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Coherent High-Speed Signal Transmission in Passive Optical Networks

Henry C. Cherutoi, David W. Waswa, & Dismas Choge

1. Department of Physics, University of Eldoret, Eldoret, Kenya

Abstract:
A comparative study of digital M-ary Quadrature Amplitude Modulation (16-QAM) and QPSK modulation formats for high-speed transmission is presented. Based on VPI optical simulation software. This paper builds a high-bit rate dual polarization (DP) QPSK and 16-QAM modulation formats coherent optical transmission system for Passive Optical Networks (PON). Higher-order modulation formats could be used to provide huge data capacity, extended coverage, and long-reach connections. Channel impairments are mitigated by using digital signal processing (DSP) for dispersion compensation, carrier frequency recovery, and carrier phase estimation. The performance of our system is analysed on Bit Error Rate (BER=1e-9), the threshold for a communication system. For a 32-Splitter PON configuration operating with 16-QAM modulation format, a data rate of 80 Gb/s per ONU is achieved after 24km using standard single mode fibre (SSMF). The results indicate that the proposed schemes are a promising solution for coherent high-speed transmission in PONs.

Keywords: Coherent detection, Dual-Polarization, Optical transmission, Dispersion.

INTRODUCTION

The significant demand for bandwidth and download speeds by end users has increased dramatically owing to emerging mobile technologies, such as 5G and data-intensive applications e.g., high-definition T.V (H.D TV), online gaming, voice over IP (VOIP), video conferencing, etc [1]. To achieve hundreds of data rates per wavelength channel, higher order modulation formats e.g Quaternary Phase-Shift Keying (QPSK) and M-ary Quadrature Amplitude Modulation need to be employed. QPSK and m-QAM in combination with coherent detection is becoming an attractive candidate for high-capacity optical systems since it increases the data rate without increasing the symbol rate or the required bandwidth thus reducing the cost per bit of the transmitted information. [2,3]. These systems are recognised as an important step in the next-generation high-capacity optical systems beyond 100 Gb/s [4]. Dual polarization (DP) of an optical signal double the number of bits transmitted while keeping the symbol rate the same when compared to a single-polarized signal. For the DP-QPSK technique, one symbol will carry four times the on-off keying (OOK) bits therefore utilizing fibre optic link resources.

However, DP signals are more vulnerable to linear and nonlinearities since it limits the transmission capacity and distance. Therefore, there is need to mitigate these impairments to increase the overall system performance. It has been shown that DSP can effectively compensate for these impairments in DP optical systems [5]. Coherent communication is being accelerated in its research and development due to the possibility of increasing the receiver sensitivity [6]. The coherent systems enhance the spectral efficiency (SE) of multilevel modulation formats and the availability of digital signal processing (DSP) to compensate for transmission impairments have turned the focus to coherent optical systems as a key technology to satisfy the increasing bandwidth demand. Coherent optical systems apply higher-order modulation formats to increase optical system capacity. These systems increase the SE of a system by utilizing three characteristics of optical field, namely; phase, intensity and polarization to transmit information. [7]. These techniques are now used in optical access network solutions to distribute high bandwidth data to customers through an optical fibre network infrastructure. With the continuous increase of bandwidth requirements by the end users, PONs have been evolved to satisfy the next generation requirements such as higher data rates and large number of users [8]. These features can be achieved by employing new topologies such as WDM and higher splitting ratios.

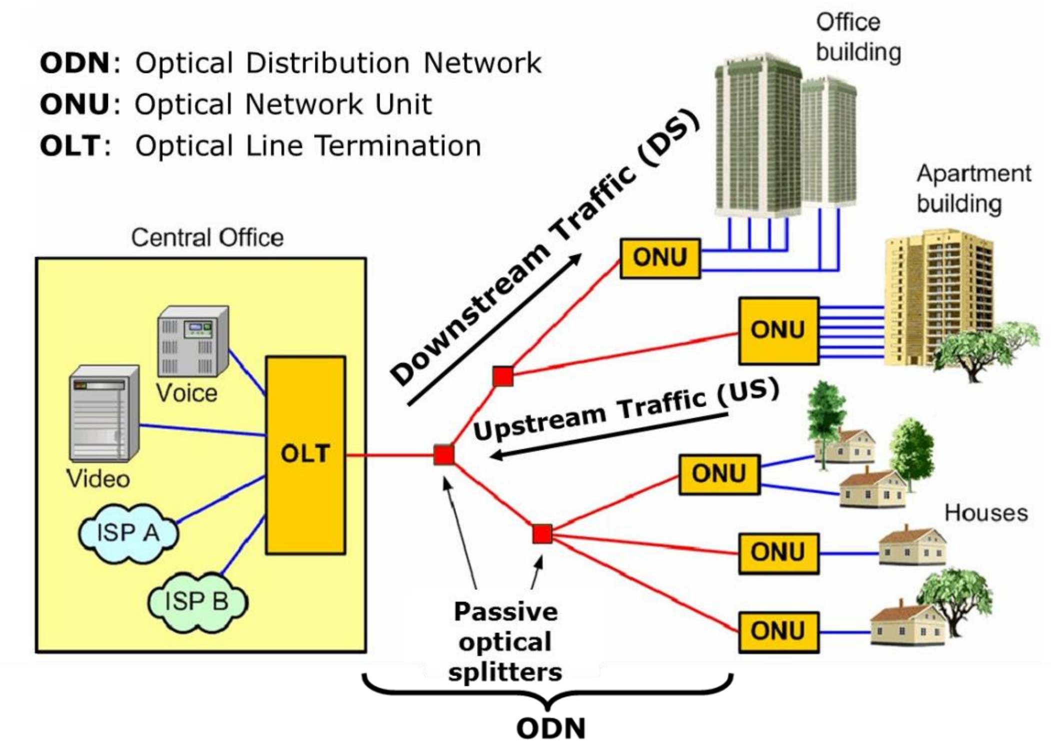

Figure 1: Passive optical network architecture [9]

The increase in the number of users and the demand for high data-rate has attracted attention towards the development of point to multipoint architecture that satisfies the NG-PON2. These high-speed PON can be realized by either bonding multiple wavelengths or increasing the data rate per wavelength [10]. In this work, a significant data rate (2500 Gb/s) will be achieved in using coherent PON employing DP technique with QPSK and m-QAM modulation formats.

THEORY

Coherent optical transmission refers to optical communication systems that apply higher order modulation format at the transmitter side and coherent detection using local oscillator (LO) laser and digital signal processing (DSP) at the receiver side. To increase the transmission bit rate (R_b) per channel, then higher-order modulation formats together with Dual Polarization (DP) multiplexing technique need to be introduced hence allowing the integration of single-wavelength channel with data rate at 100 Gb/s.

The introduction of DSP for coherent receivers made it possible to mitigate random changes in the polarization of an optical signal and linear impairments such as polarization mode dispersion

(PMD) and chromatic dispersion (CD) hence eliminating the need for dispersion compensation modules. Together with DSP, coherent detection provides new capabilities such as the use of high spectral efficient modulation formats such as QPSK and m-QAM [11]. These higher order formats are based on the vector summation technique, which aims to achieve the desired carrier phase and amplitude by summing two orthogonal components namely, In-Phase (I) and Quadrature (Q) components. However, the key challenges of multilevel coherent systems are, laser phase noise, strict laser linewidth requirements and the receiver complexity which prevent a cost-effective implementation [12]. These wavefront distortions create imbalance between the I and Q branches in the coherent systems [13].

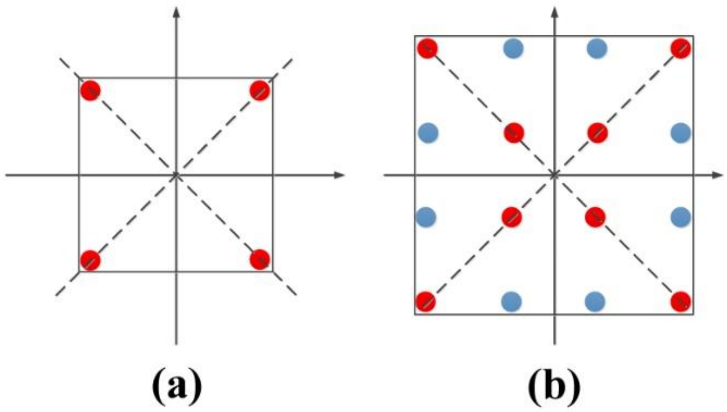

Figure 2: Constellation of (a) QPSK (b) 16-QAM

Compared to the intensity modulated-direct detection (IM-DD) systems, coherent detection provides the following advantages; increases the transmission capacity as well as the SE, improved receiver sensitivity due to DSP systems, provides a flexible programmable design that can support multiple modulation formats, and improves system tolerance to linear impairments by applying DSP.

The amplitude and phase of an optical carrier can be modulated by binary data simultaneously so that each n bits of the input data are mapped into one symbol m such that;

$$n = log_2(m) \tag{1}$$

For QPSK modulation format, four symbols are used to carry information using two number of bits (n=2 bits) therefore, more information is transmitted as compared to either amplitude or phase modulation alone. The relation between the symbol R_s rate (symbols/s) and the bit rate (bits/s) is given by the following expression;

$$R_s = \frac{R_b}{Log_2 M} = \frac{R_b}{n} \tag{2}$$

Hence, at a given bit rate, the spectral width which depends on the symbol rate is reduced, hence enhancing the spectral efficiency. To increase the SE beyond 2 bits/s/HZ, m-QAM modulation formats has been proposed [14];

$$SE = \frac{Total\ transmission\ bit\ rate}{Optical\ bandwith} \tag{3}$$

$$SE = \frac{2R_S Log_2 M}{\Delta f} \quad (4)$$

Where; R_s Symbol rate, M modulation order and $\Delta \boldsymbol{f}$ frequency spacing.

METHODOLOGY

In this study, the numerical simulation was performed using Virtual Photonics Inc. (VPI) transmission Maker Version. VPI simulation tool is widely used to simulated a huge range of optical transmission systems. These systems are used to investigate new technologies and to optimize the optical transmission systems including coding, modulation, compensation and detection [15].

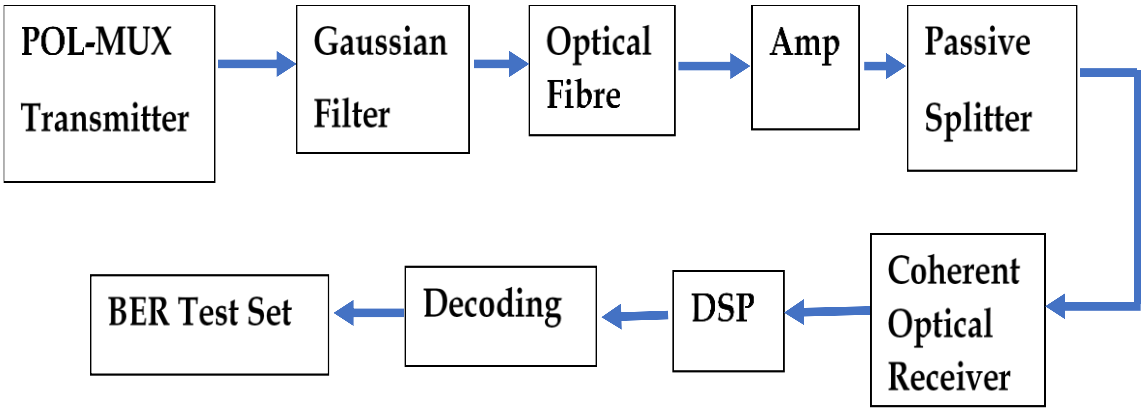

Figure 3: The block diagram of DP-QPSK and DP-16QAM transmission system.

Figure 3 illustrates the block diagram of 10 Gb/symbol DP-QPSK DP-16QAM transmission system. In the transmitter, the laser signal is divided into two channels X and Y through the polarization beam splitter (PBS) with each channel signal modulated by two MZM which consists of I and Q modulator to obtain two orthogonalized polarized QPSK signals which then pass through the polarization beam combiner (PBC) to become DP signal. The Gaussian filter is used to reduce high frequency components. The optical signals were then transmitted through a standard SMF of length 24km with dispersion of 17ps/nm/km and non-linearity of 2.6e-20m^2/W. The OSNR value was set to 30 dB to compensate for the losses in the fibre. A 32-passive splitter to used generate several ONUs. The signal is then received coherently using the local oscillator of narrow linewidth and converted to electrical domain using a balanced I-Q photodetector. The DSP at the receiving end performs carrier phase and frequency estimation as well linear compensation. BER test set is used to perform signal analysis.

RESULTS AND DISCUSSIONS

To maximize the system capacity and minimize the performance degradation caused by transmission impairments, system engineering and optimization are important. Similar to other telecommunication systems, signal modulation format is a key issue, which determines transmission quality and spectral efficiency. System design and optimization must consider all the contributing facts, such as channel data rate, transmission distance, signal optical power, amplifier, channel wavelength spacing, fibre dispersion and nonlinear parameter. These key performance indices enable the realization of next generation high data rate DWDM transmission networks. This, therefore, motivates the need to investigate and characterize high-speed signal transmission over SMFs using optimal modulation format.

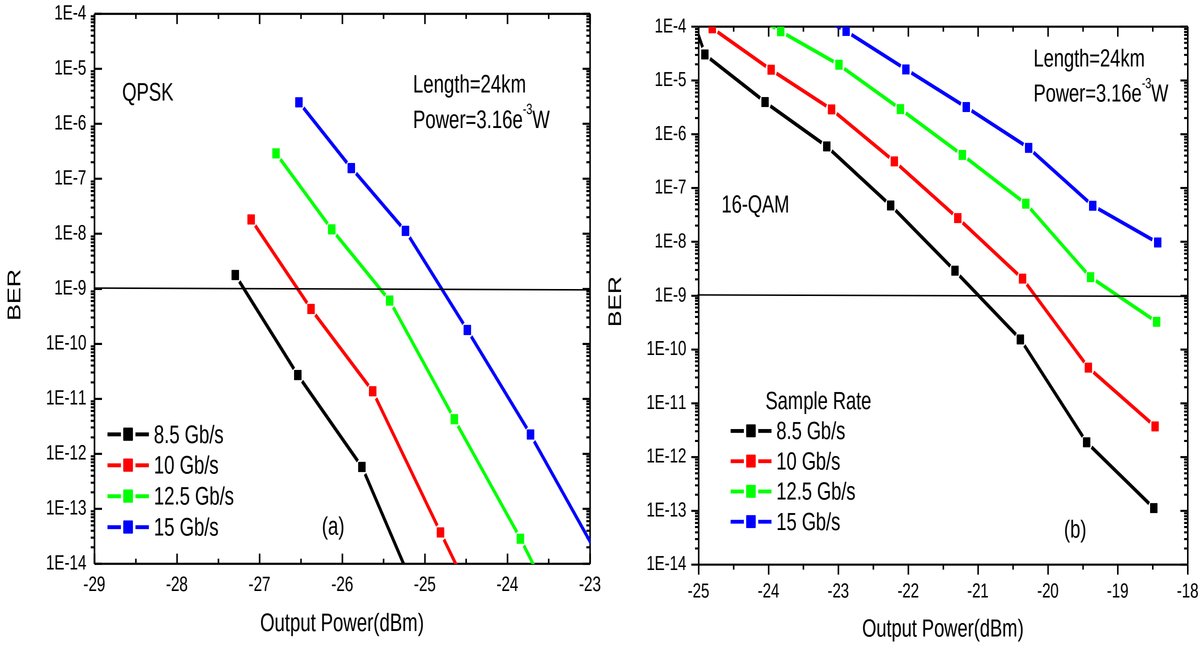

Figure 4: Characterization of optical signal transmission using; (a) QPSK (b) 16-QAM modulation formats

The bit error rate results after 24 km for QPSK and 16-QAM and the corresponding eye diagrams is illustrated in figure 4. The system performance of the DP-modulated signal is investigated by measuring the variation of BER with the received power. It is clear from the results that the BER declines with the increase in the received power. The system performance is evaluated at the communication threshold of BER=10^{-9}. For QPSK modulation formats, the receiver sensitivities (received optical power at BER of 10^{-9}) of -27.22 dBm, -26.53 dBm, -25.52 dBm and -24.79 dBm were obtained for 8.5 Gb/s, 10 Gb/s, 12 Gb/s and 15 Gb/s respectively. Therefore, less power is required at the receiver for lower symbol rates to achieve the acceptable BER value of 10^{-9}. When 16-QAM modulation format is used, receiver sensitivities of -20.95 dBm, -20.21 dBm and -18.99dBm were achieved respectively for 8.5 Gb/s, 10 Gb/s and 12.5 Gb/s transmission symbol rates.

However, flooring occurred when a symbol rate of 12.5 Gb/s was used. Error floor refers to a point at which the BER flattens without crossing the telecommunication threshold. By moving to a higher-order constellation, then more bits per symbol is transmitted, as a result, signal distortion become inevitable. This was due to the high dispersion that affected the signal resulting in the increased number of errors hence limiting the number of bits transmitted. Therefore, the transmission rate is a vital choice in optical communication since it affects the signal quality. Therefore, in our work we transmit the signal at a symbol rate of 10Gb/s over 24km SMF.

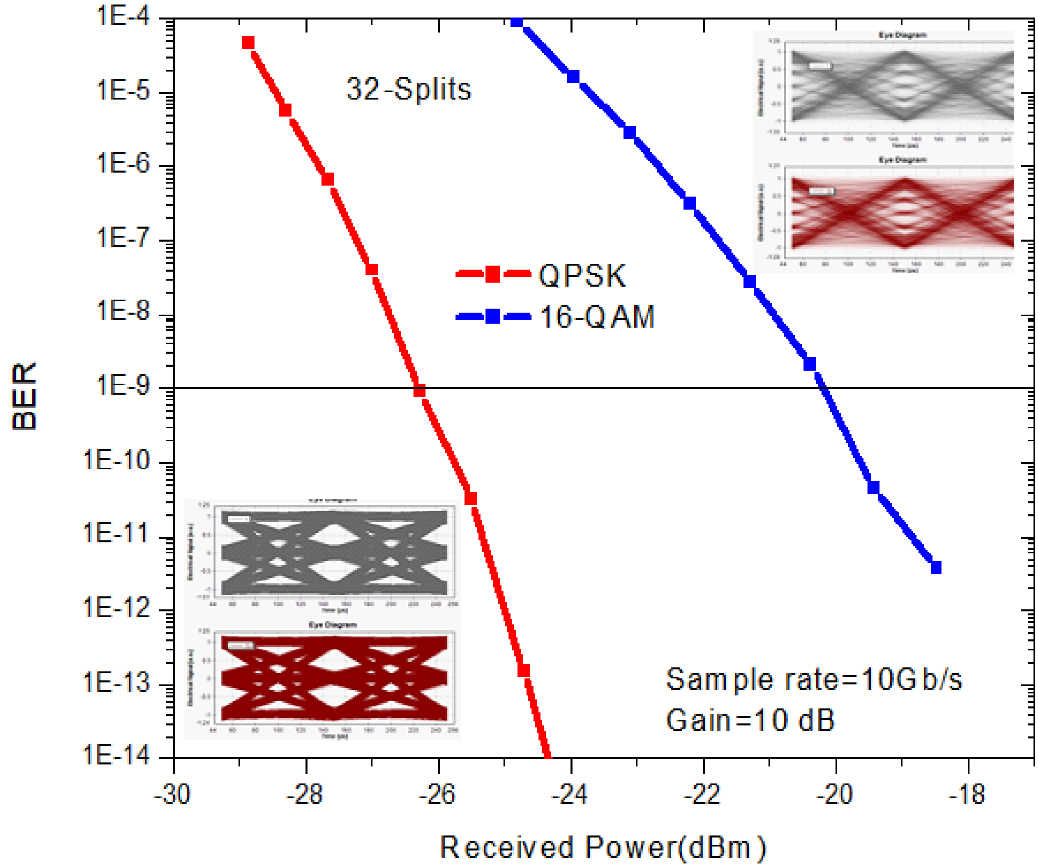

Figure 5: BER curves for QPSK and 16-QAM for 32-Splits. Inset: Respective eye diagrams.

Figure 5 illustrates a graph of BER as a function of received power for DP-QPSK and DP-16 QAM transmissions after 32-passive optical splitter. The systems are investigated at a symbol rate of 10 Gb/s. From the figure, at the BER threshold of 10e^{-9}, receiver sensitivities of -26.28 dBm and -20.17 dBm were recorded respectively for QPSK and 16-QAM modulation formats. Therefore, less power is required at the receiver for QPSK to achieve acceptable BER value. This degradation performance in 16-QAM is due to linear impairments in the transmission system which increases with the transmission rate resulting in the data overlap. The wide and open eye diagram achieved for QPSK modulation formats indicated error-free transmissions. For 16-QAM transmission, the small eye size signifies distorted data pulses due to high data rate transmission. The better eye diagrams indicate that the fibre impairements do not have a major effect on the DP signals.

It should be noted that, QPSK modulation formats transmits 2-bits per symbol compared to 4-bits per symbol transmitted by 16-QAM hence high SE efficiency is achieved using the later. Therefore, to support long-haul high bit rate signal transmission, efficient modulation need be considered. In our work, 16-QAM format achieved acceptable BER values at a low power which can be utilized in PON units to transmit high data rate to large number of users.

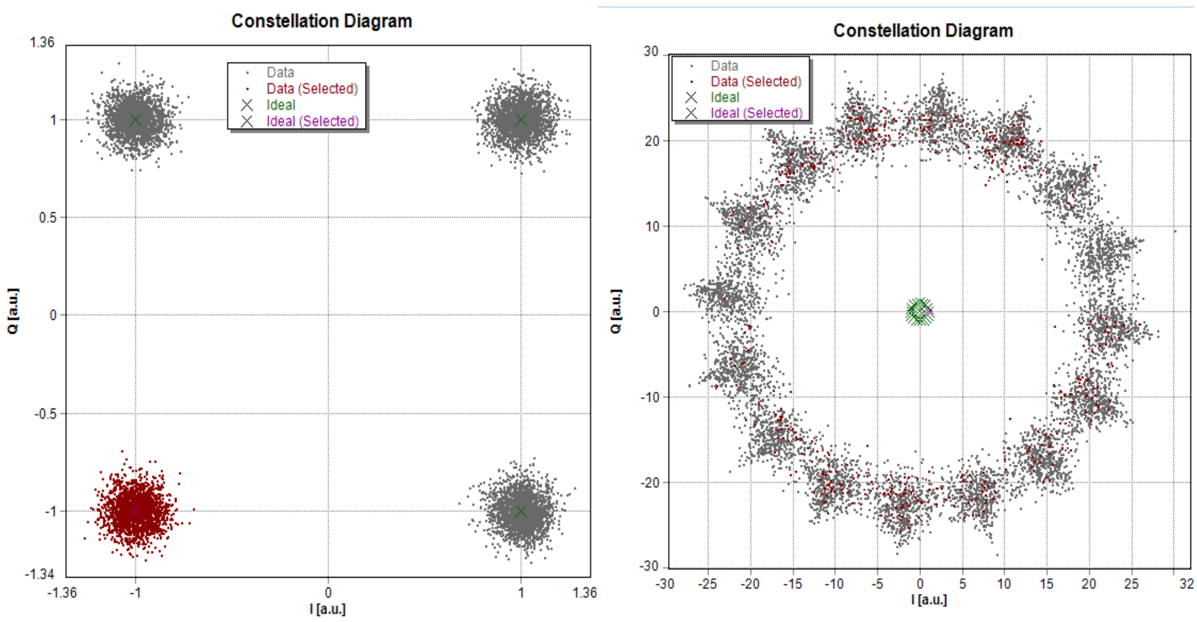

Figure 6: Constellation diagrams for QPSK and 16-QAM modulation formats

The constellation diagram is a useful representation tool in digital modulation schemes. The diagrams represent the relation between quadrature amplitude values and in-phase amplitude values. The QPSK constellation tool in figure 6 is arranged in a square grid with equal vertical and horizontal spacing indicate that the fibre impairments do not have a major effect on the DP modulated signals. It was noted from the constellation diagrams that the sampling points have even distribution around the circular ring signifying better system performance. However, for 16-QAM constellation diagram, it was noted that the sampling points have uneven distribution around the circular ring signifying signal distortion in the system. At higher order modulation, the dispersion is strong and there may be noise because of phase distribution and decentralized amplitude.

CONCLUSION

The effect of the transmission symbol rate on higher modulation formats DP-QPSK and 16-QAM has been investigated. It was noted that at high symbol rate, the optical signal is greatly affected by distortion which affects the signal quality. As the symbol rate increases, the receiver sensitivities increase when measured at the BER=$10E^{-9}$ threshold. High data transmission rate of 2.56 Tb/s was achieved after 24km signal transmission to 32-households located at the ONUs using 16-QAM modulation format. Therefore, Dual Polarization of optical signal together with higher order modulation formats is the best solution for the ever-increasing number of internet users and hungry bandwidth applications.

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