

5G fronthaul/backhaul hybrid FSO-fiber link based symmetric 1.6Tbps MDM-NGPON2 using DP-QPSK modulation scheme

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A symmetric bidirectional mode division multiplexing (MDM) based next generation passive optical network stage 2 (NGPON2) design is presented in this paper. Utilization of dual polarization quadrature phase shift keying (DP-QPSK) modulation scheme over hybrid free space optics (FSO)/fiber link indicates that the proposed design offers faithful 200 km fiber and 50 m FSO range at mode 0. Minimum received power of -18 dBm and maximum optical signal to noise ratio of 36 dB are achieved successfully. Also, the results indicate that DP-QPSK scheme allows better system performance than others schemes. Comparison of the proposed model indicates its superiority over other recent works.

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Keywords: NG-PON2, MDM, DP-QPSK, PON, FSO

1. Introduction

The telecommunication sector has exhibited a phenomenal rise in the smart devices usefulness over the last ten years. Consequently, the transmission rate requirement for furnishing to the communication requests of the users has higher main-folds. Fifth generation (5G) mobile networks evolution is a result of widespread bandwidth requirements of the current era. 5G is assumed to offer end users with high data rate, ultra-low latency as well as ubiquitous access. Currently, 5G cellular backhaul/fronthaul depend mostly on two communication technologies: microwave radio links and optical fibers. Optical fibers offers high reliability and capacity but require expensive initial investment. Also, the fixed fiber cable connections provide restricted flexibility. Alternatively, microwave has high flexibility and but provide license spectrum, lower transmission rate and low energy efficiency. Free space optics (FSO) is being regarded as a substitute to microwave that allows wireless connectively above 300GHz unlicensed band. Contrary to microwave, FSO can allow high transmission rate links between two distinct points upto thousands kilometers. It also provides an inherent security, resilience to electromagnetic interference and high reuse factor [1].

Unluckily, FSO is problematic in serve weather conditions and atmospheric turbulences. Its accessibility diminishes heavily in the condition of fog as well as rain. Thus, wireless connection reliability is of main consideration if deploying a FSO link. Accordingly, a hybrid backhaul/fronthaul incorporating FSO and fiber can be a effective solution. Fiber reliability over longer ranges

can be accompanied with the data carrying potential and cost effectiveness of FSO over shorter ranges. Again, the fiber cost over point-to-point communication can be minimized by offering connections utilizing a point-to-multipoint based passive optical network (PON) [1]. Gigabit-PON (GPON) and Ethernet-PON (EPON) have been employed. The recent PONs are generally gigabit Ethernet PON (GEAPON) at 2.5/1.25 Gbps data rate. Owing to rapidly increased call on bandwidth, the recent PONs are to be updated to 10G-class-PONs, incorporating 10G-EPON, 10G-PON and next generation PON2 (NGPON2) that are standardized at 10 Gbps downstream transmission rate. Time and wavelength division multiplexing (TWDM) is implemented in NGPON2 to enhance the bandwidth capacity. 4 λ s wavelengths TWDM-PON are utilized to offer high downlink transmission rate of 40Gbps. Also, 25/50G EPON, super-PON as well as high bandwidth PON are now some future access networks in the means of standardization [2].

Recently, a demonstration of hybrid FSO/fiber system under the impact of light sand storm condition has been presented [3]. It is shown that hybrid FSO/fiber system offer high data rate of 1.08 Tbps over 22 km fiber and 100 m FSO link. In [4], an optical code division multiple access (OCDMA) scheme based 1 Gbps hybrid fiber/FSO system has been experimentally demonstration. It is shown that the system at 50 km fiber and 2 km FSO link offer 1 Gbps data rate under the impact of multiple-access interference, background noise, thermal noise and shot noise. In another work [5], a 10 Gbps hybrid FSO and passive optical network (PON) system over 25 km fiber and 160 m FSO range has been demonstrated. Also in [6],

a 40/20 Gbps bidirectional hybrid wavelength division multiplexing (WDM) PON and FSO over 60 km fiber and 650 m FSO range has been presented. In [7], a WDM-FSO system over 25 km single mode fiber (SMF) and 6m FSO transmission channels at 10 Gbps data rate has been proposed. Moreover, a hybrid PON-FSO system over 20 km fiber and 300 m FSO transmission length at 2.5 Gbps data rate has been proposed [8]. In [9], a full-duplex 16/64-quadrature amplitude modulation (QAM) incorporated orthogonal frequency division multiplexing (OFDM) system at 60 and 25 GHz for downstream and upstream transmission respectively has been demonstrated. The results show that SMF, FSO and radio wireless transmission range of 10 km, 100 m and 2 m respectively, can be obtained successfully. In [10], a 10 Gbps WDM-PON incorporating hybrid fiber-FSO link over 50 km SMF and 880 m FSO link has been demonstrated. Besides this, a star-ring based 40/10 Gbps TWDM-PON over 70 km SMF and 180 m FSO range has been demonstrated [11]. A WDM-FSO system over 50 km SMF and 940 m FSO link at 40 Gbps data rate has been investigated [12].

Distinct multiplexing schemes have been considered to meet the high capacity requirement by using variations in the distinct physical wave parameters such as amplitude, phase, frequency and polarization in optical domain. Mode division multiplexing (MDM) scheme is employed for transferring distinct optical spatial modes via the single core fiber. Utilizing this scheme, the transmission capabilities of single fiber can be boost by 'N' times. Further, MDM based TWDM-PON may be demonstrated to widen the network capacity for a definite set of channels a fewer number of laser sources are requisite and are comprehensively researched for applying the fast optical PONs [13].

Besides, in [14], integrated MDM-OCDMA for satellite communication over wireless range of 5000 km at 10Gbps traffic rate is realized successfully. In [15], an OFDM based light fidelity system over 100 km fiber with 20 m wireless range at 200Gbps traffic rate is investigated. In [16], a MDM-NGPON design is realized over 100 km fiber with 0.8 km FSO range at 10 Gbps traffic rate. In [17], a PON-MDM system is proposed over 100 m fiber with 580 m FSO range at 10 Gbps.

Here, a bidirectional symmetric 16×100 Gbps dual polarization quadrature phase shift keying (DP-QPSK) modulation based MDM-NGPON2 system over hybrid

FSO-fiber link using donut modes 0 and 1 is reported. The performance is measured for varied fiber range, FSO range and for distinct modulation techniques.

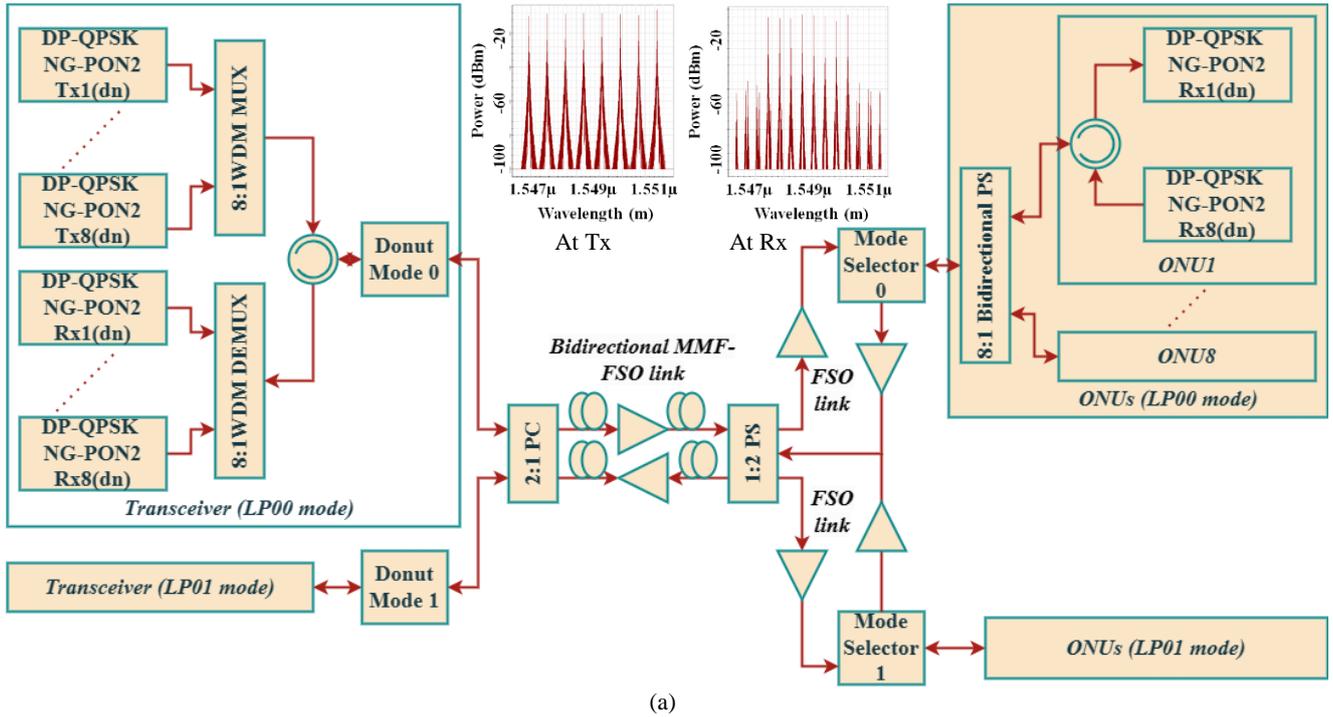
Organization of the paper: Section 2 indicates the proposed architecture of DP-QPSK modulation based MDM-NGPON2 system over hybrid FSO-fiber link. Section 3 illustrates results as well as discussion accompanied by conclusion with in Section 4.

2. Proposed architecture

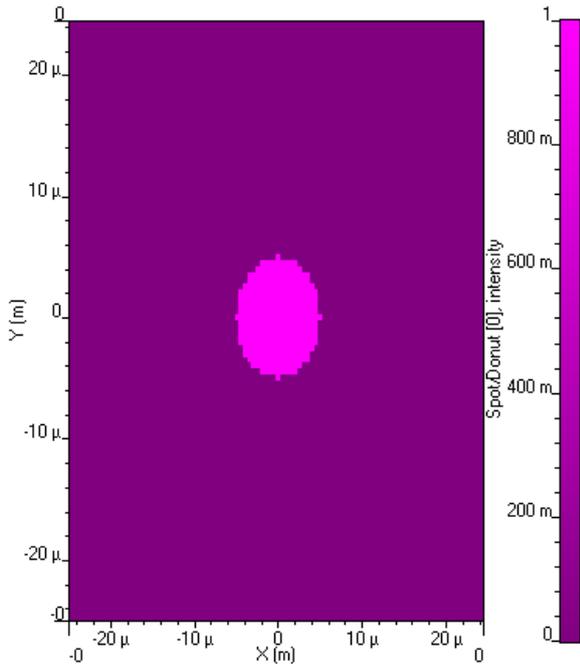
Fig. 1(a) illustrates the schematic block diagram of bidirectional symmetric 16×100 Gbps DP-QPSK modulation based MDM-NGPON2 system over hybrid FSO-fiber link using donut modes 0 and 1. For sixteen downlink and sixteen uplink signals, different transceivers operating at different modes, are used at both transmitter and receiver side [18–23]. Eight downlink (1596-1601.6 nm) and eight uplink (1527-1532.6 nm) signals having 0.8 nm channel space are generated by DP-QPSK modulator employed NG-PON2 transceivers for bidirectional transmissions at two different linearly polarized (LP) modes namely LP00 and LP01. An 8:1 WDM multiplexer (WDM MUX) and WDM de-multiplexer (DEMUX) are used to multiplex and de-multiplex the generated downlink and received uplink signals to/from an optical circulator followed by donut mode 0 respectively for transceiver operating at LP00. Similarly, the signals from another transceiver operating at LP01 are passed through bidirectional components like 2:1 power combiner (PC) followed by SMF, backhaul FSO, SMF and then 1:2 power splitter (PS).

Incoming signals are passed via fronthaul bidirectional FSO links followed by mode selector 0 and mode selector 1 to distribute the information to different ONUs operating at LP00 and LP01 modes. In each ONU, the incoming mode signals are passed through 8:1 bidirectional PS and optical circulator to distribute and obtained the downlink and uplink DP-QPSK modulation based NGPON2 signals respectively [24,25].

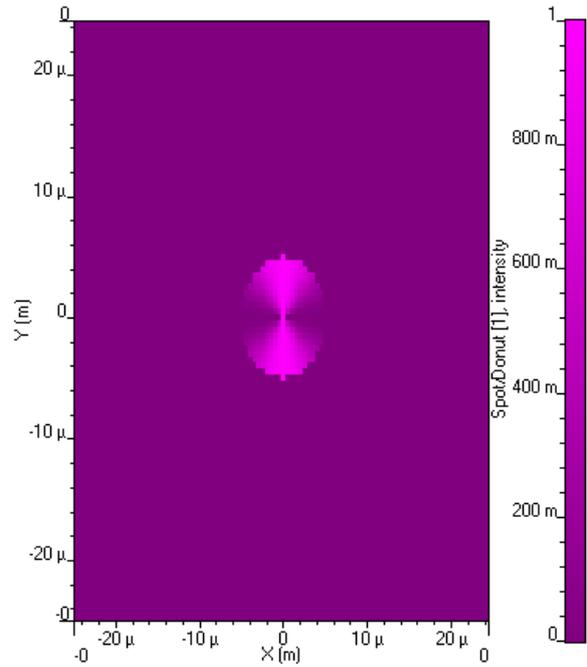
Fig. 1(b) and 1(c) indicate the donut mode 0 and 1 respectively. Fig. 2 indicates the designs of DP-QPSK modulation scheme for bidirectional transmission in the proposed design.



(a)



(b)



(c)

Fig. 1. (a) Block diagram of DP-QPSK modulation based MDM-NGPON2 system over hybrid FSO-fiber link; donut mode (b) 0 and (c) 1 (color online)

For downlink transmission as depicted in Fig. 2(a), a serial parallel converter (SPC) splits the generated information at 100 Gbps data streams by pseudorandom bit sequence, each of which is forwarded towards distinct QPSK modulators. To produce DP-QPSK signals, the outputs from QPSK modulators are combined through a polarization beam combiner (PBC). A polarization beam splitter (PBS) generates two signals at 1596 nm

wavelength with equal power as well as same polarization. For reception, the received signals from mode selector are fed to the coherent differential phase-shift keying (DPSK) receiver as well as digital signal processor (DSP) module to remove the channel distortion as depicted in Fig. 2(b). To split the incoming signal into dual orthogonally polarized beams a decision polarization component is employed and then the signals are further fed to the two

PSK decoders 1 and 2. The combined signals from parallel to serial converter (PSC) block are analysed in a bit error rate (BER) test set. Likewise, the uplink transmission, DP-QPSK signals are generated at 1527 nm wavelength as in downlink DP-QPSK modulated based transmitter as

depicted in Fig. 2(c). In uplink transmission, a buffer selector is employed to select the latest iteration of uplink signals as shown in Fig. 2(d) [26]. Various performance parameters are tabulated in Table 1 [24,25].

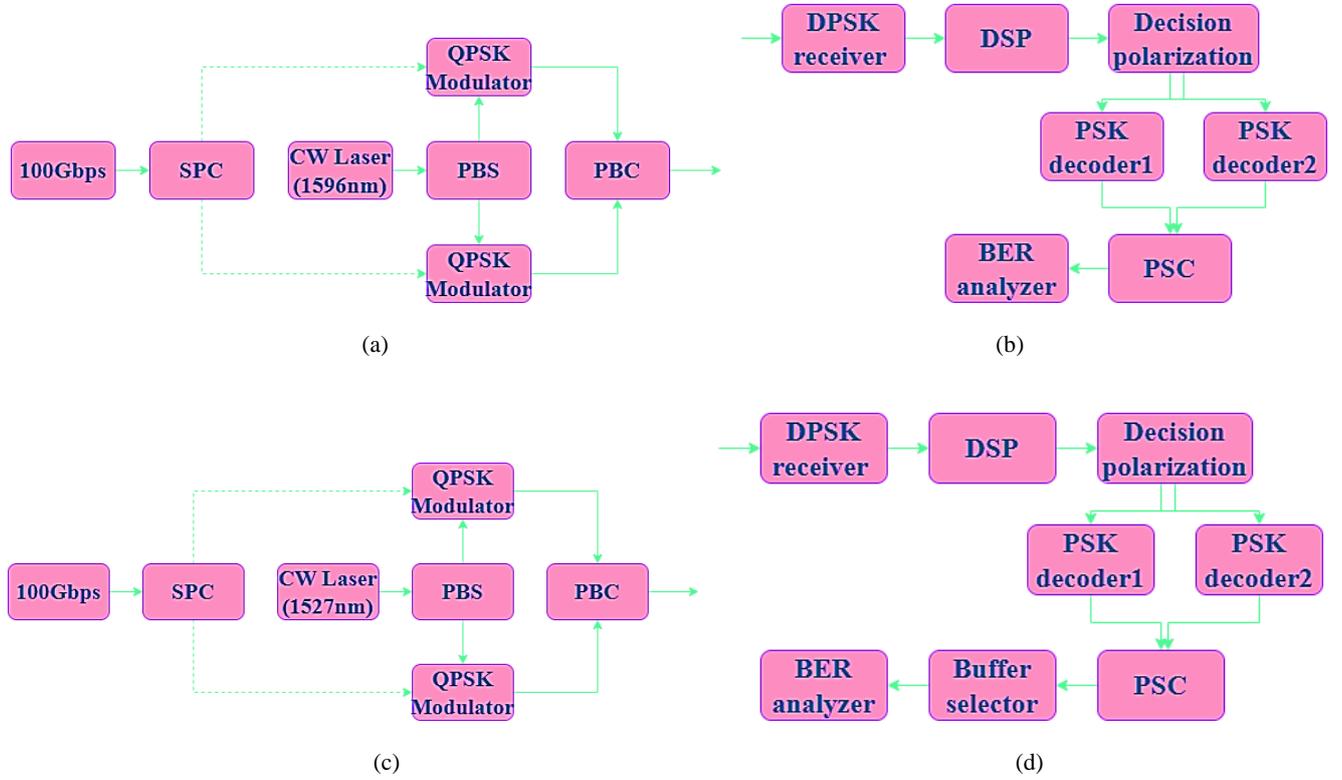


Fig. 2. Designs of DP-QPSK modulation scheme for (a) downlink transmitter, (b) downlink receiver, (c) uplink transmitter and (d) uplink receiver (color online)

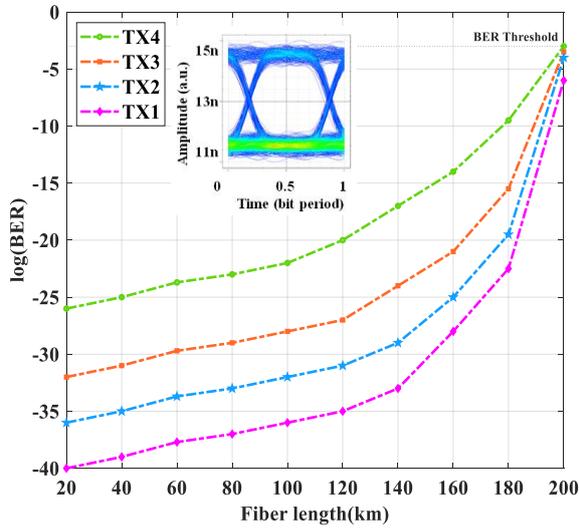
Table 1. Performance parameters [24,25]

Parameters	Values
Wavelengths	1596-1601.6 nm (for DN), 1527-1532.6 nm (for UP)
Throughput	100 Gbps
Input power	10 dBm (for DN), 0 dBm (for UP)
Reference wavelength	1550 nm
No. of channels	16
SMF length	20-200 km
FSO range	50-100 m
Tx/Tx aperture diameter	15 cm
Beam Divergence	0.25×10^{-3} rad
Dispersion	16 ps/nm×km
Attenuation	0.20 dB/km

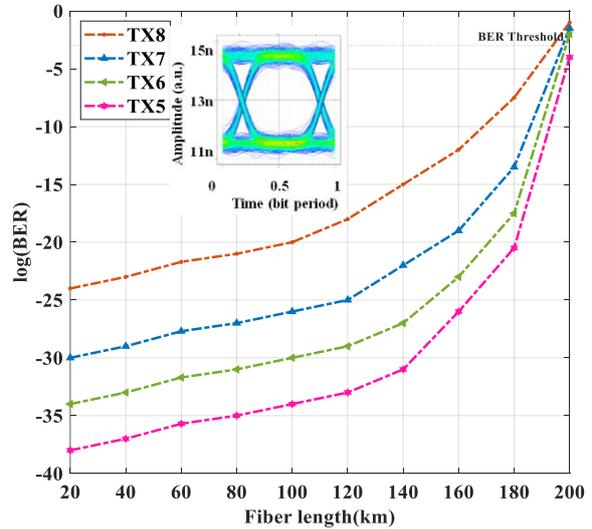
3. Results and analysis

The performance of the proposed design is analysed for varied fiber length, FSO range, optical signal to noise

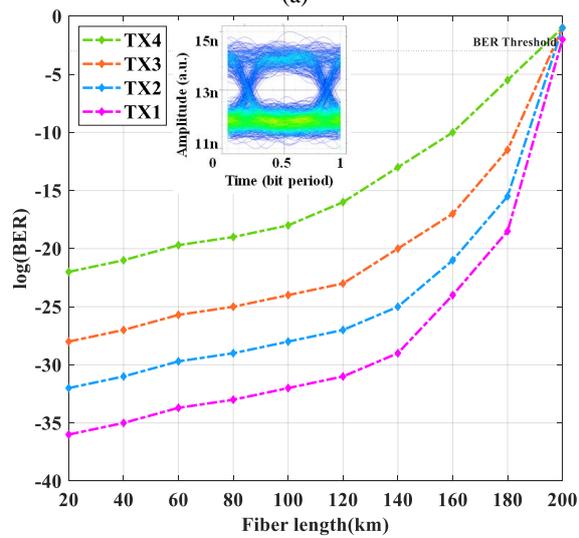
ratio (OSNR) and for distinct modulation schemes in terms of BER, received optical power and eye diagrams for various transceivers at modes 0 and 1 in both downlink along with uplink directions.



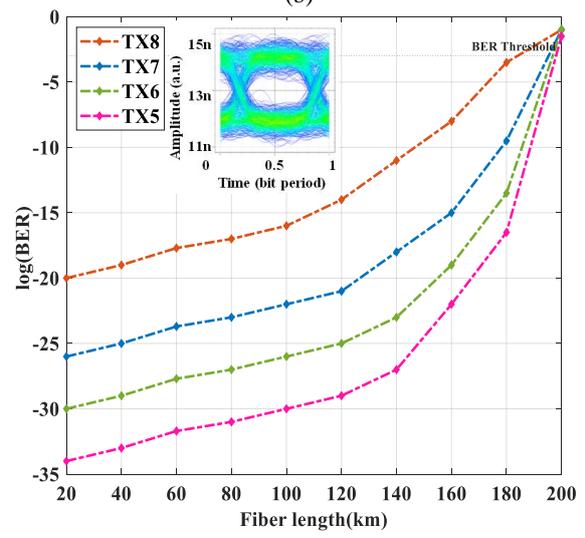
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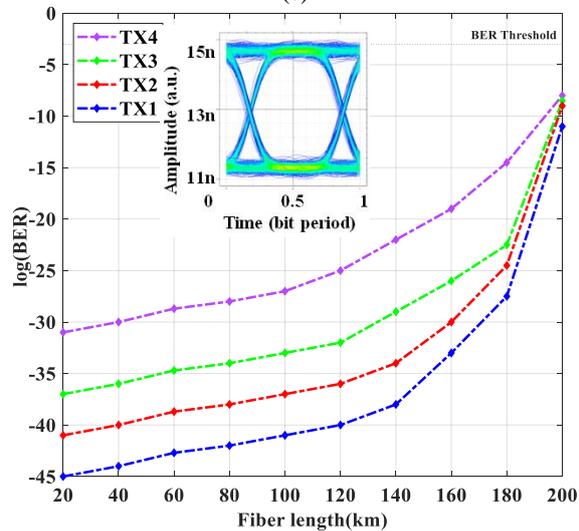
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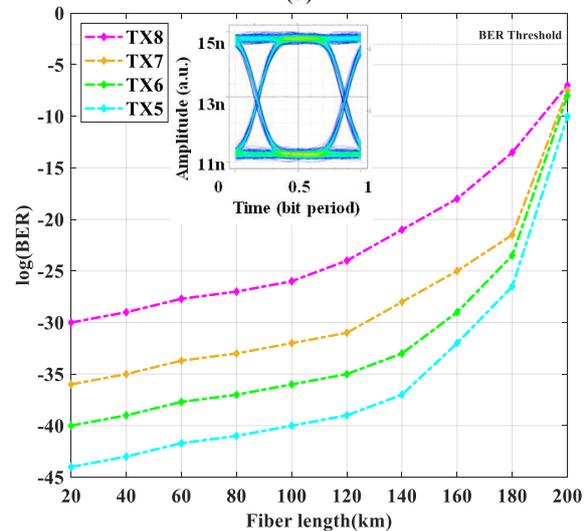
(c)



(d)



(e)



(f)

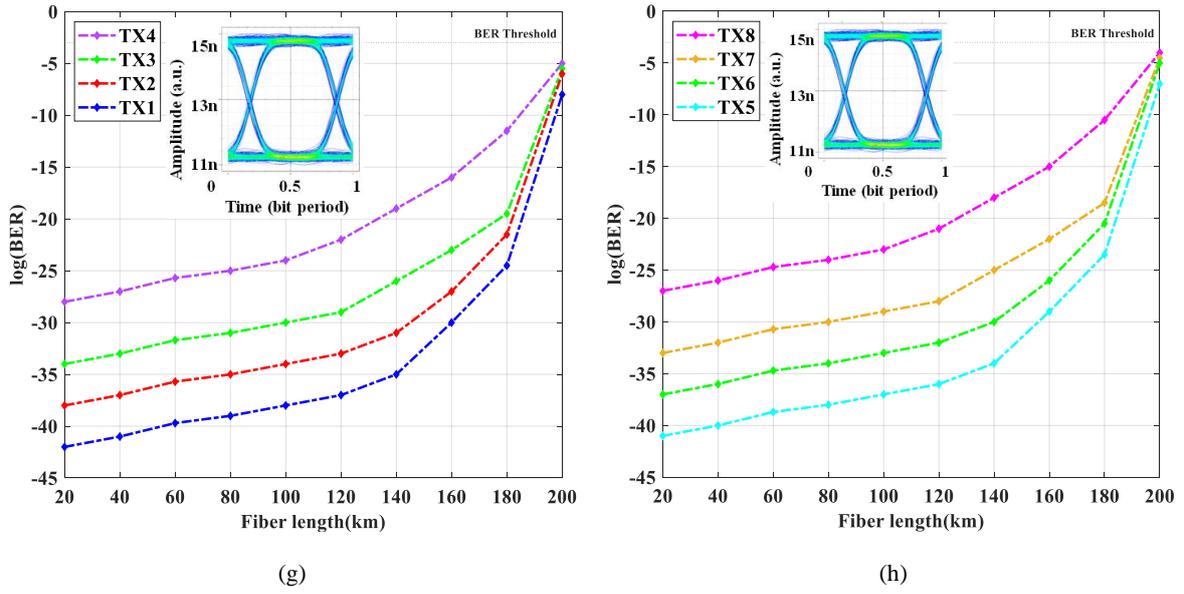


Fig. 3. Calculated BER for varied fiber length for downlink transmission at (a) mode 0 for TR1-TR4, (b) mode 1 for TR5-TR8, (c) mode 1 for TR1-TR4, (d) mode 1 for TR5-TR8; uplink transmission at (e) mode 0 for TR1-TR4, (f) mode 1 for TR5-TR8, (g) mode 1 for TR1-TR4, (h) mode 1 for TR5-TR8; Insets: eye patterns at 200 km length (color online)

The BER of the proposed design in terms of complementary error function, $erfc$ as well as signal to noise ratio, SNR is defined as [24,25]:

$$BER = \frac{1}{2} erfc \sqrt{SNR/8} \quad (1)$$

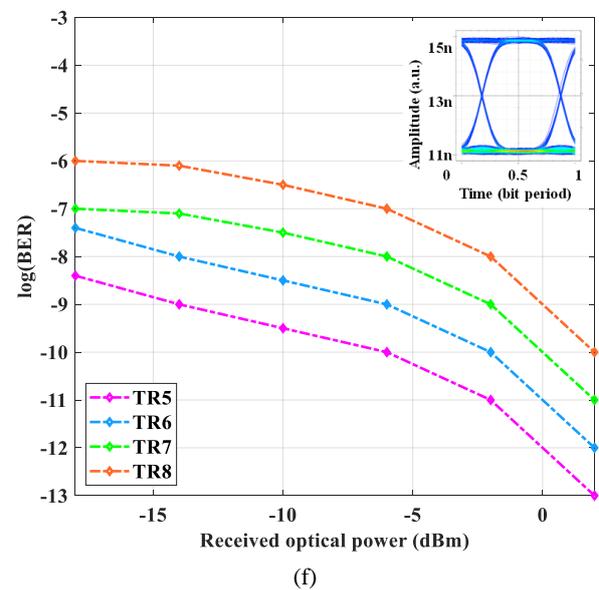
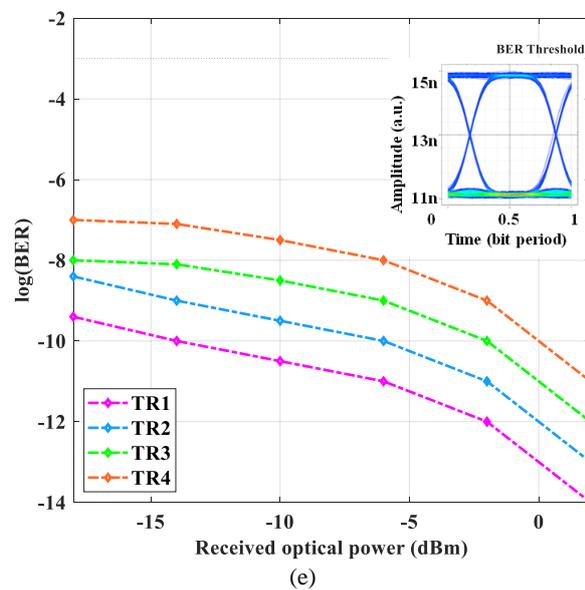
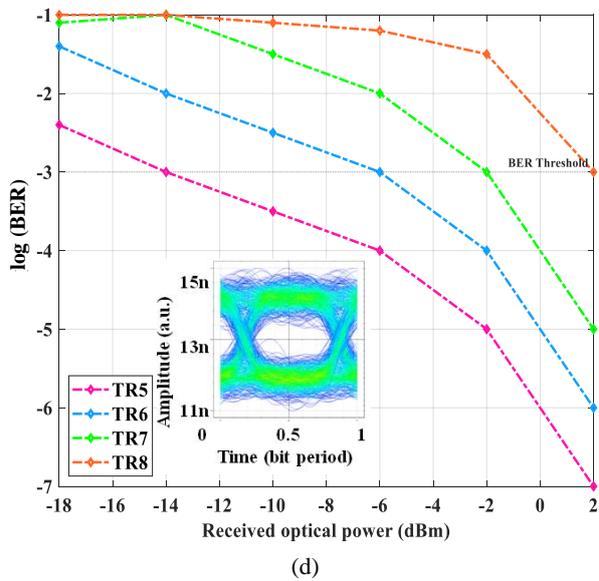
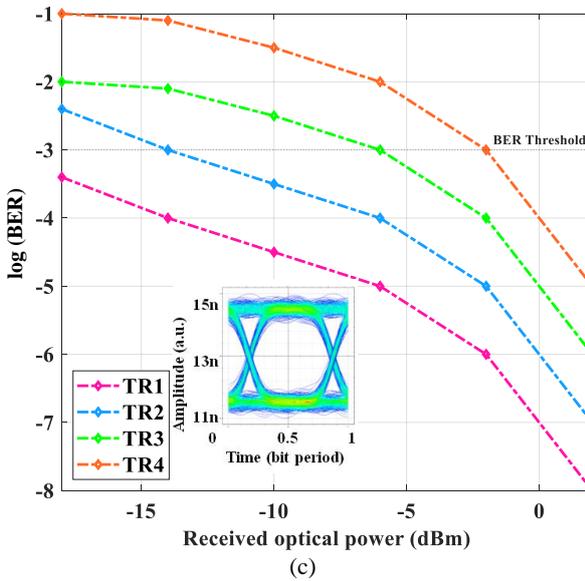
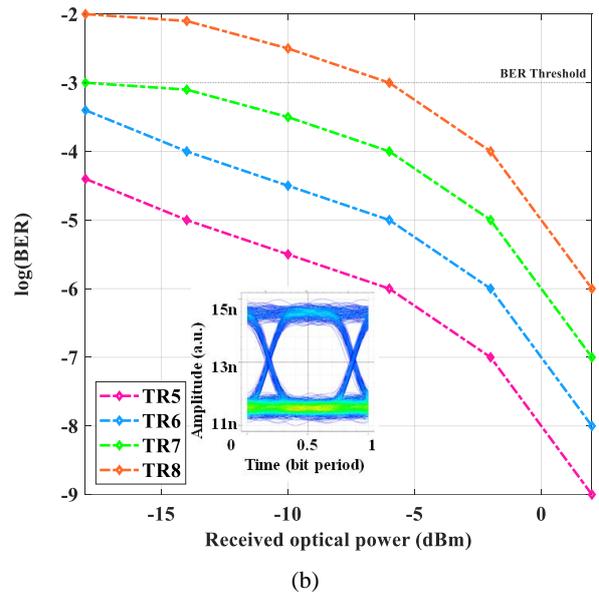
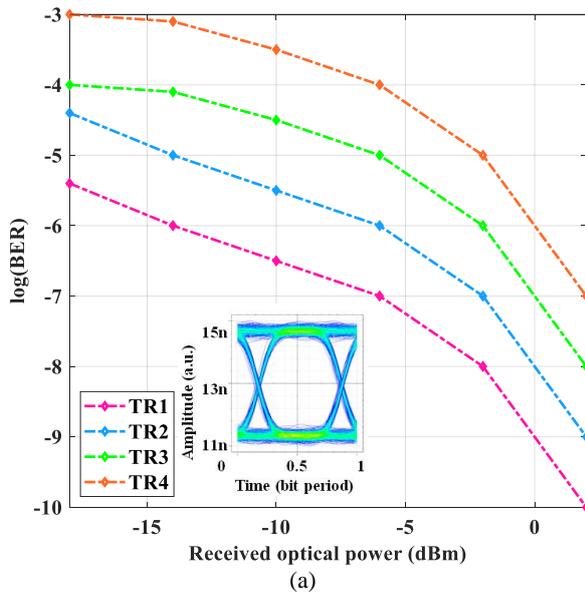
Also, the OSNR can be calculated as follow:

$$OSNR = \text{Signal Power}(dB) - \text{Noise Power}(dB) \quad (2)$$

Fig. 3 indicates the calculated BER for varied fiber length for downlink and uplink transceivers (TR1-TR8) operating at mode 0 and mode 1 over 50 m FSO range at 100 Gbps throughput. It is notified that with the increase in transmission length, BER values improve and hence system performance diminishes for all transceivers. Out of all transceivers, TR1 performs best than others in mode 0 compared to mode 1 in uplink direction over downlink direction. Performance is measured at BER limit of 10^{-3} for various TRs. Fig. 3(a) indicates that at BER limit, the maximum obtained fiber distance for downlink signals for TR1 (1596 nm), TR2 (1596.8 nm) and TR3 (1597.6 nm) operating at mode 0 is more than 200 km while for TR4 (1598.4 nm) for maximum fiber reach is 200 km. Fig. 3(b) illustrates that maximum obtained length for TR5 (1599.2 nm), TR6 (1600 nm), TR7 (1600.8 nm) and TR8 (1601.6 nm) is 200, 197, 195 and 193 km respectively at mode 0. Also, downlink TR1, TR2, TR3 and TR4 the highest range is 197, 193, 191 and 190 km respectively; while for TR5, TR6, TR7 and TR8 the obtained range is 193, 192, 191 and 182 km respectively, operating at mode 1 shown in Fig. 3(c) and 3(d). Further, for uplink signals the maximum achieved fiber length is >200 km for all

transceivers i.e. TR1-TR8 (1527-1532.6 nm) as shown in Fig. 3(e)-3(h). However, signals performs better in uplink direction at mode 0 followed by mode 1. The figured eye patterns at 200 km fiber range at mode 0 and 1 for both TR1 and TR5 strengths the above analysis. The decrease in performance is due to multiple TRs signals which can limit the transmission of presence of fiber impairments like interference, four wave mixing, dispersion and attenuation. Mode 0 i.e. fundamental mode operates better compared to mode 1 in the proposed design because mode 1 or higher modes are highly absorbed/scattered as compared to mode 0.

Fig. 4 indicates the calculate BER for the downlink and uplink transmission operating both at mode 0 and mode 1 for various TRs over 20 km fiber and 50 m fiber range at 100 Gbps throughput. Fig. 4(a) and 4(b) illustrate that the downlink TR1, TR2, TR3, TR4, TR5, TR6, TR7 and TR8 operating at mode 0, the minimum received power at photodetector is <-18 , <-18 , <-18 , -18 , <-18 , <-18 , -18 and -6 dBm respectively under BER limit. Also, for downlink TR1, TR2, TR3, TR4, TR5, TR6, TR7 and TR8 operating at mode, <-18 , -14 , -6 , -2 , -14 , -6 , -2 and 2 dBm received power is reported respectively as seen in Fig. 4(c) and 4(d). Again, the minimum received power for uplink transmission in TR1, TR2, TR3, TR4, TR5, TR6, TR7 and TR8 operating at both mode 0 and mode 1 is <-18 dBm as depicted in Fig. 4(e)-4(h). It is observed that TR1 performs best than others in mode 0 compared to mode 1 in uplink direction over downlink direction. The corresponding eye patterns for TR1 and TR5 for both modes 0 and 1 at -18 dBm received power illustrate the optimum performance of the design in uplink and downlink transmission. More and wide eye opening means clear received signal, however, distorted signals are observed for eye closure patterns.



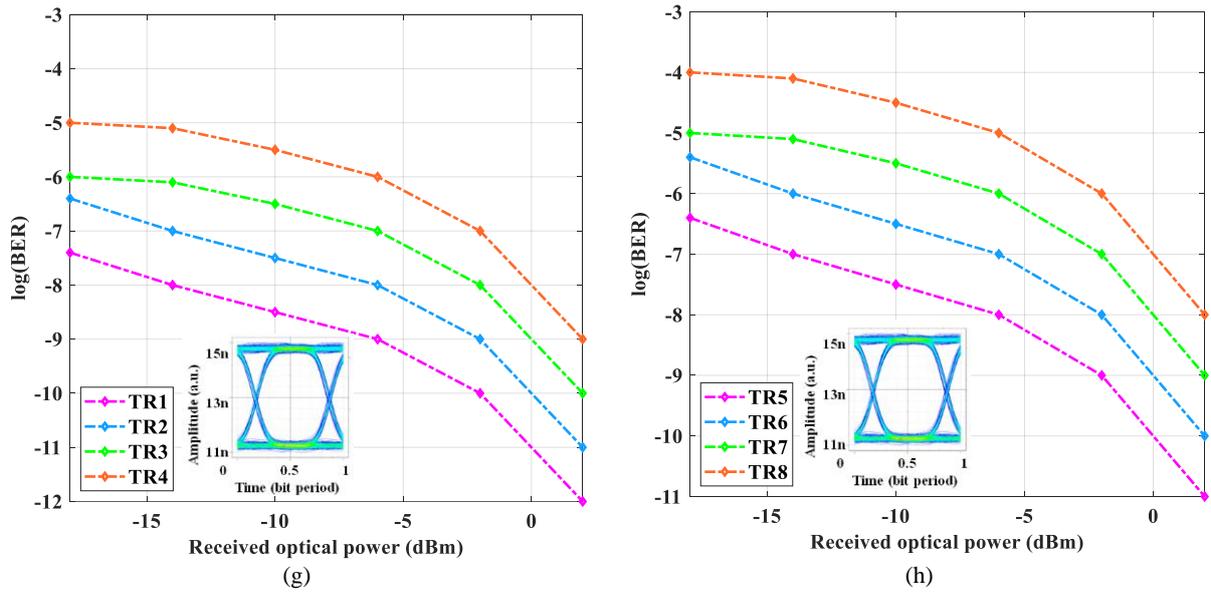


Fig. 4. Calculated BER for downlink transmission at (a) mode 0 for TR1-TR4, (b) mode 1 for TR5-TR8, (c) mode 1 for TR1-TR4, (d) mode 1 for TR5-TR8; uplink transmission for (e) mode 0 for TR1-TR4, (f) mode 1 for TR5-TR8, (g) mode 1 for TR1-TR4, (h) mode 1 for TR5-TR8; Insets: corresponding eye patterns at -18dBm received power (color online)

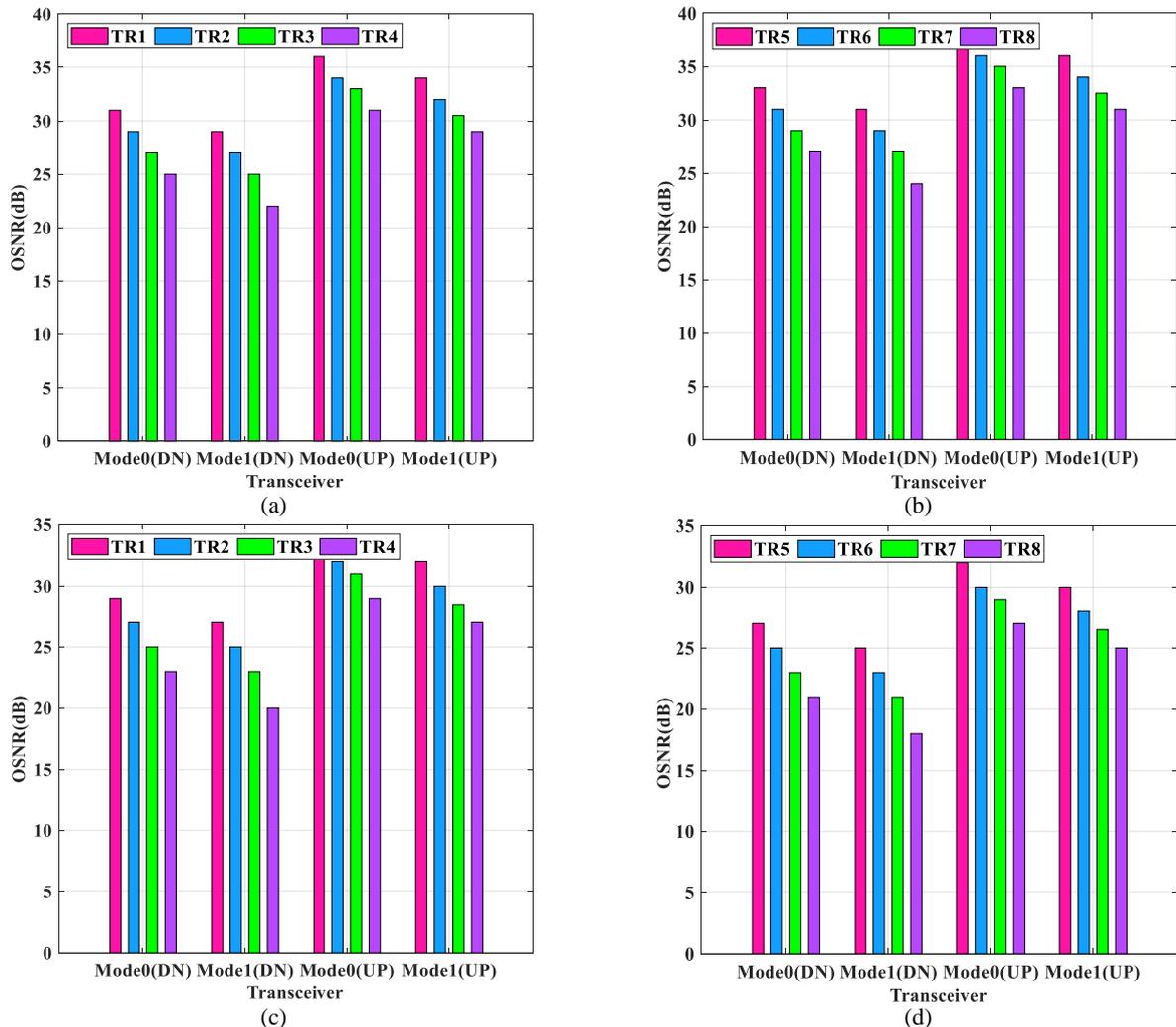


Fig. 5. Calculated OSNR for downlink and uplink transmission operating at different modes at 50 m FSO range for (a) TR1-TR4, (b) TR5-TR8; at 100 m FSO range for (c) TR1-TR4, (d) TR5-TR8 (color online)

Fig. 5 defines the calculated OSNR for the for downlink and uplink transmission operating at different modes at 10 km fiber and varied FSO range for distinct TRs. It is depicted that TR1 outperforms other TRs in both uplink as well as downlink transmission for both operating modes. In downlink, the highest obtained OSNR for TR1 at mode 0 and mode 1 is 32 and 29 dB respectively in downlink; however, the maximum OSNR value obtained

for mode 0 and 1 is 36 and 34 dB respectively in uplink, at 50 km FSO range as depicted in Fig. 5(a). For the same range, in downlink, the maximum achieved OSNR for TR5 at mode 0 and mode 1 is 33 and 31 dB respectively; while 37 and 36 dB OSNR value is obtained for TR5 at mode 0 and mode 1 respectively, in uplink as depicted in Fig. 5(b).

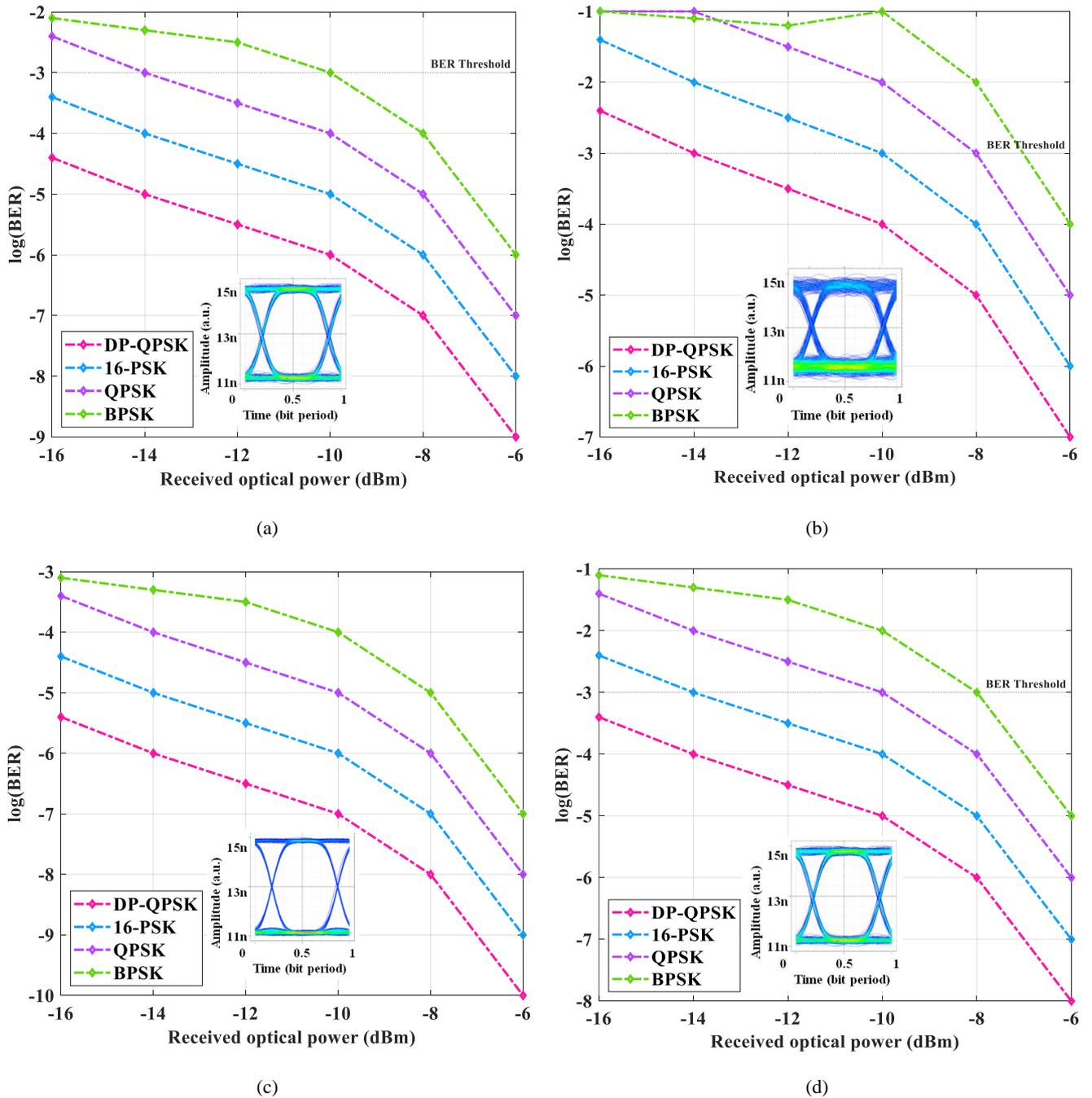


Fig. 6. Calculated BER performance at (a) mode 0 in downlink, (b) mode 1 in downlink, (c) mode 0 in uplink and (d) mode 1 in uplink direction for different modulation schemes for TR1. Insets: corresponding eye patterns at -16dBm received power (color online)

Moreover, over 100 m FSO range, the maximum OSNR of 29 and 27 dB at mode 0 and 1 respectively, in

downlink; 34 and 32 dB at mode 0 and 1 respectively, for TR1 at mode0 in uplink for TR1 is obtained successfully

as shown in Fig. 5(c). The highest obtained OSNR for TR5 at mode 0 and mode 1 is 27 and 25 dB at mode 0 and 1 in downlink; although in uplink, the OSNR of 33 and 30 dB at mode 0 and 1 respectively, is obtained in Fig. 5(d).

Fig. 6 illustrates the calculated BER analysis of bidirectional proposed design using different modulation schemes at both modes 0 and 1 over 10m FSO and 10 km fiber range for TR1. It is seen that DP-QPSK illustrates best performance over 16-PSK, QPSK and BPSK in both uplink as well as downlink transmission. Also, the received modulated signals operate best for mode 0 compared to 1. For downlink, Fig. 6(a) indicates that the minimum received power for DP-QPSK, 16-PSK, QPSK and BPSK modulation schemes is <-16, <-16, -14 and -10 dBm respectively, at mode 0. Also, the minimum received

power of -14, -10, -8 and -7 dBm is obtained for DP-QPSK, 16-PSK, QPSK and BPSK schemes respectively, at mode 1 as indicated in Fig. 6(b). As reported in Fig. 6(c) and 6(d), for uplink, the minimum received power of <-16 dBm is obtained for various schemes at mode 0. While the minimum received power of <-16, -14, -10 and -8 dBm for DP-QPSK, 16-PSK, QPSK and BPSK schemes respectively obtained.

Besides this, obtained eye patterns also indicate the above statements. Table 2 indicates the comparison of proposed design with existing ones. Again, the comparison of related previous works with existing ones indicate that the proposed design performs best in terms of maximum coverage distance, high throughput, high scalability, high flexibility and acceptable cost.

Table 2. Comparison of the proposed work with recent works

Ref.	Fiber Length (km)	FSO range (m)	Throughput (bps)	Scalability	Flexibility	Cost	Complexity
[3]	22	100	1.08T	Low	Medium	High	High
[4]	50	2000	1G	Medium	Low	Low	Low
[5]	25	160	10G	Low	Medium	High	High
[6]	60	650	40G	Low	Medium	Low	Low
[7]	25	6	10G	High	Medium	Medium	Moderate
[8]	20	300	2.5G	Low	Medium	Medium	Moderate
[9]	10	100	Not defined	Medium	Low	High	High
[10]	50	880	10G	Medium	Low	Medium	Moderate
[11]	70	180	40G	Medium	Low	Low	Low
[12]	50	940	40G	Medium	Low	Low	Low
This work	200	50	1.6T	High	High	Medium	Moderate

4. Conclusion

A symmetric 16×100 Gbps DP-QPSK modulation based MDM-NGPON2 system over hybrid FSO-fiber link using donut modes 0 and 1 is presented. It is concluded that out of various transceivers, the transceiver operating at 1596 nm in downlink and 1527 nm in uplink performs best at mode 0 followed by mode 1. The successful bidirectional transmission range of 200 km over fiber with 50 m FSO range at downlink and uplink transceivers (TR1-TR8) operating at mode 0 and mode 1 over 50 m FSO range at 100 Gbps throughput for sixteen channels is obtained at BER limit of 10^{-3} . The minimum received power for the proposed work is -18 dBm for both uplink and downlink transmission. Also, the maximum OSNR of 36 dB in uplink and 32 dB in downlink transmission is achieved over 10 km fiber and 50 m FSO range at 100 Gbps. The FSO range can be extended upto 100 m with OSNR of 34 dB in uplink and 29 dB in downlink transmission. Besides this, out of all modulation schemes, DP-QPSK offers best results with received power of -16 dBm in unlink and -14 dBm in downlink transmission. The comparison performance of the proposed work illustrates its superior performance over other. In future, it can be utilized for NG-PON3 based 5G network having

fronthaul/backhaul applications. However, the system also adds in system complexity as well as cost for 6G based networks if advanced modulation approaches are incorporated.

References

- [1] A. Mukhopadhyay, M. Ruffini, J. Light. Technol. **41**, 17 (2022).
- [2] Y. Lu, L. Cao, S. Wu, X. Mi, L. Jiang, Y. Zhai, M. Bi, Opt. Fiber Technol. **74**, 103053 (2022).
- [3] M. A. Esmail, A. Ragheb, H. Fathallah, M. S. Alouini, IEEE Photonics J. **9**, 1 (2017).
- [4] J. Ji, Q. Huang, X. Chen, L. Sun, IEEE Photonics J. **11**, 1 (2019).
- [5] C. H. Yeh, W. P. Lin, C. M. Luo, Y. R. Xie, Y. J. Chang, C. W. Chow, IEEE Access **7**, 138927 (2019).
- [6] P. Mandal, N. Sarkar, S. Santra, B. Dutta, B. Kuir, K. Mallick, A. S. Patra, Opt. Commun. **507**, 127594 (2022).
- [7] C. H. Yeh, B. S. Guo, Y. J. Chang, C. W. Chow, C. S. Gu, Opt. Commun. **435**, 394 (2019).
- [8] S. S. Jaffer, A. Hussain, M. A. Qureshi, J. Mirza, K. K. Qureshi, Opt. Fiber Technol. **63**, 102500

- (2021).
- [9] L. Vallejo, B. Ortega, J. Mora, D. N. Nguyen, C. Guerra, J. Bohata, J. Spacil, S. Zvanovec, *Opt. Fiber Technol.* **77**, 1 (2023).
- [10] C. H. Yeh, H. S. Ko, S. K. Liaw, L. H. Liu, J. H. Chen, C. W. Chow, *IEEE Photonics J.* **14**, 1 (2022).
- [11] C. H. Yeh, W. H. Hsu, B. Y. Wang, W. Y. You, J. R. Chen, C. W. Chow, S. K. Liaw, *IEEE Access* **8**, 189982 (2020).
- [12] C. H. Yeh, J. R. Chen, W. Y. You, C. W. Chow, *IEEE Access* **8**, 96449 (2020).
- [13] A. Sharma, S. Kaur, N. Nair, K. S. Bhatia, *Optik* **257**, 168855 (2022).
- [14] M. Kumari, V. Arya, *Opt. Quantum Electron.* **56**, 546 (2024).
- [15] M. Kumari, M. Banawan, V. Arya, S. K. Mishra, *Photonics* **10**, 1384 (2023).
- [16] M. Kumari, V. Arya, *Int. J. Commun. Syst.* **37**, 5647 (2024).
- [17] M. Kumari, V. Arya, *Opt. Quantum Electron.* **56**, 113 (2024).
- [18] A. Sharma, P. Chauhan, *J. Opt. Commun.* **42**, 273 (2021).
- [19] S. Chaudhary, L. Wuttisittikulkij, J. Nebhen, A. Sharma, D. Zegarra, Rodriguez, S. Kumar, *PLoS One* **17**, e0265044 (2022).
- [20] C. Zhang, P. Liang, J. Nebhen, S. Chaudhary, A. Sharma, Jyoteesh Malhotra, B. Sharma, *Opt. Quantum Electron.* **53**, 1 (2021).
- [21] A. Sharma, J. Malhotra, *Opt. Quantum Electron.* **54**, 233 (2022).
- [22] K. H. Shakthi Murugan, A. Sharma, J. Malhotra, *Opt. Quantum Electron.* **52**, 1 (2020).
- [23] Z. Zhou, H. Zhang, C. Lin, A. Sharma, *J. Opt. Commun.* **43**, 147 (2022).
- [24] M. Kumari, Y. Narayan, V. Arya, *Trans. Emerg. Telecommun. Technol.* **34**, e4699 (2022).
- [25] M. Kumari, V. Arya, *Opt. Quantum Electron.* **55**, 124 (2023).
- [26] Anuranjana, S. Kaur, R. Goyal, S. Chaudhary, *Optik* **257**, 168809 (2022).

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