with the Q–factor recognition is denoted by [4], [9]:

(3) $$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(\frac{-Q^2}{2}\right)}{Q \cdot \sqrt{2\pi}}.$$

The distribution of the likelihood level of the received signal is on the Fig.3. Levels of signal log.*1* are represented by the mean value σ_1, levels of signals log.*0* are represented by the mean value σ_2. P(1|0) and P(0|1) mark the likelihood of log.*1* evaluation while the transmitter transmitted signal log.*0* and vice versa [4], [9] and [10].

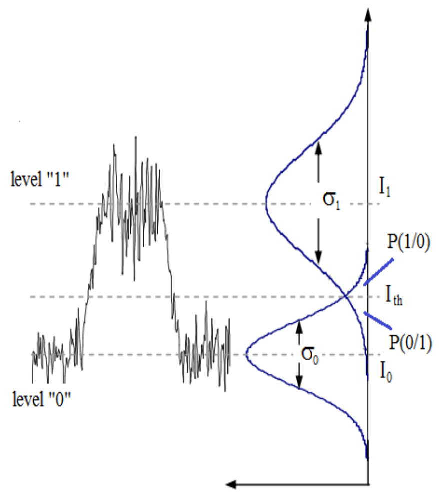

Fig.3. Received optical signal with marked noise dispersion [8]

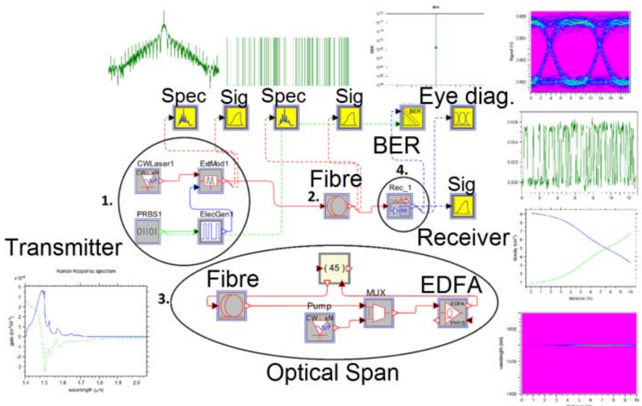

Fig.4. Topology of the optical line with the speed of 10 Gbps

Optical line simulations in the programme environment of OptSim and Matlab

Simulations were performed in the commercial software environment "*OptSim*" from RSoft Company [11], [12]. This software was utilised for the BER and Q-factor comparison for both types of simulations. The BER and Q-factor dependency was created in the "*Matlab*" programme. On Fig.4 is the topology created in the OptSim environment.

Simulation of a 10 Gbps optical line with the distance of 115 km.

The aim of this simulation is the observation of BER at constant speed of 10 Gbps for optical fibres of length of 95 km, 105 km and 115 km without optical loop. In this topology the parameters were set as follows: CW (Continuous Wave_Laser) has set the peak power to 10^{-3} W, operating at the wavelength of 1550 nm. The electric generator is the NRZ (Non-Return-to-Zero) type and its drive type is set to "on_off_ramp" with the points-per-bit 5. The external modulator uses the modulation of the "*Machzehnder*" type. The optical cable length was changed from 95 km to 115 km with increment of 10 km for the BER comparison (Fig. 5) and the results are in the Table 1. Values of BER_lo and BER_hi in Table 1. represent minimal and maximal values of BER for the respective length. The single-mode optical fibre had measurable attenuation of 0.25 dB.km^{-1} according to the standard ITU-T-G.652-D while PMD (Polarization Mode Dispersion), SBS nor the Raman effect were not taken into consideration [13]. The receiver used Bessel's filter with the bandwith of 9 GHz. The representation of the resulting values was based on the Monte Carlo type. It is considered good in optical communication if the BER is under the value of 10^{-12}.

For 95 km the measured BER =7.5159.10^{-14} which is sufficient for reliable impulse differentiation at the side of the receiver. In the 105 km simulation the simulated BER= 1.4462.10^{-5}, and for 115 km it was BER=9.1415.10^{-3} which are not values appropriate for optical communication systems. Because of that we conclude that the BER fell to the level inappropriate for usage in long distance lines and so for bridging any greater distance it is necessary to employ optical amplifiers.

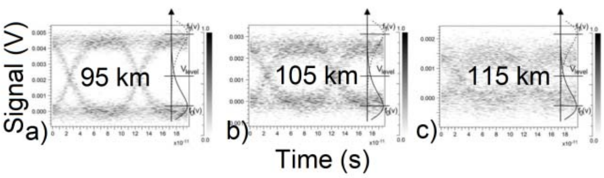

Fig.5. Eye diagrams for 95 km, 105 km and 115 km

Table 1. Output values of BER and Q for fibre length of 95 km, 105 km and 115 km

Length (km)	BER	BER_lo	BER_hi	Q^2(dB)
95	7.5159.10^{-14}	5.8209.10^{-15}	8.7016.10^{-13}	17.369
105	1.4462.10^{-5}	6.2035.10^{-6}	3.2586.10^{-5}	12.427
115	9.1415.10^{-3}	6.8273.10^{-3}	1.2116.10^{-2}	7.4576

In the current age it is needed to amplify the optical signal at all wavelengths. This ability also conditions the capacity increase and the increase in the bit speed. This means to increase the number of wavelengths which transfer the signal via one optical fibre (WDM). In our chosen simulation we could observe how the BER and Q–factor change in relation to the bit speed. The BER worsens at/in its receiving side with the increasing bit speed and the length of the optical fibre. On Fig.6 it is visible how is BER and Q–factor dependent on the length of the optical fibre and bit speed. From bit speed of 20 Gbps and more it is obvious the line quality is insufficient and BER unsatisfactory.

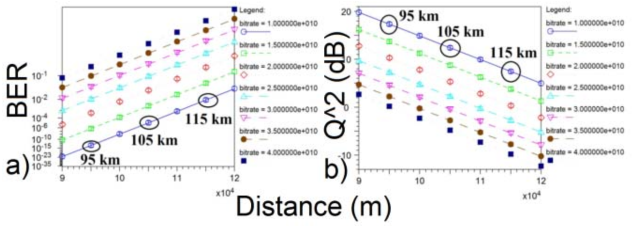

Fig.6. BER and Q–factor dependent on the length of the fibre and bit speed

Topology using EDFA

In the previous simulation it was not possible to reach a better bridging distance than 105 km to 115 km at that bit speed. For that reason it is necessary to employ optical amplifiers of the type IN-LINE that are intermittently inserted into the optical line. These types of optical amplifiers amplify a weak signal into more powerful that can bridge longer distance. The most used IN-LINE is EDFA. The EDFA amplifier used by us has there parameters: the length of erbium doped optical fibre is 10.5 m, while the laser wavelength is 980 nm with the pump power of 4 mW. On Fig. 7a is the depiction of gain with distance for EDFA and in the right part of the Fig.7b is excited erbium state for -20 dBm.

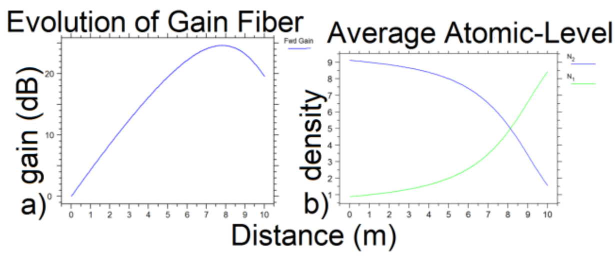

Fig.7. Distance with gain and excited erbium state for EDFA

To create long distance optical line an optical loop has been created (Fig. 4). This optical loop contained EDFA with a pump source and optical fibre of a length of 80 km according to the standard ITU-T-G.652-D [13]. On Fig.8 there is BER of are 3 loops with increment of 10 spans and in Table 2. are result values with increment of 5 spans. The point of this simulation is a demonstration of BER for the distances greater than 3200 km at the speed of 10 Gbps. For 25x spans which represents an optical line of 2000 km the BER=1.6492.10^{-20}. With the value increasing to 35x spans (2800 km) BER fell to the value of 6.4325.10^{-11} which is still an acceptable value for the long distance communication systems. The Fig. 8 has the distance of 45x spans (3600 km) where the value of BER was so small it was immeasurable. The greatest measurable distance was 43x spans (3440 km) where BER=2.9118.10^{-5} and this value is not sufficient for optical communications.

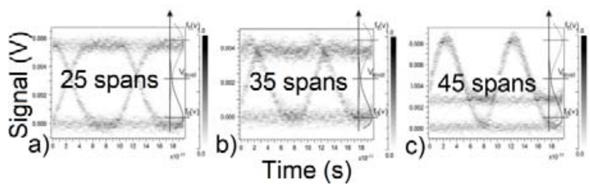

Fig.8. Eye diagram for 25x spans, 35x spans and 45x spans

Table 2. Result values of BER and Q from 25x spans to 45x spans

Spans	BER	BER_lo	BER_hi	Q^2(dB)
25	$1.6492.10^{-20}$	$1.3855.10^{-24}$	$8.1108.10^{-17}$	19.284
30	$1.5429.10^{-13}$	$6.5111.10^{-16}$	$3.7065.10^{-11}$	17.255
35	$6.4325.10^{-11}$	$1.4581.10^{-12}$	$2.1144.10^{-9}$	16.163
40	$1.5673.10^{-7}$	$1.5975.10^{-8}$	$1.3357.10^{-6}$	14.177
43	$2.9118.10^{-5}$	$5.1401.10^{-6}$	$1.5900.10^{-4}$	12.084
45	-	-	-	-

The BER is sufficient at the given bit speed of 10 Gbps. But with the bit speed increase to 20 Gbps it is not possible to bridge the distance of 2400 km. On Fig.9 are depicted bit speeds of 10 Gbps, 12.5 Gbps, 15 Gbps and 20 Gbps for the BER and Q – factor comparison and the dependence on the distance with the results in Table 3.

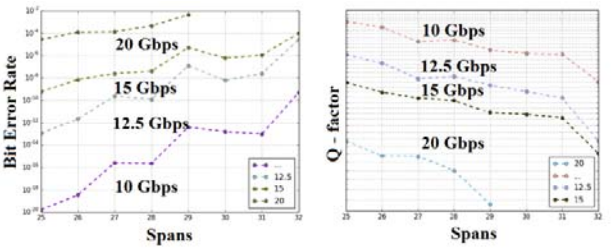

Fig.9. Dependence of BER and Q on the distance with different bit speed

Table 3. Result values of BER and Q based on distance with different bit speed

Bitrate	10 Gbps		12.5 Gbps	
Spans	**BER**	***Q-factor***	**BER**	**Q-factor**
25	$1.6492.10^{-20}$	9.2088	$1.0683.10^{-13}$	7.3400
26	$3.5741.10^{-19}$	8.8726	$2.1980.10^{-12}$	6.9238
27	$4.6242.10^{-16}$	8.0364	$2.4493.10^{-10}$	6.2223
28	$2.3057.10^{-16}$	8.1213	$1.2487.10^{-10}$	6.3271
29	$7.9538.10^{-13}$	7.0663	$1.2186.10^{-7}$	5.1625
30	$1.5429.10^{-13}$	7.0007	$6.0391.10^{-9}$	5.6986
31	$9.4673.10^{-14}$	7.3561	$2.4270.10^{-8}$	5.4566
32	$5.0708.10^{-10}$	6.1072	$2.5989.10^{-5}$	4.0466
	15 Gbps		**20 Gbps**	
25	$5.9885.10^{-10}$	6.0806	$2.7498.10^{-5}$	4.0333
26	$7.1116.10^{-9}$	5.6707	$1.2906.10^{-4}$	3.6541
27	$2.4999.10^{-8}$	5.4513	$1.3993.10^{-4}$	3.6333
28	$4.0032.10^{-8}$	5.3670	$4.8019.10^{-4}$	3.3019
29	$4.9067.10^{-6}$	4.4212	$4.4029.10^{-3}$	2.6195
30	$5.8837.10^{-7}$	4.8595		
31	$1.0455.10^{-6}$	4.7444		
32	$1.0051.10^{-4}$	3.7177		

Conclusion

The aim of this article was to point out the worsening of BER in regard to the increasing distance and the necessity of using an IN-LINE amplifier in optical communications. The first simulation by itself shows the need to use EDFA because the maximal bridging distance cannot reach 100 km. The main point of the article is probably, according to the simulations, to create a long distance optical line with a speed of 10 Gbps for up to a distance of 2800 km, given the EDFA parameters. The values used in the simulations were entered according to the catalogue values. The communication model indicated can be upgraded into a WDM but it is necessary to take into account nonlinear effects such as SPM, FWM and XPM while designing the line itself. These nonlinear effects are connected with the spacing between individual channels, the power and bit speed.

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