An architecture based on FDDC between any two ONUs for optical access network

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Abstract
A novel architecture with full-duplex direct communications (FDDC) between any two ONUs for optical access network is proposed in this paper. By designing combination switch ingeniously, the architecture is finished to realize FDDC between any two ONUs in wavelength division multiplexing passive optical networks. By utilizing interconnected optical fibers between ONUs, the network has achieved three-level protections (feeder optical fiber protection, distributed optical fiber protection and interconnected optical fiber protection). By constructing expansion module, the network can be flexibly expanded and optimized, and the CapEx and OpEx of network can be greatly reduced. Finally, by the simulation and analysis, the effectiveness of the proposed architecture is demonstrated.

Keywords Optical network unit · Full duplex direct communications · Expansion module · Three-level protections · Optical access network

1 Introduction

With the vigorous development of data centers, cloud computing, and 5G mobile communications (Li et al. 2019a), higher requirements of non-blocking and efficient communications are proposed in optical access networks (Li et al. 2018). Direct communication between ONUs is an efficient approach to handle the above challenges (Feng et al. 2015). So, the research on this project has increasingly attracted the attention of researchers (Feng et al. 2015).

To the existing network architectures of direct communications between ONUs, they are mainly divided into three types: star topology, ring topology and grid topology. At the beginning, researchers mainly focus on direct communications between ONUs in star topology and ring topology. As the advantages of grid topology in direct communication become more and more obvious, researchers gradually focus on grid topology. To direct communication between ONUs in star topology, Zhang et al. realize half-duplex
communications between ONUs by forming the ONU into a loop and using the power distribution module (Zhang et al. 2016). To direct communications between ONUs in ring topology, Baria Dipikaben Manharbhai et al. achieve half-duplex communications between ONUs by setting the FBG on the RN (Manharbhai et al. 2017). To direct communications between ONUs in grid topology, Li et al. realize half-duplex communications between ONUs by setting expansion module (EM) at RN (Li et al. 2019b). This paper will research full-duplex direct communications (FDDC) between ONUs in grid network. It will not only shorten the communication link, but also greatly reduce the probability of signal blocking.

2 Network structure and operation principle

2.1 Architecture configuration and wavelength scheme

The multi-service optical access network with FDDC between any ONUs is shown in Fig. 1. It includes a CO, a RN, n groups of ONUs. CO and RN are connected through two feeder fibers (FF). One is working fiber, the other is protection fiber. Each ONU group is connected to RN by distributed fiber (DF). Similarly, these DFs are divided into working fibers and protection fibers. In the same ONU group, adjacent ONUs can establish communication connections through interconnecting optical fibers. The network can support three types of signal transmission. These three signals are: uplink signal, downlink signal and FDDC signal.

CO includes n*n optical transmitters (Tx), a multiplexer (MUX), a circulator, an erbium-doped fiber amplifier (EDFA), a coupler, a 1*2 optical switch (OS), a demultiplexer (DEMUX), n*n optical receivers (Rx) and an EM. Here, EM consists of EMa and EMb. EMa is composed of n*m optical transceivers (TRx), an arrayed waveguide grating (AWG) and an EDFA. EMb in ONU includes m ONUs. Tx sends the downstream signal, and Rx receives the upstream signal from the ONU. TRxs send/receive data at other transmission rates.

Fig. 1  Network architecture with FDDC between ONUs
RN consists of a Coupler, an AWG and n*m OSs. Each ONU group contains n ONUs. This design reduces the manufacturing cost and the maintenance cost of the ONU device. Here, take ONU$_1$ as an example to explain the internal structure of the ONU in detail. The internal structure of ONU$_1$ is shown in Fig. 2. It includes five coarse wavelength division multiplexers (CWDM), three OSs (OS$_1$, OS$_2$, OS$_3$), three optical circulators (Cir$_1$, Cir$_2$, Cir$_3$), a fiber bragg grating (FBG), six optical splitters, a coupler, a reflective semiconductor optical amplifier (RSOA), a wavelength filter (WF), an optical power monitor (M), a tunable optical transmitter (Tx) and two optical receivers (Rx$_1$ and Rx$_2$). In the ONU, all the connection states of the three optical switches (OS$_1$, OS$_2$, and OS$_3$) are shown in Table 1. Cir$_1$ and Cir$_3$ are closed optical circulators. RSOA in ONU erases the downstream signal information from CO and re-modulates it into the upstream signal. The tunable Tx in the ONU is used to send FDDC signals between ONUs. In addition, Rx$_1$ receives the downstream signal from CO, and Rx$_2$ receives the FDDC signals between ONUs. As the above analysis shows, this design enables the network to support the transmission of uplink signals, downlink signals and FDDC signals.

Based on the WDM technology, the specific wavelength settings are shown in Fig. 3. The network allocates specific wavelengths for each ONU to transmit uplink signal, downlink signal, and FDDC signal. The wavelengths in the red band are used for uplink and downlink signals, and the wavelengths in the blue band are used for FDDC signals between

### Table 1 All connection status of OS$_1$, OS$_2$, OS$_3$

| Switch type | Normal working mode | Protection mode |
|-------------|---------------------|-----------------|
| OS$_1$      | 2→1, 3→4           | 2→1, 2→5, 2→6, 2→7, 2→4, 3→1, 3→5, 3→6, 3→7, 3→4 |
| OS$_2$      | 1→2, 1→3, 1→4, 1→5, 2→3, 2→4, 2→5, 3→4, 3→5, 4→5 | 1→2, 1→3, 1→4, 1→5, 2→3, 2→4, 2→5, 3→4, 3→5, 4→5 |
| OS$_3$      | 6→1, 6→2, 6→3, 6→4, 6→5 | 6→1, 6→2, 6→3, 6→4, 6→5 |

![Fig. 2 The structure of ONU](image_url)
ONUs. $\lambda^r_j$ is the communication signal wavelength working in the red band and allocated to ONU$^r_j$. $\lambda^b_j$ is the communication signal wavelength working in the blue band and allocated to ONU$^b_j$. Here, take ONU$^r_2$ as an example. To downlink communication, the downlink signal allocated to ONU$^r_2$ is carried on the wavelength $\lambda^r_2$. To uplink communication, after the RSOA receives the wavelength $\lambda^r_2$, then the downstream signal carried on the wavelength is erased. After that, the upstream signal is modulated to the wavelength $\lambda^b_2$ and transmitted back to the CO. To FDDC, if one ONU needs to full-duplex-and-directly communicate with the ONU$^r_2$, the ONU should send a direct communication signal carried on $\lambda^b_3$ to the ONU$^r_2$.

2.2 Normal working mode

2.2.1 Downlink signal transmission principle

In the normal working mode, as shown in Fig. 1, the n*n transmitters in CO transmit downlink signals. The modulation mode of the downstream signal is differential phase shift keying (DPSK). From CO to FF, the transmission path of the downlink signal is: MUX $\rightarrow$ port 1 of the Circulator $\rightarrow$ port 2 of the Circulator $\rightarrow$ EDFA1 $\rightarrow$ Coupler $\rightarrow$ port 1 of OS $\rightarrow$ port 2 of OS. All the downlink signals reach RN through the working fiber.

In RN, the downlink signals reach the AWG through the Coupler. According to Fig. 3, the downstream signals in the same ONU group will be output from the same output port of the AWG. Here, take Group1 as an example to explain signal transmission principle. The transmission path of the downlink signal is: coupler $\rightarrow$ port 1 of AWG $\rightarrow$ port 1 of OS1 $\rightarrow$ port 2 of OS1 $\rightarrow$ port 1 of Cir1 $\rightarrow$ port 2 of Cir1 $\rightarrow$ FBG $\rightarrow$ spl1 $\rightarrow$ Rx1. Here, all CWDMs in the ONU are used to separate red band and blue band signals. The red band signal will be output from port 1 of the CWDM, and the blue band signal will be output from port 2. The connection status of the switch OS1 in ONU under normal working mode is shown in Table 2. FBG reflects the downstream signal $\lambda^r_1$ to the splitter1. Downlink signals that are not reflected by FBG are input from port 1 of Cir2. Then, the transmission path of the signals is: port 1 of Cir2 $\rightarrow$ port 2 of Cir3 $\rightarrow$ port 3 of OS1 $\rightarrow$ port 4 of OS1 $\rightarrow$ CWDM2 $\rightarrow$ interconnected fiber between ONU$^r_1$ and ONU$^r_2$. Then, by using the same transmission principle, the signal is transmitted to ONU$^r_n$ in sequence. Now, the network has completed the transmission of downlink signals.
2.2.2 Uplink signal transmission principle

In the normal working mode, take ONU\textsuperscript{1} as an example to explain signal transmission principle in each ONU. The transmission path of the upstream signals from ONU\textsuperscript{2} to ONU\textsuperscript{1} is: CWDM2 → port 4 of OS1 → port 3 of OS1 → port 2 of Cir2 → coupler. The upstream signal from RSOA and the upstream signals from port 3 of Cir2 are combined into port 3 of Cir1 by coupler. The transmission path of combined upstream signals is: coupler → port 3 of Cir1 → port 1 of Cir1 → port 2 of OS1 → port 2 of OS1 → port 1 of CWDM1. So, the uplink signals from port 1 of CWDM1 will reach the RN through DF. In RN, Group\textsubscript{1}’s upstream signals from OS\textsubscript{1} are multiplexed into Coupler by AWG. The multiplexed uplink signals from the Coupler are transmitted to CO through FF. In CO, the transmission path of uplink signals from OS to EMa is: OS → Coupler → EDFA\textsubscript{2} → AWG → TRx. The transmission path of remaining uplink signals is: OS → Coupler → EDFA\textsubscript{1} → port 2 of Circulator → port 3 of Circulator → DEMUX → Rx. Up to now, the network has completed the transmission of the uplink signals.
2.2.3 Principle of FDDC between ONUs

Here, modes of FDDC between ONUs contain: Mode 1 (FDDC within the same ONU group) and Mode 2 (FDDC between different ONU groups).

(1) The transmission principle of Mode 1.

In Fig. 4, for inter-ONU direct communication, take ONU1 for example. When ONU1 wants to communicate with ONUn−1. Firstly, Tx in ONU1 transmits $\lambda_{bn^{-1}}$. In ONU1, the path of $\lambda_{bn^{-1}}$ is: port 3 of Cir3 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 6 of OS3 $\rightarrow$ Spl6 $\rightarrow$ CWDM5 $\rightarrow$ interconnected fiber between ONU1 and ONUn−1 $\rightarrow$ ONUn−1. In ONUn−1, the path of $\lambda_{bn^{-1}}$ is: port 2 of CWDM5 $\rightarrow$ Spl3 $\rightarrow$ port 2 of OS3 $\rightarrow$ port 6 of OS2 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 2 of Cir3 $\rightarrow$ WF $\rightarrow$ Rx2. Similarly, communication signals can be transmitted through the link of ONUn−1 $\rightarrow$ ONU1. Up to now, the network has completed the FDDC between ONU1 and ONUn−1. For the FDDC between ONUn and ONU2, in the communication mode of ONUn $\rightarrow$ ONU2, Tx in ONUn transmits $\lambda_{b2}$. In ONUn, the path of $\lambda_{b2}$ is: port 3 of Cir3 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 6 of OS3 $\rightarrow$ port 5 of OS3 $\rightarrow$ Spl5 $\rightarrow$ CWDM2 $\rightarrow$ interconnected fiber between ONU1 and ONU2 $\rightarrow$ ONUn $\rightarrow$ ONU2. In ONU2, the path of $\lambda_{b2}$ is: port 2 of CWDM3 $\rightarrow$ Spl3 $\rightarrow$ port 2 of OS3 $\rightarrow$ port 6 of OS2 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 2 of Cir3 $\rightarrow$ WF $\rightarrow$ Rx2. Similarly, communication signals can be transmitted through the link of ONU2 $\rightarrow$ ONUn. Now, the network has completed the FDDC between ONU1 and ONU2. It is worth noting that the communication of mode 2 and Fig. 5, when traffic congestion occurs in the established communication link, the network can choose alternative links.

(2) The transmission principle of Mode 2.

ONU1 in Group1 and ONUk in Group2 full-duplex-and-directly communicate with each other, as shown in Fig. 6. When ONU1 communicates with ONU2, Tx in ONU1 transmits $\lambda_{bk}$. In ONU1, the path of $\lambda_{bk}$ is: port 3 of Cir3 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 6 of OS3 $\rightarrow$ port 4 of OS3 $\rightarrow$ Spl5 $\rightarrow$ CWDM2 $\rightarrow$ interconnected fiber between ONU1 and ONU2 $\rightarrow$ ONU1. In ONU2, the path of $\lambda_{bk}$ is: CWDM1 $\rightarrow$ Spl2 $\rightarrow$ port 1 of OS2 $\rightarrow$ port 5 of OS2 $\rightarrow$ Spl6 $\rightarrow$ CWDM5 $\rightarrow$ interconnected fiber between ONU1 and ONU2 $\rightarrow$ ONU2. In ONU2, the path of $\lambda_{bk}$ is: CWDM5 $\rightarrow$ Spl6 $\rightarrow$ port 5 of OS3 $\rightarrow$ port 6 of OS3 $\rightarrow$ port 1 of Cir3 $\rightarrow$ port 2 of Cir3 $\rightarrow$ WF $\rightarrow$ Rx2. Similarly, When ONU2 communicates with ONU1, the Tx of ONU2 transmits $\lambda_{bk}$ back to ONU1 through the link of ONU1 $\rightarrow$ ONU2. The signal is received by Rx2 in ONU1. Up to now, the network has completed FDDC between ONU1 and ONU2. It is worth noting that the communication of mode 2 and

![Fig. 5 Flexible direct communication link](image-url)
mode 1 do not interfere with each other. Similarly, the communication link of Mode 2 is also flexible.

2.3 Protection mode

In view of different fiber failures, the network’s protection modes can be divided into three types: Protection Mode 1, Protection Mode 2 and Protection Mode 3 (shown in Fig. 7). In Fig. 7, ①, ② and ③ respectively represent feeder fiber failure, distribution fiber failure and interconnected fiber failure. The three types of protection modes will be respectively clarified as follows.

2.3.1 Protection mode 1

In Fig. 7, when ① occurs, the optical power monitor cannot detect the downstream signal from the CO, and the network will switch to Protection Mode 1. In the Protection Mode 1, port 1 is switched to port 3 in OS of CO. So, all the downstream signals will enter the RN through the protection fiber. In the same way, all upstream signals from the ONUs will be also transmitted from the RN back to the CO through the protection fiber. Up to now, the communication signal resumes normal transmission. Namely, the network is protected.
Fig. 7 Protection mode 1

Fig. 8 Protection mode 2
2.3.2 Protection mode 2

When ② occurs (shown in Fig. 8), the optical power monitor cannot detect the downlink signal from RN, the network will switch to Protection Mode 2. In Protection Mode 2, port 1 is connected to port 3 in OS₁ of RN. The downstream signal interrupted by failure will resume transmission through the protection fiber of DF. At this time, port 2 is connected to port 6 in OS₁ of ONU₁ⁿ⁻¹, and port 3 is connected to port 6 in OS₁ of ONU₁ⁿ. The downstream signal transmission link changes from ONU₁ → ONU₂ → … → ONUₙ⁻¹ to ONU₁ → ONU₁ → … → ONU₁⁻¹. The signal resumes communication and the network is protected. It is worth noting that the optical fiber failure in mode 2 does not affect the direct communication service at ONU.

2.3.3 Protection mode 3

When the interconnection fiber between ONU fails, the network will switch to Protection Mode 3. Taking ③ as an example, the optical power monitor in ONU₁ cannot detect the direct communication signal from ONU₂, and the optical power monitor of ONU₂ cannot detect the direct communication signal from ONU₁. Then, OSs in ONU₁ and ONU₂ change the connection state. Port 3 is connected to port 6 in OS₁ of ONU₁ and port 6 is connected to port 3 in OS₃. In OS₃ of ONU₁, port 2 is connected to port 6, port 3 is connected to port 7. Port 3 is connected to port 5 in OS₂ of ONU₁. At the same time, port 2 is connected to port 3 in OS₁ of ONU₂, and port 6 is connected to port 2 in OS₃ of ONU₂. The transmission link of the downstream signal becomes: ONU₁ → ONU₁ → ONU₂ → … → ONU₁⁻¹. The

![Diagram](image-url)
transmission link of the FDDC between ONU$_1^1$ and ONU$_1^2$ changes from ONU$_1^1$→ONU$_1^2$, ONU$_1^2$→ONU$_1^1$ to ONU$_1^1$→ONU$_n^1$→ONU$_1^2$, ONU$_1^2$→ONU$_1^0$→ONU$_1^1$. So, network communication is restored. The network can also realize multi-protection of interconnecting optical fibers by switching optical switches. FDDC between ONUs have different transmission links. So, Protection Mode 3 is flexible. Operators can choose the appropriate protection link according to actual needs.

3 Network performance analysis

3.1 Power budget and network scale

To describe clearly, define the maximum power loss of the signal as $L$, the power margin of the network as $LM$ and the power of the transmitter as $PT$. Define the sensitivity of the receiver as $PR$, the gain of EDFA as $G$, the number of ONUs supported by each ONU group as $n$. The lengths of feeder fiber between CO and RN, distributed fiber between RN and ONU and interconnecting fiber between ONUs are $d_1$, $d_2$, $d_3$ respectively. In addition, define the power losses of the optical signals at CO, RN and ONU as $L_{CO}$, $L_{RN}$ and $L_{ONU}$ respectively. The power losses of the optical signals in the links between CO and RN, RN and ONU are $L_{CO-RN}$ and $L_{RN-ONU}$ respectively. Insertion loss value of optical device related to the analysis process is shown in Table 3.

According to Sect. 2, the downstream signal received by the last ONU in each ONU group suffers the greatest power loss. So, $L$ can be expressed as:

$$L = L_{CO} + L_{CO-RN} + L_{RN} + L_{RN-ONU} + L_{ONU}$$

(1)

In Eq. (1), $L_{CO}$, $L_{CO-RN}$, $L_{RN}$, $L_{RN-ONU}$ and $L_{ONU}$ are given:

$$L_{CO} = L_{MUX} + L_{Cir} + L_{Cpl} + L_{OS}$$

(2)

$$L_{CO-RN} = d_1 \times \alpha_F$$

(3)

$$L_{RN} = L_{Cpl} + L_{AWG} + L_{OS}$$

(4)

$$L_{RN-ONU} = d_2 \times \alpha_F$$

(5)

Table 3 Insertion loss value of optical device

| Component     | Symbol | Insertion loss (dB) | References         |
|---------------|--------|---------------------|-------------------|
| MUX           | $L_{MUX}$ | 3                   | Li et al. (2018)  |
| Circulator    | $L_{Cir}$ | 0.5                | Li et al. (2018)  |
| Coupler       | $L_{Cpl}$ | 0.5                | Zhang et al. (2016)|
| Optical switch| $L_{OS}$  | 0.5                | Li et al. (2018)  |
| CWDM          | $L_{CWDM}$ | 0.5                | Feng et al. (2015) |
| FBG           | $L_{FBG}$  | 3.5               | Chen et al. (2011) |
| AWG           | $L_{AWG}$  | 3                  | Li et al. (2018)  |
| Splitter      | $L_{Spl}$  | 3                  | Li et al. (2018)  |
| Fiber         | $\alpha_F$ | 0.2 dB/km          | Li et al. (2018)  |
Suppose \( d_1 = 10 \text{ km}, d_2 = 2 \text{ km}, \text{ and } d_3 = 0.5 \text{ km}. \) Substituting them into the above equations respectively, and then according to the specific values in Table 3, \( L \) can be gotten:

\[
L = 6.6n + 12.3 \tag{7}
\]

The maximum power loss \( L \) satisfies the following inequality:

\[
P_T + G - L - L_M \geq P_R \tag{8}
\]

Assume \( L_M = 5 \text{ dB} \) and \( P_R = -30 \text{ dBm} \), inequality can be gotten:

\[
n \leq \left( P_T + G + 12.7 \right) \tag{9}
\]

When \( P_T \) is set to 0 dBm, 5 dBm and 10 dBm, the relationship between \( G \) and \( n \) is shown in Fig. 10. Obviously, \( n \) increases linearly with \( G \).

In addition, the relationship among \( P_T, G \) and \( n \) is shown in Fig. 11. Obviously, along the \( G \)-axis, when \( G \) is constant, \( n \) increases as \( P_T \) increases. Along the \( P_T \)-axis, when \( P_T \) is constant, \( n \) increases as \( G \) increases. Figure 11 shows: \( n = 6.47 \) when \( P_T = 0 \text{ dBm} \) and \( G = 30 \text{ dB} \). In practice, \( n \) should be an integer and be rounded down. When \( P_T = 0 \text{ dBm} \) and \( G = 30 \text{ dB} \), the maximum number of \( n \) is 6. The maximum number of output ports supported by an AWG is 128. So, the maximum number of ONUs supported by network is 768.

![Fig. 10](image)

*Fig. 10*  The relationship between \( G \) and \( n \) when \( P_T \) is a fixed value
3.2 Network reliability

According to Fig. 1, the downlink communication signal transmission link received by the last ONU in each ONU group is the longest. Here, the longest link will be taken as an example to analyze the reliability of network. The unreliability values of related optical devices are shown in Table 4. Define the reliability and the unreliability of the network as $A$ and $U$ respectively. The relationship between two parameters is shown:

$$A + U = 1$$  \hspace{1cm} (10)

**Table 4** Unreliability values of optical devices

| Symbol   | Unreliability (failure/10^9 h) | References               |
|----------|---------------------------------|---------------------------|
| OLT      | $U_{OLT}$                       | $5.12 \times 10^{-7}$     | Li et al. (2018)            |
| Coupler  | $U_{Cpl}$                       | $4 \times 10^{-8}$        | Zhang et al. (2016)         |
| EDFA     | $U_{EDFA}$                      | $4 \times 10^{-7}$        | Li et al. (2018)            |
| Circulator | $U_{Cir}$                     | $2 \times 10^{-7}$        | Li et al. (2018)            |
| Optical Switch | $U_{OS}$               | $4 \times 10^{-7}$        | Li et al. (2018)            |
| AWG      | $U_{AWG}$                       | $4.8 \times 10^{-6}$      | Li et al. (2018)            |
| CWDM     | $U_{CWDM}$                      | $1.44 \times 10^{-5}$     | Li et al. (2019a)           |
| FBG      | $U_{FBG}$                       | $10^{-7}$                  | Chen et al. (2011)          |
| Splitter | $U_{Spl}$                       | $4 \times 10^{-8}$        | Li et al. (2018)            |
| Fiber    | $U_{F}$                         | $2.4 \times 10^{-7}$/km   | Li et al. (2018)            |
Define the unreliability of the CO as \( U_{CO} \), the unreliability between CO and RN as \( U_{CO-RN} \), the unreliability between RN as \( U_{RN} \), the unreliability between RN and ONU as \( U_{RN-ONU} \), and the unreliability of ONU as \( U_{ONU} \). Then, the network unreliability \( U \) can be expressed as:

\[
U = U_{CO} + U_{CO-RN} + U_{RN} + U_{RN-ONU} + U_{ONU}
\]

(11)

In Eq. (11), \( U_{CO}, U_{CO-RN}, U_{RN}, U_{RN-ONU} \) and \( U_{ONU} \) are respectively given by:

\[
U_{CO} = U_{OLT} + U_{Cir} + U_{EDFA} + U_{Cpl} + U_{OS}
\]

(12)

\[
U_{CO-RN} = (d_1 \cdot UF)^2
\]

(13)

\[
U_{RN} = U_{Cpl} + U_{AWG} + U_{OS}
\]

(14)

\[
U_{RN-ONU} = (2U_{AWG} + 2U_{OS} + 2U_{Cir} + U_{FBG} + d \cdot U_F) \cdot (n - 1) \cdot d_2 \cdot U_F + (d_2 \cdot UF)^2
\]

(15)

\[
U_{ONU} = U_{CWDM} + U_{OS} + U_{Cir} + U_{FBG} + U_{Spl} + U_{OLT}
\]

(16)

Substitute the data in Table 4 to Eq. (11), \( A \) can be calculated:

\[
A \approx 1 - 2.2444 \times 10^{-5}
\]

(17)

As is illustrated in the above calculation and analysis, \( A \) is a constant. It means that the link reliability of the network is not affected by the scale of the network.

### 3.3 Performance comparison

To show the performance of proposed scheme, its characteristics is compared with them of existing schemes (shown in Table 5).

Here, in the star scheme (Zhou et al. 2010), the direct communication between ONUs is realized through a virtual ring. Direct communication signals need to be transmitted back to the RN for rescheduling. It will inevitably cause signal congestion and delay. Furthermore, the transmission link of the direct communication signal is not flexible. If the first ONU on the virtual ring wants to communicate directly with the last ONU, the transmission link must cover all ONUs between them. So, the direct communication signal received by the receiver of the target ONU will have more noise and lower power. In addition, the protection link lacks flexibility and the reliability of the network is poor.

**Table 5 Performance comparison results**

|                        | Star scheme | Ring scheme | Grid scheme | Three-dimensional grid scheme | The proposed scheme |
|------------------------|-------------|-------------|-------------|-------------------------------|---------------------|
| Signal blocking        | Large       | –           | Large       | Small                         | Small               |
| Link flexibility       | No          | No          | No          | Yes                           | Yes                 |
| Network reliability    | Weak        | Weak        | –           | –                             | Good                |
In the ring scheme (Li et al. 2017; Monoyios et al. 2014) a dedicated ring optical link is established to support direct communication between ONU{s}. Compared with virtual ring in star network, CapEx of the network is higher due to the actual ring optical link. In the ring optical link, the communication between adjacent ONU{s} is extremely dependent. So, link of direct communication signal lose flexibility. In addition, the protection link is also inflexible. The network will not be able to resume normal when multi-point fiber failure happens. So, the reliability of the network is poor.

Different from the previous two schemes realizing direct communication between ONU{s} in a specific order, the grid scheme (Li et al. 2019b) can realize direct communication between any two ONU{s}. However, direct communication signal between ONU{s} must be rescheduled in RN. Delay and signal congestion also occur in communication. In protection mode, the link of direct communication lacks flexibility. In the three-dimensional grid scheme (Lin et al. 2019), direct communication between ONU{s} can be realized at ONU. Link of direct communication is flexible. The protection mechanism of the network is based on the ring protection mechanism. So, the network can’t resist multi-point fiber failure. Furthermore, the direct communication between ONU{s} is half-duplex.

The scheme proposed in this paper is also based on grid topology. However, FDDC between any two ONU{s} can be realized at ONU. The direct communication link is further shortened, the possibility of signal blocking is greatly reduced and the transmission efficiency of direct communication is greatly improved. Furthermore, the link selection of direct communication is very flexible. The network can choose other alternative links for direct communication when signal congestion occurs in communication link. Moreover, three protection modes can resist all possible fiber failure, the reliability of the network is better.

In summary, the proposed scheme has significant advantages in many aspects, such as signal blocking, link flexibility, network reliability and so on.

### 3.4 Simulation analysis of transmission performance

#### 3.4.1 Simulation settings

In order to further demonstrate the feasibility of the proposed architecture, a simulation based on OptiSystem 7.0 (Optiwave, Ottawa, Canada) was carried out. The simulation setting includes one CO, one RN and eight ONU{s}. Under the condition of both normal mode and protection mode, the simulations of downlink communication and FDDC are realized respectively. The frequencies of downlink signals are 193.1THz~193.8THz, while the frequencies of FDDC signals are 194.5THz~195.2THz, the interval of wavelengths is 0.1THz. For group 1(ONU11~ONU14), 10Gbit/s 27−1 pseudo-random bit sequence (PRBS) is used to simulate downlink signals, while for group 2 (ONU21~ONU24), 5Gbit/s 27−1 PRBS is used to simulate downlink signals. All downlink signals are modulated in non-return to zero (NRZ) mode. The uplink signal is transmitted at the speed of 2.5Gbit/s using NRZ data. FDDC signals are simulated by PRBS of 10Gbit/s in NRZ mode. In CO, gain of EDFA is set at 30 dB. The length of FF between CO and RN is set to 5 km, the length of DF between RN and ONU is set to 1 km, and the length of the interconnected fiber between ONU is set to 0.5 km.
3.4.2 BER curve

Here, the transmission principles of ONU’s downlink signals are the same. Now, take ONU\textsubscript{1} and ONU\textsubscript{2} as examples to explain the performance of downlink signals. BER curves of downlink signals in normal and protection modes are shown in Fig. 12. The relationship between BER and optical received power is: the value of BER decreases as the received power increases. It can be seen from the figure that the signal performance of ONU\textsubscript{2} is better than that of ONU\textsubscript{1} in normal mode. The signal transmission rates of ONU\textsubscript{2} and ONU\textsubscript{1} are 5Gbit/s and 10Gbit/s respectively. The above results can further confirm the principle: under the same conditions, the faster signal transmission rate is, the higher BER of signal will be. In Fig. 12, BER of ONU\textsubscript{1} in protection mode is higher than that in normal mode. In protection mode, the signal transmitted to ONU\textsubscript{1} must pass through ONU\textsubscript{n}. So, the BER is higher and the signal transmission performance is poor by the reasons of passing through more optical devices and having more noise. In addition, it can be seen that BER of downlink signal is less than $10^{-9}$. This confirms that the proposed network meets the requirement of communication standard.

The BER curves of FDDC in normal and protection modes are shown in Fig. 13. Similarly, the BER of all signals decreases as the received power increases. It can be seen from the figure that the BER curves of (ONU\textsubscript{1}-to-ONU\textsubscript{4}) and (ONU\textsubscript{4}-to-ONU\textsubscript{1}) are very close. This is because FDDC links between ONU\textsubscript{1} and ONU\textsubscript{4} are the same one. Similarly, the BER curves of (ONU\textsubscript{1}-to-ONU\textsubscript{2}) and (ONU\textsubscript{2}-to-ONU\textsubscript{1}) almost coincide. ONU\textsubscript{1} and ONU\textsubscript{2} are in different groups. BER of communication link between ONU\textsubscript{s}
in different groups is poorer than that in one group because the former one has longer transmission link. Furthermore, when the network happens to failure, the FDDC link of (ONU$_1$-to-ONU$_4$) becomes longer, and the relative BER becomes poorer. Although the links of (ONU$_1$-to-ONU$_2$) in normal mode and (ONU$_2$-to-ONU$_4$) in protection mode are different, the number of optical devices and length of optical fiber related to the link are similar. So, BER curves of (ONU$_1$-to-ONU$_2$) in normal mode and (ONU$_2$-to-ONU$_4$) in protection mode are very close. Compared with Fig. 12, the transmission performance of FDDC signal is better, and the BER of FDDC signal is less than $10^{-16}$. This confirms that the proposed network meets the requirement of communication standard.

4 Conclusion

A novel architecture with full-duplex communications between any two ONUs for optical access network has been completed in this paper. At first, a CS is constructed to finish the architecture and further realize full-duplex communications between any two ONUs among WDM-PONs. Next, interconnected optical fibers between ONUs are utilized to provide protection for communications between ONUs so as to achieve three-level protections (feeder optical fiber protection, distributed optical fiber protection and interconnected optical fiber protection) in optical access network. The network reliability is greatly elevated to fully meet the operator’s 5 ‘9’ requirements. Furthermore, an EM is designed to
tremendously reduce the Capex and Opex of network, and flexibly expand and optimize the network. The scale of network can be normally up to 768 users. Finally, the simulation and analysis demonstrate the effectiveness of the proposed architecture.

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**Data availability** The authors declare that the data supporting the findings of this study are available within the article.

**Declarations**

**Conflict of interest** The authors have no relevant financial or non-financial interest to disclose.

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