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DEFINITION OF BIT ERROR RATE ON 16-CHANNEL DWDM SYSTEM

Petr Ivaniga[1] and Tomáš Ivaniga[2]
[1]Department of Information Networks, Faculty of Management Science and Informatics, University of Žilina, Žilina, Slovakia
[2]Department of Electronics and Multimedia Communications, Faculty of Electrical Engineering and Informatics, University of Technology Košice, Košice, Slovakia
E-Mail: tomas.ivaniga@tuke.sk

ABSTRACT

Nowadays while designing the fully optical communication system it cannot be done without software tools simulating a real network to avoid possible mistakes which could occur before the actual construction of communication system. We are experiencing still higher demand on quality and amount of transmitted data through a communication channel. A WDM (Wavelength Division Multiplexing) system is one technology which satisfies these requirements. This article describes the basic definition BER (Bit Error Rate) and related Q-factor. In modern optical communication, while creating DWDM (Dense Wavelength Division Multiplexing) system, BER should not be dropped below 10^{-12} (Q-factor approximately 7). In this paper, we will provide some experimental results from our simulations of 16-channel DWDM system with specific channel spacing.

Keywords: BER, Q-factor, eye-diagram.

1. INTRODUCTION

From the currently known WDM technologies, the most used are DWDM and CWDM (Coarse Wavelength Division Multiplex) technologies. Wavelength Division Multiplex WDM is a form of the optical signal transmission between multiple points. Among the main architecture elements belong WDM multiplexer and WDM demultiplexer. WDM multiplexer combines usually tens of channels to one informational stream, which are transmitted through the SMF (Single mode Fiber) [1], [2] [3]. An optical signal corresponds to high frequencies (an order of THz). Lasers are used as a source of an optical signal. The main parameter, which qualitatively characterizes laser, is a spectral width. We are trying to manufacture lasers with a narrow spectral width because lasers should be monochromatic light sources. Particular wavelengths have to be compound into a device so-called multiplexer.

The first possibility how to get light to the multiplexer is to have several laser sources radiated on certain frequencies. Laser source has to be modulated by the modulation signal (information signal) and then lead to the physical multiplexer. Particular wavelengths have to be defined and carefully spaced. We have two optical windows (1310 and 1550 nm) which have acceptable properties for low attenuation signal transmission. Moreover, when we transmit signal on high frequencies (THz) we have to take into account nonlinear effects. SPM (Self-Phase Modulation), FWM (Four Wave Mixing) and XPM (Cross-Phase Modulation) are having a negative influence on signal detection, its quality and BER at the receiving end [4], [5]. These effects have to be balanced with another negative effect called a chromatic dispersion. Nonlinear effects mainly SPM causes deterioration of a signal in the spectral domain which should be satisfactorily compensated by the effect of dispersion [6], [7], [8]. Dispersion degrades a signal in the time domain. In the present, there are two standards used in WDM systems (CWDM, DWDM). [9], [10]. The quality of the signal is determinate by SNR (Signal - to - Noise Ratio) and BER [11], [12].

For optical communication, BER should be lower than 10^{-9}. In this article, we will describe the simulation of xWDM architecture with 0, 25 nm channel spacing. It will be pointed out at the corresponding BER values as well as other graphical outputs regarding to a simulated xWDM.

2. BER AND QUALITY FACTORS

In this chapter, we will describe basic definition BER and SNR.

A. Signal - to - noise ratio

SNR is a very important qualitative indicator which evaluates not only the optical signal. There are basically three kinds of noises which have to be taken into account [13], [14], [15]. The first type called a shot noise $\langle i_Q^2 \rangle$ is shown in equation (1). This noise is known also as a quantum noise. It occurs due to a statistical nature of photons [16]. In other words, this noise is presented because of a statistical nature of the photons interact with a matter. We are talking about a shot noise when the optical signal can be found in the photodetector.

$$\left\langle i_Q^2 \right\rangle = 2qI_P BM^2 F(M)\,. \tag{1}$$

The second type is a dark current noise shown in equations (2), (3) having two forms: a bulk $\langle i_{DB}^2 \rangle$ and a surface $\langle i_{DS}^2 \rangle$ form. This noise occurs when there is no optical signal but still some amount of a light in a photodetector causing some of the photocurrent fluctuating.

$$\left\langle i_{DB}^2 \right\rangle = 2qI_B BM^2 F(M)\,. \tag{2}$$

$$\left\langle i_{DS}^2 \right\rangle = 2qI_S B\ . \tag{3}$$

ARPN Journal of Engineering and Applied Sciences

The third type is a thermal noise $\langle i_T^2 \rangle$ presented at the receiver end. This noise is due to a resistance necessarily used in the circuits. It is shown in equation (4) that refers to the thermal noise more or less presented during optical signal detecting.

$$\left\langle i_T^2 \right\rangle = 4KTB / R_L \,. \tag{4}$$

All mentioned noises always play a role in any optical signal and are dependent on an optical intensity. We usually define two situations: dominant shot noise and dominant thermal noise.

The SNR is therefore calculated as shown in equation (5). In equation (5), the numerator is considered as a signal power where a variance of photocurrent is $\langle i_P^2 \rangle$ and M is internal photodiode amplification (usually 1) [17], [18]. On the other hand, in the denominator, it is a sum of independent noises.

$$SNR = \frac{\left\langle i_P^2 \right\rangle M^2}{\left\langle i_Q^2 \right\rangle + \left\langle i_{DB}^2 \right\rangle + \left\langle i_{DS}^2 \right\rangle + \left\langle i_T^2 \right\rangle} \,. \tag{5}$$

B. Bit error rate

Bit Error Ratio BER is another characteristic, very useful for finding out a system performance. BER parameter describes the ratio between bits wrongly detected and a total number of bits received (transmitted). As we can see in Figure-1, there are two regions, *P(1/0)* and *P(0/1)*, needed to be discussed in detail.

The information is detected in two levels, *„0”* and *„1”*. These two levels have corresponded with current values *I1*, *I2* as well as their variances σ_1, σ_2. The variances have usually different values [19], [20]. If the incoming signal has a value within σ_1, I_1 region *„1”* is detected, the analogical process is applied with *„0”* level detection. However sometimes system makes an error and *„0”* is recognized when *„1”* was transmitted to *P(0/1)*, as shown in Figure-1 (a lower region). Complementary,*„1”* can be detected when *„0”* was sent to *P(1/0)* (an upper region). Corresponding probability functions are defined as follows:

$$P(0/1) = \frac{1}{\sqrt{2\pi}\sigma_1} \int_{-\infty}^{I_{th}} e^{-\frac{(I-I_1)^2}{2\sigma_1^2}} dI \,, \tag{6}$$

$$P(1/0) = \frac{1}{\sqrt{2\pi}\sigma_0} \int_{I_{th}}^{\infty} e^{-\frac{(I-I_0)^2}{2\sigma_0^2}} dI \,. \tag{7}$$

The next step is to define some complementary error functions for *P(0/1)* and *P(1/0)*

$$P(0/1) = \frac{1}{2} erfc\left(\frac{I_1 - I_{th}}{\sigma_1 \sqrt{2}} \right), \tag{8}$$

$$P(1/0) = \frac{1}{2} erfc\left(\frac{I_{th} - I_0}{\sigma_0 \sqrt{2}} \right). \tag{9}$$

BER has the minimum value when *P(0/1)* and *P(1/0)* regions are equal [21], [22]. From this assumption we have to set the following condition for a threshold current I_{th} which is important to be set correctly.

$$\frac{I_1 - I_{th}}{\sigma_1} = \frac{I_{th} - I_0}{\sigma_0} \Rightarrow I_{th} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_1 + \sigma_0} \,. \tag{10}$$

Now we can define another parameter called Q-factor, shown in equation (11).

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \,. \tag{11}$$

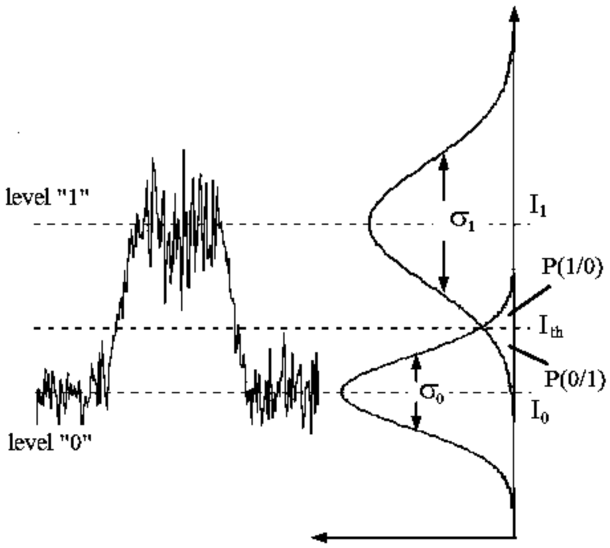

Figure-1. The probability of a detection *P(1/0)* and *P(0/1)* with corresponding variances for level *„0”* and level *„1”*.

Q-factor describes the margin between two levels, *„0”* and *„1”*, and their relation to the corresponding variances σ_1, σ_2 [23]. By assuming that BER is a sum of the regions shown in equations (8), (9), we can define the following equation (12).

$$BER = \frac{1}{4} \left\{ erfc\left(\frac{I_1 - I_{th}}{\sigma_1 \sqrt{2}} \right) + erfc\left(\frac{I_{th} - I_0}{\sigma_0 \sqrt{2}} \right) \right\}. \tag{12}$$

Now it is possible to write a final equation for BER as well as its approximation by using the exponential function as shown in the following equation.

ARPN Journal of Engineering and Applied Sciences

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{e^{-\frac{Q^2}{2}}}{Q\sqrt{2\pi}} . \qquad (13)$$

For the optical communication, we consider a Q-factor value equals 6 [23]. This number is referred as a lower acceptable limit for a noise margin in optical communications. This can be seen in Figure-2.

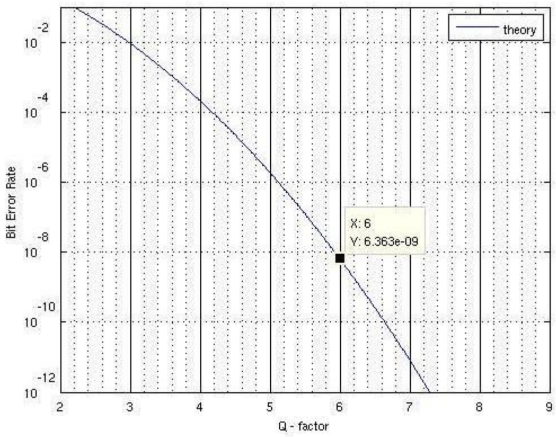

Figure-2. Theoretically calculated BER as a function of Q-factor.

3. REALIZATION OF 16 - CHANNEL XWDM SYSTEM

The optical network in the simulation package *„OptSim"* has been created for the experimental measurement. On Figure-3 is shown universal DWDM system.

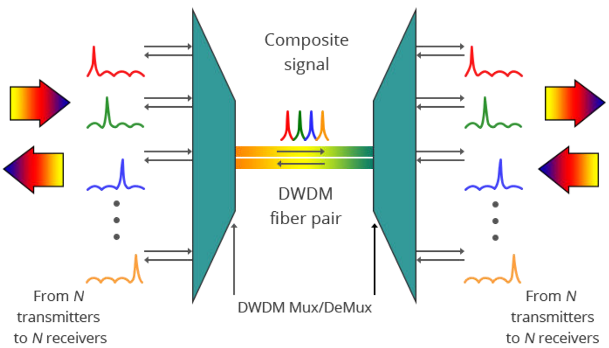

Figure-3. General DWDM system.

„OptSim" program package is an advanced simulation program, designed for a professional research on various types of multiplexing (WDM, DWDM, and TDM), cable television (CATV), optical networks LAN, parallel optical bus and other optical systems in the field of telecommunications as well as data communications working with single mode fibers.

Optical Link Termination (OLT) unit is composed of four basic blocks.

It is the source of the data stream which is used to ensure data units for ONT (Optical Network Terminal). Another block is the excitation laser which is used as a transmission medium. Block modulation NRZ (Non-Return Zero) and the last part of the broadcasting is the signal modulator.

The proposed OLT consists of 16 channels which have 0, 25 nm spacing between them and the frequency band have from 193, 134 to 193, 602 THz. At the input end of the ONT is located an optical filter (band-pass) used for adjusting the optical signal so that it does not contain undesirable wavelengths. Therefore, the signal reaches the detector, which consists of a PIN diode, and finally, the signal is smoothed by means of the *„Bessel"* filter. *„Bessel"* filter bandwidth is 7,464 dB, the width of the optical filter is 60 GHz and the carrier wave channel number varies from 193, 134 to 193, 602 THz.

The main factor for assessing the quality of the entire network is the value of BER. This value indicates the ratio of incorrectly received bits to the total number of bits received for a period of time. The electrical probe allows us to view the eye diagram. This represents a superposition of overlapping bits in the signal. From the eye, the diagram is then possible to find out the value of jitter, which is the value of delay variations of individual bits, parameter ISI (Inter Symbol Interference), which causes modulation impulse overlapping.

A. OLT simulation's results

In Figure-4 is the signal spectrum for a particular channel with the frequency 193, 477 THz. Power was measured 0, 20139mW and Highest Peak Power was 20,554974 dB [mW / THz].

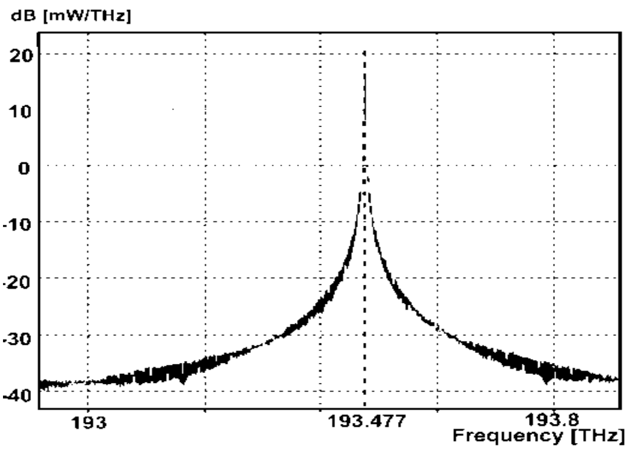

Figure-4. The frequency spectrum for a channel (frequency 193,477 THZ).

Optical fiber that was used G.652.D has a specific attenuation of 0, 4 dB/km and a length of 100 km. Amplifier output power was 4, 00498 mW with NF (Noise Figure) = 3.

In Figure-5 is the signal spectrum after the amplifier output. Power was measured 0,528919 mW and Highest Peak Power was 10,855294 dB [mW / THz].

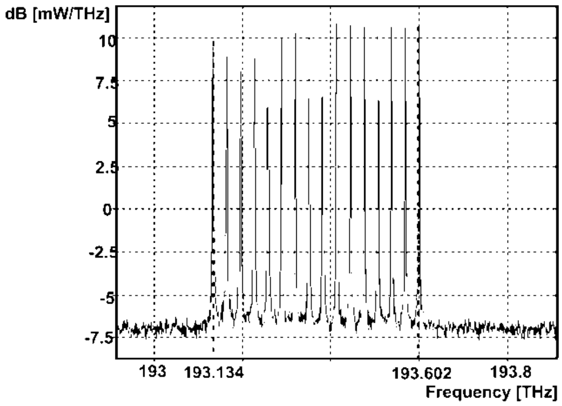

Figure-5. Spectrum of a signal (16 channels) after amplification.

B. Results of ONT simulations

For the simulations, there were four frequencies selected 193, 134 THz, 193, 352 THz, 193, 477 THz and 193,602 THz which have changed in the *„Lorentz"* filter.

a) Frequency of the *„Lorentz"* filter for 193,134 THz

The spectrum of the optical signal has the Highest Peak Power 9, 81146 dB [mW / THz] and Power 0, 0468554 mW which corresponds to the attenuation 13, 2924 dBm. At the ONT output for the channel 193, 134 THz is the BER 2, $95695 \cdot 10^{-14}$, the value of Q-factor is 7, 58187, the value of jitter 0,0943579 ns and the eye-opening value $5{,}53935 \cdot 10^{-05}$. In Figure-6 is shown the spectrum of the optical signal after filtering for frequency 193, 134 THz and BER.

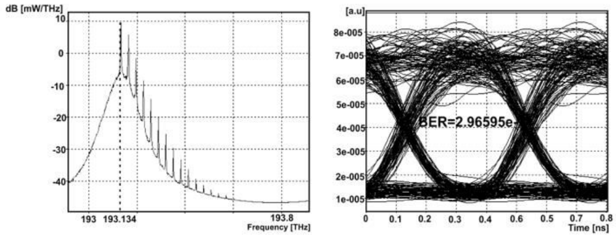

Figure-6. The spectrum of the optical signal for 193,134 THz and BER.

b) Frequency of the *„Lorentz"* filter for 193, 352 THz

The spectrum of the optical signal has Highest Peak Power 10, 594282 dB [mW / THz] and Power 0, 0602715 mW which corresponds to the attenuation 12, 1989 dBm. At the ONT output for channel 193,352 THz is BER $5{,}68702 \cdot 10^{-19}$, the value of Q-factor is 9, 03494, the value of jitter is 0,0868822 ns and the eye-opening value 7, $81673 \cdot 10^{-05}$. In Figure-7 there is the spectrum of the optical signal after filtering for frequency 193,352 THz and BER.

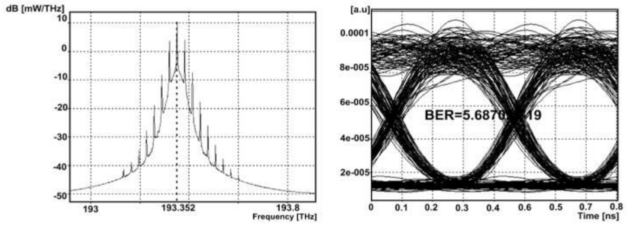

Figure-7. The spectrum of the optical signal for 193,352 THz and BER.

c) Frequency of the *„Lorentz"* filter for 193,477 THz

The spectrum of the optical signal has Highest Peak Power 10,642878 dB [mW / THz] and Power 0,0601615 mW which corresponds to the attenuation 12,2681 dBm. At the ONT output for channel 193,477 THz is BER $3.00772 \cdot 10^{-20}$, the value of Q-factor is 9, 33944, the value of jitter 0,0836725 ns and the eye-opening value 7, $69988 \cdot 10^{-05}$. Figure-8 shows the spectrum of the optical signal after filtering for frequency 193, 477 THz and BER.

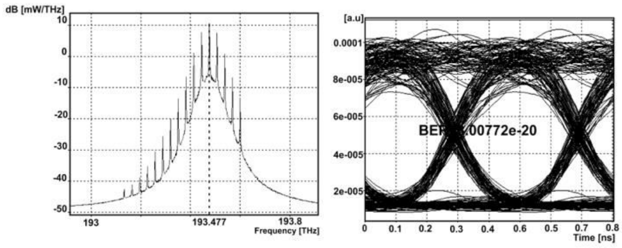

Figure-8. The spectrum of the optical signal for 193,477 THz and BER.

d) Frequency of the *„Lorentz"* filter for 193,602 THz

The spectrum of the optical signal has Highest Peak Power 10,601121 dB [mW / THz] and Power 0,0476326 mW which corresponds to the attenuation 13,2209 dBm. At the ONT output for channel 193,602 THz, the BER is 6, $210231 \cdot 10^{-14}$, the value of Q-factor is 7, 51318, the value of jitter is 0, 0845063 ns and the eye-opening value 5, $63084 \cdot 10^{-05}$. Figure-9 shows the spectrum of the optical signal after filtering for frequency 193, 602 THz and the BER.

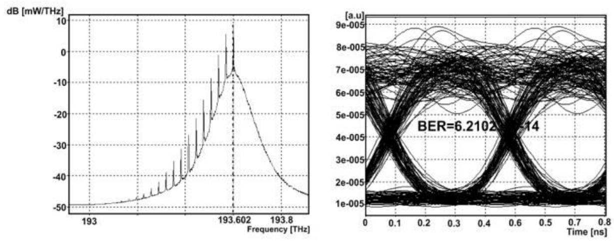

Figure-9. The spectrum of the optical signal for 193,602 THz and BER.

In Table-1 are the values of each channel at the amplifier output and the corresponding values of Power, Highest Peak Power, Q, and BER.

Table-1. BER, Q - factor, Output power and Highest Peak Power at the receiver end.

Channel	*Power [mW]*	*Highest Peak Power [mW]*	*Q factor [-]*	*BER [a.u]*
1	0,046855	9,811426	7,5818	$2{,}97\cdot10^{-14}$
2	0,057223	8,900131	9,1385	$3{,}14\cdot10^{-19}$
3	0,059511	8,093345	9,2246	$4{,}97\cdot10^{-20}$
4	0,060125	8,822955	10,001	$5{,}59\cdot10^{-23}$
5	0,060482	9,754642	10,502	$3{,}92\cdot10^{-26}$
6	0,060129	10,00159	11,711	$5{,}66\cdot10^{-30}$
7	0,060083	10,33022	9,0349	$5{,}69\cdot10^{-19}$
8	0,060271	10,59428	9,0349	$5{,}69\cdot10^{-19}$
9	0,060320	10,61964	9,3738	$7{,}20\cdot10^{-21}$
10	0,060559	10,85614	9,3813	$9{,}37\cdot10^{-21}$
11	0,060311	10,72375	9,2547	$1{,}49\cdot10^{-20}$
12	0,060161	10,64287	9,3394	$3{,}01\cdot10^{-20}$
13	0,060221	10,68264	8,6038	$4{,}69\cdot10^{-18}$
14	0,059818	10,62636	8,2746	$4{,}23\cdot10^{-16}$
15	0,057817	10,60342	8,2605	$3{,}79\cdot10^{-16}$
16	0,047632	10,60112	7,5131	$6{,}21\cdot10^{-14}$

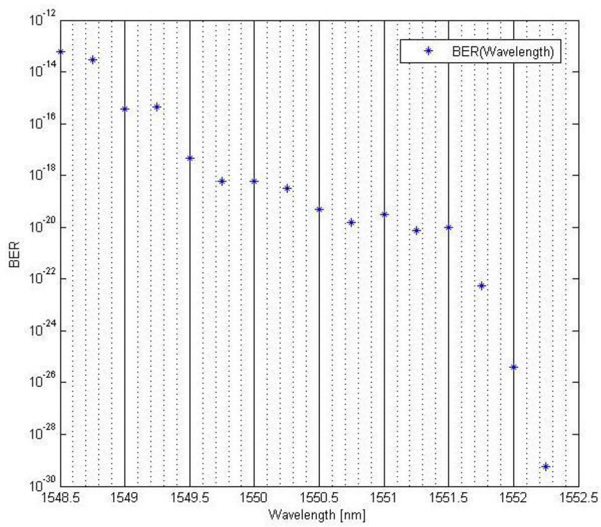

Figure-10. BER values for particular channels.

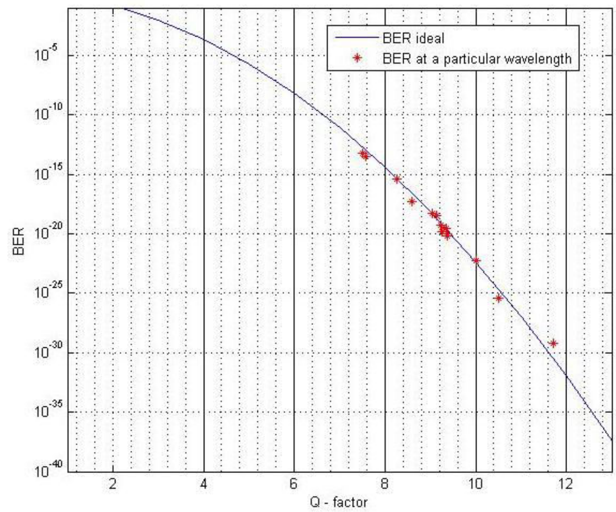

Figure-11. Comparison of ideal and measured BER for a particular channel.

4. CONCLUSIONS

This article refers to fundamental principles of WDM systems and its modifications considering the channel spacing. To get some general overview we have made practical simulations and demonstrations of xWDM in *„OptSim"* software. There is the OLT unit consisting of 16 physical channels. The channel spacing was defined as

0, 25 nm between channels. The particular channels were defined starting by 1548, 5nm for λ_1 till 1552, 25 nm for λ_{16}. The results of our simulations show that the best value for BER - in order of 10^{-30} - was achieved for Channel 6. On the other hand, we have measured the lowest BER - in order of 10^{-14} - for two channels: $\lambda_1$and λ_{16}. In Figure-11 there is an ideal BER curve as a function in Q-factor (a blue curve). It has been already mentioned that for the optical communication, in general, the acceptable BER is 10^{-9}. Red points represent simulated values of BER and Q-factor for particular channels. We assume that our simulations were correct because the differences between an ideal curve and simulated values were negligibly small.

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