



Impairment strained analytical modeling evaluation and cross-talk analysis of symmetric and coexistent channels for extended class-1 NG-PON2 access network

Rajendraprasad A. Pagare¹ · Abhilasha Mishra² · Santosh Kumar³

Received: 3 February 2022 / Accepted: 22 July 2022 / Published online: 27 September 2022

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract

The analytical modeling for linear and non-linear impairments (LNI) for single mode fiber (SMF) and simulative analysis of extended power budget class-1 i.e. E1-class of next generation passive optic network-2 (NG-PON2) is presented in the paper. The proposed power-budget class time and wavelength division multiplexing (TWDM) based NG-PON2 network configuration is delivering symmetric 2.5 point-to-multi point (PtM) representing time and TWDM XGS-PON along with 10 Gbps point-to-point (PtP) wavelength division multiplexing (WDM) symmetric and coexistent channels (Ch) in worst-case scenario. Channel modelling of LNI is carried out under the incremental and aggregate strain of estimated chromatic dispersion CD, self-phase modulation (SPM), cross-phase modulation (XPM) of single mode fiber (SMF) channel deployed in optical distributing network (ODN) between 20 and 50 km link lengths. Downlink (D/L) and uplink (U/L) ODN is optimized to $PT_{ODN} = 7.1$ dBm and 4.09 dBm, respectively and corresponding channel impairments including Kerr parameter γ , corresponding SPM, XPM, CD, four-wave mixing (FWM) analysis and corresponding component power and efficiency, interchange crosstalk (C_c) attracting power penalties (P_c) are estimated and incorporated in the simulation for the real response of lossy SMF channel. Further, splitter power budget (SP) and splitter configuration for respective PtM and PtP D/L Ch are estimated under the aggregate impact of CD, SPM, XPM and FWM. Analytical modeling of LNI and simulative analysis has confirmed the configuration delivered rise in receiver sensitivity (Rxs) of $-39.75/-33.45$ dBm and $-29/-35.34$ dBm for D/L and U/L Ch respectively. The estimated power of FWM element is between 1.34×10^{-52} to 2.15×10^{-53} and 3.87×10^{-52} to 2.41×10^{-51} contributing crosstalk between Ch (C_c) of $-31.97/-30.12$ dB for down/up spectrum under the impact of SPM and XPM respectively accommodating splitter configuration of 768 at 40 km.

Keywords XGS-PON · WDM · NG-PON2 PON · TWDM

✉ Rajendraprasad A. Pagare
rapagare@rediffmail.com

✉ Santosh Kumar
santosh@lcu.edu.cn

1 Introduction

Gigabit access line rate, high bandwidth, ensured quality-of-services (QoS), reliability and secured means of communication has already established optical access networks (OAN) as prime contender for deployment of NG-PON based applications. Users demand for faster, reliable and secure access network is not only intact post Covid-19 situation but also on the rise in future. In fact, gigabit OAN have become an integral part of every human being and the society contributing in the socio-economic development of the users and the society. Incorporating new age and disruptive technologies including Artificial Intelligence (AI), Neural Networks (NN) and Data Science Techniques (DST) have significantly improved the user experience, design, reconfigure, upgradation, monitoring and maintenance of the NG-PON OAN. WDM along with TWDM will be leading technology option for design and deployment of backhaul as well as fronthaul access networks. The demand of higher bandwidth and line rate by almost all the domains of the business including future schools, universities, agriculture, healthcare, banking, finance, gaming and entertainments, smart city applications will be supported by NG-PON2 OAN. Cisco has projected in all around 50 Billion users including fixed line internet, mobile and machine-to-machine (MtM) by 2023 will required bandwidth in the range of 44–110 Mbps per user to access new age applications (Way et al. 2016; Yuanqiu et al. 2016; Cisco 2019; Koundal and Dewra 2019).

TWDM has outplayed optical code division and orthogonal frequency division multiple access techniques to configuration NG-PON2 networks as described by G. 989.2 (02/2019/2015/2013) specifications and standards. Flexibility in network expansions, coexistence feasibility with legacy access network like GPON and XG-PON enhancing PtM and PtP nodes leading to cost-effective expansion of access networks are the key features of TWDM technology. TWDM NG-PON2 access networks can deliver symmetric 1.25 to 10 Gbps line rate can be expanded seamlessly to support 80 Gbps aggregate line rate by incorporating an array of eight 10 Gbps symmetric line rate with equal and unequal channel spacing (Sharma et al. 2016; Veen et al. 2015; Jeff et al. 2012; Goyal et al. 2017; TUT-T G. 989.2 2019; Kumar and Jamal 2014).

The end-to-end design, analytical modeling, optimization, simulation, analysis, verification and comparative performance analysis of impairment strained optical channel in optical distributing network (ODN) network supporting multichannel 2.5/10 Gbps symmetric and coexisting Ch connecting subscribers and supporting next generation communication and access networks including FTTH, 5G, and IoT enabled smart city applications and services is presented in this paper. The modeling of optical Ch is done in the sight of fiber channel linear and non-linear impairments such as chromatic dispersion (CD), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) within the frame work outlined by ITU-T G. 989.2 (2014/2019) for NG-PON2 access networks.

We have simulated and presented evaluation and performance analysis of coexistence and symmetric network configuration using E1-class of power budget of hybrid ODN comprising wavelength select (WS-ODN) and wavelength routed (WR-ODN) for downlink (D/L) and uplink (U/L) Ch for worst-case scenario supporting aggregate data rate of 80 Gbps data rate.

Based on the optimization of ODN launch power $P_{T_{ODN}}$, channel input power $P_{T_{\lambda}}$, we demonstrated extended and incremental network performance parameters and specifications such as D/S and U/S receiver sensitivities (RxS), BER, Q-factor, inter-channel crosstalk (Cc) and corresponding power penalty (Pc), extended network reach and splitter configuration for the foreseen E1-class TWDM NGPON-2 access network. The

optimization process has achieved incremental receiver sensitivity of $-39.75/-33.45$ dBm and $-29/-35.34$ dBm, C_c of $-31.97/-29.93$ dB, with 0 dB of crosstalk penalty (P_c) of or D/L and U/L Ch receiver respectively accommodating aggregate splitter configuration in the range of 768–2560 between 40 and 20 km with aggregate impact of FWM, SPM, XPM and CD impairments.

The structure of the paper is organized in six sections. Section one includes the abstract, need and the key features of the proposed network concept. The architecture of the prescribed E1-class of TWDM NG-PON 2 network and wavelength plan is described in second section. The subsequent section includes the design and optimization process of OLT, ONU, ODN launch power and estimation of D/L and U/L transmitter power for XGS-PON PtM and WDM PtP symmetric Ch. Post optimization of ODN to E1-class, the estimation and optimization of SMF for nonlinearities including Kerr parameter γ , CD, SPM, XPM, FWM and channel cross talk is described in section four. The simulative analysis of the proposed network configuration is presented in section five along with link power budget and splitter configuration analysis. Finally, conclusion based on design, simulation and analysis of the proposed network and possible future task is discussed in sixth section.

2 Block schematic of E1-Class TWDM NG-PON2 optical access network

The block scheetic of the foreseen E1-class of NG-PON2 multichannel network supporting coexistence functionality along with symmetric 2.5 and 10 Gbps Ch is presented in Fig. 1. The schematic includes three section namely optical line terminal (OLT) transceivers (Trx)housing meachnism for D/L transmitter Ch and U/L recivers. Optical network unit (ONU) consists of meachnism for detection of D/L Ch and tission of U/L Ch. The third section accomodates ODN section deployed using bidirectional SMF carrying multichannelspectrum in either direction. The channel are identified as seder-receiver channel pairs (S/R-CP) at OLT Trx, seder-receiver channel group (S/R-CG) at the output port of eight channel WDM also known as coexistence element (CE_x). The applications and services encoded in the form of bits are connected to network throughsender network interface (SNI) and connected to users at ONUs through user network interface (UNI) (Kumar and Jamal 2014; Neophytos et al. 2012; ITU-T G. 652 2019). Downlink Ch divided in to

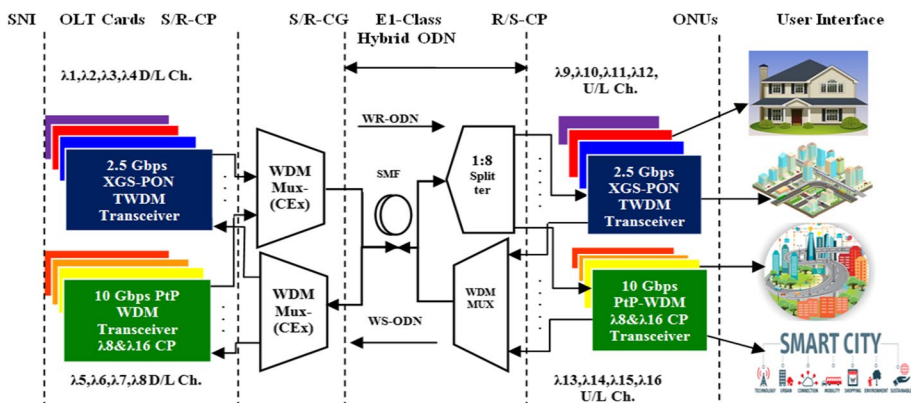


Fig. 1 Extended class-1 TWDM NG-PON2 schematic

two groups representing four each PtM 2.5 Gbps XGS-PON and PtP 10 Gbps WDM in either direction. D/L Ch are transmitted on L-band wavelength plan between 187.1 and 187.8 THz while U/L Ch are broadcasted on 195.1 THz to 195.8 THz C-band frequencies with channel spacing of $\Delta F = 100$ GHz supporting symmetric 80 Gbps aggregate line rate.

ODN section is implemented using G. 652 lossy bidirectional SMF covering distance between 20 and 50 km (Way et al. 2016; Yuanqiu et al. 2016; Veen et al. 2015; Jeff et al. 2012; Kumar and Jamal 2014; IX Blue Photo. 2019).

3 Design and optimization of N2-class NG-PON2 network subsystems

3.1 Simulation mechanism of OLT transceiver

OptiSystem-18 simulation software is used for the design and simulation of proposed E1-class access network. OptiSystem provides the reach variety of active and passive components' along the lossy and lossless unidirectional and bidirectional fiber Ch. The post simulation analysis can be carried out efficiently and effectively with latest and advanced set of test and measurement equipment's and visualizers. The simulation setup for single OLT Trx is depicted in Fig. 2. It consists of mechanism for D/L transmitter Ch and receiver for U/L Ch. Continuous wave (CW) laser is used for D/L optical transmitters. Widely used Mech-Zender Modulator (MZM) which is also known as intensity modulator (IM) is incorporated to achieve modulation of optical carrier signal. The OLT Trx mechanism depicted in Fig. 2 is repeated for eight D/L and U/L Ch. The modulated multichannel optical spectrum is applied to eight channel WDM CEx. The aggregate intensity of eight optical D/L Ch represented as $PT_{ODN} = \sum_{n=1}^8 A_k(t) = 7.1$ dBm is launed through SMF in ODN in downstream direction at S/R-CG interface. The U/L spectrum is made to propagate through Bessel filter before being detected by positive-intrinsic-negative (PIN) photodiode. The demodulated signal is propagated through LPF before being applied to BER analyzer for analysis purpose. PT_{ODN} is optimized to 7.1 dBm to keep the impact of channel nonlinearities at minimum level to enhance the performance of the network in terms of crosstalk and FWM components (ITU-T G.Sup39 2016; Neophytos et al. 2012; Veen et al. 2015). The

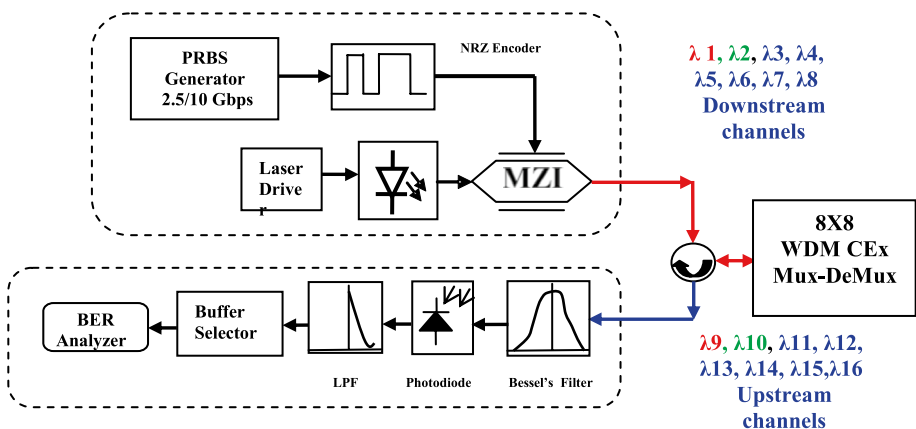


Fig. 2 Extended class-1 TWDM NG-PON2 OLT Transceiver

intensity of the U/L spectrum is identifies as $P_{T_{ODN}} = \sum_{n=1}^8 B_k(t)$ optimized to 4.01 dBm at S/R-CG interface (ITU-T G.989.2 2019; Pagare et al. 2021).

The D/L and U/L spectrum $P_{T_{ODN}}$ is optimized by referring the insertion losses (IL) introduced by MZM intensity modulator, WDM CEx devices and the circulators of 5.04 dB, 2.6 dB, and 1 dB respectively (IX Blue Photonics 2019; Ciena Corp. 2011; Cornig Opt. 2016) incorporated to establish D/L Ch.

Individual transmitter channel power $P_{TX\lambda}$ is selected randomly ensuring the aggregate transmitter power of input Ch is almost near to total ILs estimated using generate and test model (Pagare et al. 2021) described by Eq. 1 as,

$$P_{TODN} = P_{TX\lambda} - \sum_{M=1}^{N-1} P_{IL_MZI} - \sum_{C=1}^{N-1} P_{IL_Cir} - P_{IL_MUX} + \sum_{\lambda=1}^{N-1} P_{Tin_MUX} \tag{1}$$

Before optimizing $P_{TX\lambda}$, randomly selected transmitter power from eighth D/L channela has generated aggregate power of 48.40 dB at the input ports of CEx device i.e. $\sum_{\lambda=1}^{N-1} P_{TinMUX} = 48.40$. Replacing the IL of respective component and aggregate input power at CEx device in Eq. 1, the optimized channel transmitter power for 2.5 and 10 Gbps D/L chto optimize $P_{TODN} = 7$ dBm of E1-class is estimated using Eq. 2 as,

$$\begin{aligned} P_{TODN} &= P_{TX\lambda} - (5.04 \times 8) - (1 \times 8) - 2.6 + 48.40 \\ P_{TX\lambda} &= P_{TODN} + 2.55 \end{aligned} \tag{2}$$

Referring minimum (min) and maximum (max) P_{TODN} ITU-T. 989.2 (02/2019) standards i.e. 4 and 8 dBm for 2.5 Gbps and 7 and 8 dBm for 10 Gbps downstream (D/S) channel to optimize E1-class ODN,using Eq. 2, the estimated min/max transmitter power $P_{TX\lambda}$ of individual 2.5 and 10 Gbps D/S channel is 6.55 dBm, 10.55 dBm, 9.55 dBm and 13.5 dBm respectively. The sensitivity of 2.5 and 10 Gbps U/L Ch is estimated by using Eq. 3 as (ITU-T G.989.2 2019),

$$\text{Receiver sensitivity (RxS)} = \text{Received Sensitivity (dBm)} - [\text{IL}_{TOTAL} + \text{Power Penalty}] > 30.5 \text{ dBm} \tag{3}$$

Referring the IL of the individual componenets from the respective data sheets, The total IL of individual XGS-PON PtM 2.5 and WDM PtP 10 Gbps U/L Ch are estimated as 10.44 dB and 12.14 dB respectively. Incorporating total estimated insertion losses in Eq. 3, the RxS for respective Gbps U/S Ch is estimated as,

$$R_{XGS\ 2.5\ PtM_XGS-PON_U/L} = -16.56 - [10.44 + 2] = -29 \text{ dBm} > -30.5 \text{ Bm}$$

$$R_{XGS\ 10\ PtP_WDM_U/L} = -21.1 - [12.24 + 2] = -35.34 \text{ dBm} > -30.5 \text{ dBm}$$

3.2 Simulation mechanism of ONU transceiver

ONU transceiver mechanism houses assembly of optical components to demodulate and receive D/L Ch and transmit U/L Ch D/L Ch are detected by tunable PIN photo receivers along with Bessel filter and TFF based LPF as presented in Fig. 3. U/L Ch are established using cost-effective NRZ encoded direct modulated laser transmitter (DML) along with along with 2-stage of dynamic switches to connect subscribers from upstream direction in TWDM

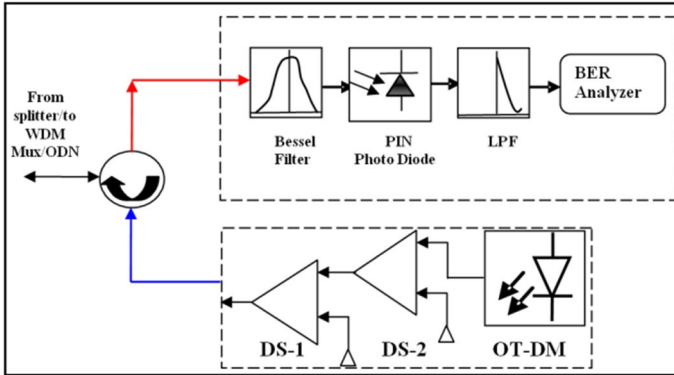


Fig. 3 Simulation mechanisms for TWDM ONU transceiver

mode. PtP WDM U/L Ch are established using NRZ encoded MZM/IM operating at 10 Gbps line rate. To estimate optimized channel transmitter power, randomly selected power of eight U/L Ch has resulted in aggregate power of 43.52 dBm at the input of WDM CEx device. Knowing the IL of passive components, the U/L channel transmitter power is estimated using Eq. 4 and Eq. 5 as (Pagare et al. 2021),

$$P_{T_{ODN}} = P_{T_{X\lambda}} - \sum_{M=1}^{N-1} P_{IL_{MZM}} - \sum_{C=1}^{N-1} P_{IL_{Cir}} - P_{IL_{switch}} - P_{IL_{MUX}} - P_{IL_{Bid-Splitter}} + \sum_{\lambda=1}^{N-1} P_{T_{inMUX}} \tag{4}$$

$$P_{T_{ODN}} = P_{T_{X\lambda}} - (30.71 + 8 + 2.40 + 2.6 + 1.25) + 43.52 \tag{5}$$

$$P_{T_{ODN}} = P_{T_{X\lambda}} - 1.44$$

Referring ITU-T G.989.2, replacing min and max ODN launch power defined for XGS-PON PtM 2.5 and WDM PtP 10 Gbps U/S Ch in Eq. 5, U/S channel transmitter power $P_{T_{X\lambda}}$ for 2.5 and 10 Gbps U/S Ch are estimated as, 5.44 dBm and 10.44 dBm for E1-Class XGS-PON PtM 2.5 and WDM PtP 10 Gbps U/S Ch respectively. Rxs of respective D/S Ch is estimated by using Eq. 6 as (ITU-T G.989.2 2019),

$$R_{Xs} = \text{Received Sensitivity (dBm)} - [IL_{TOTAL} + \text{Power Penalty}] > -30 \& -28 \text{ dBm} \tag{6}$$

where; $IL_{TOTAL} = IL(MZI + \text{Mux} + \text{Circulator})$ in dB. Total IL for XGS-PON PtM 2.5 and WDM PtP 10 Gbps D/S Ch is estimated as 8.64 dB and 9.64 dB for XGS-PON PtM 2.5 Gbps and WDM PtP 10 Gbps D/S Ch respectively. Referring 2 dB of poer penalty for worst-case analysis of TWDM based NG-PON2, using Eq. 6, Rxs of respective D/S channel are calculated as,

$$R_{XGS\ 2.5\ XGS-PON_D/S} = -29.11 - [8.64 + 2] = -39.75 \text{ dBm} > -30 \text{ dBm}$$

$$R_{XGS\ 10\ PtP_WDM_D/S} = -21.81 - [9.64 + 2] = -33.45 \text{ dBm} > -28 \text{ dBm}$$

3.3 Simulative mechanism for E1-class ODN

Losses introduced by ODN network have significant impact on overall system and splitter power budget. ODN includes the longest distribution network. Precise optimization of ODN network will enhance splitter configuration, network reach and overall performance matrix of optical access networks. ODN optimization techniques includes selection and incorporation of WR and WS ODN for Ch in either direction (ITU- incorporation of optimized launch power on ODN network instead minimum, random or maximum power T G.989.2, 2019; Pagare et al. 2021) and mitigating lossy fiber channel in ODN for its impairments. “Test and Generate” mechanism is incorporated to optimize ODN launch power (Pagare et al. 2021). The proposed mechanism accurately maintain the ODN launch power to specific class defined G.989.2 supporting coexistence data rate as well as individual line rate Ch. Since the ODN for the foreseen E1-power budget class TWDM NG-PON2 network is optimized to $PT_{ODN} = 7.1$ dBm and 4.01 dBm respectively for D/L and U/L spectrum, the transmitter power of the respective symmetric and coexistent Ch estimated in Sect. 3.1 and 3.2 along with aggregate effect of CD, SPM and XPM is summarized in Table 1 (ITU-T G.989.2 2019).

The D/L and U/L multichannel optical spectrum is propagated through wavelength routed (WR) ODN and wavelength select (WS) ODN. The measured ODN channel path loss is 18.99 dB, much less than the specification defined by G.989.2 standard. Low ODN losses will enhances the link power budget and splitter budget to support higher splitter configuration in 2.5 Gbps PtM D/L Ch (Veen et al. 2015; Way et. al. 2016; Yuanqiu et al. 2016, ITU-T G. 989.2 2019; Pagare et al. 2021).

4 Fiber channel impairment estimation and analysis for E1-class NG-PON2 network

The optimized multichannel optical spectrum with magnitude of 7.1 dBm and 4.01 dBm is propagated through bidirectional SMF in either direction. The propagation of the optical spectrum is analyzed using Schrodinger nonlinear equation (NLSE) represented by Eq. 7 as (Kumar and Jamal 2014; Neophytos et al. 2012; ITU-T G.652 2019),

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A - i\gamma |A|^2 A = 0 \tag{7}$$

where A is intensity of slowly varying optical envelope in (V/m), β_2 is group velocity dispersion (GVD) measured in ($ps^2 km^{-1}$) also identified as CD, parameter, z - Spatial position

Table 1 Range of transmitter input power (PT_{Xk}) to ensure $PT_{ODN} = 7.1$ dBm for D/S and 4.01 dBm for U/S spectrum respectively for E1- class TWDM NG-PON2 access network under the cumulative impact of estimated CD, SPM and XPM channel impairments

TWDM NG-PON2 Class	Range of PT_{Xk}	2.5 Gbps XGS-PON PtM D/S Ch	10 Gbps PtP WDM D/S Ch	2.5 Gbps XGS-PON PtM U/S Ch	10 Gbps PtP WDM U/S Ch
E1-Class NG-PON2	Minimum	6.55 dBm	9.55 dBm	5.44 dBm	5.44 dBm
	Maximum	10.55 dBm	13.55 dBm	10.44 dBm	10.44 dBm

in fiber axis in (m), γ —non-linear Kerr parameter in ($W^{-1} km^{-1}$) contributing SPM and XPM impairments. Non-linear Kerr parameter γ is estimated using Eq. 8 as (Kumar and Jamal 2014; Neophytos et al. 2012; Ali et al. 2018),

$$\gamma = \frac{2\pi n_2}{\lambda_0 A_{eff}} \tag{8}$$

It is observed that the optical field envelope intensity A is affected by Kerr parameter γ contributing SPM and XPM impairments, GVD or CD parameter β_2 and non-linear refractive index n_2 . Thus, by optimizing linear and non-linear channel impairments, the network performance parameters like bit error rate (BER), Q-factor, Rxs, power and splitter budget can be enhanced (Kumar and Jamal 2014; Neophytos et al. 2012; Habib et al. 2020).

4.1 Chromatic dispersion (CD) coefficient estimation

The impact of CD on the optical spectrum propogating through fiber channel appears interms of spreading of the the optical pulse or envelope effecting BEperformance. The CD parameter proportional to fiber channel length L and and the channel wavelength $D_{Link}(\lambda)$ is estimated using Eq. 9 as (ITU-T G.989.2 2019; ITU-T G.652 2019),

$$D_{Link}(\lambda) = L_{Link} [D_{1550} + S_{1550}(\lambda - 1550)] (\text{ps/nm} * \text{km}) \tag{9}$$

At 1550 nm, the dispersion coefficient and dispersion slope is 1550 nm and 12 ps/nm*km 0.056 ps/nm²* km respectively for G.652 fiber channel. The CD coefficient of 19.744 ps/nm*km is estimated using Eq. 9 and incorporated for simulative analysis of foreseen network between 20 and 50 km SMF channel length (Kumar and Jamal 2014).

4.2 Non-linear kerr parameter- γ and Effective area- A_{eff} estimation

Since the fiber silica is sensitive to the intensity of the optical spectrum launched through fiber channel. Any variations in the non-linear refractive index n_2 due to variations in magnitude of intensity of the optical spectrum results in non-linear phase change \emptyset_{NL} of the optical signal propagating through fiber channel proportional to kerr parameter γ . Further, γ is responsible for SPM and XPM channel impairments based on amount of non-linear phase change introduced due to variations in the magnitude of the intensity of optical spectrum. The net effect of SPM and XPM appear in the form of overlapping of adjacent Ch reducing BER performance. The non-linear phase change due to SPM and XPM is estimated using Eq. 10 and Eq. 11 as (Kumar and Jamal 2014; Neophytos et al. 2012; Habib et al. 2020; Singh and Singh 2018),

$$\emptyset_{NLXPM} = \gamma L_{eff} PT_{ODN}^p + 2 \sum_{p=1, p \neq q}^N \gamma L_{eff} PT_{ODN}^h \tag{10}$$

$$\emptyset_{NLSPM} = \gamma L_{eff} PT_{ODN}^p \tag{11}$$

where p and q represents number of D/L and U/L Ch.

The range of non-linear phase change \emptyset_{NL} is between 0.2 and 0.5 rad. Referring Eqs. 10 and 11 and incorporating $PT_{ODN}=7.1$ dBm for D/L optical spectrum, the corresponding kerr

parameter γ for SPM and XPM is estimated as $7.98 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$ and $2.00 \times 10^{-2} \text{ W}^{-1} \text{ m}^{-1}$ respectively (Kumar and Jamal 2014; Neophytos et al. 2012; Zhou et al. 2015). Replacing the estimated kerr γ parameter in Eq. 8, the effective area corresponding to SMP and XPM is estimated as $A_{eff} = 123 \mu\text{m}^2$ and $49 \mu\text{m}^2$ and incorporated for simulative analysis of proposed network between 20 and 50 km link length to analyze the impact of launch power on BER, Q-factor, Rxs, network reach and link power budget.

4.3 Estimation of Four-wave mixing (FWM) element

Multichannel optical spectrum have significant impact of FWM. The FWM develops the addition signal element of specific magnitude located at specific frequency or wavelength. This results in overlapping of the Ch also reducing the available bandwidth for the propagation of the original optical Ch (Habib et al. 2020; Singh and Singh 2018; Kumar and Jamal 2014). The magnitude of the newly developed frequency components due to FWM phenomena is estimated using Eq. 12 as (Kumar and Jamal 2014),

$$P_{FWM} = \gamma P_a P_b P_c * L_{eff}^2 * \eta_{abcn} e^{-\alpha L} \tag{12}$$

Considering the spacing between the adjacent Ch of 100 GHz and referring the GVD dispersion β_2 of 19.744 ps/nm²km as estimated in Sect. 4.1, the FWM efficiency η_{abcn} is estimated using Eq. 13 (Kumar and Jamal 2014) as,

$$\eta_{abcn} = \frac{\alpha^2}{\alpha^2 + 4\beta_2^2(2\pi\Delta f)^4} \tag{13}$$

Thus, from Eq. 14, it is confirmed that the FWM impact can be minimized by optimizing ODN channel launch power P_{TODN} , mitigating linear and non linear impairments including CD, selecting appropriate channel spacing Δf . The linear and nonlinear impairments described by Eq. 7 such as GVD parameter β_2 , Kerr parameter γ in the range of $7.98 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$ and $2.00 \times 10^{-2} \text{ W}^{-1} \text{ m}^{-1}$ respectively and estimated range of effective area A_{eff} of 123–49 μm^2 and 61–24 μm^2 for symmetric channel spectrum along with SPM and XPM non-linear impairments respectively (Singh and Singh 2018; Shrama et al. 2016; Pagare et al. 2021), resulted in FWM efficiency of 1.65×10^{-52} . The magnitude of the FWM component estimated using Eq. 12 is in the range of 1×10^{-53} to 1×10^{-52} . Thus, it is concluded that the ODN channel launch power optimizations process is successful in keeping Kerr parameter γ , FWM efficiency and FWM power level at much lower level as seen in Fig. 4a, b, minimizing impact of linear and nonlinear impairments on multichannel spectrum travelling through SMF ODN in either direction.

4.4 Estimation and analysis of Interchange crosstalk (Cc) and power penalty (Pc)

The non-linear Kerr parameter contributing SPM and XPM impairments along with CD and FWM phenomena results in crosstalk between the Ch in multichannel scenario. The crosstalk Cc for D/L and U/L spectrum is estimated using Eq. 14 and Eq. 15 respectively as (ITU-T G.989.2 2019),

$$C_C = \Delta P_{ONU} + \text{Uniformity}_{WM} + 10\text{Log}_{10} \left[2 * 10^{-\frac{-A}{10}} (N - 3) * 10^{-\frac{-NA}{10}} \right] \tag{14}$$

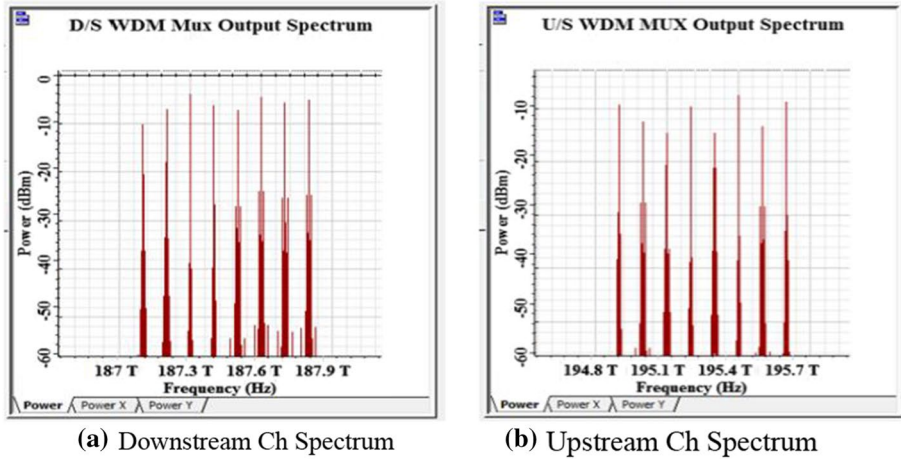


Fig. 4 a–b D/L and U/L spectrum for E1-class TWDM NG-PON2 network

$$C_C = \Delta P_{ONU} + d_{max} + 10\text{Log}_{10} \left[2 * 10^{\frac{-I_A}{10}} (N - 3) * 10^{\frac{-I_{NA}}{10}} \right] \text{dB} \tag{15}$$

where N represents the number of Ch propagating in up/down direction, ΔP_{ONU} represents the maximum channel transmitter power difference as estimated and referred from Sect. 3.1 and 3.2 for symmetric Ch respectively and d_{max} represents the maximum power difference between the placement of ONUs in U/L Ch equal to 6.54 dB. Referring uniformity factor for WDM CEx device of 1.5 dB. Isolation between the adjacent and non-adjacent Ch of $I_A = 40$ dB and $I_{NA} = 55$ dB are referred from mux filter (Corning Opti. 2016) to estimate the inter-channel crosstalk for D/L and U/L symmetric Ch using Eqs. 14 and 15 as,

$$C_C = 3 + 1.5 + 10\text{Log}_{10} \left[2 * 10^{\frac{-40}{10}} (8 - 3) * 10^{\frac{-55}{10}} \right] = -31.97 \text{ dB for D/L multi - channel spectrum}$$

$$C_C = 0 + 6.54 + 10\text{Log}_{10} \left[2 * 10^{\frac{-40}{10}} (8 - 3) * 10^{\frac{-55}{10}} \right] = -30.12 \text{ dB U/L multi - channel spectrum}$$

The crosstalk power penalty corresponds to estimated channel crosstalk for Q of 5 and 6 for symmetric Ch respectively at 50 km with an extinction ratio (ER) of 15 along with aggregate impact channel nonlinearities as estimated above, is obtained using Eq. 16 as (ITU-T G.989.2 2019),

$$P_C = -5\text{Log} \left(1 - \frac{10^{\frac{2C_C}{10}}}{N - 1} * Q^2 * \left(\frac{ER + 1}{ER - 1} \right)^2 \right) = -5\text{Log} \left(1 - \frac{10^{\frac{2(-31.97)}{10}}}{8 - 1} * 5^2 * \left(\frac{10 + 1}{10 - 1} \right)^2 \right) = 0.0 \text{ dB} \tag{16}$$

Thus, we confirm that the estimated crosstalk power penalty corresponds to estimated channel crosstalk obtained for symmetric Ch spectrum is well within the boundaries of prescribed by ITU-T G.989.2 standards.

5 Simulative analysis of network performance parameters

$\lambda 1-\lambda 4$ and $\lambda 5-\lambda 8$ Ch are supporting XGS-PON PtM 2.5 and WDM PtP 10 Gbps D/S Ch respectively. Similarly, $\lambda 9-\lambda 12$ and $\lambda 13-\lambda 16$ Ch are operating with XGS-PON PtM 2.5 and WDM PtP 10 Gbps U/S Ch respectively. D/L Ch are propagated on L-band frequencies from 187.1 to 187.8 THz while U/L Ch are propagated on C-band frequencies from 195.1 to 195.8 THz with channel spacing of 100 GHz between 20 and 50 km channel link distances. The multichannel D/L and U/L optical spectrum is optimized to $PT_{ODN}=7.1$ dBm and 4.1 dBm before launching on SMF in ODN through WDM CEx. The D/L and U/L output spectrum post optimization along with total impact of CD, SPM and XPM at 50 km is depicted in Fig. 4a, b respectively. It is observed that the Ch are spaced apart nicely without any signs of overlapping. The maximum difference in the U/L channel power recorded is $d_{max}=6.54$ dB, while for D/L Ch, the uniformity factor considered is 1.5 dB. The FWM component generated is in the range of -53 to -52 dB constituting crosstalk of $-31.97/-30.12$ dB for D/L and U/L spectrum respectively.

Figure 5a-h depicts the eye-diagram performance analysis of the optimized $\lambda 1$ - XGS-PON PtM 2.5 Gbps and $\lambda 8-10$ WDM PtP 10 Gbps D/L Ch for optimized scenario of Kerr parameter γ , FWM and CD impairments between 20 and 50 km link distance. It is noted

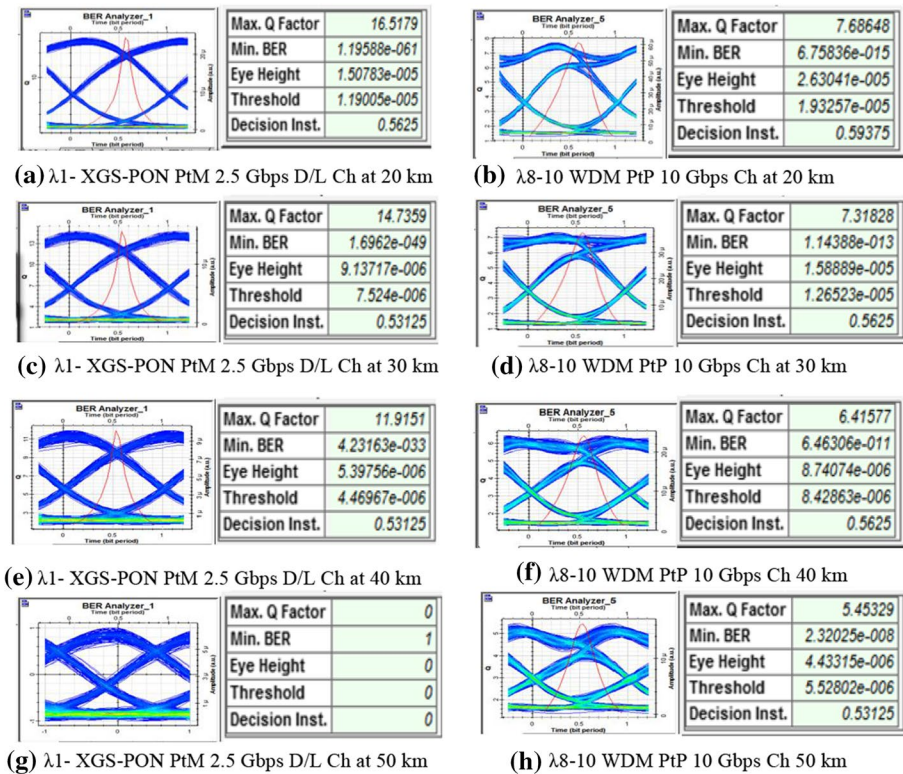


Fig. 5 a-h Eye diagram analysis of $\lambda 1$ - XGS-PON PtM 2.5 Gbps and $\lambda 8$ -WDM PtP 10 Gbps D/L Ch between 20–50 km link distance for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments

that the eye opening is good-enough up to 40 km link distance separating received 1's from 0's bits. The BER of -33 and -8 and Q of 11 and 5 λ_1 - XGS-PON PtM 2.5 Gbps and λ_8 -WDM PtP 10 Gbps D/L at 50 km comfortably satisfying ITU-T G. 989.2 specifications.

The recorded magnitude of BER, Q-factor, received power and estimated receiver sensitivity (Rxs) for λ_1 - XGS-PON PtM 2.5 Gbps and λ_8 WDM PtP 10 Gbps D/L Ch for optimized scenario of Kerr parameter γ , FWM and CD impairments between 20 and 50 km link distance are consolidated in Table 2. The observations has confirmed that λ_1 - XGS-PON PtM 2.5 Gbps D/L Ch delivers the acceptable performance parameters up to 40 km link distance, while, λ_8 -WDM PtP 10 Gbps D/L channel delivers extended reach up to 50 km.

Figure 6a–h depicts the eye diagram simulative analysis for results for λ_9 -XGS-PON PtM 2.5 Gbps and λ_{16} -WDM PtP 10 Gbps U/S Ch for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments between link distance of 20–50 km. Observations and recoding of parameters has confirmed that U/L Ch delivers acceptable BER and Q performance up to 50 km and suitable for implementation of symmetric Ch for the foreseen E1-class TWDM NG-PON2 optical access network. Although, 2.5 Gbps XGS-PON PtM U/L Ch are supported by 30 dB amplifier to archive the demonstrated simulation results, while 10 Gbps WDM PtP U/L Ch delivers the results without amplification of U/L Ch.

Table 3 summarizes the BER, Q-factor, received power and estimated receiver sensitivity (Rxs) for λ_9 –2.5 Gbps PtM XGS-PON and λ_{16} –10 Gbps PtP WDM U/L Ch for the optimized scenario of Kerr parameter γ , FWM and CD impairments between 20 and 50 km link distance.

It is confirmed that the optimization of channel power and impairments constituted an extended reach up to 50 km is demonstrated for PtM and PtP U/L Ch.

5.1 Comparative performance analysis of λ_1 – λ_9 -XGS-PON PtM 2.5 Gbps λ_8 – λ_{16} 2.5 10 Gbps symmetric channel pairs

The comparative analysis of estimated receiver sensitivity Rxs, recorded BER and Q of λ_1 – λ_9 2.5 Gbps PtM and λ_8 – λ_{16} 10 Gbps PtP symmetric channel pair (CP) along the channel length between 20 and 70 km for lossless channel and under the optimized scenario of incremental channel impairments including Kerr parameter γ , CD and FWM is depicted in Fig. 7a–f. As depicted in Fig. 7a, b, the variations of Rxs is linear with link distance. The impact of channel impairments has limited the network reach to 40 and 50 km for 2.5 Gbps and 10 Gbps D/S CP respectively. Figure 7c and d depicts the variation of BER with Rxs. The impact of channel impairments are clearly observed on both the Ch limiting the receiver sensitivity performance at acceptable BER. Similarly, the impact of channel imparities are also observed on Q-factor performance limiting the reach and Rxs of the Ch..

The BER, Q and Rxs parameters obtained clearly indicated incremental performance compared to specifications described in G. 989.2 (02/2019). Upward trends in Rxs, will felicitate inclusion of splitter with higher split-ratio.

5.2 System power and splitter budget estimation

System power budget (PB) defines the minimum amount of optical power required to receive optical signal within acceptable performance parameters. Further, splitter power budget (SB)

Table 2 Receiver sensitivity (Rxs), BER, Q-factor of $\lambda 1$ - XGS-PON PtM 2.5 Gbps and $\lambda 8$ - WDM PtP 10 Gbps D/S Ch between 20–50 km link distance for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments

S. No	Link distance (km)	$\lambda 1$ - XGS-PON PtM 2.5 Gbps D/S Ch					$\lambda 8$ -WDM PtP 10 Gbps D/S Ch				
		PT _{Xs} (dBm)	Received power (dBm)	Rxs (dBm)	Q-Factor	Log (BER)	PT _{Xs} (dBm)	Received power (dBm)	Rxs (dBm)	Q-Factor	Log (BER)
1	20	6.55	-23.33	-33.97	16	-61	9.55	-15.72	-27.36	8	-15
2	30	6.55	-25.16	-35.8	14	-49	9.55	-17.68	-29.32	7	-13
3	40	6.55	-27.14	-37.78	12	-33	9.55	-19.8	-31.44	6	-11
4	50	6.55	-29.11	-39.75	0	-1	9.55	-21.81	-33.45	5	-8

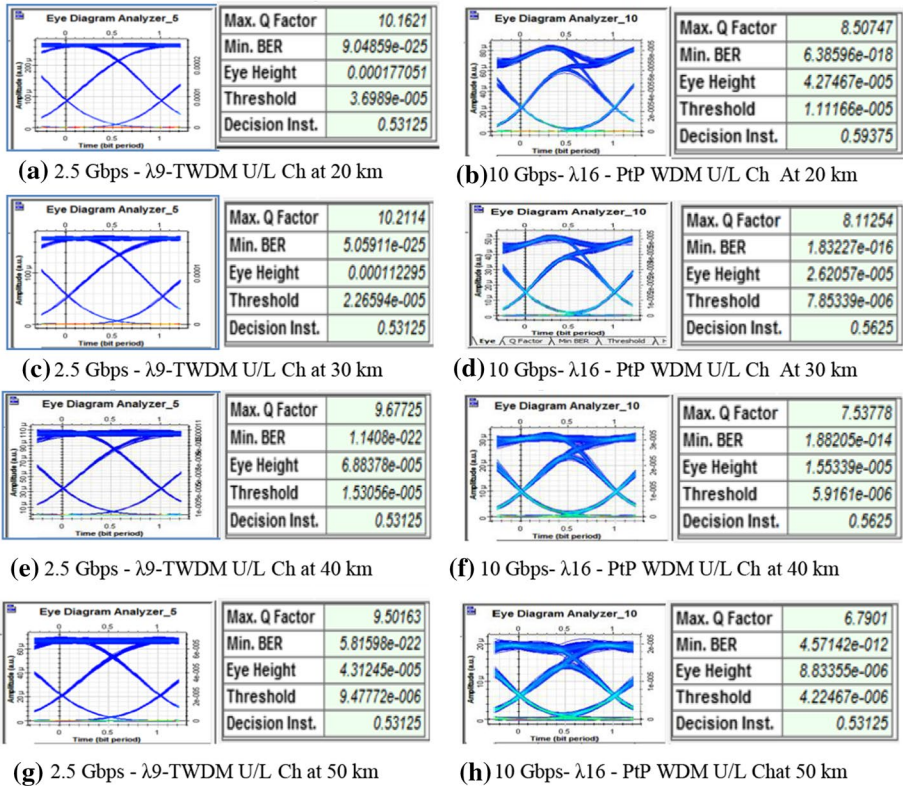


Fig. 6 a–h Eye diagram analysis of $\lambda 9$ -XGS-PON PtM 2.5 Gbps and $\lambda 16$ -WDM PtP 10 Gbps U/S Ch for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments between 20–50 km link distance

is derived from PB to confirm the splitter ratio supported by the downstream Ch. System or link PB is estimated using Eq. 17 as,

$$PB = \text{Transmitter Power } (P_{TX\lambda}) - \text{Receiver sensitivity } (R_{XS}) \tag{17}$$

Referring estimated transmitter power $P_{TX\lambda}$ and estimated receiver sensitivity R_{XS} for $\lambda 1$ -XGS-PON PtM 2.5 Gbps and $\lambda 8$ WDM PtP 10 Gbps D/L Ch at 40 km from Table 2, the PB of D/L Ch is estimated as,

$$PB_{\lambda 1-XGS-PON PtM 2.5 Gbps_D/S} = 6.55 - (-39.75) = 46.3 \text{ dB}$$

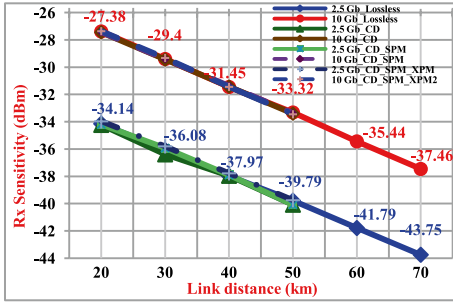
$$PB_{\lambda 8 WDM PtP 10 Gbps_D/L} = 9.55 - (-33.45) = 43 \text{ dB}$$

Similarly, for $\lambda 9$ 2.5 Gbps and $\lambda 16$ 10 Gbps U/L Ch, from Table 3, the estimated PB at 50 is 34.55 dB and 40.89 dB respectively. Since the splitter will be incorporated in D/L Ch only, SP of D/L Ch is estimated using Eq. 18 as,

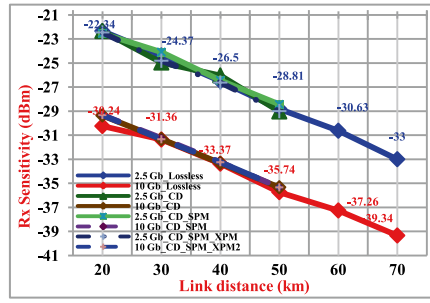
$$SP = PB - A - \text{Link Margin} \tag{18}$$

Table 3 R_{xs}, BER, Q-factor of λ 9-XGS-PON PtM 2.5 Gbps and λ 16-WDM PtP 10 Gbps U/S Ch for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments between 20–50 km link distance

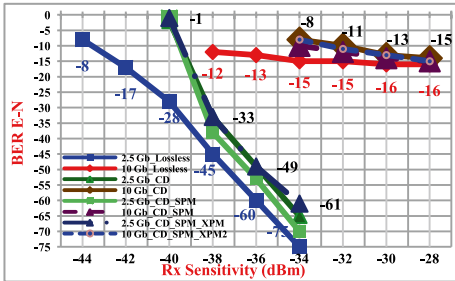
S. No	Link dis- tance (km)	Tx power (dBm)	λ 9-XGS-PON PtM 2.5 Gbps U/S Ch				λ 16-WDM PtP 10 Gbps U/S Ch			
			Received power (dBm)	R _{xs} (dBm)	Q-Factor	Log (BER)	Received power (dBm)	R _{xs} (dBm)	Q-Factor	Log (BER)
1	20	5.55	-10.02	-22.46	10	-25	-15.09	-29.33	8	-18
2	30	5.55	-12.37	-24.81	10	-25	-17.1	-31.34	8	-16
3	40	5.55	-14.19	-26.63	9	-22	-19.01	-33.25	7	-14
4	50	5.55	-16.56	-29	9	-22	-21.1	-35.34	6	-12



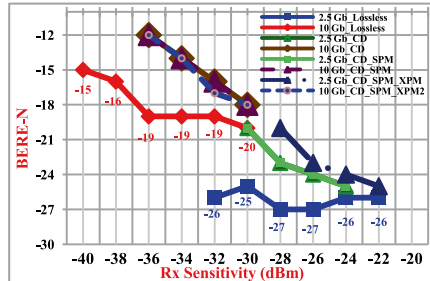
(a) Receiver sensitivity vs. link distance for λ_1 -XGS-PON PtM 2.5 and λ_8 -WDM PtP 10 Gbps D/S Ch



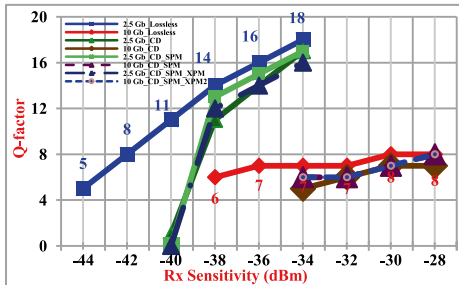
(b) Receiver sensitivity vs. link distance for λ_9 -XGS-PON 2.5 and λ_{16} -WDM PtP 10 Gbps U/S Ch



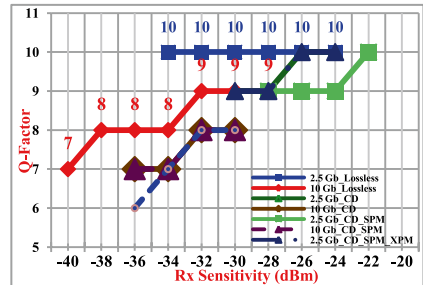
(c) BER vs Receiver sensitivity for λ_1 -XGS-PON PtM 2.5 and λ_8 -WDM PtP 10 Gbps D/S Ch



(d) BER vs Receiver sensitivity for λ_9 -XGS-PON PtM 2.5 and λ_{16} -WDM PtP 10 Gbps U/S Ch



(e) Q-factor vs Receiver sensitivity for λ_1 -XGS-PON PtM 2.5 and λ_8 -WDM PtP 10 Gbps D/S Ch



(f) Q-factor vs Receiver sensitivity for λ_9 -XGS-PON PtM 2.5 and λ_{16} -WDM PtP 10 Gbps U/S Ch

Fig. 7 a–f Comparative analysis of estimated receiver sensitivity R_x s, recorded BER and Q of $\lambda_1 - \lambda_9$ 2.5 Gbps PtM and $\lambda_8 - \lambda_{16}$ 10 Gbps PtP symmetric channel pair (CP) for lossless channel and under the optimized scenario of incremental channel impairments including Kerr parameter γ , CD and FWM along the channel length between 20 to 70 km

where A is aggregate attenuation due to passive components and the fiber channel length estimated using Eq. 19 as (ITU-T G.652 2019),

$$A = \alpha L + \alpha_s \times S + \alpha_c \times C \tag{19}$$

where L is the channel length in km, S represents the number of splices incorporated in the link and C is number of passive connectors used in the optical link. Incorporating the

losses due to passive components and attenuation due to channel length, total attenuation 'A' for respective D/L channel i.e. estimated as follows.

$$A = IL [(IL_{MZM} + IL_{MUX} + IL_{Cir} + 0.2 \times (40))] = (5.04 + 2.6 + 1 + 8) = 16.64 \text{ dB for } \lambda 1 - 2.5 \text{ Gbps PtM D/L Ch.}$$

$$A = IL [(IL_{MZM} + IL_{MUX} + IL_{Cir} + 0.2 \times (40))] = (5.04 + 2.6 + 2 + 10) = 19.64 \text{ dB for } \lambda 8 - 10 \text{ Gbps D/L Ch.}$$

From estimated power budget PB, total link attenuation A, and referring link margin of 3 dB, the splitter power budget of D/L Ch estimated using Eq. 18 as are 26.66 dB and 20.36 dB respectively.

By estimating the insertion losses introduced by the specific splitter configuration using Eq. 20 (Comp-Port TeCh 2015), the splitter ratio configuration is selected and incorporated in D/L Ch to deliver the multi-gigabit line rate to multiple subscribers

$$PIL_{Splitter} = 10 \times \log\left(\frac{1}{N}\right) \tag{20}$$

where *N* represents splitter ratio.

The analytical modeling and simulative analysis of the proposed access network has delivered an aggregate splitter configuration of 2560 at 20 km and 768 at 0 km respectively for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments (ITU-T G. 9807.1 2016; ITU-T G. 984.5 2014; ITU-T G. Sup39 2016).

5.3 Splitter budget vs link distance analysis

The variation of link power budget PB and corresponding splitter configuration along with the link distance for link distance $\lambda 1$ - XGS-PON PtM 2.5 Gbps and $\lambda 8$ WDM PtP 10 Gbps D/S Ch for optimized scenario of Kerr parameter γ , CD and FWM SMF channel impairments between 20 and 50 km is depicted in Fig. 8a, b, respectively. Since the D/L launch power is optimized to $PT_{ODN} = 7.1$ dBm, the power budget variations is linear almost similar for the incremental impact of CD, SPM and XPM impairments. The

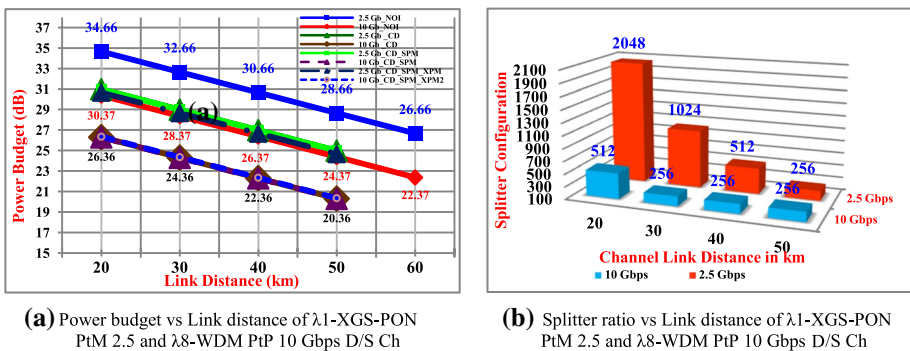


Fig. 8 a and b Variation of system power budget and aggregate splitter ratio of $\lambda 1$ -2.5 Gbps PtM XGS-PON and $\lambda 8$ -10 Gbps PtP WDM D/L Ch between 20 -60 km link distance for optimized Kerr parameter γ , FWM, and CD impairments

PB estimation has recorded almost 4 dB variations along with network reach by 20 km under the scenario of lossy fiber channel constraints. The splitter ratio accommodated by the proposed E1-class TWDM NG-PON2 optical access network is in the range of 2560 to 768 between 20 and 40 km link lengths respectively (Pagare et al. 2021; ITU T G.9807.1 2016, Comm-Port TeCh 2015).

During the entire design, analysis and validation process, we have included the actual losses introduced by the optical components. A 3 dB system margin is also included to avoid the overshoot of the power budget due to abrupt change introducing random losses in the proposed network. The measures adopted in the proposed simulation work will ensure near around similar performance in practical test bed and access network deployment scenario.

An asymmetric and coexistence approach for 8-Ch TWDM based NG-PON2 network has demonstrated the network reach up to 50 km supporting power budget 45 dB of power budget and 512 splitter configurations for the Ch operating at 1.25, 2.5 and 10 Gbps. However it is not clear the class of NG-PON2 supported by the proposed configuration (Liang et al. 2019). 4-Ch symmetric configuration supporting aggregate symmetric data rate of 100 Gbps has delivered the network reach of 25 km supporting 1024 splitter configuration. It was also not clear that which budget class configuration is supported by the proposed configuration (Zhao et al. 2015). 8 U/S-Ch configurations has delivered aggregate data rate of 80 Gbps supporting 28 dB power budget. The splitter configuration estimated for the proposed network configuration is 1:64 at 40 km link distance (Woung et al. 2013).

6 Conclusion

We have analyzed the impairment strained optical channel crosstalk subsequently affecting the link length due to dispersion, power budget limiting the channel splitter budget and splitter configuration incorporated in the system due to FWM, SPM and XPM. The optimization of ODN to E1-class by ensuring PTODN=7.1 dBm and 4.09 dBm has delivered significant improvement in the network quality parameters like BER, Q-factor, receiver sensitivities, FWM component power and efficiency, inter-channel cross talk, power penalty and link power budget subsequently extending the symmetric link reach to 40 km and improving splitter budget and splitter configuration fulfilling ITU-T G.989.2 recommendations. The Rxs delivered by lossy channels supporting 2.5 and 10 Gbps channels is -39.75 and -33.45 dBm with FWM component in the range of 1.34×10^{-52} and 2.41×10^{-51} for symmetric channels spacing of 100 Ghz. This has resulted in limiting the channel crosstalk to $-31.97/-30.12$ dB accommodating aggregate splitter configuration of 768 at 40 km. Analytical modeling, simulating analysis and performance parameters analysis indicates that the proposed access network configuration is suitable to deliver 10 Gbps line rate to corporate and business users while line rate of 2.5 Gbps can be used to serve low density individual subscribers up to 50 km link length. Future investigations should be directed in incorporating spectrally efficient efficiency modulation schemes, reducing ODN power losses to accommodate growing subscribers, dispersion and FWM compensation techniques and management, incorporation of multistage switching network along with free space optics (FSO) Ch to address last mile issues in the design and deployment of next generation optical access network for FTTX services.

References

- Ali, F., Khan, Y., Ali, A., Ahmed, G.: Minimization of nonlinear impairments and its impact on transmission performance of high-capacity long-haul optical networks. *J. Opt. Comm.* (2018). <https://doi.org/10.1515/joc-2018-0092>
- Ciena Corporation : Common optical filters for 4200 family, datasheet. Linthicum (2011). https://media.ciena.com/documents/Common_Optical_Filters_DS.pdf.
- Cisco visual networking index forecast and trends: 2017–2022, Cisco white paper (online). 01–38, CISCO, California,(2019). <http://media.mediapost.com/uploads/CiscoForecast.pdf>.
- Comm-Port Technologies : PLC splitter datasheet. Cranbu (2015). <https://www.comm-port.com/images/fiber-optic/PLC%20Splitter.pdf>
- Corning Optical Communications LLC : Optical circulators (Three Port), datasheet. Hickory (2016). www.corning.com/microsites/coc/oem/documents/CAH-140_AEN.pdf.
- Goyal, R., Kaler, R.S., Rani, M., Singh, V.: Analysis and mitigation of XPM crosstalk in the scenario of mixed line rates for next generation access networks. *J. Optoelectron. Adv. Mater. - Rapid Commun.* **11**(7–8), 440–445 (2017). <https://doi.org/10.1109/JLT.2015.2399271>
- Habib, U., Muhammad, Z., Sana, M., Talha, K., Songzuo, J., et al.: Improving FWM efficiency in bi-directional ultra DWDM-PON networking centered light source by using PMD emulator. *Results Phys.* **16**, 102922 (2020). <https://doi.org/10.1016/j.rinp.2019.102922>
- ITU-T G.652 Series-G. ITU-T : Transmission media and optical systems characteristics-Optical fiber cable single mode optical fiber and cables, ITU-T, Geneva (2019). www.itu.int/rec/T-REC-G.652-201611-I/en
- ITU-T G.984.5 Series-G. : Gigabit-capable passive optical network (GPON) Enhancement band. Geneva, (2014). www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.984.5-201405-1!!PDF-E&type-items.
- ITU-T G.989.2 Series-G. 40 Gbps capable passive optical networks 2 (NG-PON2) : Physical media dependent (PMD) layer specification, ITU-T, Geneva, (2019). www.itu.int/rec/T-REC-G.989.2-201902-I/en.
- ITU-T G.Sup39. : Optical system design and engineering considerations. Geneva, (2016). [www.http://www.itu.int/rec/T-REC-G.Sup39/en](http://www.itu.int/rec/T-REC-G.Sup39/en).
- ITU-TG.9807.1 (2016) Amendment-1 : 10-Gigabit-capable symmetric passive optical network (XGSPON), ITU-T, Geneva, 2017, www.itu-int/rec/T-REC-G.9807.1/en.
- IX-Blue Photonics : MX-LN series 1550 nm intensity modulators, datasheet. Besancon (2019) https://photo-nics.ixblue.com/sites/default/files/2021-02/MX-LN_SERIES_8.pdf
- Jeff, S., Charls, M., Lauran, H. : Broadband applications: categories, requirements and future framework, *J.Internet* **17** (11) (2012). <https://doi.org/10.5210/fm.v17i11.4066>
- Koundal, A., Dewra, S.: Performance analysis of 4x10 Gbps OFDM-PON system over ROF link. *J. Opt. Commun.* **40**(2), 113–117 (2019). <https://doi.org/10.1515/joc-2017-0049>
- Kumar, S., Jamal, M.D.: *Fiber Optics Communications: Fundamentals and Applications*. John Wiley & Sons Ltd., New York (2014)
- Liang, B., Xiangjun, Z., Shuang, Y., Tao, Z., Adam, E.T.B., Joy, J., et al.: Long-reach wavelength-routed TWDM PON: technology and deployment. *IEEE J. Lightwave Technol.* **37**(3), 688–697 (2019). <https://doi.org/10.1109/JLT.2018.2850343>
- Neophytos, A., Georgios, E., Ioannis, R.: *WDM Systems and Networks*. Springer, New York (2012)
- Pagare, R.A., Kumar, S., Mishra, A.: Design and analysis of hybrid optical distribution network for worst-case scenario of E2-class symmetric coexistence 80 Gbps TWDM NG-PON2 architecture for FTTX access networks. *Optik J. Light Electron Optics* **228**, 166168 (2021). <https://doi.org/10.1016/j.ijleo.2020.166168>
- Sharma, R., Dewra, S., Rani, A.: Performance analysis of hybrid PON (WDM-TDM) with equal and unequal channel spacing. *J. Opt. Commun.* **37**(2), 247–252 (2016). <https://doi.org/10.1515/joc-2015-0055>
- Singh, A., Singh, J.S.: A novel method for capacity enhancement of fiber and minimization of four wave mixing in WDM optical network. *Proc. Comput. Sci.* **125**, 257–266 (2018). <https://doi.org/10.1016/j.procs.2017.12.035>
- Veen, D.T.V., Houtsma, A., Gnauck, Iannoe, P.: Demonstration of 40 Gbps TDM-PON over 42- km with 31 dB optical power budget using an APD-based receiver. *J. Lightwave Technol.* **33**(8), 1675 (2015). <https://doi.org/10.1109/JLT.2015.2399271>
- Wey, J.S., Derek, N., Valvo, M., Grobe, K., Roberts, H., Luo, Y., Smith, J.: Physical layer aspect of NG-PON2 standards-Part 1: Optical link design. *J. Opt. Commun. Netw.* **8**(1), 33–42 (2016). <https://doi.org/10.1364/JOCN.8.0000433>
- Wong, E., Muller, M., Amann, M.: Colorless operation of short-cavity VCSELs in C-minus band for TWDM-PONs. *Electron. Lett.* **49–4**, 282–284 (2013). <https://doi.org/10.1049/el.2012.4332>

- Yuanqiu, L., Klaus, G., Hal, R., Maurizio, V., Derek, N., Kota, A., et al.: Physical layer aspect of NG-PON2 standards-Part 2: System design and technology feasibility. *J. Opt. Commun. Netw.* **8**(1), 43–52 (2016). <https://doi.org/10.1364/JOCN.8.000043>
- Zhao, Z., Bi, M., Xiao, S., Zhang, Y., Hu, W.: Experimental demonstration of symmetric 40 Gbps DML based TWDM-PON system. *Photonic Techno. Lett.* **27**(5), 470–473 (2015). <https://doi.org/10.1109/LPT.2014.2377271>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Rajendraprasad A. Pagare¹  · Abhilasha Mishra² · Santosh Kumar³

Abhilasha Mishra
abbhilasha@gmail.com

- ¹ Department of E&TC Engineering, Smt. Kashibai Navale College of Engineering, Savitribai Phule Pune University, Pune, Maharashtra 411042, India
- ² Department of E&TC Engineering, Maharashtra Institute of Technology, Dr. BAM University, Aurangabad, Maharashtra 431009, India
- ³ Shandong Key Laboratory of Optical Communication Science and Technology, School of Physics Science and Information Technology, Liaocheng University, Liaocheng 252059, Shandong, China