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STUDY THE COST-EFFECTIVE NEXT GENERATION PASSIVE OPTICAL NETWORKS FOR LONG DISTANCE APPLICATIONS

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ABSTRACT

A passive optical network (PON) is a crucial component in the distribution of broadband services and next-generation mobile backhaul services. It has evolved over time to meet consumer demands for enhanced data speeds, including standards such as Gigabit-class PON, Ethernet PON, 10 Gigabit-class PON, and 10E-PON. This study examines the evolution of Next Generation PON 1 and 2, encompassing Wavelength Division Multiplexed PON (WDM-PON), Dense Wavelength Division Multiplexed PON (DWDM-PON), Optical Time Wavelength Division Multiplexed PON (OTWDM-PON), and Time Wavelength Division Multiplexed PON (TWDM-PON). A hybrid WDM-OTDM NG-PON architecture is suggested, exhibiting dependable 40 Gbit/s data transmission across distances of up to 150 km. The NG-PON 2 technique, using PM-QPSK, surpasses competitors in propagation time and bit transmission rate, rendering it appropriate for forthcoming high channel capacity applications in fifth-generation communication networks. The research further delineates the modelling and evaluation of 112 Gbit/s downstream data transmission in an NG-PON 2 using coherent detection and digital signal processing methodologies. The long reach passive optical network (LR-PON) provides a dependable solution, integrating the advantages of both WDM-PON and DWDM-PON.

KEYWORD: PON, EPON, GPON, NG-PON, Optical Network

"An Optical fibre technology and wireless technologies have significantly transformed the world's most intricate services and systems at their zenith. Examples include financial services transitioning to mobile banking, transportation evolving into real-time monitoring systems, as well as advancements in home security, exercise regimens, and communication methods. All these services may be organised and managed from wireless devices (Azadeh, 2009; Lavery *et al.*, 2013). Many scholars anticipate the emergence of new, unanticipated applications and services that will provide affordable luxury for mankind. Subscribers of telecommunications access networks are now interested in new Internet technologies and services that need high bandwidth, such online gaming, video on demand, high-definition television, and peer-to-peer applications. Furthermore, several residences own Internet-connected personal computers, all of which need a bandwidth allocation (Ryu *et al.*, 1991). The rapid expansion of wireless communications systems necessitates enhancements in structural and functional modifications, in addition to maximising the capacity of existing copper connection networks. An optical fibre link conveys information using light as a medium from one point to another. In the 1970s, due to its significant attenuation, cable technology was more prevalent than optical fibre. Several scientists have succeeded in reducing optical fibre attenuation to only 0.2 dB/km. Fibre optics have three benefits: substantial communication capacity, resistance to electromagnetic interference, and minimal transmission losses (Lei *et al.*, 2010). The access network connects central office service providers with clients, including residential dwellings. In recent years, the demand for bandwidth has escalated significantly. Consumer studies after the enhancement of broadband have seen a notable increase in the proportion of customers streaming, rising from 35% to 40% (Jaiswal *et al.*, 2012). Subscriptions have increased, and the proportion of phone services went from 8% to 9% last year, despite a restricted number of requests for voice service. This has resulted in the advancement of new technologies, including fibre to the house (FTTH). FTTH employs several solutions, with PON being the most effectively executed (Bilyeu, 2003).

PASSIVE OPTICAL NETWORK

In PON, the RN is substituted by a passive optical power splitter with active components in the AON architecture (Figure 1). The optical splitter is designated as a passive variable, since it does not need power and because it simply distributes to its corresponding ONU all the information it receives (Ossieur *et al.*, 2003). The job of ONU is to sort the exact package of each subscriber into the PON architecture. As in the PON architecture, the OLT aspect is extremely important. A PON network can be regarded as the "brain." It carries out very critical

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activities, including buffer management, traffic scheduling and allocation of bandwidth (Ehrhardt *et al.*, 2011). Extra data processing activities for PON architecture are generally paid for by ONUs rather than AON architecture (Hajduczenia and Silva, 2009).

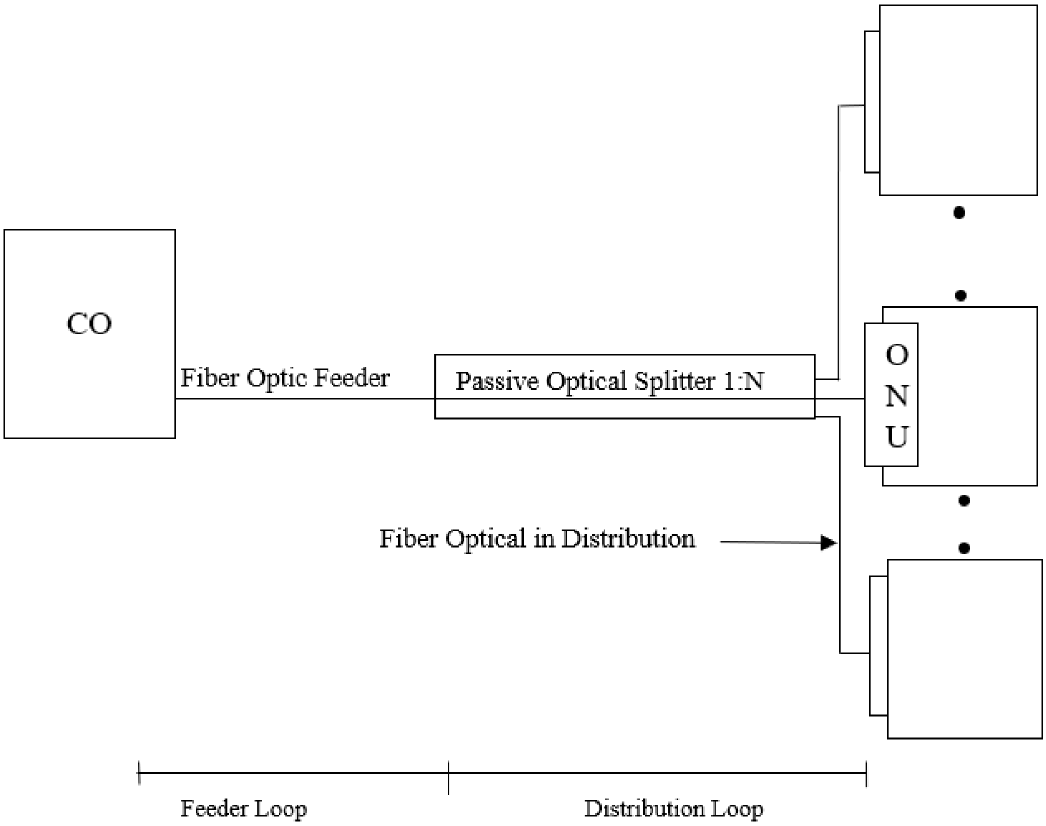


Figure 1: PON architecture

PONs have evolved to provide much more network capacity. In PON, a fibre in the service area extends from an OLT at the central office to a remote node. Every subscriber or ONU will get a fibre drop from RN (Harboe and and Souza, 2013). The primary difference in power network apparatus between AON and PON. AON employs electrically powered network apparatus in the ODN, while PON leverages passive components (passive control splitters) in the distribution network to connect the consumer to the operator network. This guarantees that electrically powered components are only available at the CO's OLT and the user's ONU (Lee, 2006).

Next Generation (NG) PON

NG-PON1 fails to meet the anticipated requirements for bandwidth and quality of service parameters due to the exponential increase of high-bandwidth software and internet networks. The study group has extensively examined alternatives to NG-PON2 and various technologies that might be integrated into NG-PON2 to meet the prospective requirements of customers and network operators, aiming to determine a viable approach for future upgrades (Elaydi, 2014). NG-PON2 has evaluated four multiplexing designs to achieve a downstream transmission of 40 Gbit/s and an upstream transmission of 10 Gbit/s. Rapid velocity TDM-PON, Innovations (Xin and Fouli, 2012). The progression of passive optical networks has advanced significantly towards NG-PON2. Prior PON technology was developed to meet bandwidth utilisation demands. Numerous PON developments are provided by FSAN, ITU-T, and the concurrent initiatives of IEEE (Chow and Yeh, 2013). Numerous PON implementations exist, including ATM standardised over APON in 1995, G.983.1 and G.983.2 with 155 Mbps upstream and downstream, BPON standardised in 2001 as G.983.3 to G.983.5, and new G.984.4 and G.984.1 for upstream and downstream. GPON, introduced in 2006, supports 2.5 Gbps downstream and 1.25 Gbps upstream. Additionally, IEEE standardised EPON in 2001 as IEEE 802.3ah for symmetrical 1 Gbps upstream and downstream, followed by G-EPON and 10G-EPON, with IEEE 802.3av standardised in 2007. NG-PON1 and NG-PON2 also address upstream and downstream requirements, alongside IEEE 802.3av for upstream specifications. (Figure 2)

Figure 2: PON generations

METHODOLOGY

First Approach

This study presents the schematic architecture of the proposed hybrid WDM-OTDM-based PON system, modelled and investigated over Optisystem simulation tool.

The proposed PON system involves downstream data transmission from 4 independent OLTs to different number of ONUs i.e. 64, 128, and 256 through a SSMF to achieve a net transmission rate of 40 Gbit/s. Further, the system performance in evaluated for propagation length of optical fibre varying from 100–150 km. For each OLT, 4 independent 2.5 Gbit/s data streams are OTDM to generate 10 Gbit/s data per OLT. In each OLT, a pseudo random bit sequence generator generates 2.5 Gbit/s binary information which is encoded to return-to-zero (RZ) electrical pulses using a RZ line encoder.

Second Proposed Approach

In the scenario of fibre to the house (FTTH) facilities, PON infrastructure is regarded as a successful approach for BPON. The many virtues include high-speed Broadband access, high-quality transmission capabilities for audio, data and video facilities, multi-point design (P2MP) and economic efficiency. Over the past several decades many PON specifications have been introduced by the ITU. IEEE and ITU are narrowly classifiable into two classes in terms of PON architecture. The first group consists of the PON (ATM PON). The second group consists of the wireless PON (BPON) and the PON gigabit (EPON). (FSAN has been ratified as ITU-T G.984 Standard and has been practically introduced in Middle East, Europe, Northern North and Australia to standardize GPON Standard Specifications. IEEE 802.3 established and introduced in Asia the EPON Norm specifications. The PON architectures have an OLT, which is linked by an optical delivery network to multiple ONU and ODN. The OLT is located at the CO premises and is linked by passive optical partitions to various UN units rendering PON an architecture for P2MP.

The schematic design of the proposed PM-QPSK modulation-based NG-PON 2 method, modelled using the Optisystem simulation tool, represented in Figure 3.

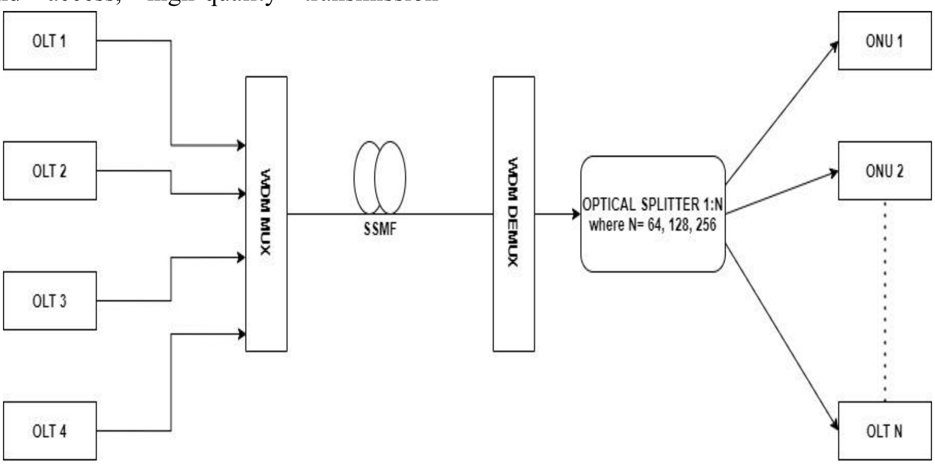


Figure 3: Schematic architecture of the proposed hybrid WDM-OTDM-based PON

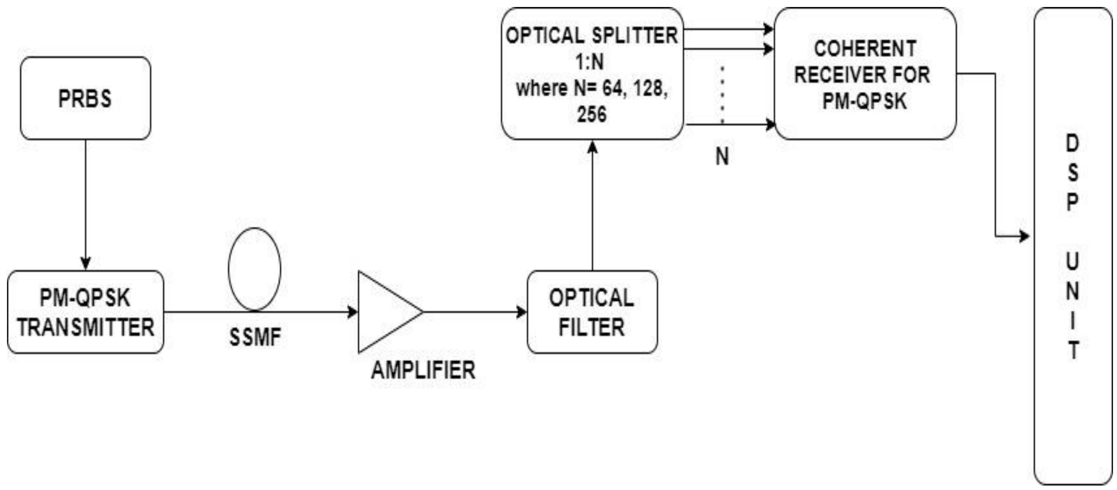


Figure 4: Proposed NG-PON 2 schematic architecture employing PM-QPSK signal

The PRBS generator generates 112 Gbit/s binary data and directs it to PM-QPSK transmitter section (Fig. 4). At the PM-QPSK transmitter, binary data bits from PRBS is serial-to-parallel (S/P) converted and directed to upper and lower QPSK modulator sections. Fig. 3 shows the internal schematic of QPSK modulator. Each QPSK modulator section is modulated using a distinct polarised beam from a CW laser and a polarisation splitter. In QPSK modulator, the function of QPSK sequence generator is to group 2-bits as a symbol. The bits are divided into even and odd bits and transmitted to upper and lower M-ary pulse generator, which generates electrical pulse based on incoming bits. The electrical pulses drive the RF plates of the dual-electrode MZM. There is a 90^0 phase shift between upper and lower arm for providing in-phase (I) and quadrature (Q) modulation. Both the I and Q modulated signals are combined using cross coupler and directed towards polarisation combiner. The 112 Gbit/s PM-QPSK signal is then directed towards SSMF having 0.2 dB/km attenuation coefficient, 16.75 ps/nm/km dispersion coefficient, 0.075 ps/$\mu m^2/Km$ dispersion slope, and 0.05 ps/$\sqrt{\mu m}$ polarisation mode dispersion coefficient."

The schematic architecture of the proposed co-existing GPON and XG-PON system, which is modelled and simulated over Optisystem simulation tool is presented in Fig. 5

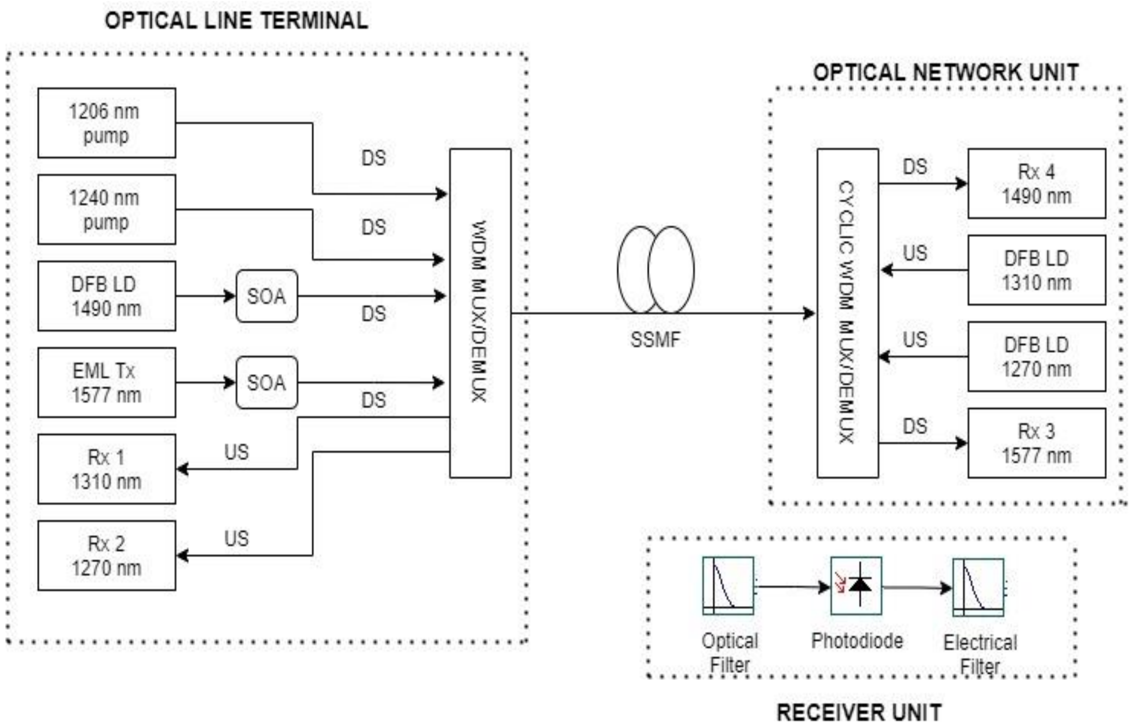


Figure 5: Schematic architecture of the proposed system

In the proposed system, for GPON downstream transmission, a DFB-LD having a transmission power of 3 dBm operating at 1490 nm wavelength and using NRZ modulation is employed. Further, for XG-PON downstream transmission, an electro-absorption modulation laser (EML) having a transmission power of 0 dBm operating at 1577 nm wavelength and using NRZ modulation is employed. As per the FSAN group, the bandwidth specifications for downstream data transmission are 1575 – 1580 nm and for upstream transmission are 1260 – 1280 nm. The spectral width of downstream transmission is only 5 nm and thus require costly EML diodes to provide stability to the wavelength. On the other hand, the spectral width for upstream transmission is 20 nm which can be maintained using cost-effective uncooled laser diodes and thus minimizing the cost and complexity at the ONUs In order to provide long-haul downstream transmission, 2 SOAs operating at 1490 nm and 1577 nm are employed at the OLT. The SOA operating at 1490 nm has a saturation power of 15 dBm and the SOA operating at 1577 nm has a saturation power of 16 dBm. The SOAs are designed to operate linearly in order to minimize distortion. Two laser pumps at operating wavelength of 1206 nm and 1240 nm having a signal power of 30 dBm and 27 dBm respectively are coupled with the bidirectional fibre to provide RAMAN amplification for XG-PON system (1260 – 1280 nm) in upstream direction and GPON system (1300 – 1320 nm) in upstream direction. A WDM combiner is employed at the OLT to combine the pump signals, the GPON downstream signal and the XG-PON downstream signal. It also separates the upstream signals from the downstream signals using suitable passband bandwidth as proposed in ITU-T standards. The bidirectional optical fibre has a reference wavelength of 1322 nm and attenuation coefficient of 0.2 dB/km.

RESULTS

For First approach

In the proposed work, we have also considered to effect of RAMAN scattering, cross-phase modulation, and self-phase modulation in the optical fibre while performing the simulations. The effective area of the optical fibre is considered to be 80 μm^2 and the non-linear refractive index is taken to be $26\times 10^{-21} m^2/W$. A cyclic MUX having a splitting ratio of 1:64 for XG-PON system and 1:32 for GPON system is employed at the ODN. Each ONU employs a GPON band pass filter (BPF) at 1490 nm operating wavelength with 10 nm bandwidth and XG-PON BPF at 1577 nm operating wavelength with 10 nm bandwidth.For GPON data, an electrical low pass filter (LPF) with cut-off frequency of 0.75×Bit rate/4 is employed whereas for XG-PON data, an electrical LPF with cut-off frequency of 0.75×Bit rate is employed. Further, a 3R regenerator is employed to regenerate the electrical signal and the signal quality is evaluated in terms of Q Factor and eye diagrams using BER tester. For 256 ONUs at a propagation length of 100, 125, and 150 km respectively. A degradation in the received signal quality is observed with increasing propagation length of the fibre which is due to increasing losses due to signal attenuation and nonlinear effects. The results demonstrates reliable 40 Gbit/s data transmission up to a propagation length of 150 km with good performance. Table 1 presents the clear eye diagrams of the received signals for different ONUs with increasing propagation length in the proposed PON system. (Fig. 6)

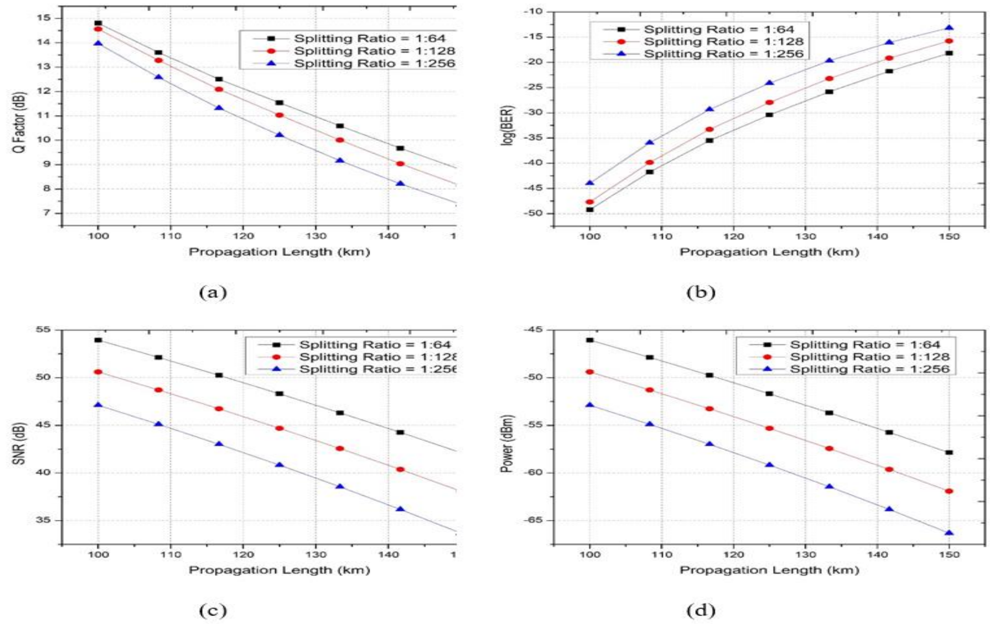
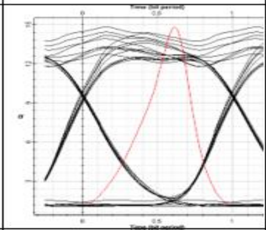
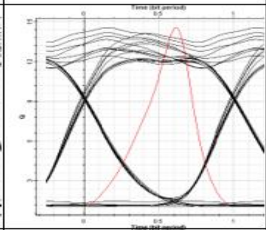
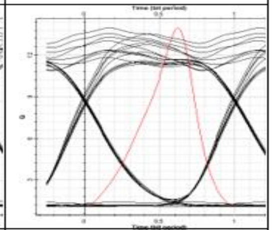
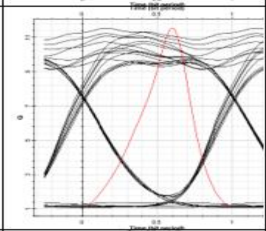
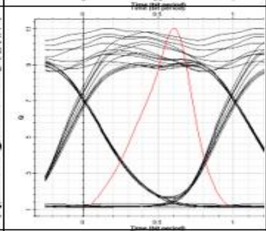
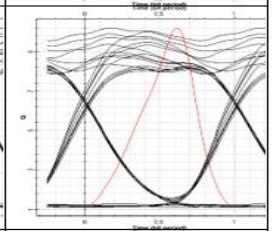
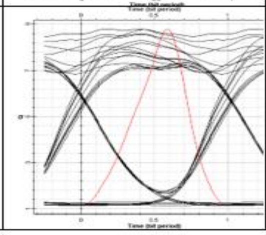
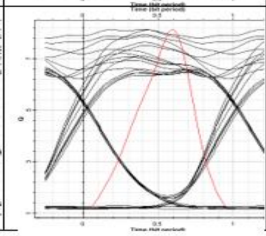
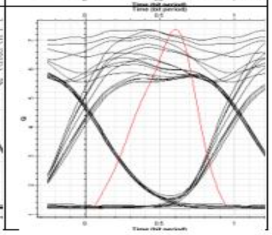


Figure 6: (a) Q Factor (b) log(BER) (c) SNR (d) Power v/s Propagation Length (km) for different ONUs

Table 1: Eye diagrams for different number of ONUs with increasing propagation length

Propagation	64 ONUs	128 ONUs	256 ONUs
100 km			
125 km			
150 km			

For Second Approach

The proposed PM-QPSK-based NG-PON 2 transmission system is investigated for increasing propagation length of fibre for different number of ONUs using bit error rate (BER), received power, and constellation graphs as the performance evaluation metrics. The results in Fig. 7(a) show that the BER is -4.81, -2.91, -1.83, and -0.83 for 64 ONUs, -3.38, -2.46, -1.49, and -0.40 for 128 ONUs, and -2.78, -1.87, -0.78, and -0.37 for 256 ONUs at a propagation length of 180, 190, 200, and 210 km respectively. The results in Fig. 6 (b) show that the received power is -38.21, -40.01, -41.70, and -43.24 dBm for 64 ONUs, -41.22, -43.02, -44.71, and -46.25 dBm for 128 ONUs, and -44.23, -46.03, -47.72, and -49.26 dBm for 256 ONUs at a propagation length of 180, 190, 200, and 210 km respectively. The results show that with increasing propagation length, the quality of received signal deteriorates due to increasing nonlinear losses and signal attenuation. The maximum achievable propagation length with acceptable BER of 3.8×10^{-3} is 185 km for 256 ONUs. Table 4.4 shows the constellation graphs of the received signal with increasing propagation length for different number of ONUs. Fig.7 depicts the frequency enhancement of the obtained signal achieved by employing the proposed DSP device in the NG-PON 2 framework.

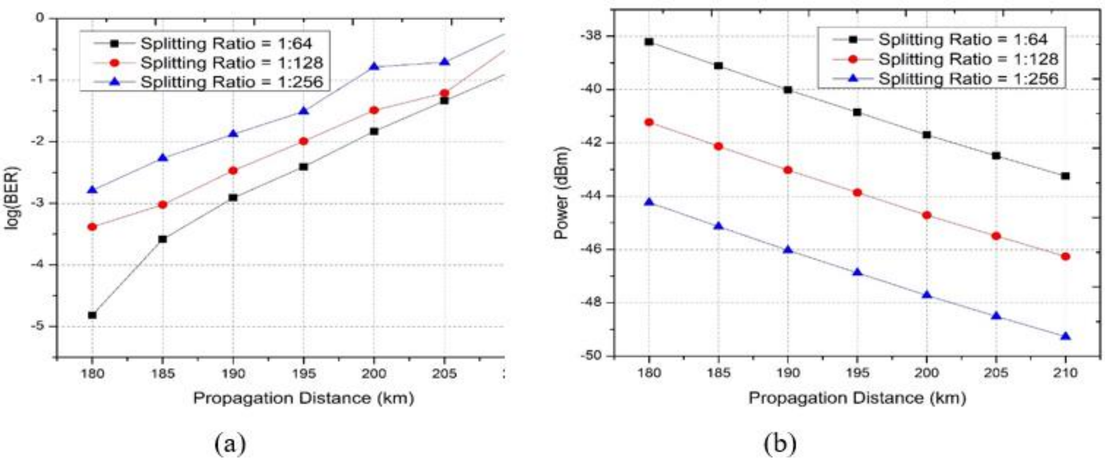


Figure 7: (a) BER (b) Received power v/s increasing Propagation Length for different number of ONUs

Table 2: Constellation graphs for different number of ONUs with increasing propagation length

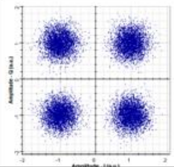
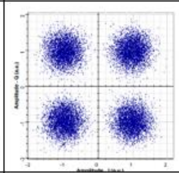
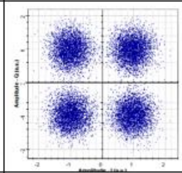
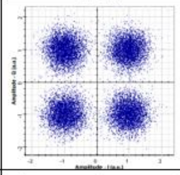
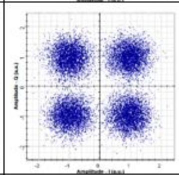
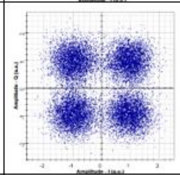
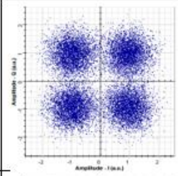
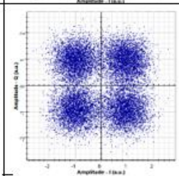
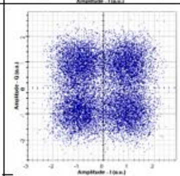
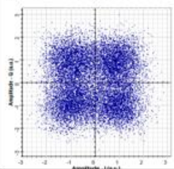
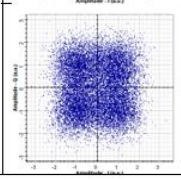
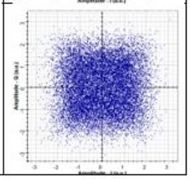
Propagation	64 ONUs	128 ONUs	256 ONUs
180 km			
200 km			
220 km			
250 km			

Table 3: Performance comparison of the proposed PM-QPSK-based NG-PON 2 system with existing literature

Reference, Authors	Journal	Technique	Propagation Length	Bit rate
Y-M Zhang *et al.*	Optoelectronics Letters, Springer	WDM-PON	16 km	10 Gbit/s
M.Kumari *et al.*	Journal of Optical Communications, DeGruyter	OTDM-PON	80 km	20 Gbit/s
A.Kumar *et al.*	Journal of Optical Communications, DeGruyter	Hybrid WDM-OTDM-PON	96 km	10 Gbit/s
H. Mrabet	Applied Sciences, MDPI	OCDMA-PON	142 km	40 Gbit/s
Y. Shao *et al.*	J. of Euro. Optical Society-Rapid Publications	OFDM-PON	42 km	5 Gbit/s
Proposed work	-	PM-QPSK- NG-PON 2 with coherent receiver and DSP	200 km	112 Gbit/s

CONCLUSION

The Passive optical networks have emerged as primary candidates for economical telecommunications services, with mobile backhaul networks being under consideration. Simulation tests are conducted to examine various configurations of optical access networks, assessing their efficiency for broadcast and mobile backhaul applications. This paper proposes a hybrid WDM-OTDM NG-PON method for varying optical fibre quantities at the receiver terminal. The system exhibits dependable 40 Gbit/s data transmission across a 150 km propagation distance with satisfactory performance. The Chebyshev filter is a viable option for long-haul PON systems. The NG-PON 2 technique, using PM-QPSK and coherent detection, has a maximum propagation distance of 185 km and improved received signal quality. The NG-PON system offers greater spectral efficiency and high-speed transmission across extended fibre propagation distances. The study analyzes the performance of PIN and APD in coexisting GPON and XG-PON systems, focusing on downstream and upstream data transmission capabilities. The results show that as propagation length increases, the quality of the received signal deteriorates due to heightened signal attenuation and non-linear effects. APD surpasses PIN regarding the Q Factor of the acquired signal for both downstream and upstream transmission in a coexisting environment. The cosine roll-off filter is found to be most appropriate for long-haul co-existing GPON and XG-PON systems. The study suggests that enhancing the Q-Factor improves the performance of NG-PON2 by increasing laser power. The optimal laser power for the engineered NG-PON2 is determined for fixed, dynamic, and fixed reach ODN configurations. The study also discusses the need for fiber-efficient topology configurations and energy-efficient framing techniques to accommodate future functionality in mobile access networks. The study also suggests investigating coherence optical communication using UDWDM-PON to decrease channel spacing under 25 GHz and leverage the benefits of high data transfer in point-to-point PON systems. (Table 2 and 3)

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