Highly Utilized Fiber Plant with Extended Reach and High Splitting Ratio Based on AWG and EDFA Characteristics

Mohammad Syuhaimi and Ibrahim Mohamed

In this paper, we propose a hybrid time-division multiplexing and dense wavelength-division multiplexing scheme to implement a cost-effective and scalable long-reach optical access network (LR-OAN). Our main objectives are to increase fiber plant utilization, handle upstream and downstream flow through the same input/output port, extend the reach, and increase the splitting ratio. To this end, we propose the use of an arrayed waveguide grating (AWG) and an erbium-doped fiber amplifier (EDFA) in one configuration. AWG is employed to achieve the first and second objectives, while EDFA is used to achieve the third and fourth objectives. The performance of the proposed LR-OAN is verified using the Optisystem and Matlab software packages under bit error rate constraints and two different approaches (multifiber and single-fiber). Although the single-fiber approach offers a more cost-effective solution because service is provided to each zone via a common fiber, it imposes additional losses, which leads to a reduction in the length of the feeder fiber from 20 km to 10 km.

Keywords: Long-reach optical access network, optical hybrid schemes, AWG, erbium-doped fiber amplifier, optical access networks, fiber-to-the-home, FTTH.

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I. Introduction

For a long time, optical fibers were used solely in backbone networks because of their massive capacity and very low attenuation. This limited use of optical fibers existed until the 1990s, when it became important to extend the use of optical fibers to access networks due to the increasing growth of broadband demand per user as a result of newly developed bandwidth-hungry services, such as high-definition television and video on demand. Fiber-to-the-home is an optical access technology in which passive optical components are deployed along the paths from a central office to end users. The first passive optical network (PON) was standardized in 1995 by the International Telecommunications Union's Telecommunication Standardization Sector (ITU-T) in the form of G.983 (broadband PON [BPON]) [1]-[3]. Gigabit-class PONs have been standardized by the Institute of Electrical and Electronics Engineers (IEEE) and ITU-T in the forms of IEEE802.3ah [4] and G.984 [5]-[7], respectively. Although the aforementioned PONs are categorized as time-division multiplexing (TDM) PONs and specify time-division multiple access (TDMA) as an access technique, they differ in the data link layer protocol. Generally, TDM-PONs provide a broadcast transmission between one optical line terminal (OLT) and several optical network units (ONUs). Each ONU can extract data destined for it through an addressing mechanism. The main disadvantage of this aspect is its traffic-sharing nature, which poses a real challenge to future upgrades [8].

To achieve some desirable goals, such as broader bandwidth per user, increased splitting ratio, and extended reach, the evolution to the next-generation of optical access was inevitable. Different architectures have been proposed in the literature for creating the next-generation optical access network structure. The high-speed TDM-PON was introduced as having the potential to be the next-generation PON (NG-PON). In 2009, the 10-Gbps Ethernet PON (10GEPON) was standardized by the IEEE802.3av standards group [9]. In 2010, the 10-Gb PON (XG-PON) was standardized as ITU-T G.987 [10]. The wavelength-division multiplexing (WDM) PON was identified as another potential technology for the NG-PON. Different configurations were introduced in an attempt to build a WDM-based PON [11]. Unlike TDM-PONs, WDM-PONs allow each ONU to handle data transmission via a dedicated wavelength with the possibility of different speeds and protocols. Therefore, WDM-PONs are considered more secure and scalable than TDM-PONs.

To exploit the advantages offered by the TDM-PON and WDM-PON technologies, a hybrid scheme was proposed [11]. The first commercial colorless gigabit hybrid TDM/WDM-PON was proposed for Korea Telecom [12]. Another competitor for next-generation optical access network implementation is the long-reach optical access network (LR-OAN). The LR-OAN was proposed to achieve some desirable results in PON systems, such as extended reach and an increased splitting ratio [13]. For long-haul optical transmission, this technology works well in compensating for losses by amplifying the signal completely in the optical domain rather than performing complex and expensive processes, such as photon-to-electron conversion, retiming, reshaping, electrical amplification, and electron-to-photon conversion, as required with conventional repeaters. Optical amplifiers are designed to work in the optical domain for signal amplification within the two long-wavelength transmission windows, 1,300 nm and 1,550 nm [14]-[16]. Moreover, they can be used to compensate for splitting losses in multiaccess networks. Erbium (Er)-doped fiber amplifiers (EDFAs) were developed for optical signal amplification at the lowest attenuation transmission window, 1,550 nm (C band), which makes them very attractive.

II. Overview of LR-OAN Technologies

It is desirable to overcome the limitations of TDM-PONs and WDM-PONs, such as low splitting ratios and limited transmission distances. To this end, LR-OANs were proposed. Additionally, LR-OANs offer a cost-effective solution by combining both the access and metro segments of the telecommunication network in one extended backhaul segment, which in turn contributes to consolidating the central office sites, resulting in a highly simplified network.

Figure 1 illustrates both the metro and access segments,

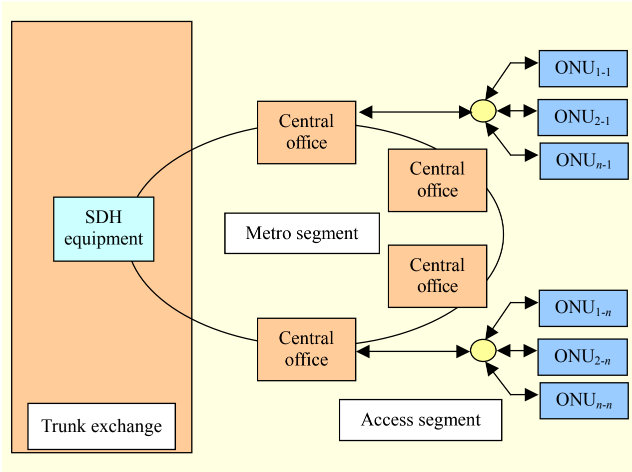

Fig. 1. Metro and access segments in telecommunication network.

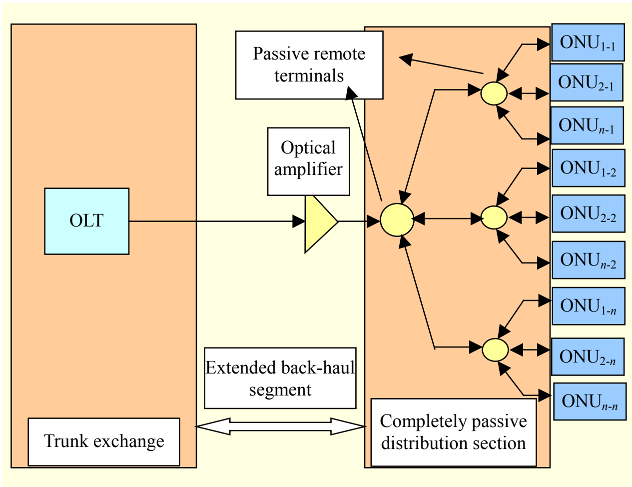

Fig. 2. Simplified LR-OAN architecture.

while Fig. 2 shows a simplified LR-OAN architecture. Although optical amplifiers are critical to the implementation of LR-OANs, it is recommended that the distribution segment of the network be completely passive. Different architectures have been proposed to implement LR-OANs. The first LR-OANs proposed were based on TDM, with a single wavelength shared among all ONUs. LR-OANs based on WDM and hybrid TDM/WDM were subsequently proposed. The photonic local access network project was initiated in the mid-1990s to develop a full-service access network known as the SuperPON [17]. The SuperPON was developed based on the possibility of upgrading the G.983 (BPON) architecture. This technology had the ability to support up to 2,048 ONUs through a partially passive distribution section over a 100-km transmission distance. However, a complex gating protocol was needed to overcome the noise funneling effect caused by the partially passive distribution section. The long-reach PON was developed for British Telecom. Although the long-reach PON can support up to 1,024 ONUs, which is half of that supported by the SuperPON, it has a completely passive distribution section and thus does not suffer from the noise funneling effect [18]. The hybrid DWDM/TDM long-reach PON was proposed by Talli and Townsend [19]. This technology can serve up to 17 TDM-PONs by assigning a dedicated wavelength to each. The long-reach GPON was developed based on the standard GPON architecture, incorporating optical-to-electrical-to-optical conversion. A wavelength-converting PON was proposed by involving a cross-gain-modulation wavelength converter (WC). The WC is used to convert each PON wavelength into a standard DWDM wavelength [20].

The contribution of this paper is the presentation of a cost-effective and scalable LR-OAN scheme. The design is based on a study of the characteristics of different optical components, including arrayed waveguide gratings (AWGs), EDFAs, and power splitters, and the possibility of integrating these components together in one configuration to develop a TDM/DWDM-based LR-OAN. The scheme that we propose here can provide a variety of services over a long distance through a common fiber to a large number of users. The remainder of this paper is divided into two parts. First, we examine the proposed hybrid by considering the AWG alone and estimate the maximum allowable distance for transmission under bit error rate (BER) constraints. In the second part of this paper, the impact of the EDFA is evaluated.

III. AWG Characteristics

An AWG is an optical device that consists of two free propagation regions (slabs) and one array of waveguides. The array, which contains a number of different waveguide lengths, is placed in the middle of the two free propagation regions. The difference in length between any two adjacent waveguides is constant. If an optical signal carrying an aggregation of wavelengths propagates in the first free propagation region, the aggregation will arrive at the input of the second propagation region with different phases, due to the different waveguide lengths. As a result, each wavelength is directed to a specific output port. This process can be envisioned as a multiplexing process. Based on the property of reciprocity, an AWG can also work as a demultiplexer [21]. An AWG with stable performance over a wide range of temperatures was proposed in a previous study [22]. The company C2V developed a silicon-based AWG model with an insertion loss of 1.26 dB, but the main drawback of this model was its large size. A smaller AWG with an insertion loss on the order of 1.09 dB was proposed by Tippinit and Asawamethapant [23].

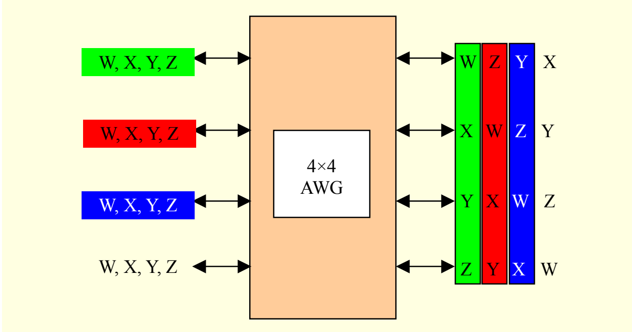

Fig. 3. Schematic diagram of WCP.

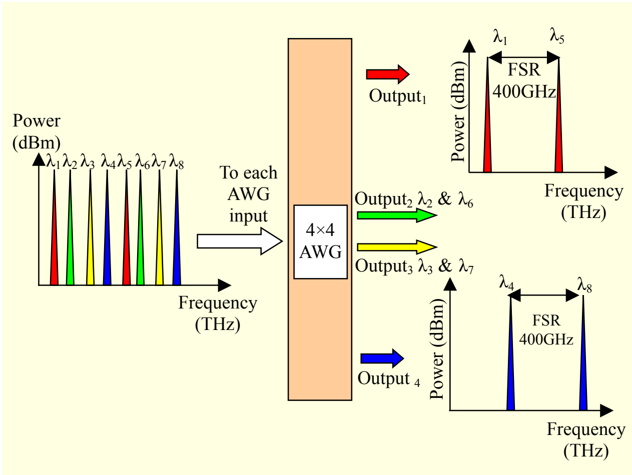

Fig. 4. Schematic diagram of FSRP.

An AWG has two main properties [24]. The first main property is its wavelength-cyclic property (WCP), through which a shift to the input port of the AWG is followed by an opposite shift to the output port. In other words, if two identical aggregations of wavelengths enter the AWG from two different input ports, they are then distributed among its output ports in a non-overlapping manner. Figure 3 shows a schematic of this property. The second main property is the free spectral range property (FSRP), which identifies the periodic operating range of the AWG. If two wavelengths enter the same input port of the AWG, they emerge from the same output port as long as they are separated by the periodic frequency range of the AWG (free spectral range [FSR]).

Of course, an AWG with a large periodic operating range is highly desirable in optical network design. Figure 4 shows a schematic diagram of this property, considering a 4 × 4 AWG with a 400-GHz FSR. An optical signal that carries an eight-wavelength aggregation with 100-GHz frequency spacing is considered at each input. Both the WCP and FSRP are targeted in this paper to achieve frequency reuse and to allow handling upstream and downstream traffic via the same input and output ports.

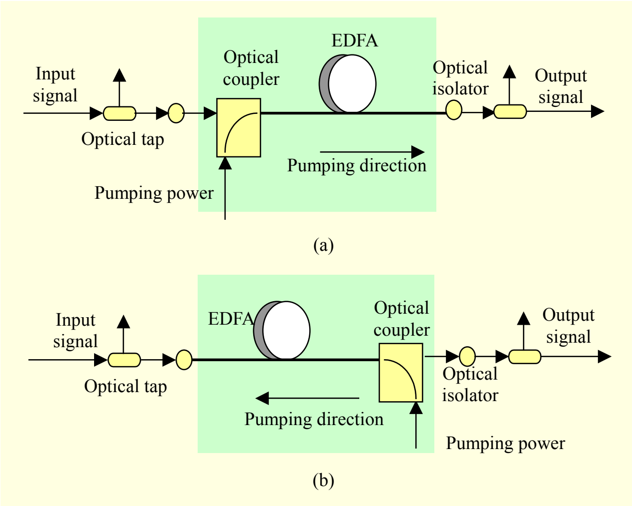

Fig. 5. (a) EDFA codirectional pumping configuration and (b) EDFA counterdirectional pumping configuration.

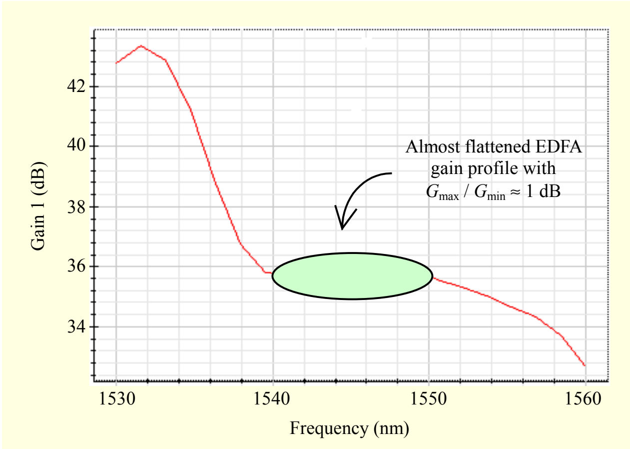

Fig. 6. EDFA gain profile over 30-nm SR (1,530 nm to 1,560 nm).

IV. EDFA Architecture and Configurations

An EDFA consists primarily of a silica fiber doped with the rare-earth element Er (the active medium), a passive wavelength coupler to couple both the signal and pump optical powers into the active medium, and one or two pump lasers that pump at either 980 nm or 1,480 nm [25], [26].

Two different configurations are commonly used for the pumping process, as shown in Figs. 5(a) and 5(b). In the first configuration, pumping of the optical power comes from the same direction in which the optical signal travels, which is known as codirectional pumping; in the second configuration, optical power is pumped in the opposite direction in which the optical signal travels, which is known as counterdirectional pumping. EDFA is characterized as working in the C band, which is the lowest attenuation band for optical transmission. Moreover, it is immune to the crosstalk effect, which makes it suitable for simultaneous amplification as long as a frequency greater than 10 kHz is used for channel spacing. This feature makes it suitable for DWDM systems in which 100-GHz frequency spacing is commonly used. However, the gain profile of an EDFA is wavelength dependent, which results in a non-constant gain over a range of wavelengths. Additionally, its wavelength-dependent profile leads to a significant difference in the signal-to-noise ratio (SNR) when cascaded EDFAs are used.

Several configurations have been proposed for EDFAs with flattened gain profiles [27]-[29]. However, these configurations require the use of additional components, which leads to an increase in the level of complexity. Conventionally, the operating region of the EDFA lies between 1,530 nm and 1,560 nm (a 30-nm bandwidth). This bandwidth can be extended to 75 nm when an EDFA is combined with a Raman fiber amplifier [30].

We perform a simple simulation by using the Optisystem software (Optiwave Systems, Inc., Ontario, Canada) as a part of our work to illustrate the EDFA gain profile over a 30-nm wavelength range (1,530 nm to 1,560 nm), as shown in Fig. 6. A codirectional pumping configuration at 0.1 W and 980 nm is chosen in the simulation due to its better noise performance and ability to achieve higher population inversion. Interestingly, although the gain profile is not equalized over the entire range from 1,530 nm to 1,560 nm, it is almost flattened between 193.1 THz and 194.6 THz. In other words, a small value of gain flatness (G_{max}/G_{min} ≈ 1 dB) is achievable over this range, making it a suitable choice for our design. This range can represent an optical signal that carries an aggregation of 16 wavelengths when 100-GHz frequency spacing is used, which is considered suitable for conducting the remaining parts of the simulation. In this chosen range, the minimum gain is achieved at 193.1 THz, and the maximum gain is achieved at 194.1 THz. To ensure the feasibility and reliability of our proposed LR-OAN architecture over the chosen range, we opt to use 193.1 THz for power budget purposes because it corresponds to the minimum gain.

V. Amplifier-Free Configuration

Figure 7 shows the proposed configuration without the use of an EDFA. This configuration is based on a hybrid TDM/DWDM PON scheme. An $N \times N$ AWG is included in the configuration to achieve two of our main objectives by exploiting its properties. When an aggregation of wavelengths (λ_1-λ_n) transmitted by OLT_1 enters the first port of the AWG, it is distributed to its output ports. If an identical aggregation (λ_1-λ_n) transmitted by OLT_2 enters the second input port of the AWG, it is also distributed among its output ports, without

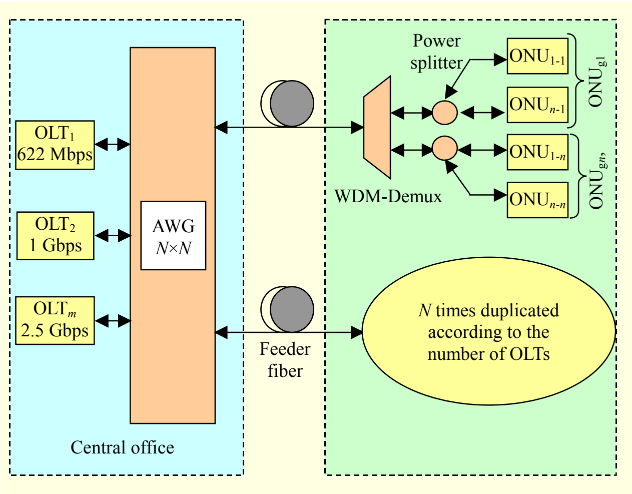

Fig. 7. Amplifier-free configuration.

overlapping with the first aggregation. In general, if a number m of identical aggregations (λ_1-λ_n) are transmitted by m OLTs and enter the N input ports of the AWG, where m=n=N, they are distributed among the output ports of the AWG in a non-overlapping manner, allowing each OLT to use the same frequency range and therefore achieve frequency reuse. Each output port carries a replica of the same frequency range, albeit from different OLTs. This common frequency in turn increases the utilization of the fiber plant, due to each wavelength representing an independent OLT. A discussion of the results related to the amplifier-free configuration is provided in subsection VII.1.

VI. Proposed LR-OAN

We have proposed a more evolved TDM/DWDM hybrid that incorporates an EDFA. Our proposed configuration is a hybrid TDM/DWDM LR-OAN. Service is provided by one trunk exchange, rather than many central offices, through 100 km of backhaul fiber. The OLTs are divided into groups, each of which includes different OLTs that handle different bitrates (622 Mbps, 1 Gbps, and 2.5 Gbps). The number of OLT groups, N_g, is equal to N/m, where N represents the number of AWG input ports and m represents the number of OLTs in one group. An aggregation of λ_1-λ_n is considered for each OLT, where n=N. Each AWG output port carries a replica of the same aggregation λ_1-λ_n, which represents all OLT groups (OLT_{g1}-$OLT_{gN/m}$). As mentioned in section IV, the AWG is used to achieve frequency reuse and to enable handling upstream and downstream traffic via the same input and output ports by exploiting its WCP and FSRP. Incorporating an EDFA provides sufficient power to the weak signal received at the local exchange to overcome the next attenuation imposed by the distribution section. The local exchange site is proposed to perform the amplification process because it contains electrical power, which eliminates the need for an electrical power supply in the distribution section. In this innovative architecture, services can be provided to N regions, and a $1 \times N$ WDM demultiplexer (Demux) can be envisioned as being located at the center of each region and providing service to N/m zones through feeder fibers under two different approaches (a multifiber approach and single-fiber approach). In the multifiber approach, a 100-km SM fiber (the backhaul fiber) is assigned for each region, while a number of 20-km SM fibers that are equivalent to the number of OLTs in one group is assigned to each zone (feeder fibers). Within one zone, each fiber provides service at a different bitrate. A two-stage power splitter that yields a total splitting size of $1 \times j$ is connected at the end of each fiber, as shown in Fig. 8. In the single-fiber approach, service is provided to each zone via a common fiber using a $(N/m) \times 1$ WDM multiplexer (Mux) and $1 \times (N/m)$ WDM-Demux, as shown in Fig. 9. Although the single-fiber approach is more cost effective and efficient because m OLTs can provide their services to any specific zone through a common fiber, these benefits might come at the expense of performance degradation, due to more losses being imposed by the additional components (Mux and Demux). This feature of the single-fiber approach is verified and discussed below.

VII. Simulation Results and Discussion

Two simulations are conducted in this study. First, a simulation is performed to verify the feasibility of the amplifier-free configuration and to evaluate the maximum allowable distance for transmission without using an EDFA. In the second simulation, the performance of the configuration is verified using an EDFA and two different approaches (the multifiber and single-fiber approaches). Both simulations are conducted using the Optisystem (Optiwave Systems, Inc.) and Matlab (The Mathworks, Inc., Natick, MA, USA) software packages under BER constraints.

1. First Simulation

In the first simulation, a 16×16 AWG, 1×16 WDM-Demux, and 1×16 power splitter are assigned, and 622-Mbps, 1-Gbps, and 2.5-Gbps pseudorandom non-return-to-zero (NRZ) data is transmitted at 0 dBm. Sixteen wavelengths (193.1 THz through 194.6 THz) with 100-GHz frequency spacing are allocated to each OLT, as shown in Fig. 10. Variable-length SM fiber with 0.2-dB/km attenuation and 16.75-ps/(nm×km) dispersion is used. An insertion loss of 1.26 dB is considered for the AWG, and a splitting/insertion

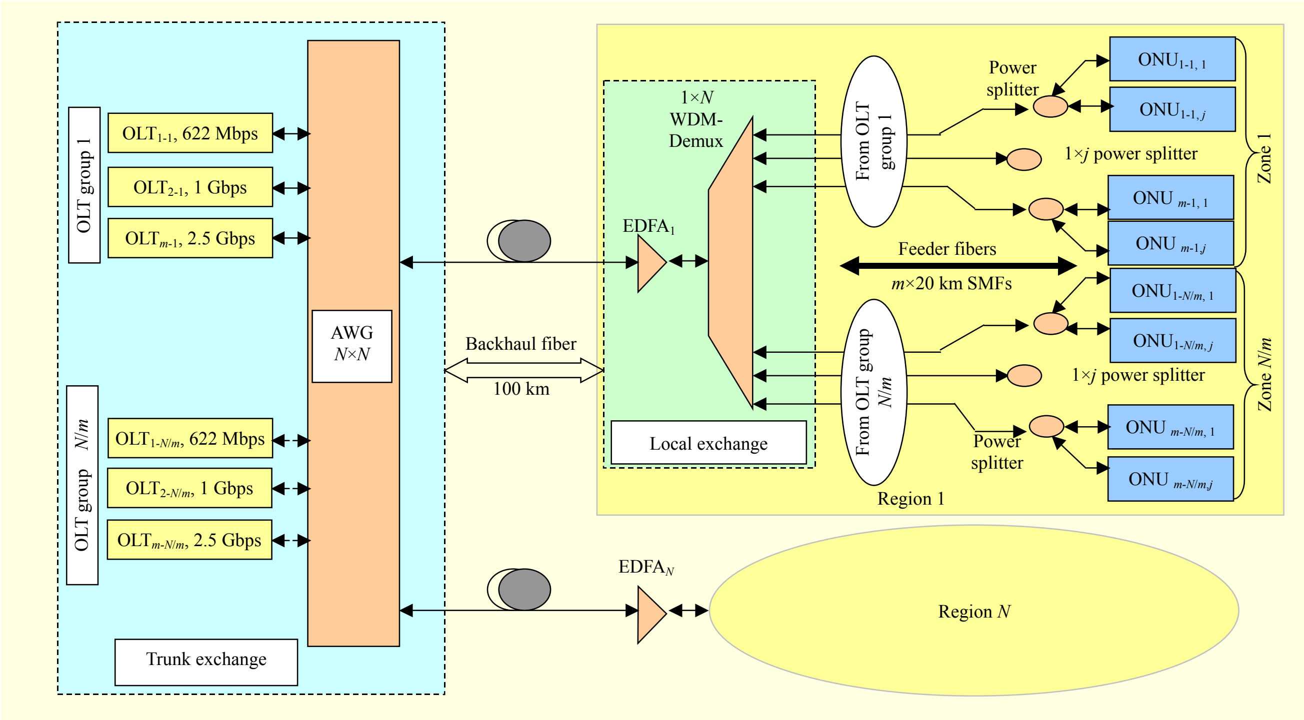

Fig. 8. Proposed LR-OAN configuration with EDFA; multifiber approach is considered.

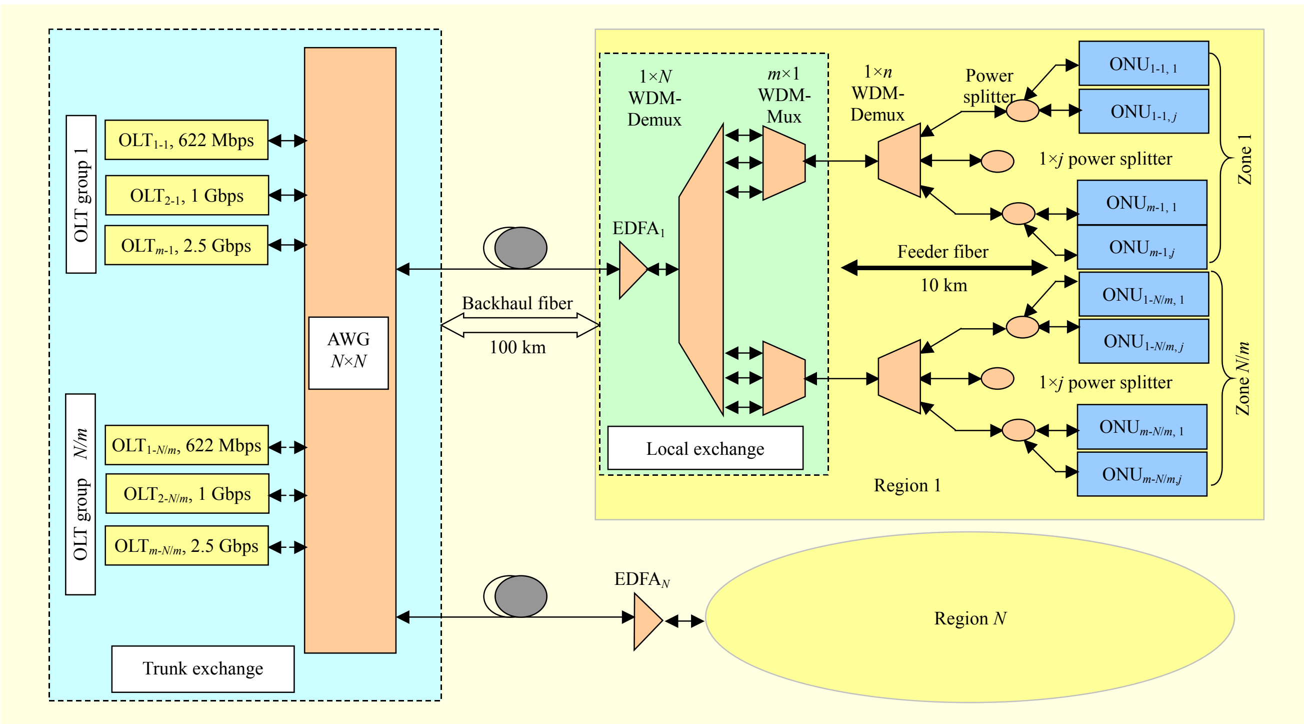

Fig. 9. Proposed LR-OAN configuration with EDFA; single-fiber approach is considered.

loss of 14.04 dB is assigned to the 1 × 16 power splitter. A p-type/intrinsic/n-type (PIN) photodiode is chosen in the simulation owing to its low biasing voltage and low cost. A BER of 10^{-9} is chosen as a reference for operational requirements (the maximum allowable value). Figure 11 shows the BER versus fiber length at 0 dBm and different bitrates. It is obvious that the BER increases as the fiber length increases until it reaches a value of 10^{-9} at 24 km and 2.5 Gbps. The

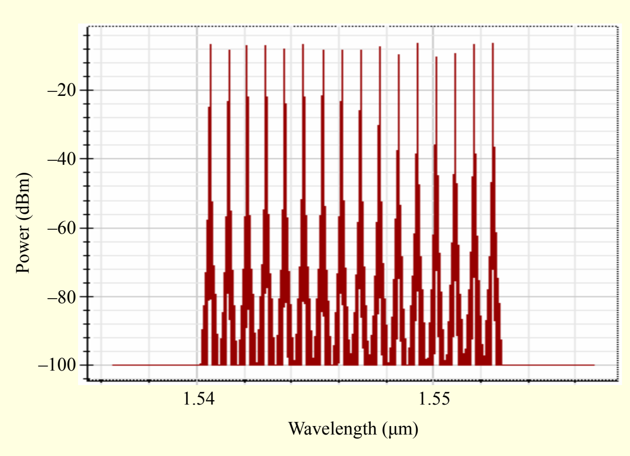

Fig. 10. Optical spectrum from each OLT (193.1 THz to 194.6 THz).

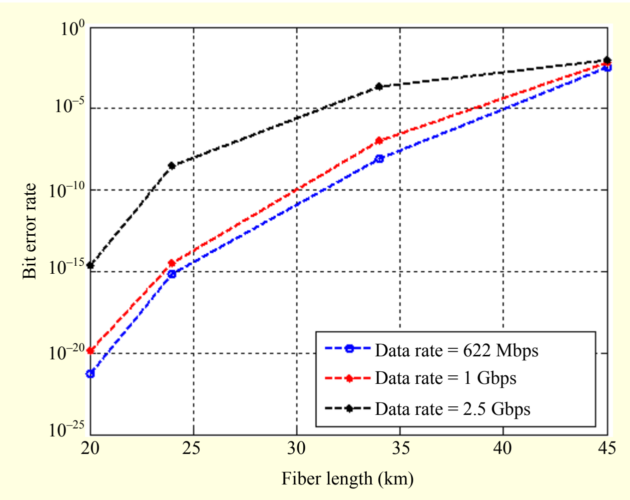

Fig. 11. BER vs. fiber length at 0 dBm and different bitrates.

BER reaches a value of 10^{-9} at 30 km and 33 km at 1 Gbps and 622 Mbps, respectively, and then continues to increase as the fiber length increases. Based on these results, we can conclude that transmission is possible with the amplifier-free configuration up to 24 km, which is the shortest distance obtained for simultaneous transmission. Figure 12 shows eye diagrams of 622 Mbps at 33 km, 1 Gbps at 30 km, and 2.5 Gbps at 24 km, with a sampled BER value for each, for which acceptable receiver performance can be simply and visually indicated by the clearly opened eyes, which confirms our findings. Eye diagrams are so called because of their resemblance to eyes.

2. Second Simulation

In the second simulation, the performance of the proposed

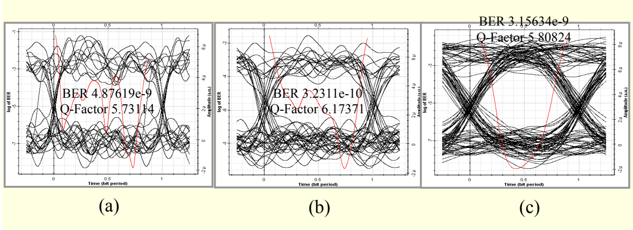

Fig. 12. Eye diagrams of (a) 622 Mbps at 33 km, (b) 1 Gbps at 30 km, and (c) 2.5 Gbps at 24 km.

LR-OAN is evaluated using two different approaches, the multifiber approach and the single-fiber approach, in accordance with the configurations shown in Figs. 8 and 9. Three different bitrates are considered in the second simulation to examine the feasibility of our proposed LR-OAN.

The three bitrates of pseudorandom NRZ data are 622 Mbps, 1 Gbps, and 2.5 Gbps. A 15 × 15 AWG and 1 × 15 WDM-Demux with a 1.26-dB insertion loss are assigned. Three power splitters are assigned to each zone. Each one consists of two stages of splitting, 1 × 4 (splitting/insertion loss of 8.02 dB) and 1 × 64 (splitting/insertion loss of 20.06 dB), for a total of 1 × 256. A 100-km SMF with 0.2 dB/km of attenuation and 16.75 ps/(nm×km) of dispersion is assigned as a region provider (backhaul fiber), while a 20-km SMF with the same attenuation and dispersion is assigned as a zone provider (feeder fiber). A five-meter, 100-mW codirectional pumped EDFA is assigned for the DWDM signal amplification. All bitrates are transmitted within the C band at 0 dBm. A PIN photodiode is used for signal reception in this simulation owing to its low biasing voltage and low cost. A BER of 10^{-9} is chosen as a reference for operational requirements (the maximum allowable value). To verify the feasibility of the proposed LR-OAN, the simulation is performed under BER constraints, considering the losses experienced by each passive element.

A. Performance Evaluation for Multifiber Approach

In the multifiber approach, the simulation is set up according to the configuration shown in Fig. 8. In this approach, three 20-km SMFs (feeder fibers) are assigned for each zone such that three different bitrate services are provided separately. Figure 13 shows the BER versus the feeder length at 2.5 Gbps and 0 dBm for a 100-km backhaul fiber. The BER increases as the feeder fiber length increases until it reaches 10^{-9} at 20 km and then continues to increase as the feeder fiber length increases. Figure 14 shows the BER versus feeder fiber length for bitrates of 622 Mbps and 1 Gbps at 0 dBm, for which a BER of 10^{-9} is reached at 30 km and 25 km, respectively, making it possible to service beyond 20 km, that is, 25 km at 1 Gbps and 30 km at 622 Mbps. Based on these results, we

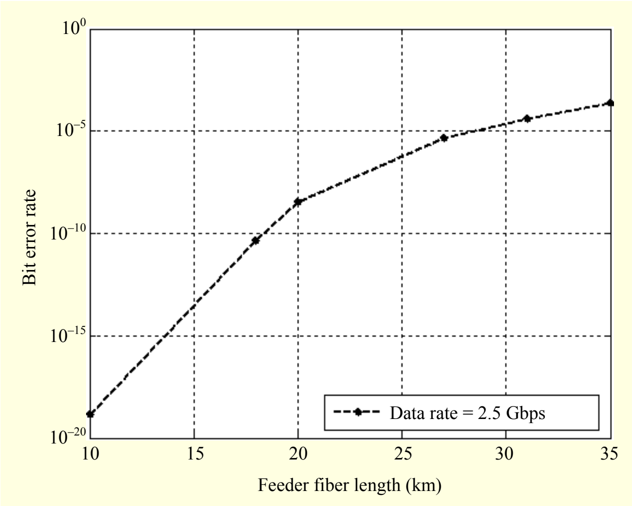

Fig. 13. BER vs. feeder fiber at 0 dBm and 2.5 Gbps.

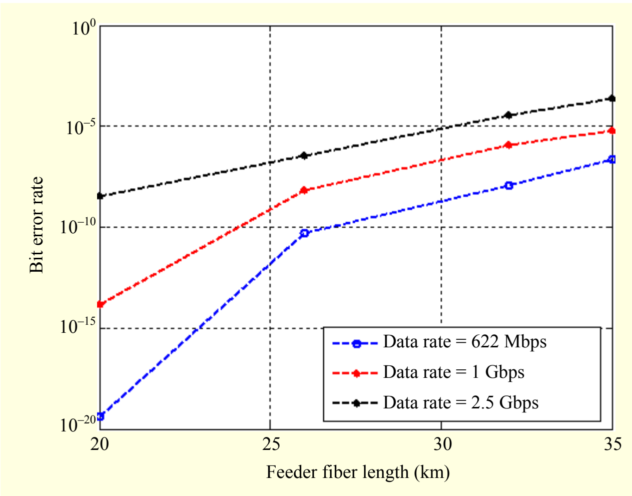

Fig. 14. BER vs. feeder fiber at different bitrates and 0 dBm.

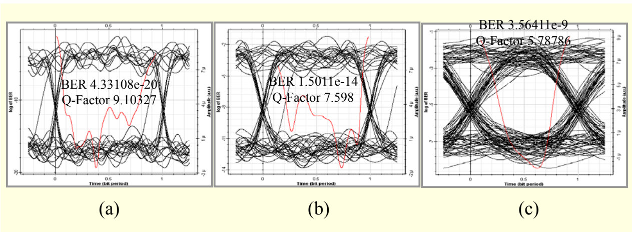

Fig. 15. Eye diagrams of (a) 622 Mbps, (b) 1 Gbps, and (c) 2.5 Gbps at 0 dBm and 20-km feeder fibers.

choose 20 km as the maximum allowable distance for transmission within each zone to ensure provision of reliable service because it is the shortest distance obtained for simultaneous transmission.

Figure 15 presents eye diagrams for 622 Mbps, 1 Gbps, and 2.5 Gbps at 0 dBm for 20-km feeder fibers with a sampled BER value for each, for which acceptable receiver performance is simply and visually established through the clearly opened eyes, which confirms our findings.

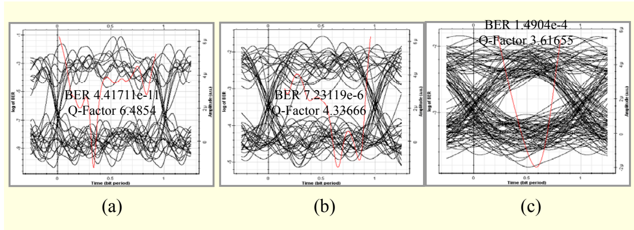

Fig. 16. Eye diagrams of (a) 622 Mbps, (b) 1 Gbps, and (c) 2.5 Gbps at 0 dBm and 20-km feeder.

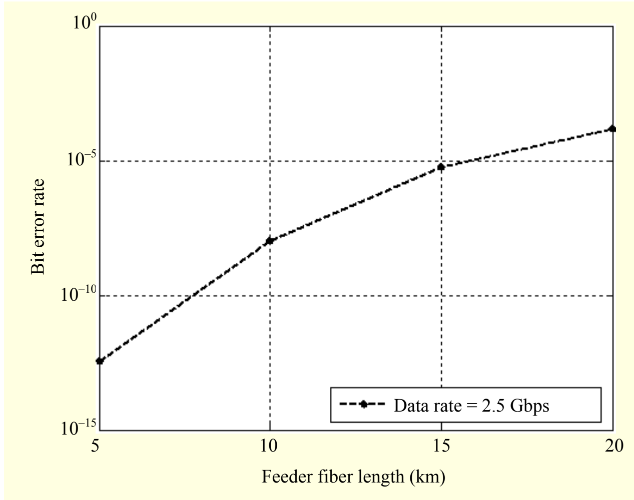

Fig. 17. BER vs. feeder fiber at 0 dBm and 2.5 Gbps.

B. Performance Evaluation for Single-Fiber Approach

In the single-fiber approach, the simulation is set up according to the configuration shown in Fig. 9. In this approach, a shared fiber (20-km feeder fiber) is assigned to each zone using a 3 × 1 WDM-Mux and 1 × 3 WDM-Demux. Figure 16 shows eye diagrams for 622 Mbps, 1 Gbps, and 2.5 Gbps at 0 dBm with a sampled BER value for each, for which degraded receiver performance is simply and visually established through the almost-closed eye at 2.5 Gbps. By comparing the sampled BER values with the BER value required for operation, we conclude that simultaneous transmission is not possible due to the higher BERs obtained at 1 Gbps and 2.5 Gbps.

Figure 17 shows the BER versus feeder length at 2.5 Gbps and 0 dBm for a 100-km backhaul fiber. This figure shows that transmission is possible up to 7 km because a BER of 10^{-9} is reached at this distance. Figure 18 shows the BER versus feeder fiber length for 622 Mbps and 1 Gbps at 0 dBm, for which a BER of 10^{-9} is reached at 20 km and 15 km,

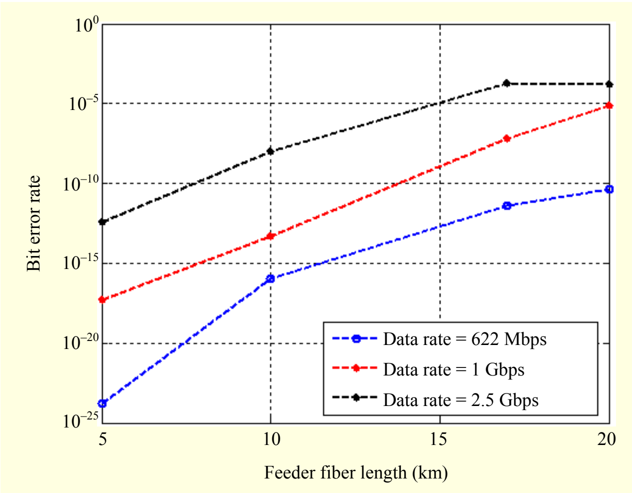

Fig. 18. BER vs. feeder fiber at different bitrates and 0 dBm.

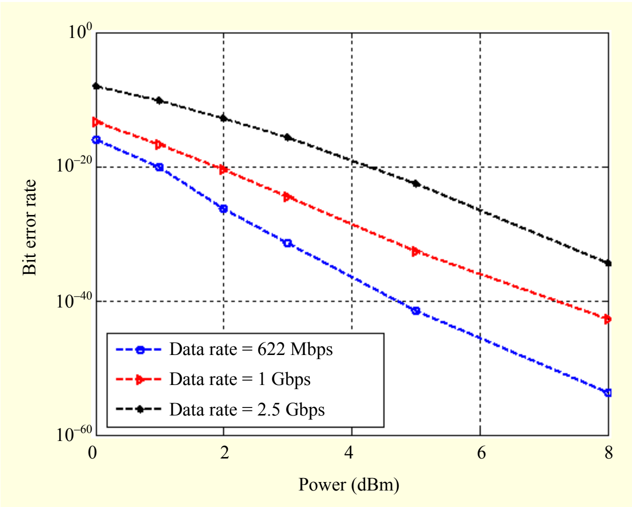

Fig. 19. BER vs. power at 10-km feeder fiber and different bitrates.

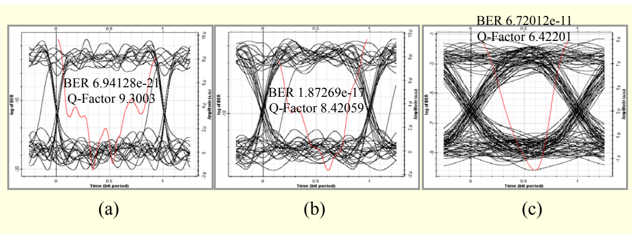

Fig. 20. Eye diagrams of (a) 622 Mbps, (b) 1 Gbps, and (c) 2.5 Gbps at 1 dBm and 10-km feeder.

respectively, making it possible to provide service beyond 7 km, that is, 15 km at 1 Gbps and 20 km at 622 Mbps. However, we choose 7 km as the maximum allowable distance for transmission within each zone to ensure provision of reliable service because it is the shortest distance obtained for simultaneous transmission.

We also consider a compromise involving shortening the feeder fiber from 20 km to 10 km while increasing the power to 1 dBm. Figure 19 shows the BER versus power (dBm) at a 10-km feeder fiber length for 622 Mbps, 1 Gbps, and 2.5 Gbps. Figure 20 shows eye diagrams for 622 Mbps, 1 Gbps, and 2.5 Gbps at a power of 1 dBm and feeder fiber length of 10 km, with sampled BER values lower than 10^{-9}. Acceptable receiver performance is simply and visually illustrated by the clearly opened eyes, compared with the almost-closed eye shown in Fig. 16(c), which confirms the validity of our proposed approach.

VIII. Conclusion

A cost-effective and highly scalable LR-OAN can be developed using both an AWG and EDFA in one configuration and exploiting their characteristics. Incorporating an AWG achieves the objective of frequency reuse, which allows several OLTs to use the same frequency band because of the WCP of the AWG, which increases the utilization of the fiber plant and increases the efficiency. In addition, the FSRP of the AWG makes it possible to handle upstream and downstream traffic via the same input/output port. The periodic nature of the FSRP can be exploited to multiply the system capacity. Using an EDFA contributes to the cost effectiveness of the scheme because both the access and metro segments can be combined in one extended backhaul segment, making it possible to provide service with one trunk exchange rather than many central offices. In addition to its role in extending the reach and increasing the splitting ratio, the EDFA adds a new dimension in that it allows for a simpler and more evolved network in which service can be provided through 100-km backhaul fibers to 15 regions. Each region can provide service to up to five zones with different bitrates for each through feeder fiber used with either a multifiber or single-fiber approach. The simulation results indicate that transmission is possible by the proposed LR-OAN under the two different approaches (multifiber and single-fiber) based on the acceptable BER values obtained. Although the single-fiber approach offers a more cost-effective solution because service is provided to each zone through a common fiber, it imposes additional losses, which necessitates shortening the feeder fiber. The multifiber approach has an advantage over the single-fiber approach in that service can be provided at varying distances within one zone because a dedicated fiber is assigned for each bitrate. An EDFA with a flattened gain profile is required to ensure uniform DWDM signal amplification for both the upstream and downstream directions. A further extension of the flattened gain profile is required to ensure activation and exploitation of the FSRP to multiply the system capacity. To avoid network complexity associated with gain flattening implementation, wavelengths can be allocated according to the users' locations, for which the wavelengths with the highest power are assigned to the users located farthest away. Because each wavelength received refers to an individual OLT, self-upgrading can be performed using suitable filtering and simple reconnection without affecting the legacy system. However, a colorless ONU would be needed to accomplish this self-upgrading task.

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