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Impact of three different plans on the Next Generation Passive Optical Networks stage two for downstream transmission

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ABSTRACT

In this work, a simulative analysis of 40 Gb/s downstream time and wavelength division multiplexing-passive optical network (TWDM-PON) for next-generation passive optical network second stage (NG-PON2) had been designed and demonstrated. The performance of three different wavelength plans in TWDM-PON are evaluated as the solution to NG-PON2 to support 40Gbit/s bandwidth requirement. A four 10-Gb/s TWDM-PON signals are stacked using four different wavelengths in the downstream direction and externally modulated. The system performance is observed using Bit Error Rate (BER) and Optical Signal-to-Noise Ratio (OSNR) with respect to the design parameters such as distance, number of users and received optical power. Thus, the proposed system was able to support 512 number of users and 80 km transmission distance. When the system is tested upon transmission of triple play services over 80km distance with 512 users, it is shown that BER of 8.9 × 10-10, 3.9 × 10-9 and 1.3 × 10-4 are achieved for data, voice and video, respectively.

1. Introduction

In recent years, Time-Wavelength Division Multiplexing (TWDM) technique received research attention due to its advantages. TWDM is the most accepted solution to provide aggregate bandwidths. It can provide 40 Gb/s for the Fiber-To-The-Home (FTTH) systems. TWDM-passive optical networks (TWDM-PON) system is the cost-effective communication, reliable and able to fulfill high demand for higher bandwidth. Among several techniques developed for Next Generation Passive Optical Network Stage Two (NG-PON2) systems, TWDM is known as a suitable option for reach-extended optical communication networks (Du et al., 2019; Gay et al., 2018; Li et al., 2018; Porto et al., 2018; Xiao et al., 2018; Zhang et al., 2019).

Many operators had a great concern to create a cost-effective and smooth-upgrade network without requiring any major modifications to the Optical Distribution Network (ODN). Therefore, the TWDM-PON technology provides a feasible answer for a smooth-capacity upgrading by combining the multiple wavelengths for the existing time division multiplexing (TDM)-PON (Yi et al., 2012). Luo, Yuanqiu, et al. demonstrated a 40-Gb/s TWDM-PON design through deployment

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of four wavelengths in the downstream to obtain transmission line of 20 km and 512 splitters (Luo et al., 2013). Later, Yi, Lilin, et al. extended this achievable distance to 25km but with lower number of split ratio which is 256 (Yi et al., 2013). Bi, Meihua, et al. proposed a 40 Gbps TWDM-PON prototype using four 10Gbps for downstream direction with 256 split ratio over 50 km transmission distance (Bi et al., 2013). Yi, L., et al. proposed an 80-Gb/s TWDM-PON wavelengths stacked for low supportable number of user and green distance (Yi et al., 2012). However, there is no study that compares the different plans outlined by International Telecommunication Union (ITU-T) to support NG-PON2 implementation. Therefore, in this paper, three different wavelength plans based on the PON standards outlined by ITU-T recommendations are investigated. The effects of distance and number of supportable users are evaluated in the downstream direction to choose the best out of the three different plans. The first choice is to reuse the Gigabit Passive Optical Networks (XG-PON) wavelength bands which is a finer grid inside NG-PON band. The next choice is to redefine the C-band enhancement band based on the first option to include the upstream and downstream wavelengths. The third option is a hybrid plan which combines features of the above two plans. This paper presented the simulation design and compare three different options to investigate their suitability for NG-PON2 system. Next section explains the architecture of the proposed system that had been simulated using Virtual Photonics Inc (VPI) simulator.

2. Simulation Design

TWDM is a multiple wavelengths PON solution whereby individual wavelength is distributed among several Optical Network Units (ONUs) and further divided using time division multiplexing mechanism. This study deploys cost-efficient components, to design the NG-PON2 architecture based on the model detailed in the reference standard using VPI simulator. Each device is modeled in different subsystems which are optical line terminal (OLT), ODN and ONU. This study was particularly focused on the comparison of performance of three different wavelength plans. Characteristics like splitting ratio and fiber reach were tested and taken into consideration as crucial performance indicators. Figure 1 depicts the proposed NG-PON2 architecture and reference points for downstream transmission line of TWDM-PON technology using VPI simulator.

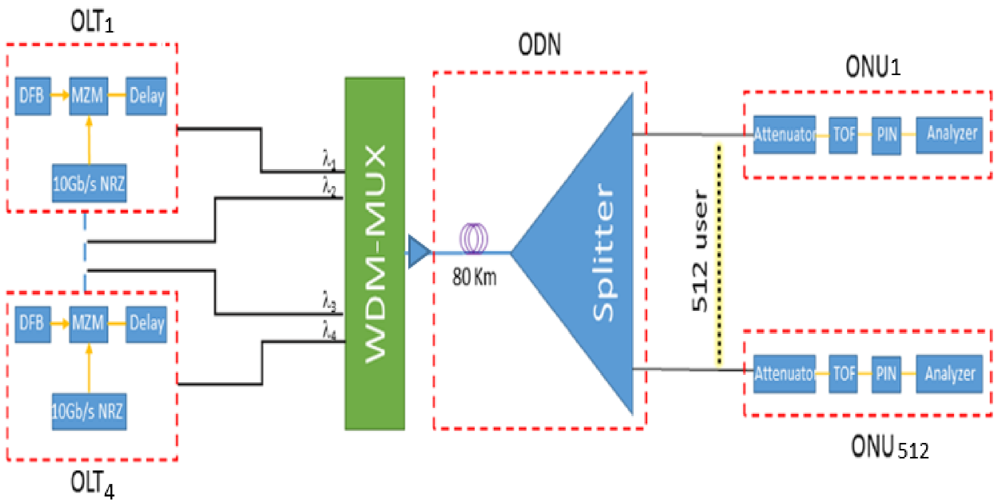

Figure 1. The proposed NG-PON2 architecture

TWDM-PON system contains the OLTs at one end point and ONUs at the other end point. ODN which connecting the OLT and ONU consists of 80 km single mode fiber (SMF) with 0.2 dB/km attenuation coefficient and chromatic dispersion coefficient of 16.75 ps/nm/km, and passive splitters. In order to achieve splitting ratio which is 1:512, two cascaded passive splitters with different splitting ratio were used, which are 1:8 and 1:64, respectively. The carrier wavelengths were multiplexed and transmitted over the same SMF using WDM multiplexer. Distributed feedback laser (DFB) lasers with 10 dBm input power were used to transmit all four downstream signals to the receiver. Figure 2 illustrates the 4 multiplexed signals generated from externally modulated DFB lasers.

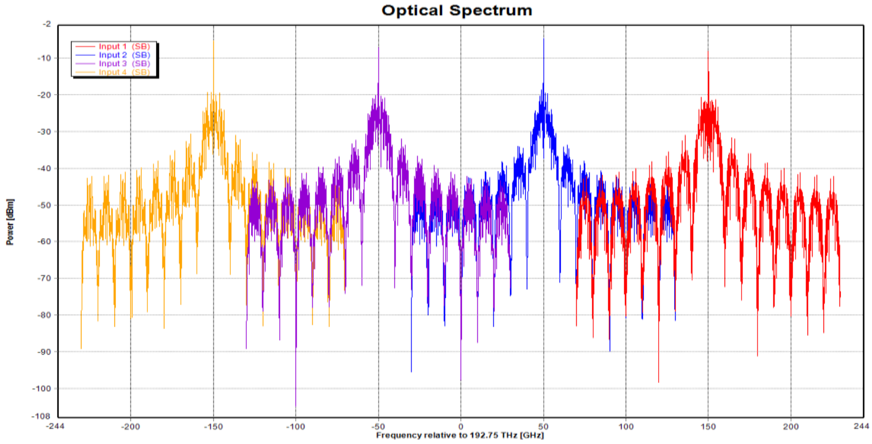

Figure 2. Spectrum of the transmitted signals multiplexed from four OLTs

In the case of video transmitter, DFB laser and quadrature amplitude modulator (QAM), where the value of M-ary is 4 are deployed. After the different signals being multiplexed for transmission, they are split into 512 users using optical power splitter. At the receiver side, each ONU is dedicated for a single user where it consists of tunable filter, PIN photodetector and an electrical bandpass filter. Tunable filter was used to select specific downstream wavelength before being detected by a photodetector. The detected and filtered signal is then analyzed by Bit Error Rate (BER) analyzer to observe the performance. For the video receiver part, tunable optical filter (TOF), photodetector, quadrature demodulator, M-ary threshold detector, and QAM sequence decoder were used. Table 1 summarizes the parameters deployed in the simulation to model the transmission fibers, lasers, and the photodiodes used in the receivers while Table 2 indicates the principal attributes of the proposed TWDM-PON architecture.

Table 1. Simulation parameters

	Parameters	Value
Transmitter (Tx) Parameters		
	Emission frequencies	192.9 THz –192.6 THz
	Channels	4
	Channel spacing	100 GHz
	modulation	Mach- Zehnder Modulator (MZM)
Fiber parameters		
	Dispersion	19.66 ps/km*nm
	Dispersion slope	0.056 ps/km*nm^2
	Attenuation	0.2 dB/km
	Length	0 – 100 km
Optical filter parameters		
	Filter type	Gaussian
	Filter order	2
	Bandwidth	100 GHz
Receiver (Rx) Parameters		

PD type	Positive Intrinsic Negative (PIN) receiver
PD responsivity	0.7 A/W
PD thermal noise	10^{-12} PA/Hz$^{1/2}$
PD electrical filter type	Bessel
PD electrical filter order	4
PD electrical filter order B/W	0.75 × Bit Rate

Table 2. Parameters of TWDM-PON architecture

Parameter	**TWDM-PON**
Aggregate BW	40 Gbit/s
Bit Rate per channel	10 Gbit/s
Number of users	512
Wavelength channels	4
Wavelength spacing	100 GHz
Distance	80 km

The TWDM-PON wavelength plan was the basis for coexistence of former generations of PONs in the legacy ODN. There are three options proposed for the TWDM-PON wavelengths as described in ITU-T recommendations:

1. The first choice is reusing the XG-PON wavelengths band. It gives a finer grid internally in the previously defined bands detailed in NG_PON1. This wavelengths plan leverages the developed work that has gone into XG-PON optics. It is compatible with GPON (ITU, 2008) and the 1555 nm radio frequency (RF) video overlay channel, but blocks standardized XG-PON. Its loss budget is similar to that of XG-PON. The typical loss budget value is about 33 dB. This wavelength plan is illustrated in Figure 3 (Luo et al., 2013).

2. The next choice is by redefining the C-band improvement band including both the upstream and downstream wavelengths. The optical attributes include an erbium-doped fiber amplifiers (EDFAs) for signal amplification, and a lower transmission fiber loss. A system of this capacity will have a higher power budget and a longer reach. Figure 4 illustrates this wavelength plan. The design of this plan makes it compatible with GPON and XG-PON. With EDFAs, this wavelength plan could achieve a loss budget of about 38 dB (Luo et al., 2013).

3. The third option is a hybrid version of the first two plans. The downstream channels of this plan are designed in the L-minus band, while the upstream channels are located in the C-minus band. This type of plan is illustrated in Figure 5. It maintains the GPON and RF video channels. The downstream broadcast in this plan seems like the wavelength plan shown in Figure 3. The wavelength plan is made to be conducive to be used with GPON with RF video overlay stations, but blocks XG-PON. C-band components will work together with an EDFA preamplifier to create more power budget. In the downstream however, an L-band amplifier is needed to increase the power level. A lower power budget up to 38 dB can be attained with this plan (Luo et al., 2013).

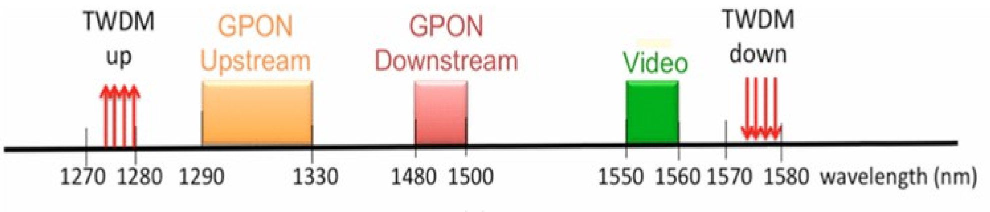

Figure 3. C-minus/L-minus band wavelength (Luo et al., 2013)

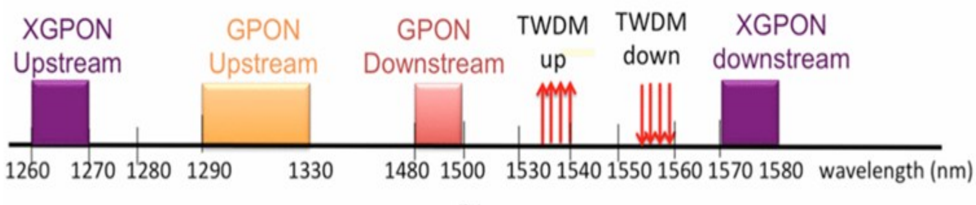

Figure 4. XG-PON wavelength reuse (Luo et al., 2013)

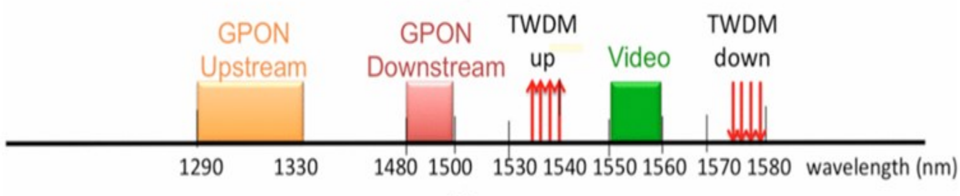

Figure 5. C-band wavelength plan (Luo et al., 2013)

In TWDM-PON, the basic principle to coexist with past PONs systems in ODN essentially depends on the three option wavelength plans. Some studies had pointed out that the three different wavelength plans improves the best-fit approach for the system (Bindhaiq et al., 2015; Luo et al., 2013; Ma et al., 2012) . These studies developed the system using different wavelength plans to achieve higher performance parameters such as high bandwidth per customer, flexibility in resource allocation, extended reach longer than the current G-PON/ G-EPON architectures, low cost and coexistence with existing technology. However there is no study focus on comparing the three option plans to perceive the effects. For further details on the three wavelength plans, refer to our previous work (MAHMOOD, 2017).

3. Results and Discussion

Three wavelength plan options defined by ITU-T recommendation as discussed in (Luo et al., 2013) have been applied for NG-PON2 system using TWDM technique. The proposed TWDM system was implemented using different wavelength plans in order to study and analyze their performance. Four downstream wavelengths were demonstrated each carrying 10 Gbit/s bandwidth in TWDM system. The downstream wavelength band in plan 1 and 3 are located in the same range of 1560 nm to 1580 nm so the simulation setup and results for plan 1 and 3 are the same. The downstream wavelength band for plan 2 located in the range of 1550 nm to 1560 nm have been simulated and the results are analyzed. Table 4 shows the three different wavelength plans for downstream and upstream transmission. This study focuses on downstream transmission range. Hence, only the downstream wavelength range is applicable.

Table 4. The downstream and the upstream wavelength range for the three plan options

Plan	Downstream wavelength	Upstream wavelength
1	1560 nm – 1580 nm	1260 nm – 1280 nm
2	1550 nm – 1560 nm	1535 nm – 1540 nm
3	1560 nm – 1580 nm	1535 nm – 1540 nm

The simulation results of the TWDM-PON architecture for plan 1 and 3 of 512 users over 80 km is depicted in Figure 6(a). The signals are transmitted at 190.2 THz, 190.1 THz, 190.0 THz and 189.9 THz optical frequencies. The received optical power for the four downstream channels are -25.3 dBm, -23.3 dBm, 23 dBm, and - 21.6 dBm, respectively at BER of 10^{-9}. The results for plan 2 is depicted in Figure 6(b). The signals are transmitted at 192.9 THz, 192.8 THz, 192.7 THz and 192.6 THz where channel spacing is set to 100 GHz. It can be seen that BER performance of the four channels are 8.9×10^{-10}, 1.1×10^{-9}, 3.5×10^{-9} and 3.9×10^{-9} at received optical power of -27.3 dBm to -25.2 dBm. From the figure the power penalty between the first channel that is at 192.9 THz and the fourth channel transmitting at 192.8 THz for the downstream signals is around 2 dB in plan 2 while the power penalty between the first channel transmitting at 190.0 THz and the fourth channel transmitting at 190.1 THz for the downstream signals is around 3.7 dB in plan 1 and 3. Therefore, it can be concluded that less power is needed by plan 2 compared to plan 1 and 3 in order to achieve the same BER of 10^{-9} over the same transmission distance.

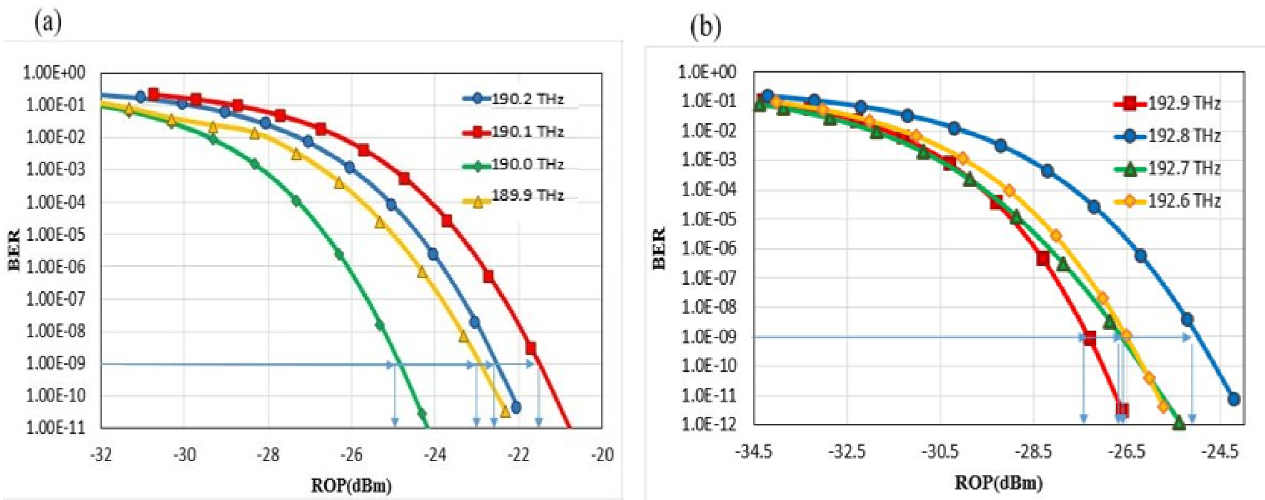

Figure 6. BER against received optical power in TWDM-PON for 512 users over 80 km distance for (a) plan 1 and 3 and (b) plan 2

The OSNR versus received optical power for the NGPON2 system deploying plan 1 and 3 is plotted in Figure 7(a). It illustrates the performance of the four downstream signals with a variation of received optical power over 80 km transmission line for a system with 512 users. The OSNR calculated in this work are represented by the following equation (MAHMOOD, 2017):

$$\mathrm{OSNR} = {\left(1.7 - \log_{10}\mathrm{BER}\right)}\Big/{1.75}$$

In Figure 7(a) the received optical power range from -24.3 dBm to -20.6 dBm at OSNR of 15 dB for the four downstream signals serving 512 users. The power penalty noted from the figure is around 3.7 dB between the first channel transmitting at 190.1 THz and the fourth channel transmitting at 190.0 THz for the downstream signals.

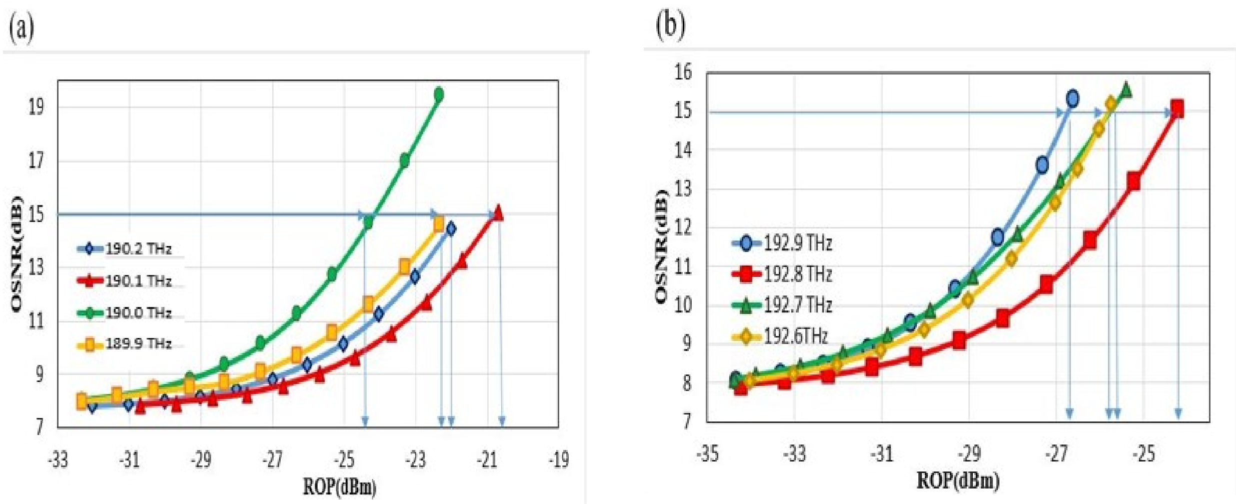

Figure 7. OSNR versus received optical power in TWDM-PON for 512 users over 80 km distance (a) plan 1 and 3 (b) plan 2

The OSNR versus received optical power for the NGPON2 system deploying plan 2 was plotted in Figure 7(b). The received optical power ranges from -24.2 dBm to -26.6 dBm at OSNR of 15 dB. The power penalty is around 2.4 dB between the first channel transmitting at 192.9 THz and the fourth channel transmitting at 192.8 THz for the downstream signals. Meanwhile, for plan 1 and 3, the received optical power range from -24.3 dBm to -20.6 dBm at OSNR of 15 dB and the power penalty is 3.7 dB. Furthermore, the received power obtained in the four downstream channels for plan 2 in Figure 7(b) are higher than the one in Figure 7(a) at 15 dB of OSNR. Thus, the proposed system which deploys plan 2 is more efficient than the system deploying plan 1 and 3.

Figure 8(a) depicts the relation between BER and the transmission distance for plan 1 and 3. The obtained BER are 3.43×10^{-9}, 9.38×10^{-8}, 7.1×10^{-7} and 4.44×10^{-7} for the four different wavelengths at 80 km. Figure 8(b) shows the results for plan 2 with BER of 6.87×10^{-9}, 1.09×10^{-9}, $3.65\ 10^{-8}$ and 5.63×10^{-8} obtained by the four wavelengths. The BER performance of TWDM architecture for plan 2 is slightly better than plan 1 and 3. Due to the superior performance of plan 2 compared to the rest, it is selected to be tested for the transmission of the triple play services. Apart from that, its availability to include RF video is also another advantage.

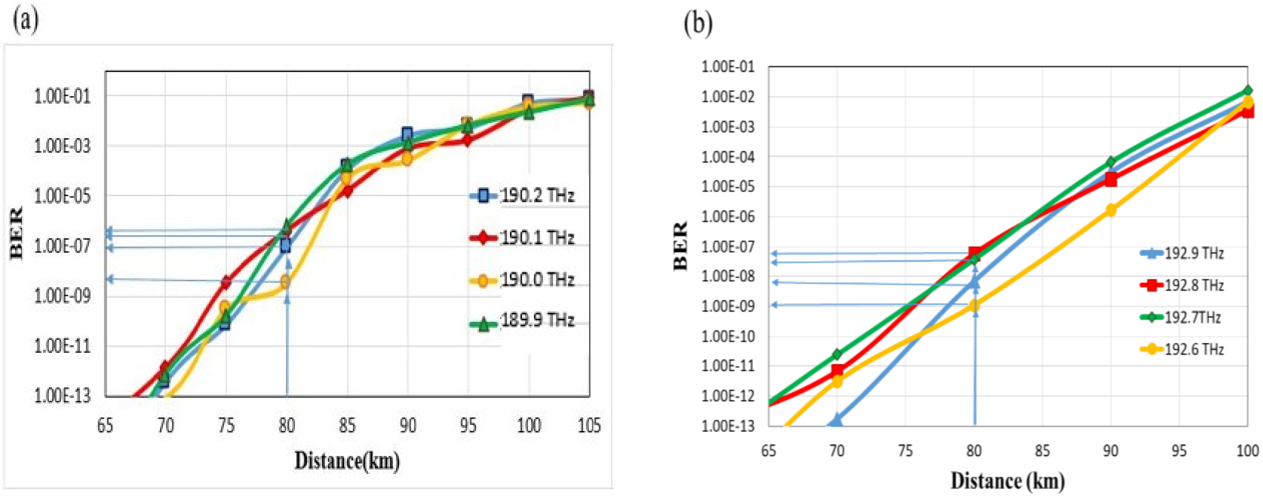

Figure 8. BER versus distance in TWDM-PON for 512 users (a) plan 1 and 3 (b) plan 2

Figure 9 illustrates the BER as a function of received optical power for 3 downstream signals representing data, voice and video. As shown in the figure, the obtained BER are 8.9 $\times 10^{-10}$, 3.9 $\times 10^{-9}$ and 1.3 $\times 10^{-4}$ for data, voice and video at -27.3 dBm, -25.2 dBm and - 18.1 dBm, respectively. The proposed TWDM architecture obtaining better BER for data and voice but lower BER for video over 80 km distance serving 512 users.

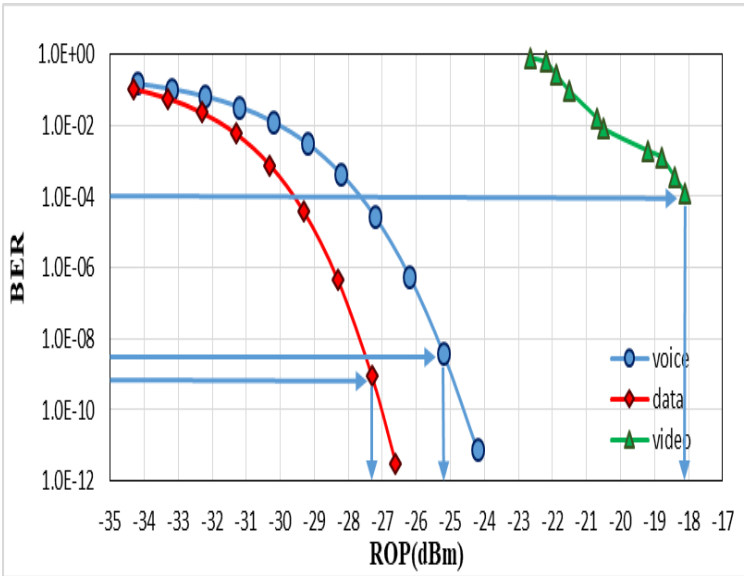

Figure 9. TWDM-PON triple play serving 512 users over 80 km distance

Figure 10 shows the received constellation diagram of video signal for system supporting 512 users over 80km distance. A perfect signal is obtained in Figure 10(a) of back-to-back where a uniform constellation that is perfectly symmetric about the origin. Meanwhile in Figure 10(b) the constellation is scattered after the video signal being transmitted over 80 km distance.

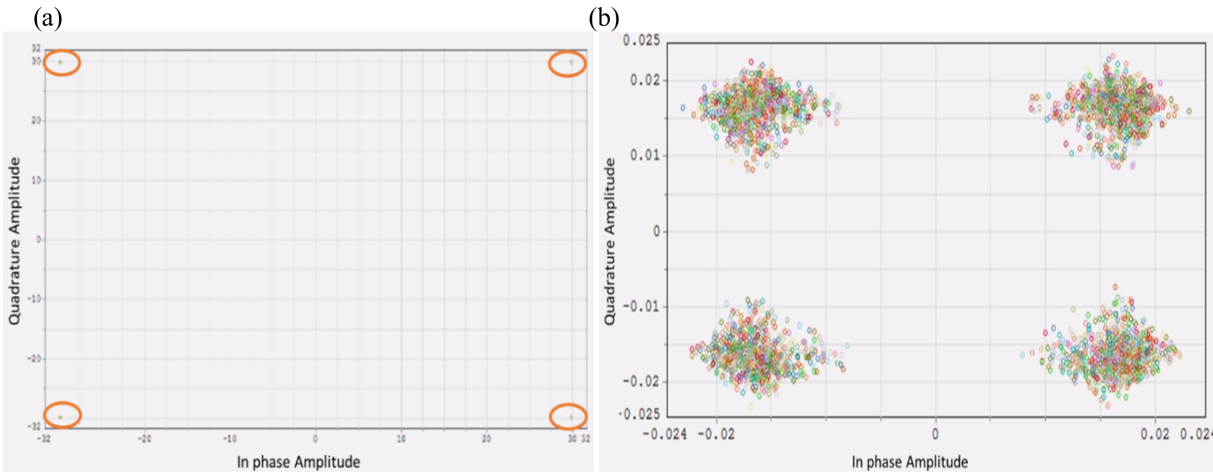

Figure 10. Received constellation diagram for (a) at back to back and (b) at 80km.

4. Conclusion

This paper has described and presented a comparative performance analysis of three different wavelength plans recommended by ITU-T for NG-PON2 system. By using VPI simulator, simulation model of downstream transmission over TWDM-PON system was proposed and the results were evaluated. The three plans are simulated for 40 Gbit/s downstream wavelengths over 80 km distance. The second plan are selected to present the triple play services due to its superior performance than the other two and its inclusion of RF overlay in the spectrum band. Based on the simulation results, the enhanced architecture achieves distance up to 80 km with split ratio 1:512 at satisfactory BER of 10^{-9}. Moreover, the proposed prototype shows excellent flexibility, high number of supportable users, and long transmission distance. The high efficiency of the proposed NG-PON2 system make it a suitable candidate to fulfill the requirements of broadband next generation access networks.

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