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Toward 600 Gbps and 1 Tbps per Wavelength Data Transmission for Coherent WDM-PON Supporting 5G and Beyond Services

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Abstract Next generation mobile networks are expected to operate with more than 100 Gbps (toward 1 Tbps) per single wavelength data rate and high-order modulation (HOM) format to support the required ultra-high data services. Wavelength-division multiplexing (WDM) access techniques could be used to provide huge data capacity, extended coverage, long reach connection, and high flexibility. In this paper, design issues for coherent WDM passive optical networks (PONs) to support fifth-generation (5G) and beyond 5G services are presented. The target is to achieve 600 Gbps and 1 Tbps data rates per single wavelength through using HOMs, dual polarization (DP) 64- and 128-QAM, to support eight and sixteen small cells per macro cell; each small cell is served by a single wavelength. The designed configurations are implemented using Optisystem software ver. 15.0. For a 16-small cell configuration operating with 64-QAM modulation format, the achieved maximum reach L_{max} is 60 and 20 km for data rate per wavelength R_b = 600 Gbps and 1 Tbps, respectively. Further, L_{max} = 45 and 15 km for the same cell configuration operating with 128-QAM signaling and R_b = 600 Gbps and 1 Tbps, respectively.

Keywords High-order modulation (HOM), Wavelength-division multiplexing (WDM), Passive optical network (PON), WDM-PON, 5G network

1. Introduction

The specification of fifth-generation (5G) mobile networks has already passed the standardization phase, and these networks are being rolled out around the world since 2020. The 5G technology was driven by the commercial operators to accommodate future data capacity requirements for this customer base, as well as complemented by efficient manufacturing demands from industry in the shape of internet of things (IoT) [1]. On the other hand, the demand for the high-speed passive optical networks (PONs) has been increasing due to the spread of broad services [2-6]. Recently, the IEEE 802.3ca Task Force has commenced discussion of the first 100 Gbps-based PON standard in the form of 100G Ethernet PON (100G-EPON) [7]. This PON can support the first stage of the growing bandwidth demands for forthcoming 5G networks.

Figure 1 illustrates the bandwidth demands for forthcoming 5G mobile front-haul (MFH) and mobile back-haul (MBH) networks based on PON. The future MFH/MBH can operates with a data rate of 100 Gbps per small cell and up to around 1 Tbps per macro cell incorporating multiple small cells. Further, the transmission rate per small cell is itself expected to increase exponentially to a maximum MFH link rate of 1 Tbps, depending on future wireless user rates such as beyond 5G (B5G) and sixth-generation (6G) mobile systems [8]. The wavelength-division-multiplexing (WDM) access techniques could provide huge data capacity, extended coverage, long reach connection, and high flexibility [9]. Thus, it is expected that the performance of PON is enhanced strongly when its operation is based on the WDM technique, especially for mobile network applications [10-15]. In this case, the WDM-PON serves each small cell with a single wavelength for downstream (upstream) signal. The WDM-PON performance will be enhanced further when coherent optical detection is used to recover the data at the user end, which this leads to what is known as coherent WDM-PON. The coherent technology is considered a promising candidate for realizing such higher-bandwidth PONs due to its high receiver sensitivity, superior to intensity modulation/direct detection-based PON [10]. Further the coherent PON easily leaves space for inserting additional wavelength to accommodate additional users (optical node units) with the same optical distribution network. Another advantage of coherent PON is that it is the only technique available right now for carrying a signal at

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100 Gbps or more per single wavelength.

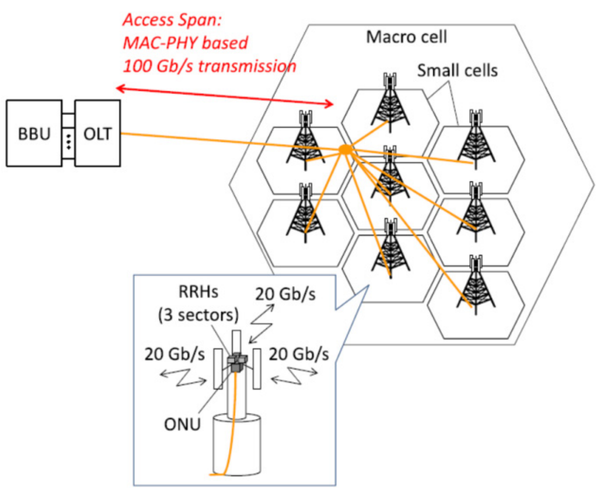


Figure 1. Bandwidth demand for 5G MFH/MBF-based PON technology [8]

To support the operation of next generation mobile networks (i.e., advanced 5G, B5G, and 6G), the performance of coherent PON needs to be investigated carefully for the case of delivering data rate R_b from 100 Gbps to 1 Tbps for each WDM channel [8]. This issue is addressed in the paper for two values of R_b, 600 Gbps and 1 Tbps. To increase R_b toward 1 Tbps, one can use a hybrid of techniques, including high-order modulation (HOM), high symbol rate, and dual-polarization (DP) multiplexing. Increasing modulation order means increasing the number of bits carried by each symbol while decreasing the distance between symbols in the constellation diagram. This leads to decrease in the transmission distance. Although, increasing the symbol rate R_s will increase R_b for the same value of modulation order. Most of the coherent optical communication systems and optical networks demonstrated in the literature use R_s not exceeding 100 GSps due to the speed limit of electronic-to-optical (and vice versa) conversion. Increasing the symbol rate requires increasing the speed of the digital-to-analog (DAC) (and vice versa ADC) conversion. Note that increasing either the symbol rate or modulation order has advantages and disadvantages. Depending on the system requirements, some combination of them is likely to be used. This issue is addressed on this paper as related to next generation mobile networks.

It is worth to mentioning here that different research groups have started an investigation to design coherent WDM optical communication system carrying data rates of 1 Tbps per wavelength. Most of their results appeared as a short announcement on multimedia websites [16]. Recently, Buchali et al. [17] have reported the implementation of 128 GSps DAC to enable 1.52 Tbps single-carrier transmission over 80 km of single-mode fiber. Nokia has given a talk in OFC 2021 summarizing their progress in beyond 1 Tbps transmission [18]. Even these works are related to point-to-point optical communication systems, the concepts may be adapted or modified to support the goals to be achieved by future coherent WDM-PON for next generation mobile networks.

2. Related Works

In 2017, Suzuki et al. [10] presented the 100 Gbps per λ-based coherent WDM-PON prototype system. A real-time 100 Gbps coherent transceiver with a simplified digital signal processing (DSP) suitable for access spans was highlighted.

In 2018, Suzuki et al. [8] presented design concepts for a coherent WDM-PON operating with a 100 Gbps data rate per channel. Issues related to miniaturization optimization of DSP-based embedded coherent transceivers were given.

In 2018, Matsuda et al. [19] demonstrated hardware-efficient carrier phase recovery and adaptive equalization for 100 Gbps per λ based coherent WDM-PON systems. Downstream transmission with 32 Gbaud (GSps) DP-quadrature phase shift keying (QPSK) signals and offline DSP was demonstrated.

In 2019, Shbair and Nahal [20] reviewed the latest progress of coherent WDM-PON technology operating with 100 Gbps per λ and investigated the system performance when QPSK and DP-QPSK modulation formats are used.

In 2019, Luo et al. [21] proposed a scheme of coherent ultra-dense WDM-PON for symmetrical operations between the uplink and downlink. They experimentally used a real-time field-programmable gate array-based transceivers were used to demonstrate a field trial operation.

In 2020, Segarra et al. [22] reported a low-cost coherent ultra-dense WDM-PON with 6.25 GHz channel spacing. The optical network unit was made by implementing coherent transceivers that have two paired low-cost distributed feedback lasers.

In 2020, Luo et al. [23] proposed a 100 Gbps coherent ultra-dense WDM-PON structure with EDFA that was placed with high power budget at the OLT side for optical signals amplification for both the uplink and downlink. A real-time 4 × 25 Gbps network at 12.5 GHz channel spacing over 50 km SSMF was experimentally demonstrated.

In 2021, Zhou et al. [24] experimentally demonstrated DSP-free 8 × 10 Gbps 4-level pulse-amplitude modulation transmission for coherent WDM-PON cost-effective with channel spacing of 20 GHz in the C-band. The polarization-independent coherent receiver was used at the ONU.

It is clear from this survey that most of the work was related to about 100 Gbps per λ data rate and to modulation order 16 or less. Next generation networks are expected to operate with more than 100 Gbps per λ data rate (toward 1 Tbps per λ) and high-order modulation format (64- and 128-QAM) to support the required ultra-high data services. These issues will be addressed in this paper.

3. Design Issues and Configurations for Coherent WDM-PONs Supporting 5G and Beyond Services

This section presents the design issue for coherent WDM-PONs to support 5G and beyond 5G (B5G) services. The target is to achieve 600 Gbps and 1 Tbps data rates per single wavelength through using high-order modulations, dual-polarization (DP) 64- and 128-QAM. The designed configurations are implemented using Optisystem software ver. 15.0.

Figure 2 illustrates the schematic of WDM-PON for distributing mobile services. The mobile front-haul (MFH) networks consist of: (i) an optical line terminal (OLT) incorporating an optical multiplexer to collect the data from the baseband network unit (BBU) located in the base station after optical modulations; (ii) optical network unit (ONU) incorporating optical demultiplexer to serve multi optical receiver/antenna units; and (iii) standard single-mode fiber (SSMF) acting as the transmission link between the OLT and the ONU.

The following requirements are needed to be satisfied for the WDM-PONs designed in this work

(i) The WDM system operates in the C band of the optical communication spectrum. This band is located around the 1550 nm wavelength, where the SSMF has a minimum loss of ≈ 0.2 dB/km. Note that the C band is usually used for optical communication systems, and therefore, one expects that most of the required optical devices for WDM-PONs are available in the market.

(ii) The optical channels frequencies of the WDM system are selected according to the frequency-grid standard issued by the International Union Telecommunication-Telecommunication Standardization Sector (ITU-T). This WDM grid specifies the optical frequencies of the used lasers for different optical frequency spacing Δf of 25, 50, …, 200 GHz.

(iii) No active element is inserted in the transmission fiber link, such as optical amplifiers and optical-to-electrical (and vice versa).

(iv) The ONU supports the service to a macro cell incorporating multiple small cells with each cell is related to one of the used WDM channels wavelengths. Each cell has its own remote radio head (RRH), i.e., antenna, covering 3 or 6 sectors. Since the standard WDM system uses $N_{ch} = 2^n$ channels, where n is a positive integer, $N_{ch} = 8$ and $N_{ch} = 16$ are adopted in the design (see Figs. 3a and b).

(v) The symbol rate R_s of each WDM channel should not exceed 100 GSps since it is limited by the speed of the available electronics. To increase the transmission bit rate per channel (i.e., per wavelength) R_b, one should go to higher-order QAM modulation supported by polarization multiplexing technique (i.e., DP transmission).

(vi) The design should be issued first to support 600 Gbps per λ and then extended to support 1 Tbps per λ. These two values of R_b are recommended by different research groups for future WDM-PONs serving 5G and B5G network services.

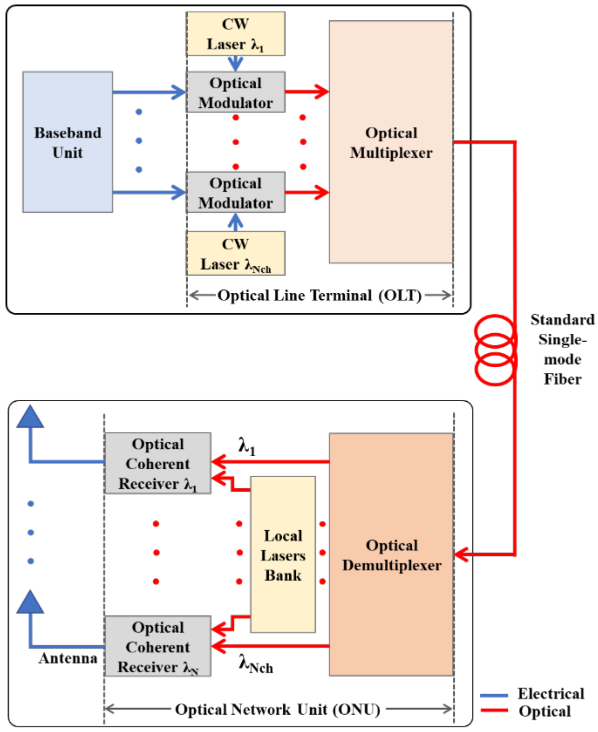


Figure 2. Simplified schematic of the WDM-PON for mobile service

Few remarks related to the aforementioned points are given the following

(i) The total bit rate $(R_b)_{tot}$ served by the MFH link is computed from

$$(R_b)_{tot} = 2N_{ch}R_s Log_2 M \tag{1}$$

assuming DP transmission over N_{ch} channels using M-QAM modulation format. The spectral efficiency (measured in bps per Hz) is computed as

$$S_E \equiv \frac{Total\ transmiision\ \ bit\ rate}{Optical\ \ bandwidt\ h} = \frac{2N_{ch}R_s Log_2 M}{N_{ch}\ \Delta f} = \frac{2R_s Log_2 M}{\Delta f} \tag{2}$$

and it is independent on N_{ch}.

(ii) To ensure zero intersymbol interference (ISI) at the input of the electrical decision circuit used in each channel receiver, the symbol pulse shape should have a raised-cosine filter (RCF) spectrum at the input of this circuit. The filter bandwidth (i.e., the symbol message electrical bandwidth) is given by

$$B_{me} = (1 + r)R_s/2 \tag{3}$$

where r is the RCF roll-off factor. The R_s ideal case (i.e., Nyquist filter) corresponds to r = 0, which gives an ideal lowpass filtering spectrum and leads to $B_{me} = R_s/2$. The other extreme is r = 1, which yields a full RCF spectrum having $B_{me} = R_s$. Note that when the symbols are used to modulate the optical carrier, the generated modulation optical signal has approximately an optical bandwidth $B_{mo} = 2B_{me} = (1+r)R_s$ due to the generation of upper and lower sidebands.

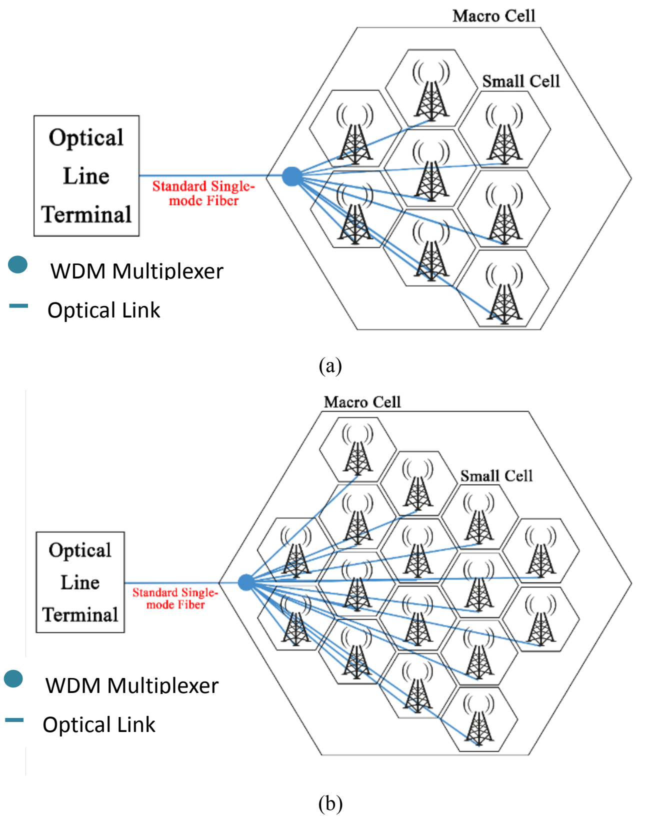


Figure 3. Mobile fronthual for coherent WDM PON. (a) 8-small cell configuration. (b) 16-small cell configuration

Consider the case of R_b = 600 Gbps. The corresponding symbol rate ($R_s = R_b/Log_2M$) equals 50 and 42.9 GSps when 64- and 128-QAM formats are used, respectively. To prevent overlapping between neighboring channels at the optical demultiplexer output, B_{mo} should be less than Δf. In other words, the following condition should be satisfied in the design of the demultiplexer

$$B_{mo} = (1+r)R_s < \Delta f \tag{4a}$$

Thus, the maximum value of r that can be used is given by

$$r_{max} = \frac{\Delta f}{R_s} - 1 \tag{4b}$$

Using lasers with channel spacing Δf = 75 GHz from the WDM grid yields r_{max} = 0.5 and 0.75 for 64- and 128-QAM formats, respectively. Note that one can choose Δf = 100 GHz for the case of 64-QAM formats signaling to yield r = 1 (i.e., full RCF) but the spectral efficiency reduces since it is inversely proportional to Δf (see Eqn. 2).

Now consider the second case of R_b = 1 Tbps. The symbol rate R_s equals to 83.3 and 71.4 GSps for 64- and 128-QAM formats. Choosing Δf = 100 GHz yields r_{max} = 0.2 and 0.4, respectively. One can go to Δf = 125 GHz to relax the demultiplexer design while reducing the spectral efficiency to 80%. The corresponding r_{max}, which in this case is 0.6 and 0.75, respectively.

4. System Parameters Used to Produce the Simulation Results of the Designed WDM-PONs

The results are presented in two scenarios corresponding to two data rates per channel, 600 and 1000 Gbps. Each scenario includes two main parameters, modulation format and number of channels. The simulation is executed using Optisystem software ver. 15.0. The maximum transmission length (i.e., maximum reach) is estimated when the bit error rate (BER) at the received side approaches 4.6×10^{-3}. This BER level corresponds to the BER threshold of 7% hard decision (HD) forward error correcting (FEC) code.

The simulation results are presented for two coherent WDM-PONs operating with 600 and 1000 Gbps data rate per channel (i.e., per wavelength λ). Each network is designed to support 8- and 16-antenna cells using either dual-polarization (DP) 64-QAM or 128-QAM signaling format. This yields eight PONs under observation. Each PON is labelled by three indices, namely (R_G, M, N_{ch})-PON, where R_G, M, and N_{ch} stand, respectively, for data rate in Gbps carried by a single WDM channel, order of the QAM format, and the number of WDM channels. Therefor R_G takes the value of 600 or 1000, M takes the number 64 or 128, and N_{ch} is either 8 or 16. These PONs are also classified into two categories, A or B depending whether the data rate per channel is 600 or 1000 Gbps, respectively. Accordingly

Class-A PONs

- PON-A1 ≡ (600, 64, 8) PON
- PON-A2 ≡ (600, 128, 8) PON
- PON-A3 ≡ (600, 64, 16) PON
- PON-A4 ≡ (600, 128, 16) PON

Class-B PONs

- PON-B1 ≡ (1000, 64, 8) PON
- PON-B2 ≡ (1000, 128, 8) PON
- PON-B3 ≡ (1000, 64, 16) PON
- PON-B4 ≡ (1000, 128, 16) PON

For comparison purposes, results related to a single-channel counterparts (i.e., N_{ch} = 1) are also presented for both data rates and both signal formats.

The frequencies of the WDM channels are selected in the C band (i.e., 1550nm region) according to International Telecommunication Union-Telecommunicate Standardization Sector (ITU-T) [25]. The ITU offers a frequency grid corresponding to frequency channel spacing Δf of 25, 50, 75, ...GHz. The channel frequency matches the frequency of the unmodulated laser frequency used for this channel. The channel spacing should be selected to be equal to or less than the bandwidth of the modulated optical carrier

$$\Delta f \le (1+r)R_S = (1+r)R_b/Log_2M \tag{5}$$

where R_S is the symbol rate, R_b is the bit rate, M is the QAM order, and r is the roll-factor of the raised-cosine filter used for pulse shaping required to achieve zero intersymbol interference (ISI) at the input of the receiver decision circuit. For R_b = 600 Gbps, R_s = 50 and 42.86 GSps for 64- and

128-QAM signaling, respectively. Choosing Δf = 75 GHz for this data rate requires that r should be kept less than 0.5 and 0.75 for these formats, respectively. For 1 Tbps data rate networks, Δf = 125 GHz is used for both M = 6 and 7 formatting where R_s = 83.3 and 71.4 GSps, respectively. In this case r should be chosen to be less than 0.5 and 0.75, respectively.

From the previous discussion, r = 0.2 is chosen in this work for the designed coherent WDM-PONs, which ensures that the bandwidth of the modulated optical carrier B_{mo} is within the corresponding Δf and with enough frequency guard, $\Delta f_G = \Delta f - B_{mo}$, between the neighboring channels. For R_b = 600 Gbps and r = 0.2, $B_{mo} = (1 + r)R_s$ = 60 and 51.4 GHz assuming 64- and 128-QAM, respectively. This design offers a frequency guard Δf_G of 15 and 23.6 GHz, respectively. These values are to be compared with Δf_G= 25 and 39.3 GHz for R_b = 1 Tbps and r = 0.2, respectively. Note, that in this case, B_{mo} = 100 GHz and 85.7 GHz for 64- and 128-QAM signaling, respectively.

Table 1. Channels frequencies for 16-channel WDM system

Channel	Channel Frequency (THz)	
	Δf = 75 GHz	Δf = 125 GHz
1	192.500	192.100
2	192.575	192.225
3	192.650	192.350
4	192.725	192.475
5	192.800	192.600
6	192.875	192.725
7	192.950	192.850
8	193.025	192.975
9	193.100	193.100
10	193.175	193.225
11	193.250	193.350
12	193.325	193.475
13	193.400	193.600
14	193.475	193.725
15	193.550	193.850
16	193.625	193.975

Table 2. Values of main system parameters used in the simulation

Subsystem	Device	Parameter	Value
WDM Transmitter (C band)	Channel Transmitter	Laser Power	10 dBm
		Laser Linewidth	0 MHz
		Modulation Format	193.1 THz
		Central Channel Frequency	193.1 THz
	Booster Optical amplifier	Gain	18 dB (64-QAM) 15 dB (128-QAM)
		Noise Figure	4 dB
	Multiplexer	Loss	0
		Filter Bandwidth	0.9 Δf
		Filter order	10
Transmission Link	Standard Single-Mode Fiber	Attenuation	0.2 dB/km
		Group-Velocity Dispersion	17 ps/(nm.km)
		Dispersion Slope	0.075 ps/nm^2/km
WDM Receiver	Demultiplexer	Loss	0
		Filter Bandwidth	0.9 Δf
		Filter Order	10
	PIN Photodiode	Quantum Efficiency	1 A/W
		Noise Power Spectral Density	W/Hz
	Local Laser	Power	10 dB
		Linewidth	0 MHz

It is interesting to introduce a normalized frequency guard $\Delta f_{GN} = \Delta f_G/\Delta f$ as a parameter to assess the overlapping degree between neighboring channels. For 600 Gbps and 1Tbps networks, Δf_{GN} = 0.2 and 0.32 for 64- and 128-QAM signaling, respectively. Note that

$$\Delta f_{GN} = \frac{\Delta f}{\Delta f_G} = \frac{\Delta f}{\Delta f - B_{mo}} = \frac{1}{1-\frac{B_{mo}}{\Delta f}} = \frac{1}{1-\frac{(1+r)R_b}{\Delta f \log_2 M}} \quad (6)$$

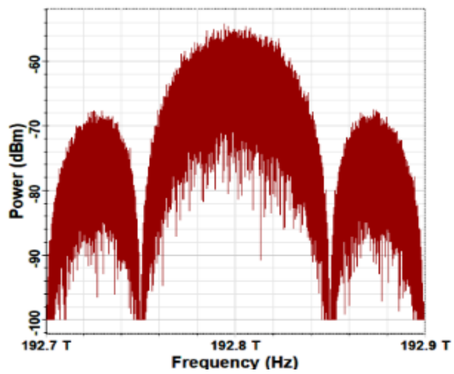
In the WDM system, the number of multiplexed channels N_{ch} is chosen as even number with a central channel is corresponding to $(1 + N_{ch}/2)_{th}$ channel. If the channel indices are labeled from 1 to N_{ch}, channel 5 and 9 correspond to the central channels for 8- and 16-channel WDM systems, respectively. The central channel frequency is set to 193.1 THz (i.e., λ = 1.554 nm) in the simulation.

Table 1 lists the used channel frequencies for the 16-channel WDM system with Δf = 75 and 125 GHz adapted for R_b = 600 Gbps and 1 Tbps, respectively.

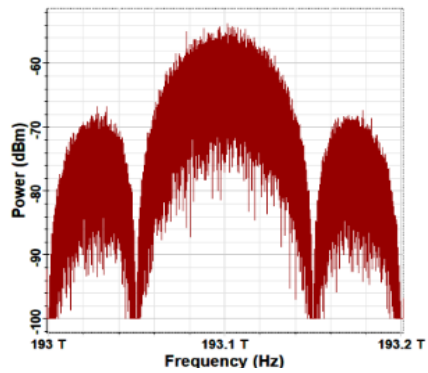
Unless otherwise stated, the main system parameters used in the simulation values are listed in Table 2.

5. Simulation Results of 600 Gbps WDM-PONs

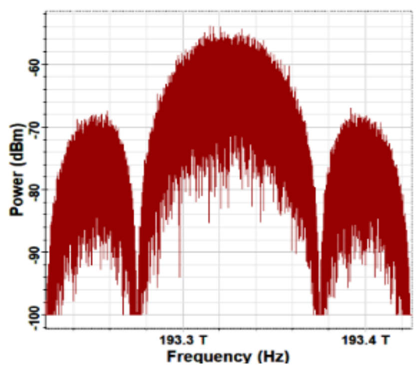
This section presents simulation results related to coherent WDM-PONs operating with 600 Gbps per λ data rate. Results are presented for both 64- and 128-QAM signals and for two numbers of multiplexed channels, N_{ch} = 8 and 16. Results for a single-channel PON are also included for comparison purposes.



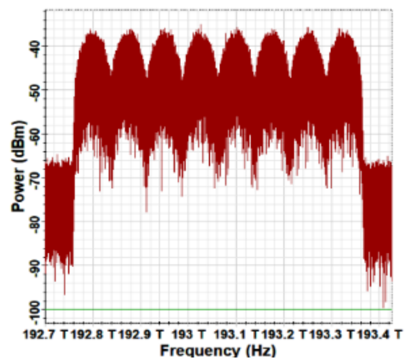
(a) Transmitted optical signal of Ch1.



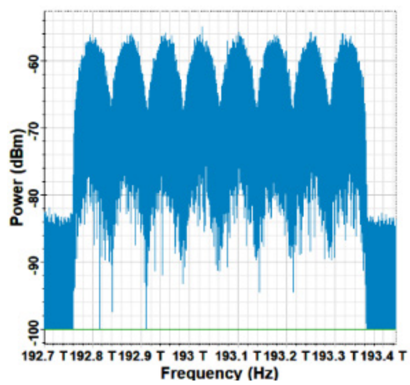
(b) Transmitted optical signal of Ch5.



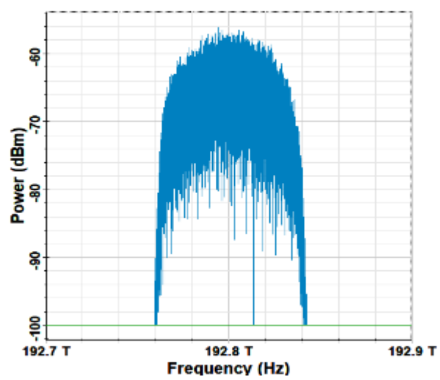
(c) Transmitted optical signal of Ch8.



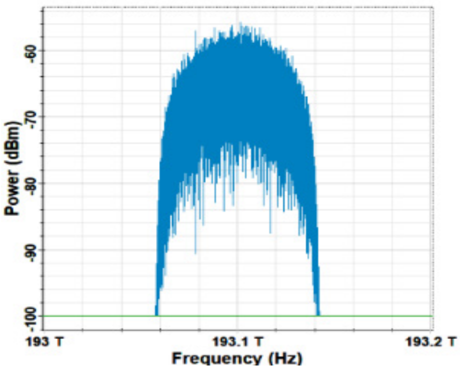
(d) WDM multiplexed signal.



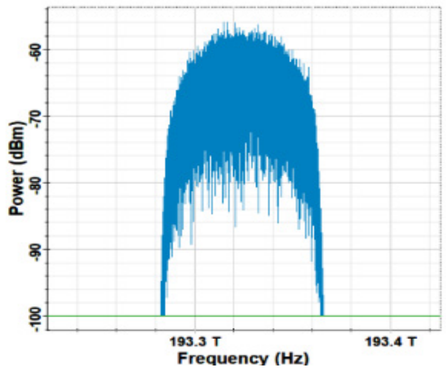
(e) WDM received signal.



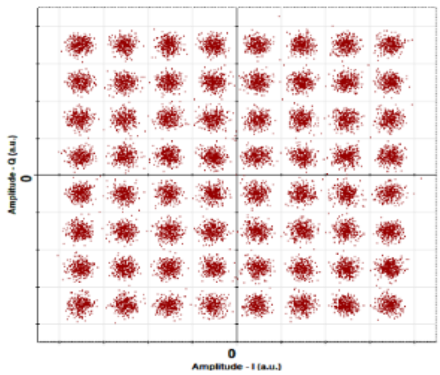
(f) Demultiplexed optical signal Ch1.



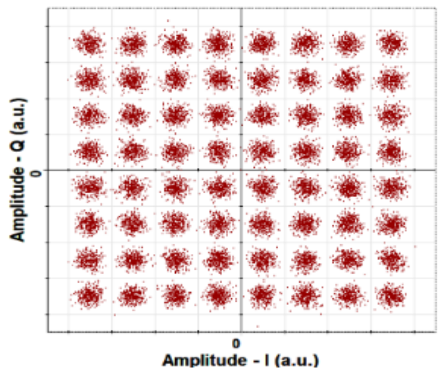
(g) Demultiplexed optical signal Ch5



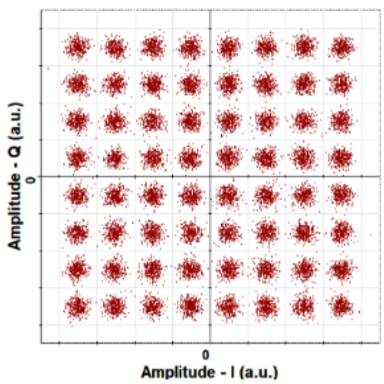
(h) Demultiplexed optical signal Ch8



(i) Received constellation diagram of Ch1.



(j) Received constellation diagram of Ch5.



(k) Received constellation diagram of Ch8.

Figure 4. Signals spectra and received constellation diagrams related (600, 64, 8) PON

5.1. 8-Antenna 600 Gbps PON

This subsection presents simulation results for 600 Gbps per λ PONs that use 8-channels WDM system. Two PONs are considered here depending on whether 64-QAM or 128-QAM signal format is used

- PON-A1 ≡ (600, 64, 8) PON
- PON-A2 ≡ (600, 128, 8) PON

Note that the total data rate transmitted over the transmission link is 8 x 600 Gbps = 4.8 Tbps. A frequency channel spacing Δf and roll-factor r used in the simulation for both PONs are 75 GHz of 0.2, respectively. The following remarks are taken in the simulation.

(i) Each demultiplexed channel at the receiver side uses its own DP DSP whose parameters are shared with other DSPs used for other demultiplexed channels (Fiber length, SSMF parameters, ...), but it has its own channel frequency.

(ii) Each channel DSP is enabled to yield GVD compensation for the transmission link estimated at the operating channel frequency. Note that the GVD parameter D is varied slightly with the operating wavelength. All the receivers DSPs use D = 17 ps/(nm.km) and dispersion slope S = 0.075 ps/nm2/km at 1550 nm reference wavelength. These data are used by the DSP to estimate the GVD at the channel wavelength according to Eqn. (7).

$$D_\lambda = D_{ref} + (\lambda - \lambda_{ref})S \tag{7}$$

(iii) The BERs of all 8 channels are kept under observation at the receiver side. The maximum reach L_{max} is estimated when the BERs of all the channels do not exceed the threshold level of $4.6\text{x}10^{-3}$.

5.1.1. Simulation Results of (600, 64, 8) PON

PON-A1 uses 8-channels WDM system to transmit 600 Gbps DP 64-QAM signal per channel from the base station to the cell. The network is simulated and the results are shown in Fig. 4. Parts a-d show the spectrum of three transmitted channels (i.e., first channel Ch1, central channel Ch5, and last channel Ch8) along with the WDM multiplexed signal. The spectrum of the received WDM signal is given in part e of the figure, when the fiber length is set to 100 km which corresponds to the maximum reach. The spectrum and constellation diagrams corresponding to three demultiplexed signals (Ch1, Ch5, and Ch8) are illustrated in part (f, g, and h) and (i, j, and k), respectively. The BERs of these three channels are 4.18×10^{-3}, 1.24×10^{-3}, and 3.34×10^{-3}, respectively; all BERs are less than BER_{th}.

The variation of BERs of the 8 channels with transmission distance (i.e., length of the SSMF link) is illustrated in Table 3. At L = 100 km, the BERs of all the channels are below $BER_{th} = 4.6 \times 10^{-3}$. Increasing L to 105 makes the BER of Ch1 (i.e., BER1) more than BER_{th}. Therefore, the maximum reach is taken according to this channel. Increasing L further to 110 km makes, another channel (Ch2) not satisfy the required BER level. Note that PON-A1 can support the transmission to 8, 7, 6, and 1 antenna when L=100, 105, 110, and 115 km, respectively. At L= 120 km, the BERs of all the received channels are higher than BER_{th}.

Figure 5 illustrates the dependence of the BERs of channels 1, 5, and 8 with the transmission distance. Note that Ch5 supports a longer transmission distance than channels 1 and 8. While channel 8 supports a longer distance compared with Ch1. It is clear that Ch1 determines the maximum reach of this network.

5.1.2. Simulation Results of (600, 128, 8) PON

The simulation is repeated for PON-A2 that uses 600 Gbps DP 128-QAM signal over 8-channels WDM system. The results are depicted in Figs. 6 and 7 and Table 4. The spectra of the signals at different points of the system are given in Fig. 6, along with the receiver constellation diagrams. The transmission length is set to the maximum reach (L_{max} = 85 km).

Table 3. Variation of BERs of the eight channels with transmission distance for (600, 64, 8) PON

Distance (km)	100	105	110	115	120
Channel 1	4.18E-03	4.72E-03	5.50E-03	6.11E-03	7.53E-03
Channel 2	3.81E-03	4.18E-03	5.31E-03	6.50E-03	8.67E-03
Channel 3	2.58E-03	3.06E-03	3.77E-03	5.29E-03	7.18E-03
Channel 4	2.08E-03	2.78E-03	3.90E-03	4.77E-03	6.55E-03
Channel 5	1.24E-03	1.77E-03	2.28E-03	3.36E-03	5.43E-03
Channel 6	2.24E-03	2.56E-03	3.36E-03	4.79E-03	5.79E-03
Channel 7	2.56E-03	3.47E-03	4.16E-03	5.49E-03	8.26E-03
Channel 8	3.34E-03	3.78E-03	4.28E-03	5.42E-03	7.21E-03

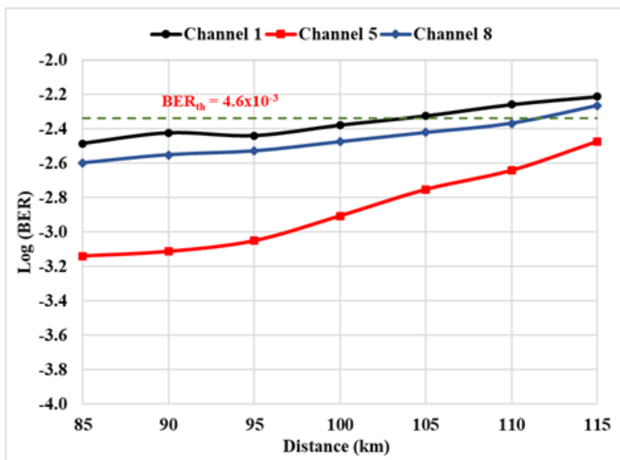
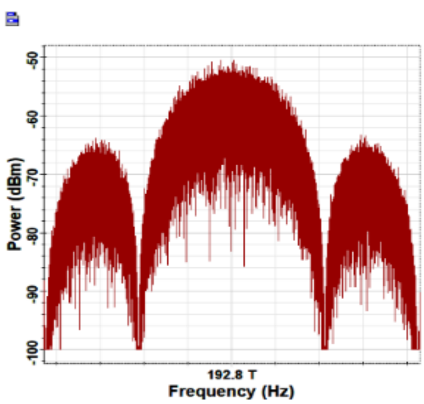
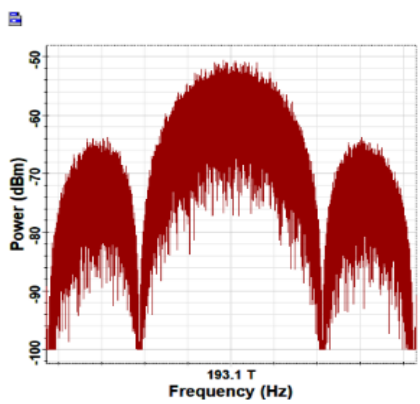


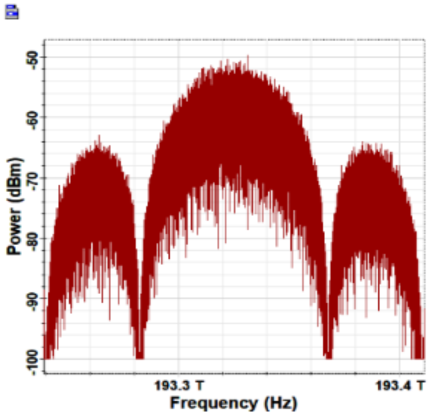
Figure 5. Variation BERs of channels 1, 5, and 8 with a transmission distance for (600, 64, 8) PON



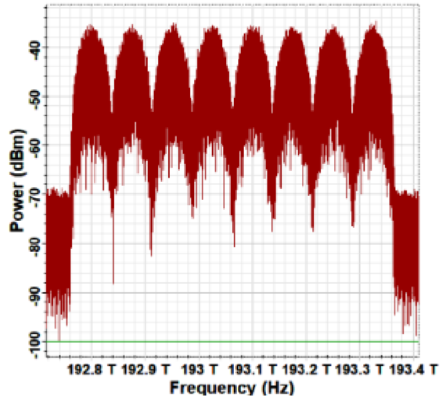
(a) Transmitted optical signal of Ch1.



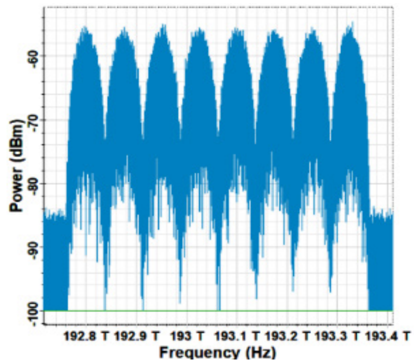
(b) Transmitted optical signal of Ch5.



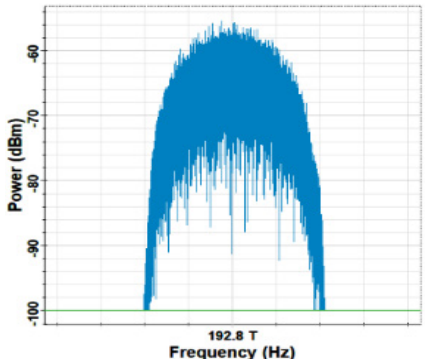
(c) Transmitted optical signal of Ch8.



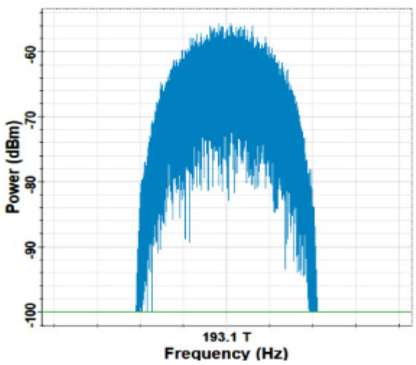
(d) WDM multiplexed signal.



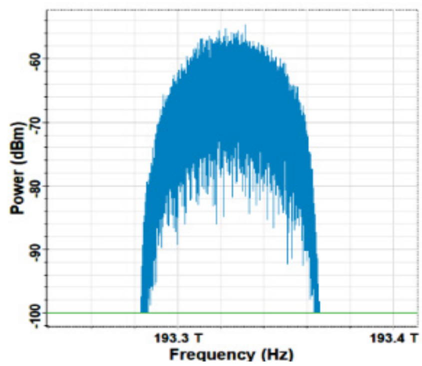
(e) WDM received signal.



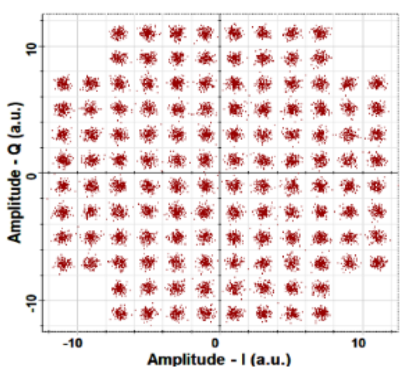
(f) Demultiplexed optical signal Ch1.



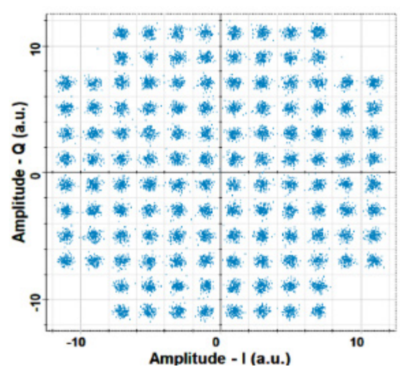
(g) Demultiplexed optical signal Ch5.



(h) Demultiplexed optical signal Ch8.



(i) Received constellation diagram of Ch1 (x polarization).



(j) Received constellation diagram of Ch1 (y polarization).

Figure 6. Signals spectra and received constellation diagrams related (600, 128, 8) PON

Figure 7 illustrates the dependence of the BERs of channels 1, 5, and 8 with the transmission distance. Note that channel 5 supports a longer transmission distance than channel 1 and 8. Further, Ch8 supports longer distance compared with Ch1. It is clear that Ch1 determines the maximum reach of this network.

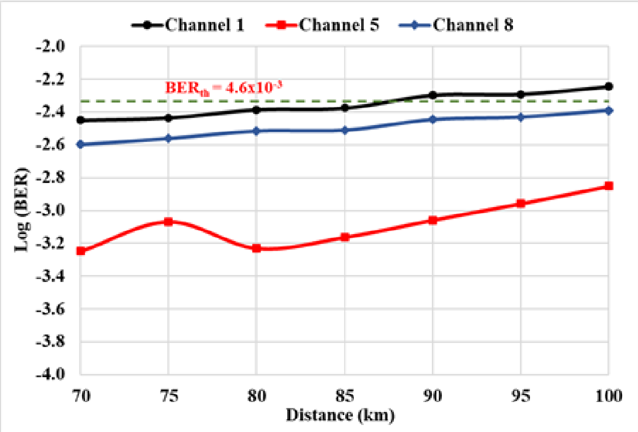


Figure 7. Dependence of BERs of channels 1, 5, and 8 on transmission distance (600, 128, 8) PON

Table 4 lists the BERs of the 8 channels for different values of fiber length L. The results in this table highlight the following facts

(i) The maximum reach for the network is 85 km. Operating with L≤ 85 km ensures that all received channels BERs are less than BER_{th}.

(ii) Increasing L to 90 km makes channel 1 operate unsatisfactory, giving received BER > BERth.

(iii) Increasing L further does not alters the BER picture effectively till L approaches 100 km. At L= 100 km, two additional channels (Ch2 and Ch8) get out of the required-BER operation (i.e., BER > BERth).

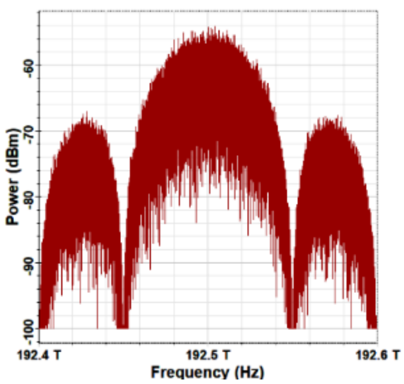
(iv) The network can support the required BER condition for 8, 7, and 5 antennas when L = 85, 105, and 110 km, respectively. At L = 115 km, the BERs of all the received channels are less than BER_{th}.

5.2. 16-Antenna 600 Gbps PON

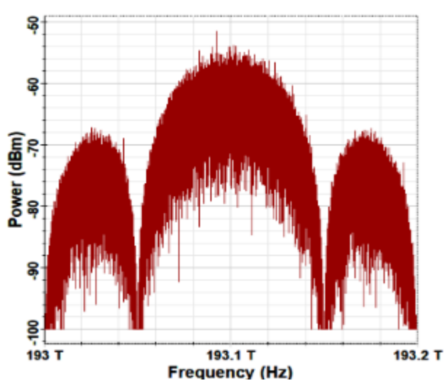
This subsection presents simulation results for PON-A3 and PON-A4, which support 600 Gbps per λ data rate and 16-Channel WDM transmission under 64- and 128-QAM signaling, respectively.

Table 4. BERs variation of 8 channels with a transmission distance (600, 128, 8) PON

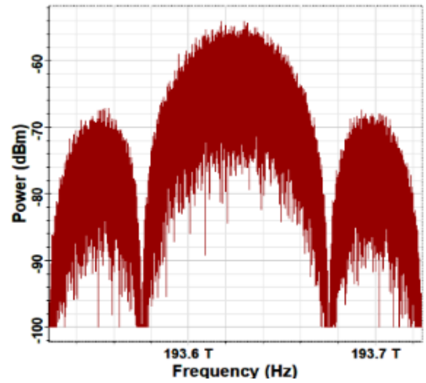
Distance (km)	90	95	100	105	110	115
Channel 1	5.04E-03	5.11E-03	5.68E-03	6.45E-03	7.74E-03	9.29E-03
Channel 2	3.70E-03	3.83E-03	4.45E-03	4.81E-03	5.68E-03	9.09E-03
Channel 3	2.62E-03	2.69E-03	3.02E-03	3.62E-03	5.18E-03	8.09E-03
Channel 4	1.78E-03	1.64E-03	1.90E-03	2.75E-03	3.83E-03	5.37E-03
Channel 5	8.74E-04	1.10E-03	1.40E-03	1.74E-03	2.75E-03	5.23E-03
Channel 6	1.31E-03	1.63E-03	2.20E-03	2.77E-03	3.22E-03	6.82E-03
Channel 7	2.45E-03	2.69E-03	3.08E-03	3.97E-03	4.30E-03	9.22E-03
Channel 8	3.57E-03	3.70E-03	4.07E-03	5.03E-03	6.07E-03	9.02E-03



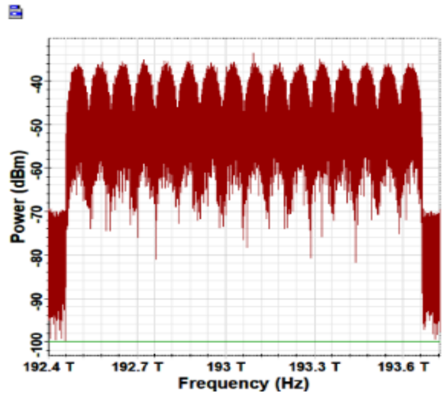
(a) Transmitted optical signal of Ch1.



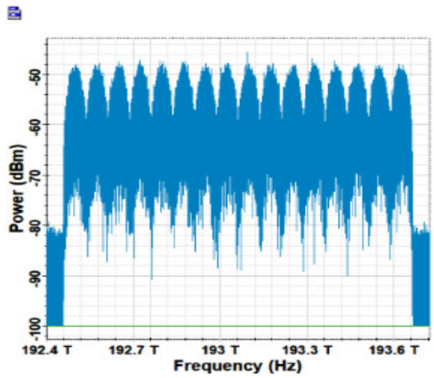
(b) Transmitted optical signal of Ch9.



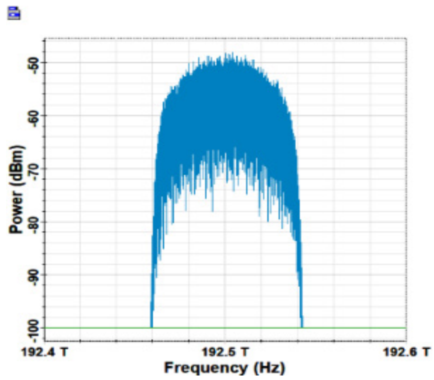
(c) Transmitted optical signal of Ch16.



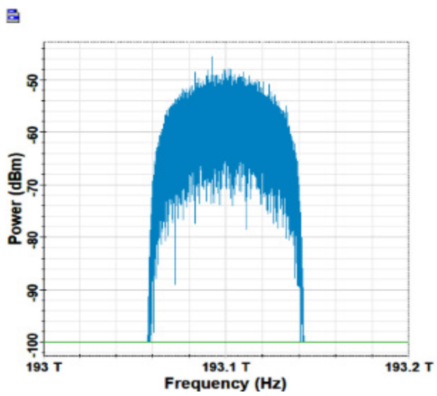
(d) WDM multiplexed signal.



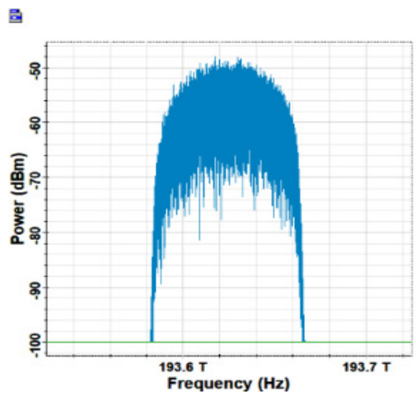
(e) WDM received signal.



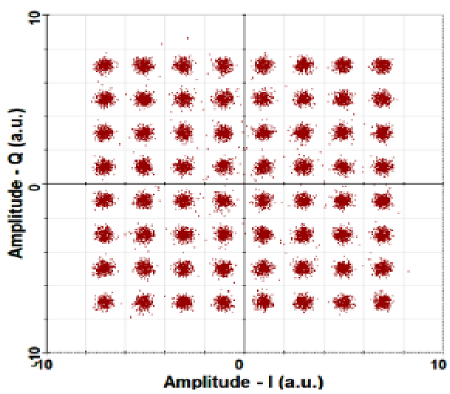
(f) Demultiplexed optical signal Ch1.



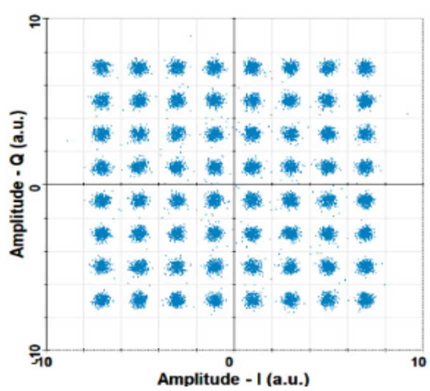
(g) Demultiplexed optical signal Ch9.



(h) Demultiplexed optical signal Ch16.



(i) Received constellation diagram of Ch1
(x polarization).



(j) Received constellation diagram of Ch1
(y polarization).

Figure 8. Signals spectra and received constellation diagrams related (600, 64, 16) PON

Table 5. BERs variation of 16 channels with transmission distance (600, 64, 16) PON

Distance (km)	60	65	70	75	80	85	90
Channel 1	4.62E-03	4.86E-03	5.31E-03	5.65E-03	5.72E-03	6.44E-03	6.60E-03
Channel 2	4.26E-03	4.27E-03	4.63E-03	5.00E-03	5.15E-03	5.60E-03	6.17E-03
Channel 3	3.52E-03	3.46E-03	3.68E-03	4.36E-03	4.52E-03	4.86E-03	5.27E-03
Channel 4	2.79E-03	3.07E-03	3.25E-03	3.30E-03	3.52E-03	3.90E-03	4.41E-03
Channel 5	2.24E-03	2.74E-03	2.75E-03	2.96E-03	3.27E-03	3.48E-03	3.63E-03
Channel 6	1.61E-03	1.79E-03	2.09E-03	2.22E-03	2.51E-03	2.67E-03	3.00E-03
Channel 7	1.28E-03	1.24E-03	1.32E-03	1.52E-03	1.77E-03	1.69E-03	1.72E-03
Channel 8	6.56E-04	6.26E-04	7.82E-04	8.20E-04	8.62E-04	1.05E-03	1.13E-03
Channel 9	3.24E-04	3.17E-04	2.71E-04	3.81E-04	4.27E-04	4.62E-04	4.04E-04
Channel 10	7.48E-04	6.91E-04	8.20E-04	9.12E-04	9.27E-04	1.29E-03	1.18E-03
Channel 11	1.14E-03	1.25E-03	1.24E-03	1.43E-03	1.52E-03	1.65E-03	1.82E-03
Channel 12	1.73E-03	1.96E-03	2.05E-03	1.96E-03	2.03E-03	2.55E-03	2.87E-03
Channel 13	2.38E-03	2.54E-03	2.62E-03	2.90E-03	2.86E-03	3.15E-03	3.42E-03
Channel 14	2.71E-03	2.96E-03	3.04E-03	3.48E-03	3.85E-03	3.94E-03	4.61E-03
Channel 15	3.18E-03	3.66E-03	3.91E-03	4.27E-03	4.46E-03	4.65E-03	5.15E-03
Channel 16	3.81E-03	4.17E-03	4.50E-03	4.78E-03	5.09E-03	5.42E-03	5.83E-03

5.2.1. Performance of (600, 64, 16) PON

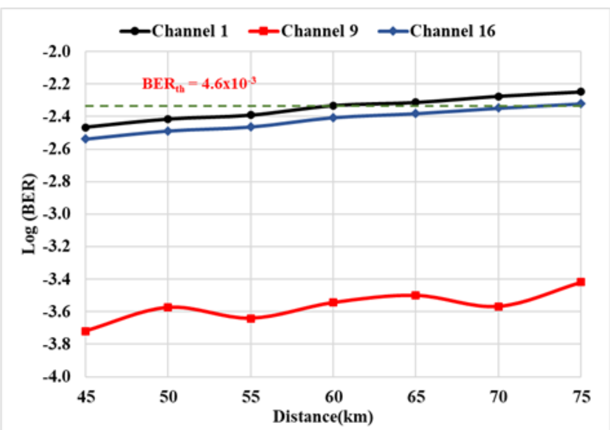


Figure 9. BERs of channels 1, 5, and 8 versus transmission distance (600, 64, 16) PON

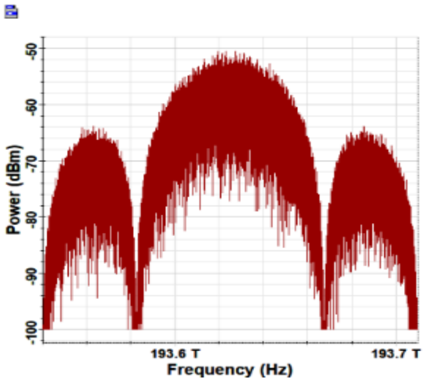
PON-A3 is denoted by code (600, 64, 16) PON and its simulation results are depicted in Figs. 8 and 9 along with Table 5. The results in Fig. 8 are plotted for a transmission link length of 60 km corresponding to the maximum reach. The spectra of the Ch1, Ch9, and Ch16 are presented in this, assuming Ch9 is the central channel. The received BERs are 4.62×10^{-3}, 3.24×10^{-3}, and 3.81×10^{-3} for Ch1, Ch9, and Ch16, respectively.

Figure 9 indicate that Ch1 determines the maximum reach of this network. Further, Ch9 gives the best transmission performance supporting longer transmission distance in compression to the other channels. Whereas, the Ch16 transmission distance is longer than Ch1.

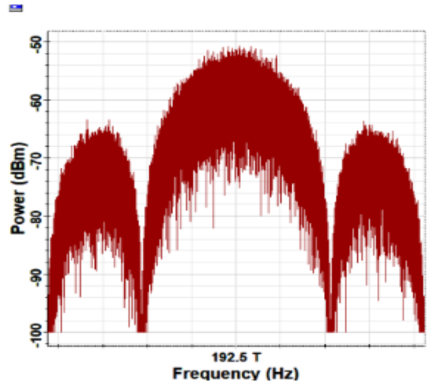
Table 5 clarifies the variation of BERs with the transmission distance of the 16 channels. When $L \leq 60$ km, the BER is less than BER_{th} for all the 16 channels. Rising L to 65 km makes Ch1 BER more than the BER_{th}. Increasing L to 90 km makes the BERs of the first and last three channels above BER_{th}.

5.2.2. Performance of (600, 128, 16) PON

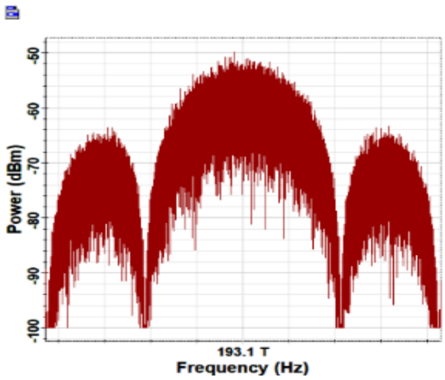
Simulation results related to PON-A4 are given in Fig. 10, Fig. 11, and Table 6. The maximum reach for this network is 45 km and determined by the behaving of Ch1. The signal spectra of three transmitted channels (Ch1, Ch9, and Ch16) at different points of the system are listed in Fig. 10. Also, the corresponding received constellation diagrams of (x polarization) are included.



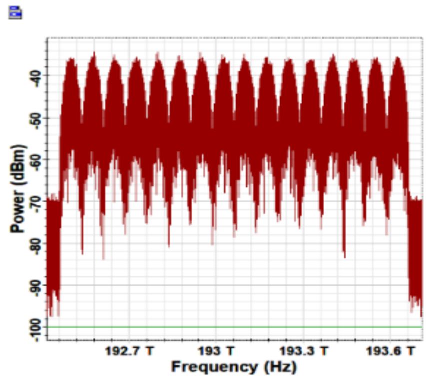
(a) Transmitted optical signal of Ch1.



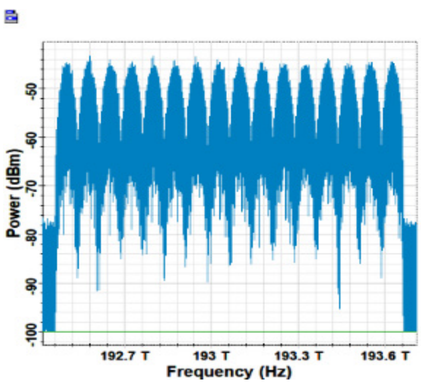
(b) Transmitted optical signal of Ch9.



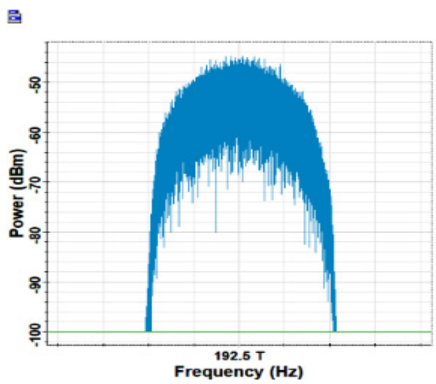
(c) Transmitted optical signal of Ch16.



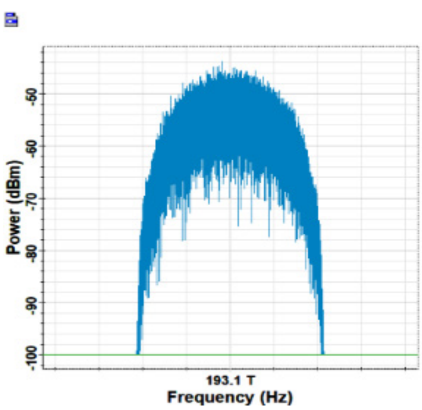
(d) WDM multiplexed signal.



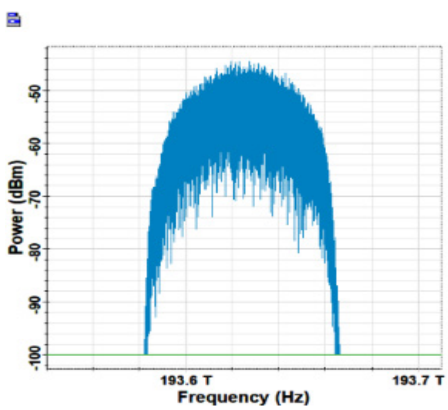
(e) WDM received signal.



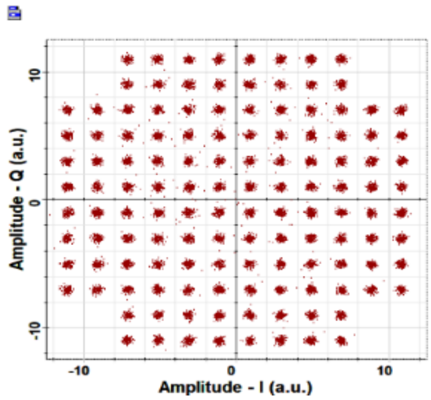
(f) Demultiplexed optical signal Ch1.



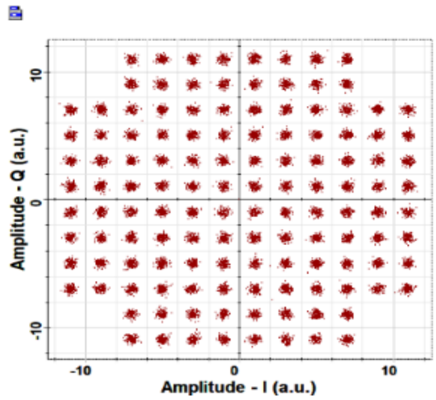
(g) Demultiplexed optical signal Ch9.



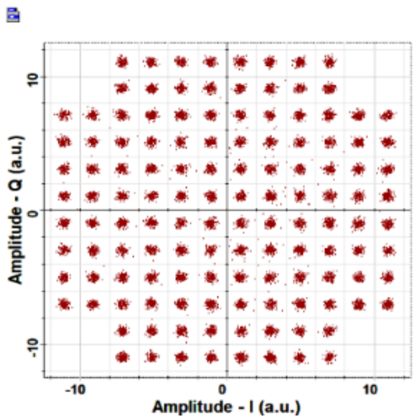
(h) Demultiplexed optical signal Ch16.



(i) Received constellation diagram of



(j) Received constellation diagram of



(k) Received constellation diagram of

Figure 10. Signals, spectra and received constellation diagrams related (600, 128, 16) PON

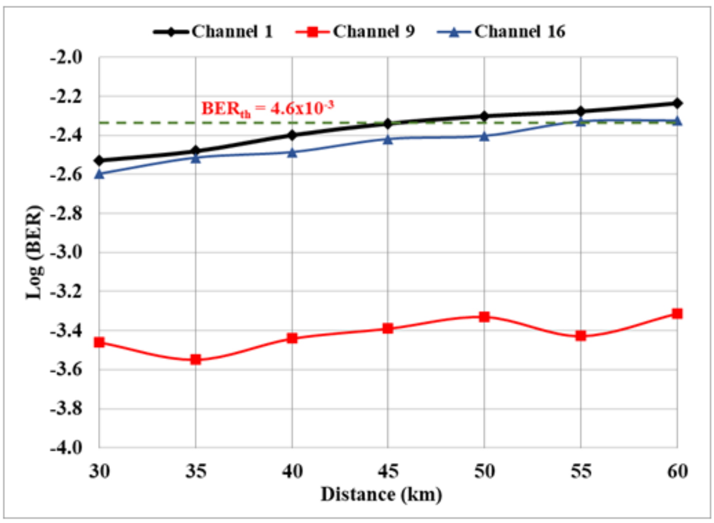


Figure 11. BERs of channels 1, 9, and 16 versus transmission distance (600, 128, 16) PON

Figure 11 shows the effect of transmission distance on BERs of channels 1, 9, and 16. Note that center channel Ch9 has the longest transmission distance compared to all system channels. Recall that Ch1 determines the longest transmission distance support of the system.

Table 6 lists the BERs of the 16 channels as a function of fiber length. The results in this table show that using L = 45 km keeps the BERs of all channels under the BER_{th}. Increasing L to 50 km makes the BER of Ch1 above the threshold limit ($BER1>BER_{th}$). Using L =65, 70, and 75 km makes the first three and the last two channels BER above the BER_{th}. While channels (Ch4 to Ch14) still satisfy the required BER_{th}.

Table 6. BERs variation with a transmission distance (600, 128, 16) PON

Channels	Distance (km)						
	45	50	55	60	65	70	75
Channel 1	4.57E-03	4.99E-03	5.27E-03	5.79E-03	6.50E-03	6.50E-03	7.17E-03
Channel 2	3.78E-03	4.27E-03	4.56E-03	5.15E-03	5.49E-03	6.14E-03	6.58E-03
Channel 3	3.37E-03	3.61E-03	4.05E-03	4.41E-03	4.86E-03	5.01E-03	5.50E-03
Channel 4	2.68E-03	3.11E-03	3.41E-03	3.86E-03	4.16E-03	4.12E-03	4.35E-03
Channel 5	2.35E-03	2.46E-03	2.74E-03	3.09E-03	3.29E-03	3.47E-03	3.75E-03
Channel 6	1.66E-03	1.85E-03	2.15E-03	2.36E-03	2.44E-03	2.83E-03	2.82E-03
Channel 7	1.17E-03	1.33E-03	1.54E-03	1.57E-03	1.77E-03	1.79E-03	2.01E-03
Channel 8	7.17E-04	7.55E-04	9.04E-04	8.97E-04	1.01E-03	1.02E-03	1.28E-03
Channel 9	4.08E-04	4.69E-04	3.74E-04	4.88E-04	4.39E-04	5.19E-04	6.26E-04
Channel 10	6.87E-04	8.13E-04	9.31E-04	8.70E-04	1.02E-03	9.88E-04	1.19E-03
Channel 11	1.16E-03	1.40E-03	1.49E-03	1.54E-03	1.79E-03	1.90E-03	2.08E-03
Channel 12	1.74E-03	1.74E-03	2.07E-03	2.23E-03	2.56E-03	2.55E-03	2.70E-03
Channel 13	2.30E-03	2.39E-03	2.72E-03	3.04E-03	3.28E-03	3.43E-03	3.69E-03
Channel 14	2.70E-03	2.95E-03	3.28E-03	3.47E-03	3.91E-03	4.10E-03	4.47E-03
Channel 15	3.28E-03	3.40E-03	3.90E-03	4.31E-03	4.70E-03	4.93E-03	5.05E-03
Channel 16	3.82E-03	3.96E-03	4.70E-03	4.75E-03	5.33E-03	5.69E-03	6.07E-03

6. Simulation Results of 1000 Gbps WDM-PONs

In this section, simulation results of coherent WDM-PONs operating with 1000 Gbps per λ data rate are given. In addition, the results include two QAM signals, 64 and 128, and for two multiplexed channels, $N_{ch} = 8$ and 16. Moreover, to prove the performance, a single-channel PON is involved.

6.1. 8-Antenna 1 Tbps PON

In this subsection, the results for 1000 Gbps per λ PONs and 8-channels WDM system are presented for the following cases

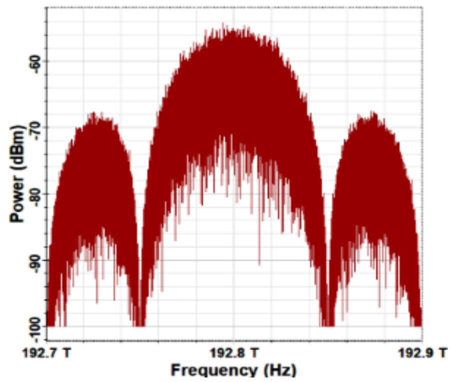
- PON-B1 ≡ (1000, 64, 8) PON
- PON-B2 ≡ (1000, 128, 8) PON

The total transmission data rate over the link is 8 × 1000 Gbps = 8 Tbps. For both PONs, the frequency channel spacing and roll-factor utilized in the following simulation are 125 GHz and 0.2, respectively. Note that the received BERs of all the WDM channels are kept under observation during the simulation. The maximum reach (L_{max}) is estimated when all the channels BERs do not exceed the threshold level of $4.6x10^{-3}$.

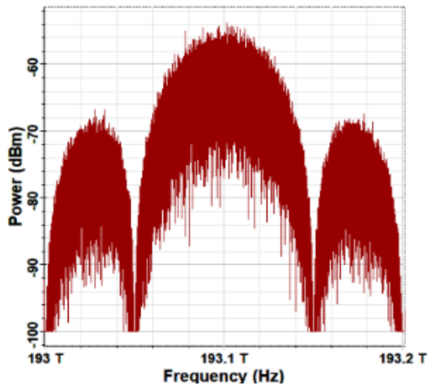
6.1.1. Simulation Results of (1000, 6, 8) PON

PON-B1 utilizes 8-channels WDM system to transmit 1000 Gbps DP 64-QAM signal per channel from the base station to the cell. Figure 12 shows the results of the simulation. Parts a-d of this figure depicts the spectrum of three transmitted channels (i.e., first channel Ch1, central channel Ch5, and last channel Ch8) along with the WDM multiplexed signal. In addition, part e shows the spectrum of received WDM signal when the fiber length is set to 40 km, which corresponds to maximum reach. The spectrum and constellation diagrams corresponding to three demultiplexed signals (Ch1, Ch5, and Ch8) are illustrated in parts (f, g, and

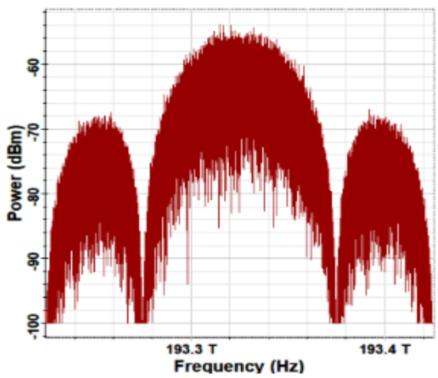
h) and (i, j, and k) of the figure, respectively. The BERs of these three channels are 4.15×10^{-3}, 6.91×10^{-4}, and 3.07×10^{-3}, respectively; all BERs are less than BER_{th}.



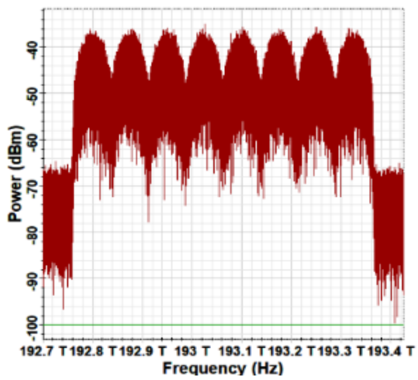
(a) Transmitted optical signal of Ch1.



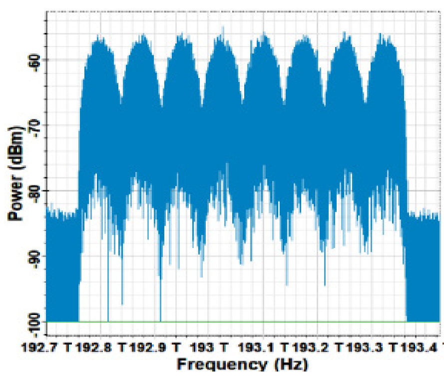
(b) Transmitted optical signal of Ch5.



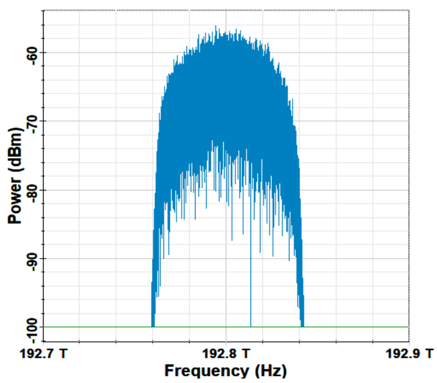
(c) Transmitted optical signal of Ch8.



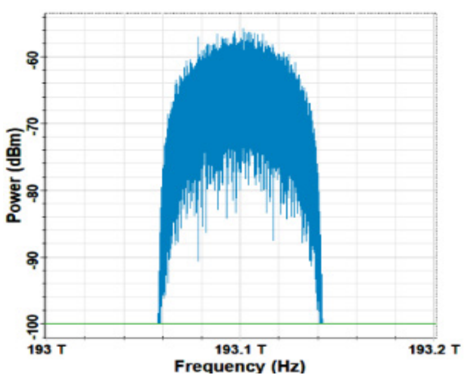
(d) WDM multiplexed signal.



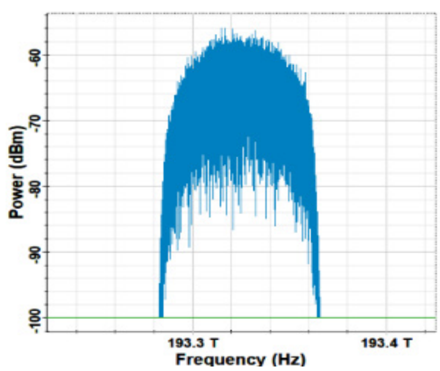
(e) WDM received signal.



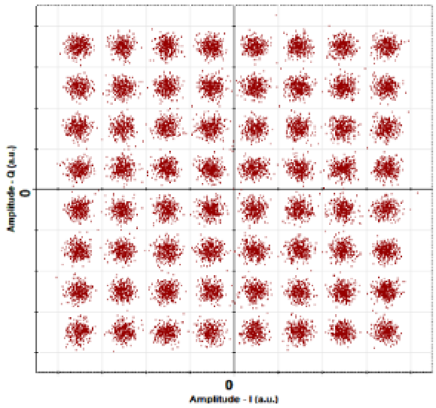
(f) Demultiplexed optical signal Ch1.



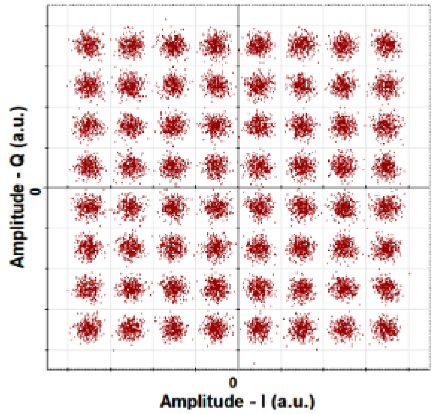
(g) Demultiplexed optical signal Ch5.



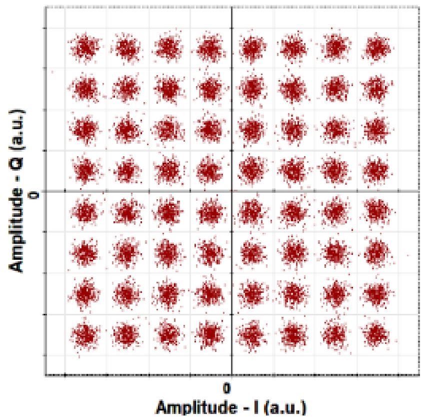
(h) Demultiplexed optical signal Ch8.



(i) Received constellation diagram of Ch1



(j) Received constellation diagram of Ch5



(k) Received constellation diagram of Ch8.

Figure 12. Signals spectra and received constellation diagram related (1000, 64, 8) PON

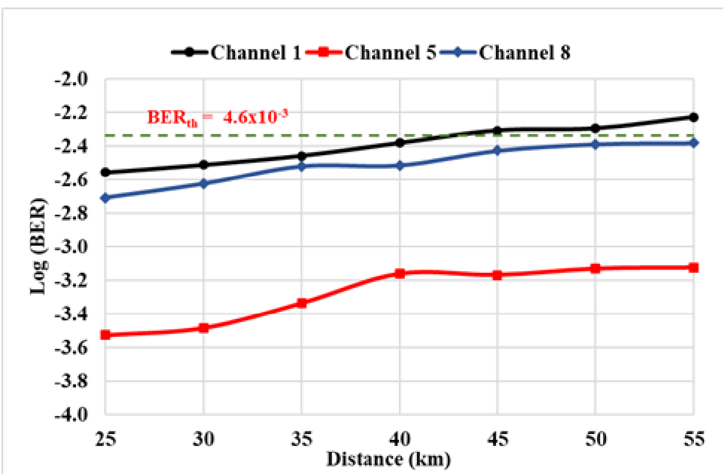


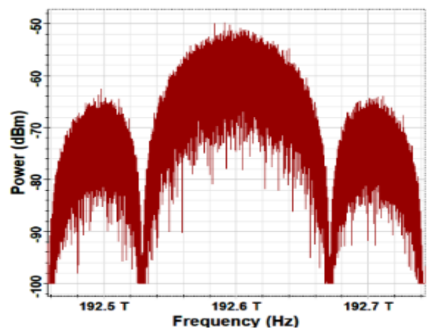
Figure 13. BERs of channels 1, 5, and 8 with transmission distance FOR (1000, 64, 8) PON

The dependence of the BERs of channels 1, 5, and 8 on the transmission distance are shown in Figure 13. Note that Ch5 supports a longer transmission distance than channel 1 and 8. However, Ch8 supports longer distance compared with Ch1. It is clear that Ch1 determines the maximum reach of this network.

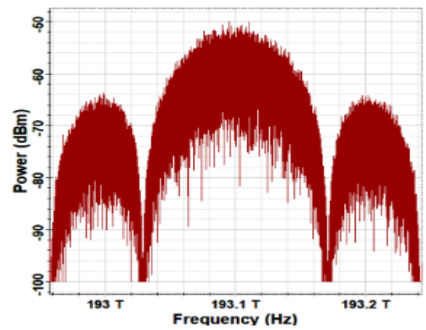
Table 7 lists the variation of BERs for the 8 channels with transmission distance (i.e., length of the SSMF link). At L = 40 km, the BERs of all the channels are below $BER_{th} = 4.6 \times 10^{-3}$. Increasing L to 45 km makes the BER of channel 1 (i.e., BER1) more than BER_{th}. Therefore, the maximum reach of 40 km is taken for this network. Increasing L further to 55 km makes another channel (Ch2) does not satisfy the required BER level. At L= 70 km, the BERs of channels 3 to 6 are less than the BER_{th}.

Table 7. BERs variation with a transmission distance for (1000, 64, 8) PON

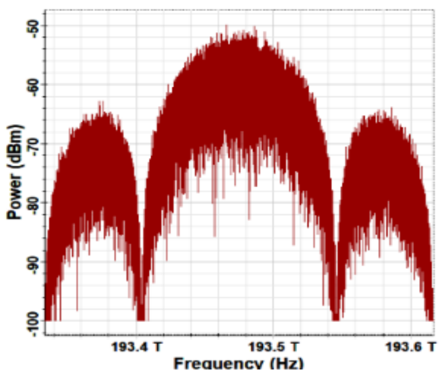
Distance (km)	40	45	50	55	60	65	70
Channel 1	4.15E-03	4.93E-03	5.07E-03	5.91E-03	6.38E-03	6.83E-03	7.55E-03
Channel 2	3.25E-03	3.72E-03	4.16E-03	4.71E-03	5.04E-03	5.12E-03	5.75E-03
Channel 3	2.24E-03	2.91E-03	2.88E-03	2.99E-03	3.74E-03	3.86E-03	4.05E-03
Channel 4	1.22E-03	1.49E-03	1.58E-03	1.68E-03	1.75E-03	2.22E-03	2.45E-03
Channel 5	6.91E-04	6.79E-04	7.40E-04	7.52E-04	9.61E-04	1.03E-03	9.65E-04
Channel 6	1.35E-03	1.43E-03	1.66E-03	1.56E-03	1.78E-03	2.12E-03	2.19E-03
Channel 7	2.23E-03	2.41E-03	2.85E-03	3.11E-03	3.53E-03	3.55E-03	3.70E-03
Channel 8	3.07E-03	3.75E-03	4.10E-03	4.16E-03	5.03E-03	5.28E-03	5.75E-03



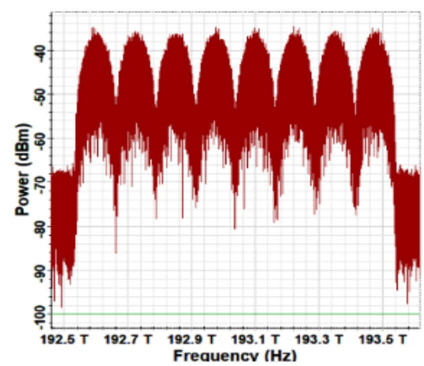
(a) Transmitted optical signal of Ch1.



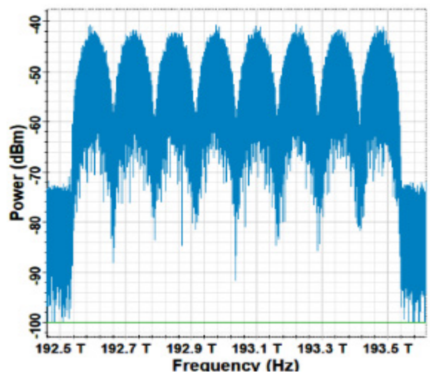
(b) Transmitted optical signal of Ch5.



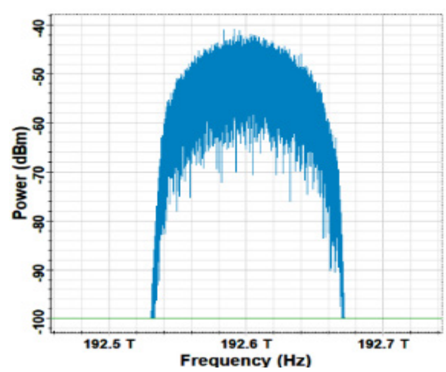
(c) Transmitted optical signal of Ch8.



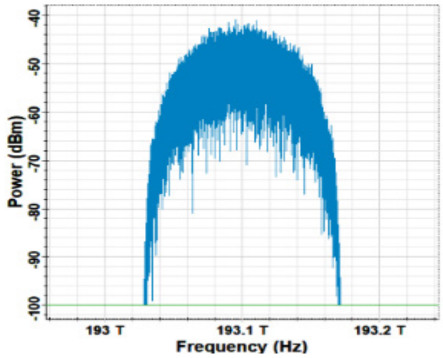
(d) WDM multiplexed signal.



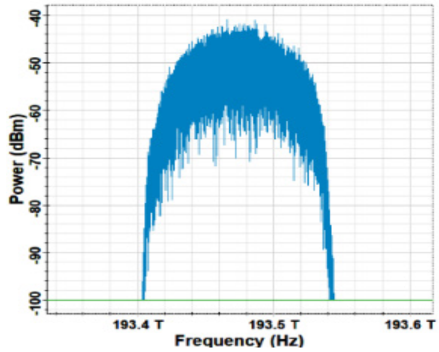
(e) WDM received signal.



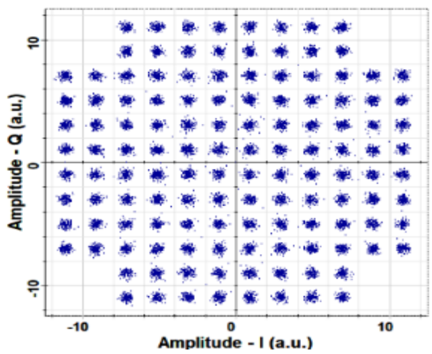
(f) Demultiplexed optical signal Ch1.



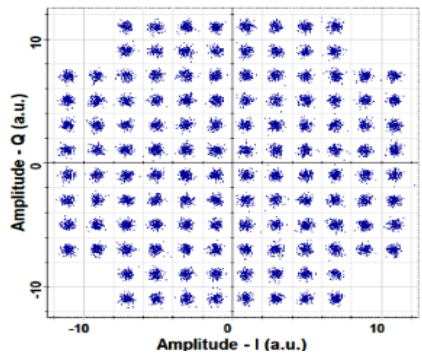
(g) Demultiplexed optical signal Ch5.



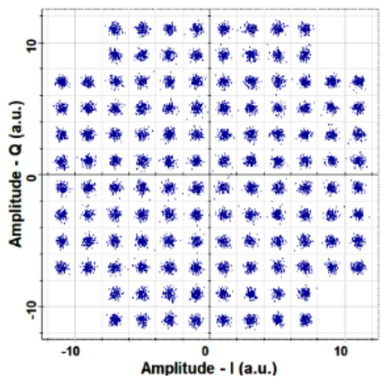
(h) Demultiplexed optical signal Ch8



(i) Received constellation diagram of Ch1.



(j) Received constellation diagram of Ch5.



(k) Received constellation diagram of Ch8.

Figure 14. Signals spectra and received constellation diagram related (1000, 128, 8) PON

6.1.2. Simulation Results of (1000, 128, 8) PON

The simulation is repeated for PON-B2 that uses 1000 Gbps DP 128-QAM signal over 8-channels WDM system. Figures 14 and 15 and Table 8 depict the obtained results. Figure 14 shows the spectra of the signals at different points of the system, along with the receiver constellation diagrams. The transmission length is set to the maximum reach (L_{max} = 30 km).

Figure 15 illustrates the dependence of the BERs of channels 1, 5, and 8 on the transmission distance. Note that Ch5 supports a longer transmission distance than channel 1 and 8. While Ch8 supports a longer distance compared with Ch1. It is clear that Ch1 determines the maximum reach of this network.

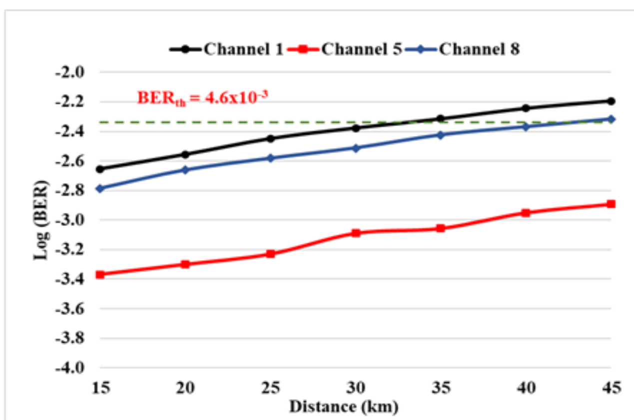


Figure 15. Varitation of BERs of channels 1, 5, and 8 with a transmission distance of (1000, 128, 8) PON

Table 8 lists the BERs of the 8 channels for different values of fiber length L. The results in this table highlight the following facts

(i) The maximum reach for the network is 30 km. Operating with L≤ 30 km ensures that all received channels BERs are less than BER_{th}.

(ii) Increasing L to 35km makes Ch1 to operate improbably, giving received BER > BERth.

(iii) Increasing L further does not alter the BER picture effectively till L approaches 60 km. At L= 60 km, two additional channels (Ch2 and Ch8) lags out of the required-BER operation (i.e., BER > BERth).

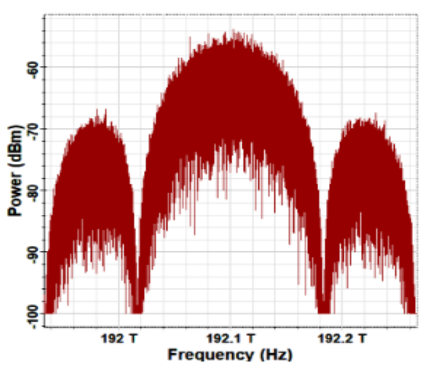
(iv) The network can support the required BER condition for 8, 7, and 5 antennas when L= 30, 55, and 60 km, respectively.

6.2. 16-Antenna 1 Tbps PON

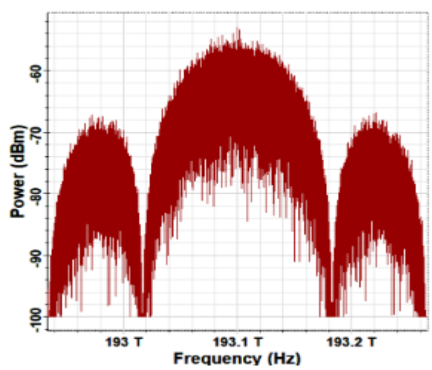
This subsection presents the results of simulation for 1000 Gbps per λ data rate and 16-channel WDM transmission assuming 64- and 128-QAM signaling represented by PON-B3 and PON-B4, respectively.

Table 8. BERs variation with a transmission distance of (1000, 128, 8) PON

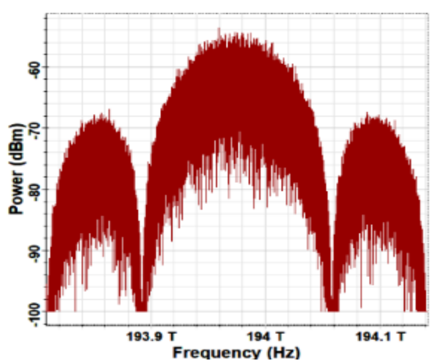
Distance (km)	30	35	40	45	50	55	60
Channel 1	4.20E-03	4.84E-03	5.71E-03	6.41E-03	6.86E-03	7.63E-03	8.38E-03
Channel 2	3.20E-03	3.64E-03	4.52E-03	4.89E-03	5.31E-03	6.06E-03	6.58E-03
Channel 3	2.30E-03	2.73E-03	3.22E-03	3.46E-03	3.90E-03	4.26E-03	4.67E-03
Channel 4	1.32E-03	1.70E-03	2.00E-03	2.26E-03	2.24E-03	2.24E-03	2.48E-03
Channel 5	8.13E-04	8.77E-04	1.12E-03	1.28E-03	1.37E-03	1.64E-03	1.46E-03
Channel 6	1.24E-03	1.43E-03	1.82E-03	1.91E-03	2.06E-03	2.19E-03	2.75E-03
Channel 7	2.21E-03	2.64E-03	3.01E-03	3.36E-03	3.80E-03	4.03E-03	4.74E-03
Channel 8	3.07E-03	3.77E-03	4.28E-03	4.82E-03	5.04E-03	5.86E-03	6.43E-03



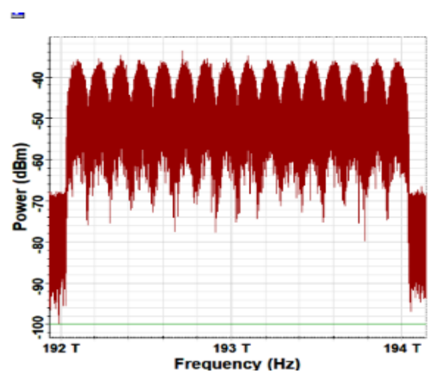
(a) Transmitted optical signal of Ch1.



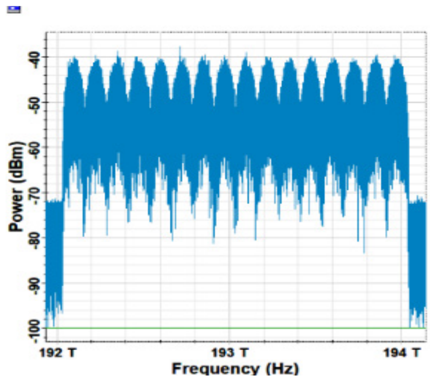
(b) Transmitted optical signal of Ch9



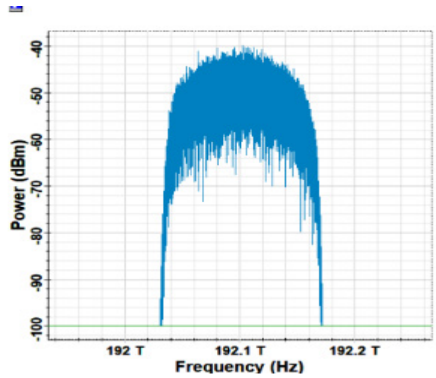
(c) Transmitted optical signal of Ch16.



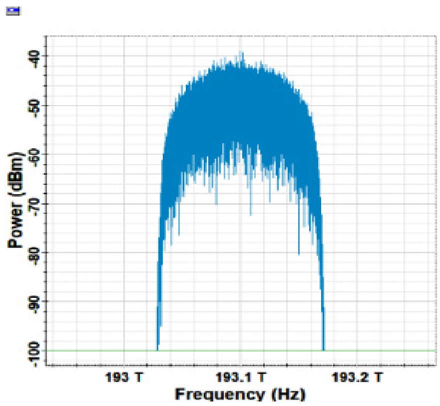
(d) WDM multiplexed signal.



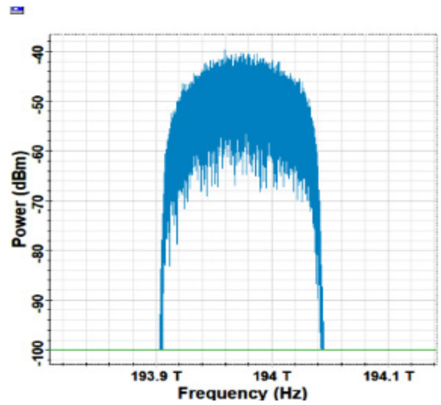
(e) WDM received signal.



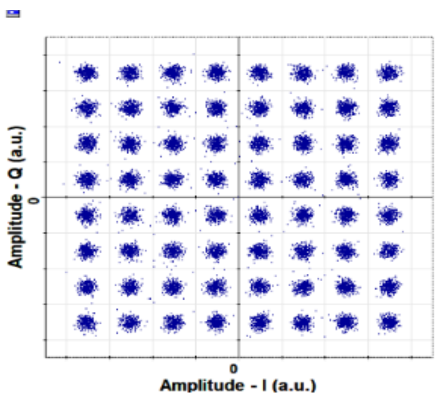
(f) Demultiplexed optical signal Ch1.



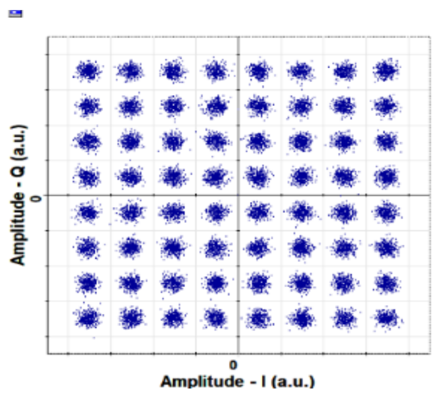
(g) Demultiplexed optical signal Ch9.



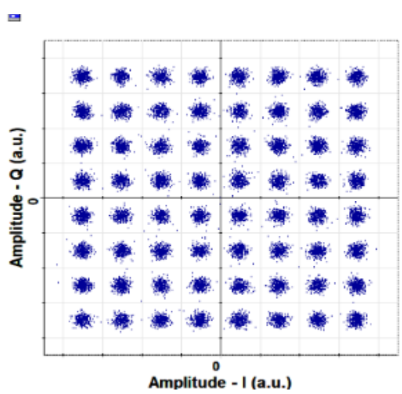
(h) Demultiplexed optical signal Ch16.



(i) Received constellation diagram of Ch1.



(j) Received constellation diagram of Ch9.



(k) Received constellation diagram of Ch16.

Figure 16. Signals spectra and received constellation diagram related (1000, 64, 16) PON

6.2.1. Simulation Results of (1000, 6, 16) PON

Figures 16 and 17 along with Table 9 depict the simulation results for PON-B3, which is denoted by code (1000, 64, 16) PON. Figure 16 shows the results corresponding to transmission link length of 20 km (maximum reach). The spectra of the Ch1, Ch9, and Ch16 are presented in this figure, assuming Ch9 is the central channel. The received BERs are 4.04×10^{-3}, 2.94×10^{-4}, and 3.72×10^{-3} for Ch1, Ch9, and Ch16, respectively.

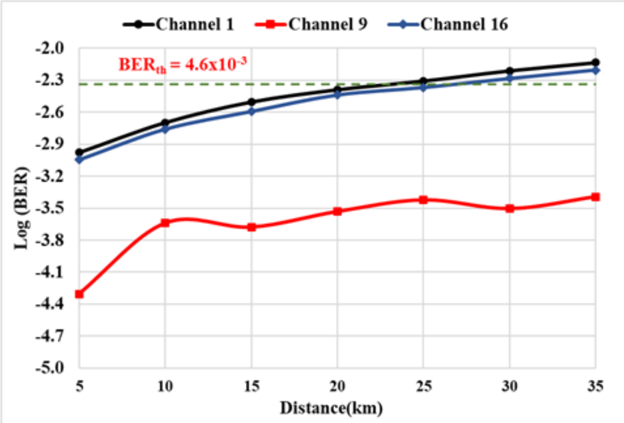


Figure 17. Variation of BER with a transmission distance of Ch1, Ch9, and Ch16 of (1000, 64, 16) PON

Figure 17 indicate that Ch1 determines the maximum reach of this network with L = 25 km. Further, Ch9 gives the best transmission performance compared to other channels. On the other side Ch16 support transmission distance more than Ch1.

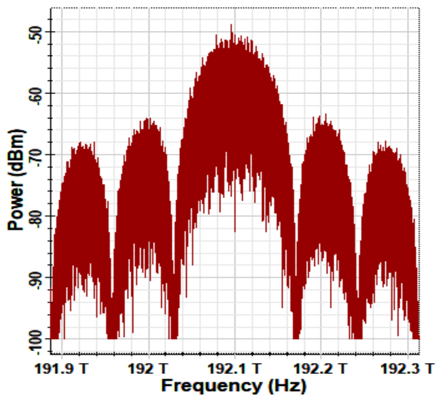
The BER variation with a transmission distance of the 16 channels is illustrated in Table 9. The first state in the table of transmission distance indicates that all BERs of the 16 channels are operating lower than BER_{th} at L = 20. Increasing L to 25 km makes Ch1 BER higher than BER_{th}. Increasing L to 30, 35, and 50 km makes only 11, 9, and 6 antennas to operate below BER_{th}, respectively.

6.2.2. Simulation Results of (1000, 128, 16) PON

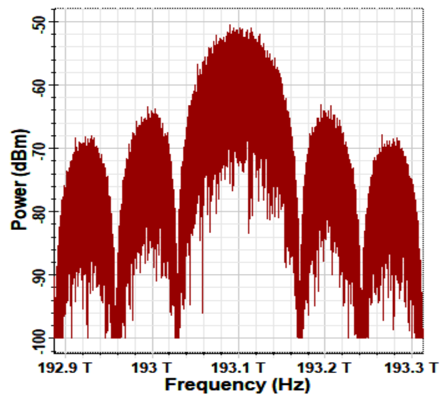
Simulation results of PON-B4, which is denoted by code (1000, 128, 16) PON are depicted in Figs. 18 and 19 and Table 10. The corresponding maximum reach of transmission link length is 15 km. The spectra and constellation diagram results are plotted in Fig. 18 for a 15 km transmission distance. The spectra of the Ch1, Ch9, and Ch16 are also presented in this figure, assuming Ch9 is the central channel. The received BERs for three channels Ch1, Ch9, and Ch16 are $4.12 \text{x} 10^{-3}$, $3.47 \text{x} 10^{-4}$, and $3.37 \text{x} 10^{-3}$, respectively.

Table 9. BERs variation with a transmission distance of (1000, 64, 16) PON

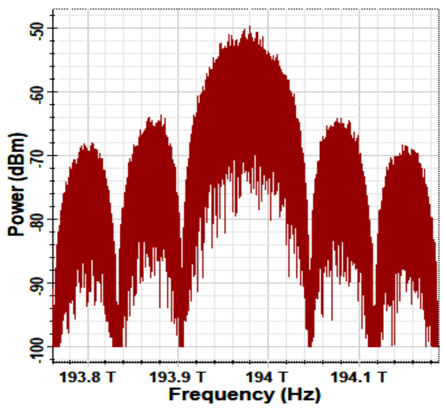
Distance (km)	20	25	30	35	40	45	50
Channel 1	4.04E-03	4.94E-03	6.15E-03	7.33E-03	8.35E-03	9.64E-03	1.03E-02
Channel 2	3.82E-03	4.53E-03	5.38E-03	6.47E-03	7.32E-03	8.82E-03	9.21E-03
Channel 3	3.11E-03	4.04E-03	4.66E-03	5.22E-03	6.28E-03	7.55E-03	8.32E-03
Channel 4	2.63E-03	3.19E-03	3.74E-03	4.80E-03	5.24E-03	6.28E-03	7.07E-03
Channel 5	2.12E-03	2.69E-03	3.11E-03	3.87E-03	4.25E-03	5.15E-03	6.22E-03
Channel 6	1.46E-03	1.98E-03	2.36E-03	2.81E-03	3.35E-03	4.20E-03	4.63E-03
Channel 7	1.16E-03	1.35E-03	1.61E-03	2.25E-03	2.29E-03	2.95E-03	3.41E-03
Channel 8	6.18E-04	8.77E-04	8.66E-04	1.08E-03	1.31E-03	1.93E-03	2.18E-03
Channel 9	2.94E-04	3.78E-04	3.13E-04	4.04E-04	6.14E-04	1.37E-03	1.05E-03
Channel 10	6.94E-04	9.16E-04	8.47E-04	1.08E-03	1.35E-03	1.90E-03	1.88E-03
Channel 11	1.23E-03	1.30E-03	1.53E-03	1.95E-03	2.06E-03	3.13E-03	3.28E-03
Channel 12	1.61E-03	2.20E-03	2.33E-03	2.94E-03	3.25E-03	4.28E-03	4.48E-03
Channel 13	2.16E-03	2.58E-03	2.90E-03	3.46E-03	4.20E-03	5.16E-03	6.03E-03
Channel 14	2.54E-03	3.23E-03	3.87E-03	4.67E-03	5.33E-03	6.55E-03	6.95E-03
Channel 15	3.07E-03	4.02E-03	4.75E-03	5.40E-03	6.19E-03	7.34E-03	8.32E-03
Channel 16	3.72E-03	4.29E-03	5.21E-03	6.25E-03	7.22E-03	7.96E-03	9.03E-03



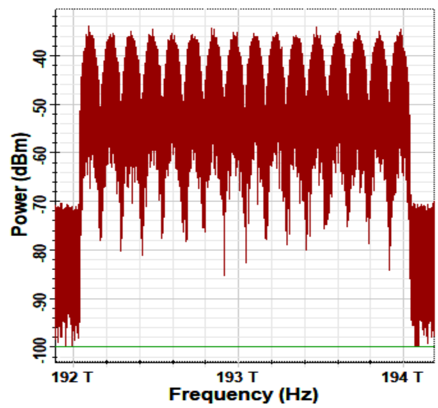
(a) Transmitted optical signal of Ch1.



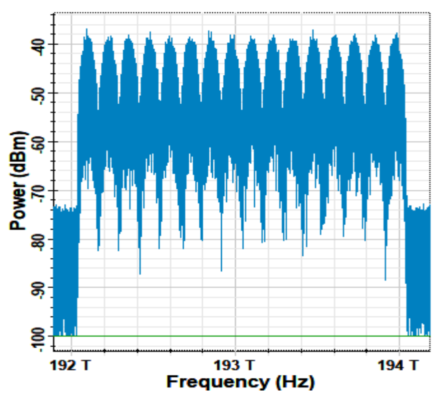
(b) Transmitted optical signal of Ch9.



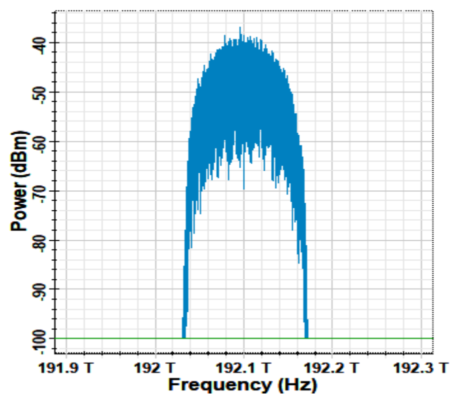
(c) Transmitted optical signal of Ch16.



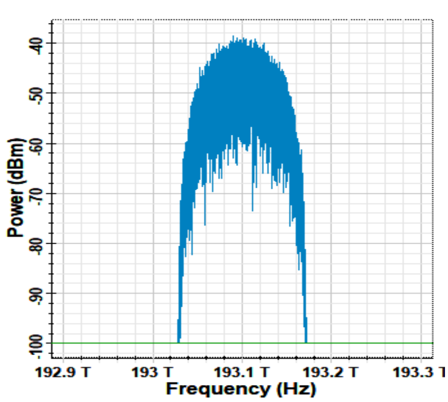
(d) WDM multiplexed signal.



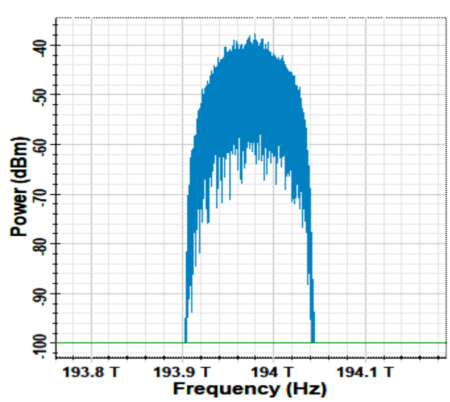
(e) WDM received signal.



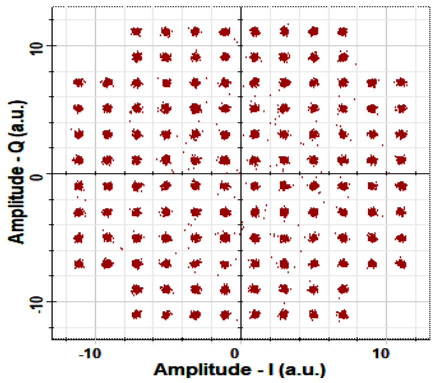
(f) Demultiplexed optical signal Ch1.



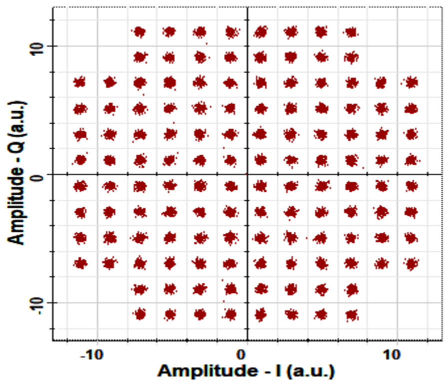
(g) Demultiplexed optical signal Ch9.



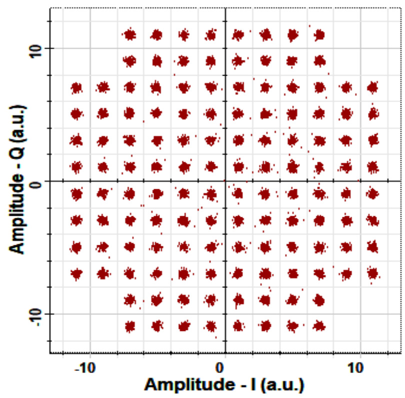
(h) Demultiplexed optical signal Ch16.



(i) Received constellation diagram of Ch1.



(j) Received constellation diagram of Ch9



(k) Received constellation diagram of Ch16

Figure 18. Signals spectra and received constellation diagram of (1000, 128, 16) PON

Table 10. Variation of BERs of the 16 channels with a transmission distance of (1000, 7, 16) PON

Distance (km)	15	20	25	30	35	40	45
Channel 1	4.12E-03	5.49E-03	6.69E-03	8.15E-03	9.69E-03	1.07E-02	1.19E-02
Channel 2	3.67E-03	4.55E-03	6.26E-03	7.13E-03	8.45E-03	9.51E-03	1.05E-02
Channel 3	3.12E-03	4.17E-03	5.09E-03	6.40E-03	7.60E-03	8.47E-03	8.95E-03
Channel 4	2.61E-03	3.41E-03	3.99E-03	5.40E-03	6.22E-03	7.18E-03	7.74E-03
Channel 5	2.30E-03	3.01E-03	3.46E-03	4.19E-03	5.14E-03	5.68E-03	6.46E-03
Channel 6	1.62E-03	2.21E-03	2.46E-03	3.19E-03	3.77E-03	4.17E-03	4.81E-03
Channel 7	1.16E-03	1.53E-03	1.90E-03	2.04E-03	2.65E-03	3.44E-03	3.36E-03
Channel 8	6.52E-04	7.74E-04	1.03E-03	1.48E-03	1.58E-03	1.67E-03	2.03E-03
Channel 9	3.47E-04	4.39E-04	4.20E-04	6.37E-04	7.94E-04	1.02E-03	1.12E-03
Channel 10	6.33E-04	9.58E-04	9.69E-04	1.46E-03	1.42E-03	1.68E-03	1.95E-03
Channel 11	1.03E-03	1.44E-03	2.04E-03	2.21E-03	2.66E-03	3.30E-03	3.34E-03
Channel 12	1.64E-03	2.14E-03	2.53E-03	3.26E-03	3.52E-03	4.12E-03	5.02E-03
Channel 13	1.96E-03	2.75E-03	3.49E-03	3.97E-03	4.62E-03	5.31E-03	5.94E-03
Channel 14	2.50E-03	3.44E-03	4.06E-03	4.92E-03	5.87E-03	6.42E-03	7.42E-03
Channel 15	3.03E-03	3.97E-03	4.97E-03	6.02E-03	6.91E-03	7.71E-03	8.64E-03
Channel 16	3.37E-03	4.62E-03	5.84E-03	6.71E-03	7.91E-03	9.20E-03	9.89E-03

Figure 19 shows the dependence of the BERs of Ch1, Ch9, and Ch16 on the transmission distance. Note that Ch1 sets the maximum reach distance of the system. Whereas, Ch9 represents the central channel and supports the longer transmission distance from all other channels. Further, Ch16 has a longer transmission distance than Ch1.

Table 10 illustrates the variation of BERs for the 16 channels with transmission distance. At L = 15 km, the BERs of all the channels are below $BER_{th} = 4.6 \times 10^{-3}$. Increasing L to 20 km makes the BER of channel 1 and channel 16 more than BER_{th}. Increasing L further to 25 km makes other channels (Ch2, Ch3, and Ch15) not satisfy the required BER level. At L= 45 km, the BERs of channels 7 to 11 are only less than the BER_{th}.

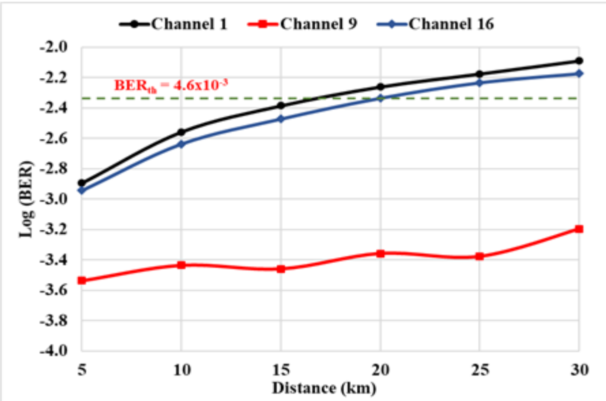
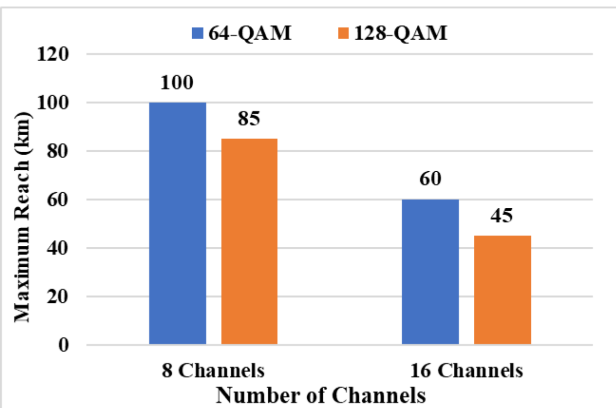


Figure 19. BER variation with a transmission distance of Ch1, Ch9, and Ch16 of (1000, 128, 16) PON

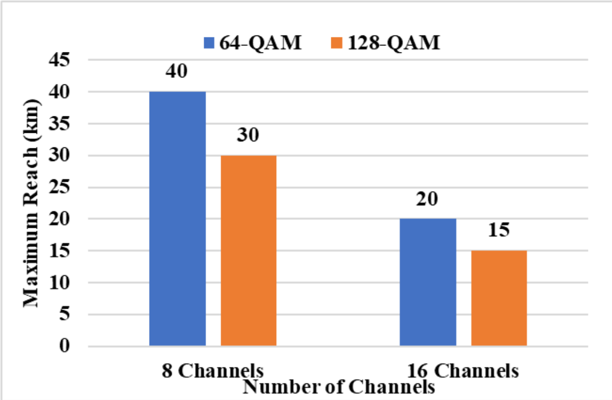
7. Performance Comparison

This section presents a brief performance comparison for the PONs investigated in this chapter. The performance measure used for comparison purpose is the maximum reach L_{max} corresponding to BER_{th} of 4.6×10^{-3}. Recall that the PONs have been investigated for two modulation formats (64- and 128-QAM), two numbers of multiplexed WDM channels R_b (600 Gbps and 1 Tbps).

Figures 20a and b show chart bars corresponding to L_{max} as a function N_{ch} and modulated formats assuming 600 Gbps and 1 Tbps data rate per channel, respectively.



(a)



(b)

Figure 20. Variation of maximum reach with the number of channels. (a) $R_b = 600\ Gbps$. (b) $R_b = 1\ Tbps$

Table 11 is deduced for Figs. 20 a and b and lists the ratio $(L_{max})_{128-QAM}/(L_{max})_{64-QAM}$ which is denoted here by the parameter r_{Format}. The results are given for different values of N_{ch} and R_b. Note that going from 64-QAM to 128-QAM signaling yields $r_{Format} = 0.75$. This indicates that the maximum reach reduces to 75%.

Table 11. Effect of modulation format on the performance of the designed PONs

Bit rate per channel R_b	$r_{Format} \equiv (L_{max})_{128-QAM}/(L_{max})_{64-QAM}$	
	$N_{ch} = 8$	$N_{ch} = 16$
600 Gbps	0.85	0.75
1 Tbps	0.75	0.75

An alternative look for performance comparison $r_{channel} \equiv (L_{max})_{Nch=16}/(L_{max})_{Nch=8}$ as depicted in Table 12. According to this table, one can say 16-cahnnel PON reduces L_{max} to about 50% of the 8 channels PON.

Table 12. Effect of the number of WDM channels on the performance of the designed PONs

Bit rate per channel R_b	$r_{channel} \equiv (L_{max})_{Nch=16}/(L_{max})_{Nch=8}$	
	64-QAM	128-QAM
600 Gbps	0.60	0.53
1 Tbps	0.50	0.50

It is worth to extending the comparison measure to include the parameter "Total bit rate-maximum reach product", which is computed as $(R_b)_{total} \times L_{max}$ and denoted here by the parameter "BLP". Note that $BLP = N_{ch} \times R_b \times L_{max}$. The results corresponding to this parameter is given in Table 13 investigating the results in this table highlights the following findings

(i) Operating with $R_b = 600$ Gbps offers higher BLP compared with $R_b = 1$ Tbps assuming the same number of WDM channels and modulation format.

(ii) Higher BLP is achieved when the PON is designed with 64-QAM signaling rather than the 128-QAM signaling.

(iii) For fixed R_b and modulation format, the 16-channel PON offers higher BLP compared with 8-channels

PON.

(iv) The highest BLP is 576 Tbps.km, which is achieved in a PON designed with Nch = 16, R_b =600 Gbps, and 64-QAM format.

Table 13. Dependence of total bit rate ratio-maximum reach product (BLP) on modulation format, number of WDM channels and bit rate per channel

Bit rate per channel R_b	Total bit rate-maximum reach product (Tbps.km)			
	8-channels WDM		16-channels WDM	
	64-QAM	128-QAM	64-QAM	128-QAM
600 Gbps	480	408	576	432
1 Tbps	320	240	320	240

8. Conclusions

The transmission performance of coherent WDM-PON has been investigated to support 5G and B5G service distribution. The PON sends (receives) the data to (from) a macro cell consisting of 8 or 16 small cells; each small cell uses one of the WDM wavelength. 64- and 128-QAM signaling have been used to support data rate transmission R_b of 600 Gbps and 1 Tbps per single wavelength. Simulation results based on Optisystem software ver. 15.0 have been obtained to determine the maximum reach L_{max} for each WDM-PON designed in this work. The main conclusions drawn from this study are

(i) WDM channel spacing Δf of 75 and 125 GHz is suitable to transmit 600 Gbps and 1 Tbps data rate, R_b, to each small cell, respectively. These values of Δf are applicable for both DP 64- and 128-QAM signaling.

(ii) Adapting the parameters of each channel receiver DSP makes the DSP capable to compensate the effect of fiber dispersion on the channel performance. This statement is valid for both values of R_b, 600 Gbps and 1 Tbps, and for both modulation formats.

(iii) When both R_b and the number of WDM channels Nch are kept fixed, the use of 128-QAM format rather than 64-QAM format reduces the maximum reach to approximately 75%. For example, when R_b = 600 Gbps and Nch = 16, L_{max} reduces from 60 to 45 km when 128-QAM signaling is used in place of 64-QAM. These values of L_{max} are to be compared with 20 and 15 km, respectively, when R_b= 1 Tbps.

(iv) When both modulation format and R_b are kept constant, the maximum reach reduces by 50% approximately when the WDM-PON is designed to serve 16-small cells configuration rather than 8-small cell configuration. For example, using 64-QAM signaling and R_b = 600 Gbps yields L_{max} = 100 and 60 km when Nch = 8 and 16, respectively. These values are to be compared with L_{max} = 85 and 45 km, respectively when 128-QAM signaling is used.

(v) Going from R_b= 600 Gbps to 1 Tbps reduces L_{max} to approximately the third. Using Nch = 16 and 64-QAM signaling yields L_{max} = 60 and 20 km when R_b = 600 Gbps and 1 Tbps respectively. If 128-QAM signaling is used, L_{max} = 45 and 15 km, respectively.

(vi) The DP 64-QAM modulation formats can support 1 Tbps transmission if the symbol rate R_s of 84 GSps is used. If extra is transmitted as a header, one can go to 128-QAM signaling at the same value of R_s. this yields 1/7 ($\approx$ 14%) header.

(vii) Higher bit rate-length product (BLP) is obtained when one uses R_b = 600 Gbps rather than 1 Tbps, 64-QAM rather the 1280-QAM, and N_{ch} = 16 rather than 8. The highest value of BLP is 576 Tbps.km which is achieved in a PON designed with N_{ch} = 16, R_b = 600 Gbps, and DP 64-QAM format.

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