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Four-fold increase in users of time-wavelength division multiplexing (TWDM) passive optical network (PON) by delayed optical amplitude modulation (AM) upstream

Vivek Kachhatiya, Shanthi Prince *

Department of Electronics and Communication Engineering, SRM University, Kattankulathur 603203, Tamil Nadu, India

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ABSTRACT

In this paper, we have proposed and simulated optical time division multiplexed passive optical network (TDM-PON) using delayed optical amplitude modulation (AM). Eight upstream wavelengths are demonstrated to show optical time wavelength division multiplexed (TWDM) by combining optical network units (ONU) users data at the remote node (RN). Each ONU generates 2.5 Gb/s user data, and it is modulated using novel return to zero (RZ) delayed AM. Optical TDM aggregates 10 Gb/s data per wavelength from four 2.5 Gb/s upstream user data, which facilitates four different ONU data on the same wavelength as 10 Gb/s per upstream wavelength and, simplify the laser requirements (2.5 Gb/s) at each optical network unit (ONU) transmitter. Upstream optical TWDM-PON is investigated for eight wavelengths with wavelength spacing of 100 GHz. Novel optical TDM for upstream increased the number of the simultaneous user to fourfold from conventional TWDM-PON using delayed AM with a high-quality-factor of received signal. Despite performance degradation due to different fiber reach and dispersion compensation technique, Optical TWDM link shows significant improvement regarding receiver sensitivity when compared with common TWDM link. Hence, it offers optimistic thinking to show optical TDM at this phase as one of the future direction, where complex digital signal processing (DSP) and coherent optical communication are frequently demonstrated to serve the access network. Downstream side conventional TWDM eight wavelengths are multiplexed at the OLT and sent downstream to serve distributed tunable ONU receivers through an optical distribution network (ODN). Each downstream wavelengths are modulated at the peak rate of 10 Gb/s using non-return to zero external modulation (NRZ-EM). The proposed architecture is cost efficient and supports high data rates as well as "pay as you grow" network for both service providers and the users perspectives. Users are classified into two categories viz home-user and business-user, with an option for easy up-gradation. Proposed architecture operates on next generation passive optical network stage 2 (NG-PON2) wavelength plan, with symmetrical data rate. Downstream performance is investigated by comparing, high power laser source with a conventional laser source and the L-band Erbium-doped fiber amplifier (EDFA) of gain 10 dB and 20 dB. Downstream eight wavelengths perform error-free up to 40 Km fiber reach and 1024 splitting points. Power budget of the proposed architecture incorporates the N1, N2, E1 and E2 optical path loss class.

1. Introduction

The modern optical access network demands the high data rate and a large number of users with support of a variety of the high-end user applications [1,2]. To satisfy the predicted demand for the optical access network, coherence technologies [3–5] may be implemented, as it supports the high-capacity backbone network and metro networks. Recent approach [6] has demonstrated the low-cost coherent system with a loss budget of 40 dB with fully polarization independent operation. Coherent Technologies are highly expensive at the access network segment and highly complex concerning access level operation. Another approach to fulfilling the demand is advanced modulation format integrated with the access network segment and analyzed to deliver high data rate as describe in [7–9], but it results in shorter reach, complex and expensive implementation and requires higher receiver sensitivity. Coherent systems and advanced modulation format require digital signal processing (DSP) to mitigates inter-channel-interference.

* Corresponding author.
E-mail addresses: vivek.kachhatiya@gmail.com (V. Kachhatiya), shanthi.p@ktr.srmuniv.ac.in (S. Prince).

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Although using DSP after the optical and electrical filter, a system can transmit on reduced channel spacing equal to the symbol rate, which is known as Nyquist-WDM-super-channel but at the same time, complexity and cost are challenging [10–12].

Time-wavelength division passive optical network (TWDM-PON) has been selected as the primary solution for next generation passive optical network stage 2 (NG-PON2) by the full-service access network (FSAN) due to its advantages of component availability, backward compatibility and simple mature technology [13–16]. Architectural summary of TWDM-PON described in the general requirements of G.989.1 [17]. 1596–1603 nm wavelength window for downstream and 1520–1544 nm wavelength window for upstream operating on an ITU-T grid with each carrying 10 Gb/s or 2.5 Gb/s modulated data is suggested in the recommendation of G.989.2 [18]. Due to growing demand for bandwidth-intensive applications and increase in a number of subscribers, high-capacity TWDM-PON system with four wavelengths is investigated widely [19–23] as the first step solution to deliver high data rates downstream[24–26]. According to predicted aggregated data rate [2], eight wavelength is the future requirement, and option are also avail by NG-PON-2 recommendation [18].

Proposed TWDM architecture gain advantages of high data rate and high splitting ratio for downstream direction. Upstream optical time division multiplexing (TDM) supports aggregates 10 Gb/s data rate on each upstream wavelengths and the fourfold number of users with a dedicated upstream data rate of 2.5 Gb/s per user. Besides high data rate and a large number of users, the significant concern is cost-effectiveness, easy upgradeability, and reliability of futuristic architecture that supports the variety of users simultaneously. Architecture is provisioned with "pay as you grow" network and easy up-gradation for the user. Users are categorized into two categories and provisioned with easy up-gradation. First is home-user similar to fiber to the home (FTTH) with peak data rate of 2.5 Gb/s and second user category is business-users with peak data rate of 10 Gb/s.

A major focus of our work is symmetrical data rate on each wavelength, support a large number of users with error-free performance, easy up-gradation of a network as well as ONU users. Bit error rate (BER) value less than 10^{-9} is considered as an error-free performance. The equal data rate on each upstream and downstream wavelength are called symmetrical data rate, and it is highly recommended for business users. Electrical delay modulation scheme described in [26] can be merged with the idea presented in the paper for future improvisation

The performance of the proposed architecture is analyzed in detail using time and frequency domain analyzer. Section 2 presents TWDM-PON architecture design and explanation of an optical TDM. Section 3 shows TWDM-PON simulated system design using Optisystem-13 and tabulates the simulation parameters and the corresponding possible hardware. Section 4 deals with a discussion on simulated results. Section 5 tabulates power budget calculation for downstream and upstream followed by conclusion in Section 6

2. TWDM-PON architecture

2.1. Downstream system design

Fig. 1 shows the architecture of TWDM-PON system. Wavelengths λ1 to λ8 are modulated at the peak data rate of 10 Gb/s using non-return to zero external modulation (NRZ-EM). Aggregate 80 Gb/s data is transmitted downstream using WDM multiplexer (WDM-MUX) which multiplexes eight downstream wavelengths. The amplifier at OLT plane strengthens multiplexed downstream optical signal against losses during fiber propagation and other passive component losses. Optical distributed network (ODN) consists of the bidirectional optical fiber and remote node (RN). 1:32 splitter is used at RN to split the signal equally to each output port.

Each user is connected to a single output port of the splitter. For initial inventory management, the 32 users are divided into four groups, each group of 8 ONU share one downstream wavelength from OLT. ONU-1 to ONU-8 share λ1, ONU-9 to ONU-16 share λ2, similarly ONU-25 to ONU-32 share λ4. Each ONU is equipped with a fixed optical filter and act as a home-user. Out of 32-users, only 16 users are upgraded to the business-user by applying an additional block of the tunable optical filter (TOF) at the receiver. ONU receiver block diagram for the home-user is shown in Fig. 2 (a) and business-user is shown in Fig. 2(b). TOF tune to single or multiple downstream wavelengths from λ5 to λ8. OLT-2 wavelengths serve only to business-user as a special connection so, ONU-17 to ONU-32 can further be tuned to any single or multiple downstream wavelengths from λ5 to λ8. At any point in time, a user can upgrade them to the high-end user.

2.2. Upstream system design

Each ONU modulates the 2.5 Gb/s upstream data on the dedicated upstream wavelength. Block diagram of delayed AM modula-

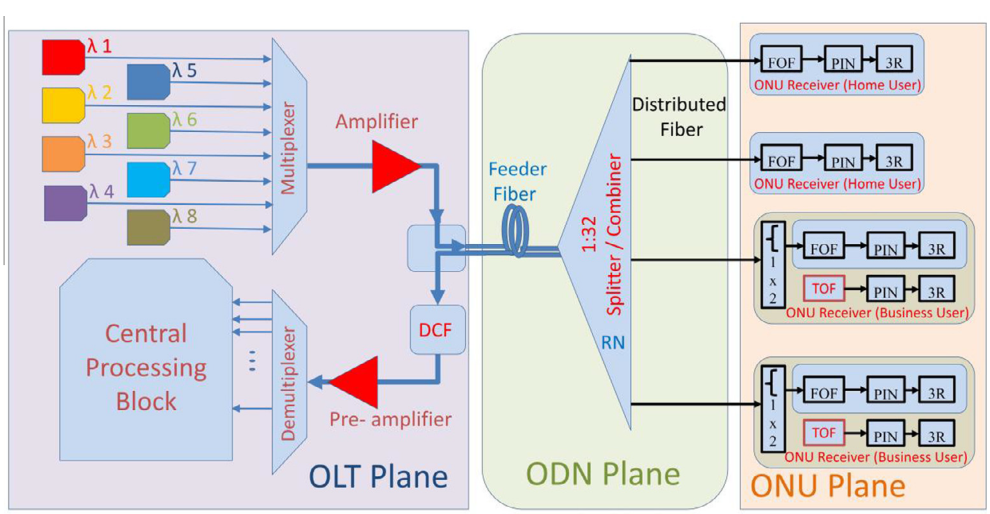

Fig. 1. Architecture of TWDM-PON system.

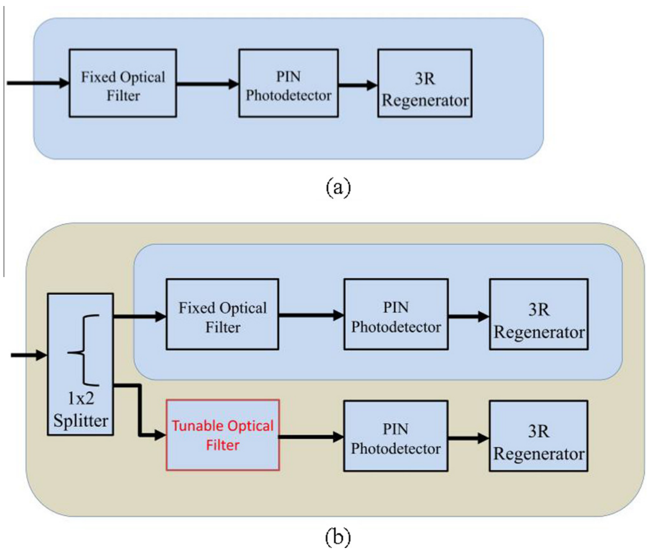

Fig. 2. Block diagram of ONU receiver for (a) Home user (b) Business user.

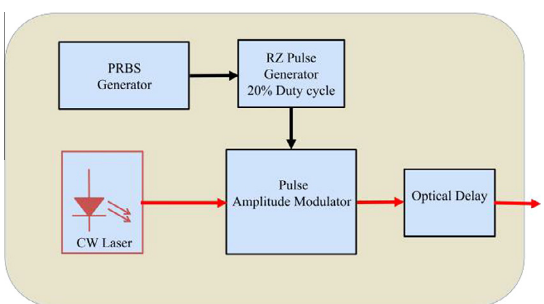

Fig. 3. Block diagram of ONU transmitter at 2.5 Gb/s.

tion is shown in Fig. 3. PRBS generates the train of a random bit sequence; pulse generator generates a return to zero (RZ) pulses with a duty cycle of 20%. AM is applied for continuous transmission of upstream wavelength followed by an optical delay. Four users transmit on the same wavelength at a data rate of 2.5 Gb/s and optically time division multiplexed by adjusting the optical delay at the modulator.

Assigning fixed optical delay on dedicated wavelength multiplexes four 2.5 Gb/s upstream user data to aggregated 10 Gb/s per wavelength (detail given in Section 2.2.1). Each upstream wavelengths are combined by the 32:1 combiner at RN and transported back to OLT through the bidirectional optical fiber. Dispersion compensating fiber (DCF) compensates the aggregated fiber dispersion and a pre-amplifier amplifies the received upstream signal at OLT. Conditioned received optical signal is demultiplexed using wavelength division multiplexed demultiplexer (WDM-DEMUX). Each demultiplexed wavelength is processed and detected independently and simultaneously by central processing block at the OLT.

2.2.1. Optical TDM using delayed AM

Fig. 4 shows the optical TDM with a time slot of four individual ONU. Each upstream wavelength is divided into four slots for each optical users with fixed optical delay. User-1 transmit their data without any delay (0 s), whereas user-2 transmits with a delay of 0.1 ns, user-3 with a delay of 0.2 ns and finally user-4 with a delayed of 0.3 ns. Due to fixed optical delay per user, individual data occupies the pre-assigned time slot as shown in Fig. 4. Hence,

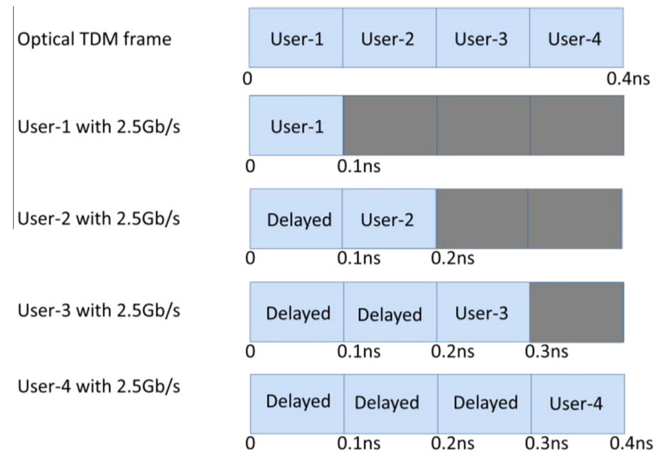

Fig. 4. Optical TDM timing diagram of a bit period with time slots.

four 2.5 Gb/s data stream are modulated on the same wavelength but with a different delay, which is optically combined as 10 Gb/s stream per wavelength.

At the receiver side, delayed amplitude demodulator demodulates each optical TDM timeslots. Demodulated optical signal is detected using APD diode and filtered using a Gaussian electrical filter. Instead of each ONU with 10 Gb/s laser transmitter module, each ONU with 2.5 Gb/s laser transmitter module and optical TDM is economic, which can utilize the existing transmitter infrastructures and delivers the 10 Gb/s per wavelength. Optical TDM fourtime increases the number of simultaneous users per wavelength when compared with conventional electrical TDM of 10 Gb/s. Each optical TDM users can work according to NG-PON2 recommendations. The four ONU clients of same upstream wavelength are separated at OLT.

Optical TDM based delayed AM signal are demodulated using AM demodulator. Equations for modulation and demodulation are explained below.

$$O_{OTDM}(T) = \sum_{X=0}^{3} (O_{out}(T) + \Delta T), \tag{1}$$

$$O_{out}(T) = O_{in}(T) \cdot \sqrt{1 + MI.(E_X(t) - 1)}, \tag{2}$$

$$\text{where } \Delta T = \sum_{t=0}^{T} t - (0.1X) \quad n\,\text{sec} \tag{3}$$

O_{OTDM}, O_{out} and O_{in} are the optical TDM, modulated optical output and input carrier laser signal respectively. *MI* is modulation index of the AM modulator, where *T* is bit period of upstream data rate and *X* refers to the fixed user number per wavelength which takes value from 0 to 3. ΔT refers to the fixed optical delay of the *X* user. Time delay ΔT is dependent on the fixed value of *X* and it takes discrete value 0 s, 0.1 ns, 0.2 ns, 0.3 ns delay for $X = 0, 1, 2, 3$ respectively. The upstream data signal is represented by $E_X(t)$ as RZ pulses with the duty cycle of 20% given by [14].

$$E1(t) = \begin{cases} 1 - e^{-(t/c_r)}, & 0 \leqslant t \leqslant t_r \\ 1, & t_r \leqslant t \leqslant t_0 \\ e^{-(t/c_f)}, & t_0 \leqslant t \leqslant t_f \\ 0, & t_f \leqslant t \leqslant T \end{cases}. \tag{4}$$

where t_r is rise time, t_0 is duty cycle period and t_f is fall time of RZ pulse with c_r and c_f as the coefficient of rise and fall respectively. $O_X(T)$ is de-multiplexed individual optical TDM user signal and is given by

$$O_X(t) = \sum_{X=0}^{3} O_{OTDM}(T) \cdot \sqrt{1 + MI.(E_X(T) - 1)}, \tag{5}$$

$$E_X(T) = E_{X,1}(t) + \Delta T, \tag{6}$$

$E_{X,1}(T)$ is electrical 1's of RZ pulses with the duty cycle of 25% to demodulate the received optical signal and extract the intended user information from the wavelength.

3. Simulated TWDM architecture

The simulated system architecture is shown in the Fig. 5, and simulation parameters are tabulated in Table 1. The continuous wave (CW) laser of frequency 187.1 THz (wavelength 1602.31 nm) is modulated with 10 Gb/s NRZ-PRBS bit sequences of order 7 using MZM with an extinction ratio of 10 dB. 10 Gb/s modulated eight downstream wavelengths are multiplexed by 8:1 MUX and fed to signal conditioning block where Erbium-doped fiber amplifier (EDFA) amplifies the signal by 20 dB with a noise figure of 4 dB. Signal is distributed to RN through bidirectional optical feeder fiber of length 40 Km. The RN is equipped with 1:32 power splitter and 32:1 combiner. Home-user and business-user ONU are fitted with a fixed optical filter, APD photodetector, and Gaussian electrical filter, in addition, business-user ONU is also equipped with tunable optical filter and detector unit.

The ONUs transmit 2.5 Gb/s RZ data signal as the modulating signal with 20% duty cycle modulates upstream CW laser using delayed AM with modulation index 1 and fixed discrete delay as per the user. All the upstream wavelengths are combined at RN using combiner and received at OLT through the bidirectional fiber of 40 Km. At OLT, received signal is compensated for aggregated fiber dispersion using DCF of negative dispersion value −667 ps/nm/Km. Compensated signal amplified by EDFA amplifier of gain 23 dBm. The conditioned optical signal is demultiplexed using WDM-DEMUX and each signal sent to central processing block for optical TDM demultiplexing, detection and analysis. Crosstalk penalty is accounted in the simulation by substituting practical parameter values of bandwidth, ripple, and depth of the WDM-Multiplexer, De-multiplexer and optical filter.

Simulation is carried out to analyze the performance of proposed TWDM-PON architecture. Downstream and upstream performance is analyzed for 3 cases each as described in Table 2. Downstream case-1 is configured with EDFA amplifier with a gain of 20 dBm and fixed laser power of 0 dBm at OLT. Downstream case-2 is configured as EDFA amplifier with a flat gain of 10 dBm and fixed laser power of 0 dBm. Downstream case-1 and case-2, is to identify the maximum increase in the number of users by compensating splitter loss with respect to the gain of EDFA amplifier. Downstream case-3 is without EDFA amplifier and with an increased laser power of 10 dBm each. To verify the downstream performance in the absence of EDFA amplifier and thereby save initial capital and operational investment as well as to compare type-A and type-B architecture of NG-PON-2. Downstream cases are analyzed by keeping the reach of the fiber constant at 40 Km and varying splitter value discretely for each case. Upstream case-1 is with 100 GHz uniform channel spacing with delayed AM, optical TDM of 10 Gb/s per wavelength. Upstream case-2 is with 100 GHz uniform channel spacing with conventional electrical TDM-PON of peak data rate 10 Gb/s per wavelength whereas case-3 is 100 GHz uniform spacing with conventional electrical TDM-PON of peak data rate 2.5 Gb/s per wavelength. Upstream case-1 and case-2 are simulated to identify the performance improvement of delayed AM modulation over conventional modulation for 8λ and 10 Gb/s each. The impact of optical TDM on the upstream performance of TWDM architecture is analyzed.

4. Results and discussion

Simulation is carried out as per the configuration listed in Table 2, to analyze the performance of the proposed eight wavelengths TWDM-PON system architecture and proposed optical TDM. The performance parameters are observed in terms of the minimum log of bit error rate (Log (BER)). An optical spectrum is analyzed to compare nonlinearities for different cases, and conclusions are drawn.

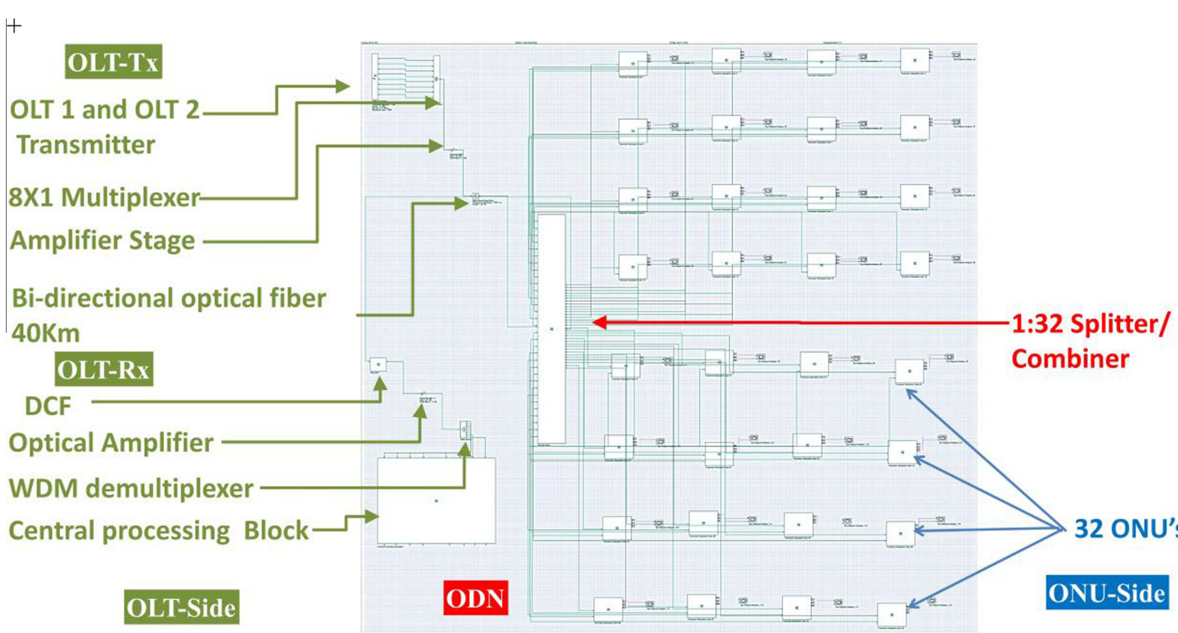

Fig. 5. TWDM-PON system architecture layout in OptiSystem.

Table 1
Simulation parameters based on market available network components.

Components name	Description	Component parameters	Parameter value	Unit	Numbers required in proposed prototype	Max power Loss of component (dB)
L-band Laser source	UC INSTRUMENTS CORP.GM82009L	Output Power	10	dBm	8	0.3
		Wavelength resolution	1.0	pm		
		Typical wavelength accuracy	<5	pm		
		Typical power stability	+/−0.1	dB		
		Relative intensity noise	<−135	dB		
MZM Modulator	Thor Lab LN81S-FC	Operating rage	1525–1605	Nm	40 (8 downstream and 32 upstream)	5.5
		PRBS optical extinction ratio	13	dB		
		Electro optic bandwidth	10	GHz		
		Optical insertion loss	5.0	dB		
		Optical return loss	40	dB		
		Output optical power monitoring range	−5 to 10	dBm		
PRBS + Pulse Generator	Key sight N4970A	Operating range	0.05 to 12.5	Gb/s	40 (8 downstream and 32 upstream)	0
		Output pattern	2^7-1, 2^{10}-1, 2^{15}-1, 2^{23}-1, 2^{31}-1			
		Rise/Fall times	~25	ps		
		Jitter	~1	ps		
8X1 Multiplexer	8MDD-1RU-1-FSDWDM	Wavelength Range = ITU channels	186.6 to 196.1	THz	1	2.95
		Channel spacing	100, 200	GHz		
		Adjacent channel isolation	>30	dB		
		Non-adjacent channel isolation	>45	dB		
		Return loss	>45	dB		
		Optical power <500 mW	<27	dBm		
		Insertion loss	<2.8	dB		
L band amplifier	OPT-AMP-L	Operating Wavelength	1570 to 1605	nm	1	0
		Input power range	−15 to 8	dBm		
		Output power resolution	0.1	dB		
		Standard gain range (0 dB gain tilt) is	12 to 24	dB		
Bidirectional Optical fiber	2 Fiber SM LSZH-FTTH Drop Cable GJXFH-2KL	Attenuation	<0.22	dB/Km	40 Km X 1	0.22/Km
		Dispersion	16.75	ps/nm/Km		
		Dispersion slop	0.075	ps/nm^2/Km		
Passive Splitter and Combiner	PLC SPLITTER PLC-L-1X32	Insertion loss	17.3	dB	2	20.4
		Return loss	50	dB		
		Wavelength dependent loss	0.5	dB		
Tunable optical filter	OPTOPLEX TOF TF-1000	Wavelength range	1567 to 1603	nm	16	5.5
		Tuning resolution or ITU grid	10	pm		
		Peak insertion loss	3	dB		
Fixed optical filter	ABS Box Simplex Shenzhen	Channel Spacing	100	GHz	32	1.7
		Centre wavelength accuracy	0.05	nm		
		Max. Insertion loss	3	dB		
		Adjacent channel isolation	25	dB		
Photo diode	GCS, LLC InGaAs PD P/N: DO262_45um_E1	Bandwidth	10	GHz	48	1
		Capacitance	0.13	pF		
		Responsivity	0.90	A/W		
		Dark current	5	nA		

Table 2
TWDM-PON system architecture configurations.

Downstream		Upstream	
Case-1	Laser power of 0 dBm, EDFA amplifier Gain of 20 dB	Case-1	Optical TDM of 10 Gb/s per wavelength using Delayed AM
Case-2	Laser power of 0 dBm, EDFA amplifier Gain of 10 dB	Case-2	Electrical TDM of 10 Gb/s per wavelength using conventional NRZ-EM
Case-3	High power laser 10dBm, No Amplifier	Case-3	Electrical TDM of 2.5 Gb/s per wavelength usind conventional NRZ-EM

4.1. Upstream case analysis

The idea of delayed AM modulator and optical TDM is simulated as discussed in Section 2. Individual ONUs modulated at 2.5 Gb/s and the optical bitstream is shown in Fig. 6(a)–(d) for ONU-1 to ONU-4 respectively with each at channel 196.4 THz. Fig. 6(e) shows the aggregated 10 Gb/s optical TDM multiplexed data of four 2.5 Gb/s ONUs stream at channel 196.4 THz. It is clearly observed from Fig. 6 that each ONU data occupies predefined timeslot without any interference with the neighboring ONUs timeslot.

Since timeslots of each user is fixed, and delay value is predefined for each user, varying transmitter delay is not an option but if fixed transmitted signal delay is varied then it distort the transmitted signal to such a degree that signal integrity is severely impaired and system performance deter significantly due to crosstalk.

At the OLT, central processing block demultiplexes and demodulates the optical TDM. Fig. 7 shows the time domain

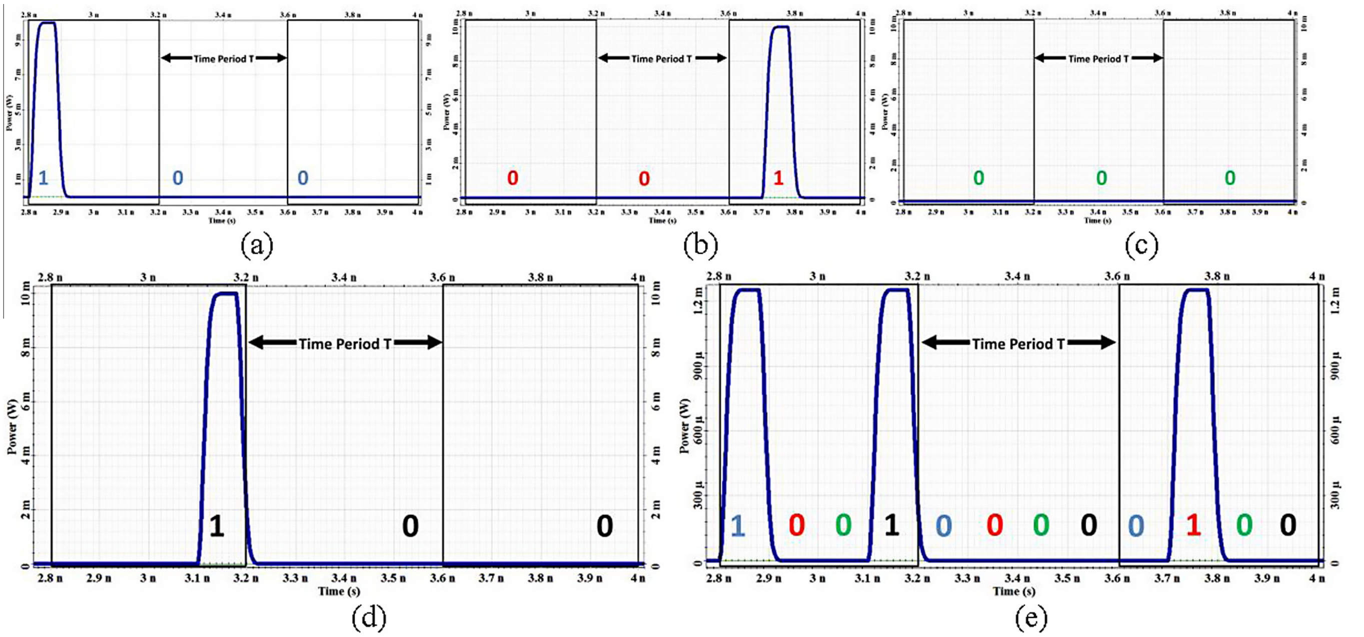

Fig. 6. Transmitted upstream signal as visualized in optical time domain analyzer (a) ONU-1, (b) ONU-2, (c) ONU-3, (d) ONU-4, (e) optical TDM at channel 196.4 THz (1526.44 nm).

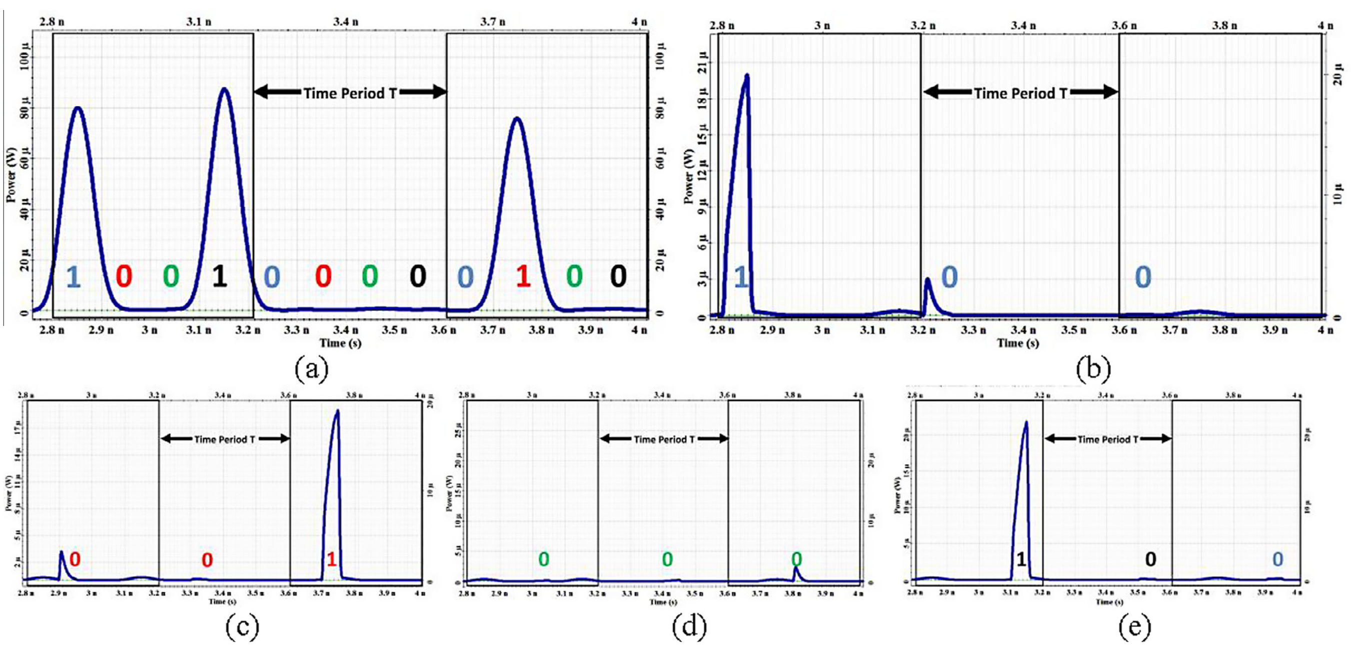

Fig. 7. Received upstream signal as visualized in optical time domain analyzer at OLT for (a) Channel 196.4 THz (1526.44 nm), (b) ONU-1, (c) ONU-2, (d) ONU-3, (e) ONU-4.

waveform of the demultiplexed channel 196.4 THz, Fig. 7(a) shows the WDM-demultiplexed optical signal at channel 196.4 THz in the time domain and Fig. 7(b) to (e) shows the Optical TDM-demultiplexed signal of ONU-1, to ONU-4 respectively. After Optical TDM-demultiplexing, the 2.5 Gb/s signal of each ONU is detected at OLT central processing block.

Central processing block first splits the incoming wavelength using 1:4 splitter. Each of the four stream is optical time demodulated by delayed electrical RZ pulses. Received single optical wavelength contains four optical TDM signal, hence first user signal is detected by demodulating the received signal with appropriate 25% duty cycled series of electrical 1's at the rate of 2.5 Gb/s. Second user is detected by demodulating the received signal with 25% duty cycle series of electrical 1's at the rate of 2.5 Gb/s, but here electrical series of 1's are delayed by 0.1 ns. Similarly third and fourth users are demodulated by delaying electrical 1's by 0.2 ns and 0.3 ns respectively.

Upstream performance is analyzed in terms of Log (BER) vs. the received optical power as shown in the Fig. 8 for three cases given in Table 2. It is observed from Fig. 8 that case-1 configuration outperforms case-2 and case-3 configuration in terms of performance parameters. It is observed that case-1 performs 4 dB and 2 dB better than case-2 and case-3 regarding receiver sensitivity respectively.

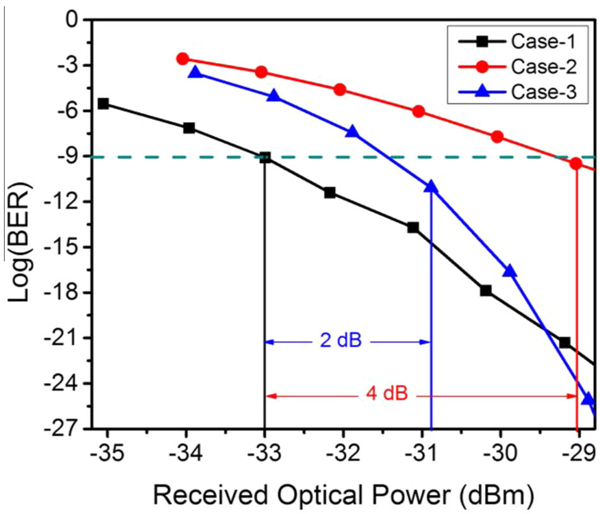

Fig. 8. Log(BER) vs received optical power(dBm) at 196.4 THz for 10 Gb/s optical TWDM upstream transmission in black-square, in red-circle conventional 10 Gb/s TWDM upstream transmission and blue-triangle are 2.5 Gb/s TWDM upstream transmission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The eye diagram of case-1 configuration at 196.4 THz is observed in Fig. 9, when received optical power is attenuated to −30 dBm. Based on the time period assigned, the eye pattern for ONU-1 to ONU-4 are shifted in the time domain, and their respective values of BER and Q-Factor are tabulated in Table 3. From the Table 3, it is clear that ONU-1 to ONU-4 performs equally well and error free.

As we know the system is designed and meant for distribution of broadband signal to multiple users, one of the critical study is to include varying fiber length. To identify the effect of varying length the following analysis are carried out. Feeder fiber length (that is from OLT to RN) is kept fixed at 40 Km and distributed fiber length (that is from RN to ONU) is varied and effect on upstream performance is observed for different scenarios.

Scenario-1 Four ONUs utilizing same wavelength λ1 is fed to distributed fiber, which is terminated at the RN. At RN, λ1 is combined with λ2 to λ8 and sent to OLT through feeder fiber of length 40 Km. Performance of the upstream system with respect to different distribution fiber reach is evaluated as shown in the Fig. 10, scenario -1. It is inferred from the Fig. 10 that maximum reach of distribution fiber for individual wavelength and individual ONU is 25 Km.

Scenario-2 Two wavelengths (two set of four ONUs utilizing same wavelength) λ1 and λ2 are combined together near ONU and the combined signal is sent through single distributed fiber to RN. At RN, λ1and λ2 combined with λ3 to λ8 and sent to OLT through feeder fiber of length 40 Km. Performance of the upstream system with respect to different distribution fiber reach is evaluated as shown in the Fig. 10, scenario-2.

Scenario-3 Four wavelengths λ1 to λ4 which are combined together near ONU and sent through single distributed fiber to RN. At RN, previously combined signal (λ1 to λ4) is combined with λ5 to λ8 and sent to OLT through feeder fiber of length 40 Km. Performance of the upstream system with respect to different distribution fiber reach is evaluated as shown in the Fig. 10, scenario-3.

It is clearly observed from Fig. 10 that as number of simultaneous wavelength increases the distributed fiber reach decreases abruptly.

4.2. Downstream analysis

The multiplexed downstream optical spectrum is analyzed as shown in Fig. 11, Fig. 12 and Fig. 13 for downstream case-1, case-2, and case-3 respectively. Sub-section (a) of Fig. 11, Fig. 12 and Fig. 13 show the multiplexed downstream optical spectrum at the input of feeder fiber. Sub-section (b) of Fig. 11, Fig. 12 and

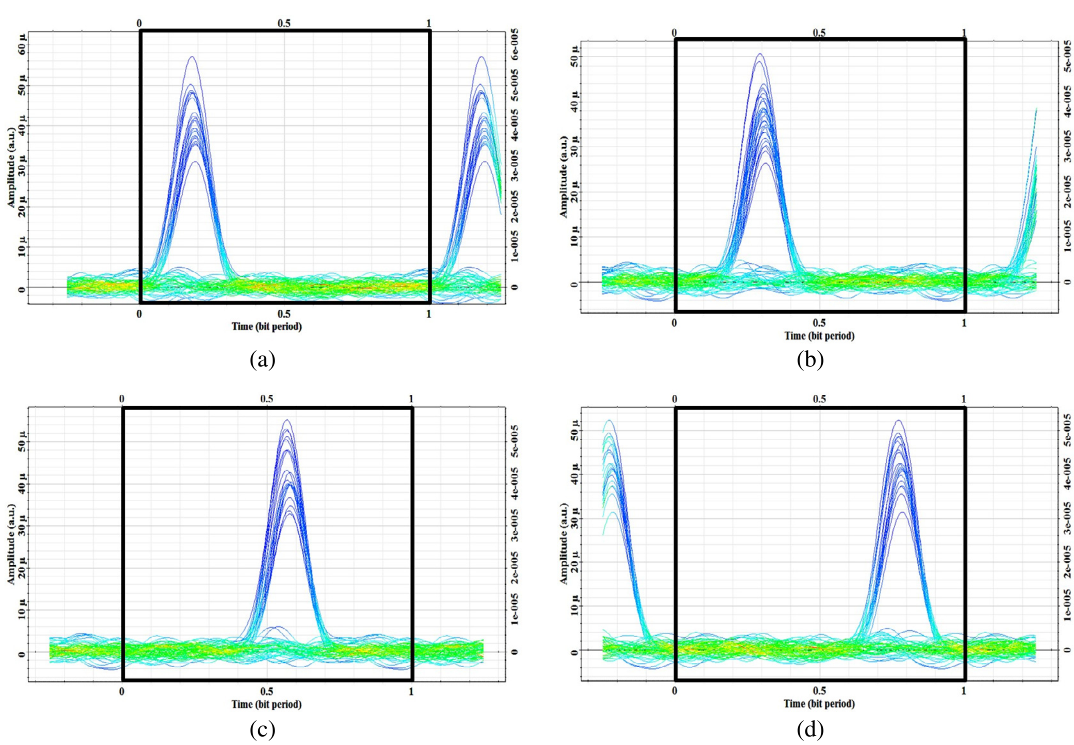

Fig. 9. Eye diagrams of case-1 upstream at operating at 196.4 THz (a) ONU-1, (b) ONU-2, (c) ONU-3, (d) ONU-4.

Table 3
Upstream performance parameters at channel 196.4 THz.

Parameters	ONU-1	ONU-2	ONU-3	ONU-4
Max. Q Factor	8.70324	7.98142	6.85047	11.3262
Min. Log(BER)	−17.8778	−15.2503	−11.5945	−29.4799

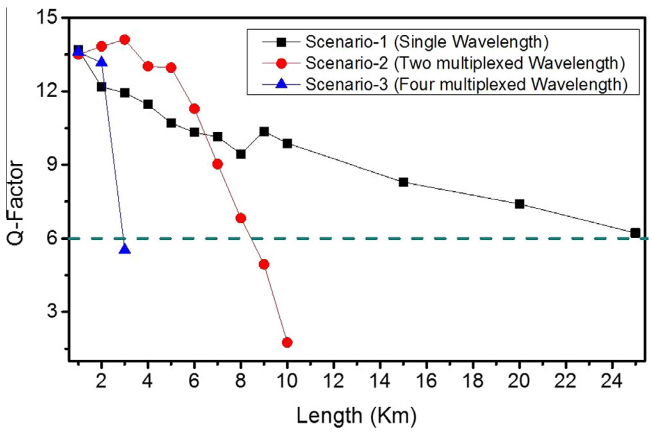

Fig. 10. Upstream distributed fiber reach analysis, Scenario-1 Single wavelength, Scenario-2 Two wavelength multiplexed, Scenario-3 Four wavelength multiplexed.

Fig. 13 show the downstream optical spectrum after 40 Km fiber reach.

It is observed from Fig. 13(a) that peak power of each downstream laser are above 10 dBm. It is observed from Fig. 11(a) and Fig. 12(a) that peak in both cases are above 0 dBm but multiplexed spectrum of Fig. 12(a) is spread and the magnitude of peaks are varying with respect to adjacent one due to L-band EDFA amplifier characteristics. In case-1, aggregated 23.2 dBm power is launched into the fiber and received 14.4 dBm at the output of 40 Km fiber. In case-2, aggregated 13.3 dBm power is launched into the fiber and at the output of 40 Km fiber power received is 4.4 dBm. Similarly in case-3, aggregated 12.2 dBm power launched into the fiber and at an output of fiber 3.4 dBm received.

The bidirectional optical fiber is a single-mode fiber. The dispersive effect, Kerr nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman (SRS) and Brillouin (SBS) scattering effects of bidirectional fiber are enabled during simulation. It is inferred from the Fig. 11(b), Fig. 12(b) and Fig. 13(b) that as the optical launch power increases nonlinearities in the propagation of fiber increases. The degree of nonlinearities observed is high in Fig. 11(b), moderate in Fig. 12 (b) and least in Fig. 13(b). Hence, in the Fig. 11(b) side lobes are clearly visible with peak power of −40 dBm, in Fig. 12(b) side lobes with weak peak power of −60 dBm and almost negligible sidelobes power of −80 dBm are witnessed in the Fig. 13(b). It is also observed from Fig. 12(b) and Fig. 13(b) that fiber nonlinearities not only depend on the launch power at the input but also dependent on the amplified spontaneous emission (ASE) noise of EDFA

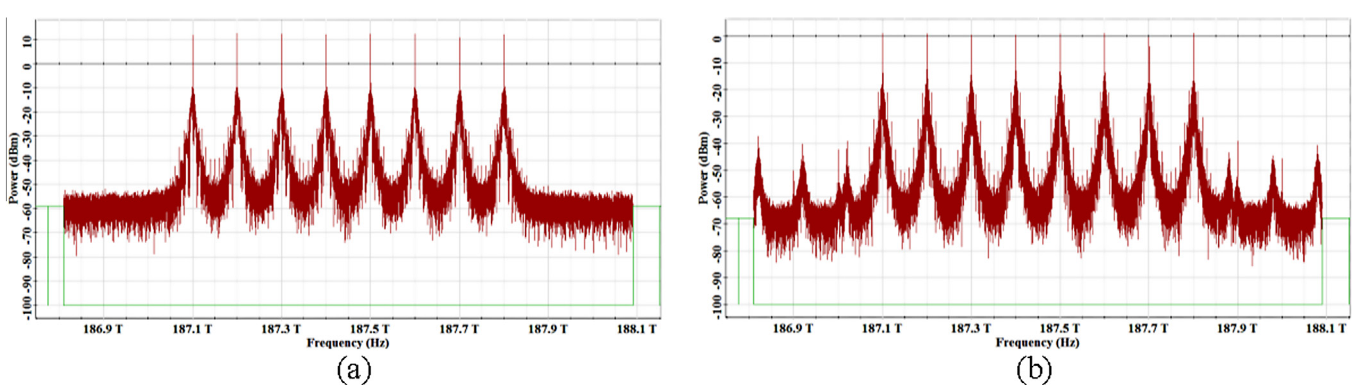

Fig. 11. Downstream case-1 (a) Multiplexed optical spectrum at output of OLT (b) Optical spectrum after 40 Km fiber reach.

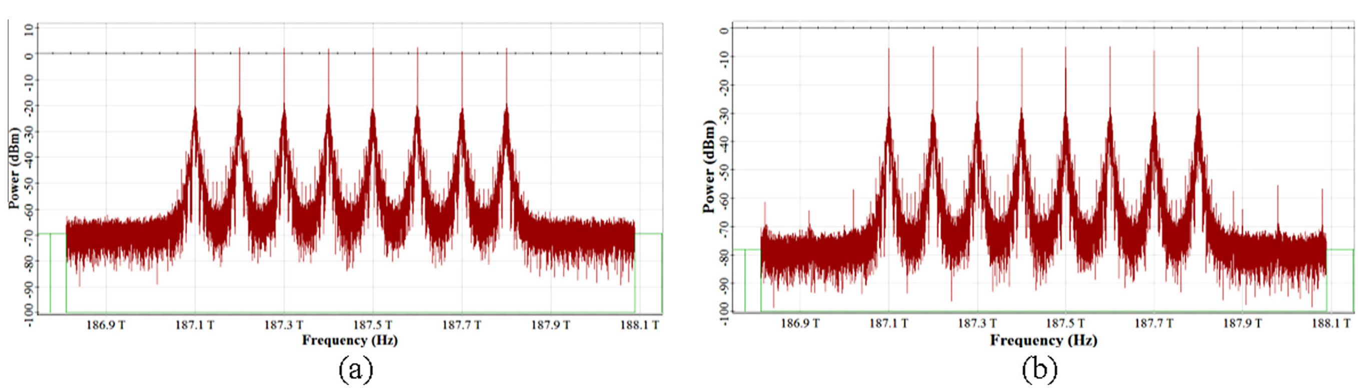

Fig. 12. Downstream case-2 (a) Multiplexed optical spectrum at output of OLT (b) Optical spectrum after 40 Km fiber reach.

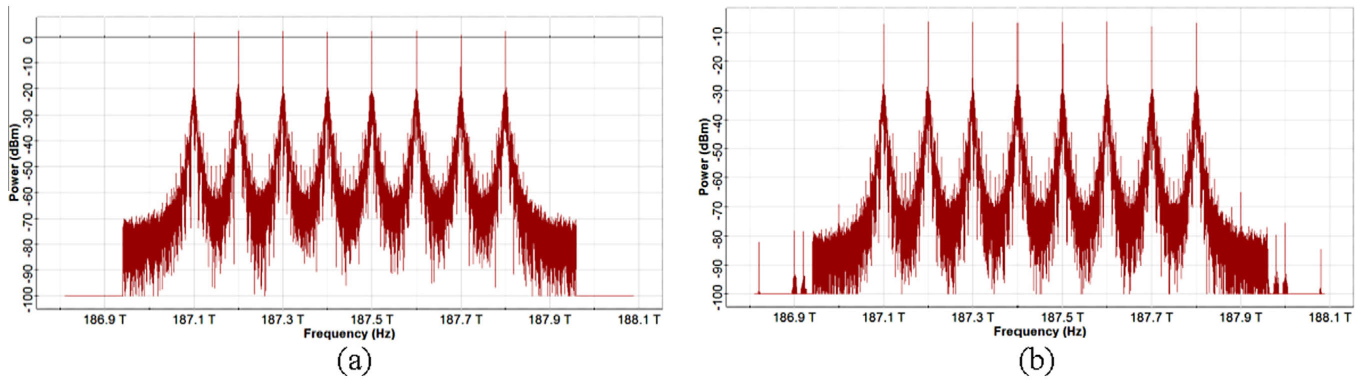

Fig. 13. Downstream case-3 (a) Multiplexed optical spectrum at output of OLT (b) Optical spectrum after 40 Km fiber reach.

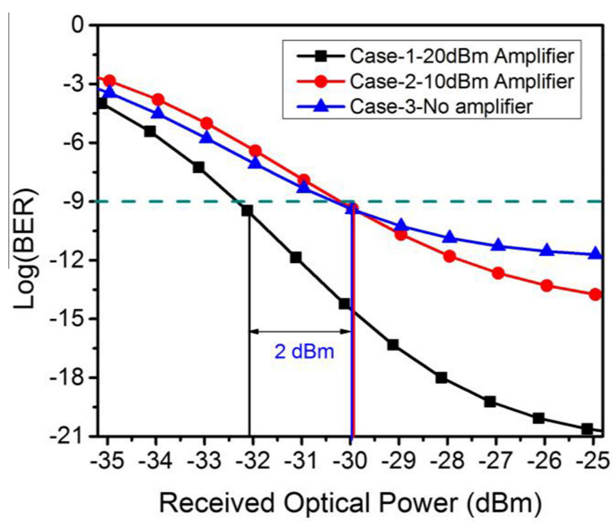

Fig. 14. BER vs received optical power for case-1, case-2 and case-3 in downstream transmission at187.1 THz.

Fig. 14 shows the downstream performance plot, the Log (BER) versus ONU received optical power. The downstream performance plot of the 187.1 THz channel for case-1, case-2 and case-3 is observed from Fig. 14. For case-1, the receiver sensitivity is ∼−32 dBm, which is ∼2 dB better that case-2 and case-3. Receiver sensitivity of case-2 and case-3 is ∼−30.1 dBm. It is also seen from the Fig. 14 that performance of case-2 and case-3 are comparable only up to error free threshold point after that Log (BER) difference increases for received optical power from −30 dBm to − 25dBm. Hence, it concluded that, despite high nonlinearity observed in Fig. 11 and Fig. 12, for case-1 and case-2 during fiber propagation, receiver sensitivity is improved as shown in Fig. 14, due to high signal to noise ratio at the receiver.

Table 4
Downstream performance parameters at 187.1 THz.

Parameters	Case-1	Case-2	Case-3
Max. Q Factor	7.4881	6.12781	6.14765
Min. Log(BER)	−14.228	−9.35894	−9.41582

For all three downstream cases received optical power reduced to −30 dBm using a variable attenuator and eye diagram for downstream channel 187.1 THz is shown in Fig. 15, respective values of log(BER) and Q-Factor are tabulated in Table 4.

Case-1 Architecture is preferred while deploying NG-PON-2 architecture over other two cases due to following reasons. An initial investment of eight high power lasers is as equal as eight conventional lasers and EDFA. Again as shown in case-2, installing small gain EDFA and then in future upgrade it to high power EDFA can be preferred to save initial capital and operational expenditure.

5. Power budget

Budget analysis for downstream and upstream are tabulated in Table 5 and Table 6 respectively for simulated environments shown in Table 2. Power margin depends on the transmitted power, the receiver sensitivity, and loss budget. Passive and active losses in the TWDM-PON architecture are summarized as a loss budget. The passive loss includes the connector loss, fiber loss, splice loss and couplers or splitters in the link. Active components losses are WDM-MUX, WDM-DEMUX, modulator power loss.

$$L_T = \alpha.L + L_C + L_S \tag{7}$$

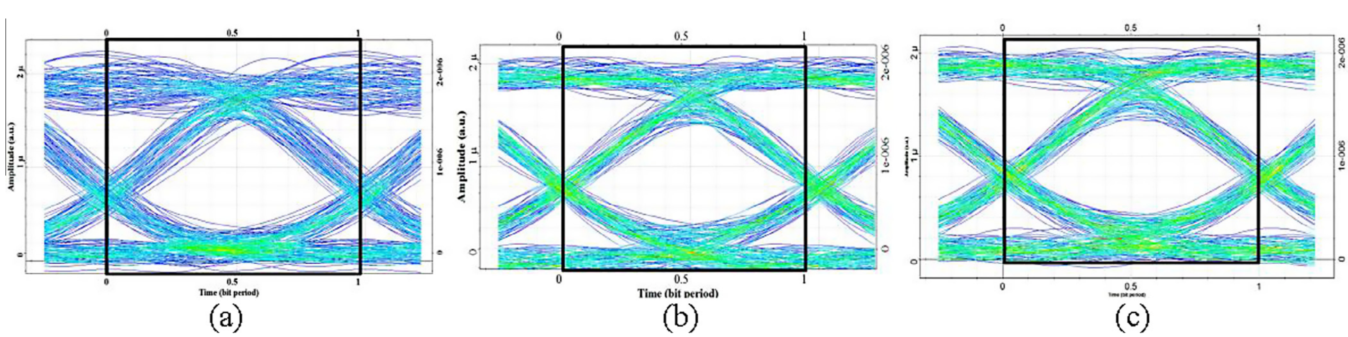

Fig. 15. Eye diagram of downstream transmission at operating wavelength of 1602.31 nm (187.1 THz) (a) Case-1, (b) Case-2, (c) Case-3.

Table 5
Downstream power budget.

Power budget	Downstream								
	Case-1 Receiver sensitivity is −32 dBm			Case-2 Receiver sensitivity is −30 dBm			Case-3 Receiver sensitivity is −30 dBm		
Business users	Loss budget (dB)	Received optical power (dB)	Power margin (dB)	Loss BUDGET (dB)	Received optical power (dB)	Power margin (dB)	Loss budget (dB)	Received optical power (dB)	Power margin (dB)
32 Users (1:64 Splitter)	−38	−18	14	−38	−27	3	−38	−28	2
64 Users (1:128 Splitter)	−42	−22	10	−42	−30	0	−42	−31	NA
128 Users (1:256 Splitter)	−44	−24	8	−44	−34	NA	−44	−34	NA
512 Users (1:1024 Splitter)	−50	−30	2	−50	−40	NA	−50	−40	NA

NA, Not Applicable (Since received optical power is less than the receiver sensitivity).

Table 6
Upstream power budget.

Power budget analysis for 8 wavelength upstream								
Case-1 (Delayed AM) 100 GHz spacing 10 Gb/s per wavelength			Case-2 (NRZ-EM) 100 GHz spacing 10 Gb/s per wavelength			Case-3 (NRZ-EM) 100 GHz spacing 2.5 Gb/s per wavelength		
ODN loss (dB)	Received optical power after processing (dB)	Power margin (dB)	ODN loss (dB)	Received optical power after processing (dB)	Power margin (dB)	ODN loss (dB)	Received optical power after processing (dB)	Power margin (dB)
−17	−24	8	−17	−11	17	−17	−11	19

L_T – Total loss (dB)
α – Fiber attenuation (dB/Km)
L – Length of fiber (Km)
L_c – Connector loss (dB)
L_s – Splice loss & Splitter loss (dB)

Table 5 shows the downstream power budget analysis for all 3 cases; loss budget is nothing but total loss in the system. Power margin is the difference between receiver sensitivity and received optical power at the APD photodetector. Receiver sensitivity of the downstream cases are referred from Fig. 10 plots as −32 dBm for case-1 and −30 dBm for case-2 and case-3. It is observed from the Table 5 that case-3 supports, 32 business-users with 2 dB power margin. case-2 supports 64 business-users or 128 home-users ONUs efficiently due to power budget constraint. Case-1 is the optimal solution to serve maximum 512 business-user ONUs users and maximum 1024 home-users ONUs with power margin of 2 dB. Case-2 and case-3 configuration do not support large splitting ratio due to its power budget constraints.

The upstream transmission includes the optical signal processing at the OLT hence for better system analysis; losses are divided into two. First optical losses from ONU to OLT as distributed network loss and second as optical losses during optical signal processing. For the scenarios considered in the upstream case-1, optical losses due to change in link length can be compensated by pre-amplifier of 23 dB at OLT. Since optical signal processing uses regenerator and amplifiers, which do not have PON restriction, as it is placed at the OLT side. Hence, the losses due to optical signal processing are depicted in Table 6 as received optical power after processing.

It is evident from Table 6 that as the number of wavelengths increases received optical power after optical signal processing decreases whereas the distributed network loss remains constant. Both cases perform the error-free operation, but case-1 gains the advantage of optically combining four 2.5 Gb/s/user into 10 Gb/s/wavelength using delayed AM modulation.

6. Conclusion

TWDM-PON architecture simulated with 8λ, to provide 80 Gb/s aggregate downstream data rate with a reach of 40 Km. Three downstream configurations are analyzed in detail and it found that to save initial capital and operational expenses, the low gain amplifier must be preferred over eight high power lasers. Low gain amplifier configuration (case-2) performs better than the high power laser source (case-3) at higher receiver optical signal powers. Case-3 performs error-free, up to 64 splitting points using 1:64 splitters, with Log(BER) of -9.415 and power margin of 2 dB. Case-2 performs error-free up to 128 splitting points with Log (BER) of -9.359. Case-1 supports up to 1024 splitting points with Log(BER) of -14.22 and power margin of 2 dB. L-band wavelengths are used as per the NGPON-2 ITU-T grid, which gives the advantage to future proof architecture design and does not get obsolete prematurely. The architecture provides various options to the user, to up-gradate from home user to business user by adding a block of the variable optical filter in ONU. The number of simultaneous users in proposed network is increased fourfold by optical TDM as compared with the conventional TWDM-PON network. Upstream 10 Gb/s performs error-free up to eight channels. Optical TDM open new paradigm to work on existing, inexpensive 2.5 Gb/s laser components, and 10 Gb/s/wavelength is enabled by Optical TDM of four 2.5 Gb/s/user using delayed AM. Optical TWDM using delayed optical AM modulation, improves the receiver performance of the system architecture up to 4 dB and 2 dB when compared with conventional 10 Gb/s TWDM and 2.5 Gb/s TWDM configuration with 8λ. Delayed AM shift complexity of 10 Gb/s ONU transmitter module toward OLT-side hence, ONU becomes simple. The power consumption due to electrical signal processing is reduced at the expense of optical signal processing at the OLT. Optical signal processing is complex and expensive but required only at OLT side. Fourfold increased user profit can keep up the central office capital expense since OLT and ODN operational cost are shared among ONUs. Since upstream network distributed loss is 17 dB, the reach of the fiber may be extended for future network expansion. It is found that upstream single wavelength can serve up to distributed fiber reach of 25 Km and it decreases to 8 Km and 2 Km for two and four number of wavelength multiplexed respectively.

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