A high-reliability optical network architecture based on wavelength division multiplexing passive optical network*

CHEN Baoren (陈宝仁)[1]**, **HONG Danke** (洪丹轲)[1], **WANG Li** (王力)[1], **OU Yongtong** (区永通)[2], **TAN Yizhi** (谭艺枝)[3], **LI Xuewu** (李学武)[2], **and ZHONG Xinhui** (钟昕辉)[2]

1. China Southern Power Grid Power Dispatching Control Center, Guangzhou 510030, China

2. China Southern Power Grid Digital Grid Research Institute Co., Ltd., Guangzhou 511458, China

3. School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China

(Received 3 November 2020; Revised 24 November 2020)

A highly reliable wavelength division multiplexing passive optical network architecture for the fifth generation (5G) applications is designed by combining a tree topology with a dual-fiber ring. While the tree topology ensures the transmission quality of the network, the dual-fiber ring topology allows one to achieve flexible switching between the nodes, which aims to provide fault protection and network reliability. The signal transmission under the normal and three types of protection modes are analyzed. The performance analysis verifies the feasibility of the proposed architecture.

Document code: A **Article ID:** 1673-1905(2021)07-0422-5

DOI https://doi.org/10.1007/s11801-021-0174-7

With the advent of the fifth generation (5G) era, large bandwidth and low transmission delay have become of great importance due to higher requirements for optical networks[1,2]. Currently, the fiber direct connection, the wavelength division multiplexing passive optical network (WDM-PON), and the wavelength division multiplexing active optical network are the three major deployment methods for the 5G fronthaul[3]. Among all the candidates, WDM-PON is considered a promising solution[4,5] due to the ability to achieve large capacity, efficient spectrum utilization, simple system deployment, relatively low costs, and high scalability for future network implementations.

WDM-PON is mainly composed of an optical line terminal (OLT), some remote nodes (RNs), some optical network units (ONUs) and some fibers[6]. Compared with the time division multiplexed passive optical network, there are three main advantages for WDM-PON. First, a fixed bandwidth is occupied by each user without using the dynamic bandwidth allocation algorithms. Second, data packets are mapped to wavelength channels, making WDM-PON transparent to various protocols and data rates, which makes network management and protection easier. Third, a specific wavelength is used by each ONU during the upstream transmission, so no special medium-access control (MAC) protocol is required, which reduces system complexity and improves transmission efficiency.

The most common WDM-PON architectures are based either on tree topology[7] or ring topology[8]. In the tree topology, the OLT is connected to the RN through a feeder fiber, and the RN is linked with an ONU through a distributed fiber. The tree topology is easy to deploy and possesses a low transmission delay. However, the main problem is that fiber resources are easily wasted due to redundant protection. In the ring topology, the OLT and the RNs (or the ONUs) are connected into a ring, which can transmit data in both directions, ensuring load balancing and high-performance transmission. Although the ring topology is mature enough to provide fault protection and high reliability, the number of nodes and fiber length upon transmission distance increase, which decreases the signal quality with rapidly increasing delay. Currently, the mentioned topologies within the WDM-PON-based 5G network architectures are employed separately without combining them.

Thus, considering the advantages and shortcomings of the above topologies, this work is aimed at designing a highly-reliable and low-latency WDM-PON-based network architecture for 5G purposes by combining the tree topology with a dual-fiber ring. In normal mode, the signal is transmitted through the tree topology to improve signal quality and reduce transmission delay. The dual-fiber ring structure can ensure that the communication is not interrupted when a failure occurs, which improves the reliability of the network. To verify the feasi-

* This work has been supported by the China Southern Power Grid Research Foundation (No.000000KK52190155), and the Natural Science Foundation of Guangdong Province (No.2018A030310593).

** E-mail: 164910384@qq.com

bility of the proposed network architecture, the comparative analysis of the transmission reliability and power loss analysis is verified.

A schematic of the topology proposed in this paper is shown in Fig.1. The OLT is connected to the RN through a feeder fiber. Each RN and the corresponding ONU are linked through a distributed fiber. All RNs are connected by a dual-fiber ring. The signal is transmitted through the tree topology in the normal mode, while the dual-fiber ring is responsible for fault protection. When in protection mode, the downstream signals are transmitted clockwise in the outer fiber while the upstream signals are transmitted in a counterclockwise direction in the inner fiber.

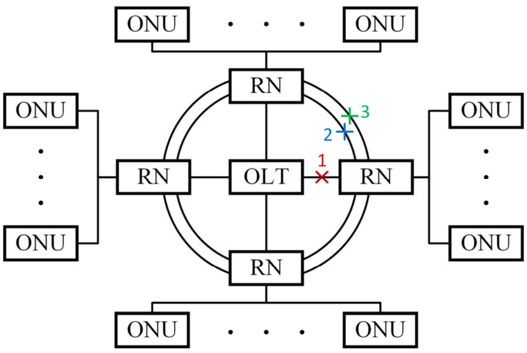

Fig.1 Schematic of the proposed topology, where labels 1, 2, 3 represent the different fiber failures

The OLT is composed of *n* transmitters, *n* receivers (RX), two arrayed waveguide gratings (AWGs), one erbium-doped fiber amplifier (EDFA), one circulator (Cir) and one splitter, as depicted in Fig.2. The downstream signals are generated by the transmitters, multiplexed by the AWG, and amplified by the EDFA. After passing through the Cir and splitter, they are sent to each RN through the feeder fibers.

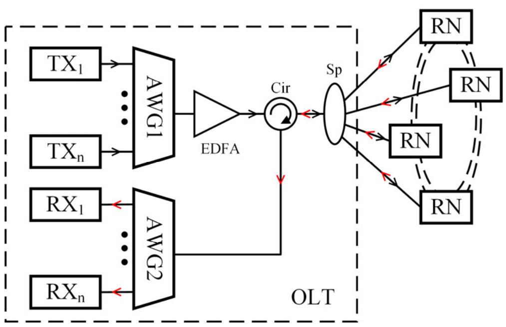

Fig.2 OLT structure

A schematic of the internal structure of the RN is illustrated in Fig.3. The main components are seven Cirs, five optical switches (OSs), one fiber Bragg grating (FBG), one coupler (CP) and one AWG. The inner and outer fibers are selected by switching the OSs.

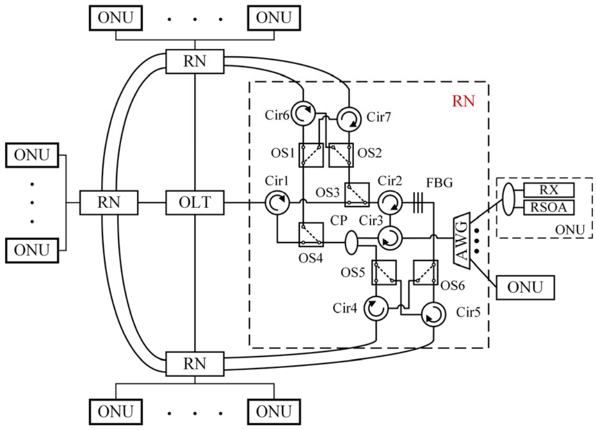

Fig.3 RN structure

In the normal mode, the upstream and downstream signals are transmitted through a feeder fiber between the OLT and the RN. The transmission of downstream and upstream signals is displayed in Fig.4. Inside the RN, the downstream signals alternatively pass through the Cir1, OS3 and FBG. A part of the downstream signals is reflected by FBG[9], demultiplexed by the AWG, and sent to the appropriate ONU.

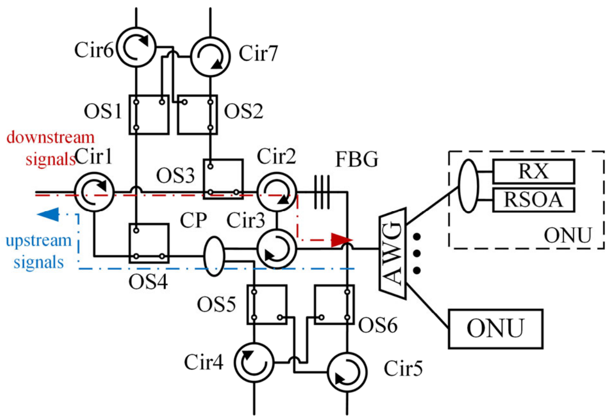

Fig.4 Normal mode

In the ONU, one part of the downstream signals is received by the receiver, whereas another enters the reflective semiconductor amplifier (RSOA) for erasing the downstream signal by gain saturation and implementing the upstream signal modulation[10]. After that, the upstream signals are multiplexed by the AWG and pass alternatively through the Cir3, CP, OS4, and Cir1. Finally, the upstream signals enter the OLT through a feeder fiber to be received by the receivers in the OLT.

The transmission link of the downstream signals is as follows: OLT→Cir1→OS3→Cir2→FBG→Cir2→Cir3→AWG→ONU, while that of the upstream signals can be written as: ONU→AWG→Cir3→CP→OS4→Cir1→OLT.

In the proposed topology, there are three kinds of fiber failure considered, namely the feeder fiber failure, the outer fiber and feeder fiber failure, and the inner fiber and feeder fiber failure. By changing the connection state of the OS1, OS2, OS3, OS4 of the faulty RN and the OS5, OS6 of the adjacent RN, the downstream signals and upstream signals can be transmitted through the dual-ring fiber. The corresponding transmission is depicted in Tab.1, where the links in the parentheses represent the transmission of signals in the adjacent RN.

Tab.1 The transmission link of the downstream signals and upstream signals

Failure type	Downstream signals transmission	Upstream signals transmission
Feeder fiber	OLT→(Cir1→OS3→Cir2→FBG→OS6→Cir5)→ Cir7→OS2→OS3→Cir2→FBG→Cir2→Cir3→AWG→ONU	ONU→AWG→Cir3→CP→OS4→OS1→Cir6→(Cir4→OS5→CP→OS4→Cir1)→OLT
Outer fiber and feeder fiber	OLT→(Cir1→OS3→Cir2→FBG→OS6→Cir4)→Cir6→OS2→OS3→Cir2→FBG→Cir2→Cir3→AWG→ONU	ONU→AWG→Cir3→CP→OS4→OS1→Cir6→(Cir4→OS5→CP→OS4→Cir1)→OLT
Inner fiber and feeder fiber	OLT→(Cir1→OS3→Cir2→FBG→OS6→Cir5)→Cir7→OS2→OS3→Cir2→FBG→Cir2→Cir3→AWG→ONU	ONU→AWG→Cir3→CP→OS4→OS1→Cir7→(Cir5→OS5→CP→OS4→Cir1)→OLT

Reliability is an important factor that should be considered when designing network architecture. It depends on the appliance manufacture and service time of optical components. The normal mode and the protection mode are established to evaluate the reliability of the architecture designed.

In the normal mode, the reliability model of each branch can be described by a sum of the unreliability parameters of the tree-type network components:

$$U_{normal}=U_{CO}+U_{CO\text{-}RN}+U_{RN}+U_{fiber}+U_{ONU}, \quad (1)$$

where U_{normal} denotes the branch unreliability (since branches are independent of each other, this parameter is equal for all of them), U_{CO} represents the unreliability of the OLT, $U_{CO\text{-}RN}$ denotes the unreliability of a segment from the OLT to the RN, and U_{fiber} denotes the unreliability of a fiber. U_{RN} and U_{ONU} refer to the unreliability of the RN and the ONU units.

In the case of x RNs and y ONUs, the unreliability of the normal mode is expressed as

$$U^{total}_{normal}=U_{CO}+x(U_{CO-RN}+U_{RN})+y(U_{fiber}+U_{ONU}) . \quad (2)$$

Since RNs in our topology are connected by a dual-fiber ring that serves as parallel links, these cannot be considered as independent in protection mode. Hence the system transmission interrupts only when all the RNs fail. According to the analysis above, the unreliability of the protection mode can be described by

$$U_{pro}=U_{CO}+U_{CO\text{-}RN'}+U_{RN}+U_{fiber}+U_{ONU}, \quad (3)$$

where $U_{CO\text{-}RN'}$ represents the unreliability of a segment between the OLT and RN in the protection mode. If there are x RNs in the topology, $U_{CO\text{-}RN'}$ can be expressed as

$$U_{CO-RN'}=U_{CO-RN}\{U'_{RN1}+U_{CO-RN}[U'_{RN2}+U_{CO-RN}(...)]\} . \quad (4)$$

Then Eq.(3) can be rewritten as

$$U_{pro}=U_{CO}+U'_{RN1}\frac{U_{CO-RN}-U^{x}_{CO-RN}}{1-U_{CO-RN}}+U^{x}_{CO-RN}+ U_{RN}+U_{fiber}+U_{ONU} , \quad (5)$$

where U'_{RN1} refers to the unreliability of the RN when in protection mode. According to Eq.(5), the unreliability of each link in the proposed topology is related to the number of RNs. The higher is the number of RNs, the more links can be chosen by the signal and the lower is the unreliability of each link.

When there are x RNs and y ONUs in the proposed topology, the unreliability takes the form:

$$U^{total}_{pro}=U_{CO}+x(U'_{RN1}\frac{U_{CO-RN}-U^{x}_{CO-RN}}{1-U_{CO-RN}}+U^{x}_{CO-RN}+U_{RN})+ y(U_{fiber}+U_{ONU}) . \quad (6)$$

A comparison of Eqs.(6) and (2) reveals the difference between the reliabilities calculated for the two modes. Thus, subtracting Eq.(6) from Eq.(2) results in:

$$\Delta U_{total}=x(U_{CO-RN}-U'_{RN}\frac{U_{CO-RN}-U^{x}_{CO-RN}}{1-U_{CO-RN}}+U^{x}_{CO-RN})= x(\frac{(1-U'_{RN}-U_{CO-RN})(U_{CO-RN}-U^{x}_{CO-RN})}{1-U_{CO-RN}}) . \quad (7)$$

Since $U_{CO\text{-}RN}$ and U'_{RN} are far less than 1, hence $\Delta U_{total}>0$, indicating that the reliability of the protection mode is better than that of the normal mode.

The unreliability data and the representing symbol of conventional optical components are shown in Tab.2. According to Tab.2, the unreliability of U_{CO}, U_{RN}, U'_{RN} and $U_{CO\text{-}RN}$ is:

$$U_{CO}=U_{OLT}+U_{EDFA}+U_{Cir}+U_{Sp}, \quad (8)$$

$$U_{RN}=2\times U_{OLT}+U_{OS}+U_{FBG}+U_{AWG}, \quad (9)$$

$$U'_{RN}=3\times U_{Cir}+3\times U_{OS}+U_{FBG}+U^{2}_{fiber} , \quad (10)$$

$$U_{CO\text{-}RN}=U_{fiber}+U_{Cir}. \quad (11)$$

Tab.2 Unreliability data for conventional optical components

Component	Symbol	Unreliability (Failure/10^9 h)	References
OLT	U_{OLT}	5.12×10^{-7}	[11]
EDFA	U_{EDFA}	4×10^{-7}	[11]
Coupler	U_{Cp}	4×10^{-8}	[11]
OS	U_{OS}	4×10^{-7}	[11]
ONU	U_{ONU}	5.12×10^{-7}	[11]
Circulator	U_{Cir}	2×10^{-7}	[11]
AWG	U_{AWG}	4.8×10^{-6}	[12]
Fiber	U_{fiber}	2.4×10^{-7}/km	[11]
FBG	U_{FBG}	2.4×10^{-7}	[12]
Splitter	U_{Sp}	4×10^{-8}	[11]

Assuming the distance between the OLT and the RN, the distance between RNs themselves and that between the RN and the ONU are as long as 5 km. The unreliability as a function of x and y for the two topologies is shown in Figs.5 and 6. As seen, the unreliability factor follows the same trend for both topologies: the number of optical components increases with the increasing number of RNs and ONUs, thus enhancing the total unreliability. Meanwhile, the unreliability of our topology under the same conditions is found to be inferior to that of the common tree topology, as illustrated in Fig.7. This means that applying the proposed WDM-PON-based network topology allows one to improve network robustness.

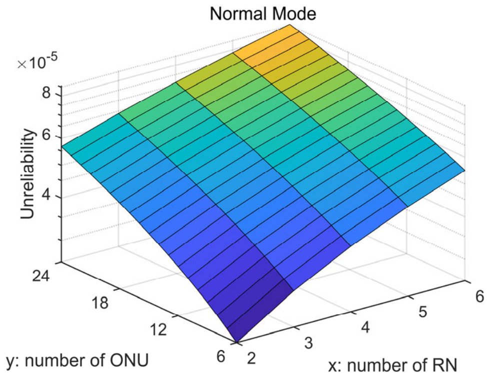

Fig.5 Unreliability of the normal mode

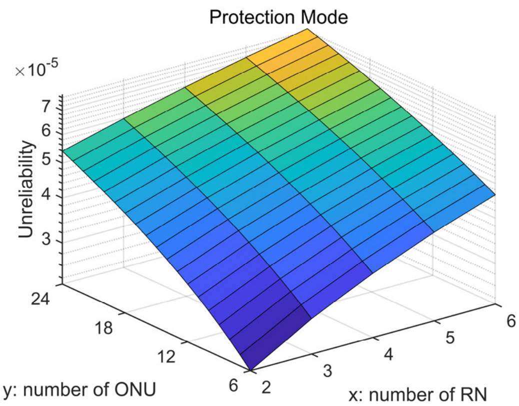

Fig.6 Unreliability of the protection mode

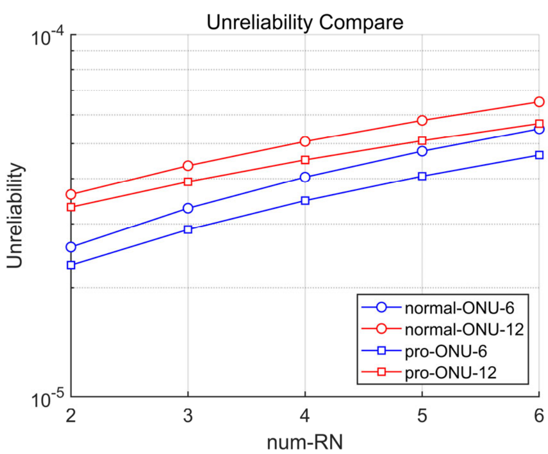

Fig.7 Unreliability as a function of the number of RNs and ONUs for the normal mode and protection mode

in this network

Link loss is an important factor to influence the scale of a network. In this section, the power budget is discussed. According to the operation principle of the network, if there are n RNs in the network and only one of the feeder fibers works normally, the ONUs connected to the RN adjacent to the normal feeder fiber have the maximal loss. L_O is defined as representing the link loss of the special ONU. P_T, G, L_M and P_r denote the output power of the transmitter, the gain of EDFA, the power redundancy of the system, and the receiver sensitivity. d represents the distance between the RN and the ONU, or OLT and RN, or the adjacent RNs, and is assumed to be 5 km. The insertion loss and the representing symbol of optical components are shown in Tab.3. Thus,

$$L_O=2L_{AWG}+2L_{Sp}+L_{Cir}+d\times\alpha_F+(n-2)\times L_{OS}+n\times(3L_{Cir}+2L_{OS}+L_{FBG}+d\times\alpha_F). \quad (12)$$

According to Tab.3, L_O can be rewritten as

$$L_O=12.5+7.5n. \quad (13)$$

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

$$P_T+G-L_O-L_M\geq P_r, \quad (14)$$

where one can assume that P_T=1 dBm, L_M=3 dB and P_r=−30 dBm. After substituting Eq.(13) into Eq.(14), the inequality about n and G can be expressed as

$$n\leq(15.5+G)/7.5. \quad (15)$$

Tab.3 Insertion loss of optical components

Components	Symbol	Insertion loss (dB)	References
AWG	L_{AWG}	3	[12]
Coupler	L_{Cp}	0.5	[11]
OS	L_{OS}	0.5	[11]
Circulator	L_{Cir}	0.5	[11]
Fiber	α_F	0.2 dB/km	[11]
FBG	L_{FBG}	3.5	[12]
Splitter	L_{Sp}	3	[11]

Fig.8 shows that the relation between n and G is linear. When G=0, $n\approx2$, which means that the network can still support two RNs even if there is no EDFA in the OLT.

The upstream signals transmission paths are almost the same like that of the downstream signals, and the output saturation power of the RSOAs is approximately 3 dBm[13] so that the power loss of the upstream signals is similar to that of the downstream signals.

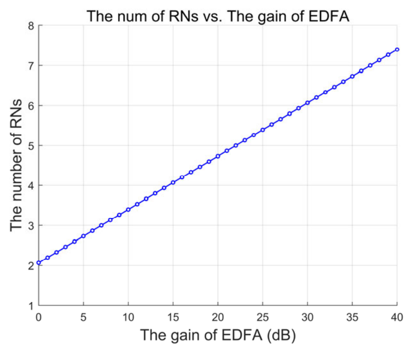

Fig.8 The relation between the number of RNs *n* and the gain of EDFA *G*

A highly reliable wavelength division multiplexing passive optical network architecture was designed for 5G applications. In that architecture, the tree topology was combined with a dual-fiber ring to provide fault protection and to ensure the network reliability. The authenticity of the proposed network architecture was proved via a comparative analysis of the transmission reliability in the normal and fault protection modes, and the power loss analysis proves the feasibility of the proposed network.

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