Power budget calculations of high-speed TWDM based next-generation passive optical network for different data types

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The symmetric 80 Gbps TWDM –PON is tested for non-return to zero (NRZ), return to zero (RZ), carrier suppressed return to zero (CSRZ), and duobinary modulation formats for PIN and Avalanche photodiodes (APD). To improve the power budget the distributed RAMAN amplification provides gain. The proposed 80 Gbps TWDM PON system supports a reach of 20km fiber with a 44.5dB power budget for duobinary modulation format and APD photodiode receiver utilizing forward error correction (FEC) and 40.5 dB without FEC. The system serves 1024 optical network units (ONUs) in compliance with the international telecommunication union-telecommunication (ITU-T) recommendation G.989.2.

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1. Introduction

The PON standards established by ITU are broadband passive optical network (BPON), gigabit passive optical network (GPON), a 10-gigabit-capable passive optical network (XG-PON) and NGPON2 [1, 2]. According to ITU-T G989.2 recommendation, the TWDM will be the access technique of NG-PON2 [3]. In TWDM access technology, each group of ONUs shares a single wavelength. Also, according to Full Service Access Network (FSAN) and ITU-T, N111G-PON1 (XG-PON) is a midterm upgrade to GPON without affecting the infrastructure, whereas NG-PON2 would be a long-term solution [4]. According to ITU-T standards, NG-PON2 technology should outperform NGPON1 in terms of an optical distribution network (ODN) compatibility, bandwidth, capacity, and cost-effectiveness [1]. The primary obstruction in the path of development of TWDM based NG-PON is the up-gradation cost involved. The cost of TWDM-PON depends on the power budget of the system, and it reduces to a large extent by just improving the power budget [5]. The selection of modulation format and photodiode is crucial for high data rate capable PON without sacrificing a large split ratio. With the improvement in the power budget, the system can handle more ONUs. Thus, the overall cost per ONU decreases. Table 1 lists the recent experimental/simulative demonstrations with respective modulation format, data rate, reach length, number of ONUs, and presented power budget. Lilinin et al. presented TWDM-PON having multiple wavelengths for upstream and also assessed the system feasibility for burst mode transmitters. Authors have reported acceptable performance using tunable optical filter (TOF) based directly modulated laser (DML), ring laser, and reflective semiconductor optical amplifier (RSOA). Dynamic bandwidth allocation to users is the main attraction of this paper. With this approach, they achieved 1.25 Gbps per wavelength for upstream and 10 Gbps for downstream transmission over 25 km single-mode fiber (SMF) [6]. Zhengxuan et al. presented a very simple TWDM PON. To implement the TWDM concept, they used a 1×N splitter to filter out the intended signal for each ONU. For a 1.25 Gbps upstream data rate, they report a stable working for upstream laser whose wavelength can be tuned in the range 1535 nm-1565 nm [7].

Table 1. Recent TWDM demonstrations

Ref.	Format	Data Rate (Gbps)	L (km)	ONUs	Power budget (dB)
[6]	NRZ	10/1.25	25	32	18.7
[7]	NRZ	10/2.5	25	32	17
[8]	NRZ	80/10	25	32	16
[9]	NRZ	40/40	25	256	31
[10]	NRZ	40/10	20	512	38
[11]	NRZ	40/40	50	256	38
[12]	NRZ	40/40	25	100	39
[13]	NRZ	40/40	100	64	43
[14]	NRZ	40/40	40	200	51
[15]	NRZ	40/40	100	512	53
[16]	Duobinary	40/10	40	64	31
[17]	NRZ	100	40	128	36
[18]	NRZ	80/80	42	256	-
[19]	NRZ-OOK+APD	40	140	512	56.6

Lilnin et al. proposed a stacking approach for compatibility of WDM and TDM and tested system for eight wavelengths with a 1×32 split ratio. They designed the system using RSOA and TOF. The reported system capacity of the proposed method in 25 km long fiber was 8 ×10Gbps for downstream and 8 ×1.25 Gbps for upstream [8]. Zhengxuan Li et al. used TOF at each ONU for selecting signals intended for the downstream. With this approach, DML upstream chirp was managed to a large extent, which resulted in power budget improvement. The proposed 40Gbps TWDM PON system supports a reach of 25 km with a 256 splitting ratio having a power budget of 31dB for NRZ modulation [9]. Yuanqiu Luo et al. presented TWDM PON working at 40Gbps/10Gbps data rate for downstream/upstream, the system works well up to 20 km fiber length for 1x512 split, and the system power budget obtained was 40 dB for downstream and 38 dB for upstream [10]. Meihua Bi et al. presented the use of delay interferometer (DI) at ONU for the implementation of DPSK demodulation. This technique is useful for managing upstream DML signal chirp. A system achieves a power budget of 38 dB for 50 km fiber length. With the presented method, 11 dB power budget improvement was reported [11]. Lilin et al. showed a technique of power budget improvement to 39dB for 40 Gbps TWDM PON for 25 km fiber length with the use of a chirp management filter at the optical line terminal (OLT) instead of ONU. Upstream data was transferring using DML, which were tuned thermally for intended wavelengths. By using the preamplifier stage of RSOA, the receiver sensitivity enhancement of 12 dB was reported [12]. Meihua et al. experimentally extended the power budget of a system supporting 64 ONUs for both downstream and upstream signals to 43.2 dB for 100 km fiber length with the help of DML and DI at the OLT. Maximum reach of 50 km, 75 km, and 100 km with the presented power budget of 1024, 256 and 64 split, respectively, was achieved for the BER level of 10×10^{-3} [13]. Zhengxuan Li et al. evaluated a 51 dB power budget for a 40 Gbps symmetric PON using a semiconductor optical amplifier (SOA) in a system supporting 2000 ONUs reaching 40 km. They used RSOA as a downstream preamplifier as well as an upstream booster, the binary phase-shift keying (BPSK) modulation format overcomes the pattern effect of RSOA [14]. Zhengxuan Li et al. presented a power budget of 53 dB for a symmetric 40 Gbps TWDM-PON with the use of DI and optical amplifiers (Erbium-doped fiber amplifier (EDFA), Raman amplifier). The system could support 1024 ONUs for 100 km without repeater [15]. Zhengxuan Li et al. reported a 40 km reach for 28 Gbps signal with a 31dB power budget supporting 64 users, DI with duobinary modulation format was used to compensate dispersion effect [16]. Zhengxuan Li et al. presented a transmission of 25 Gbps/channel for the realization of 100 Gbps system, they insisted on chirp management and dispersion compensation in the optical domain rather than digital signal processing (DSP). They implemented non return to zero on-off keying (NRZ-OOK), pulse amplitude modulation (PAM-4), and duobinary. They conclude that for the 100 Gbps system, NRZ format provides superior performance in terms of launch power and receiver sensitivity [17]. Patrick Iannone et al. presented an 8×10 Gbps bidirectional TWDM-PON system. They achieved 42km reach with 1:256 split, and improved power budget using distributed RAMAN amplification. The system deploys remote intelligent splitter module (ISM) performing protection switching and to shut down the rogue ONUs [18]. B. Salem proposed the use of DCF in OLT with 10 Gb/s NRZ DMLs to improve the power budget of a symmetric 40 Gb/s TWDM-PON system. A power budget of 56.6dB for 140 km SMF length supporting 512 users was evaluated [19].

From the literature, we observe that researchers carried out a sufficient power budget analysis for NG-PON as listed in Table 1, But 80Gbps TWDM system lacks such analysis. Also, choosing a modulation format and a photodiode are crucial considerations while designing the NG-PON system. For different modulation formats, receiver sensitivity would vary because of their different responses to dispersion, non-linearity effects, etc. Similarly, choosing a photodiode at the receiver side is also an important task. Although the advanced modulation formats such as QAM, QPSK, DPSK, hybrid modulation could be considered, we have discussed the modulation formats that can be detected by directed detections to keep NGPON receiver design as simple as possible. APD is known for better receiver sensitivity because of current multiplication, but PIN photodiode has a lesser noise level and higher bandwidth, so there is a need to analyze the system for choosing a suitable photodiode. Receiver sensitivity for different modulation formats would be different, and hence power budget is needed to be evaluated for each modulation format. In this work, we investigated the performance of symmetric 80 Gb/s, high split TWDM PON for NRZ, RZ, CSRZ, and duobinary modulation formats. This paper organization is as follows: section 1.2 describes the system architecture, in section 1.3 power budget is calculated from results; we have concluded the findings in section 1.4.

2. Symmetric 80 Gb/s, high-split TWDM PON architecture

As per ITU-T recommendation G.9089.2, TWDM architecture is most suitable for the NG-PON, Fig. 1 shows the TWDM PON. The presented system is symmetric, i.e., the transmitted data rate is 80Gbps for both upstream and downstream transmissions. For downstream transmission, eight stacked transmitters are assigned with wavelengths starting from 1596 nm with an incremental spacing of 0.8 nm. Each downstream transmitter transmits a 10 Gbps data rate. All these wavelengths are multiplexed and transmitted simultaneously over single-mode fiber (SMF). In the remote node (RN), all eight wavelengths are de-multiplexed by an array waveguide grating (AWG). Each wavelength is split into 128 parts using a 1×128 power splitter after AWG, and then each split part is sent to a respective ONU. Distributed Raman amplification provides the gain to downstream signals, the transmission fiber itself acts as a Raman amplification media, and the pump wavelength of 1535 nm interacts with the downstream signals.

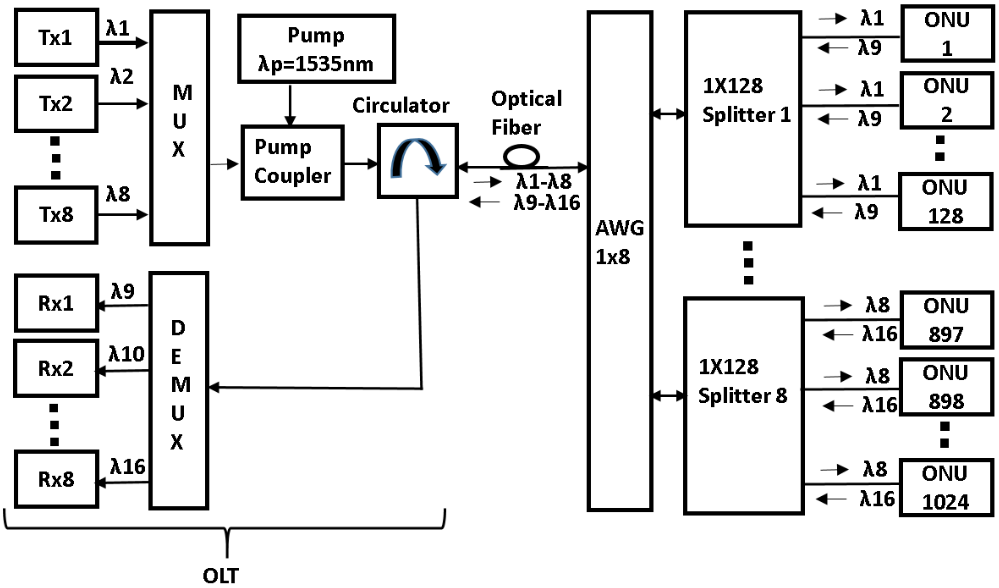

Fig. 1. Simulation architecture of symmetric 80 Gbps TWDM PON

For upstream transmission, the stacked wavelengths are ranging from 1524 nm to 1529.6 nm, with 0.8 nm spacing, and the wavelengths are according to NGPON2 specifications. As a group of ONUs shares a single wavelength, each ONU of a group using a typical wavelength transmits data using the TDM technique. Each ONU transmits data as per allotted time slots, and the start time and end time of transmission for an ONU are given by following equations (1) & (2).

Switching Starting time=Time Slot× (1/ (Bit rate)) × (Sequence length)/Split (1)

Switching Ending time=Time Slot× (1/ (Bit rate)) × (Sequence length)/Split+ (Time window)/Split (2)

In the system, each time slot assigned is 0.2ns, which changes as per requirements. The simulation parameters are listed below in Table 2.

Table 2. Simulation parameter

NAME	VALUE
Fiber length	20 km
Bit rate (Upstream/Downstream)	80 Gbps
Split per wavelength	128
Total Number of ONUs	1024
Number of wavelengths (Downstream)	8 (1524-1529.6) nm
Number of wavelengths (Upstream)	8 (1596-1601.6) nm
Channel spacing (Upstream/Downstream)	0.8 nm
Attenuation of Fiber	0.2 dB/km
Pump wavelength (for Downstream)	1535 nm
Pump power (for Downstream)	400 mw
Sequence length	256 Bits
Time window	56.6×10^{-9} second

For evaluating the effect of modulation format on system performance, we have compared NRZ, RZ, CSRZ, and duobinary modulation formats. Fig. 2 shows the setup for the optical NRZ/RZ generation. Pseudo random bit sequence generator (PRBS) generates a bit sequence randomly.

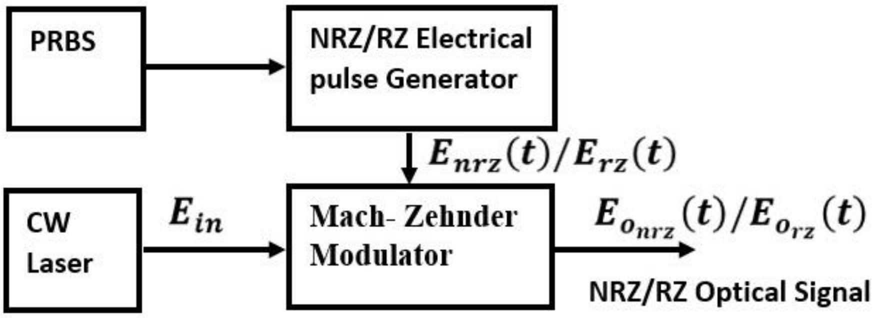

Fig. 2. Optical NRZ/RZ generation

In the case of NRZ, if the bit equals zero, then the output of the NRZ pulse generator is $E_{\ nrz}(t) = 0$. But for a high bit, the output of the NRZ electrical pulse generator can be expressed as given below.

$$E_{nrz}(t) = \begin{cases} 1 - e^{-\left(\frac{t}{C_r}\right)}, 0 \leq t < t_1 \\ 1, t_1 \leq t < t_2 \\ e^{-\left(\frac{t}{C_f}\right)}, t_2 \leq t < T \end{cases} \qquad (3)$$

where c_r and c_f are the rise time and fall time coefficients of the pulse. The parameter T is the bit period derived from the data rate. For a 1 bit (high), the magnitude remains high between time t_1 and t_2. Similarly, in the case of RZ, the output of the RZ electrical pulse generator can be expressed as

$$E_{rz}(t) = \begin{cases} 1 - e^{-\left(\frac{t}{C_r}\right)}, 0 \leq t < t_1 \\ 1, t_1 \leq t < t_2 \\ e^{-\left(\frac{t}{C_f}\right)}, t_2 \leq t < t_c \\ 0, t_c \leq t < T \end{cases} \qquad (4)$$

In this case, the parameters c_r, c_f and T are the same as in the case of NRZ format. However, the pulse remains high for time t_1 and t_c (duty cycle duration) for a logic 1 bit, the pulse reduces to zero after time t_c. For a 0 bit, the signals stay as $E_{rz}(t) = 0$ for the entire bit period. The outputs $E_{nrz}(t)$ or $E_{rz}(t)$ are normalized between 0 to 1 level. The Mach-Zehnder modulator (MZM) takes the first input from a continuous wave (CW) laser ($E_{in}(t)$). The other input takes the values as $M(t)$=$E_{nrz}(t)$ or $M(t)$=$E_{rz}(t)$ in the case of NRZ, RZ, respectively. In the particular instances of NRZ and RZ. The optical output of the MZM is $E_{o_{nrz}}(t)$ or $E_{o_{rz}}(t)$ [20].

$$E_{o_{nrz}}(t)\ or\ E_{o_{rz}}(t) = E_{in}(t).cos\big(\Delta\theta(t)\big).e^{j.\Delta\varphi(t)} \qquad (5)$$

where $\Delta\theta(t)$ is the phase difference between the two branches within MZM, and the following expression defines $\Delta\theta(t)$.

$$\Delta\theta(t) = \pi/2.(0.5 - (1 - 4/\pi.arc\ \tan(1/\sqrt{}(e\_r\ ))\ ).(M(t) - 0.5)) \qquad (6)$$

The signal phase change $\Delta\varphi(t)$ *is* defined as.

$$\Delta\varphi(t) = \Delta\theta(t).\frac{(1+SF)}{(1-SF)} \qquad (7)$$

where e_r is the extinction ratio(ER) of 30dB, SF=-1 is the symmetry factor. We have normalized the electrical input signal between 0 and 1. The third considered modulation format is a CSRZ format. Fig. 3 shows the setup for the generation of optical CSRZ modulation.

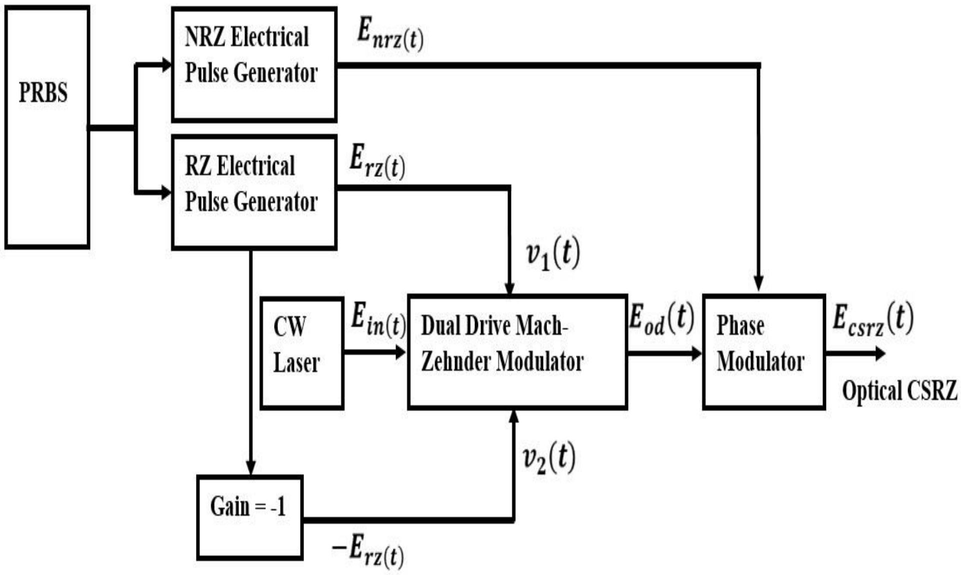

Fig. 3. Optical CSRZ signal generation

The following expression gives the output of the dual-drive MZM [21, 22].

$$E_{od}(t) = \frac{E_{in}(t)}{10^{\left(\frac{IL}{20}\right)}}.\left[\gamma . e^{\left(\frac{j\pi v_{2(t)}}{v_{RF}}+\frac{j\pi v_{bias2}}{v_{\pi RF}}\right)} + (1-\gamma). e^{\left(\frac{j\pi v_{1(t)}}{v_{\pi RF}}+\frac{j\pi v_{bias1}}{v_{\pi DC}}\right)}\right. \quad (8)$$

where $E_{in}(t)$ is the input (optical) signal from the laser, IL is insertion loss (0dB). The input electrical voltages for the upper and lower modulator arms are $v_1(t)= E_{rz}(t)$ and $v_2(t)= -E_{rz}(t)$. The voltages $v_{bias1}(t)$ (0V) and $v_{bias2}(t)$ (2V) are the bias voltage1 and bias voltage2, the $V_{\pi RF}$ (4V) is the Switching modulation voltage, $V_{\pi DC}$ (4V) is the Switching bias voltage, the γ denotes the power splitting ratio of both Y-branch waveguides (assumed to be symmetrical), The second stage of modulation (phase modulation) gives the optical CSRZ optical signal, which is provided by the following expression [20].

$$E_{csrz}(t) = E_{od}(t). e^{(j.\Delta\varphi.E_{nrz}(t))} \quad (9)$$

where $E_{csrz}(t)$ represents the output CSRZ optical signal. The parameters $\Delta\varphi$ (phase deviation) and $E_{nrz}(t)$ are already defined in eq.7 and eq.5, respectively. NRZ modulation. Fig. 4 shows the setup for optical duobinary signal generation. Logical bits generated from the PRBS generator are inverted by a NOT gate whose output is the input to the duobinary pre-coder. For recursive decoding, a pre-coder executes the exclusive-or gate with delayed feedback. Following is the expression of the pre-coding function.

$$b_k = d_k \oplus b_{k-d} \quad (10)$$

where b_k and d_k represents the output and input to the precoder module. The parameter d signifies the number of bits delayed, in our work d=1.

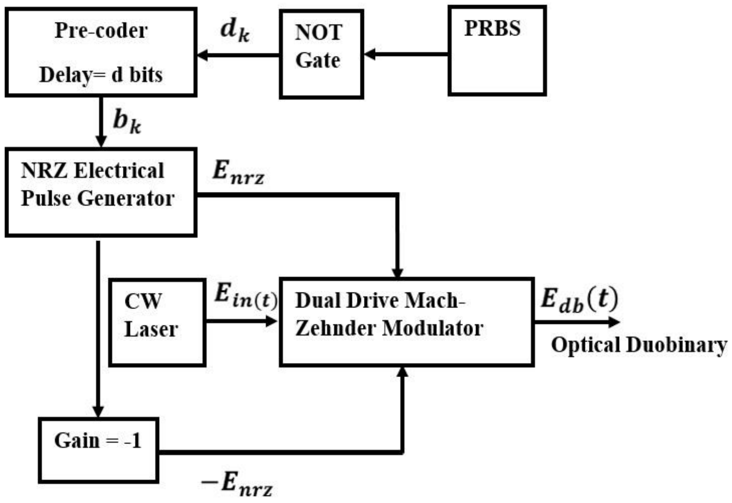

Fig. 4. Optical duobinary signal generation

The dual-drive MZM produces the optical duobinary modulation, as given below [21,22].

$$E_{db}(t) = \frac{E_{in}(t)}{10^{\left(\frac{IL}{20}\right)}} . [\gamma . e^{\left(\frac{j\pi v_{2(t)}}{v_{RF}} + \frac{j\pi v_{bias2}}{v_{\pi RF}}\right)} + (1-\gamma). e^{\left(\frac{j\pi v_{1(t)}}{v_{\pi RF}} + \frac{j\pi v_{bias1}}{v_{\pi DC}}\right)} \tag{11}$$

where $v_1(t) = E_{nrz}(t)$ and $v_2(t) = -E_{nrz}(t)$ are the input electrical voltages for the upper and lower modulator arms, $v_{bias1}(t)$ (0dB), and $v_{bias2}(t)$ (4V) are the settings for bias voltage1 and bias voltage2. $V_{\pi RF}$ (4V) is the Switching modulation voltage, $V_{\pi DC}$ (4V) is the Switching bias voltage. γ denotes the power splitting ratio of both Y-branch waveguides (assumed to be symmetrical). The duobinary format is a three-level modulation format, whereas NRZ, RZ, and CSRZ formats are two-level formats. For showing the difference in two-level and three-level modulation formats, the time-domain spectrum of the transmitted signals in NRZ format and duobinary modulation format are shown in Fig. 5.

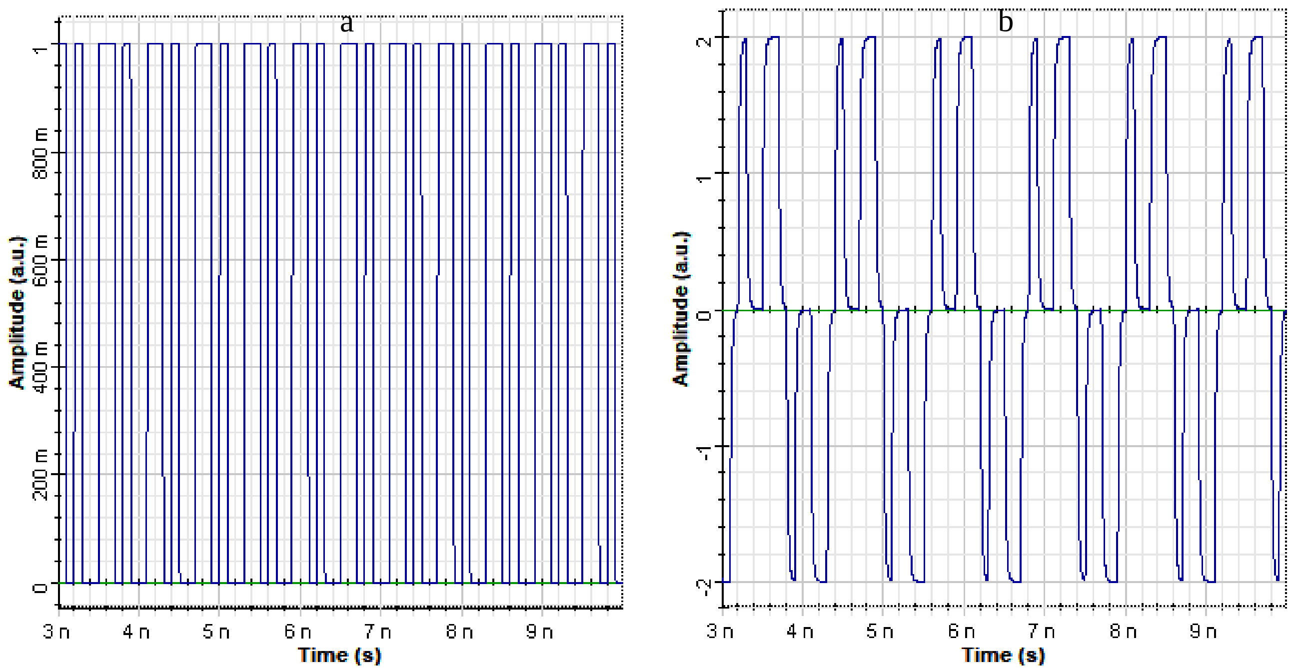

Fig. 5. Time-domain spectrum of (a) NRZ (b) Duobinary

Fig. 6 shows the optical spectrum of the NRZ, RZ, CSRZ, and Duobinary modulation formats for the same laser center wavelength. The duobinary seems to be most bandwidth-efficient as it is narrower in the frequency domain than the other formats.

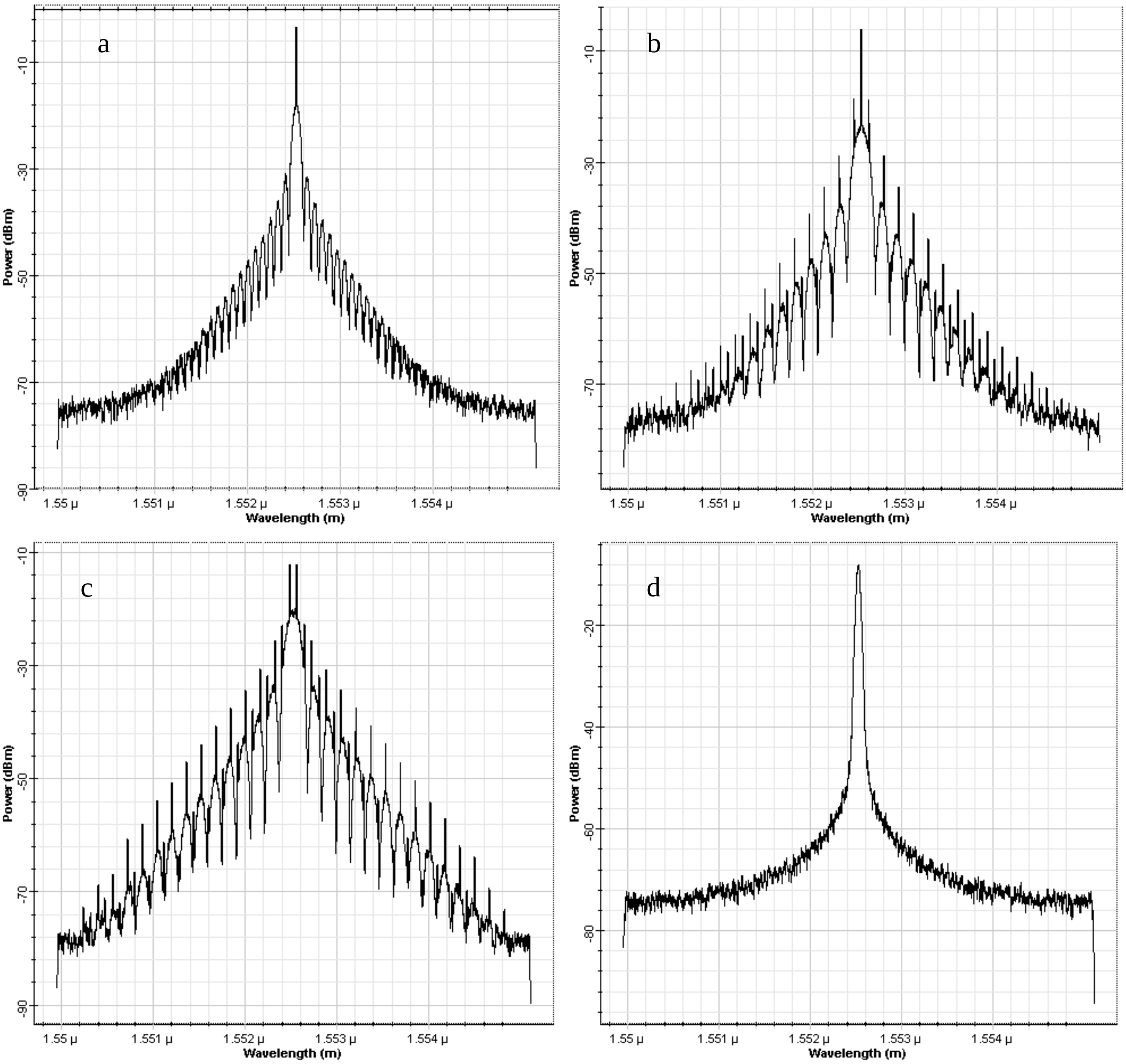

Fig. 6. Spectrum of Modulation formats (a) NRZ, (b) RZ, (c) CSRZ (d), Duobinary

Most of the applications use NRZ and RZ modulation formats because of their simplicity and decent performance. But, the duobinary modulation format being a three-level format is superior to the conventional NRZ, RZ, and CSRZ in terms of dispersion tolerance. In the duobinary modulation format, the signal spectrum shrinks in the frequency domain and broadens in the time domain. With a narrow frequency spectrum, the duobinary modulation format becomes more resilient to signal distortion. NRZ requires a bandwidth of R Hz to transmit R bits/sec, and this is twice the minimum Nyquist bandwidth of R/2Hz. On the other hand, duobinary modulation requires less than R/2 Hz bandwidth to transmit R bits per second. Therefore the duobinary modulation format is more bandwidth-efficient as compared to conventional NRZ/RZ modulation format.

3. Power budget calculation

The evaluation of BER assesses the performance for upstream and downstream. By varying the downstream power, the effect of the change on BER has observed.

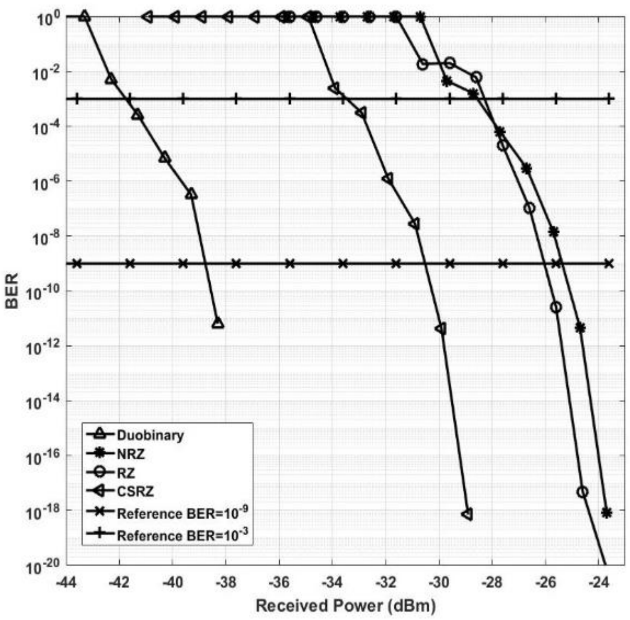

Fig. 7. BER vs. Received power for PIN photodiode

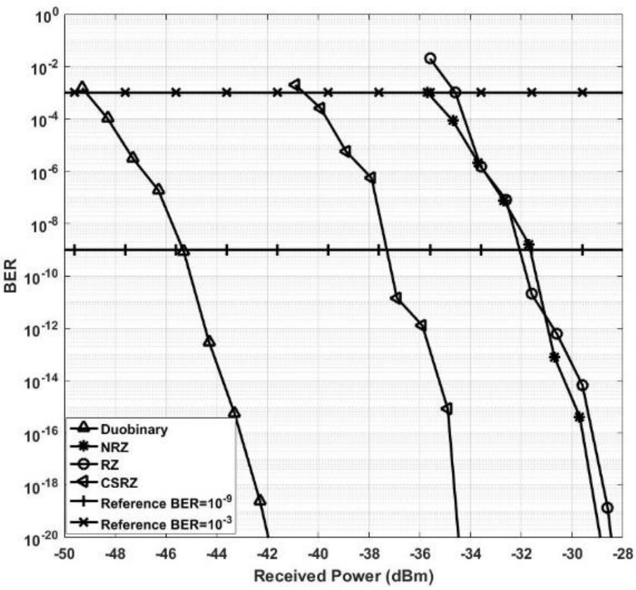

Fig. 8. BER vs. Received power for APD photodiode for downstream transmission

The transmission length of fiber is 20 km, which is the minimum requirement of 80 Gbps NG-PON as recommended by ITU-T. Figs. 7 and 8 shows the graph between received downstream power and BER for PIN photodiode and APD photodiode for modulation formats. The reference BER for both the cases is 10^{-9} (Without forward error correction (FEC)) and 10^{-3} (with FEC). Best receiver sensitivity is of duobinary in the case of a PIN photodiode. The performance deteriorates in the order of CSRZ, RZ to NRZ, which is due to the difference in their spectral efficiency. For the 10^{-9} BER level, the receiver sensitivity for duobinary is -39 dB, and for NRZ is -26dB; therefore, there is a 13 dB enhancement for duobinary over NRZ. For BER level 10^{-3} (FEC limit), the best receiver sensitivity achieved for the duobinary format is -42 dB. The results get improved by using APD in place of PIN in all cases. Duobinary with APD provides the best receiver sensitivities of -45.5 dB (without FEC) and -49.5 dB (with FEC). There is no significant difference between the performance of RZ and NRZ formats.

Figs. 9 and 10 show the graphical representation of BER versus received power in the case of upstream for PIN/APD photodiode. In both cases, duobinary is outperforming other modulation formats because of better spectral efficiency. The best receiver sensitivity found in the case of a PIN photodiode for duobinary modulation format is -58.4 dB (with FEC), and -55 dB (Without FEC). The performance deteriorates in the order of CSRZ, RZ to NRZ. In the case of APD, the best receiver sensitivities achieved are -68.5 dB (with FEC), -63.5 dB (Without FEC). With the duobinary modulation format, the receiver sensitivity improves by ~10 dB over the NRZ modulation format (with FEC). There is no significant difference in the performance of NRZ and RZ modulation formats. Table 3 lists the power budget evaluated using the following expression, system margin of 5dB provisions the sudden unexpected power change.

$$P_T = P_R + C_L + M_S \quad (12)$$

where P_T is average launched power, P_R is receiver sensitivity, C_L is total channel loss, and M_S is system margin [23].

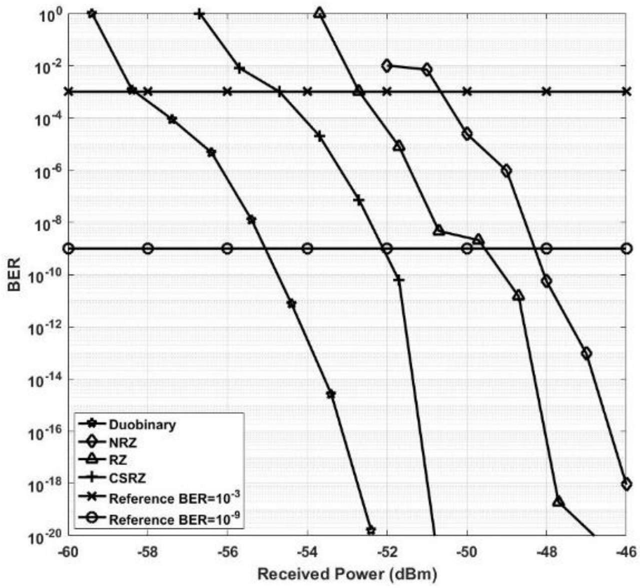

Fig. 9. BER vs. Received power for PIN photodiode for upstream transmission

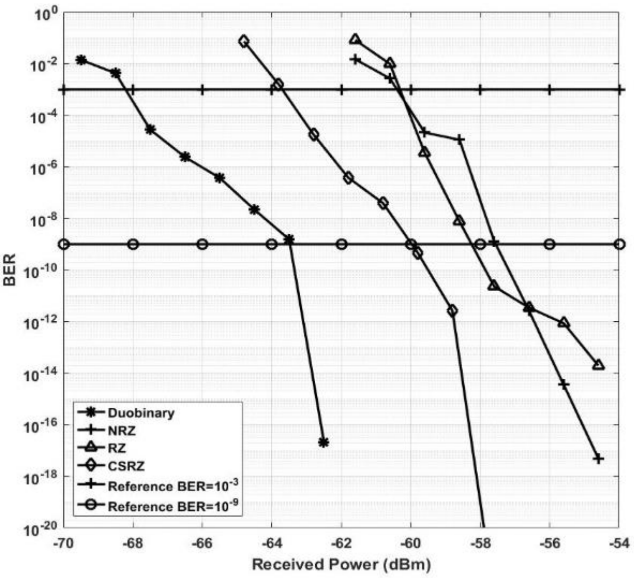

Fig. 10. BER vs. Received power for APD photodiode for upstream transmission

Table 3. Evaluated Power Budget

Format	Receiver Sensitivity (Without FEC)	Receiver Sensitivity (With FEC)	Allowed Power Budget (Without FEC)	Allowed Power Budget (With FEC)
NRZ	-31.7 dB	-35.7 dB	26.7 dB	30.7 dB
RZ	-32.0 dB	-34.6 dB	27.0 dB	29.6 dB
CSRZ	-37.3 dB	-40.8 dB	32.3 dB	38.8 dB
Duobinary	-45.5 dB	-49.5 dB	40.5 dB	44.5 dB

4. Conclusion

As the power budget plays an essential role in any PON configuration to maintain the cost of the system. Most researchers have done work on the improvement of the power budget by using different techniques, as discussed in table 1. In this paper, we proposed a high data rate, high system capacity, and a low-cost system with improved power budget for future TWDM-PON. Through simulations, we demonstrated and analyzed a symmetric 80 Gbps TWDM based NG-PON system for different modulation formats and photodiodes. We investigate the system based on BER for received power for both downstream and upstream links over 20 km SMF transmission. We have compared NRZ, RZ, CSRZ, and duobinary modulation formats for PIN and APD photodiode. The combination of duobinary modulation format with APD photodiode achieves best receiver sensitivity, and among other considered cases, it has maximum receiver sensitivity. The CSRZ shows the second-best performance, and there is no significant difference in the case of NRZ and RZ modulation formats. For downstream link, duobinary with APD provides maximum receiver sensitivity of -49.5 dB (With FEC) and -45.5 dB (Without FEC). For upstream transmission, duobinary with APD photodiode provides the best receiver sensitivity of -68.9dB (With FEC), and -63.9 dB (Without FEC). The duobinary with APD offers the best power budget of 44.5 dB(FEC) and 40.5 dB(without FEC), which is round 14dB power budget improvement over the NRZ for 1024 users. The proposed architecture may be valuable for practical implementation in the future TWDM-PON system.

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