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Dual-Fiber-Ring Architecture Supporting Discretionary Peer-to-Peer Intra-Communication and Bidirectional Inter-communication in Metro-Access Network

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ABSTRACT Direct communication among optical network units (ONUs) is very significant for next-generation optical networks. In this paper, a metro-access optical network architecture supporting intra-communication and inter-communication is proposed based on dual-fiber ring topology. By adopting two tunable fiber Bragg gratings and one arrayed waveguide grating in the remote node, direct peer-to-peer communication of ONUs can be achieved. By designing the architecture to provide inter-communication in two opposite transmission directions, not only the efficiency and flexibility of inter-communication can be guaranteed depending on the shortest transmission path, but also the inter-communication can be supported even if a dual-fiber fault occurs. By allocating three wavelengths to one ONU, not only the intra-communication and inter-communication for one ONU can be carried out simultaneously, but also the inter-communication for different ONUs can be realized simultaneously. By using a dual-fiber ring structure, both the scale and the reliability can be improved. Because the network capacity and scale are relatively large, the relative construction-and-maintenance cost of the network is low. The availability of the proposal can be verified via the performance analyses and the simulations.

INDEX TERMS Metro-access optical network, dual-fiber ring, intra-communication, inter-communication, wavelength division multiplexing.

I. INTRODUCTION

In metro-access optical network, convergence layer and access layer are integrated into a metro-access layer [1]. This progress can increase network capacity, reduce both construction and operation maintenance cost, and improve transmission efficiency. Therefore, metro-access optical network has been regarded as a prospective solution for next generation optical networks [2], [3].

With the continuous improvement of the transmission rate of optical communication, reliability and scale are very important for a network [4]–[6]. Because of the self-healing characteristic of ring structure, ring network has nature advantage in network reliability [7]. Although the number of fibers required in dual-fiber ring doubles that in single-fiber ring, the dual-fiber ring network can carry out the protection of multiple faults. Because dual-fiber ring network has simple protection mechanism, the recovery time of faults is relatively short [8]. In addition, by deploying optical amplifier in remote node (RN), the scale of ring network can be increased dramatically [9]. Therefore, owing to the prominent advantages in reliability and scale, dual-fiber ring network has been widely concerned.

On the other hand, in previous wavelength division multiplexed passive optical networks (WDM-PONs), direct communication of optical network units (ONUs) cannot be achieved. The communication information must be first propagated to central office (CO), next re-modulated, re-routed

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to target ONUs [10]. This will lead to increase transmission delay, congest at CO, and consume bandwidth of both downstream and upstream channels. Therefore, it is highly desirable for subscribers and operators to carry out direct communication of ONUs. In present, some schemes about direct communication of ONUs have been reported. Generally, they include three kinds: broadcast, virtual ring, and ONU ring. Chae *et al*. propose a simple structure to support direct communication of ONUs in time division multiplexed PON (TDM-PON) via employing fiber Bragg grating (FBG) in RN [11]. After the direct communication signals are reflected by the FBG, they will be broadcasted to entire ONUs via the power splitter in RN. Garg and Janyani propose a two stage flexible PON architecture to realize inter-communication of overall or subgroup ONUs [12]. In this architecture, power loss can be decreased and communication security can be improved. Tran *et al*. design a PON architecture via using a $N \times N$ coupler and $N - 1$ isolators in RN [13]. With the help of optical switch in ONU, downstream/upstream transmission and internetworking of ONUs can be supported depending on TDM technology. Based on a $1 \times N$ AWG followed by 50 GHz interleavers, Garg and Janyani propose an architecture to achieve simultaneous downstream/upstream transmission with ONU interconnection [14]. Manharbhai *et al*. report a flexible architecture to realize direct ONU internetworking via employing FBG array in RN [15]. All these schemes introduced above to realize direct communication of ONUs are broadcast manner. Tian *et al*. present an all-optical virtual private network (VPN) in a multiple PONs using ASK/FSK format [16]. But, it cannot support the discretionary direct communication of ONUs between two WDM-PONs. That is because the communication information is transmitted from source ONU to only one destination ONU of every WDM-PONs. This direct communication method can be considered as a semi-broadcast method. Based on code division multiplexed technique, the security can be improved via employing encoders and decoders in ONUs [17]. Nevertheless, this solution need additional encoders and decoders. Obviously, communication security is still the largest challenge for broadcast manner to be applied. For virtual ring manner, Zhou *et al*. employ $N + 1$ coarse wavelength division multiplexers (CWDMs) and a circulator with $N + 1$ ports in RN to support direct communication of ONUs [18]. Similarly, an optical VPN circulator device (OVCD) is designed by Deng *et al*. [19]. It can be used to realize direct communication between intra and inter-PON ONUs. With the help of wavelength routing property of arrayed waveguide grating (AWG), Feng *et al*. achieve the direct communication of ONUs via utilizing an AWG in RN [20]. About ONU ring manner, all ONUs are connected into a real ring to realize direct communication of ONUs [21]. In this proposal, the communication information of ONUs pass orderly all ONUs along the ring. In our recent research, the direct communication of ONUs focused on grid architecture is discussed [22].

Above all, the security of broadcast manner is the biggest challenge for its application. To virtual ring and ONU ring manners, the communication information of ONUs must get through all the ONUs between source ONU and destination ONU along the ring. The transmission process of communication information is similar to the process of a relay race. The discretionary peer-to-peer direct communication of ONUs cannot be realized. Therefore, the flexibility and efficiency of direct communication is reduced. In our latest research result, the flexibility and efficiency is still not advanced [23]. In addition, it can only support the direct communication among ONUs connected with same RN. Moreover, the existing schemes to support direct communication of ONUs are mainly based on star topology. The network scale and reliability has great limitation. On the contrary, for ring network, not only the network scale can be increased, but also the reliability can be improved greatly. However, the existing schemes based on ring topology to support direct communication of ONUs are rare [21], [23], [24]. In this article, we present a dual-fiber ring architecture. It can not only support the discretionary peer-to-peer intra-communication among ONUs connected at same RN, but also realize the bidirectional inter-communication among ONUs connected at different RN. Because the network capacity is relatively large, and the number of users can be supported by the network is numerous, the relative construction-and-maintenance cost of the network is low.

II. NETWORK ARCHITECTURE CONFIGURATION AND OPERATION PRINCIPLE

A. DUAL-FIBER RING ARCHITECTURE

The dual-fiber ring architecture is shown in Fig. 1. It is consisted of one CO and n RNs. Besides, each RN is connected with m ONUs. So, the network can accommodate $n \times m$ ONUs in total. It should be noted that not every RN must be connected with m ONUs. Actually, m is the maximum of ONUs

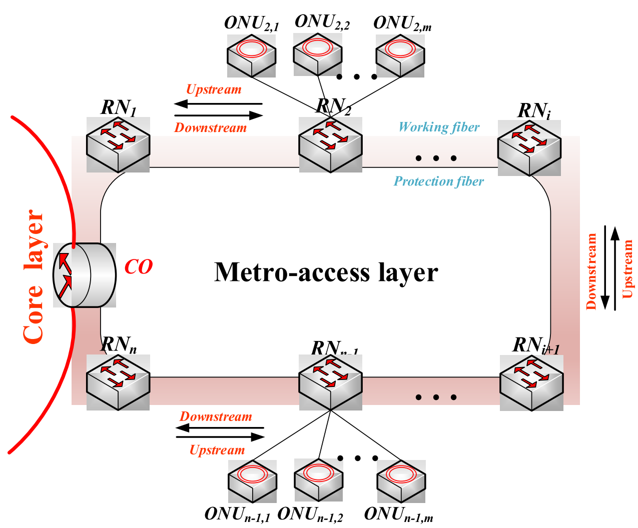

FIGURE 1. Schematic of dual-fiber ring architecture.

connected with a RN. It is mainly limited by the number of AWG's ports. When the number of ONUs connected with a RN is less than m, we only need to let several ports of AWG be idle. In the architecture, all RNs and CO are connected by a dual-fiber ring. The outer fiber is working fiber. The inner fiber is protection fiber. All the outer and inner fibers are called feeder fibers. Three kinds of signals are supported by the network, including downstream signals, upstream signals, and direct communication signals of ONUs. The direct communication signals of ONUs further include intra-communication signals among ONUs connected at same RN and inter-communication signals among ONUs connected at different RNs.

B. OPERATION PRINCIPLE OF DOWNSTREAM AND UPSTREAM SIGNALS

When the network works in normal mode, the downstream and upstream signals are transmitted in working fiber along clockwise and anticlockwise directions, respectively. The schematic of CO is depicted in Fig. 2. The CO is consisted of $n \times m$ transmitters (Tx), $n \times m$ receivers (Rx), one wavelength division multiplexer (MUX), one wavelength division de-multiplexer (DEMUX), one splitter, three couplers, two circulators, two CWDMs, two isolators, one erbium-doped fiber amplifier (EDFA), and three optical switches (OSs).

The wavelength allocation scheme of the network is depicted in Fig. 3. In this scheme, $n \times m$ wavelengths ($\lambda_1^1 \ldots \lambda_n^m$) locating in red band are used to transmit downstream and upstream signals. $n \times m$ wavelengths ($\lambda_{a1}^1 \ldots \lambda_{an}^m$) locating in blue band are used to transmit intra-communication signals. Besides, $n \times m$ wavelengths ($\lambda_{e1}^1 \ldots \lambda_{en}^m$) locating in blue band are used to transmit inter-communication signals. Actually, because the inter-communication signals are only transmitted within a WDM-PON, the wavelengths allocated to inter-communication can be reused by different WDM-PON. The intra-communication signals are also transmitted only between ONUs connected at one RN, the wavelengths allocated to intra-communication can also be reused by intra-communication between ONUs connected at different RNs. At the moment, the wavelength spacing of $\lambda_{a1}^1$and$\lambda_{e1}^1$is one free spectral range (FSR). But, for the convenience of description, we assign different wavelengths for intra-communication under different RNs. Therefore, for the ONU_i^j connected to RN_i, three wavelengths are allocated to it, i.e., λ_i^j, λ_{ai}^j, andλ_{ei}^j. The wavelength spacing of the three wavelengths is n FSRs of the AWG adopted in RN.

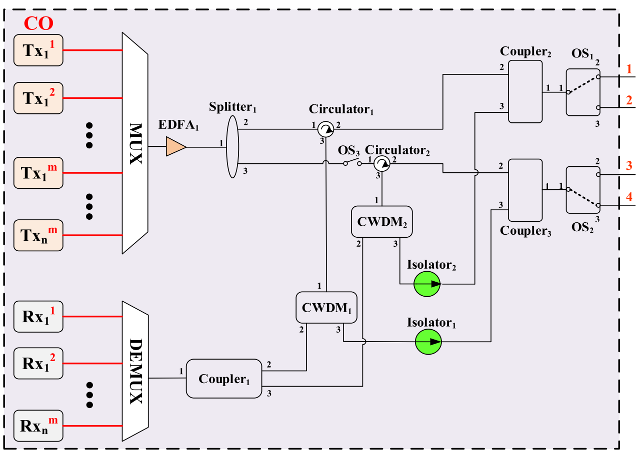

FIGURE 2. Schematic of CO.

In CO, all the transmitters adopt differential phase-shift keying (DPSK) modulation format to carry downstream signals. After the $n \times m$ downstream wavelength signals are multiplexed by the MUX, they will be amplified by the $EDFA_1$. Then, the signals are split into two parts by the $splitter_1$. The signals outputted from port 3 of the $splitter_1$ are used for fault protection. The signals outputted from port 2 of the $splitter_1$ pass the $circulator_1$, $coupler_2$, and OS_1 orderly. For OS_1, the port 1 is connected with port 2. Thus, the downstream signals will propagate to RN_1 from the CO along the outer fiber.

The schematic of RN is described in Fig. 4. The RN is consisted of four optical switches, one splitter, one wavelength blocker (WB), three circulators, three couplers, one CWDM, two tunable FBGs, one AWG, and one bidirectional EDFA. Of course, the bidirectional EDFA is not necessary for all RNs.

Here, we take the RN_i as an example to explain the operation principle. When the downstream signals enter into RN from port 1 of the RN, they will go through the OS_1 and OS_3 and, next, to the splitter. The downstream signals outputted from port 3 of the splitter will reach to the WB. Here, the WB is used to block the downstream wavelengths ($\lambda_i^1, \lambda_i^2 \ldots \lambda_i^m$) and inter-communication wavelengths ($\lambda_{ei}^1, \lambda_{ei}^2 \ldots \lambda_{ei}^m$) dropped by the ONUs connected to RN_i. Then, the rest wavelength signals will pass through the $coupler_2$, $circulator_3$, OS_3 to the bidirectional EDFA. After these signals are amplified by the bidirectional EDFA, they will get through the OS_2. Finally, they are outputted from port 3 of RN_i and transmitted to RN_{i+1} through the working fiber. On the other hand, the downstream wavelength signals outputted from port 2 of the splitter will orderly pass the $circulator_1$, $coupler_1$, $circulator_2$ to an AWG. Then, the wavelength signals ($\lambda_i^1, \lambda_i^2 \ldots \lambda_i^m$) will be de-multiplexed by the AWG and, next, propagated to target ONUs through the distribution fibers between the RN_i and ONUs. Meanwhile, the other downstream wavelength signals ($\lambda_{i+1}^1, \lambda_{i+1}^2 \ldots \lambda_n^m$) will be abandoned by the AWG.

The schematic of ONU is depicted in Fig. 5. In the figure, ONU is composed of one CWDM, one splitter, two circulators, three optical receivers, one reflective semiconductor optical amplifier (RSOA), and two tunable optical transmitters. Here, the Tx_1 and the Rx_1 are used for transmitting and receiving intra-communication signals, respectively. The Tx_2 and the Rx_2 are used for transmitting and receiving inter-communication signals, respectively.

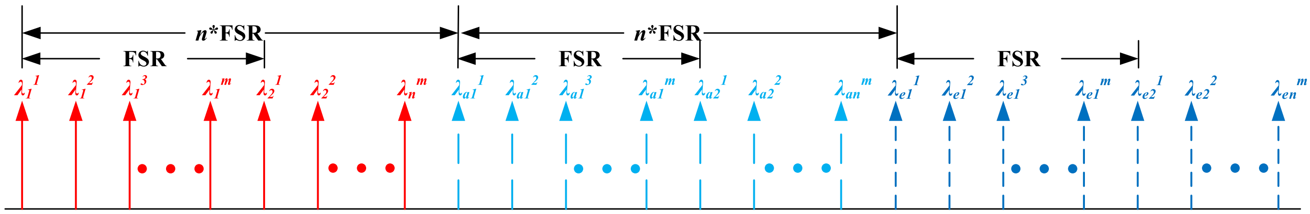

FIGURE 3. Wavelength allocation scheme of the network.

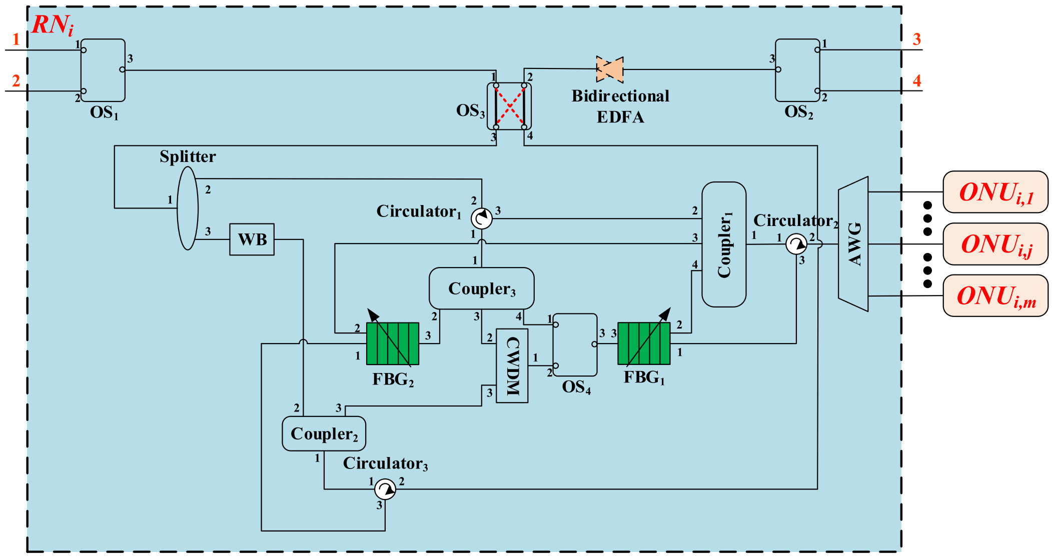

FIGURE 4. Schematic of RN.

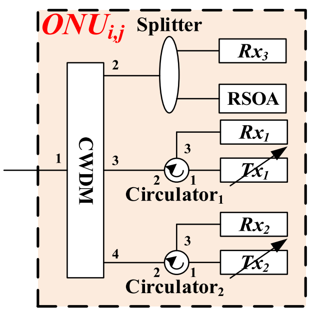

FIGURE 5. Schematic of ONU.

Because the three wavelengths of an ONU locate in different wavelength bands, they can be separated by a CWDM and outputted from different ports of CWDM. When the downstream signals enter into the ONU, we assume that they will be outputted from the CWDM's port 2. Specially, to $ONU_{i,j}$, λ_i^j will be outputted from the CWDM's port 2. Then, the downstream signals will be split two parts by the splitter. One part enters into the receiver, the other part is propagated to a RSOA and re-modulated as upstream signals.

After the upstream signals output from the RSOA, they will pass the splitter and CWDM orderly. Then, these upstream signals will be transmitted to RN_i through the distribution fiber between the $ONU_{i,j}$ and RN_i. In RN_i, these upstream wavelength signals go through the AWG and circulator$_2$ and, next, to the tunable FBG$_1$. Because the Bragg wavelength of the FBG$_1$ is not the upstream wavelength, the upstream wavelength signals will be propagated to the OS$_4$. For OS$_4$, if the port 3 is connected to the port 1, the upstream signals will be transmitted to the port 4 of the coupler$_3$ directly. If the port 3 of the OS$_4$ is connected with the port 2 of the OS$_4$, the upstream wavelength signals will be propagated to the CWDM firstly. Because the upstream wavelength signals locate in red band, they will be outputted from the CWDM's port 2. Then, they are transmitted to the port 3 of the coupler$_3$. In addition, the upstream signals of the ONUs connected with RN_{i+1} to RN_n will be inputted from the port 2 of the coupler$_3$. Actually, some inter-communication signals might be inputted from the port 2 of the coupler$_3$ simultaneously. All these signals will be coupled by the coupler$_3$. After that, these signals pass the circulator$_1$, splitter, OS$_3$, and OS$_1$ successively. After they are outputted from the port 1 of the RN_i, they will be propagated to RN_{i-1} along the outer fiber. At last, all these upstream wavelength signals will enter into the CO.

In the CO, the upstream signals get through the OS$_1$ to the coupler$_2$. To the coupler$_2$, the upstream signals outputted from port 3 are insulated by the isolator$_2$.

Moreover, the upstream signals outputted from port 2 pass the circulator$_1$ to the CWDM$_1$. After they are outputted from the CWDM$_1$'s port 2, they will get through the coupler$_1$. At last, the upstream signals will be de-multiplexed by the DEMUX and received by respective receivers.

The maximum of ONUs connected with a RN is m. When the number of ONUs connected with a RN is less than m, and new ONU wants to connect to network, the new ONU only needs to be connected to the idle ports of AWG. The rest of operation required is to reconfigure the network via network management system. By this manner, online expansion can even be realized. Of course, when the network wants to expand a new RN, the idle wavelengths between $\lambda_n^m$and λ_{a1}^1, the idle wavelengths between $\lambda_{an}^m$and λ_{e1}^1, and the idle wavelengths after λ_{en}^m will be assigned to the new RN. The previous wavelength allocation schemes will be unchanged. After the new RN is connected to the network, the rest of operation required is also to reconfigure the network via network management system.

C. THE DIRECT COMMUNICATION OF ONUS

In our proposal, the network cannot merely carry out the direct communication among ONUs connected at one RN, but also achieve the direct communication among ONUs connected at different RN.

1) THE INTRA-COMMUNICATION OF ONUS

When the $ONU_{i,j}$ wants to communicate with $ONU_{i,k}$, the tunable transmitter Tx$_1$ generates the intra-communication signals carried by wavelengthλ_{ai}^k. Then, the intra-communication signals get through the circulator$_1$ and CWDM. After they are outputted from the $ONU_{i,j}$, the intra-communication signals will be propagated to the RN_i through the distribution fiber. In RN_i, the intra-communication signals pass the AWG, circulator$_2$ to the FBG$_1$. By setting the Bragg wavelength of the FBG$_1$ as λ_{ai}^k, the intra-communication signals will be reflected by the FBG$_1$ and transmitted to the coupler$_1$. Next, they will get through the circulator$_2$ and AWG. Because the wavelength spacing of λ_{ai}^k and λ_i^k is n FSRs, the intra-communication signals λ_{ai}^k will also be outputted from the k-th port of the AWG. Then, the intra-communication signals will be propagated to the $ONU_{i,k}$ from the RN_i. In the $ONU_{i,k}$, the intra-communication signals will get through the CWDM, circulator$_1$ and reach to the Rx$_1$. Finally, they will be received by the Rx$_1$. Surely, when the number of ONUs wanted to communicate with the $ONU_{i,k}$ is more than one, the intra-communication can be achieved by TDM manner. All in all, when one source $ONU_{i,j}$ wants to communicate with another target $ONU_{i,k}$, the intra-communication signals must be carried by the wavelength λ_{ai}^k. The Bragg wavelength of the FBG$_1$ should also be adjusted to the same wavelengthλ_{ai}^k. With the help of the AWG and tunable FBG$_1$ in RN, the peer-to-peer direct intra-communication among arbitrary ONUs can be achieved.

2) THE INTER-COMMUNICATION OF ONUS

If the $ONU_{i,j}$ wants to communicate with $ONU_{r,s}$ ($1 \le r \le n$and$1 \le s \le m$), the tunable transmitter Tx$_2$ in the $ONU_{i,j}$ generates the inter-communication signals carried by wavelength λ_{er}^s. After the inter-communication signals get through the same path as the intra-communication signals pass, they will reach to the FBG$_1$ in the RN_i. If the Bragg wavelength of the FBG$_1$ is inconsistent with λ_{er}^s, the inter-communication signals will be outputted from the FBG$_1$'s port 3. Then, they will be transmitted to the OS$_4$. In order to transmit the inter-communication signals to destination ONU along the shortest path, the transmission direction of the inter-communication signals is designed to be alterable.

When $r > i$ and $r - i < n + 1 - (r - i)$, the inter-communication signals will be transmitted to $ONU_{r,s}$ from $ONU_{i,j}$ along clockwise direction. The holistic transmission path of the signal is: $RN_i \rightarrow RN_{i+1} \rightarrow \ldots \rightarrow RN_r$. Thus, to the OS$_4$ in RN_i, the port 3 connects to port 2. Because the wavelength λ_{er}^s is in blue band, the inter-communication signals will be outputted by the CWDM's port 3. Then, they will pass in order through the coupler$_2$, circulator$_3$, OS$_3$, bidirectional EDFA, and OS$_2$. Finally, the inter-communication signals will be outputted by port 3 of the RN_i and transmitted to the RN_{i+1}. In the RN_{i+1}, the transmission path of the inter-communication signals is: $OS_1 \rightarrow OS_3 \rightarrow Splitter \rightarrow WB \rightarrow Coupler_2 \rightarrow Circulator_3 \rightarrow OS_3 \rightarrow Bidirectional\ EDFA \rightarrow OS_2$. At last, the inter-communication signals will be transmitted to the RN_r. In RN_r, they orderly pass the OS$_1$, OS$_3$, splitter, circulator$_1$, coupler$_1$, circulator$_2$ to the AWG. Because the wavelength spacing of λ_{er}^s and λ_{ar}^s is n FSRs, the inter-communication signals λ_{er}^s will also be outputted through the s-th port of the AWG.

When $r > i$ and $r - i > n + 1 - (r - i)$, the inter-communication signals will be transmitted to $ONU_{r,s}$ from $ONU_{i,j}$ along anticlockwise direction. The holistic transmission path of the signal is: $RN_i \rightarrow RN_{i-1} \rightarrow \ldots \rightarrow RN_1 \rightarrow CO \rightarrow RN_n \rightarrow \ldots \rightarrow RN_{r+1} \rightarrow RN_r$. Therefore, to the OS$_4$ in RN_i, the port 3 is connected to port 1. Next, the transport route of the inter-communication signals inRN_i is: $Coupler_3 \rightarrow Circulator_1 \rightarrow Splitter \rightarrow OS_3 \rightarrow OS_1$. After they are outputted by the port 1 of the RN_i, they will be propagated to RN_{i-1}. In RN_{i-1}, the transmission path of the inter-communication signals is same with that of the upstream signals, i.e., $OS_2 \rightarrow Bidirectional\ EDFA \rightarrow OS_3 \rightarrow Circulator_3 \rightarrow FBG_2 \rightarrow Coupler_3 \rightarrow Circulator_1 \rightarrow Splitter \rightarrow OS_3 \rightarrow OS_1$. When the inter-communication signals and the upstream signals are inputted to CO through the port 1, they will pass OS$_1$, coupler$_2$, circulator$_1$ to CWDM$_1$. Because the inter-communication wavelength and the upstream wavelength are in blue band and red band correspondingly, the inter-communication signals and upstream signals will be separated by the CWDM$_1$. The inter-communication signals will be outputted from the CWDM$_1$'s port 3. Then, they get through the isolator$_1$, coupler$_3$, and OS$_2$ orderly. After they are outputted from the CO, they will be transmitted to RN_n. In RN_r, the transmission path of the inter-communication signals is: $OS_2 \rightarrow Bidirectional\ EDFA \rightarrow OS_3 \rightarrow Circulator_3 \rightarrow FBG_2 \rightarrow Coupler_1 \rightarrow Circulator_2 \rightarrow AWG$.

When $r < i$ and $i - r < n + 1 - (i - r)$, the inter-communication signals will be transmitted to $ONU_{r,s}$ from $ONU_{i,j}$ along anticlockwise direction. The holistic transmission path of the signal is: $RN_i \rightarrow RN_{i-1} \rightarrow \ldots \rightarrow RN_{r+1} \rightarrow RN_r$. Hence, to the OS_4 in RN_i, the port 3 connects to port 1. Next, the transport route of the inter-communication signals in RN_i is: $Coupler_3 \rightarrow Circulator_1 \rightarrow Splitter \rightarrow OS_3 \rightarrow OS_1$. In RN_r, the transmission path of the inter-communication signals is: $OS_2 \rightarrow BidirectionalEDFA \rightarrow OS_3 \rightarrow Circulator_3 \rightarrow FBG_2 \rightarrow Coupler_1 \rightarrow Circulator_2 \rightarrow AWG$.

When $r < i$ and $i - r > n + 1 - (i - r)$, the inter-communication signals will be transmitted to $ONU_{r,s}$ from $ONU_{i,j}$ along clockwise direction. The holistic transmission path of the signal is: $RN_i \rightarrow RN_{i+1} \rightarrow \ldots \rightarrow RN_n \rightarrow CO \rightarrow RN_1 \rightarrow \ldots \rightarrow RN_{r-1} \rightarrow RN_r$. Consequently, to the OS_4 in RN_i, the port 3 connects to port 2. Then, the transport route of the inter-communication signals in RN_i is: $CWDM \rightarrow Coupler_2 \rightarrow Circulator_3 \rightarrow OS_3 \rightarrow BidirectionalEDFA \rightarrow OS_2$. When the inter-communication signals enter into the CO, the transmission path is: $OS_2 \rightarrow Coupler_3 \rightarrow Circulator_2 \rightarrow CWDM_2 \rightarrow Isolator_2 \rightarrow Coupler_2 \rightarrow OS_1$. In RN_r, the transmission path of the inter-communication signals is: $OS_1 \rightarrow OS_3 \rightarrow Splitter \rightarrow Circulator_1 \rightarrow Coupler_1 \rightarrow Circulator_2 \rightarrow AWG$.

After the inter-communication signals λ_{er}^{s} are outputted from the RN_r, they will be propagated to $ONU_{r,s}$ through distribution fiber. In $ONU_{r,s}$, these inter-communication signals are outputted from port 4 of CWDM firstly. After getting through the circulator$_2$, the inter-communication signals will be received via Rx_2. Above all, our proposed architecture can support bidirectional inter-communication.

III. PROTECTION MECHANISM

A. SINGLE-FIBER FAULT PROTECTION

If the outer-fiber between RN_i and RN_{i+1} fails (as shown in the I place in Fig. 6), the OS_2 in RN_i need to be switched.

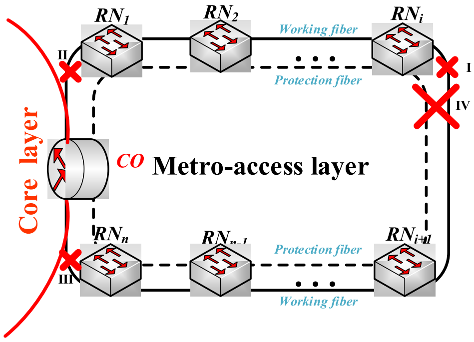

FIGURE 6. The locations of faults.

The port 3 should be connected with port 2. Besides, to the OS_1 in RN_{i+1}, the port 2 will be connected with port 3. By means of transferring the services to the protection fiber, normal communication can be restored. Similarly, when the working fibers between CO and RN break down (as shown in the II and III place in Fig. 6), the corresponding optical switch (OS_1 and OS_2) in CO need to be switched to realize fault protection. In addition, even if multiple single-fiber faults occur simultaneously, normal communication can still be restored.

B. DULE-FIBER FAULT PROTECTION

If a fault occurs on the dual-fiber between RN_i and RN_{i+1} (as shown in the IV place in Fig. 6), the network will work in protection mode. In CO, the OS_3 should be closed. The dual-fiber ring is divided into upper and lower branches. Besides, all the OS_3 in RN_{i+1} to RN_n should be shifted from parallel status to cross status. By this way, the downstream and upstream signals of $ONU_{i+1,1}$ to $ONU_{n,m}$ can be restored. The dual-fiber fault in the IV place has no effect on the downstream and upstream signals of $ONU_{1,1}$ to $ONU_{i,m}$. In addition, the protection switch can be finished without disturbing the normal work of $ONU_{1,1}$ to $ONU_{i,m}$. More importantly, the inter-communication will not be interrupted during dual-fiber fault protection because the inter-communication can be realized via two transmission directions.

Above all, when the working fiber fault occurs, we only need to switch related optical-switch from one port to another port. There is signals in only one fiber at any time. The protection mechanism is simple. Complicated operation for protection switching is not required. Therefore, energy consumption of protection switching will also be saved.

IV. NETWORK PERFORMANCE ANALYSES

A. NETWORK SCALE ANALYSIS

Link loss is a limiting factor for network scale. According to the operating principle of the network, the loss is maximal when the ONUs connected to RN_n work in normal mode. We define L as representing the link loss of the ONUs connected to RN_m in normal work mode. P_T, G_1, G_2, L_M and P_r indicate the output power of transmitter, the gain of $EDFA_1$ in the CO, the gain of bidirectional EDFA in the RN, the power redundancy of system and the receiver sensitivity, respectively; d_1 denotes the fiber length between adjacent RNs, CO and RN; and d_2 represents the fiber length between RN and ONU. We assume $d_1 = 5km, d_2 = 2km$. The insertion loss and representing symbol of optical components is shown in Table 1. Thus,

$$L = n \times \left(d_1 \times \alpha_F + 4L_{OS} + L_{Sp} + L_{WB} + L_{Cpl} + L_{Cir}\right) + 2L_{AWG} + 2L_{Sp} + 2L_{Cir} + L_{Cpl} + L_{CWDM} + d_2 \times \alpha_F - L_{WB} - L_{OS}. \quad (1)$$

According to the Table 1, we can get

$$L = 10.9 + 10n. \quad (2)$$

TABLE 1. Insertion loss of optical components.

Component	Symbol	Insertion Loss (dB)	References
AWG	L_{AWG}	3	[25]
Splitter	L_{Sp}	3	[26]
Circulator	L_{Cir}	0.5	[25]
Coupler	L_{Cpl}	0.5	[9]
CWDM	L_{CWDM}	0.5	[27]
Optical switch	L_{OS}	0.5	[25]
WB	L_{WB}	3	[28]
Fiber	α_F	0.2 dB/km	[9]

The power budget of downstream signals must meet the following inequality:

$$P_T + G_1 - L - L_M \geq P_r. \tag{3}$$

Here, assume $L_M = 5$dB, and $P_r = -30$dBm. After substituting (2) into (3), we can get

$$n \leq (P_T + G_1 + 14.1)/10. \tag{4}$$

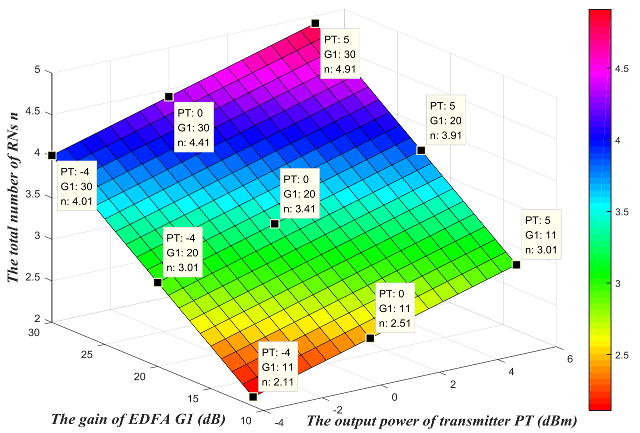

FIGURE 7. Relations among P_T, G_1, and n.

The relations among P_T, G_1, and n are shown in Fig. 7. From the figure, with the increase of P_T or G_1, $n$will increase linearly. Please pay attention to the $n$shown in Fig. 7. It is only a theoretical value. In order to guarantee the required power of receiver, the $n$need to be rounded down in engineering applications, i.e., $\lfloor n \rfloor$. For instance, when $P_T = 0$ and $G_1 = 30$, $n = 4.41$. So, $\lfloor n \rfloor = 4$. It means that the network can still support four RNs even though no EDFA is employed in RN. At present, the number of ports that one AWG can support is 128 [23]. Hence, the network can accommodate a total of $128 \times 4 = 512$ ONUs. In case of more ONUs want to be contained, EDFA has to be adopted in RN. Of course, EDFA is not necessary for every RN. According to analysis, the downstream signals will suffer 10dB power loss when they pass through one RN. Thus, if $G_2 = 30dB$, the network will support three more RNs when one bidirectional EDFA employs in a RN.

Because three sets of transceivers are required in the ONU, and the structures of CO and RN are also a little complicated, the absolute construction cost of the network is a little high. However, because the network capacity is relatively large, and the number of users can be supported by the network is numerous, the relative construction-and-maintenance cost of the network is low. That is because the cost is shared by all subscribers. Furthermore, with the maturity of manufacturing technique and the improvement of integration technology, the cost of devices and components will decrease. Above all, the proposed architecture is cost-effective for next generation networks.

B. NETWORK RELIABILITY ANALYSIS

Reliability is very important for us to design a network architecture. In the succeeding texts, we mainly discuss the failure situation caused by internal factor. It is limited by the service time and manufacture of optical components. For conventional optical components, the representing symbol and unreliability data is shown in Table 2. Here, U denotes the network unreliability for ONUs connected with RN_i.U_{CO} indicates the unreliability of the CO. U_{CO-RN_i} and U'_{CO-RN_i} represent the unreliability of the parts from CO to RN_i along clockwise direction and anticlockwise direction, correspondingly. U_{RN_i-ONU} denotes the unreliability of the part from RN_i to ONU.

TABLE 2. Unreliability data of conventional optical components.

Component	Symbol	Unreliability (Failure/10^9 h)	References
OLT	U_{OLT}	5.12×10^{-7}	[9]
EDFA	U_{EDFA}	4×10^{-7}	[25]
Splitter	U_{Sp}	4×10^{-8}	[9]
Circulator	U_{Cir}	2×10^{-7}	[9]
Coupler	U_{Cpl}	4×10^{-8}	[9]
Optical switch	U_{OS}	4×10^{-7}	[25]
WB	U_{WB}	1.2×10^{-6}	[29]
AWG	U_{AWG}	4.8×10^{-6}	[25]
ONU	U_{ONU}	5.12×10^{-7}	[9]
Fiber	U_F	2.4×10^{-7} / km	[9]

So, the unreliability$U$ is

$$U = U_{CO} + U_{CO-RN_i} \times U'_{CO-RN_i} + U_{RN_i-ONU}, \tag{5}$$

whereas

$$U_{CO} = U_{OLT} + U_{EDFA} + U_{Sp}, \quad (6)$$

$$U_{CO-RN_i} = \left[(d_1 \times U_F)^2 + 4U_{OS} + U_{Sp} + U_{WB} + U_{Cpl} + U_{Cir}\right] \times (i-1) + U_{Cir} + U_{Cpl} + U_{OS} + (d_1 \times U_F)^2 + 2U_{OS}, \quad (7)$$

$$U'_{CO-RN_i} = \left[(d_1 \times U_F)^2 + 4U_{OS} + U_{Sp} + U_{WB} + U_{Cpl} + U_{Cir}\right] \times (n-i) + 2U_{OS} + U_{Cir} + U_{Cpl} + (d_1 \times U_F)^2 + 2U_{OS}, \quad (8)$$

$$U_{RN_i-ONU} = 2U_{Sp} + 2U_{Cir} + U_{Cpl} + U_{AWG} + d_2 \times U_F + U_{ONU}. \quad (9)$$

The network reliability A is

$$A = 1 - U. \quad (10)$$

According to the Table 2, we can get

$$A = 1 - 7.264 \times 10^{-6} - 10^{-12} \times (3.08 \times i - 1.64) \times [1.84 + 3.08 \times (n-i)]. \quad (11)$$

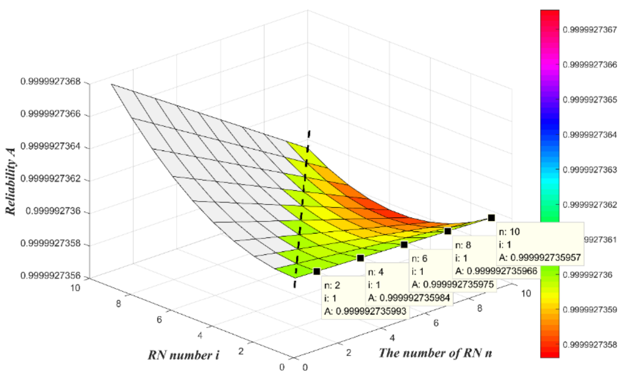

FIGURE 8. Relations among A, n, and i.

Figure 8 further shows the relations among A, n, and i. From the figure, we can see that the relation between A and n is linear. The relation between A and i is nonlinear. Of course, since i and n must satisfy $i \leq n$ according to actual application conditions, the gray portion located on the upper-left of the dotted line in the figure is meaningless. Most importantly, for ONUs connected with any RN, the network reliability is more than 99.999%. Besides, even if the number of RN increases greatly, the reliability decreases tardily. This means that the proposed architecture can satisfy the reliability requirement of telecommunication operator, i.e., five "9".

C. PERFORMANCE COMPARISONS

So as to highlight the superiority of our proposal, the performance of our proposal and the performance of existing schemes are compared. Table 3 shows the comparison results. According to the table, the superiority of our proposal are prominent. Firstly, because the architectures in this paper and [23] adopt dual-fiber ring topology, even if multiple single-fiber faults occur simultaneously, normal communication can still be restored. On the contrary, the architectures in [11] and [20] do not have the ability on fault protection. Secondly, because the networks in [11] and [20] are based on star topology, they can only support one RN regardless of how parameters about the networks are changed. Their network scale is constant. In [23], the network can accommodate up to three RNs when $G = 30$ and $P_T = 0$. Whereas, our proposal can still contain four RNs even though no EDFA is employed in RN. More importantly, this network can be expanded because of ring topology. Thirdly, all these schemes can realize intra-communication. Nevertheless, the means to support intra-communication is broadcast manner in [11]. In spite of the communication security can be improved via adopting two stage RN or employing encoders and decoders in ONUs, numerous additional FBGs, encoders and decoders are required. Thus, the cost of construction and maintenance increases tremendously. Moreover, due to broadcast manner, serious crosstalk may be occur between different intra-communication signals. In [20] and [23], authors use virtual ring and ONU ring manner to support intra-communication. The communication information of ONUs must get through all the ONUs between source ONU and destination ONU along the ring. The transmission process of communication information is similar to the process of a relay race. The discretionary peer-to-peer direct communication of ONUs cannot be realized. Therefore, the flexibility and efficiency of direct communication is reduced. On the contrary, our proposal can finish the discretionary peer-to-peer intra-communication among ONUs connected at same RN. Furthermore, it can also accomplish bidirectional inter-communication among ONUs connected at different RN. Above all, the solution proposed in this paper to support direct communication of ONUs performs better than existing schemes in terms of security, efficiency, and flexibility.

TABLE 3. Performance comparisons.

Comparison Index	Architecture in this paper	Broadcast [11]	Virtual ring [20]	ONU ring [23]
Reliability	Good	Bad	Bad	Good
Network scale	Large	Small	Small	Large
Intra-communication	Good	Weak	Weak	Weak
Inter-communication	Good	No	No	No

V. SIMULATION ANALYSIS

With the help of OptiSystem 13.0 (Optiwave, Ottawa, Canada), we finished a simulation. Figure 9 depicts the simulation setup. Two RNs and three ONUs are simulated.

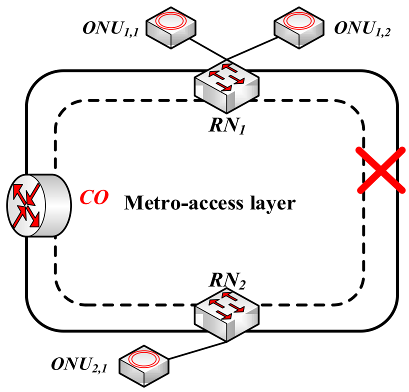

FIGURE 9. Simulation setup of the proposed architecture.

The transmitters in CO and ONUs are directly modulated lasers operating at 10 Gbps with $2^7 - 1$ pseudorandom binary sequence (PRBS) non-return-to-zero (NRZ) data. Three wavelengths 193.1 THz, 193.2 THz, and 193.3 THz are allocated to ONU_{11}, ONU_{12}, andONU_{21} for carrying downstream and upstream signals, correspondingly. 195.1 THz is used to carry intra-communication signals from ONU_{11} to ONU_{12}. 195.2 THz is used to carry inter-communication signals from ONU_{11} to ONU_{21}. In CO, the EDFA's gain is 25 dB. The fiber length between CO and RN (or between two RNs) is 5 km. The length of fiber between RN and ONU is 2 km. In ONU, upstream wavelength is modulated at 2.5 Gbps with NRZ data. Here, only the situation of dual-fiber fault is simulated. That is because in the case of single-fiber fault protection, the transmission route of signals will not be changed. Hence, the protection switching will not affect the transmission performance of signals.

In normal work mode and protection mode, the bit-error ratio (BER) curves of downstream and upstream signals are depicted in Fig. 10. According to the figure, the downstream signals of ONU_{11} perform best. In normal work mode, the downstream signals of ONU_{21} are transmitted along clockwise direction. They have to go through RN_1 to RN_2. Undoubtedly, they must pass more optical components and bear more crosstalk, noise, link loss, and other impairments. When the network work in protection mode, the dual-fiber ring is split into upper and lower branches. So, the downstream signals of ONU_{21} are directly transmitted from CO to RN_2 along anticlockwise direction. The downstream signals' transport route of ONU_{21} in protection mode is similar to that of ONU_{11} in normal mode. In addition, because the downstream signals of ONU_{21} need to get through the OS_3 in the CO, the downstream signals of ONU_{11} in normal work mode perform slightly better than the downstream signals of ONU_{21} in protection mode. For the upstream signals, they are produced via RSOA re-modulation. They also are transmitted more distance. It is undoubtable to suffer more impairment and noise. According to the simulation results of all downstream and upstream signals, an acceptable performance ($\mathrm{BER} < 10^{-9}$) can be acquired.

For ONU_{21}, the performance of downstream signals in protection mode is better than that in normal mode. Readers may ask why protection mode is not used directly. That is because only one transmission direction of inter-communication can be supported by the network when the dual-fiber ring is split into two branches.

The BER curves of intra-communication and inter-communication signals are depicted in Fig. 11. Apparently, the intra-communication signals perform best. They get through the minimum number of optical components. Therefore, they will introduce less crosstalk, noise, link loss, and other impairments. Receiver sensitivity indicates the minimum signal strength that the receiver can receive and still work properly. If $\mathrm{BER}=10^{-9}$ is the lowest requirement to receive, the receiver sensitivity of the intra-communication from ONU_{11} to ONU_{12} is -22.1 dBm. For the inter-communication signals from ONU_{11} to ONU_{21} along clockwise direction, they are transmitted from RN_1 to

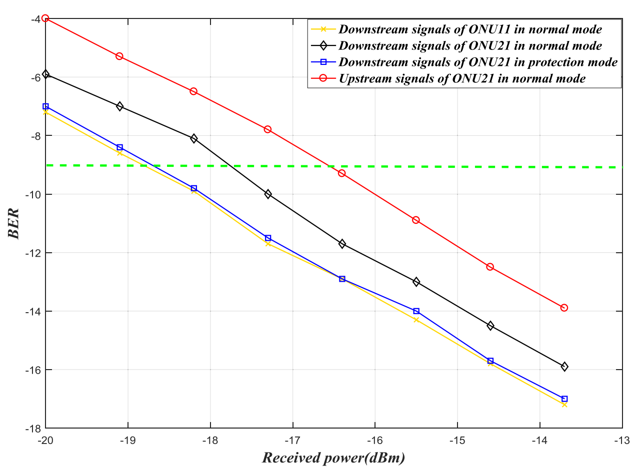

FIGURE 10. BER curves of downstream and upstream signals in normal and protection modes.

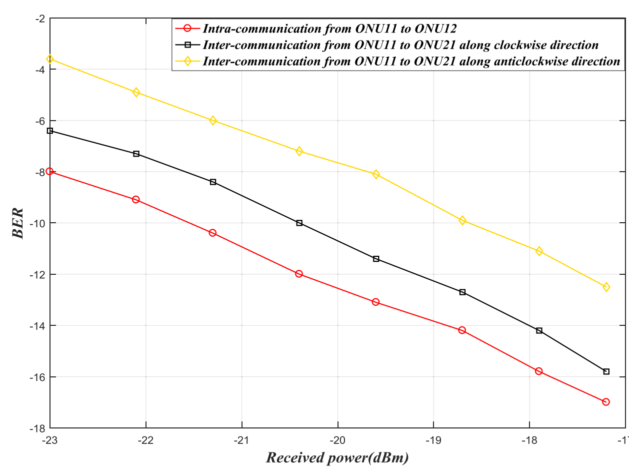

FIGURE 11. BER curves of intra-communication and inter-communication signals.

RN_2 directly. The receiver sensitivity is −21 dBm. However, for the inter-communication signals from ONU_{11} to ONU_{21} along anticlockwise direction, they are transmitted from RN_1 to CO firstly. Then, they will be transmitted from the CO to RN_2. They must pass more optical components. Thus, the inter-communication signals from ONU_{11} to ONU_{21} along anticlockwise direction perform worst. The corresponding receiver sensitivity is −19.2 dBm.

VI. CONCLUSION

A metro-access dual-fiber ring architecture supporting intra-communication and inter-communication is proposed. The network architecture can achieve discretionary peer-to-peer direct communication of ONUs by employing two tunable FBGs and one AWG in a RN. Based on bidirectional inter-communication, not only the efficiency and flexibility of inter-communication can be guaranteed depending on the shortest transmission path, but also the inter-communication can be supported even if a dual-fiber fault occurs. In addition, we allocate three wavelengths to one ONU, not only the intra-communication and inter-communication for one ONU can be carried out simultaneously, but also the inter-communication for different ONUs can be realized simultaneously. Besides, by means of dual-fiber ring topology, not only the network scale can be increased, but also the reliability can be improved greatly. Even though no EDFA is employed in RN, the network can still support 512 ONUs. For ONUs connected with any RN, the network reliability is more than 99.999%. The proposed architecture can satisfy the reliability requirement of telecommunication operator, i.e., five "9". Because the network capacity is relatively large, and the number of users can be supported by the network is numerous, the relative construction-and-maintenance cost of the network is low. According to the performance comparisons, the solution proposed in this paper to support direct communication of ONUs performs better than existing schemes in terms of security, efficiency, and flexibility.

REFERENCES

[1] C. Zhang *et al.*, "Metro-access integrated network based on optical OFDMA with dynamic sub-carrier allocation and power distribution," *Opt. Express*, vol. 21, no. 2, pp. 2474–2479, Jan. 2013. doi: 10.1364/OE.21.002474.

[2] Y. Luo *et al.*, "Time- and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2)," *J. Lightw. Technol.*, vol. 31, no. 4, pp. 587–593, Feb. 15, 2013. doi: 10.1109/JLT.2012.2215841.

[3] T. Kuri, H. Harai, N. Wada, T. Kawanishi, and M. Hosokawa, "Adaptable access system: Pursuit of ideal future access system architecture," *IEEE Netw.*, vol. 26, no. 2, pp. 42–48, Mar./Apr. 2012. doi: 10.1109/MNET.2012.6172274.

[4] N. Cheng *et al.*, "Flexible TWDM PON system with pluggable optical transceiver modules," *Opt. Express*, vol. 22, no. 2, pp. 2078–2091, Jan. 2014. doi: 10.1364/OE.22.002078.

[5] F. J. Effenberger, "PON resilience," *J. Opt. Commun. Netw.*, vol. 7, no. 3, pp. A547–A552, Mar. 2015. doi: 10.1364/JOCN.7.00A547.

[6] P. Chanclou, A. Cui, F. Geilhardt, H. Nakamura, and D. Nesset, "Network operator requirements for the next generation of optical access networks," *IEEE Netw.*, vol. 26, no. 2, pp. 8–14, Mar./Apr. 2012. doi: 10.1109/MNET.2012.6172269.

[7] K. Gou, C. Gan, X. Zhang, and Y. Zhang, "A tangent-ring optical TWDM-MAN enabling three-level transregional reconfigurations and shared protections by multipoint distributed control," *Opt. Commun.*, vol. 410, pp. 855–862, Mar. 2018. doi: 10.1016/j.optcom.2017.11.052.

[8] X. Li, C. Gan, Z. Liu, Y. Yan, and H. Qiao, "Novel WRM-based architecture of hybrid PON featuring online access and full-fiber-fault protection for smart grid," *Opt. Commun.*, vol. 407, pp. 69–82, Jan. 2018. doi: 10.1016/j.optcom.2017.09.001.

[9] S. Zhang, W. Ji, X. Li, K. Huang, and Z. Yan, "Efficient and reliable protection mechanism in long-reach PON," *J. Opt. Commun. Netw.*, vol. 8, no. 1, pp. 23–32, Jan. 2016. doi: 10.1364/JOCN.8.000023.

[10] X. Hu, L. Zhang, P. Cao, G. Zhou, F. Li, and Y. Su, "Reconfigurable and scalable all-optical VPN in WDM PON," *IEEE Photon. Technol. Lett.*, vol. 23, no. 14, pp. 941–943, Jul. 15, 2011. doi: 10.1109/LPT.2011.2142299.

[11] C.-J. Chae, S.-T. Lee, G.-Y. Kim, and H. Park, "A PON system suitable for Internetworking optical network units using a fiber Bragg grating on the feeder fiber," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp. 1686–1688, Dec. 1999. doi: 10.1109/68.806888.

[12] A. K. Garg and V. Janyani, "Overall/ subgroup ONU intercommunication based on two stage flexible PON network," in *13th Int. Conf. Fiber Opt. Photon., OSA Tech. Dig.*, Kanpur, India, 2016, pp. 1–3, Paper W3A.1.

[13] A. V. Tran, C.-J. Chae, and R. S. Tucker, "Bandwidth-efficient PON system for broad-band access and local customer Internetworking," *IEEE Photon. Technol. Lett.*, vol. 18, no. 5, pp. 670–672, Mar. 2006. doi: 10.1109/LPT.2006.870058.

[14] A. K. Garg and V. Janyani, "WDM-PON network for simultaneous upstream transmission with ONU interconnection capability," in *13th Int. Conf. Fiber Opt. Photon., OSA Tech. Dig.*, Kanpur, India, 2016, pp. 1–3, Paper Tu4A.13.

[15] B. D. Manharbhai, A. K. Garg, and V. Janyani, "A flexible remote node architecture for energy efficient direct ONU internetworking in TDM PON," in *Proc. Int. Conf. Comput., Commun. Electron. (Comptelix)*, Jaipur, India, Jul. 2017, pp. 453–457.

[16] Y. Tian, T. Ye, and Y. Su, "Demonstration and scalability analysis of all-optical virtual private network in multiple passive optical networks using ASK/FSK format," *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1595–1597, Oct. 15, 2007. doi: 10.1109/LPT.2007.904561.

[17] M. Gharaei, S. Cordette, P. Gallion, C. Lepers, and I. Fsaifes, "Enabling Internetworking among ONUs in EPON using OCDMA technique," in *Proc. 3rd Int. Conf. Signals, Circuits Syst. (SCS)*, Medenine, Tunisia, Nov. 2009, pp. 1–4.

[18] Y. Zhou, C. Gan, B. Chen, and X. Ma, "An upgradeable WDM-PON for broadcast and LAN services," *Opt. Quantum Electron.*, vol. 42, no. 3, pp. 157–163, Feb. 2010. doi: 10.1007/s11082-011-9441-3.

[19] L. Deng, Y. Zhao, X. Pang, X. Yu, D. Liu, and I. T. Monroy, "Intra and inter-PON ONU to ONU virtual private networking using OFDMA in a ring topology," in *Proc. Int. Top. Meeting Microw. Photon. Jointly Held Asia-Pacific Microw. Photon. Conf.*, Singapore, Oct. 2011, pp. 176–179.

[20] C. Feng, C. Gan, S. Ma, and Z. Gao, "A simple WDM-PON supporting LAN services by spectrum-sliced technology," *Photonic Netw. Commun.*, vol. 34, no. 1, pp. 45–51, Aug. 2017. doi: 10.1007/s11107-016-0681-9.

[21] D. Monoyios, A. Hadjiantonis, K. Vlachos, and G. Ellinas, "Efficient inter-ONU communication in ring-based WDM-PONs," in *Proc. 16th Int. Conf. Transparent Opt. Netw. (ICTON)*, Graz, Austria, Jul. 2014, pp. 1–4.

[22] X. Li, C. Gan, Y. Yan, and H. Qiao, "Grid architecture of a metro-access optical network to support discretionary peer-to-peer intracommunication and intercommunication between ONUs," *J. Opt. Commun. Netw.*, vol. 11, no. 3, pp. 130–139, Mar. 2019. doi: 10.1364/JOCN.11.000130.

[23] X. Li, C. Gan, Z. Liu, and J. Hua, "The analysis of network scale and reliability in ring-and-tree-based metro-access network with LAN service," *Fiber Integr. Opt.*, vol. 36, nos. 4–5, pp. 203–217, Sep. 2017. doi: 10.1080/01468030.2017.1377787.

[24] W. Jin, C. Zhang, C. Chen, Q. Zhang, and K. Qiu, "Scalable and reconfigurable all-optical VPN for OFDM-based metro-access integrated network," *J. Lightw. Technol.*, vol. 32, no. 2, pp. 318–325, Jan. 2014. doi: 10.1109/JLT.2013.2293344.

[25] X. Li, C. Gan, Z. Liu, H. Qiao, and Y. Yan, "Resilient intersection-ring architecture featuring online expansion and intersectional mutual protection," *IEEE J. Opt. Commun. Netw.*, vol. 10, no. 6, pp. 613–623, Jun. 2018. doi: 10.1364/JOCN.10.000613.

[26] R. Ullah *et al.*, "Flattened optical multicarrier generation technique for optical line terminal side in next generation WDM-PON supporting high data rate transmission," *IEEE Access*, vol. 6, pp. 6183–6193, 2018. doi: 10.1109/ACCESS.2018.2789863.

[27] C. Feng, C. Gan, S. Guo, Z. Gao, W. Li, and Y. Fang, "A novel modularized twin-ring wavelength-division multiplexer access network with fiber-fault protection and wavelength tetra-reuse," *Fiber Integr. Opt.*, vol. 34, no. 3, pp. 112–130, Jul. 2015. doi: 10.1080/01468030.2015.1049723.

[28] Y. Xiong, P. Sun, and Z. Li, "Novel ring-based architecture for TWDM-PON with high reliability and flexible extensibility," *Opt. Commun.*, vol. 384, pp. 41–49, Feb. 2017. doi: 10.1016/j.optcom.2016.10.013.

[29] X. Li, C. Gan, W. Li, and C. Wu, "A low-cost RN design for large-scale metro-access network based on dual-fiber ring," *Recent Adv. Commun. Netw. Technol. (Formerly Recent Patents Telecommun.)*, vol. 5, no. 2, pp. 108–120, Aug. 2016. doi: 10.2174/2215081106666170109123859.

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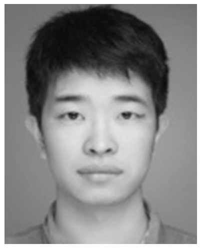

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