Rastislav RÓKA, Martin MOKRÁŇ

Slovak University of Technology, Slovakia

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Simulation Platform for Analyzing Environmental Effects in Multi-Wavelength Transmission Systems in Matlab Simulink

***Abstract**. For reliable communication of multi-wavelength transmission systems, significant environmental effects on transmitted information signals must be investigated and analyzed. This paper presents a specific simulation platform that allows analyzing environmental effects due to the optical transmission medium at the multi-wavelength signal transmission. This simulation platform represents the signal transmission in the optical single-mode fiber medium for both CWDM and DWDM systems with four wavelength channels and allows analyzing the impact of optical transmission medium on transmitted multi-wavelength information signals*

Streszczenie.** Dla niezawodnej komunikacji transmisji o wielu długościach fali powinien być analizowany efekt wpływu środowiska. W artykule zaprezentowano metodę symulacji umożliwiającą analizę z transmisją światłowodową typu CWDM i DWDM z czterema kanałami. **Platforma symulacyjna do nalizy wpływu środowiska na światłowodowy wielokanałowy system transmisji.

Keywords: optical single-mode fiber, simulation platform, wavelength division multiplexing, multi-wavelength transmission systems
Słowa kluczowe: komunikacja światłowodowa, transmisja o wielu długościach fali.

Introduction

One of methods that can increase a transmission capacity of the optical fiber is the Wavelength Division Multiplexing (WDM). Various forms of wavelength multiplexing techniques are considered for utilization in future metro-access networks with a combination of different network topologies [1]-[5]. Moreover, advanced modulation formats are investigated for utilization in next-generation passive optical networks with the WDM implementation [6]. This work aims to investigate environmental effects in multi-wavelength transmission systems and their specific influences on transmitted information signals [7]-[11]. With regard of the utilized frequency spectrum, two WDM forms can be under consideration [12]-[13]. One of advantages for Coarse WDM systems [14] is a cheaper implementation, since there is a larger channel spacing that allows using of simpler components like lasers and optical filters. Their main disadvantages are a smaller maximum count of transmitted channels and a complicated amplification, since a wider spectral transmission band is used and optical amplifiers are usually designed for a narrower spectrum. One of main advantages for Dense WDM systems [15] is a larger count of transmitted channels (up to hundreds) and a simpler possibility of optical amplification e.g. using EDFA amplifiers.

For our investigation, it is crucial to prepare and create a reliable simulation platform that can be used for analyzing environmental effects at multi-wavelength signal transmission in optical systems. Therefore, the main part of this paper is intended for detailed description of particular block functionalities in the specific simulation platform for WDM systems and, subsequently, for analysis of environmental effects in CWDM and DWDM transmission systems.

Principles of WDM Systems and Their Available Frequency Spectrum

WDM systems allow transmitting of multiple user data channels through the one optical transmission path. The principle scheme of the WDM system is shown on Fig. 1. Each channel is represented using different wavelengths (from λ_1 to λ_n) of the optical signal. A task of the WDM multiplexer is to merge n incoming signals (channels), which are coupled using the optical coupler, into one common signal. This common optical signal is after a transmission through the optical fiber divided into individual signals (channels). A task of the WDM demultiplexer is to split incoming multiplexed signal into individual signals (channels) using the optical splitter and a set of optical filters. Through particular optical filters should pass wavelengths corresponding to wavelengths incoming into the WDM multiplexer (i.e. from *λ1* to *λn*) [5], [6], [9], [10].

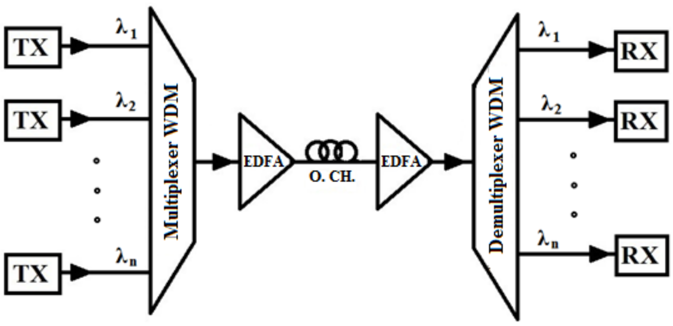

Fig. 1. The principle scheme of the WDM system

The capacity of WDM systems is strongly dependent on the channel spacing (i.e. number of transmitted channels). If the channel spacing is smaller, then more channels can be transmitted in optical transmission windows. With regard to the available optical bandwidth and the channel spacing, wavelength multiplexing techniques can be divided into [12], [14], [15]:

- Coarse Wavelength Division Multiplexing,
- Dense Wavelength Division Multiplexing.

The Coarse Wavelength Division Multiplexing (CWDM) is a simpler version of the WDM multiplexing technique, where no optical amplifiers are considered. Therefore, its simulation and analyzing is much easier than the Dense Wavelength Division Multiplexing (DWDM).

For the CWDM system, there is used a larger channel spacing that allows utilizing simpler and therefore cheaper system components, e.g. non-cooled lasers with a larger wavelength tolerance and optical filters with a wider passband. The CWDM system uses transmission wavelengths from 1270 nm to 1610 nm (i.e. II. and III. optical transmission window) with 20 nm channel spacing [14]. Therefore, the maximum number of transmitted channels is 18.

The CWDM technology is used for short and medium distance network applications [12].

The DWDM system uses for transmission wavelengths from 1530 nm to 1565 nm for C optical transmission band resp. from 1565 nm to 1625 nm for L optical transmission band with channel spacing from 0,1 nm to 0,8 nm. The maximum number of transmitted channels can be varied in dependence of channel spacing from 45 to 360 channels [11], [13], [15]. DWDM systems can be further divided according to channel spacing into:

- systems with a fixed channel spacing,
- systems with a flexible channel spacing.

The DWDM system with a fixed channel spacing has the equal channel spacing for each transmitted channel. Channel frequencies are defined by ITU-T G.694.1 by equations:

(1a) $$193{,}1 + n_{p12,5}\,.\,0{,}0125\ [THz]\ \textit{for the}\ 12{,}5\,GHz\ \textit{spacing}$$

(1b) $$193{,}1 + n_{p25}\,.\,0{,}025\ [THz]\quad \textit{for the}\ 25\,GHz\ \textit{spacing}$$

(1c) $$193{,}1 + n_{p50}\,.\,0{,}050\ [THz]\quad \textit{for the}\ 50\,GHz\ \textit{spacing}$$

(1d) $$193{,}1 + n_{p100}\,.\,0{,}010\,[THz]\quad \textit{for the}\ 100\,GHz\ \textit{spacing}$$

where $n_{p12,5}$, n_{p25}, n_{p50} a n_{p100} are integers (positive, negative or zero). Example of the DWDM frequency grid with the 50 GHz fixed channel spacing is shown on Fig. 2.

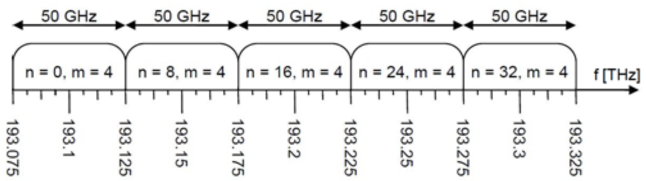

Fig. 2. The DWDM frequency grid with the 50 GHz fixed spacing

The DWDM system with a flexible channel spacing allows multiplexing channels with different transmission speeds. For this case, nominal central frequencies are defined by:

(2a) $$193{,}1 + n_f\,.\,0{,}00625\ [THz]$$

where n_f is an integer (positive, negative or zero) and a slot width is defined by:

(2b) $$\Delta f = 12{,}5\,.\,m\ [GHz]$$

where *m* is a positive integer.

The recommendation [15] allows any combinations of frequency slots as long as no two frequency slots overlap. On Fig. 3, an example of the frequency grid with one 50 GHz channel and two 75 GHz channels is shown. The frequency slot between 193,125 THz and 193,18125 THz is unallocated and left as a guard band between two sets of channels. Instead of this guard band, this slot can be used for another 50 GHz channel [13].

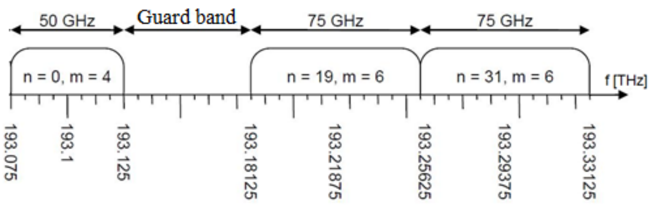

Fig. 3. The DWDM frequency grid with the flexible channel spacing

The Simulation Platform for Multi-Wavelength Transmission Systems

Simulations of WDM systems are performed in MATLAB Simulink 2017b with additional libraries like Communications System Toolbox and DSP System Toolbox. To fully understand all details and parts of the simulation platform described in this paper, it is recommended to become familiar with previous works, which were dealt with a created model of the optical transmission path [7]-[10], [16-20]. The complete simulation platform scheme of 4-channel WDM systems is shown on Fig. 4. This scheme is identical for both CWDM and DWDM multiplexing. Main differences are in the settings of CW optical signals generators and WDM demultiplexer (resp. internal filters settings). These differences result from different channel spacing that means different wavelengths used for a signal transmission. Another simulation form of the DWDM system is designed in the VPIphotonics software [21]. However, there is no presented possibility for analyzing environmental effects in the utilized DWDM data system.

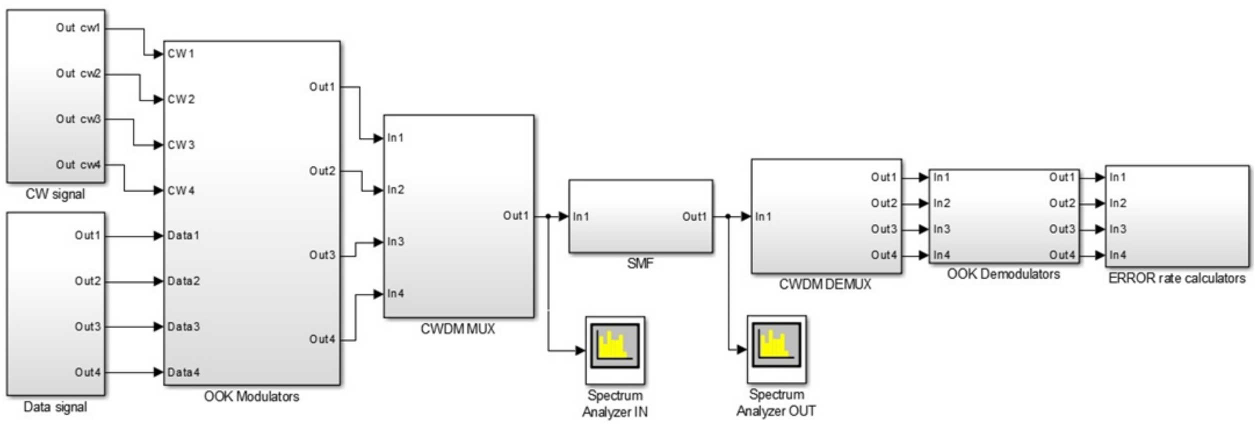

Fig. 4. The simulation platform for the WDM optical transmission systems

This Simulink platform for WDM optical transmission systems consists of next parts of the optical transmission path:

- Sources of data signals
- Sources of CW optical signals
- OOK Modulators
- WDM Multiplexer
- Model of the SMF optical transmission
- WDM Demultiplexer
- OOK Demodulators
- ERROR rate calculator

Sources of data signals consist of four independent (Bernoulli) binary generators that represent informative data flows of four user channels which are later modulated and multiplexed. The scheme of internal connections for data signal sources is shown on Fig. 5.

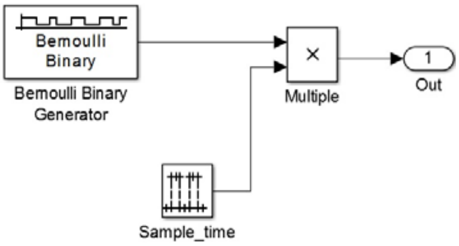

Fig. 5. The detailed scheme of the data signal source

Sources of CW optical signals represent carrier waves that enter the OOK Modulators block. These signal generators are main elements for simulating a data transmission through the optical transmission medium. One carrier signal source consists of several sine generators that are set to generate many continuous wave (CW) signals at the same time, since a real source of the optical radiation is not monochromatic (i.e. it has not only one carrier wavelength (λ), but there are more wavelengths ($\Delta\lambda$)). The scheme of internal connections for CW signal source is shown on Fig. 6.

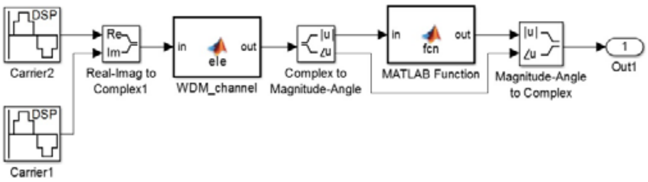

Fig. 6. The detailed scheme of the CW signal source

Outputs from data sources and optical CW signal sources are entering into OOK modulators. A task of the modulator is to change (i.e. modulate) entering optical signal in dependence of entering data signal. One OOK Modulators block consists of four MZM modulators. Its scheme with internal connections in the 4-channel WDM system is shown on Fig. 7. The detailed internal connection of a MZM modulator is described in [16], [17].

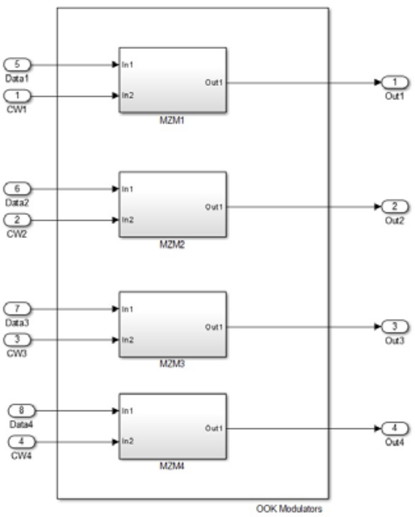

Fig. 7. The internal connection scheme of the OOK Modulators block

Signals that leave the OOK Modulators block enter into the 4-channel WDM MUX block (Fig. 8), where they are coupled into one combined signal subsequently entering the SMF block representing the optical signal transmission in the single-mode fiber transmission environment.

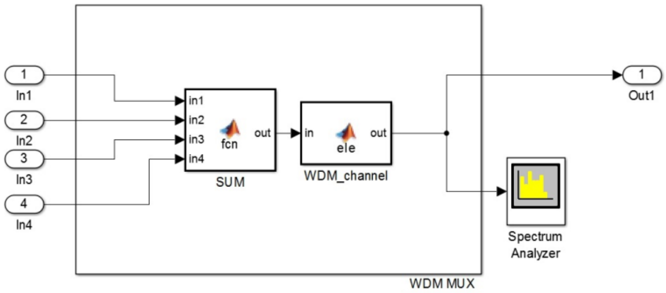

Fig. 8. The internal connection scheme of the WDM MUX block

The signal that leaves the WDM MUX block enters the SMF block (i.e. a model of the single-mode fiber optical transmission), that simulates environmental influences with both linear and nonlinear effects on transmitted optical signals in the optical transmission medium. Following environmental effects are included in the SMF block:

- Chromatic Dispersion (CD)
- Polarization Mode Dispersion (PMD)
- Four-Way Mixing (FWM)
- Self-Phase Modulation (SPM) & Cross Phase Modulation (XPM)
- Stimulated Raman Scattering (SRS) & Stimulated Brillouin Scattering (SBS)
- Attenuation (ATT)

Details about modeling of environmental influences at the signal transmission in the single-mode optical fiber are available in [8], [18], [19]. For investigating, systems utilizing various multi-channel digital techniques for compensation the nonlinear impairments [22]-[24] can be very interesting in

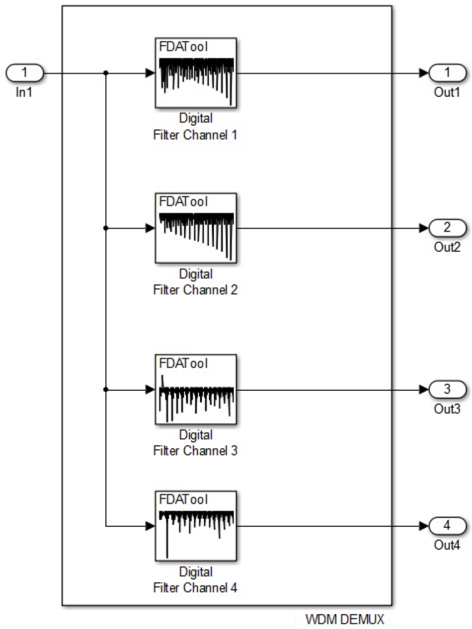

Fig. 9. The internal connection scheme of the WDM DEMUX block

nonlinear optical communication.

After transmission through the SMF block, a signal enters the WDM DEMUX block (Fig. 9). A task of the demultiplexer is to split incoming signal into separate signals (channels) i.e. only one independent optical signal containing one data flow (transmission channel) is present on each output of the WDM demultiplexer. The WDM demultiplexer consists of a set of optical filters where an independent filter is used for each channel. The optical filters in a simulation platform are designed using Simulink *Digital Filter Design* tool that is contained in the *Matlab Simulink DSP System Toolbox*.

Outgoing signals from the WDM DEMUX block enter the OOK demodulators that interpret received optical signals as binary (user) data streams.

Results of Analyzing Environmental Effects in CWDM and DWDM Transmission Systems

The simulations of WDM systems are performed in Matlab Simulink 2017b and consist from extensions of the simulation model for the optical transmission path [7-8], [18-19] using multiplexers and demultiplexers to four channel CWDM and four channel DWDM system. In simulations, it is assumed the fiber length L = 80 km, the total attenuation a_{total} = 16,8 dB, the specific attenuation $\alpha_{specific}$ = 0,21 dB/km, CD = 10 ps/km, PMD = 10 ps/(nm.√km), as parameters of the single-mode fiber at the λ = 1551 nm wavelength. In the CWDM system simulation, parameters related for other wavelengths are also used. For simulations, the OOK modulating technique is used with the same 10 Gbit/s transmission speed for each transmitted channel.

Because the 20 nm channel spacing is used for the CWDM system, the selected wavelengths are:

1. channel: λ_1 = 1571 nm => f_1 = 190,83 THz
2. channel: λ_2 = 1551 nm => f_2 = 193,29 THz
3. channel: λ_3 = 1531 nm => f_3 = 195,81 THz
4. channel: λ_4 = 1511 nm => f_4 = 198,41 THz

Since a larger channel spacing is used in the CWDM system, it is a premise that parameters of the optical transmission path are different for each transmitted channel. Therefore, the transmission through a model of the SMF optical transmission path is simulated “individually” i.e. a common transmission path is divided into four paths (each channel has its own path) that are interconnected with each other. These interconnections influence the transmitted channel using adjacent channels (i.e. the first channel is affected with second, third and fourth channels, the second channel is affected with first, third and fourth channels, etc.) and coupled after transmission trough the simulation model of optical fiber. Details of this method are available in [9], [10]. The complete block scheme of the CWDM system with detailed internal connections is shown on Fig. 10.

On the next Fig. 11, spectral characteristics of environmental influences on transmitted CWDM signals present in the optical transmission medium are shown. The input signal spectrum entering in the SMF block is marked as “IN” and the outgoing signal spectrum is marked as “OUT”.

As can be seen on Fig. 11, the second channel has higher power level than other three channels. It is caused by the dependence of optical transmission medium’s environmental influences on utilized signal wavelengths (the outgoing signal power level is affecting by dependences of nonlinear effects and by the specific attenuation $\alpha_{specific}$ on utilized wavelengths presented in Table 1).

Table 1. Determined values of the attenuation parameters in the simulation platform

$\lambda_{channel}$ [nm]	$\alpha_{specific}$ [dB/km]	a_{total} [dB]
1511	0,21375	17,1
1531	0,2	16
1551	0,21	16,8
1571	0,21375	17,1

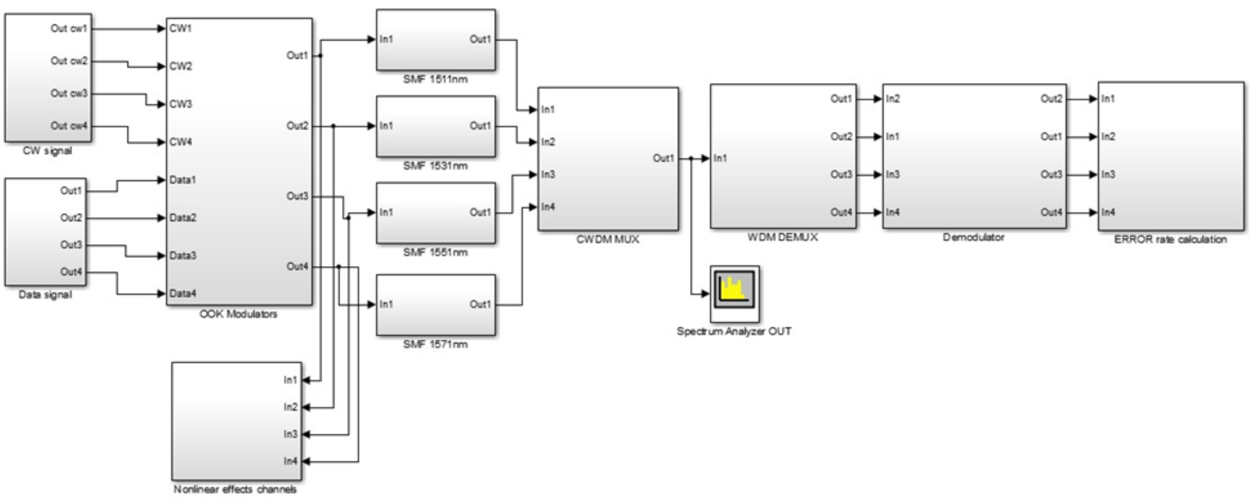

Fig. 10. The detailed block scheme of the 4-channel CWDM system

Because the 0,4 nm channel spacing is pre-determined for the DWDM system, the selected wavelengths are:

1. channel: λ_1 = 1553,3288 nm => f_1 = 193,00 THz
2. channel: λ_2 = 1552,9265 nm => f_2 = 193,05 THz
3. channel: λ_3 = 1552,5244 nm => f_3 = 193,10 THz
4. channel: λ_4 = 1552,1225 nm => f_4 = 193,15 THz

On the next Fig. 12, spectral characteristics of environmental influences on transmitted DWDM signals present in the optical transmission medium are shown. Fig. 12 is marked in the same manner as Fig. 11, i.e. “IN” is the spectrum of input signals entering in the SMF model and “OUT” is the spectrum of outgoing signals. As can be seen, there are new optical signals on 192,95 THz and 193,2 THz wavelengths. These additional signal frequency components are generated as a result of the FWM nonlinear influence on the transmitted signals utilizing DWDM multiplexing.

Conclusion

This paper deals with a specific simulation platform for wavelength division multiplexing systems, namely CWDM and DWDM, which are used to increase a transmission capacity of the single-mode optical fiber signal transmission.

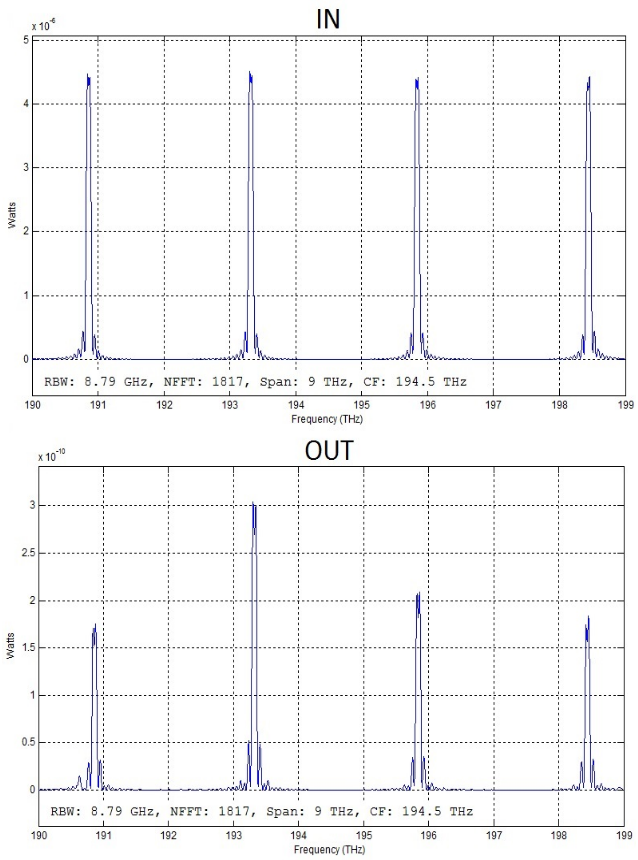

Fig. 11. Spectral characteristics of transmitted CWDM signals in the simulation platform

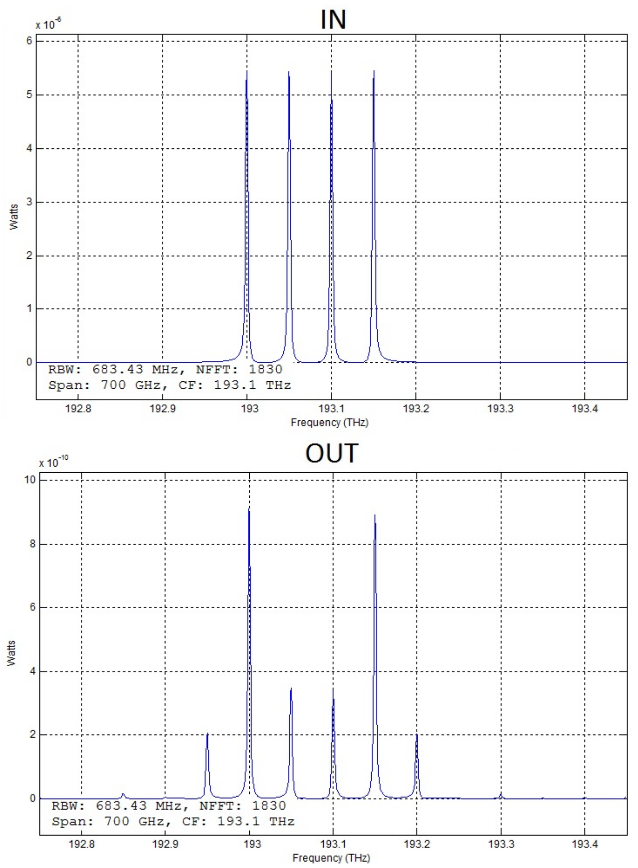

Fig. 12. Spectral characteristics of transmitted DWDM signals in the simulation platform

The simulation platform allows analyzing environmental effects due to the optical transmission medium at the multi-wavelength CWDM and DWDM signal transmissions. The optical transmission path includes both linear and nonlinear environmental effects on transmitted optical signals in the single-mode fiber medium.

In simulations, a detailed description of particular block functionalities in the specific simulation platform for WDM systems are presented. Then, specific differences between CWDM and DWDM multiplexing techniques are described with more details. Spectral characteristics of transmitted CWDM and DWDM signals show that the impact of environmental effects is more crucial in DWDM transmission systems, above all concerning the FWM effect. This knowledge is important for future research related to more effective utilization of the available transmission capacity in the optical transmission medium by means of Elastic Optical Networks (EON).

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***Authors**: assoc. prof. MSc. Rastislav Róka, PhD., Slovak University of Technology, Faculty of Electrical Engineering and Information Technologies, Institute of Multimedia Information and Communication Technologies, Ilkovičova 3, 812 19 Bratislava, Slovakia, E-mail: rastislav.roka@stuba.sk;*
MSc. Martin Mokráň, Slovak University of Technology, Faculty of Electrical Engineering and Information Technologies, Institute of Multimedia Information and Communication Technologies, Ilkovičova 3, 812 19 Bratislava, Slovakia, E-mail: tp.martinm@gmail.com.

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