

Adaptive bandwidth mechanism using dual rate OLT for energy efficient WDM–TDM passive optical network

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Abstract This paper reviews various energy efficient approaches in existence and proposes a Hybrid WDM–TDM PON architecture that allows the adaptive bandwidth allocation mechanism to reduce central office power consumption with acceptable performance. Our proposed architecture allows sending two signals, one broadband and other narrowband to each optical networking unit so an appropriate signal can be utilized according to the traffic demand. In case of very low traffic, only narrowband signal is used and a significant amount of energy consumption and OPEX is reduced. By using $2 \times N$ power splitter and interleaver, proposed architecture provides broadcasting at both broadband and narrowband signal depending on the required link rate. This further reduces energy consumption and OPEX by avoiding the transmission of same signal from multiple sources. Offered data rates to the optical distribution networks (ODNs) may also be varied by doubling the wavelength spacing of remote node AWG so that two contiguous wavelengths can be transmitted at each port or ODN. This provides the geographical dynamic bandwidth allocation. Proposed architecture also support simultaneous transmission of both broadband and narrowband signals to the ODN to provide bandwidth scalability and network extensibility for supporting future access network in terms of new users and data rates. As two signals are reaching to any ODN, resiliency against OLT TRx and line card failure is also achieved. The performance of the proposed design is verified by simulation results in terms of bit error rate and receiver sensitivity

to demonstrate its feasibility for the next-generation optical access network.

Keywords Time division multiplexing · Wavelength division multiplexing · Optical access network · Optical line terminal · Optical networking unit

1 Introduction

Due to the emergence of fiber to the home (FTTH) infrastructure, and to support high bandwidth demand applications such as video on demand (VOD), teleconferencing, e-commerce and high definition television (HDTV), optical access network (OAN) have become imperative across the globe. Passive optical network (PON) is one of the popular optical access network deployed today to fulfill the required bandwidth demand [1]. Nowadays PONs are also incorporated in data center networks in order to reduce cost and increase energy efficiency and reliability of today's networks [2, 3]. Time division multiplexed (TDM) PON is the most popular standard adopted by industries to provide up to 1 Gbps data rates. In TDM-PON standard, tree based point to multipoint architecture is employed in which total bandwidth is shared among multiple subscribers by using power splitters (PS). Commonly a TDM-PON can be shared among 16 to 64 subscribers to provide them up to 64 Mbps data rates [4]. TDM based PON architecture is cost and energy efficient as it requires least central office (CO) resources to serve multiple subscribers [5]. However, the data rates provided by this architecture are not enough to support multiple subscribers for expected future bandwidth demands. In TDM-PON architecture, optical line terminal (OLT) broadcast the entire downstream data to all optical networking units (ONUs) and a particular ONU accesses only the data

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which is intended for it at a specific time specified by medium access control and discards all the other data. Due to the broadcasting of downstream signals, TDM-PON is comparatively less secure [4,6]. In TDM-PON, different ONUs use the same wavelength to transmit upstream data in different time slots by using time division multiple accesses (TDMA). TDMA mechanism is controlled and organized by medium access control (MAC) at OLT. TDM-PON requires highly complicated burst mode transmitters and receivers at ONU and OLT respectively. Currently, development of high-speed burst mode transmitters and receivers are still not at matured stage [7]. Insertion losses of TDM-PON are also high and become significant for higher fan-out ratios [1,8].

To overcome the problem of security, high insertion loss and to provide high data rates, various architectures of wavelength division multiplexed (WDM) PONs have already been proposed, which are capable of providing up to ten times or even higher data rates as compared to the conventional TDM-PON [9]. In WDM-PON, different wavelength signals are multiplexed and transmitted over a single fiber cable and do not need any sophisticated burst mode transmitter and receiver. Arrayed waveguide grating (AWG) is used to combine and separate different wavelength signals [10,11]. In WDM-PON, many transceivers are required at OLT to transmit downstream and receive upstream wavelength signals. Due to the use of many transceivers and line cards (LC) to hold them, OLT is liable to consume the significant amount of energy [12]. The use of multiple transceivers is resulting in an increment of the overall cost of the architecture. WDM-PON requires separate sources to provide dedicated (point to point) service to each optical networking unit (ONU). That is, the WDM-PON does not allow any resource sharing thus resulting in its poor resource utilization. Due to this static nature of WDM-PON, none of the sources can be powered off during low load/traffic. Hence pure WDM-PON is not cost and energy efficient solution [6,8].

Nowadays, energy efficiency in the optical access networks has become a serious concern as the energy consumption is increasing exponentially with increasing broadband services. Natural energy resources on earth are not expected to serve the energy demand for distant future. With increasing energy consumption, emission of CO₂ and Green-house gases (GHGs) is also increasing which is a leading cause of global warming and deteriorating the environment. To reduce the energy consumption along with OPEX, hybrid WDM TDM PONs may be utilized which take advantages of both TDM-PON and WDM-PON.

In this paper, we propose an energy efficient and low OPEX hybrid WDM-TDM PON flexible architecture which provides the dual rate 1G/10G transmission as per the traffic demand. By utilizing the lower bandwidth whenever possible, a significant amount of energy consumption and OPEX is reduced. Since two wavelengths are reaching to the same

ODN, proposed architecture also provides the resiliency to the OLT TRx and line card failure. Just by 100 Ghz shift in the 10G and/or 1G transmitted wavelengths, the proposed architecture enables broadcasting at both 10G and/or 1G which is very essential for HDTV, e-education services. Using proposed architecture, bandwidth scalability to any specific geographical part of the network (from as low as 2 Gbps to as high as 20 Gbps) may also be provided by allocating two contiguous wavelengths to that part. To the best of author's knowledge, all these features mentioned above are not available together in any other single hybrid WDM-TDM PON architecture. All the above-mentioned advantages enhance the survivability of the architecture for supporting the future optical access networks. Before proceeding further, a brief of previous related work on OLT energy efficiency in hybrid WDM-TDM PON is given below.

2 Previous related work

Energy efficiency for tree based 10G EPON and ring based hybrid TWDM-PON network is evaluated in [13], and it is observed that for 2, 4, 8 & 16 wavelengths, ring topology based TWDM PON is more energy efficient than tree topology based EPON. TWDM PON with 4 wavelengths provides the maximum energy efficiency and reduces maximum up to 58.7% energy consumption as compared to EPON [13]. In ring based TWDM PON, energy efficiency is achieved by forming a ring of the different remote nodes (RN), and redistributing the signal to multiple ONUs with the help of splitters. In this, only one wavelength may handle all ONUs available in the network [13]. However, due to the ring nature, latency is higher for the ONUs which are connected to the last node.

By employing a channel combine/split (CCS) module at the remote node (RN), required number of OLTs at the central office are reduced. CCS module is a combination of power splitters (PS) and switches (SW) and used for aggregating the load of different ONUs so that minimum number of OLTs are required. For example, for downstream transmission, with the help of splitter and switch, minimum OLTs are used to serve all active subscribers [14]. As the active subscribers in network increases, and if the working OLT is out of capacity, another OLT is used. For upstream, power splitters act as combiners and consolidate the traffic of several PONs to the single OLT. All active ONUs are tuned to the same upstream wavelength (say λ_1) thus upstream traffic is aggregated to one OLT (OLT 1). This architecture provides invest-as-costumer-comes approach. Effective take-up rate (ratio of subscribed customers to the portion of system capacity utilized) of the system is increased by this architecture, and up to 35 and 20% power can be saved at the time of minimum traffic demand and full operating stage respectively [14]. Using two OLT

and MUX at the central office, wavelength routing is done to reduce the power consumption. For achieving the wavelength routing, different optical networking units (ONU) are employed with tunable transmitters. By changing the ONU upstream wavelength and with the help of the wavelength router, load of upstream signals can be routed to any one of the two OLTs thus allowing other OLT to sleep during traffic below a certain threshold [15]. However, resiliency against OLT TRx and/or line card failure is not provided. The complexity of the system is also much higher for real-time routing and aggregation of numerous wavelengths.

At central office, a wavelength selective switch (WSS) is used instead of static AWG to allocate the wavelength dynamically according to the instantaneous traffic demand [16]. By incorporating WSS switch to connect OLT and different ODNs, the number of assigned wavelengths are also changed depending upon the load of particular ODN. This provides the dynamicity in the resource sharing and routes the wavelengths towards the high traffic load of the network for load balancing. By reducing effective number of required wavelengths, up to 60% of the OLT energy is reduced [16]. However, dual rate and broadcasting features are not available in the schemes proposed in [14–16].

In the presence of narrowband (1G) traffic, the use of wideband (10G) resources are avoided to reduce significant energy consumption. The power consumption of each 10G LC in OLT is approximately 3.5 W while for 1G LC it is around 0.5 W [17]. In this work [17], an $(n + 1) \times (n + 1)$ AWG is used at RN, whose first input port is connected to $(n + 1)$ line cards (n 10G and remaining one 1G) through an $((n + 1) \times 1)$ coupler. n output ports of this AWG is used for connecting it to n ODNs and remaining one output port is used to loopback the narrowband signal to its n input ports with $(1 \times (n + 1))$ coupler. Due to the cyclic property of AWG, $(n + 1)$ wavelengths transmitted from OLT are distributed to $(n + 1)$ output ports. n broadband wavelengths are reaching to n ODNs directly. Remaining narrowband wavelength is looped-back and broadcasted to n input ports. Broadcasted narrowband wavelength is transmitted at its n output ports and thereby reaching all ODNs. For low traffic broadcasting, all 10G line cards are switched off to reduce power consumption. To receive dual rate wavelengths, each ONU is equipped with a dual rate (1G/10G) tunable transceiver [17]. However, dual rate broadcasting is not considered in this work.

To reduce the burden on OLT transceivers imposed due to local LAN services (ONU services), direct inter-ONU technique may be utilized [18, 19]. This reduces the requirement of complex re-routing, re-modulation of LAN service at OLT. Direct inter-ONU communication also reduces the latency for LAN service and provides an opportunity to utilize bandwidth and energy more efficiently. By using an architecture having two remote nodes cascaded with fiber Bragg gratings (FBGs) respectively, LAN communication may be achieved

within the subgroup of ONUs or overall ONUs available in the network. Whenever possible, by communicating within the subgroup instead of overall ONUs, occurring insertion losses are reduced therefore less input power is required and provide an opportunity to save a significant amount of energy [19].

A flexible TWDM PON architecture has been proposed [18] in which hybrid AWG/splitter module is used between the OLT and ODNs. Hybrid module constitutes a 4×4 AWG with a 4×4 power splitter connected in parallel. A 100 GHz optical interleaver is inserted before as well as after the hybrid module. The purpose of the first interleaver is to divert the 100 GHz tuned wavelengths towards splitter. OLT transmitter module transmits a set of downstream wavelengths with 200 GHz spacing. Each 200 GHz spaced incoming wavelength is passed through the interleaver towards AWG for transmitting dedicated wavelengths to ONU. The second set of wavelengths shifted by 100 GHz with respect to the first set of wavelengths can also be transmitted from the OLT transmitter module. 100 GHz shifted wavelengths are diverted by interleaver towards splitter for broadcasting the wavelengths. At the receiver side, second interleaver combines the wavelengths coming from splitter and AWG. Hence in this architecture, each OLT transmitter can be used for one to one service, one to many services or many to many services according to the traffic load [20, 21].

A comparison of different hybrid WDM TDM PON architectures discussed above is summarized in Table 1, along with the features of our proposed architecture. As can be seen, the proposed architecture permits broadcasting only at 1G and/or 10G, and the maximum capacity of the network is limited upto 44 Gbps.

Dual rate mechanism have been utilized for saving energy in other type of access networks such as hybrid fiber-coaxial (HFC) access networks [22–25]. Master-slave line card (LC) based traffic scheduling algorithm has been proposed to provide the energy efficiency in the HFC networks. Based on traffic load, reported algorithm dynamically transfers packets to either master or slave LC and idle LC is toggled to sleeping mode to save energy [22]. To support DOCSIS (Data Over Cable Service Interface Specification) 3.0 standard in HFC network, traffic aware algorithms have been reported [23] that change the operation status of two primary network elements cable modem (CM) and cable modem termination system (CMTS) dynamically. At CM side, reported algorithm optimizes its energy consumption and provides 37.5–42.2% energy saving as compared to the conventional static CM operation. At CMTS side, by supporting CM connections with least numbers of CMTS ports, 31.08–32.61% energy saving is achieved as compared to the conventional CMTS [23, 24]. Channel bonding algorithms are also proposed for both network side and customer side [24, 25]. These algorithms could be utilized by cable operators to allow a CM

Table 1 Comparison of different hybrid WDM TDM PON architectures

Paper	Max energy saving (%)	Bandwidth scalability at particular node	Resiliency to TRx/line card failure	Geographical network scalability	Limitations
Song et al. [13]	58.7	No	No	No	Only fixed rate, no broadcasting, latency is higher for the ONUs connected to the last node of the ring
Feng et al. [14]	35	Yes	No	No	Only fixed rate, no broadcasting
Kani et al. [15]	–	No	No	No	Only fixed rate, no broadcasting
Dixit et al. [16]	60	Yes	No	Yes	Only fixed rate, no broadcasting
Tadokoro et al. [17]	75	No	No	No	Dual rate, no broadcasting at 10 Gbps
Cheng et al. [20,21]	–	Yes	No	No	Fixed rate, no broadcasting at 1 Gbps
Proposed	61.2	Yes	Yes	Yes	Broadcasting only at 10G and/or 1G, maximum capacity limited upto 44 Gbps

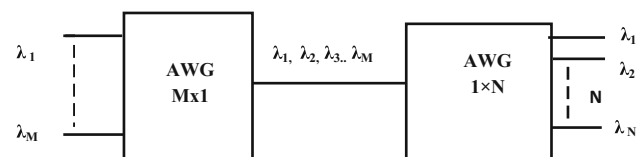
to tune for numerous channels parallel to provide energy efficiency of cable access network. The operation mode of CM and CMTS are adjusted dynamically based on traffic fluctuations and other channels are switched off to achieve energy saving. Proposed scheduling algorithm in [25] achieved up to 75% power saving as compared to normal operation in which TRs are always active [25].

Nowadays, elastic optical networks (EON) are also becoming much popular due to their distinctive characteristics like bandwidth segmentation, bandwidth aggregation, traffic grooming and arrangement of variable data rates to develop energy efficient architectures [26–29]. Routing and spectrum allocation policies may be utilized to allocate the spectrum in the form of different number of narrow slots according to the traffic load [26,27]. Bandwidth variable transponders (BVT) and sliceable bandwidth variable transponders (SBVT) can be used for providing multiple data rates to the networks. Therefore, spectrum utilization efficiency and energy saving could also be improved by using EON. Detailed unique characteristics of EON with its architecture and operational principle are provided in [26–29].

The rest of this paper is organized as follows. Section 3 includes the proposed network architectures. While Sect. 4 covers the bandwidth scalability and network resiliency against OLT TRx and line card failure. Network extensibility is covered in Sect. 5. Other illustrative examples of proposed architecture are discussed in Sect. 6. Section 7 discusses the simulation setup and results of the proposed network. Finally, Sect. 8 concludes the paper.

3 Proposed architecture

In this paper, we propose a network architecture using two cascaded stages of AWG to provide flexibility, energy effi-

**Fig. 1** Conventional hybrid WDM–TDM PON architecture ($M = N$)

ciency, OPEX efficiency and resiliency to TRx and line card failure. Also we use a $2 \times N$ PS in parallel to enable the broadcasting capability at both broadband and narrowband transmission in the same architecture. Before discussing the proposed architecture (as Case 2), conventional architecture is discussed first as Case 1.

Case 1: When the number of input ports of CO AWG and that of the output ports RN AWG are equal ($M = N$) [24], then designed network works as a conventional WDM-PON network in which, a set of M wavelengths are provided to $1 \times N$ AWG as shown in Fig. 1. As M and N are equal, each output port of RN AWG receives only one dedicated wavelength irrespective of load. Due to the dedicated wavelengths reaching at individual port, this architecture is not suitable for varying traffic load environment. When traffic load is small, WDM-PON is not energy efficient since wavelengths are not fully utilized, and when the network is overloaded, the quality of service may not be guaranteed as dynamic bandwidth/wavelength allocation is not possible. In case of any particular transmitter/line card failure, resiliency is also not provided. To add the flexibility in the network, we proposed an architecture as discussed in case 2.

Case 2: To make the conventional architecture flexible, energy efficient, OPEX efficient and resilient to OLT TRx/line

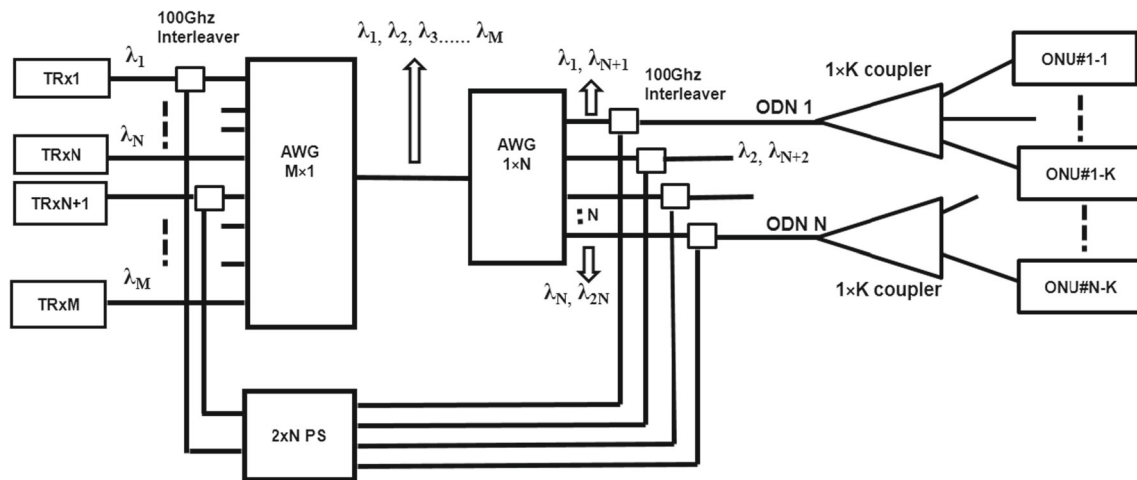


Fig. 2 Proposed hybrid WDM–TDM PON architecture ($M/2 = N$)

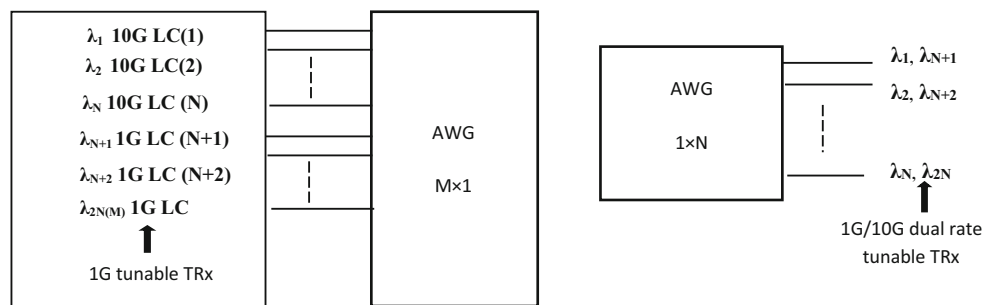


Fig. 3 Line cards connections at OLT

card failure, we designed a tree-topology based network as shown in Fig. 2. Proposed architecture is also capable of supporting narrowband as well as broadband traffic along with dual rate broadcasting capability. The architecture is designed in such a way that it satisfies $M/2 = N$ for CO and RN AWG ports. To utilize the bandwidth efficiently and to reduce the power consumption in the network, OLT is equipped with first $(M-N)$ line cards with 10Gbps (10G LCs) to support broadband traffic and remaining N line cards with 1Gbps (1G LCs) for narrowband traffic. RN AWG ($1 \times N$ AWG) separates the set of M incoming wavelengths at its N output ports. As in proposed architecture, $M/2 = N$, due to the cyclic property of AWG; two wavelengths (one 10G and one 1G) are transmitted at each output port of RN AWG. Incoming wavelengths of $1 \times N$ AWG start repeating its output port after the free spectral range (FSR) [30, 31]. OLT line cards and tunable ONU is shown in Fig. 3. The energy efficiency of this architecture can be achieved both at higher as well as lower traffic loads. In normal case, when OLT has to send high data rate downstream signals, all 10G LCs transmit data at wavelengths $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_N$ and all 1G LCs are switched off. For low traffic load at ONU, all 1G LCs send narrowband signals at wavelengths $\lambda_{N+1}, \lambda_{N+2}, \lambda_{N+3}, \dots, \lambda_{2N}$ and all 10G LCs are switched off. Each ONU must be

equipped with one 1G/10G dual rate tunable transceiver so that it can receive the downstream signal at both 1 and 10Gbps data rates at any wavelength. To achieve the broadcasting at both 10 and 1Gbps in proposed architecture, a $2 \times N$ PS is inserted between OLT and ODNs by connecting its I/O and O/P ports to 100GHz interleavers. Its two input ports are connected to one 10Gbps and one 1Gbps transmitter to broadcast at dual rates. For broadcasting the signal, transmitted wavelengths are 100GHz shifted from the main downstream wavelengths. 100GHz interleavers divert these wavelengths towards $2 \times N$ PS. After that, broadcasted wavelengths are combined at each ODNs with the help of other N 100GHz interleavers. Each ODN is distributing the broadcasted signal to K ONUs with the help of another $1 \times K$ coupler. The designed architecture supports bandwidth scalability, resiliency to OLT TRx/line card failure, and network extensibility and described in following sections.

4 Bandwidth scalability and resiliency to OLT TRx/line card failure

Bandwidth scalability is to increase the offered bandwidth to some ODN whenever required. Bandwidth is an impor-

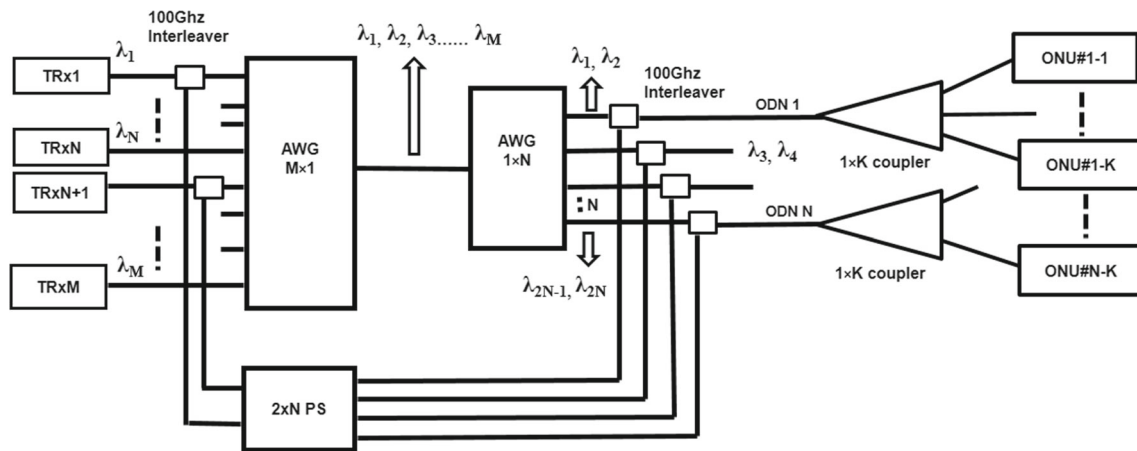


Fig. 4 Proposed network architecture with coarseness factor ($M/2 = N, C = 2$)

tant parameter as its demand is growing continuously and expected to increase more and more in future. Bandwidth demand per ODN can be increased by increasing the data rates, but this is not a cost effective approach since all the ONUs needs to adapt the new data rates. Our proposed system can offer comparatively more bandwidth by using all OLT transmitters (1G and 10G) simultaneously. One major advantage of the proposed system is added resiliency to the network thus in case of any transmitter or line card failure, the network will continue to serve because each ONU is receiving two wavelengths. In this case, ONU is tuned to alternative working wavelength until the recovery of failed wavelength. This unique feature is neither available in TDM PON nor in WDM-PON systems. However, offered bandwidth will depend on working transmitter/line card.

By using the proposed architecture, dynamic geographical bandwidth scalability is also possible i.e. allocation of more bandwidth to any particular network segment depending upon the user demand is also possible. This can be performed by using special parameter coarseness factor (C) of RN AWG where C represents the number of contiguous wavelength channels allocated to the same port of AWG [32]. C can be adjusted by changing the frequency spacing of AWG. For $C = 2$, frequency spacing of RN AWG is kept twice than the input frequency spacing to pass two contiguous wavelengths. Now as case depicted in Fig. 4, output wavelengths of RN AWG changes from the previous one shown in Fig. 2. By designing such architecture, first half ports of RN AWG can support extremely high bandwidth (capable of supporting 20 Gbps data rates). This part of the network can also be used for serving the extended network (new users added in the network). The remaining half ports of remote node AWG support low bandwidth applications. The offered bandwidth to different ports can be changed dynamically by changing the center frequency of remote node AWG as wavelength routing of AWG depends on its center frequency.

5 Network extensibility

Network extensibility is to support the newly added users in the already deployed network with acceptable performance to support the future generation optical network. As proposed system is bandwidth scalable, by allocating multiple broadband wavelengths to specific part of the network (distribution network), it can easily support the newly added users within the power budget matching conditions. New users can be served by inserting extra remote AWG or power splitter in cascade before the individual PON branch. If all ports are scaled with 1×2 power splitter then network can support twice of previously supported users. Insertion losses of AWG are about 5–6 dB regardless of the output ports and for power splitter it is about to $3.5 \log_2(n)$. Where n is the number of output ports of power splitter. So to employ AWG having four ports or more gives superior power budget than the power splitter. To verify the performance of the proposed architecture, results are validated with the help of simulation.

6 Other illustrative examples of proposed architecture

OLT is equipped 8 LCs out of which four are 10G and remaining four are 1G. 10G LCs provide the output wavelengths $\lambda_1, \lambda_2, \lambda_3$ and λ_4 and 1G LCs provide the output wavelengths $\lambda_5, \lambda_6, \lambda_7$ and λ_8 . Due to the cyclic property, CO AWG multiplexes $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_8$ wavelengths and outputs to the signal output port. At remote node 1×4 AWG separates all these wavelengths at different ports. Each output port of remote node AWG supports 32 ONUs with the help of 1×32 power splitter. The power consumption of each 10G LC is 3.5 W while for 1G LC it is approximately 0.5 W. Hence, the total power consumed by 10G LCs is 14W and by 1G LCs is 2 W. Input wavelengths have the wavelength spacing of

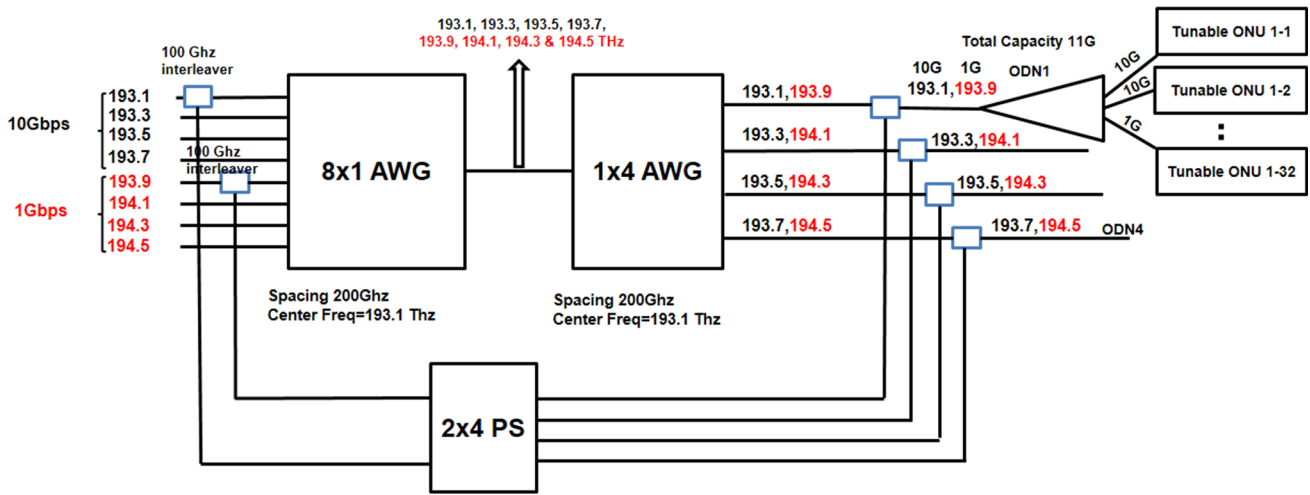


Fig. 5 Dual rate OLT for efficient wavelength utilization

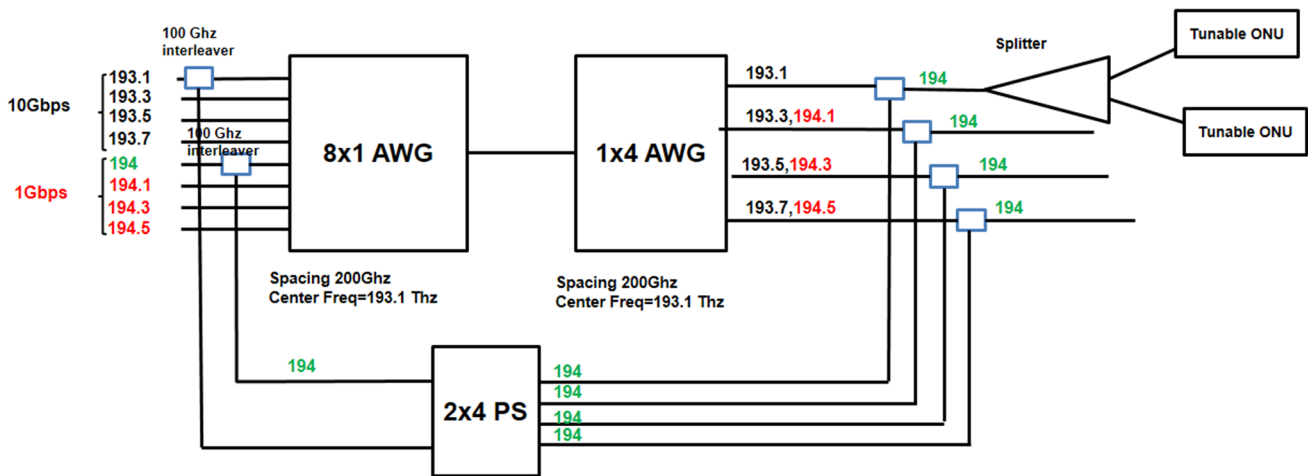


Fig. 6 Broadcasting at 1 Gbps

200GHz and are considered to be 193.1, 193.3, 193.5 and 193.7 Thz respectively at 10Gbps and 193.9, 194.1, 194.3 and 194.5 Thz respectively at 1 Gbps, as shown in Fig. 5. We assumed that for traffic load above the certain threshold, 10Gbps lines are used otherwise 1 Gbps lines are used i.e. for higher traffic load 1 Gbps line cards are switched off and for lower traffic load 10Gbps line cards are switched off. For providing upto 11 Gbps to each ODN, both the line cards (10G and 1G) are kept switched ON. Since all the ONUs are tunable, ONUs having load above threshold are tuned at 10G wavelength and ONUs with load lower than threshold are tuned at 1G wavelength. For example, ODN1 has 32 ONUs, out of which 20 ONUs have load below threshold and remaining 12 have load above threshold. In this case, 20 low load ONUs are tuned at 1G wavelength and remaining 12 ONUs are tuned at 10G.

In the architecture shown in Fig. 6, two 100GHz interleavers, one for 10Gbps and one for 1 Gbps are used at the

central office to separate out the even multiple of 100GHz and odd multiple of 100GHz wavelengths. Even multiple of 100GHz wavelength is transmitted by the interleaver and reached at 8×1 AWG. While 100GHz shifted wavelength from the original (odd multiple of 100GHz) is separated and diverted by the interleaver towards 2×4 PS for broadcasting. Broadcasting can be done at 10G or 1G or both depending upon the shifted wavelength. At the optical distribution network (ODN), four 100GHz interleavers are used as wavelength combiners to combine the broadcasted wavelengths with downstream wavelengths. As all ONUs are equipped with a dual rate and tunable transceivers, each ONU can receive any wavelength within the network. Broadcasting at 1G and 10G are shown in Figs. 6 and 7 respectively. If active users are less but demand high data rate, broadcasting is done at 10 Gbps by shifting the 10Gbps wavelength and vice versa. In both the cases, a significant amount of energy and operational expenditure (OPEX) is saved by turning off all transmitters except

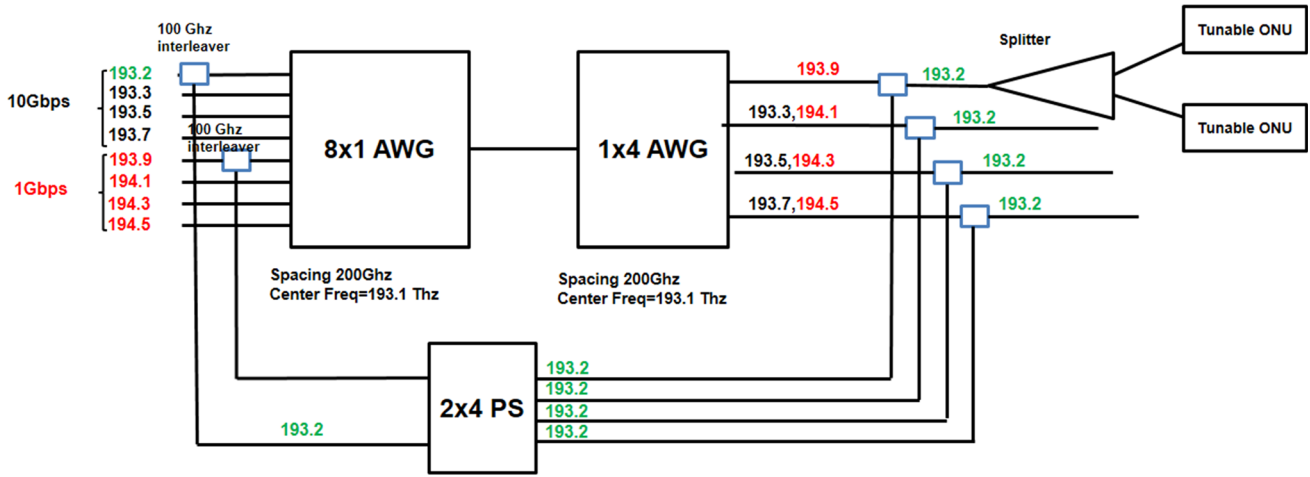


Fig. 7 Broadcasting at 10 Gbps

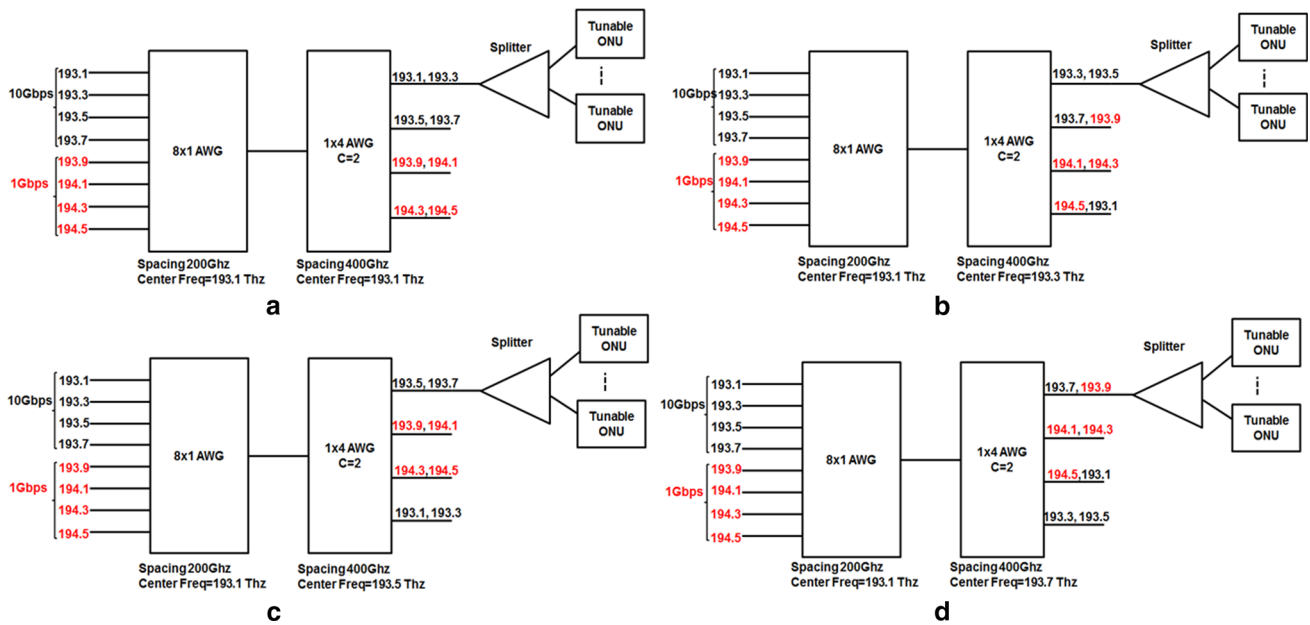


Fig. 8 Dynamic wavelength allocation for different center frequency

the broadcasting one. Another advantage of this architecture is reliability. When a particular transmitter fails, data can be transmitted on broadcasted wavelength and services remain continue on broadcasted wavelength until the recovery of failed transmitter.

In Fig. 8a, data rates provided to ODN1, ODN2, ODN3 and ODN4 are 20, 20, 2 and 2 Gbps respectively. By changing the center frequency from 193.1 to 193.3 THz, the data rate provided for different ODNs change as shown in Fig. 8b. Data rates provided in this case are 20, 11, 2 and 11 Gbps at ODN1, ODN2, ODN3 and ODN4 respectively. Likewise changes take place as shown in Fig. 8c, d when changing the center frequency to 193.5 and 193.7 THz respectively. In Fig. 9, the wavelength spacing of RN AWG is kept twice the CO AWG

(coarseness factor $C = 2$). At each output port of RN AWG, two contiguous wavelengths are transmitted, thus providing up to 20 Gbps data rate. To increase the AWG channel spacing or to shift the AWG central frequency, electro-optical tunable AWG [33,34] or thermo-optical tunable AWG [33–35] can be used. Thermo-optic tunable silicon-based AWG using TiN heater has already been demonstrated in [34]. Effective refractive index n_{eff} of silicon AWG is highly sensitive to the temperature variations. As wavelength spacing of AWG depends on its effective refractive index spacing, changing n_{eff} by means of temperature, wavelength spacing of AWG can be achieved [35–37] and given by $\Delta\lambda = \Delta n_{eff} \cdot \lambda_0/n_g$, where $\Delta\lambda$ is the frequency spacing of the AWG, λ_0 is AWG wavelength. Δn_{eff} is the effective refractive index of the

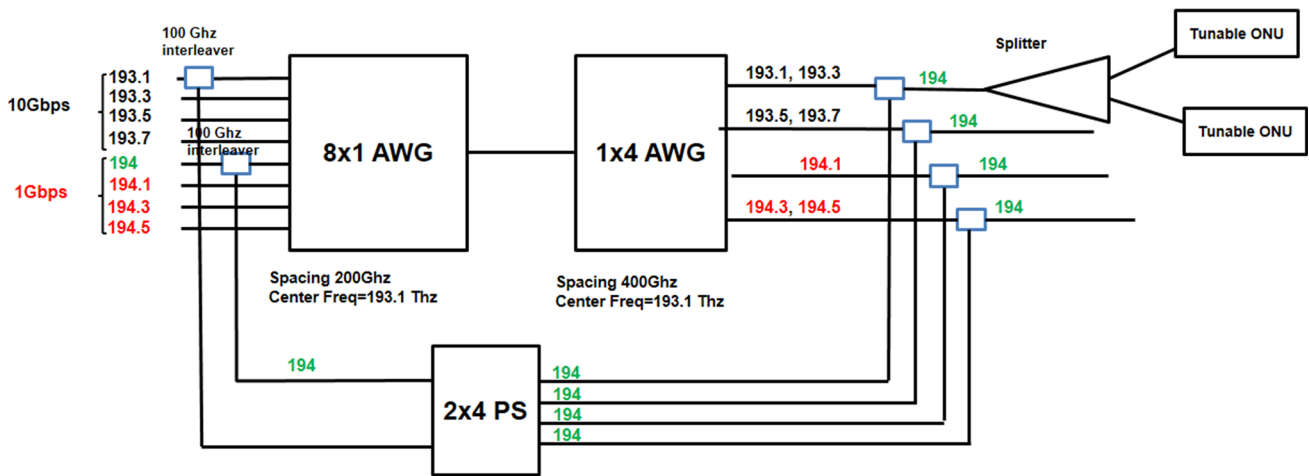


Fig. 9 Broadcasting at 1 Gbps with coarseness factor $C = 2$

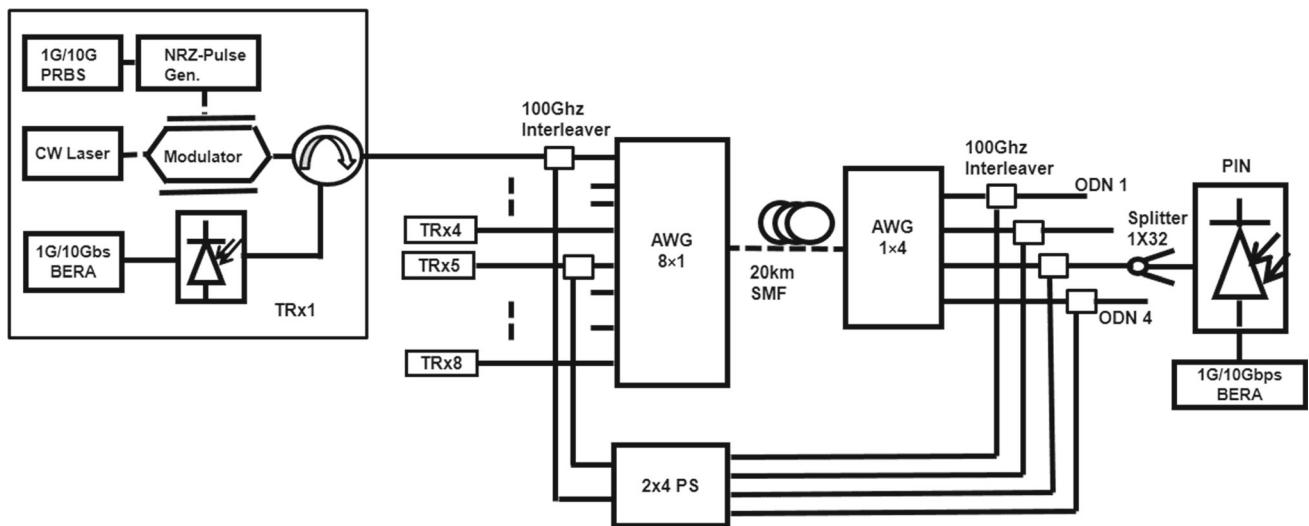


Fig. 10 Simulation setup of proposed network architecture

AWG. n_g is the group index. Center frequency of AWG also depends upon n_{eff} and given by $\lambda_c = 2n_{eff} \cdot \Lambda$ [34]. Just by changing the n_{eff} by means of above-mentioned techniques, central frequency can also be easily changed. As both wavelength spacing and central frequency of AWG are dependent on n_{eff} (temperature), for a desired frequency spacing $\Delta\lambda$, λ_0 may be chosen such that its final central frequency should be λ_c .

To support extended network or to provide bandwidth scalability to any specific part of network, proposed architecture is used with interleaver and coarseness factor $C = 2$ as shown in Fig. 9. The 100 GHz interleavers separate the 1G/10G wavelength for broadcasting at wavelength 1G/10G. Here, figure shows only 1G broadcasting at 194 THz. This provides a significant amount of energy saving by turning off all other wavelengths/transmitters whenever traffic load goes below a certain threshold.

7 Simulation setup and results

To demonstrate the system characteristics and capabilities of proposed tree topology based hybrid WDM TDM PON, we simulated it with the help of a system level simulator Optisystem 13.0 as depicted in Fig. 10. OLT consists of laser sources along with 1G and 10G pulse generator that generates the pseudo random binary sequence (PRBS) data of $2^{31} - 1$ length.

Due to low driving power and broadband property [38], LiNbO₃ Mach–Zehnder modulator is used to modulate the signal externally. The extinction ratio of MZM is kept 30 dB. OLT sends four 10G and four 1G downstream wavelengths to 8×1 CO AWG ($M = 8$) located at CO. This AWG has the channel spacing of 200 GHz (1.608 nm) and center frequency of 193.1 THz. Output wavelengths of 8×1 CO AWG is transmitted through 20 km single mode fiber. Fiber attenua-

tion and dispersion losses are considered to be 0.2 dB/km and 16.75 ps/nm/km respectively; fiber output signal is applied to 1×4 RN AWG located at the remote node. Channel spacing and center frequency of RN AWG are kept same as that of CO AWG. Again downstream data is shared among multiple ONUs through the 1×32 optical splitter. We assumed the insertion losses of 3 dB [34] for both CO AWG and RN AWG. 16.5 dB losses are also considered for the splitter [39]. At ONU, output optical signal is filtered out by a tunable optical filter to pass the desired signal and remove all other unwanted signals. Operating frequency of this filter depends on required narrowband or broadband signal. PIN photoreceiver with a responsivity of 1A/W and dark current of 10 nA is used to detect the optical signal. The output electrical signal is filtered by the electrical filter with cutoff frequency of $0.75 \times$ bit rate. ONU is installed with a dual rate receiver so that it can receive both 1G and 10G downstream signals.

The performance of the proposed architectures is evaluated with and without broadcasting for both 1 and 10Gbps transmission. BER v/s received optical power for all the cases are observed and plotted in Figs. 11 and 12 which shows the clear reception of transmitted signals at the receiver. Power received at the receiver is given by Eqs. (1) and (3):

$$P_{Rx} = P_{Tx} - L_{Ch} \tag{1}$$

$$L_{Ch} = L_{Interleaver} + L_{AWG} + L_{Fiber} + L_{AWG} + L_{Interleaver} + L_{1 \times K.PS} \tag{2}$$

$$P_{Rx} = P_{Tx} - L_{Interleaver} - L_{AWG} - L_{Fiber} - L_{AWG} - L_{Interleaver} - L_{1 \times K.PS} \tag{3}$$

where P_{Tx} and P_{Rx} are the transmitted and received power in dBm. L_{Ch} is the total loss occurring in the channel and

given in dB. Channel losses are depending upon the various passive components utilized in the path and for downstream transmission, losses are given by Eq. (2). For broadcasting path, losses due to CO and RN AWGs are saved. However it faces losses of 2×4 PS. Losses and received power with broadcasting are given by Eqs. (4) and (5) respectively.

$$L_{Ch} = L_{Interleaver} + L_{2 \times 4.PS} + L_{Fiber} + L_{Interleaver} + L_{1 \times K.PS} \tag{4}$$

$$P_{Rx} = P_{Tx} - L_{Interleaver} - L_{2 \times 4.PS} - L_{Fiber} - L_{Interleaver} - L_{1 \times K.PS} \tag{5}$$

Total losses occurring for 20km reach in the system for downstream and broadcasting system are 27.5 and 28dB respectively. 3 dB insertion losses occur due to each CO AWG and RN AWG. Insertion losses of each interleaver and 2×4 power splitter are 0.5 and 6.5 dB respectively. Broadcasting architecture suffers 0.5 dB more insertion losses, and this power margin can be used for supporting additional users without increasing input power. By providing 0 dBm optical power, received optical powers are -27.5 and -28 dBm respectively and at these received optical powers, observed BER is reasonably good.

Since proposed network utilizes total 8 wavelengths out of which four are used for transmitting signals at 10Gbps and remaining four for 1Gbps, the total capacity of the network is to support up to 44Gbps. To analyze the power saving capability of proposed architecture, we have assumed the representative traffic pattern for different days of a week for 24 h as shown in Fig. 13. We have some assumptions as follows: The traffic is assumed to be random in nature and varying randomly up to 44Gbps for the duration of 24 hours

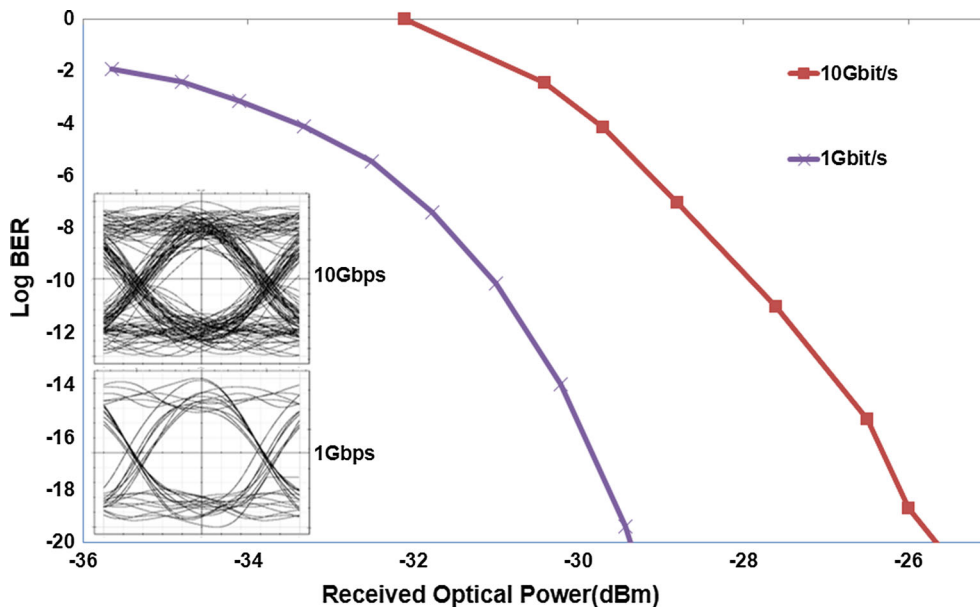


Fig. 11 Received optical power (dBm) versus BER for 20km fiber without broadcasting

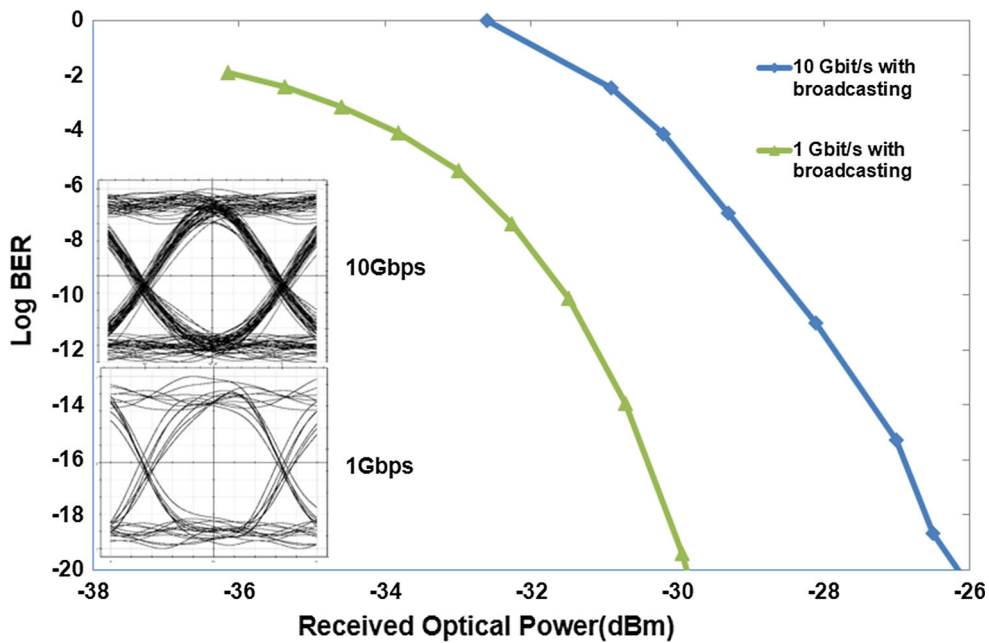


Fig. 12 Received optical power (dBm) versus BER for 20km fiber with broadcasting

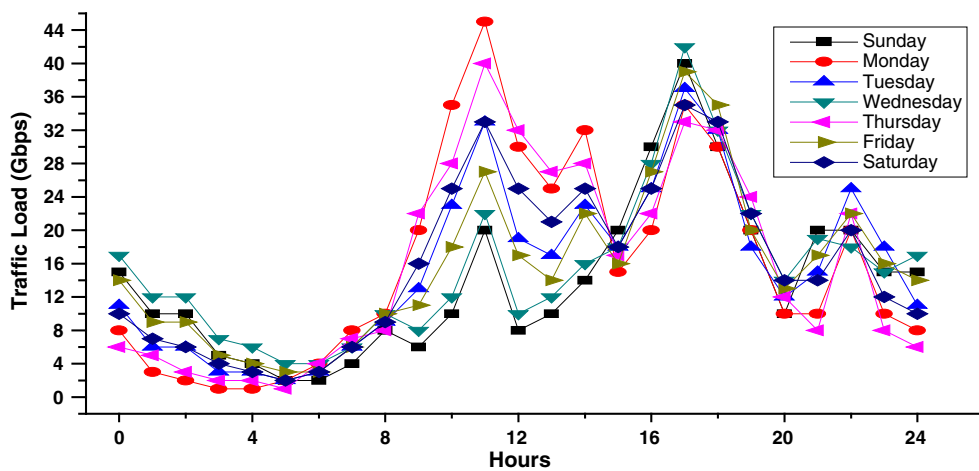


Fig. 13 Representative traffic pattern for 1 week

on each day. Also traffic has different loads for different days from Monday to Saturday. Each particular day will follow the same traffic pattern in upcoming weeks.

By using the proposed architecture with broadcasting, power saving in percentages at a particular day will be given by Eq. (6):

$$1 - \frac{\left[\sum_{n=1}^4 h_{10,n} n_{10G} \times P_{10G} + \sum_{n=1}^4 h_{1,n} n_{1G} \times P_{1G} \right]}{[HN_{10G} \times P_{10G}]} \tag{6}$$

where n_{10G} and $h_{10,n}$, denote number of working 10G transmitters and duration of n working 10G transmitters respectively, while the terms n_{1G} and $h_{1,n}$ are the respective

terms for the 1G transmitters. P_{10G} and P_{1G} denote the power consumed by each 10G and 1G transmitters respectively. H , N_{10G} and N_{1G} denote the total duration, total number 10G transmitters and total number of 1G transmitters respectively. The numerator part shows the power consumed by the proposed architecture on a particular day and denominator part represents the power consumed by the conventional architecture as shown in Fig. 1.

Based on the above calculations, energy efficiency of the proposed architecture as compared to conventional architecture discussed in case 1 (Fig. 1) is analyzed for different days and is depicted in Fig. 14, which clearly shows the up to 61.2% energy can be saved by using proposed architecture.

Fig. 14 Power saving for 1 week

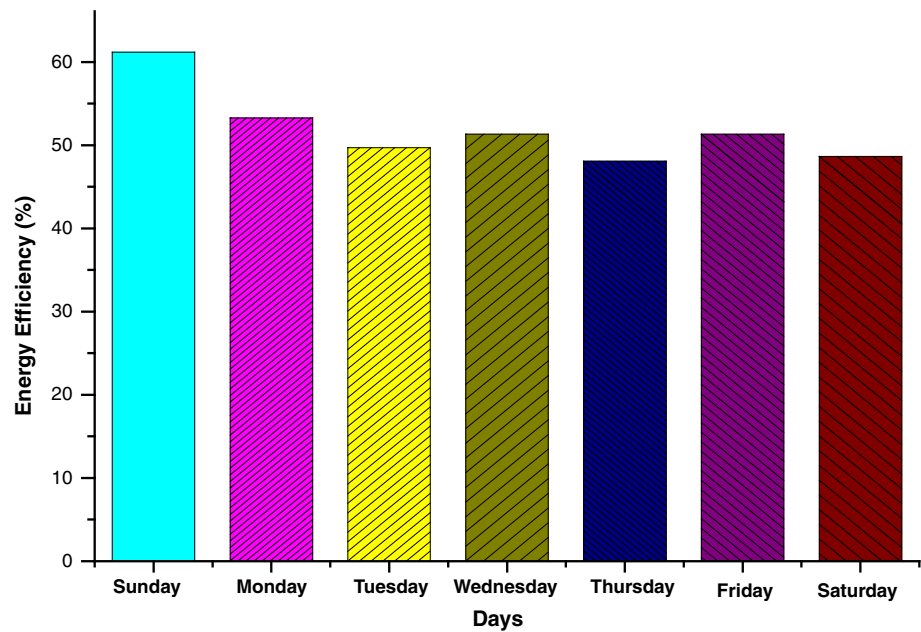
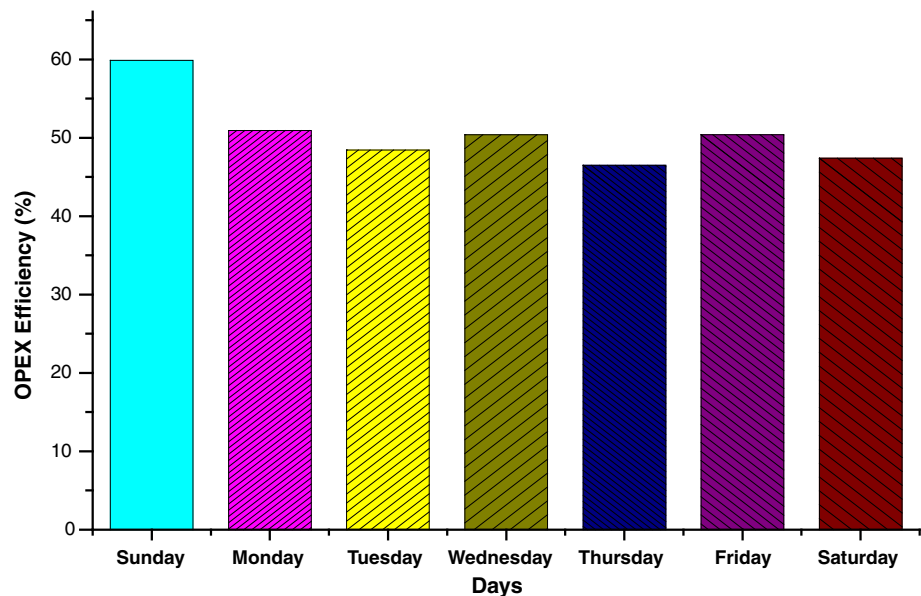


Fig. 15 OPEX reduction on different days of a week



Confidence interval (in %) of the reported results are 51.94 ± 3.1 and 51.94 ± 4 for 95 and 99% confidence level respectively. The confidence interval is calculated based on Eq. (7):

$$\bar{X} \pm Z \frac{\sigma}{\sqrt{n}} \quad (7)$$

where \bar{X} , σ and n indicate the mean, standard deviation and sample size respectively. Z is the value of a variate for a given confidence level. It has the values 1.96 and 2.57 for confidence level 95 and 99% respectively. Though, the cost of the proposed architecture is increased as compared to conventional architecture because it requires additional four 1G transceivers. The cost of Hilink 10G transceiver is

approximately \$320.00 [40] while it is approximately \$86.00 [40] for 1G transceiver. Thus overall CAPEX of architecture is increased about 26.87%. One USA's premier internet provider "US Internet" costs approximately \$298.00/month for 10Gbps upstream/downstream [41] and \$65.00/month for 1Gbps upstream/downstream transmission [41]. By considering these costs, the reduction in OPEX for the assumed traffic pattern is given by Eq. (8):

$$1 - \frac{\left[\sum_{n=1}^4 h_{10,n} n_{10G} \times B_{10G} + \sum_{n=1}^4 h_{1,n} n_{1G} \times B_{1G} \right]}{[HN_{10G} \times B_{10G}]} \quad (8)$$

where B_{10G} and B_{1G} denote the 10G and 1G bandwidth cost respectively. The numerator part shows the OPEX of pro-

posed architecture on a particular day and denominator part represents the OPEX of conventional architecture. Effective OPEX reduction on different days for assumed traffic is given in Fig. 15.

Based on Eq. (7), confidence interval for OPEX efficiency are 50.56 ± 3 and 50.56 ± 4 for 95 and 99% confidence level respectively.

8 Conclusion

This paper proposed an energy-efficient hybrid WDM–TDM PON architecture which allows the dual rate 1G/10G transmission depending upon the traffic load. At central office, this efficient bandwidth utilization provides opportunity to reduce a significant amount of energy consumption and OPEX. In proposed architecture, two wavelengths are reaching to the same ODN, therefore it provides the resiliency to the OLT TRx and line card failure. Under low load scenario, services may remain continued on an alternative wavelength until the recovery of failed wavelength. By tuning the transmitted wavelength by 100 GHz, broadcasting at 10G and/or 1G is also achieved simultaneously to support various applications like HDTV, e-education services etc. By allocating two contiguous wavelengths, proposed architecture also supports bandwidth scalability to any specific geographical part of the network. For the considered representative traffic, using proposed broadcasting architecture, maximum energy consumption, and OPEX is reduced up to 61.2 and 59.9% respectively. When operating at full capacity, the proposed architecture is capable of providing up to 44 Gbps data rates to the network. Finally, proposed architecture is more flexible, resilient to OLT TRx and line card failure, bandwidth scalable, OPEX and energy efficient to support next generation optical networks. We would also like to consider Elastic Optical Networks for the future research directions in a view to get added advantages and flexibility.

References

- Lee, C., Sorin, W., & Kim, B. (2006). Fiber to the home using a PON infrastructure. *Journal of Lightwave Technology*, 24(12), 4568–4583.
- Indre, R. M., Pesic, J., & Roberts, J. (2014). POPI: A passive optical pod interconnect for high performance data centers. In *2014 International conference on optical network design and modeling* (pp. 84–89), Stockholm.
- Ni, W., Huang, C., Liu, Y. L., Li, W., Leong, K. W., & Wu, J. (2014). POXN: A new passive optical cross-connection network for low-cost power-efficient datacenters. *Journal of Lightwave Technology*, 32(8), 1482–1500.
- Kazovsky, L., Shaw, W., Gutierrez, D., Cheng, N., & Wong, S. (2007). Next-generation optical access networks. *Journal of Lightwave Technology*, 25(11), 3428–3442.
- Gong, X., Guo, L., Liu, Y., & Zhou, Y. (2015). System performance analysis of time-division-multiplexing passive optical network using directly modulated lasers or colorless optical network units. *Optical Engineering*, 54(5), 056110.
- Luo, Y., Zhou, X., Effenberger, F., Yan, X., Peng, G., Qian, Y., et al. (2013). Time- and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON Stage 2 (NG-PON2). *Journal of Lightwave Technology*, 31(4), 587–593.
- Yuang, M., Hsu, D., Tien, P., Chen, H., Wei, C., Chen, S., et al. (2013). An energy and cost efficient WDM/OFDMA PON system: Design and demonstration. *Journal of Lightwave Technology*, 31(16), 2809–2816.
- Garg, A. K., & Janyani, V. (2015). Power budget improvement in energy efficient long reach hybrid passive optical network. In *2015 International conference on microwave and photonics (ICMAP)* (pp. 1–2), Dhanbad.
- Banerjee, A., Park, Y., Clarke, F., Song, H., Yang, S., Kramer, G., et al. (2005). Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: A review [Invited]. *Journal of Optical Networking*, 4(11), 737–758.
- Effenberger, F., Cleary, D., Haran, O., Kramer, G., Li, R. D., Oron, M., et al. (2007). An introduction to PON technologies. *IEEE Communications Magazine*, 45(3), 17–25.
- Garg, A. K., & Janyani, V. (2015). Identification of cost and energy efficient multiplexing techniques for LR-PON for different network scenario. In *IEEE workshop on recent advances in photonics (WRAP)* (pp. 1–4). IISc Bangalore: IEEE.
- Skubic, B., Betou, E., Ayhan, T., & Dahlfors, S. (2012). Energy-efficient next-generation optical access networks. *IEEE Communications Magazine*, 50, 122–127.
- Song, J., Yang, C., Zhang, Q., Ma, Z., Huang, X., et al. (2015). Energy efficiency evaluation of tree-topology 10 gigabit ethernet passive optical network and ring-topology time- and wavelength-division-multiplexed passive optical network. *Optical Engineering*, 54(9), 090502.
- Feng, H., Chae, C., Tran, A. V., & Nirmalathas, A. (2011). Cost-effective introduction and energy-efficient operation of long-reach WDM/TDM PON systems. *Journal of Lightwave Technology*, 29(21), 3135–3143.
- Kani, J., Shimazu, S., Yoshimoto, N., & Hadama, H. (2011). Energy efficient optical access network technologies. In *OFC/NFOEC* (pp. 1–3).
- Dixit, A., Lannoo, B., Das, G., Colle, D., Pickavet, M., & Demeester, P. (2013). Flexible TDMA/WDMA passive optical network: Energy efficient next-generation optical access solution. *Optical Switching and Networking*, 10(4), 491–506.
- Tadokoro, M., Kubo, R., Nishihara, S., Yamada, T., & Nakamura, H. (2012). Adaptive bandwidth aggregation mechanisms using a shared wavelength for energy-efficient WDM/TDM-PON (pp. 87–88).
- Garg, A. K., & Janyani, V. (2016). WDM-PON network for simultaneous upstream transmission with ONU interconnection capability. In *The international conference on fiber optics and photonics (PHOTONICS 2016), India Tu4A.13*.
- Garg, A. K., & Janyani, V. (2016). Overall/subgroup ONU intercommunication based on two stage flexible PON network. In *The international conference on fiber optics and photonics (PHOTONICS 2016), India W3A.1*.
- Cheng, N., Gao, J. H., Xu, C., et al. (2014). Flexible TWDM PON system with pluggable optical transceiver modules. *Optical Express*, 22(2), 2079–2091.
- Cheng, N. (2015). Flexible TWDM PON with WDM overlay for converged services. *Optical Fiber Technology*, 26, 21–30.
- Yuan, Y., Lu, P., Rodrigues, J., & Zhu, Z. (2013). Improving energy-efficiency of HFC networks with a master-slave linecard

- configuration. In *Proceedings of IEEE international conference on communications (ICC)* (pp. 4159–4163).
23. Zhu, Z. (2012). Design of energy-saving algorithms for hybrid fiber coaxial networks based on the DOCSIS 3.0 standard. *IEEE/OSA Journal of Optical Communications and Networking*, 4(6), 449–456.
 24. Zhu, Z., Lu, P., Rodrigues, J., & Wen, Y. (2013). Energy-efficient wideband cable access networks in future smart cities. *IEEE Communications Magazine*, 51(6), 94–100.
 25. Lu, P., Yuan, Y., Yang, Z., & Zhu, Z. (2013). On the performance analysis of energy-efficient upstream scheduling for hybrid fiber-coaxial networks with channel bonding. *IEEE Communications Letters*, 17(5), 1020–1023.
 26. Chatterjee, B. C., Sarma, N., & Oki, E. (2015). Routing and spectrum allocation in elastic optical networks: A tutorial. *IEEE Communications Surveys & Tutorials*, 17(3), 1776–1800.
 27. Chatterjee, B. C., & Oki, E. (2015). Performance evaluation of spectrum allocation policies for elastic optical networks. In *2015 17th international conference on transparent optical networks (ICTON)* (pp. 1–4), Budapest.
 28. Zhang, G., Leenheer, M. De, Morea, A., & Mukherjee, B. (2013). A survey on OFDM-based elastic core optical networking. *IEEE Communications Surveys & Tutorials*, 15(1), 65–87.
 29. Zhang, G., Leenheer, M. De, & Mukherjee, B. (2012). Optical traffic grooming in OFDM-based elastic optical networks [Invited]. *IEEE/OSA Journal of Optical Communications and Networking*, 4(11), B17–B25.
 30. Bock, C., Prat, J., & Walker, S. D. (2005). Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation. *Journal of Lightwave Technology*, 23(12), 3981–3988.
 31. Zhang, J., & Ansari, N. (2009). Minimizing the arrayed waveguide grating cost and the optical cable cost in deploying WDM passive optical networks. *IEEE/OSA Journal of Optical Communications and Networking*, 1(5), 352–365.
 32. Maier, G., Martinelli, M., Pattavina, A., & Salvadori, E. (2000). Design and cost performance of the multistage WDM-PON access networks. *Journal of Lightwave Technology*, 18(2), 125–143.
 33. Dai, J., Zhou, F., Zhang, M., & Liu, D. (2014). Electro-optical tunable arrayed waveguide grating based on liquid crystal clad waveguide. In *International photonics and optoelectronics meetings, OSA Technical Digest*, paper OTh4C.8.
 34. Horn, W., Kroesen, S., Herrmann, J., Imbrock, J., & Denz, C. (2012). Electro-optical tunable waveguide Bragg gratings in lithium niobate induced by femtosecond laser writing. *Optical Express*, 20(24), 26922–26928.
 35. Toyoda, S., Ooba, N., Kitoh, T., Kurihara, T., & Maruno, T. (2001). Wide tuning range and low operating power AWG-based thermo-optic wavelength tunable filter using polymer waveguides. *Electronics Letters*, 37(18), 1130–1132.
 36. Yang, Y., et al. (2015). Thermo-optically tunable silicon AWG with above 600 GHz channel tunability. *IEEE Photonics Technology Letters*, 27(22), 2351–2354.
 37. Zhang, H., Ma, C., Qin, Z., Zhang, X., Zhang, D., & Zhang, D. (2007). Thermo-optic tunable polymer arrayed waveguide grating. *Optical Engineering*, 46(5), 054601-1–054601-4.
 38. Haxha, S., Rahman, B., Langley, R., Sciences, M., & Square, N. (2005). Broadband and low-driving-power LiNbO₃ electrooptic modulators. *Optical and Quantum Electronics*, 36(14), 1205–1220.
 39. Zhang, S., Ji, W., Li, X., Huang, K., & Yan, Z. (2016). Efficient and reliable protection mechanism in long-reach PON. *IEEE/OSA Journal of Optical Communications and Networking*, 8(1), 23–32.
 40. <http://www.aliexpress.com>.
 41. <http://fiber.usinternet.com/plans-and-prices/>.



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