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Performance evaluation of the dense wavelength division multiplexing system using reconfigurable optical add/drop multiplexer based on digital switches

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Abstract

ROADM technology has reformed optical networking and an intimate part of recent optical communication offering enormous bandwidth for data conveyance at least expense. In this paper, reconfigurability in the dense wavelength division multiplexing system is analyzed with the placement of digital switches by varying the bit rate from 10 to 40 Gbps by adding and dropping certain wavelengths. The performance of the dense wavelength division multiplexing system is characterized in terms of the quality factor, bit error rate and optical signal to noise ratio. It is observed that the signal can be communicated over a distance of 780 km with 16 channels, 420 km with 32 channels and 300 km with 64 channels having a low input power of −10 dBm with an acceptable bit error rate and quality factor. Furthermore, the performance of the system is calculated by varying the number of fiber spans with input power of −10 dBm with a bit rate of 40 Gbps. This structural design permits for remote traffic provisioning at the wavelength level in network node, operation cost reduction, better consumption of communication bandwidth, simplification of network design and implementation.

Keywords Reconfigurable optical add drop multiplexer · Dense wavelength division multiplexing system · Digital switches · Bit rate

1 Introduction

The data transmission industry demands a major rise in the bandwidth of the communication channel. The huge demand of high speed internet for enormous data transmission makes the tremendous growth in bandwidth for dense wavelength division multiplexing [(DWDM)] system (Kumar and Goyal 2017; Nair et al. 2018). Transmission with DWDM channels were put into exercise as the experienced use of fiber bandwidth as cost-effective

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and reliable for transport data bits in long haul metro networks. The DWDM repeaters on the transmitting and receiving channels were restricted due to cost and complexity of system. So the competent exercise of fiber bandwidth was to exploit the costly network resource, for that several substitutes have been tried in combination with DWDM. Now to handle with dynamically fluctuating traffic requires the scheme reconfigurable OADM were devised, which can alter the selected channel routing to the optical networks. It decreases requirement for optical-to-electrical-to-optical (O-E-O) translations. An optical transport network (OTN) comprising ROADM nodes with various add/drop abilities describes numerous flexibilities for the setup of light paths reconfigurability. Such abilities allow network operators quickly and flexibly act in response to network modifications. Reconfigurability in the network does not require rescheduling for the carriers and the light paths were set up or broken down at once at any time. ROADMs do not add/drop the same wavelengths permanently and they remotely organize to add/drop different wavelengths at different times. The effective usage of fiber bandwidth turns out to be serious as per the number of DWDM channels are increased. The ability to adaptably add and drop different channels or collection of channels in a composite traffic pattern signifies cost saving and proficient system usage (Zong et al. 2006; Shaikh et al. 2011). The usage of DWDM repeaters on the communicating and receiving channels becomes excessive and enhances the system complexity and cost (Dewra 2013; Kumar and Goyal 2018). The repeaters can be removed by using a refined routing and switching reconfigurable optical add/drop multiplexer (ROADM). ROADMs are a crucial facilitator of the recent days to keep up the remote provisioning of the optical links and recognize the reconfigurable optical network topologies (Sequeira et al. 2018). A ROADM allows remotely arrangement of wavelengths at any node whether a wavelength is added, dropped or passed through the network (Dewra 2016). ROADM structures regulate powers on an ongoing basis and offer per channel power control spread over the link to manage a new channel. It is mandatory to consider the power levels in Erbium doped fiber amplifier (EDFAs) inputs when the channels are added or dropped through the node and compensate the variations to have a suitable signal quality at the output side (Suzuki et al. 2017). Al Sayeed et al. (2007) described a hybrid ROADM of insertion loss 7 dB for express channels and proposing generalization and cost advantage. The channels were communicated at 2.48 Gbps. Hybrid ROADM moves towards the exclusive low loss structures that will allow facility benefactors to attain considerably larger fiber distance of a maximum of 65 km. Abedifar et al. (Po-Tsung et al. 2019) proposed ROADM architectures with a five-node mesh topology. The first issue of usage of ROADMs was the deviation of the bit error rate of passed through channels by varying the number of added/dropped channels in intermediate nodes of a light path. The gain spectrum dependence of EDFAs on the input power level is also a major concern. It is necessary to accomplish add/drop of channels accurately and compensate for its influence on the quality of other channels. This is achieved through the use of flexible attenuators in particular positions of a light path. Tibuleac and Filer (Keyworth 2005) described the WSS (wavelength selective switches) components at 40 Gbps data rates functioning on the 50 GHz channel spacing over wide range networks. The same ROADMs are also predictable to provide 100 Gb/s broadcast in the future. The progress of low cost WSS technologies is permitting ROADMs to develop into edge networks. The impact of insertion loss, signal bandwidth, polarization dependent loss depends on the transmitter and receiver types and the WSS characteristics. Jaumard and Kien (Abedifar et al. 2013) proposed the ROADM switching connectivity to raise the grade of service for a definite amount of ports. The grade of service can vary by up to 30% depending on the transferring connectivity. To yield advantages of all-optical switching fabrics with high efficiency, the wavelength switched optical networks were designed. The wavelength selective switches signify the fundamental switching components with colorless, directionless and contention less switching technology. Vlachos (Tibuleac and Filer 2010) investigated the ROADM architecture processing high order offset QAM signals. The structure was modular based on an interferometer structure and depend on time-domain sampling and FFT/IFFT filtering. The scaling capability of the ROADM scheme was up to offset 32-QAM. The performance is restricted by the rising time of the transmitter. Sanjeev Dewra (Jaumard and Kien 2014) investigated the effect of crosstalk of dynamic reconfigurable optical add/drop multiplexer based on DCE (Dynamic Channel Equalizer) obtained at 40×10 Gbps with 100 GHz channel spacing. The influence of the increase in length of the fiber was investigated to evaluate the performance of the communication system. The dynamic power transient with the dynamic channel equalizer was also studied which equalizes the power variations with a single ROADM. It was found that the signal can be communicated with the acceptable optical output power of -40 dBm using dynamic ROADM based on dynamic channel equalizer up to the maximum transmission distance of 220 kmat 15 dB crosstalk. Ennser et al. (Vlachos et al. 2018) investigated ROADM architecture, components and technologies based on various technologies and components obtainable to implement the ports of an OXC. The WSS has been designated as an encouraging switching element to construct the basic bidirectional port. The arrangement based on two WSSs is assumed for high node degree at low loss but costly. This structure leads to higher physical impairments and shortages on broadcasting ability and merits as low cost, low channel impairments. The work studies physical and networking features including modeling and simulations for optimization of the switching node. Simmons and Saleh (Dewra 2015) presented alternative wavelength selective ROADM strategies that need smaller OXCs whereas providing corresponding functionality. As optical transport networks become more configurable, the need for ROADMs that is colorless, directionless and contentionless enhances. In contrast, the wavelength selective class of ROADMs, where the central component is an optical cross-connect (OXC), inherently delivers the CDC properties. However, this structure is limited by the achievable size of the OXC.

In this paper, we propose the architecture of ROADM based on digital switches. The digital switches are employed to switch the propagation direction of a particular wavelength channel without affecting other wavelength channels and provide independent and dynamic wavelength routing. The previous work presented in (Al Sayeed et al. 2007; Jaumard and Kien 2014) is restricted to the transmission distance and bit rate. We have extended the work to a higher bit rate of 40 Gbps with the improvement in transmission distance using ROADM based on the digital switches.

This paper is organized as follows. Section II describes the details of the system setup of DWDM transmission as well as ROADM structure. In section III, the network performance is evaluated. Finally, in section IV, the conclusion of this work is presented.

2 Simulation setup

The reconfiguration of the DWDM system is analyzed with sixteen, thirty-two and sixty-four channels. An optical communication system is realized into three stages, i.e. transmitter, ROADM and receiver as shown in Fig. 1.

In the proposed system, the channel wavelength designated between 193.1 THz and 199.4 THz having a channel spacing of 100 GHz. The continuous wave (CW) laser array

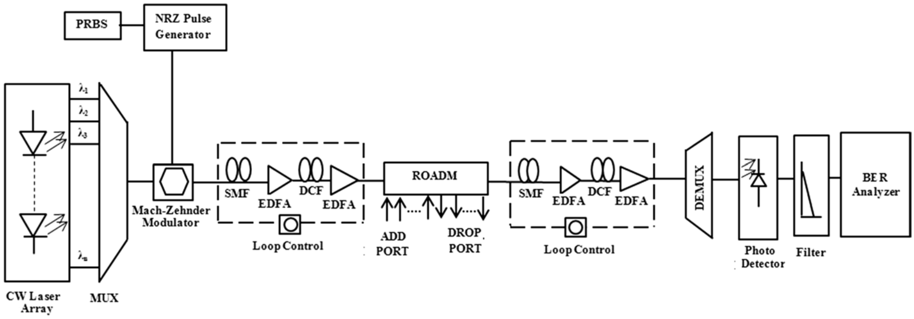


Fig. 1 Functional block diagram of the DWDM system

has −10 dBm initial input power, ideal laser noise bandwidth (BW), 0.1 MHz line width, 0.8 nm channel spacing and a bit rate of 40 Gbps. The output from the CW laser array is fed to a multiplexer to multiplex the incoming wavelengths. The output from the multiplexer is fed to the optical amplitude modulator. Modulation driver generates data format of the type NRZ rectangle Gaussian pulse shape with a signal dynamics, i.e. low level −1 and high level + 1 (Table 1).

The pulses are then modulated and the modulated signal is passed through the combination of SMF and DCF (single mode fiber and dispersion compensation fiber). The length of the fibers is considered to be 50 km and 10 km fiber spans respectively. The SMF attenuation is 0.2 dB/km, dispersion is 16.75 ps/nm-km, PMD coefficient is 0.5 ps/km, effective area is 70 μm^2 and DCF attenuation is 0.5 dB/km. To compensate for the effect of dispersion, dispersion compensating fiber (DCF) is employed at the end of SMF. The signal is amplified by an EDFA before entering the input port of the ROADM. The EDFA delivers a gain of 5 dB and the noise figure of EDFA is not more than 6 dB. EDFA is used to boost the intensity of optical signals being carried through an optical fiber.

The architecture of ROADM is shown in Fig. 2. The reconfigurable optical add-drop multiplexer is used to add/drop and switch channels. The ROADM allows automatic balancing of the wavelengths' optical power across the network. ROADM module is built using a demultiplexer, digital switches and multiplexer. The digital switches permit

Table 1 Parameters of DWDM system

Parameter	Value
Channel wavelength	193.1–199.4 THz
Bit rate	4o Gbps
Channel spacing	100 GHz
Initial input power	– 10 dBm
Line width of laser	0.1 MHz
SMF length	50 km
DCF length	10 km
EDFA gain	5 dB
Centre frequency of photodiode	193.1 THz
Responsivity	1 A/W
Dark current	zero

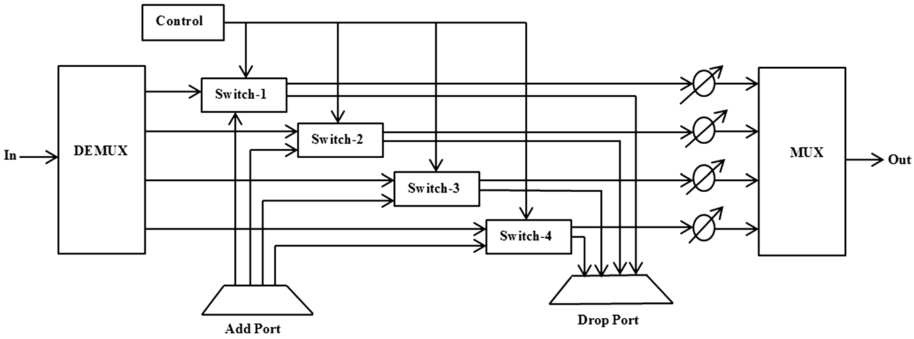


Fig. 2 Internal architecture of ROADM based on digital switches

individual or various wavelengths having data channels to be added and/or dropped from a transport fiber deprived of the necessity to change the signals into electronic signals and back to optical signals. The digital switch routes the optical signals according to the control signal. The control scheme simulates a non-ideal optical switch or gate, a drive of 0 turns the switch off, a drive of 1 turns it on. If the control signal is 0, then the optical signal at input port is passed to output port and the wavelengths at add port is received at drop port. If the control signal is 1, then the wavelengths present at input port are dropped and the added wavelengths are passed through the output port. It is necessary to manage the add/drop of channels accurately and compensate for its result on the other channel's quality. The flexible attenuators in definite locations of the light path are used. After the variable attenuators, all the wavelengths are multiplexed and passed through a combination of SMF and DCF. This architecture adds a level of flexibility, allowing wavelengths to route or drop from any line to any line. ROADM brings per-channel power monitoring and leveling to equalize the entire DWDM signal and provides full traffic control from the remote network operation center. At the receiver side, the demultiplexer is used to demultiplex the channels. The output from the demultiplexer is fed to the low pass Bessel filter to remove noise in the signal. The output from the optical filter is passed through photo detector to convert the light signal into an electrical signal. The PIN photodiode is used as a photo detector at the receiver side with center frequency 193.1 THz, gain 5 dB, responsivity 1 A/W and zero dark current. BER analyzer is connected to investigate the performance parameters of the system at the receiver.

3 Results and discussions

The performance of the DWDM system based on ROADM subsystem is calculated in terms of Q-factor, BER and OSNR (optical signal to noise ratio). The bit rate is varied from 10 to 40 Gbps to evaluate the performance of the DWDM optical system. The results are recorded on the first channel having emission frequency 193.1THz.

BER can be defined in terms of Q-factor as shown in equation in eq. (Vlachos et al. 2018)

$$\mathrm{BER} = \frac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{1}$$

where, Q is a quality factor and can be described as (Dewra 2015)

$$Q = \frac{I_1 - I_D}{\sigma_1} \tag{2}$$

In Eq. (1), σ_1 is a noise variance and equation has to be modified and can be defined as,

$$BER = \frac{1}{8}\, erfc\left[\begin{array}{c} \left(\dfrac{I_1 - I_D + I_{XT0}}{\sigma_1\sqrt{2}}\right) \\ +\left(\dfrac{I_1 - I_D + I_{XT0}}{\sigma_1\sqrt{2}}\right) \\ +\left(\dfrac{I_0 - I_D + I_{XT1}}{\sigma_1\sqrt{2}}\right) \\ +\left(\dfrac{I_0 - I_D + I_{XT1}}{\sigma_1\sqrt{2}}\right) \end{array}\right] \tag{3}$$

In Eq. (3),I_1 is photocurrent for a transmitted bit ‘a’ and I_0 is photocurrent for transmitted bit ‘b’. I_{XT0} and I_{XT1} represent the power of crosstalk for bit “1” and “0”.

Figure 3 shows the quality factor versus bit rate with 16, 32 and 64 channels having −10 dBm input power. The signal can be communicated up to 780 km with 16 channels, 420 km with 32 channels and 300 km with 64 channels. The total power on optical fiber increases as the quantity of added channels in the intermediary node increases. The

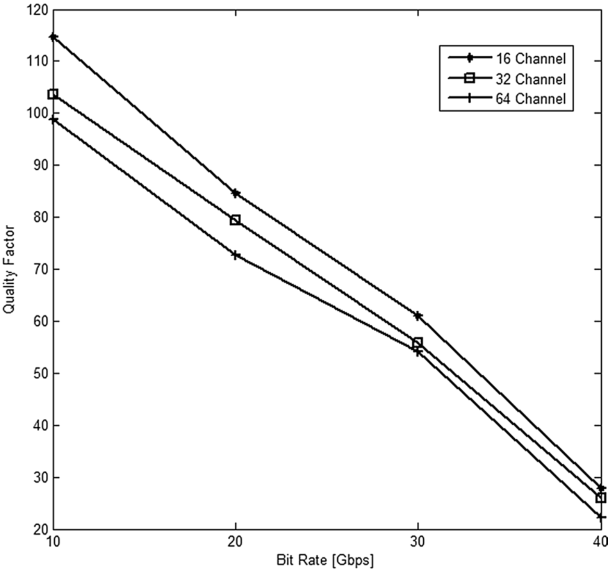


Fig. 3 Quality Factor versus bit rate at −10 dBm input signal power for 16, 32 and 64 channels

quality factor decreases and BER of received channel increases because of more nonlinearity and fiber attenuation. The quality factor at the first channel is 27.87, 25.92 and 22.12 with 16, 32 and 64 channels at 40 Gbps bit rate respectively. The quality factor is varied from 114.71 to 27.87, 103.65 to 25.92, and 98.79 to 22.12 having a bit rate of 10 Gbps to 40 Gbps with 16, 32 and 64 channels respectively. Our result shows improvement over the results described in (Al Sayeed et al. 2007; Dewra 2015) in terms of optical transmission distance and bit rate.

The bit error rate versus bit rate at −10 dBm input power for 16, 32 and 64 channels is depicted in Fig. 4. The variation in the bit error rate is 4.26e-184 to 1.98e-91 for 16 channels, 8.66e-151 to 7.53e-78 and 4.53e-138 to 4.53e-72 is observed at −10 dBm signal input power. It is found that the bit error rate enhances with the rise in the bit rate and the number of channels due to fiber nonlinearities.

The optical signal to noise ratio is plotted with respect to bit rate as shown in Fig. 5. The OSNR increases as an increase in the number of channels. In the case of 40 Gbps, the value of OSNR is 31.32 dB for 16 channels, 34.34 dB for 32 channels and 36.09 for 64 channels. The power of the persisting channels rises or falls after channels are added or dropped by the network's reconfiguration or failure due to cross saturation in the amplifiers. Power excursion of persisting channels can cause signal distortion by nonlinear effects or degradation of optical signal to noise ratio.

The quality factor and bit error rate are plotted with respect to the number of fiber spans as shown in Figs. 6 and 7. The graphs reveal that when fiber spans are increased, the quality factor decreases and bit error rate increases. The combination of SMF and DCF having length 50 km and 10 km respectively is used. It is analyzed that the signal can be transmitted up to distance of 780 km with 16 channels, 420 km with 32 channels and 300 km with 64 channels at input power of −10 dBm with the acceptable bit error rate (1×10^{-9}) and quality factor (6 dB).

The quality factor, bit error rate and OSNR as a function of wavelength at different fiber spans is depicted in Figs. 8, 9 and 10. The value of quality factor at 193.1 THz (channel 1)

Fig. 4 Bit error rate versus bit rate at −10 dBm input signal power for 16, 32 and 64 channels

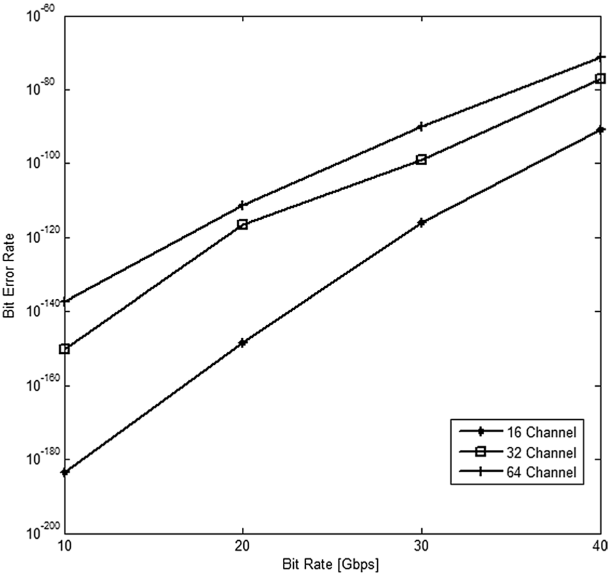


Fig. 5 Optical signal to noise ratio versus bit rate at −10 dBm input signal power for 16, 32 and 64 channels

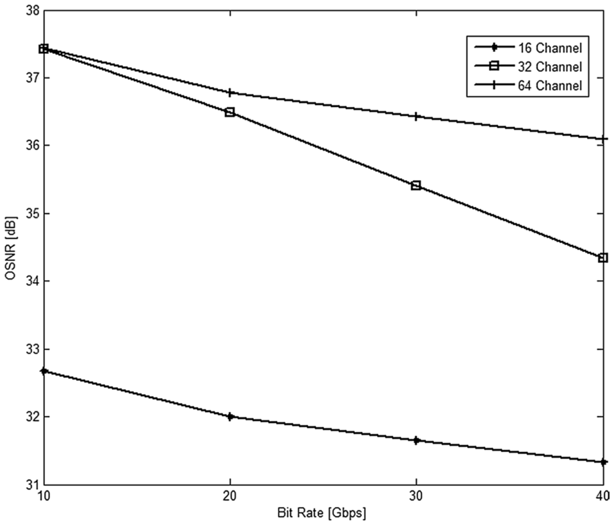
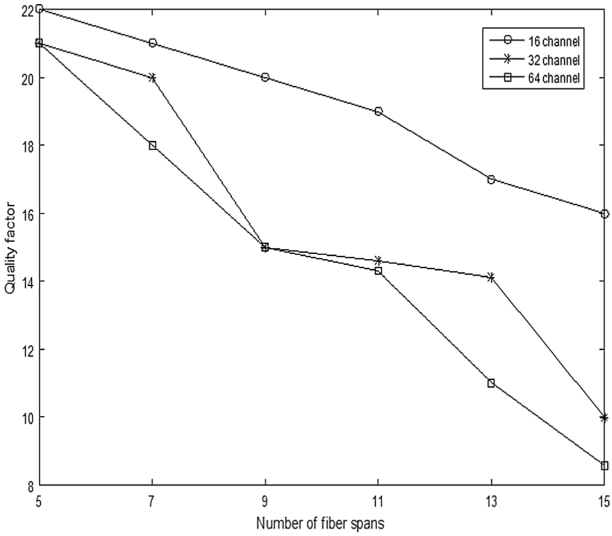


Fig. 6 Quality factor versus number of fiber spans at 40 Gbps bit rate



is 27.27, 28.91, 27.84 and at 199.6 THz (channel 64) is 12.11, 10.87, 11.06 at fiber span 1, 2 and 3 respectively. The bit error rate of signal is varied from 1.78e-40 to1.91e-35 at 193.THz and at 199.6 THz it is varied from 1.21e-18 to 1.17e-10. The optical signal to noise ratio at 193.1THz is 40.69 dB, 37.91 dB, 35.84 dB and at 199.6 THz is 28.65 dB, 21.31 dB, and 24.16 dB at fiber span 1, 2 and 3 respectively. The eye diagrams of received signal for 8, 16, 32 and 64 channels is illustrated in Fig. 11.

Figure 12a–c shows the optical spectrum of add and drop channels for 16, 32 and 64 channels with −10 dBm input power at 40 Gbps bit rate. The optical spectrum shows the variations in output power for varying number of channels and for bit rate.

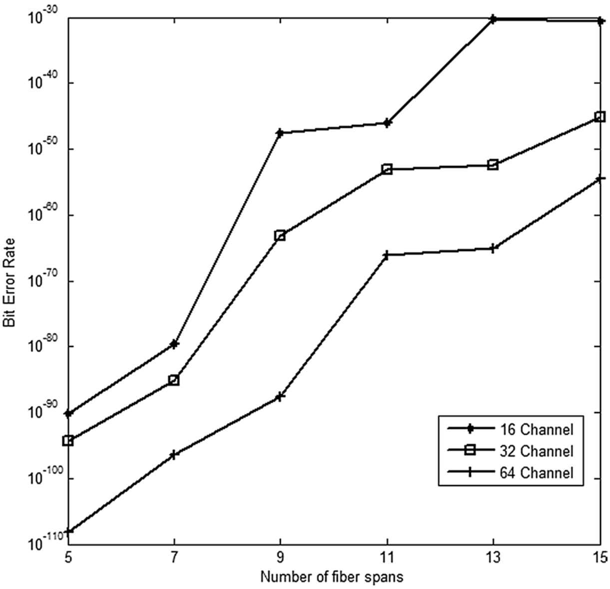


Fig. 7 Bit Error Rate versus number of fiber spans at 40 Gbps bit rate

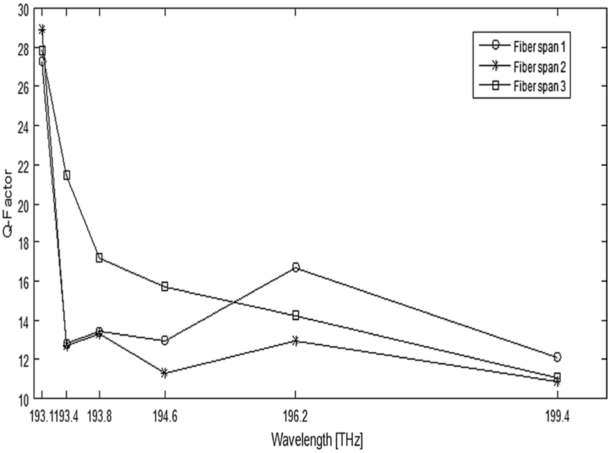


Fig. 8 Quality factor versus wavelength at different fiber spans at 40 Gbps bit rate

4 Conclusion

A ROADM is an optical subsystem that allows remote configuration of wavelengths at any node. The network operator can choose whether a wavelength is added, dropped or passed through the node because it is software provisionable. In this paper, reconfigurability in 16, 32 and 64 channel DWDM system is analyzed using digital switches by

Fig. 9 Bit error rate versus wavelength at different fiber spans at 40 Gbps bit rate

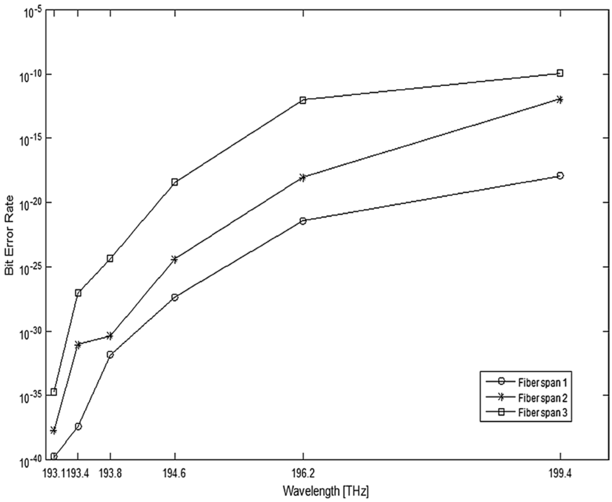
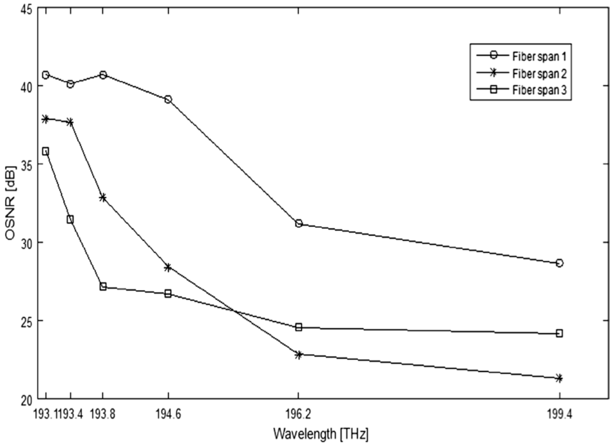
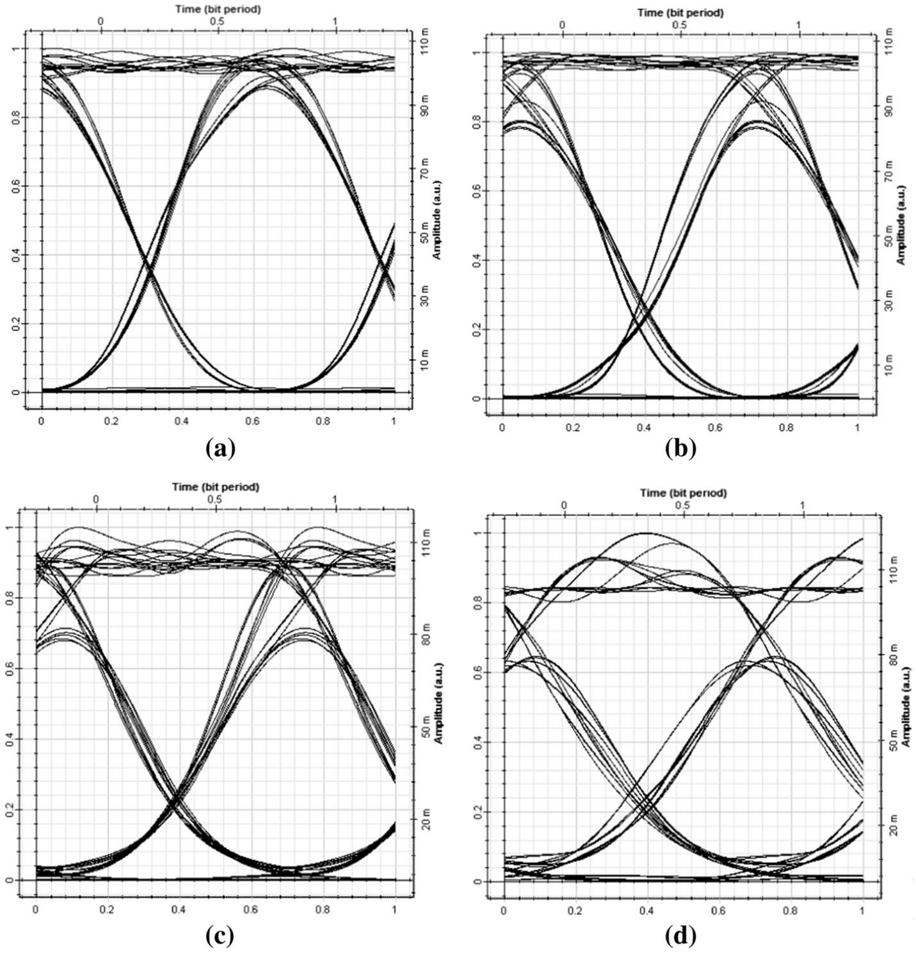


Fig. 10 OSNR versus wavelength at different fiber spans at 40 Gbps bit rate



varying the bit rate from 10 to 40 Gbps and different fiber spans. It is observed that the maximum transmission distance achieved with 16 channels is 780 km, 420 km with 32 channels and 300 km with 64 channels at a low input power of −10 dBm having a bit rate of 40 Gbps. The proposed ROADM based on digital switches can also be applied with more number of channels. Therefore with this approach, high bit rate and transmission distance are achieved and applicable for the DWDM system.



(a)

(b)

(c)

(d)

Fig. 11 Eye diagrams of received signal for **a** 8 channels, **b** 16 channels, **c** 32 channels, **d** 64 channels

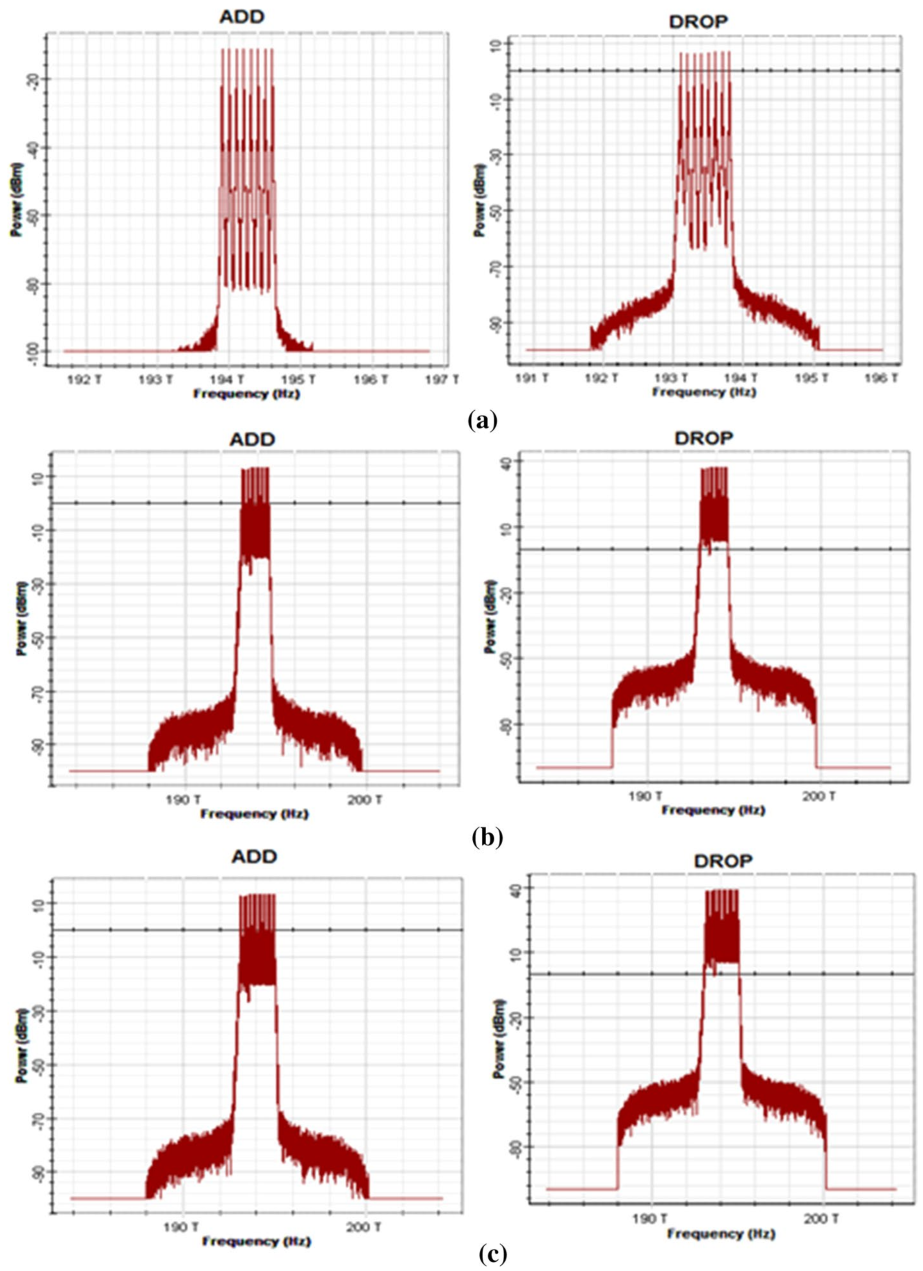


Fig. 12 Optical spectrum of add and drop channels for **a** 16 channels, **b** 32 channels, **c** 64 channels

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