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RESEARCH ARTICLE

Increasing the Capacity in NG-PON Using QPSK, 4-QAM, and 8-QAM Modulation Formats

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Abstract: This work demonstrates the potential of a dual-polarized multilevel modulation format with coherent detection (CD) to maximize the spectral efficiency to meet the demand of the next-generation passive optical network (NG-PON). Maximizing capacity and spectral efficiency in NG-PON networks is particularly crucial for improving high-speed internet access, bridging the digital divide, and enabling new services and opportunities in rural and underserved areas, ultimately contributing to their socio-economic development. The proposed NG-PON system based on a higher modulation format can support 64 subscribers accessing the medium simultaneously at a 10 Gb/s data rate. The power splitting network was investigated using the Virtual Photonics Incorporation simulation tool. In this paper, we optimize the downstream transmission of the 1550.1 nm channel over 20 km standard single-mode fiber using Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (4-QAM and 8-QAM) formats. A digital signal processing system was employed to mitigate fiber dispersion and losses. The modulation format of 8-QAM was discovered to maximize the spectral efficiency of the carrier. From the bit error rates analysis, an aggregate transmission capacity of 3.84 Tbps was achieved for 64 users using the 8-QAM format. The findings showed that CD with higher modulation formats improved receiver sensitivity by more than 7 dB to –22.69 dBm, compared to direct detection reported in the literature. This enhancement increases the capacity of optical networks. The study also provides an analytical perspective on high-capacity NG-PON systems utilizing advanced modulation techniques for diverse users.

Keywords: passive optical network, modulation formats, spectral efficiency, sensitivity

1. Introduction

The increasing development of data communications and 5G applications has driven the need for broadband access networks with higher bandwidth and low latency requirements. Passive optical networks (PONs) have become promising technologies that fulfill these demands, providing advantages such as high bandwidth, increased reach, greater subscriber density, flexibility, and security [1]. PONs use point-to-multipoint (P-to-MP) tree topologies based on a power splitter to provide overall bandwidth to users over greater distances. There exist various competing technologies for high-speed access networks, and the adoption of this technology depends on several factors such as cost, demand, and the subscriber's environment [2]. To support high bandwidth demand, optical fiber transmission allows access to fiber-to-the-home (FTTH) networks. The FTTH architecture in PONs is particularly suitable for rural and underserved areas, providing triple-play services (voice, video, and data) using an optical splitter to distribute connections from the optical line terminal (OLT) to optical network units (ONUs) at user premises [3].

In the past, several evolutions of PON have been standardized to meet single-channel requirements. These technologies employ intensity modulation and direct detection (IM/DD) based on On-Off Keying Non-Return to Zero (OOK-NRZ) modulation formats [4]. A proposed modeling of a 5G topology system based on PON has been reported to use the IM/DD technique [5]. The simulation results reported in this work achieved an acceptable bit error rate (BER) at a receiver sensitivity of -18 dBm for a 1:64 split ratio [6]. However, this technique can be more susceptible to noise and signal degradation over long distances. Additionally, this format is less spectrally efficient and may not fully utilize the available bandwidth [7]. As emerging technologies like 5G and Internet of Things (IoT) expand, passive networks will need to support internet applications such as remote education, smart agriculture, and healthcare services. Hence, the IM-DD PON systems might not be sufficient to handle the diverse requirements of these technologies due to their limitations in terms of capacity and bandwidth. The IM-DD technologies are normally limited by receiver noise and fiber dispersion, which cause significant distortions in the optical pulses [8, 9]. Therefore, to bridge the foregoing gap, the next-generation passive optical network (NG-PON) as an access network was developed [10]. The NG-PON aims to provide effective solutions to the ever-increasing bandwidth demand of end users with data

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rates of 10 Gb/s or more and can successfully meet this growing communication bandwidth need [11, 12]. These NG-PON systems can be realized by either bonding multiple wavelengths or increasing the data rate per wavelength [13, 14].

To improve the receiver sensitivity and the overall performance of a communication system, coherent detection (CD) in the NG-PON is considered a promising technique [15]. A local oscillator (LO) laser at the receiver would beat at the photodiode, enhancing the sensitivity. Moreover, the CD can recover the amplitude and the phase information of the optical signal. The evolution of PON systems has progressed from Broadband PON (BPON) to Gigabit PON (GPON) and 10 Gigabit PON (XG-PON), each offering increased bandwidth and capacity to meet single-channel requirements [16–18]. The earlier PON systems offered broadband passive optical networks (BPON) for residential users only. However, the capacity of BPON cannot be able to meet the future demand for internet services. To address this, the gigabit passive optical network (GPON) recommendations were developed [19]. The GPON, utilizing a 1:32 split ratio and enhanced communication bandwidth, encounters significant challenges related to signal degradation over long distances, which becomes problematic in high signal transmission systems. With the increase in broadband demand, XG-PON (10 Gb/s PON) was developed to meet this increasing demand [20]. The XG-PON (10 Gb/s) has emerged to provide higher transmission rates and longer transmission systems [21]. This technology allows the transmission of high-speed internet over single-mode fiber (SMF), enhancing network capacity and efficiency. These standards are classified according to their bidirectional data rates and distance between the OLT and the Optical Network Unit (ONU) as illustrated in Figure 1 [22].

However, as the user demand for bandwidth continues to grow, the XG-PON will not be able to meet the future demand for bandwidth and quality of services (QoS) requirements. In data transmission rates exceeding 10 Gbps, dispersion impairments emerge as a significant limiting factor, constraining spectral efficiency (SE) [23]. These effects limit the bandwidth, and the power fading degrades the overall transmission performance of the system. The integration of low SE channels into higher orders in advanced modulation formats presents a promising solution for the future of networks [24]. The SE improvement will not only enhance the network performance but also meet the increasing demand of the end user. Increasing the number of customers in NG-PON can be achieved by using high splitting ratios, such as 1:64, without changing the optical modules [25]. The emergence of 5G communication technology has driven the emergence of new signal processing techniques, enhancing the quality and speed of transmitted signals [26]. High-speed technologies such as digital signal processing (DSP) with CD can provide improved tolerance to system impairments, enhanced efficiency, and greater overall capacity [27]. Together with DSP algorithms, the NG-PON systems enable high spectrum utilization, increased capacity, and extended reach, which are crucial for providing broadband services in internet-underserved regions. Innovative techniques such as advanced modulation formats [28] enable the consolidation of multiple services onto a single optical infrastructure, offering a cost-effective alternative for broadband access.

Given the rapid growth in mobile applications and end-user demands, there is a pressing need to modernize the existing infrastructure through technological innovation. This modernization relies on the adoption of advanced modulation formats to enhance the transmission rate of optical communication. To address this increasing demand for data bandwidth, various advanced modulation techniques have been proposed [29]. Advanced modulation techniques like Quadrature Phase Shift Keying (QPSK) and multi-Quadrature Amplitude Modulation (m-QAM) have gained significant attention due to their ability to achieve high spectral efficiency (SE) [30, 31]. Combining intensity and phase, these techniques reduce the number of states for the same number of symbols, enabling substantial data capacity and long-distance signal transmission in access networks [32]. By transmitting more than one bit per symbol, the bandwidth per user for a given bit rate reduces, while the SE increases significantly [33]. Together, these innovations underscore the dynamic and rapidly evolving

Figure 1
PON standards development in ITU-T and IEEE

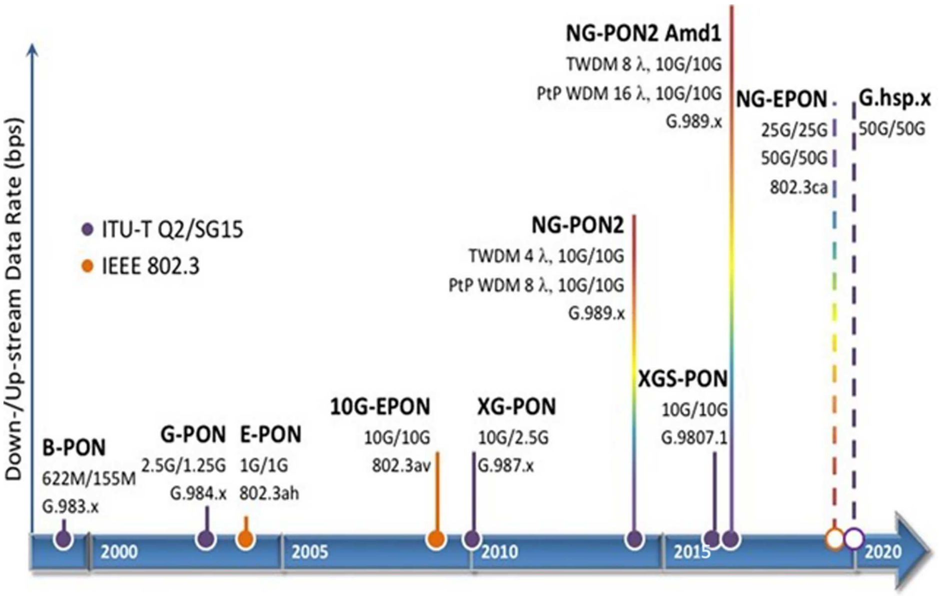
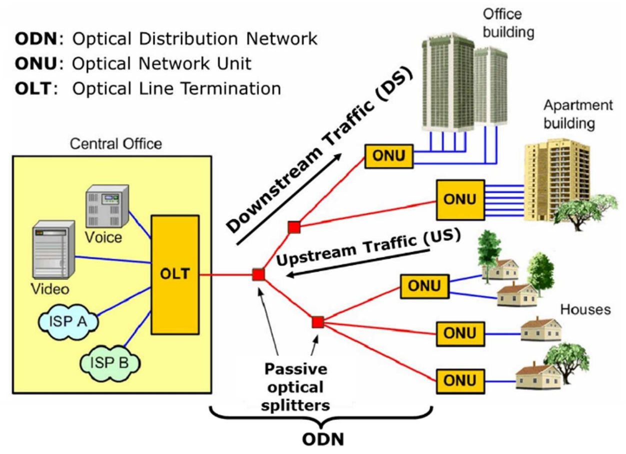


Figure 2
Passive optical network architecture



field of fiber optic communications, driving the industry toward greater performance, capacity, and reliability to meet the increasing demands of broadband access. A typical PON architecture in which unpowered optical splitters are used to enable an SMF to serve multiple premises is shown in Figure 2 [34].

The integration of NG-PON with multilevel modulation holds great promise to meet the growing bandwidth demands of modern optical networks. To fulfill the demands for developing ultrafast optical transmitters, the capacity of the modern communication formats has been scaled up from 10 Gb/s per channel to 20 Gb/s and beyond [35]. This growth is fueled by the increasing demand for higher bandwidths to support the continuously rising volume of data traffic. Recently, a spectrally efficient QPSK scheme has been demonstrated, enabling the transmission of 32 channels at data rates of up to 10 Gb/s per channel, achieving an aggregate capacity of 300 Gb/s using coherent technology [36]. In previous work, the 4-QAM modulation format has been employed to transmit data to 64 subscribers located at remote endpoints. The ONUs demonstrated high per-user capacity [37]. A comparison of various detection techniques employing advanced modulation formats in NG-PON2 has been presented [38]. The results demonstrated improved BERs with a 1:64 ratio using QPSK, 8-QAM, 16-QAM, and 64-QAM modulation formats. Furthermore, the transmission of an energy-efficient optical signal was successfully achieved over 20 km of SMF. However, this system is limited by dispersion, thereby degrading the overall performance of the transmission system.

With the continuous growth in user demand for bandwidth, NG-PON2 may fall short of meeting future bandwidth and QoS requirements. To address this challenge, dual-polarized (DP) systems – which transmit two orthogonally polarized signals – can offer a promising solution for meeting the growing demand for communication bandwidth [39, 40]. The DP technique has emerged as an effective approach to further enhance the SE of multilevel modulation formats by transmitting two distinct signals at the same wavelength over orthogonally polarized channels, effectively doubling the SE. The digital processing systems (DSP) mitigation in DP signals can reduce the processing power per channel and hence increase the overall efficiency of the communication system. This can be realized by designing an NG-PON2 system that transmits a dual-polarized (DP) signal using advanced modulation formats to various users (splits) with each ONU receiving more than 40 Gb/s with increased receiver sensitivity. This work provides network operators with crucial information required for selecting the appropriate modulation format for each ONU. This was achieved by analyzing BER measurements and receiver sensitivity, tailored to a specific user, based on their transmitted data rates. This study presents a simulation analysis of 10 Gb/s data per symbol using a higher-level modulation format over a 20 km standard single-mode fiber (SSMF) in the C-band based on the Virtual Photonics Incorporation (VPI) photonics simulation tool. We provide a comprehensive comparison scheme of 16, 32, and 64 subscribers using DP QPSK, 4-QAM, and 8-QAM modulation formats. In this paper, Section 2 explains the advanced modulation in PON. Section 3 describes the architectural designs of the proposed work. Section 4 discusses the results of the BER performance. Section 5 concludes the findings of this work and outlines potential directions for future research.

2. Advanced Modulation in PON

QPSK modulation is a form of phase modulation where the phase of the laser optical light is used for encoding data. Each symbol corresponds to a discrete phase value that is imposed on the optical carrier with a constant amplitude.

The signal representation, $S(t)$ in QPSK, can be expressed as:

$$S(t) = A\cos(2\pi f_c t + \varnothing^0) \quad (1)$$

where f_c is the carrier frequency carrier and $\varnothing^0 = 0^0, 90^0, 180^0, 270^0$ describes the phase shifts. The transmission of four phases enables the encoding of 2 bits of data per symbol, doubling the bit rate as compared to OOK in the same bandwidth, hence increasing the SE [41].

To increase the SE beyond 2 bits/s/Hz, m-QAM modulation formats have been proposed [42]. This modulation format can achieve high SE by using three characteristics of the optical field, that is, phase, intensity, and polarization [43]. The QAM modulation format combines Amplitude Shift Keying and Phase Shift Keying with 90^0 out of phase with each other.

The signal representation, $S(t)$ in QAM, can be expressed as [44]:

$$S(t) = A_I\cos(2\pi f_c t) + A_Q\sin(2\pi f_c t) \quad (2)$$

where A_I and A_q are data beat streams split into in-phase and quadrature points. In PON technology, a passive splitter is used to divide the signal equally to all consumers; hence, the receiver requires a minimum optical power (receiver sensitivity) to operate in an error-free region. For an ideal splitter with the number of subscribers N, the optical power budget is expressed as:

$$P(dBm) = 10log_{10}N \quad (3)$$

To improve the efficiency of a transmission system, the receiver sensitivity needs to be improved to reduce the power required to achieve error-free transmission [45].

In higher modulation formats, the amplitude and phase of an optical carrier can be modulated by binary data simultaneously, so that each n bit of the input data is mapped into one symbol M such that:

$$n = log_2 M \quad (4)$$

Each constellation point is represented by a symbol made up of several bits. For n bits per symbol, the number of constellation points or symbols is given by $M = 2^n$. Using the multilevel signaling, data bits are transmitted at a reduced symbol rate, R_s of:

$$R_s = \frac{R_b}{Log_2 M} = \frac{R_b}{n} \tag{5}$$

where R_b is the bit rate.

3. Simulation Setup

The setup used to demonstrate the operation of the PON network utilizing QPSK, 4-QAM, and 8-QAM is shown in Figure 3. A signal at 1552.52 nm transmission wavelength with a symbol data rate of 10 Gb/s was used to transmit the signal from the OLT located at the central office. Channel performance in a communication system is influenced by optical signal-to-noise ratio (OSNR), dispersion, and nonlinear effects. As a result, it is essential to optimize the OSNR level in optical networks while minimizing the input power, as excessive power can lead to nonlinearity, ultimately reducing the received signal strength. To address this, an optical power of 10 dBm and a signal-to-noise ratio of 6 dB were maintained throughout the simulation. The modulated signal was then transmitted over an SSMF with a length L = 20 Km (typical length for PON). An erbium-doped fiber amplifier (EDFA) with a power gain of 20 dB was employed after the SMF to mitigate the effect of power losses and extend the reach of the PON signal. A passive optical splitter was used to divide the downstream signal from the OLT at the network edge into multiple, identical signals that were broadcast to the ONUs. At the receiver end, the LO was used to recover the transmitted data signals for BER measurements and simultaneous analysis. The pre-amplifier was used to amplify both signals that carried the information and the accompanying noise generated by signal dispersion in the fiber. Several DSP functions and algorithms were employed to aid in recovering the incoming transmission channel(s) after CD was performed on the receiver side. These include quadrature imbalance, linear compensation, timing recovery, and carrier phase estimation. These algorithms compensate for signal impairments and aid in recovering the incoming signal.

Figure 3
Simulation setup for the transmission of dual-polarized (DP) modulated signal in PON: m-QAM: multi-quadrature amplitude modulation; EDFA: erbium-doped fiber amplifier; DSP: digital signal processing; 2-D: two-dimensional analyzer

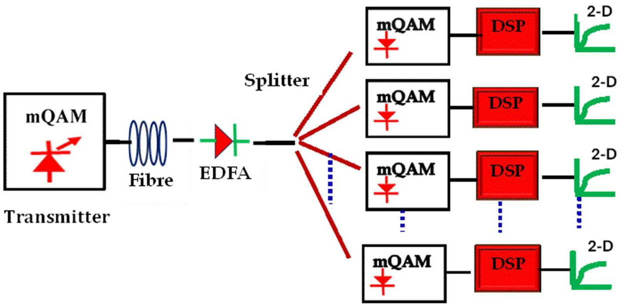


Table 1
Simulation parameters considered for the PON link

Parameter	Value
Symbol rate	10 Gb/s
Laser center wavelength	1552.52 nm
Input optical power	10 dBm
Fiber length	20 km
Attenuation	0.22 dB/km
Dispersion	16.75 ps/nm/km
Laser linewidth	0.1 MHz
Photodetector responsivity	1 A/W
Photodetector dark current	10 nA

4. Results and Discussions

To provide higher capacity and meet the performance requirements of an optical transmission system, it was therefore necessary to explore the 100 G and beyond PONs. The analytical investigation of the proposed NG-PON was conducted for several ONUs, that is, 16, 32, and 64, under the effect of fiber attenuation and dispersion. We present the DP QPSK, 4-QAM, and 8-QAM operating with a symbol rate of 10 Gb/s. Performance is evaluated using BER, received optical power, and constellation points of the signals at the ONUs. The BER measurements were recorded at 1E-9, the threshold for the communication system. The BER and constellation diagrams were observed by varying the number of subscribers while employing system performance parameters in Table 1. Both point-to-point and point-to-multipoint were considered for system analysis.

4.1. Performance analysis at QPSK, 4-QAM, and 8-QAM modulation for different split ratios

Figure 4 illustrates the BER performance of the DP 40 Gb/s QPSK-modulated signal at various split ratios, along with the corresponding constellation diagrams. It was observed that BER reduced with an increase in output power. A receiver sensitivity of -27.63 dBm was recorded for a single user.

However, as more subscribers accessed the medium simultaneously, the receiver sensitivity decreased to -26.45 dBm, -26.23 dBm, and -26.01 dBm for 16, 32, and 64 users, respectively. The power penalty between 16 and 32 splits is less than 1.5 dB. The low power penalty was due to compensation techniques (i.e., DSP algorithms), which minimized the signal impairments and recovered the transmitted symbols, lowering the power penalty. This trend was also reflected in the constellation diagrams for the modulated signal at different split ratios, shown in the inset of Figure 4. Distinct constellation points were observed for all the ratios, signifying good signal quality. Noted also was the rotation of the constellation diagrams due to dispersion in the fiber, which affects the transmitted signal.

Figure 5 shows the BER performance for the 40 Gb/s DP-4-QAM coherent system and the corresponding constellation diagrams for different numbers of users at ONUs.

It was observed that as the BER decreases, the received sensitivity increases. The required power to maintain an acceptable BER is -26.53 dBm for a single user. However, as the number of users increased, the sensitivity dropped to -26.25 dBm, -25.89 dBm, and -25.09 dBm for 16, 32, and 64 users, respectively. From the figure, it can be observed that the constellation points are distinct, signifying minimal signal distortions. This implies that inter-symbol interference and dispersion have minimal effects on the transmitted signal in the 4-QAM modulation format.

Figure 6 shows the BER performance curves for different split ratios using the 8-QAM modulation formats. It is observed that the BER declines with an increase in the power received. Moreover, better BER performance was recorded for point-to-point transmission with a receiver sensitivity of -26.95 dBm. However, to achieve a BER threshold of 1e-9, the respective receiver sensitivities of -25.13 dBm, -24.14 dBm, and -22.69 dBm were required to transmit a signal to 16, 32, and 64 users at the ONUs. The performance of the 8-QAM signal was noted to achieve an error-free transmission at high receiver sensitivity.

Figure 4
Variation of BER with received power for QPSK format at different splitting ratios

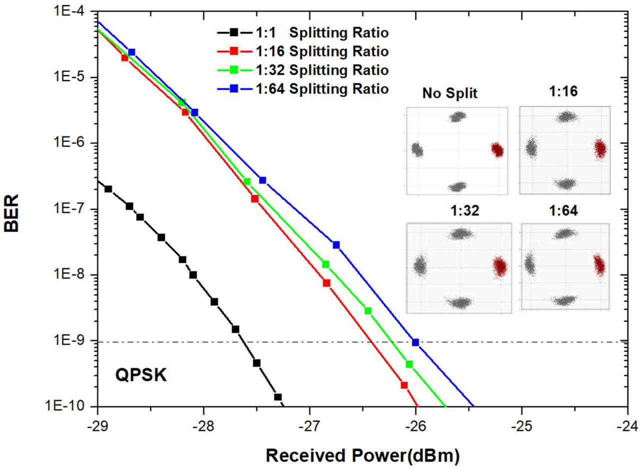
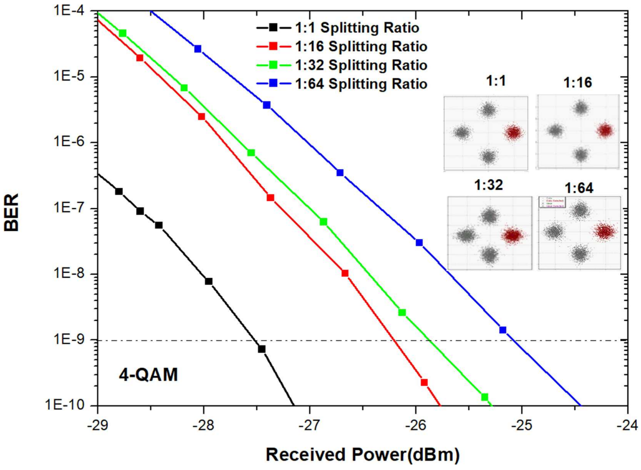


Figure 5
BER performance of 4-QAM modulation format at the different splitting ratio



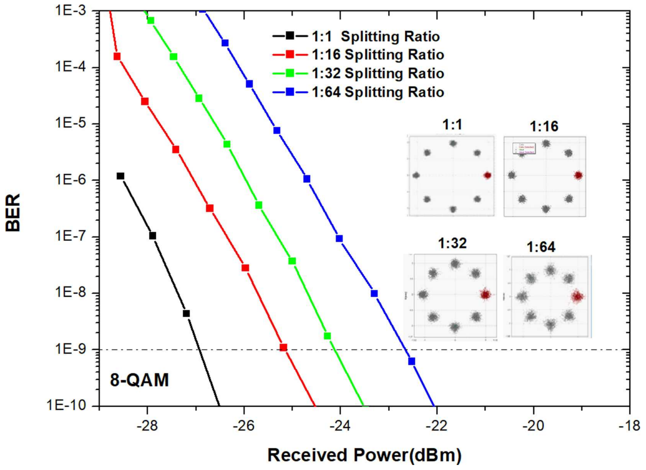
4.2. Performance comparison between QPSK, 4-QAM, and 8-QAM for 64 users

Figure 7 shows the effect of different modulation formats on the BER performance for 64 subscribers. Receiver sensitivities of -26.01 dBm, -25.09 dBm, and -22.69 dBm were recorded for QPSK, 4-QAM, and 8-QAM, respectively. It was also noted that the difference between QPSK and 4-QAM modulation techniques is minimal. This is because both methods transmit two bits per symbol, with the former encoding the information in phase, while the latter encodes the information in both the phase and the amplitude. Notably, the 8-QAM had a reduced sensitivity compared to other formats for 64 users. This is because dispersion and interference have an impact on higher modulation formats. With the increased number of bits per symbol, the dispersion tolerance becomes weaker. Therefore, 8-QAM modulation formats enable higher data throughput with the same spectral bandwidth, hence high SE. The combination of CD, DP signals, and advanced modulation formats enables PON systems to achieve very high data rates, making them suitable for next-generation networks that need to support bandwidth-intensive applications such as cloud computing and IoT. The proposed 8-QAM model has the capability to support up to 64 users concurrently situated 20 km from the OLT, with a data rate of 60 Gb/s per user.

Figure 8 shows the receiver sensitivity values for 16, 32, and 64 users using QPSK, 4-QAM, and 8-QAM formats. It is observed that the QPSK and 4-QAM modulation formats are more resilient to noise and interference, maintaining better receiver sensitivity even with the increased number of users. A significant reduction in the receiver's sensitivity was noted as the number of splits increased for the 8-QAM format. This was because 8-QAM modulation formats transmit three bits per symbol, and therefore, more power was required to distinguish the received bits. The compensation techniques (i.e., DSP algorithms) minimized the signal impairments and recovered the transmitted symbols. A high receiver sensitivity of -26.01 dBm was achieved for the QPSK modulation format. QPSK transmits two bits per symbol with the signal encoded in phase. Therefore, less power was required at the receiver to recover the information, hence high receiver sensitivity.

The 4-QAM format achieved a receiver sensitivity of -25.09 dBm. This format transmits two bits per symbol in amplitude and

Figure 6
BER versus received power using 8-QAM modulation formats



phase variations. More power is therefore required to recover the received bits compared to the QPSK format. The 8-QAM has a reduced sensitivity of -22.69 dBm. The 8-QAM modulation formats transmit three bits of information in amplitude and phase form. Therefore, dispersion and interference have a greater impact as the modulation order increases. More power at the receiver end was required to distinguish the received bits in 8-QAM, hence reducing receiver sensitivity. In contrast, 8-QAM, while offering high data rates, suffers from reduced sensitivity due to bit-overlap, resulting in received error bits. Therefore, the choice of modulation scheme in a multi-user environment affects the receiver's sensitivity.

5. Conclusion

We have investigated the performance of a PON transmission system operating at a symbol rate of 10 Gbps using QPSK, 4-QAM, and 8-QAM modulation formats across various splitting ratios. Higher modulation formats transmit multiple bits per symbol, increasing the SE and maximizing the bandwidth usage in PON, making them ideal for this network application. Notably, the optimized PON architecture can deliver 60 Gbps of downstream data over 20 km of SSMF to ONUs. This was achieved using the 8-QAM modulation format, which provided a receiver sensitivity of -22.69 dBm. From the BER analysis, an aggregate transmission capacity of 3.84 Tbps was achieved for 64 users utilizing the 8-QAM format. The transmitted signals were successfully recovered using DSP techniques. The DSP compensation technology, together with CD, mitigates linear effects, preserves signal integrity, and extends data rate transmission in PON. Therefore, passive optical splitting is a fundamental aspect of PONs that allows a single optical fiber to serve multiple users by splitting the optical signal into several paths. Determining the optimal split ratio is crucial for balancing the number of users served by the network and the signal quality. A higher split ratio allows more users to be connected to a single fiber, but it results in greater signal attenuation, hence reduced receiver sensitivity. Limited reach can therefore necessitate the use of additional network infrastructure, such as optical amplifiers, to maintain adequate signal over long distances, thereby increasing the overall cost and complexity of the network. These results validate the successful aggregations of different modulation formats, enabling higher SE while maintaining acceptable signal quality.

Figure 7
BER curves for QPSK, 4-QAM, and 8-QAM for 64 users

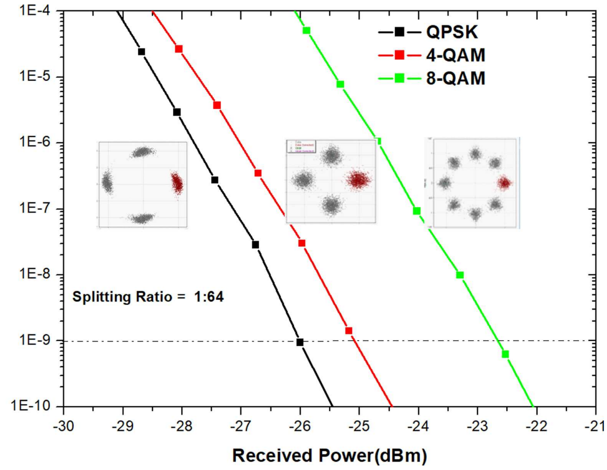
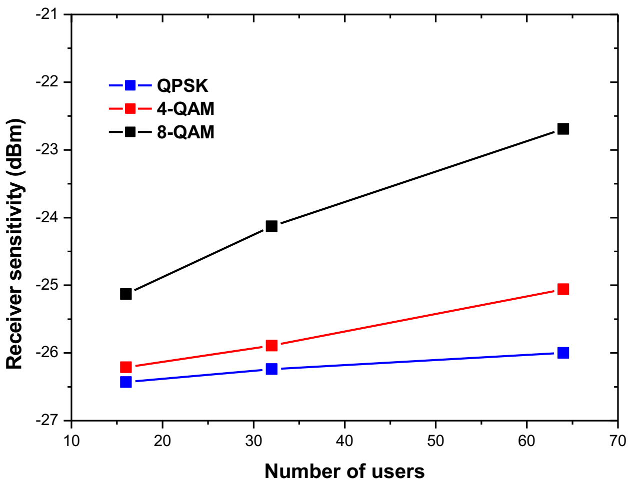


Figure 8
Receiver sensitivities for different numbers of users



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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Henry C. Cherutoi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Dismas K. Choge:** Conceptualization, Validation, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **David W. Waswa:** Conceptualization, Validation, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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