112 Gb/s coherent NG-PON2 downstream transmission using advance polarization multiplexed modulation formats

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This paper investigates downstream transmission of 112 Gb/s coherent next generation-passive optical network II (NG-PON2) over multiple end users by deploying different polarization multiplexed phase shift formats. Here, a simulation over B2B configuration and fiber based optimization is performed for maximum reach, provided nonlinear propagation of optical signal with amplification over uncompensated link. The analytical behaviour of the proposed NG-PON2 is numerically measured in terms of receiver sensitivity, bit error rate, optical signal to noise ratio, error vector magnitude and constellation diagram with acceptable performance. Exceptionally good power budget is also calculated for different modulation formats. This analysis enables an efficient understanding of NG-PON2 under the influence of different polarization multiplexed formats along with varying number of end users.

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1. Introduction

In recent years, passive optical network (PON) has emerged as an active research domain of fiber based access networks due to high rate broadband services like TV broadcast and video on demand (VOD) [1]. PON enables point-to-multi-point (P2MP) features into a network. The basic design of PON system consists of an optical line terminal (OLT) at the service provider’s end, i.e. central office (CO), a fully passive optical distribution network (ODN) and several optical network units (ONUs) at the user’s premises [2]. Since PON does not require any electrical power supply, backup or batteries to energize the distribution elements, operational costs and complexity is lowered and hence requiring a smaller number of ports in the P2MP network than point to point (P2P) approach [3,4].

Recently researchers are working on different types of PON, such as broadband-PON (B-PON) [5], Ethernet-PON (E-PON) [6], Gigabit-PON (GPON) [7], 10-Gigabit-PON (XG-PON) [8], 40-Gigabit-PON (XLG-PON) [9,10], 10-Gigabit symmetrical- PON (XGS-PON) [11], wavelength division multiplexed-PON (WDM-PON) [12], time and wavelength division multiplexed- PON (TWDM-PON) [13], WDM-TDM-hybrid network [14], colorless PON [12], Next Generation Ethernet Passive Optical Network (NG-EPON) [15] and next generation-PON2 (NG-PON2) [16].

In 2011, NG-PON network over 40 km bidirectional standard single mode fiber (SSMF) was designed with splitting ratio 1:1024 supporting downstream data rate less than 5 Gb/s, which was too small to cope up with high capacity requirement [17]. In year 2012, 10.3 Gb/s downstream WDM-PON network was designed supporting QPSK format up to 80 km reach, using reflective semiconductor optical amplifier (RSOA) [8]. In the same year, NG-long reach PON was established with XLG-PON (i.e. 40 Gb/s) downstream and XG-PON (i.e.10Gb/s) upstream signal transmission using quadrature amplitude modulation (QAM) with orthogonal frequency division multiplexing (OFDM) format [10], as it supported large ONUs with high spectral efficiency. Later in 2012, again 112 Gb/s downstream long reach coherent PON was experimentally demonstrated based on polarization multiplexed- quadrature phase shift keying (PM-QPSK) format, supporting 100 km SSMF long reach and 1:128 splitting ratio with power budget of 43.5 dB [1]. In 2018, low cost RSOA based bidirectional Triple-play services using WDM radio on free-space-optics passive optical network (WDM-RoFSO-PON) is demonstrated to transmit 10 Gb/s data/voice and 1.49 Gb/s HDTV services simultaneously [18]. NG-PON2 based on ITU-T G.989 standard is most promising and efficient solution at high data rates, in terms of dealing with dramatically increasing bandwidth requirement and fulfilling huge traffic demand of next generation network. NG-PON2 is also a successor to XGPON or NG-PON [11]. Key characteristics of NG-PON2 based optical network are; transmission rate greater than 40 Gb/s upstream or downstream transmission, 40-60 km reach and higher splitting ratio (1:256) or more [2].

It is observed that at transmission rate greater than 40 Gb/s, chromatic dispersion (CD), polarization mode dispersion (PMD) and Kerr nonlinearities are limiting factors, which affect maximum reach and receiver sensitivity in optical transmission [19]. These limitations can be reduced in NG-PON2, by using powerful tool coherent detection technology along with digital signal processing (DSP). DSP allows compensation of fiber impairments electronically or programmatically, rather than implementing complex physical impairments compensation links [20]. Coherent detection technology also supports higher order modulation formats with polarization multiplexing, such as PM-QPSK and polarization multiplexed-QAM (PM-QAM), which decreases symbol rate and results into lowering the sampling rate of analog to digital conversion (ADC), which makes DSP functioning faster [1,21]. Hence, coherent detection technology facilitates NG-PON2 to enhance bottleneck of existing PON with the aid of delivering transparency, bandwidth enhancement, redundancy, long haul transmission, power budgeting, ODN compatibility, big splitting ratio, high receiver sensitivity, forward error correction and cost efficiency [1,22]. NG-PON2 supports high speed electronics (i.e. > 100 Gb/s) in the presence of digital coherent technology, which is an advent over signal regenerator and dispersion compensation fiber (DCF). Digital coherent technology, which is comprised of coherent receiver with DSP unit at ONU terminal, facilitates NG-PON2 to achieve dynamic polarization control and channel impairments mitigation in the electronic domain and leads to long haul transmission along with reduced system complexity and cost [20].

In this communication, 112Gb/s downstream coherent NG-PON2 is modelled for back to back (B2B) transmission and over 10 km - 80 km SSMF fiber using advance polarization multiplexed modulation formats, i.e. polarization multiplexed- binary phase shift keying (PM-BPSK), PM-QPSK and PM-16QAM for different splitting ratio of 1:128, 1:256 and 1:512 at ODN. Apart from fiber based optimizations, power budget analysis is also performed for different modulation formats. At receiver end, ONU contains DSP to mitigate channel impairments across the fiber channel. Key algorithms used for channel impairment mitigation are frequency domain CD compensation, carrier phase estimation (CPE) using Viterbi-Viterbi algorithm and polarization demultiplexing using blind constant modulus algorithm (CMA) equalizer. Performance of the proposed NG-PON2 model is analysed efficiently in terms of key parameters i.e. bit error rate (BER), optical signal to noise ratio (OSNR), receiver sensitivity, error vector magnitude (EVM), constellation diagram and power budget.

This paper is structured as follows: In section 2, we have given a brief detail of the proposed model of 112 Gb/s NG-PON2 with design considerations. In section 3, obtained results are discussed explicitly. Finally, the paper ends up with effective conclusion in section 4.

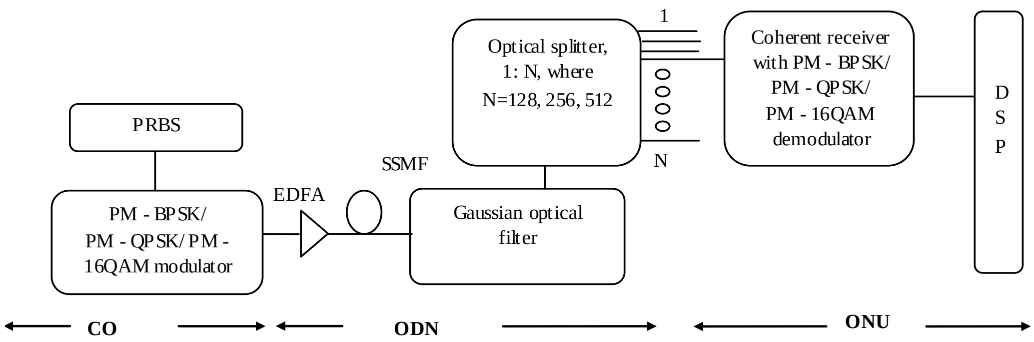

Fig. 1. Architecture of proposed coherent NG-PON2 transmission

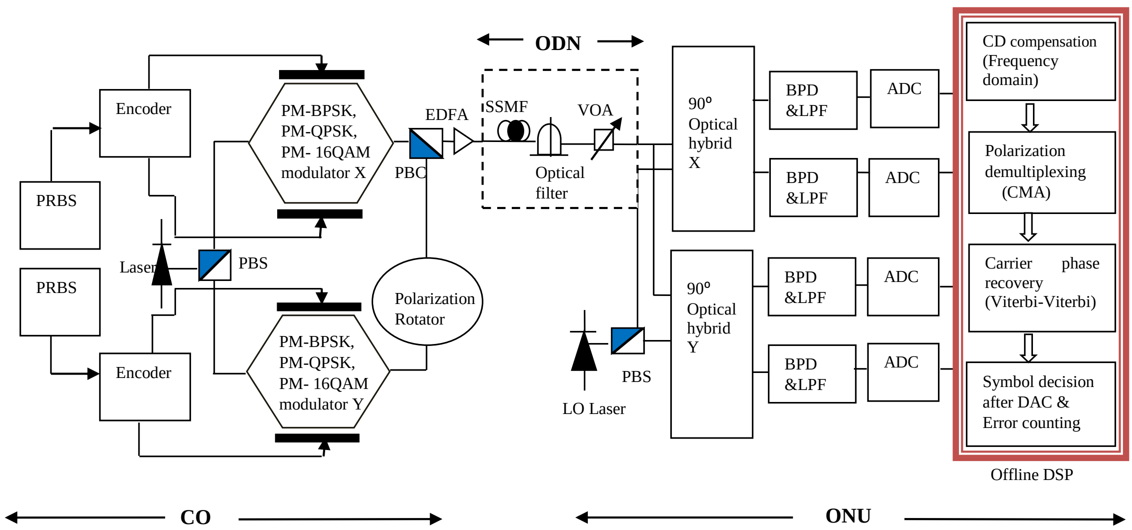

Fig. 2. Detailed simulation model of 112 Gb/s downstream coherent NG-PON2 transmission

2. Proposed model and design consideration

2.1. Proposed model

Architecture of the proposed 112 Gb/s coherent NG-PON2 is shown in Fig. 1, where CO unit consists of pseudo random bit sequence (PRBS) generator with advance polarization multiplexed transmitters, i.e. PM-BPSK, PM-QPSK or PM-16QAM modulator. The transmitted signal is amplified using Erbium doped fiber amplifier (EDFA), which is an active element. ODN unit consists of all passive elements, which are SSMF of 10 km-80 km fiber length with Gaussian optical filter and varying number of optical splitters with ratio 1:N, where N is an integer presenting number of end users. In this paper, value of N is considered as 128, 256 and 512. Variable optical attenuator (VOA) is preferred over fixed power splitter component, due to avoiding tedious calculation of analytical work, cost and complexity prospects. At ONU terminal, coherent receiver as per modulation format is used with DSP.

The detailed simulation model of the proposed work is shown in Fig. 2. A serially generated PRBS bit sequence data of length 2^{13}-1 or 8192 bits for PM-BPSK and 2^{16}-1 or 65536 bits for both, PM-QPSK and PM-16QAM modulation format is transmitted at CO terminal. As transmitted samples per bit is 4, so transmitted numbers of samples are 32768, 262144, 262144 for PM-BPSK, PM-QPSK and PM-16QAM formats respectively. Encoder is applied as modulator driving component, consists of serial to parallel converter. A laser source is used at CO with power = 10 dBm, sharp linewidth = 0.1 MHz. Further, launched optical signal with 0° phase, splits into two lights with polarization beam splitter (PBS) with 45° angle and reaches to two separate advance modulators (namely PM-BPSK, PM-QPSK and PM-16QAM) for X and Y polarizations. These advance modulators consist of a key component, $LiNbO_3$ Mach Zehnder modulator (MZM) with extinction ratio 60 dB, switching bias and RF voltage 3 V and insertion loss 5 dB. Now, X and Y polarized modulated optical signals are combined, finally by power beam combiner (PBC) at an angle of 0°. Optical amplifier i.e. EDFA has noise figure 4dB.

Next, modulated optical signal enters into ODN unit, which consists of all passive components. Here, SSMF of 10 km to 80 km length is used with following parameter values; attenuation 0.2 dB/km, dispersion coefficient 16.75ps/nm/km, dispersion slope 0.075 ps/nm^2/km, differential group delay (DGD) 0.2 ps/km, PMD coefficient 0.05 ps/(km)$^{-1/2}$ and effective area 80 µm^2. First order Gaussian optical filter has optical bandwidth 100GHz. This filtered optical signal is passed through VOA, which is arranged at the front end of the coherent receiver with power values of -21.072 dB, -24.082 dB and -27.093 dB as per required 128, 256 and 512 end users respectively.

In ONU unit, received optical signal firstly enters into the coherent receiver, which consists of laser with identical power and laser linewidth as local oscillator, balance photo detector (BPD) with PIN diode of following specifications; gain value 3, ionization ratio 0.9, responsivity 1 A/W and dark current 10 nA. Here third order Bessel low pass filter (LPF) is used before DSP with specifications; cut off frequency 42 GHz for PM-BPSK, 21 GHz for PM-QPSK and 10.5 GHz for PM-16QAM format. Now, In phase and quadrature phase component reaches to DSP unit, which performs five key functions; i.e. ADC, CD compensation, polarization demultiplexing, carrier phase noise mitigation and digital to analog (DAC) conversion [20,23]. This is kept in mind that during simulation, all the Lasers and filters lie in C band.

2.2. Mathematical modelling

Digital coherent technology comprises coherent receiver with DSP unit, which provides dynamic polarization control and linear-nonlinear channel impairments mitigation in the electronic domain wherewith following key functions; i.e. ADC of digitized data by resampling, CD compensation in frequency domain, polarization demultiplexing using PMD compensation, carrier phase noise mitigation by adaptive equalization and finally accurate decision by DAC conversion. In down sampling process through ADC, symbol rate is set as 56 Gbaud, 28 Gbaud and 14 Gbaud for PM-BPSK, PM-QPSK and PM-16QAM respectively, while number of symbols is set as 4092, 16384 and 8192 for PM-BPSK, PM-QPSK and PM-16QAM respectively.

i. Chromatic Dispersion Compensation

Effect of only chromatic dispersion on envelop A(z, t) of optical pulse is modelled as; [20]

$$\frac{\partial \mathrm{A(z,t)}}{\partial \mathrm{z}} = \mathrm{j}\frac{\mathrm{D}\lambda^2}{4\pi\mathrm{c}}\frac{\partial^2 \mathrm{A(z,t)}}{\partial \mathrm{t}^2} \quad (1)$$

Here, D (ps/nm/km) is chromatic dispersion parameter, z is the propagation length, λ is the light wavelength, t is the time variable in a frame, c is the speed of light. Assuming that fiber channel is impaired with only chromatic dispersion, channel is considered here as finite impulse response (FIR) filter. Hence, the transfer function of the dispersed channel $\mathrm{H}(z, \omega)$ is expressed as

$$H(z,\omega) = \exp\left[j\,\frac{D\lambda^2 z}{4\pi c}\,\omega^2\right] \quad (2)$$

To achieve chromatic dispersion compensation in DSP dispersed optical field is multiplied with the transfer function of CD compensation filter, defined by the inverse of dispersed channel transfer function of FIR filter. Transfer function of CD compensation filter is 1/ H (z,ω), i.e.

$$\mathrm{H}_{\mathrm{Comp.}}\,(z,\omega) = \exp\left(-\mathrm{j}\frac{D\lambda^2 z}{4\pi c}\,\omega^2\right) \quad (3)$$

one can raise the order of the filter. Fourier inverse transform of Eq. 3, results into impulse response of CD compensation filter as:

$$I_{Comp}(z, t) = \sqrt{\frac{jc}{D\lambda^2 z}}\exp\left(\frac{\pi c}{D\lambda^2 z}t^2\right) \quad (4)$$

In this proposed model, during dispersion compensation (DC) calculation [20,23] in 'frequency' domain, channel wavelength and DC reference wavelength 1550 nm, dispersion coefficient 16.75 ps/nm-km, residual dispersion slope 0.075 ps/nm^2 km, number of taps 181, DSP length for dispersion compensation is 50 km for B2B transmission, while 10 km-80 km as per fiber transmission length.

2.2.1. Constant Modulus Algorithm (CMA)

This method is based on blind adaptive equalization, in which the transmitted signal is treated with constant reference amplitude 1 [24]. Equalizer output $y(n)$ and step size $\mu(n)$ with 'n' as time index. Filter coefficient $w(n)$ is updated in iterative manner with error vector

$$e(n) = 1 - |y(n)|^2,$$
$$w(n+1) = w(n) + \mu(n).x^*(n).e(n).y(n) \quad (5)$$

2.2.1.1. Polarization Mode Dispersion (PMD) Equalization

Received PM-BPSK, PM-QPSK or PM-16QAM signal at the coherent receiver is undergone the process of polarization de-multiplexing, using CMA algorithm. Polarized signal is represented as [24]

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = T\begin{pmatrix} E_{in,x} \\ E_{in,y} \end{pmatrix} \quad (6)$$

where T is Jones matrix of fiber transmission, represented as

$$T = \begin{bmatrix} \sqrt{\alpha e^{i\delta}} & -\sqrt{1-\alpha} \\ \sqrt{1-\alpha} & \sqrt{\alpha}e^{-i\delta} \end{bmatrix} \quad (7)$$

where α and δ signify power splitting ratio and the phase mismatch between both polarization modes and de-multiplexing can be achieved by inverse of matrix (T) using CMA algorithm [25, 26]. Thus, de-multiplexed outputs signals are

$$\begin{pmatrix} E_X \\ E_Y \end{pmatrix} = \begin{pmatrix} l_{xx} & l_{xy} \\ l_{yx} & l_{yy} \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix} \quad (8)$$

Here, matrix l is an adaptive FIR filter and its elements go on updated. E_X, E_Y, E_x and E_y show complex optical output and input in x and y polarization respectively. In the proposed model, various PMD compensation parameters are likewise; step size 2×10^{-6} for PM-BPSK, 5×10^{-6} for PM-QPSK and 1×10^{-6} for PM-16QAM, number of taps of FIR filter 9, average window size 512 and samples per block 2048.

2.2.1.2. Carrier Phase Estimation (CPE)

Accumulated effect of laser phase noise, amplified spontaneous emission (ASE) and cross phase modulation (XPM) distorts the signal phase, which gets recovered by "Viterbi - Viterbi" CPE Algorithm [27]. This compensates the phase and frequency discrepancy between transmitting laser and local oscillator. Here, received QPSK or BPSK signal R_k which is further raised with order M= 4 to get rid of quaternary signal is represented by

$$R_k(t) = A\exp\{j[\theta_s(t) + \theta_c(t)]\} \quad (9)$$

$\varphi_k\tilde{}$ is the phase estimated from output signal, processed out from DSP. $\theta_s(t)$ and $\theta_c(t)$ are transmitted signal phase and Local Oscillator phase respectively [25]. This signal reaches to detector and divided by 4. n_k is ASE noise. Estimated phase of the received signal is further subtracted from its argument for correct carrier phase

$$\varphi_k\tilde{} = \frac{1}{4}.Arg\left(\sum_{k=-N}^{k=N}\{e^{j\theta_d + j\theta_k} + n_k\}^4\right) \quad (10)$$

Using Viterbi - Viterbi CPE [25, 27] to mitigate laser phase noise, CPE symbols per block 14 for PM-BPSK, 30 for PM-QPSK and 40 for PM-16QAM, interpolation in CPE 0, delay between X and Y polarization is 0. Interpolation type used in re-sampling of ADC and DAC is 'cubic', which is a linearly filtering process in one dimension. Nonlinear impairment compensation is also applied to mitigate Kerr nonlinearities with parameters identical to optical fiber values, with additional parameter nonlinear coefficient 0.76 W^{-1} km^{-1} and nonlinear ratio 0.48.

The entire simulation model is implemented using commercial OPTISYSTEM software. Here, all the analysis is shown only for single end user, because obtained results will remain same for all left over end users.

3. Results and discussion

3.1. Back to Back (b2b) transmission

In Fig. 3(a), the receiver sensitivity is plotted for b2b transmission with varying launched power between 0 to 15 dBm for different polarization multiplexed modulation formats at CO terminal and different splitting ratio at ODN. It is observed that without fiber, obtained receiver sensitivity is quite linear, due to the absence of fiber attenuation, distortion and Kerr nonlinearities. On applying twice increment in number of splitters, (i.e. 128, 256, 512), the receiver sensitivity reduces with a penalty of 3 dBm value for each modulation format. Apart from this, on applying corresponding modulation formats, i.e. PM-BPSK, PM-QPSK and PM-16QAM, OSNR requirement at receiver increases due to growing constellation size.

Hence, while approaching from PM-BPSK to PM-QPSK, PM-QPSK to PM-16QAM and PM-BPSK to PM-16QAM format, a sensitivity penalty range of 3.5-4.0 dBm, 7.6-9.5 dBm and 11.2-13.5 dBm is achieved respectively. It is validated from obtained results that on increasing number of users, receiver sensitivity decreases to achieve same BER value. Fig. 3(b) illustrates BER behaviour with respect to OSNR value for the three modulation formats at three power splitting ratios. Instead of introducing noise additionally in the system, low noise floor is added to the optical signal while setting OSNR during simulation.

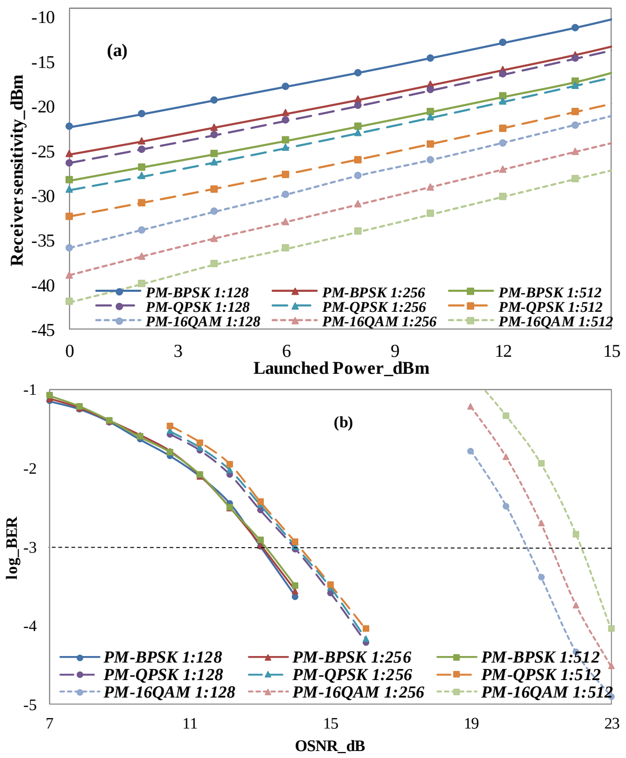

Fig. 3. (a) Receiver sensitivity is plotted against the launched power (b) BER is plotted against OSNR, for b2b transmission of 112 Gb/s NG-PON2 using different polarization multiplexed formats for different number of splitters (color online)

In Fig. 3(b), for achieving BER= 1×10^{-3}, PM-QPSK format suffers an OSNR penalty of approximately 1dB more than PM-BPSK format, irrespective of power splitting ratios. But PM-16QAM format with huge constellation size, suffers with highest OSNR penalty of 7.7dB, 8.35dB and 9.0dB with respect to PM-BPSK format for 128, 256 and 512 splitters respectively. Hence, PM-BPSK format requires only 2/3 OSNR value than that of PM-16QAM format to achieve same BER=1×10^{-3}. This is also validated from Fig. 3(b) that on increasing constellation size of higher order modulation formats, BER decreases correspondingly.

3.2. Optimization of maximum reach against splitting ratio

After discussing the receiver sensitivity and BER analysis for b2b transmission, optical fiber in the ODN section, along with an EDFA in the CO section is introduced in NG-PON2. Presence of fiber increases receiver sensitivity penalty due to attenuation, dispersion and nonlinearities along the fiber. Under this section, fiber based optimization is done using different fiber length between 10 km-40 km for 512 splitters, 40 km-60 km for 256 splitters and 60 km-80 km for 128 splitters for each of three modulation formats. Here performance parameters such as receiver sensitivity, BER, EVM and constellation diagram are considered only for the best cases of each splitting ratios, which is 20 km for 512 splitters, 60 km for 256 splitters and 70 km for 128 splitters for all three modulation formats. A constellation diagram exhibits two dimensional scatter diagrams in the complex plane at sampling instant and visualizes one dimensional eye pattern phenomenon [22]. EVM is estimated from constellation diagrams and is based on the error between received symbols and transmitted symbols. EVM considers both amplitude and phase distortions [28]. EVM is a figure of merit for down conversion of modulated signal and is a measure of SNR.

In Table 1, receiver sensitivity penalty is summarized for different power splitter based optimized fiber length and b2b transmission for each modulation format. On comparing Fig. 3(a) and Fig. 4, it is clearly observed that on applying twice increment in power splitting ratio i.e. from 128 to 256, transmission reach almost remains same (i.e. 60 km-70 km), at a cost of double sensitivity penalty for each modulation format. While, quadrupling the end users from 128 to 512, effective transmission reach is limited only up to 20 km, provided with a sensitivity penalty of eight fold for PM-BPSK or PM-QPSK, while six fold for PM-16QAM format.

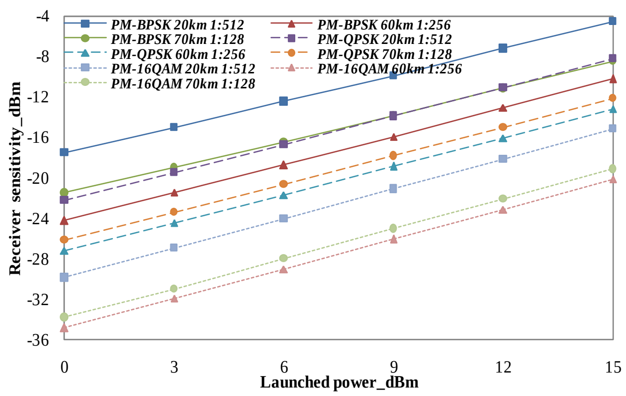

Fig. 4. Receiver sensitivity is plotted against the launched power for 112 Gb/s NG-PON2 at optimized fiber length. Here, solid line, dashed line and dotted line shows PM-BPSK, PM-QPSK and PM-16QAM format respectively, while circle, triangle and square represents 128, 256 and 512 splitters, for optimized fiber length i.e. 70 km, 60 km and 20 km respectively (color online)

Also, relevant information can be drawn from Table 1 that in the fiber based transmission, PM-QPSK and PM-16QAM formats suffer 3-5 dBm and 7-12 dBm sensitivity penalty than that of PM-BPSK format, with supporting various power splitters.

In Fig. 5(a)-5(c), a graph between BER and receiver sensitivity is plotted along with sixteen points, four point and two point constellation diagrams for PM-16QAM, PM-QPSK and PM-BPSK formats respectively, for different splitting ratios, i.e. 128, 256, 512 at corresponding optimized fiber length for each, i.e.70 km, 60 km and 20 km.

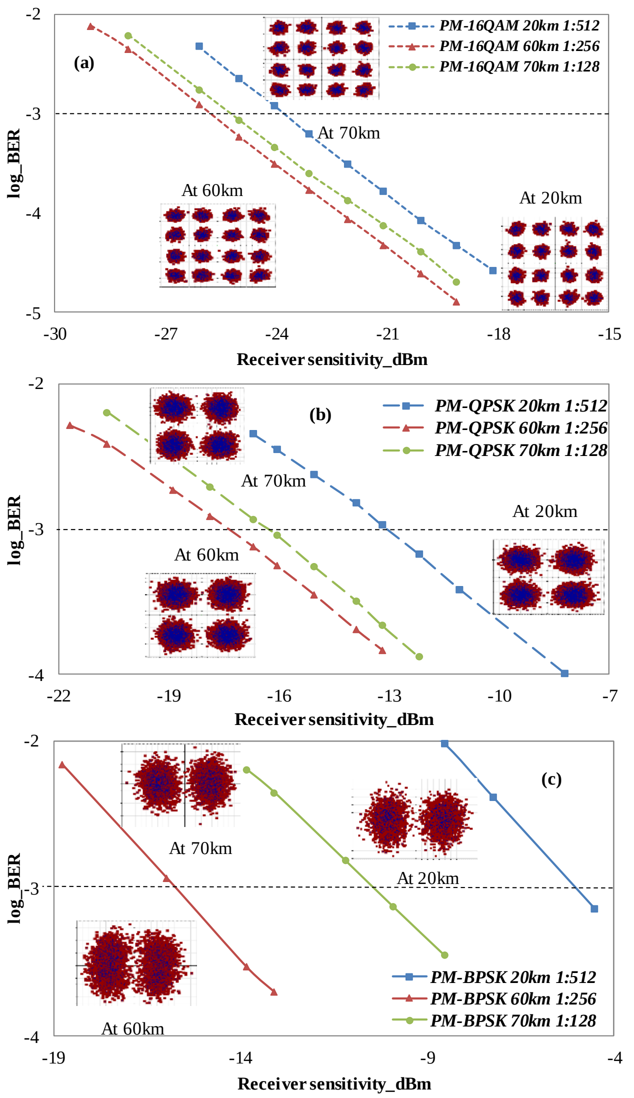

Fig. 5. BER is plotted against the receiver sensitivity for 112 Gb/s NG-PON2 using (a) PM-16QAM format, (b) PM-QPSK format and (c) PM-BPSK format, along with exhibiting obtained constellation diagram at each optimized fiber length. Here, solid line, dashed line and dotted line shows PM-BPSK, PM-QPSK and PM-16QAM format respectively, while circle, triangle and square represents 128, 256 and 512 splitters, for optimized fiber length i.e. 70 km, 60 km and 20 km respectively (color online)

Further on focusing 1×10^{-3} BER value; in Fig. 5(a) it is observed that PM-16QAM format exhibits -25.7 dBm receiver sensitivity for 256 splitters at 60 km distance. But on halving number of splitters into 128, transmission coverage is increased by 10 km with a sensitivity penalty of 0.7 dBm. Apart from this, on doubling the splitters number into 512, a transmission reach is limited only up to 20 km with 2 dBm sensitivity penalty. Similarly in Fig. 5(b) and Fig. 5(c), PM-QPSK and PM-BPSK formats exhibit -17.2 dBm and -15.6 dBm sensitivity respectively for 256 splitters at 60 km distance. But on halving number of splitters into 128, transmission coverage is increased by 10 km with a sensitivity penalty of 1.2 dBm and 4.8 dBm for PM-QPSK and PM-BPSK formats respectively, which is twice and six times of the penalty of PM-16QAM format. Apart from this, on doubling the number of splitters into 512, a transmission reach is limited only up to 20 km with 4.1 dBm and 10.6 dBm sensitivity penalty respectively. It is observed from Fig. 5(a)-5(c) that these sensitivity penalties in PM-QPSK and PM-BPSK formats are double and six fold to the sensitivity penalty of PM-16QAM format, respectively to achieve same BER.

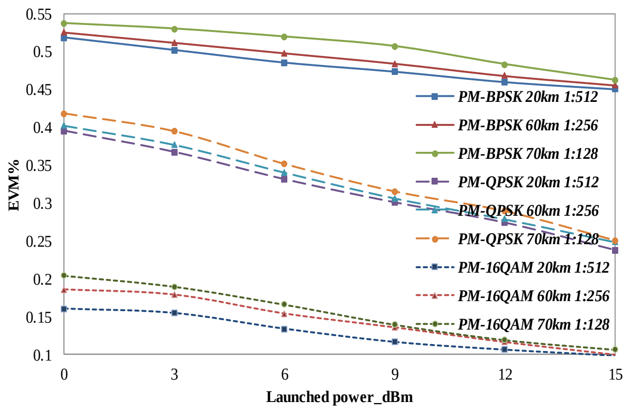

Fig. 6. EVM against the launched power for 112 Gb/s NG-PON2 at optimized fiber length (color online)

Aside from performance parameters e.g. BER and receiver sensitivity, one more parameter i.e. EVM is plotted here in Fig. 6, against the launched power. Fig. 6 shows that at 0 dBm power, EVM% is 0.16-0.20, 0.39-0.42 and 0.51-0.54 for PM-16QAM, PM-QPSK and PM-BPSK formats respectively, which is exceptionally good. While on increasing power up to 15dBm, EVM % improves with received values 0.1 for PM-16QAM, 0.24-0.25 for PM-QPSK and 0.47-0.49 for PM-BPSK formats. It is validated from Fig. 6 that EVM decreases with increasing power.

Table 1. Receiver Sensitivity Penalty

Power splitters	Fiber length	Receiver sensitivity penalty on comparison (Fig. 4) with respect to b2b transmission (Fig. 3(a))			Receiver sensitivity penalty with respect to PM-BPSK format (Fig. 4)	
		PM-BPSK	**PM-QPSK**	**PM-16QAM**	**PM-QPSK**	**PM-16QAM**
1:128	70 km	0.82-1.48 dBm	0.13-1.58 dBm	1.9-2.0 dBm	3.5-4.0 dBm	7-12 dBm
1:256	60 km	1.07-3.05 dBm	2.12-3.61 dBm	3.9-4.0 dBm	3.0 dBm	7-10 dBm
1:512	20 km	10.8-11.58 dBm	10.14-11.6 dBm	11.87-12 dBm	3.5-5.0 dBm	7-12 dBm

3.3. Power budget analysis

The power budget is defined as the difference between transmitter end output power and the receiver sensitivity requirement at receiver end. On the other hand, total fiber loss is the average losses of each component across the cable plant. Long distance and high splitting ratio leads in high link loss, hence power budget is the deciding factor of long reach NG-PON2 [29].

In Fig. 7(a)-7(c), power budget is plotted against fiber length considering 10 km-40 km for 512 splitters, 40 km-60 km for 256 splitters and 60 km-80 km for 128 splitters respectively, provided for all three modulation formats. These figures show an increasing nature of power budget with increasing fiber length for all modulation formats due to varying fiber loss. PM-16QAM format exhibits highest power budget for all splitters with values 28-34 dB for 512 splitters, 31-35 dB for 256 splitters and 32-36 dB for 128 splitters at less than 0.15 dB power budget improvement with increasing launched power from 3 dBm to 15 dBm, which is exceptionally high, as shown in Fig. 7(a)-7(c).

Similarly, PM-QPSK format exhibits a power budget of 20.5-26.5 dB for 512 splitters, 23.5-28.5 dB for 256 splitters and 24.5-28.5 dB for 128 splitters, at less than 0.7 dB power budget improvements with increasing launched power from 3 dBm to 15 dBm, as shown in Fig. 7(a)-7(c). Likewise, again on observing Fig. 7(a)-7(c), PM-BPSK format exhibits a power budget of 16-22 dB for 512 splitters, 19-24.5 dB for 256 splitters and 20-24 dB for 128 splitters, at less than 1.5 dB power budget improvement with increasing launched power from 3 dBm to 15 dBm. Table 2 is comprised of a summarized power budget analysis, for three different values of launched power, i.e. 3 dBm, 9 dBm and 15 dBm, for optimized fiber length only, i.e. 20 km for 512 splitters, 60 km for 256 splitters and 70 km for 512 splitters for each modulation format.

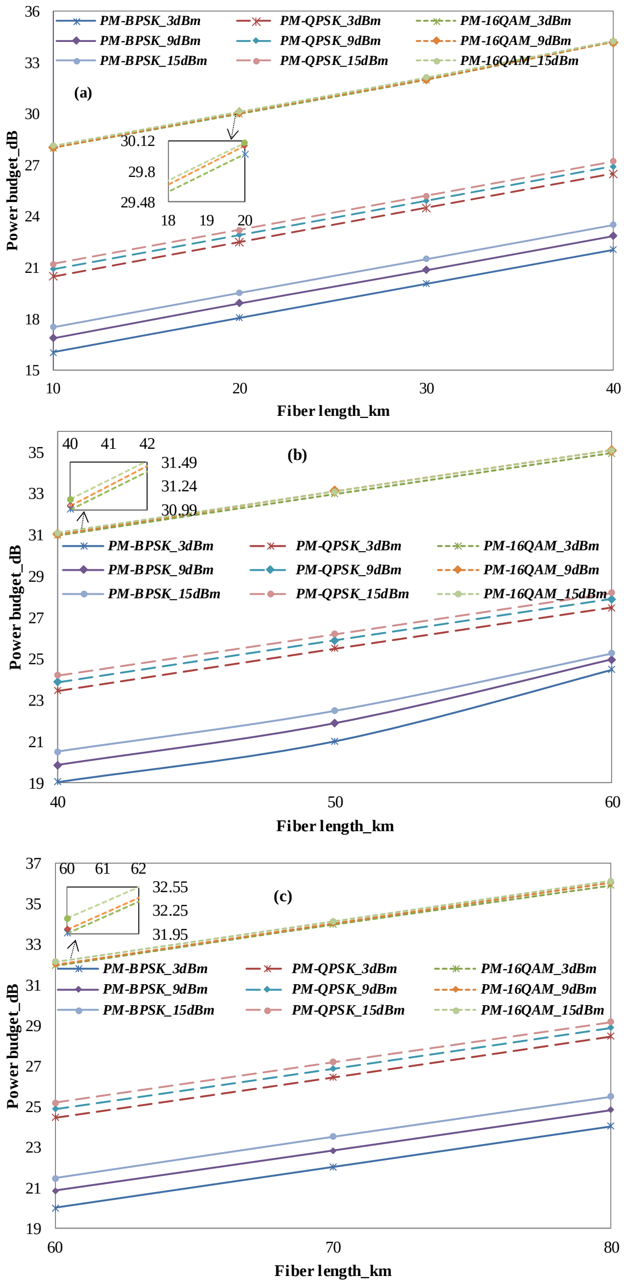

Fig. 7. Power budget plot for 112 Gb/s NG-PON2 with (a) 1:512 splitting ratio at 10-40 km fiber length, (b) 1:256 splitting ratio at 40-60 km fiber length and (c) 1:128 splitting ratio at 60-80 km fiber length (color online)

On observing Table 2, it is clear that the attenuation loss increases with increasing fiber length, while keeping fixed value of fiber loss for each splitting ratio, with total loss 15.093 dB, 20.082 dB and 21.072 dB for 512, 256 and 128 splitters respectively, irrespective of modulation format. Apart from this, a very interesting finding occurs, which reflects an identical power budget and power margin enhancement of value 3 dB and 10 dB, on noticing PM-QPSK and PM-16QAM respectively over PM-BPSK format, at fixed 15 dBm launched power, irrespective of number of splitters. This occurs due to high OSNR requirement at the receiver end on increasing constellation size of the modulation format. Also, again at fixed 15dBm launched power, while doubling the number of splitters from 256 to 512, power budget and power margin decrease with a value of 5-5.7 dB and 0.1-0.5 dB, respectively for all three modulation formats, due to deploying fiber of only 1/3 optimized fiber length (from 60 km to 20 km), which causes reduction in total fiber loss. While on halving the number of splitters from 256 to 128, power budget and power margin values decrease with a value of 1-1.7 dB and 2-3 dB respectively, for all three modulation formats, due to deploying fiber of increased 10km length (from 60 km to 70 km). Also, from Table 2, it is noticed that on increasing launched power from 3 dBm to 15 dBm, power margin increases with less than 1.5 dB for PM-BPSK format, while with less than 1 dB for PM-QPSK and PM-16QAM, irrespective of the number of splitters.

It is clearly observed from Table 2 that in the proposed NG-PON2 downstream transmission, advance polarization multiplexed formats are used at very high data rate with coherent receiver and DSP to mitigate nonlinear effects, instead of using direct modulation-direct detection (DM-DD) format with on-off keying (OOK) [29], which is unsuitable at high rate due to strong frequency chirping and preferable at low data rate to support upstream transmission and very high number of end users as well. From the obtained results, it is also analysed that for supporting high number of users, i.e. 512, 112 Gb/s PM-16QAM format exhibits excellent performance with highest information per symbol with good power budget of 34 dB, which is being reported first time in NG-PON2 with a reach of 40 km due to poor BER performance at same OSNR.

Table 2. Power Budget Evaluation

Launch Power (dBm)	**Evaluation parameters**	**512 splitters**			**256 splitters**			**128 splitters**		
		PM-BPSK	**PM-QPSK**	**PM-16QAM**	**PM-BPSK**	**PM-QPSK**	**PM-16QAM**	**PM-BPSK**	**PM-QPSK**	**PM-16QAM**
3	Receiver sensitivity (dBm)	-15.03	-19.48	-26.98	-21.47	-24.47	-31.95	-19.01	-23.44	-30.98
9		-9.90	-13.90	-21.11	-15.95	-18.89	-26.10	-13.83	-17.87	-25.03
15		-4.51	-8.20	-15.12	-10.26	-13.19	-20.10	-8.51	-12.18	-19.13
3	Power budget (dB)	18.03	22.48	29.98	24.47	27.47	34.95	22.01	26.44	33.98
9		18.90	22.90	30.11	24.95	27.89	35.15	22.83	26.87	34.03
15		19.51	23.20	30.12	25.26	28.19	35.10	23.51	27.18	34.13
3 9 15	Fiber loss (dB)	8 (for 20 km)			12 (for 60 km)			16 (for 70 km)		
	splitter loss(dB)	27.093			24.082			21.072		
	Amplifier gain (dB)	16			16			16		
	Total loss (dB)	15.093			20.082			21.072		
3	Power margin (dB)	2.94	7.39	14.88	4.38	7.38	14.87	0.94	5.37	12.90
9		3.80	7.81	15.02	4.87	7.81	15.06	1.75	5.79	12.96
15		4.42	8.10	15.01	5.18	8.10	15.02	2.44	6.11	13.06

While for lesser number of users i.e. 128 and 256, 112 Gb/s PM-BPSK format delivers best power budget of 25 dB for 80 km and 60 km coverage respectively, with low carrying capacity. Also for high number of users i.e. 512, PM-BPSK format exhibits poor BER. But, 112 Gb/s PM-QPSK format exhibits a moderate performance in terms of number of end users, transmission reach, carrying capacity, BER and power budget. Hence, there exists a trade-off among different polarization multiplexed modulation formats i.e. PM-BPSK, PM-QPSK and PM-16QAM in terms of number of users, transmission reach, information carrying capacity and BER performance. The proposed work can be extended into an upstream data transmission using RSOA at ONU [30] and a flexible colourless PON by providing tuneable transmitter and receiver at ONU, with centralized wavelength control using OFDM or using Nyquist sinc pulse shaping [12].

4. Conclusion

Present work reports downstream transmission of 112 Gb/s coherent NG-PON2 using PM-BPSK, PM-QPSK and PM-16QAM modulation formats with 2, 4 and 16 constellation points respectively. During analysis it is verified that as constellation size increases, OSNR requirement at receiver increases, which results in high receiver sensitivity penalty. Hence, PM-BPSK format requires only 2/3 OSNR value than that of PM-16QAM format to achieve BER = 1×10^{-3}. Observed receiver sensitivity penalty of PM-16QAM format is very small, either on doubling or halving the number of splitters, which is high in PM-QPSK and PM-BPSK formats. This simulative study also shows a trade-off between the number of users, transmission reach, information carrying capacity and BER performance during choosing a suitable modulation format for NG-PON2. In the considered scenario, PM-16QAM, PM-QPSK and PM-BPSK formats exhibit respectively highest, moderate and lowest power budget for all splitters, which improves with increasing fiber length. But on increasing the launched power, power margin increases, irrespective of the number of splitters. Hence, the proposed NG-PON2 architecture can be a good solution to existing GPON based broadband connectivity, while supporting a point to multipoint network, with delivering high data rate, high transmission capacities and increased power budget.

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