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Zhang et al.

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(45) Date of Patent: Aug. 19, 2025

(54) **REDUNDANCY LINKS, RESILIENCY ARCHITECTURES, AND PROTECTION METHODS FOR PASSIVE OPTICAL NETWORKS**

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(73) Assignee: **Cable Television Laboratories, Inc.**, Louisville, CO (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 260 days.

(21) Appl. No.: **17/952,022**

(22) Filed: **Sep. 23, 2022**

Related U.S. Application Data

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(51) **Int. Cl.**

H04Q 11/00	(2006.01)
H04B 10/27	(2013.01)
H04B 10/61	(2013.01)

(52) **U.S. Cl.**

CPC ***H04Q 11/0062*** (2013.01); ***H04B 10/27*** (2013.01); ***H04B 10/614*** (2013.01); *H04Q 2011/0081* (2013.01)

(58) **Field of Classification Search**

CPC ... H04B 10/27; H04B 10/614; H04Q 11/0062 (Continued)

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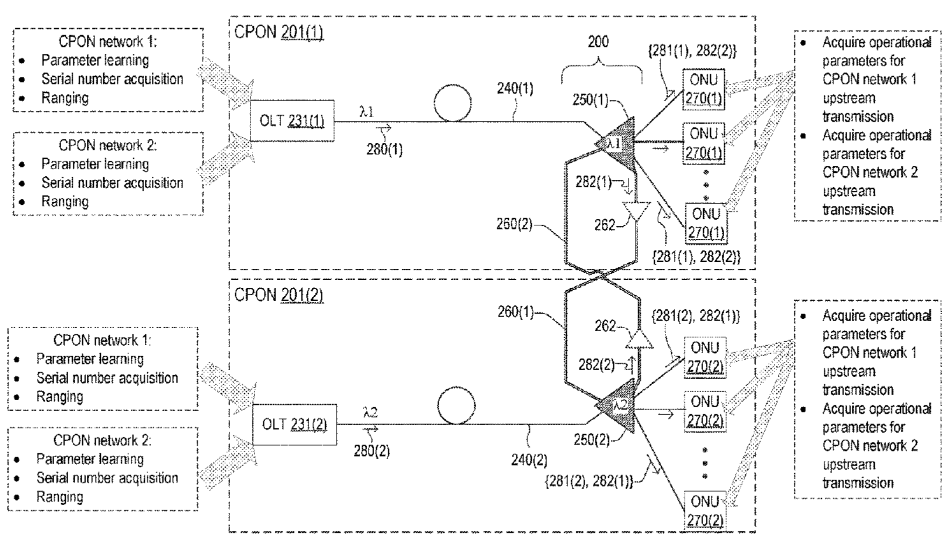
(74) *Attorney, Agent, or Firm* — Cozen O'Connor

(57) **ABSTRACT**

A redundancy link includes a first optical splitter and a second optical splitter. The first optical splitter includes (i) a first hub-side port that optically couples to a first optical line terminal, a first hub-side failover-mode port, (iii) a first plurality of node-side splitter-ports each optically coupled to the first hub-side port and the first hub-side failover-mode port, (iii) a first failover-mode port coupled to the first hub-side port. The second optical splitter includes (i) a second hub-side port that optically couples to a second optical line terminal, a second hub-side failover-mode port optically coupled to the first failover-mode port, (iii) a second plurality of node-side splitter-ports each optically coupled to the second hub-side port and the second hub-side failover-mode port, (iii) a second failover-mode port coupled to the second hub-side port.

23 Claims, 24 Drawing Sheets



Related U.S. Application Data

filed on Sep. 24, 2021, provisional application No. 63/278,988, filed on Nov. 12, 2021.

(58) **Field of Classification Search**
USPC 398/5
See application file for complete search history.

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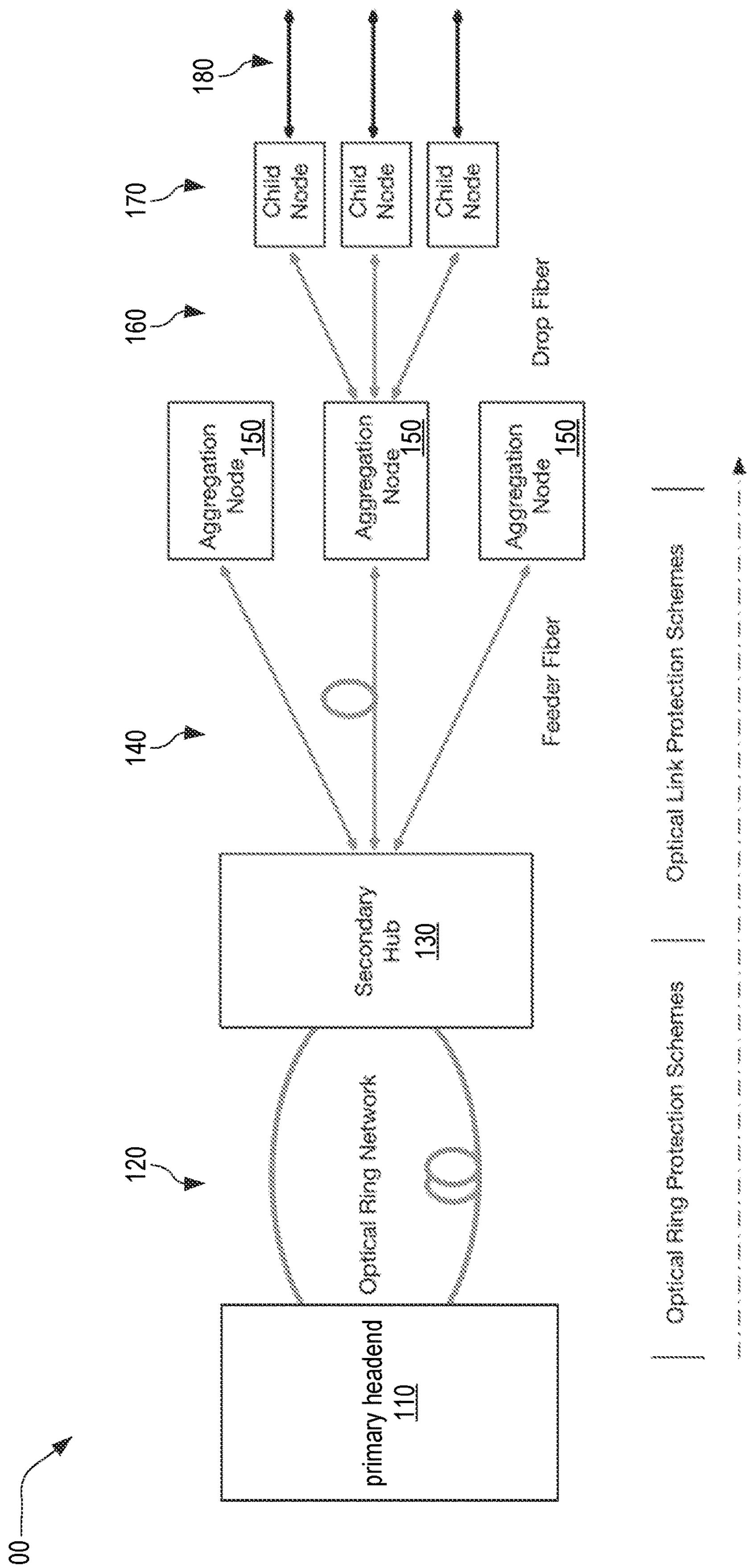
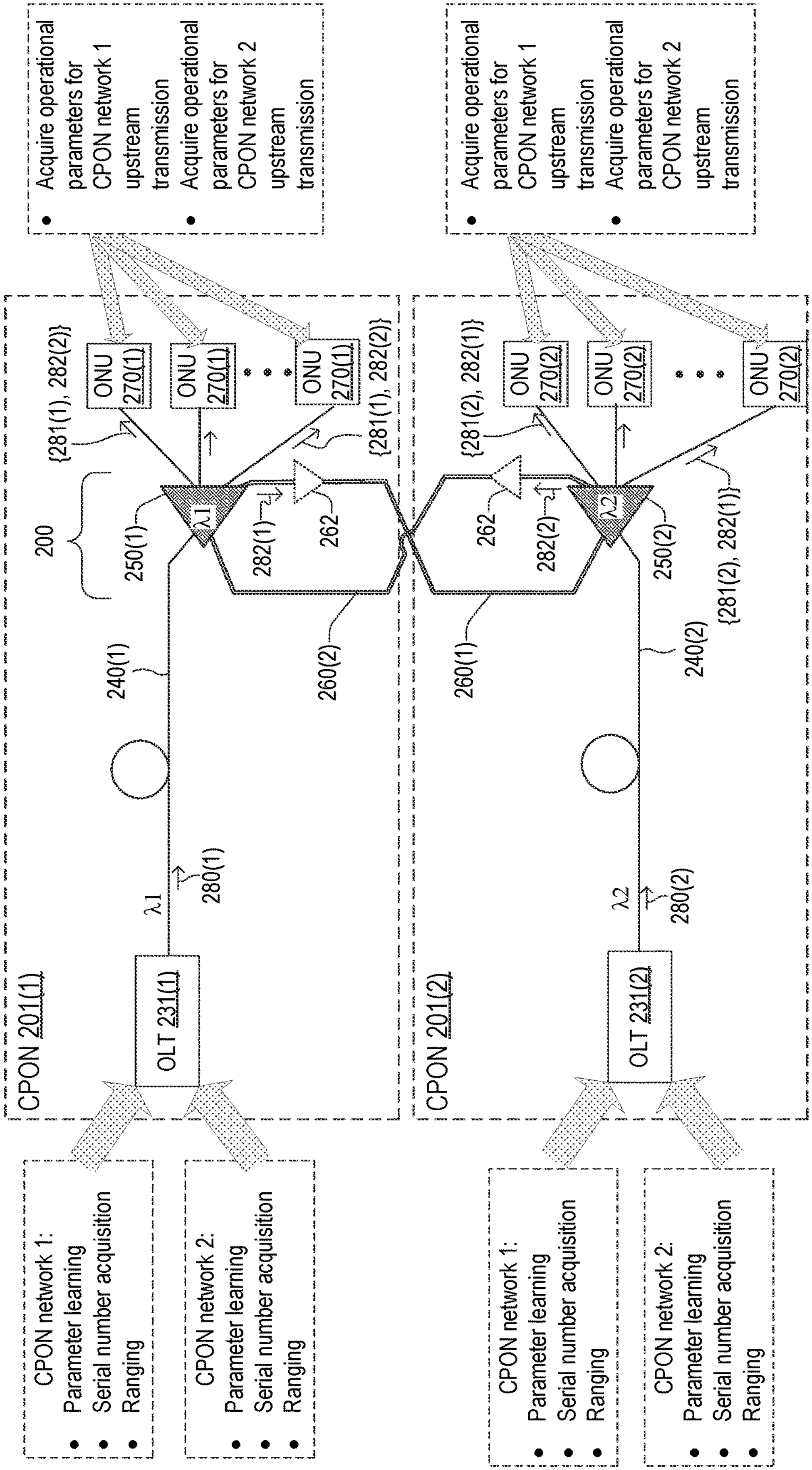

100
primary headend 110
120
Optical Ring Network
Secondary Hub 130
140
Feeder Fiber
Aggregation Node 150
Aggregation Node 150
Aggregation Node 150
160
Drop Fiber
170
Child Node
Child Node
Child Node
180
Optical Ring Protection Schemes
Optical Link Protection Schemes

FIG. 1



Acquire operational parameters for CPON network 1 upstream transmission
Acquire operational parameters for CPON network 2 upstream transmission
Acquire operational parameters for CPON network 1 upstream transmission
Acquire operational parameters for CPON network 2 upstream transmission
CPON 201(1)
CPON 201(2)
OLT 231(1)
OLT 231(2)
λ1
λ2
280(1)
280(2)
240(1)
240(2)
260(1)
260(2)
250(1)
250(2)
282(1)
282(2)
262
262
200
ONU 270(1)
ONU 270(2)
{281(1), 282(2)}
{281(1), 282(2)}
{281(2), 282(1)}
{281(2), 282(1)}
CPON network 1:
Parameter learning
Serial number acquisition
Ranging
CPON network 2:
Parameter learning
Serial number acquisition
Ranging

FIG. 2

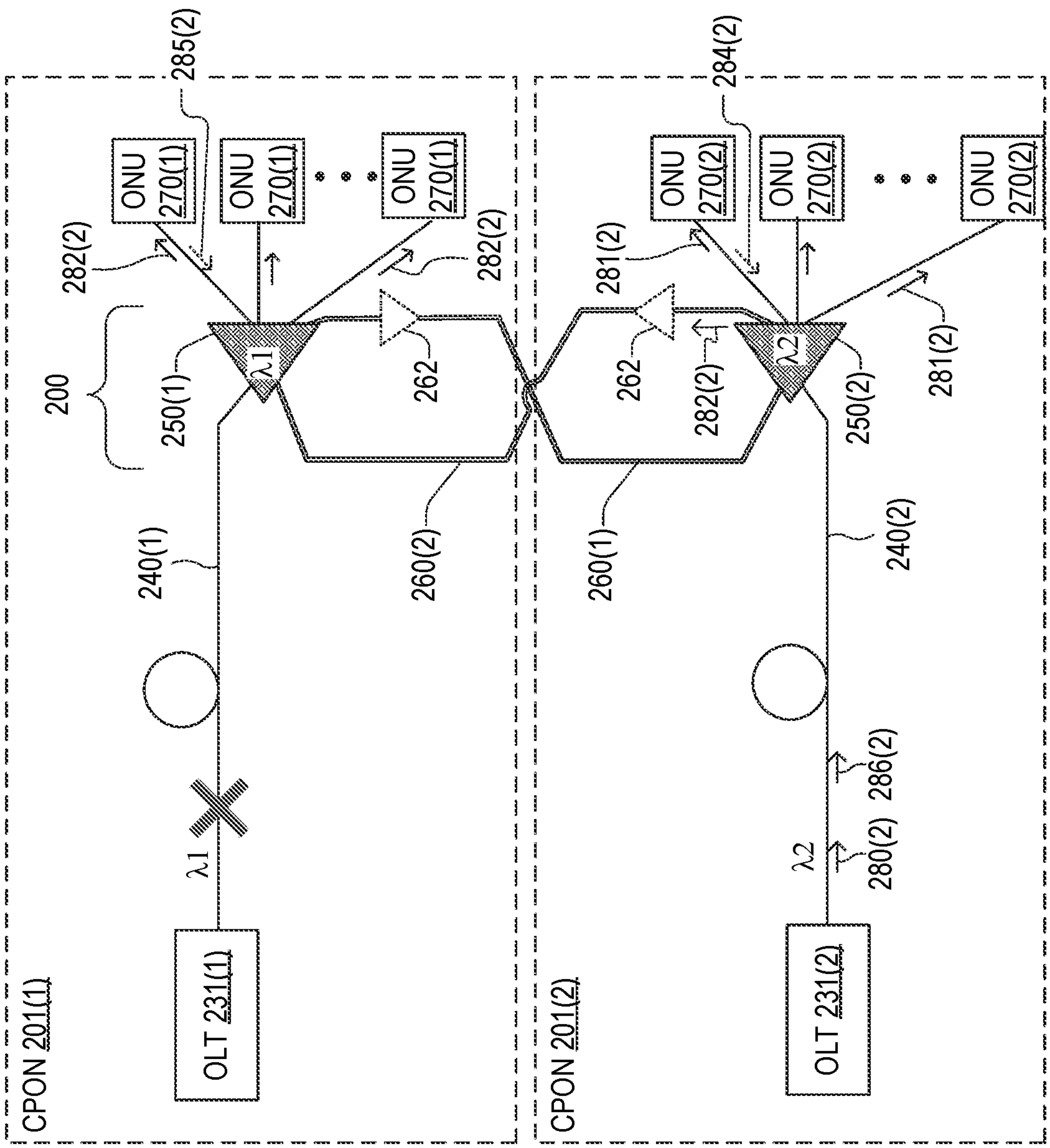

CPON 201(1)
OLT 231(1)
λ1
240(1)
200
250(1)
λ1
282(2)
285(2)
ONU 270(1)
ONU 270(1)
ONU 270(1)
282(2)
262
260(2)
CPON 201(2)
OLT 231(2)
λ2
280(2)
286(2)
240(2)
260(1)
262
282(2)
250(2)
λ2
281(2)
284(2)
ONU 270(2)
ONU 270(2)
ONU 270(2)
281(2)

FIG. 3

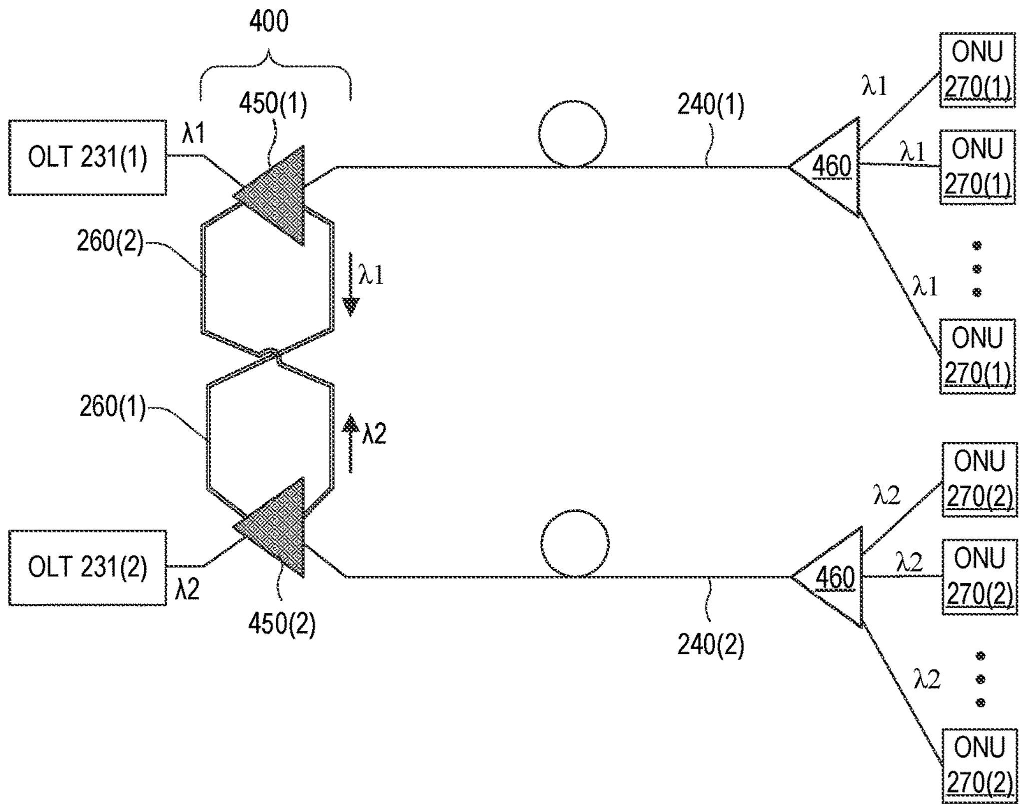

400
450(1)
OLT 231(1)
λ1
260(2)
λ1
260(1)
λ2
OLT 231(2)
λ2
450(2)
240(1)
240(2)
460
460
λ1
ONU 270(1)
λ1
ONU 270(1)
λ1
ONU 270(1)
λ2
ONU 270(2)
λ2
ONU 270(2)
λ2
ONU 270(2)

FIG. 4

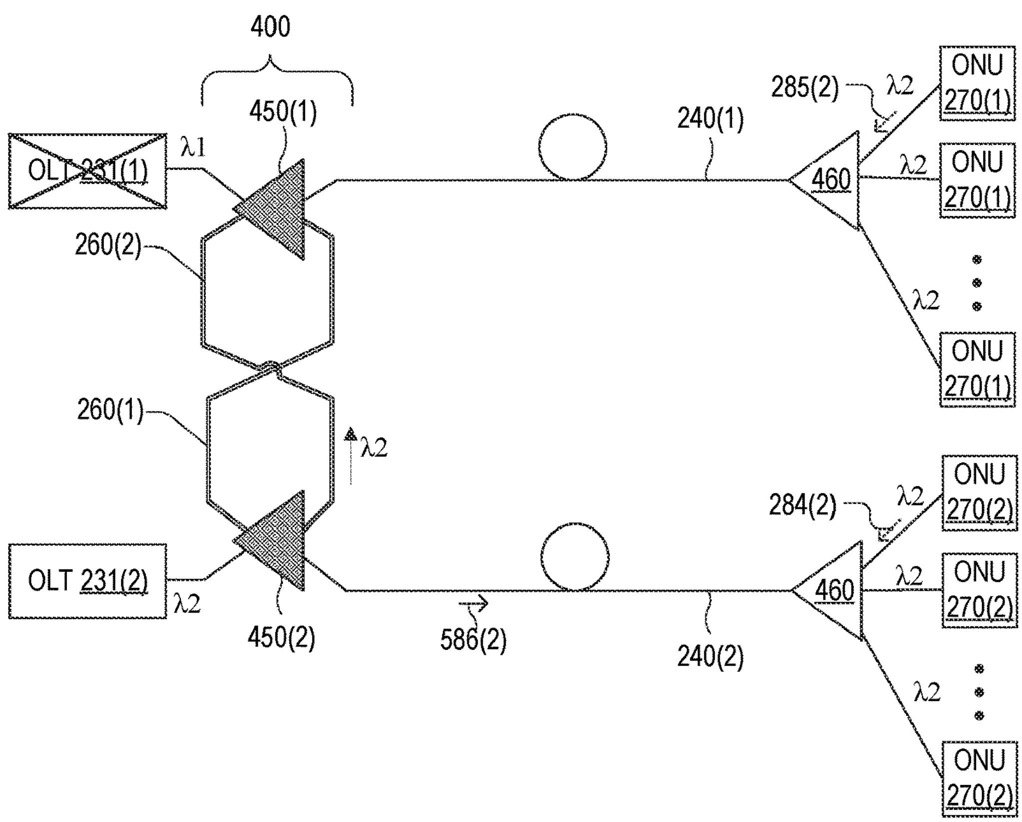

400
450(1)
OLT 231(1)
λ1
260(2)
260(1)
λ2
OLT 231(2)
λ2
450(2)
586(2)
240(1)
240(2)
285(2)
284(2)
460
460
λ2
ONU 270(1)
λ2
ONU 270(1)
λ2
ONU 270(1)
λ2
ONU 270(2)
λ2
ONU 270(2)
λ2
ONU 270(2)

FIG. 5

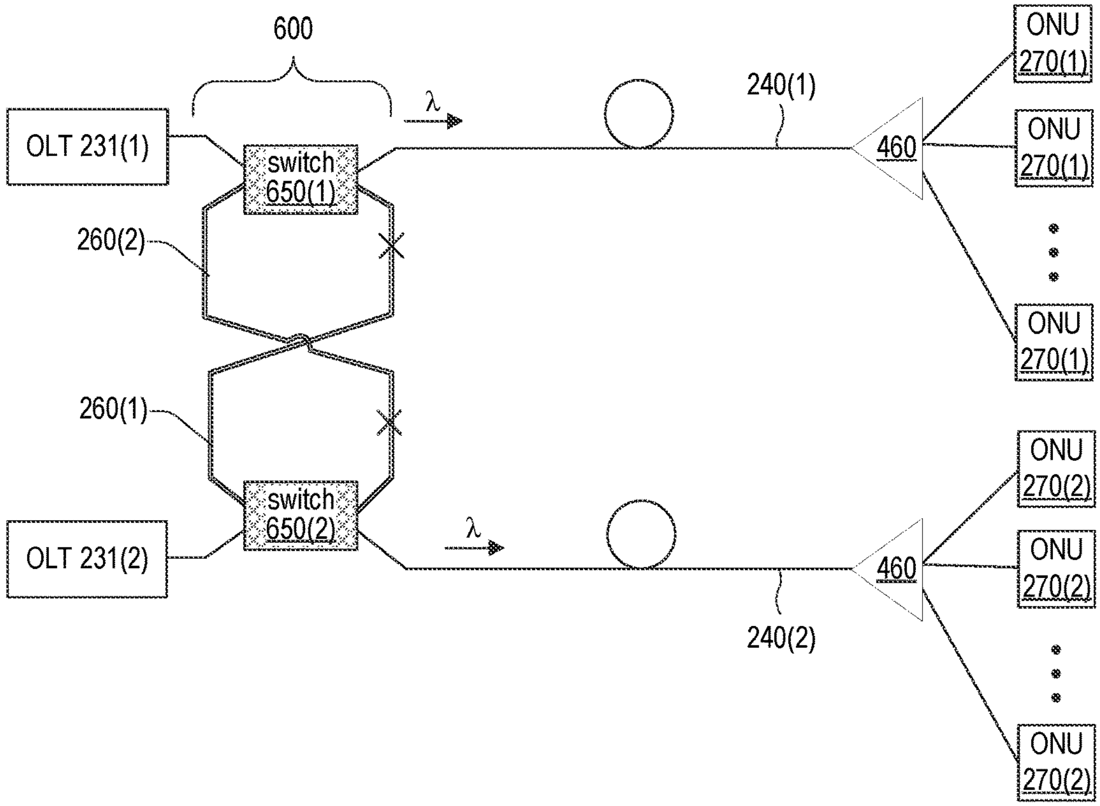

600
λ
OLT 231(1)
switch
650(1)
240(1)
460
ONU
270(1)
ONU
270(1)
ONU
270(1)
260(2)
260(1)
switch
650(2)
OLT 231(2)
λ
460
240(2)
ONU
270(2)
ONU
270(2)
ONU
270(2)

FIG. 6

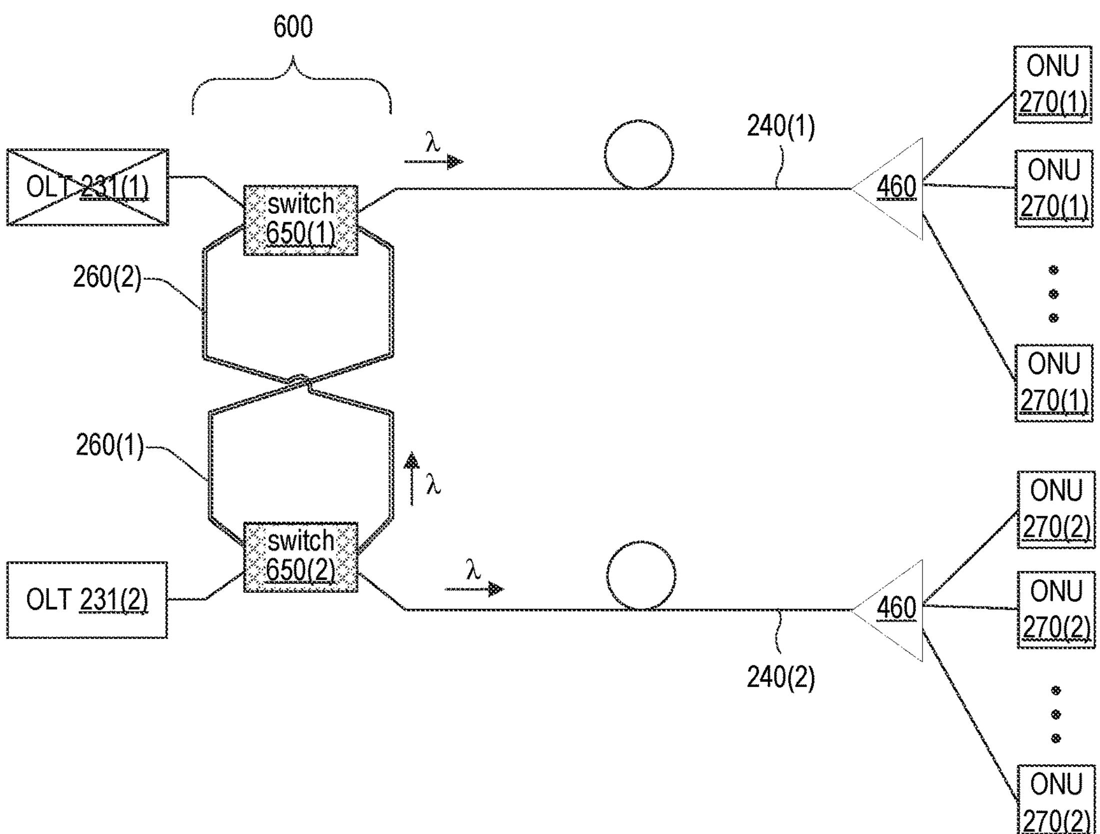

600
λ
OLT 231(1)
switch
650(1)
240(1)
460
ONU
270(1)
ONU
270(1)
ONU
270(1)
260(2)
260(1)
λ
switch
650(2)
OLT 231(2)
λ
460
240(2)
ONU
270(2)
ONU
270(2)
ONU
270(2)

FIG. 7

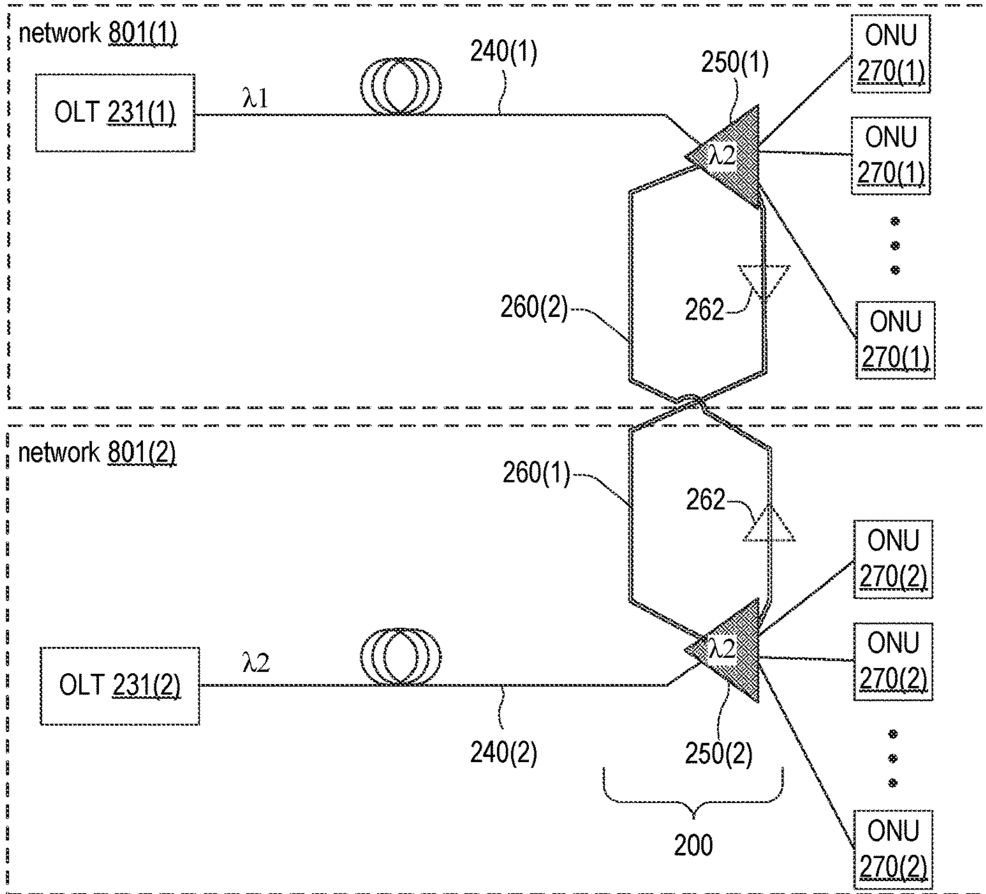

network 801(1)
OLT 231(1)
λ1
240(1)
250(1)
λ2
ONU 270(1)
ONU 270(1)
ONU 270(1)
260(2)
262
network 801(2)
260(1)
262
ONU 270(2)
ONU 270(2)
OLT 231(2)
λ2
λ2
240(2)
250(2)
200
ONU 270(2)

FIG. 8

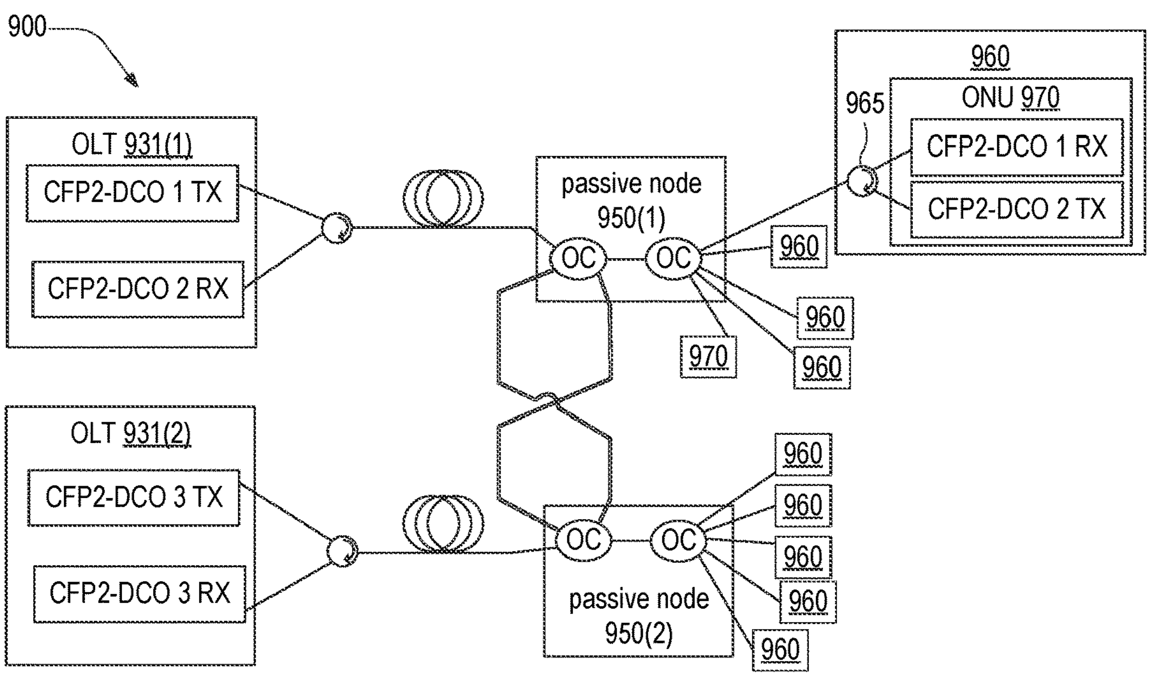

900
960
ONU 970
965
CFP2-DCO 1 RX
CFP2-DCO 2 TX
OLT 931(1)
CFP2-DCO 1 TX
CFP2-DCO 2 RX
passive node 950(1)
OC
OC
960
960
970
960
OLT 931(2)
CFP2-DCO 3 TX
CFP2-DCO 3 RX
OC
OC
passive node 950(2)
960
960
960
960
960

FIG. 9

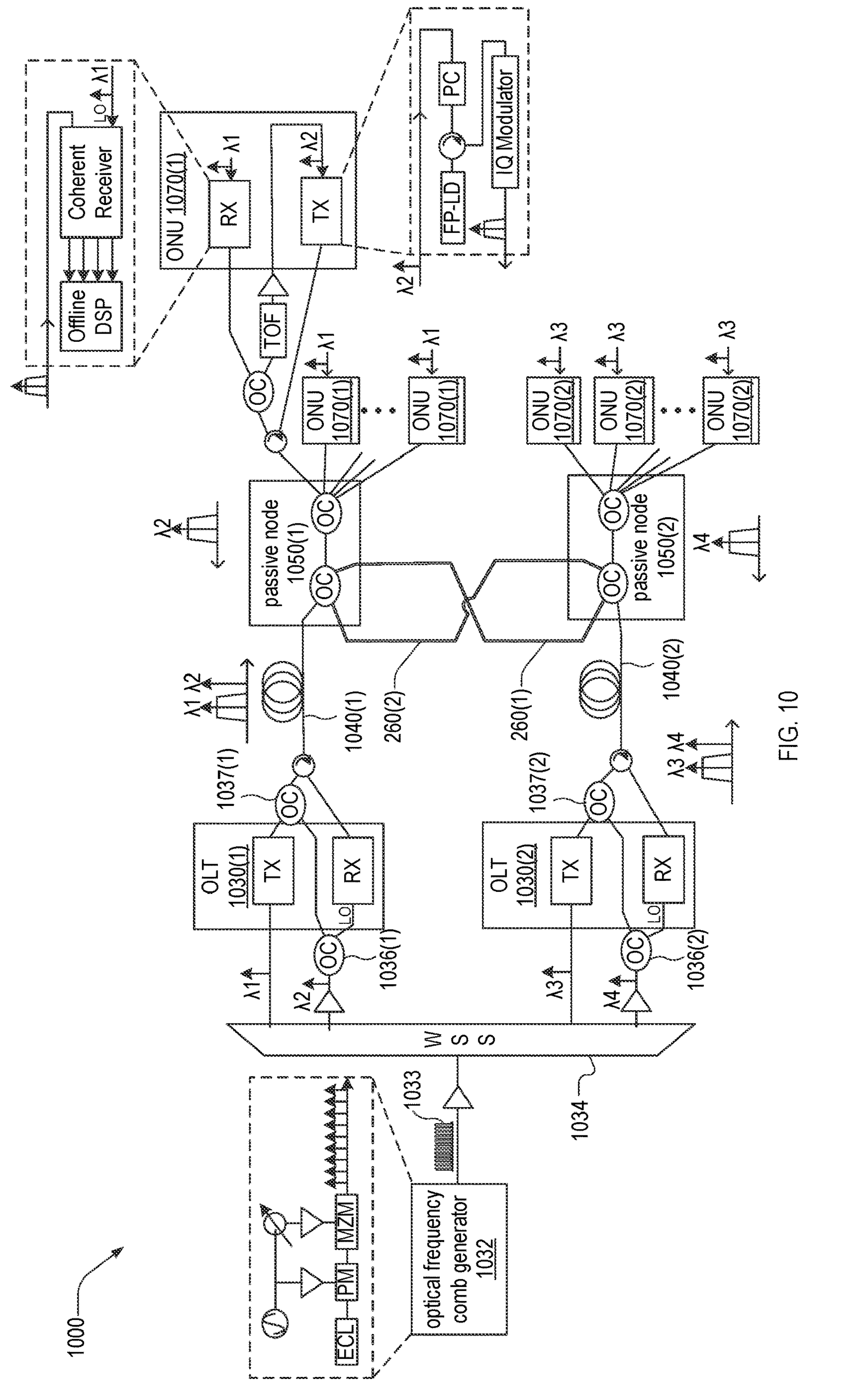

1000
optical frequency comb generator 1032
ECL
PM
MZM
1033
1034
W S S
λ1
λ2
λ3
λ4
OC
1036(1)
1036(2)
OLT 1030(1)
OLT 1030(2)
TX
RX
LO
1037(1)
1037(2)
1040(1)
1040(2)
260(2)
260(1)
passive node 1050(1)
passive node 1050(2)
ONU 1070(1)
ONU 1070(2)
TOF
Offline DSP
Coherent Receiver
FP-LD
PC
IQ Modulator

FIG. 10

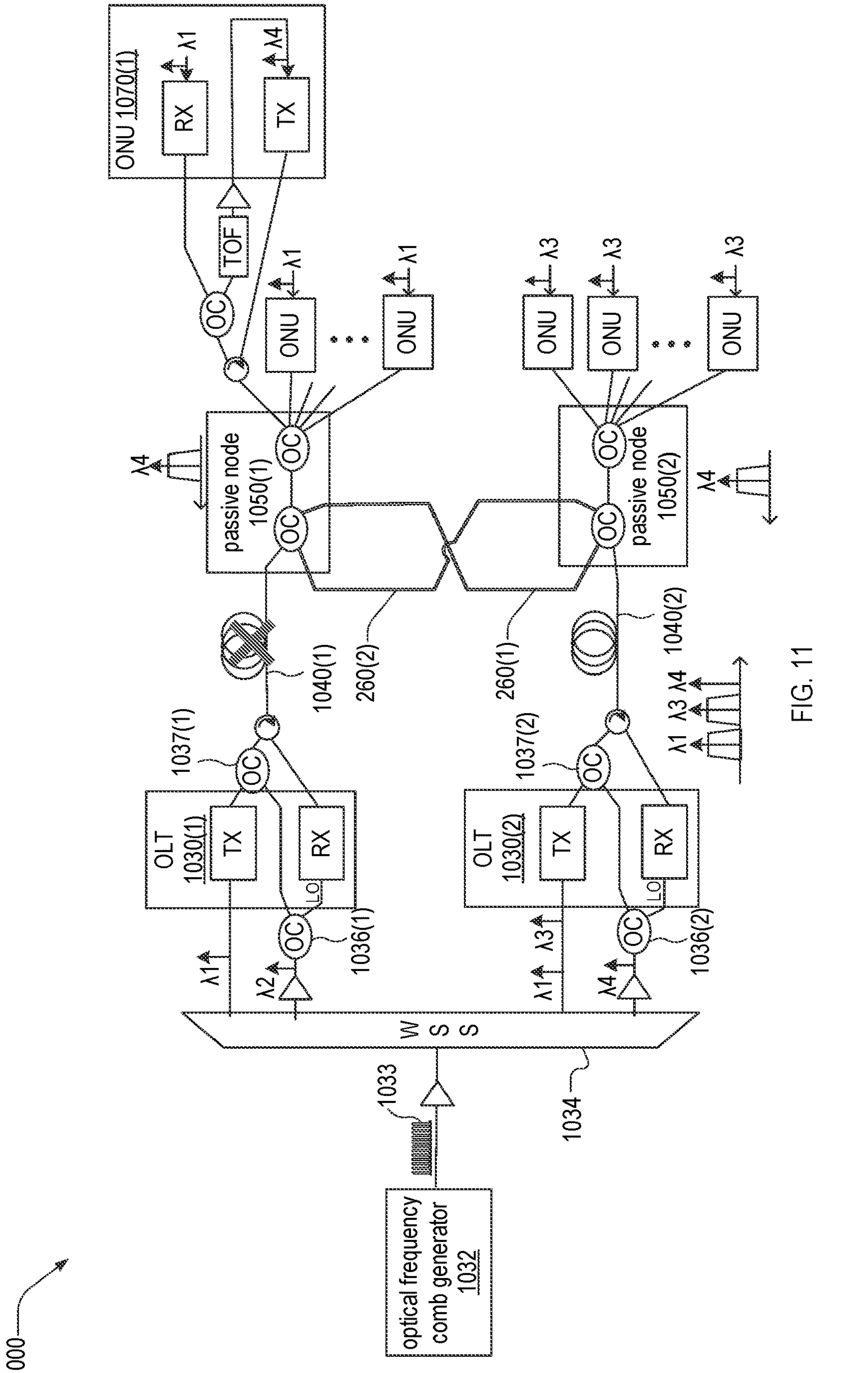

1000
optical frequency comb generator 1032
1033
1034
WSS
λ1
λ2
λ3
λ4
OC
1036(1)
1036(2)
LO
OLT 1030(1)
OLT 1030(2)
TX
RX
1037(1)
1037(2)
1040(1)
1040(2)
260(2)
260(1)
passive node 1050(1)
passive node 1050(2)
ONU
TOF
ONU 1070(1)

FIG. 11

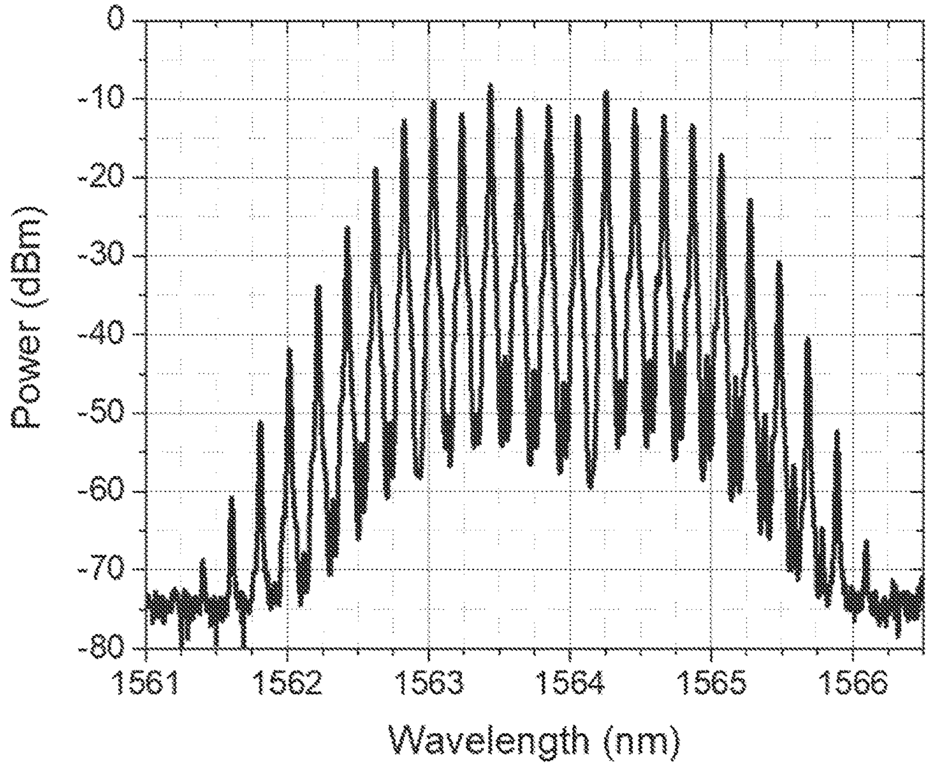

0
-10
-20
-30
-40
-50
-60
-70
-80
Power (dBm)
1561
1562
1563
1564
1565
1566
Wavelength (nm)

FIG. 12

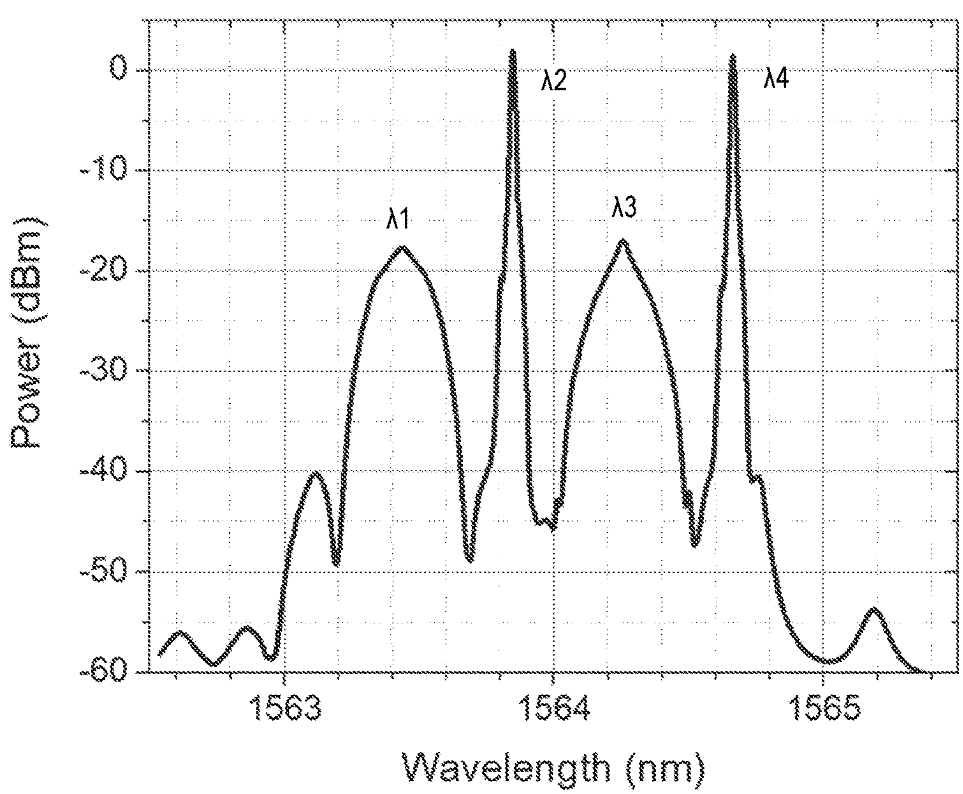
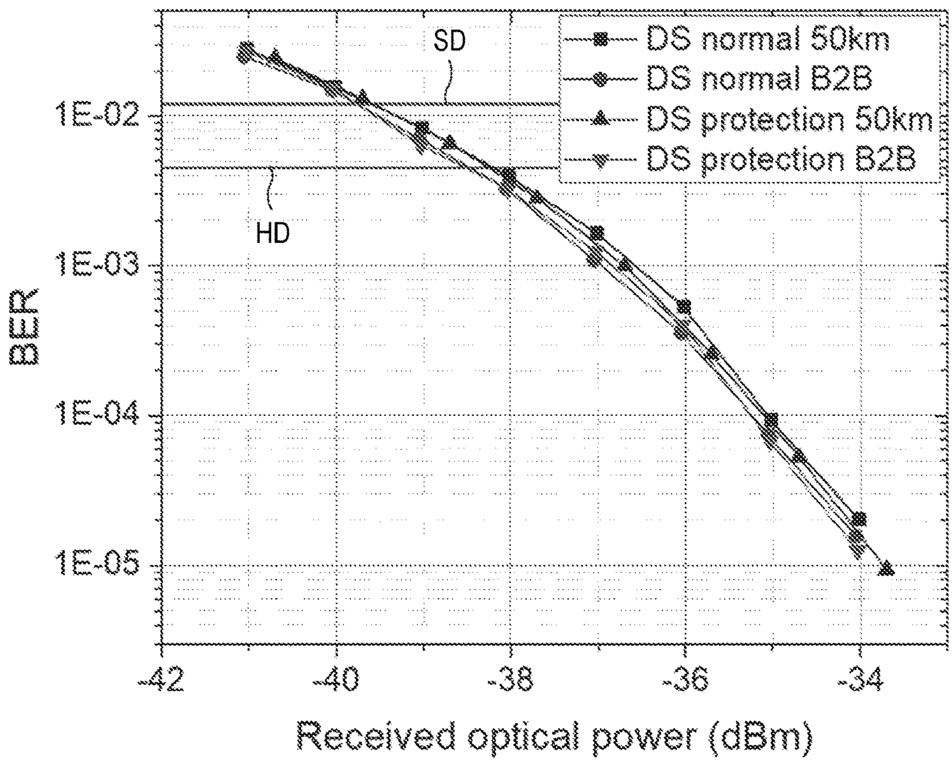
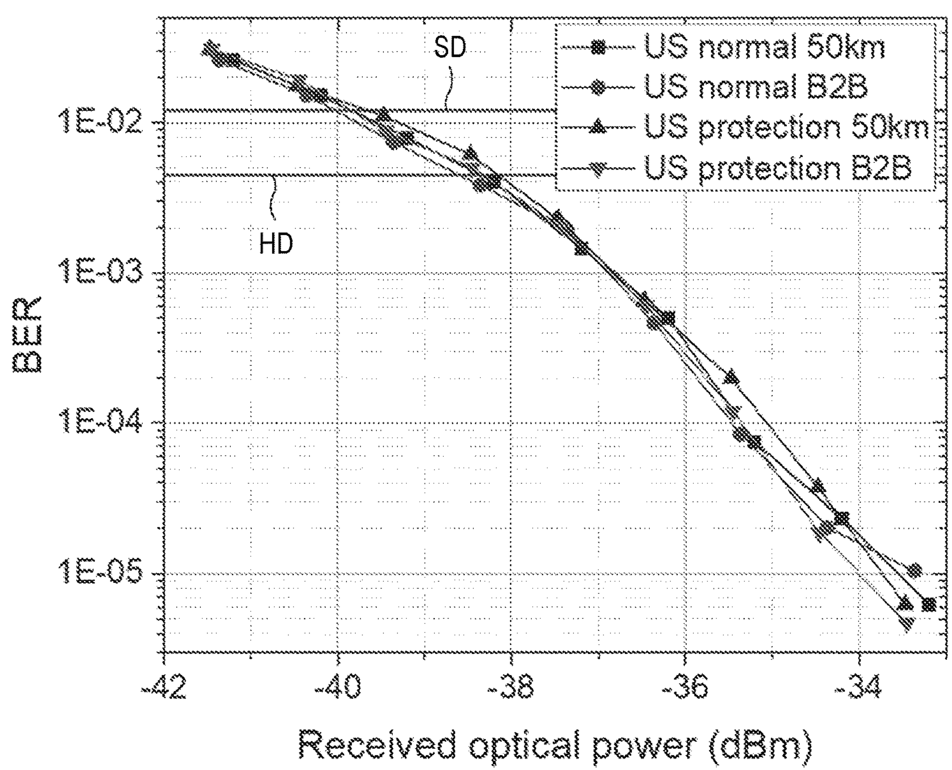

λ1
λ2
λ3
λ4
0
-10
-20
-30
-40
-50
-60
Power (dBm)
1563
1564
1565
Wavelength (nm)

FIG. 13



SD
HD
DS normal 50km
DS normal B2B
DS protection 50km
DS protection B2B
BER
1E-02
1E-03
1E-04
1E-05
-42
-40
-38
-36
-34
Received optical power (dBm)

FIG. 14



SD
HD
US normal 50km
US normal B2B
US protection 50km
US protection B2B
BER
1E-02
1E-03
1E-04
1E-05
-42
-40
-38
-36
-34
Received optical power (dBm)

FIG. 15

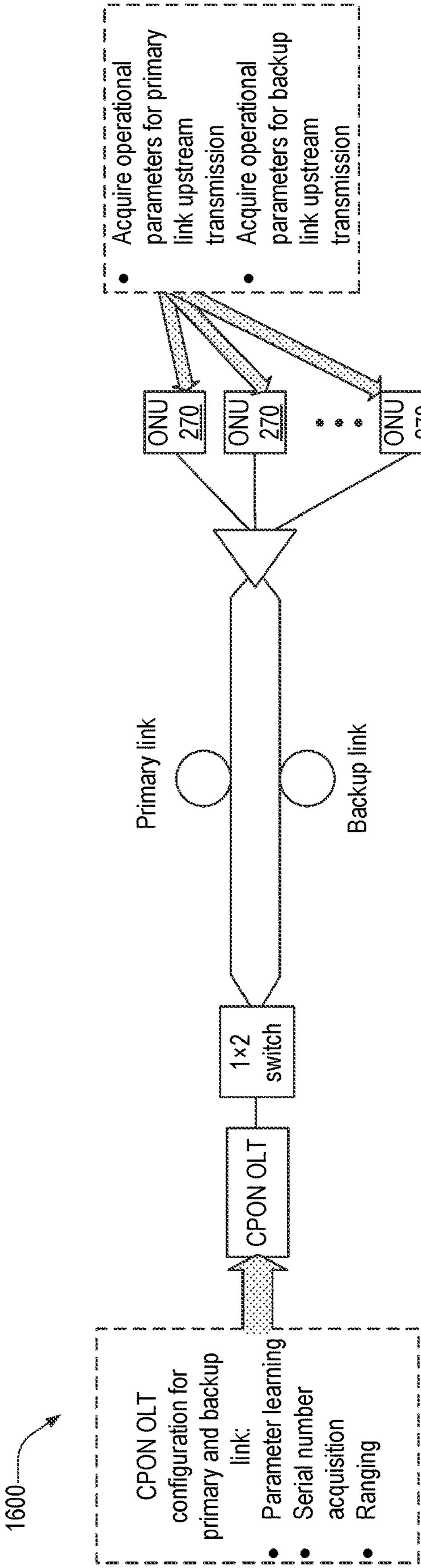

1600
CPON OLT configuration for primary and backup link:
• Parameter learning
• Serial number acquisition
• Ranging
CPON OLT
1×2 switch
Primary link
Backup link
ONU 270
ONU 270
ONU 270
• Acquire operational parameters for primary link upstream transmission
• Acquire operational parameters for backup link upstream transmission

FIG. 16

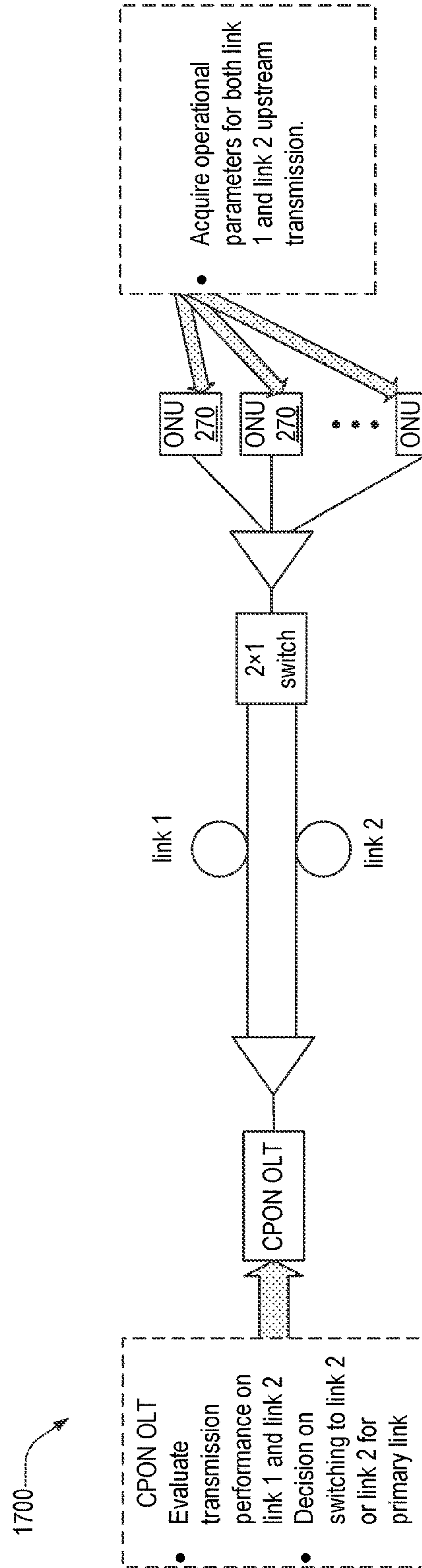

1700
CPON OLT
• Evaluate transmission performance on link 1 and link 2
• Decision on switching to link 2 or link 2 for primary link
CPON OLT
link 1
link 2
2×1 switch
ONU 270
ONU 270
ONU 270
• Acquire operational parameters for both link 1 and link 2 upstream transmission.

FIG. 17

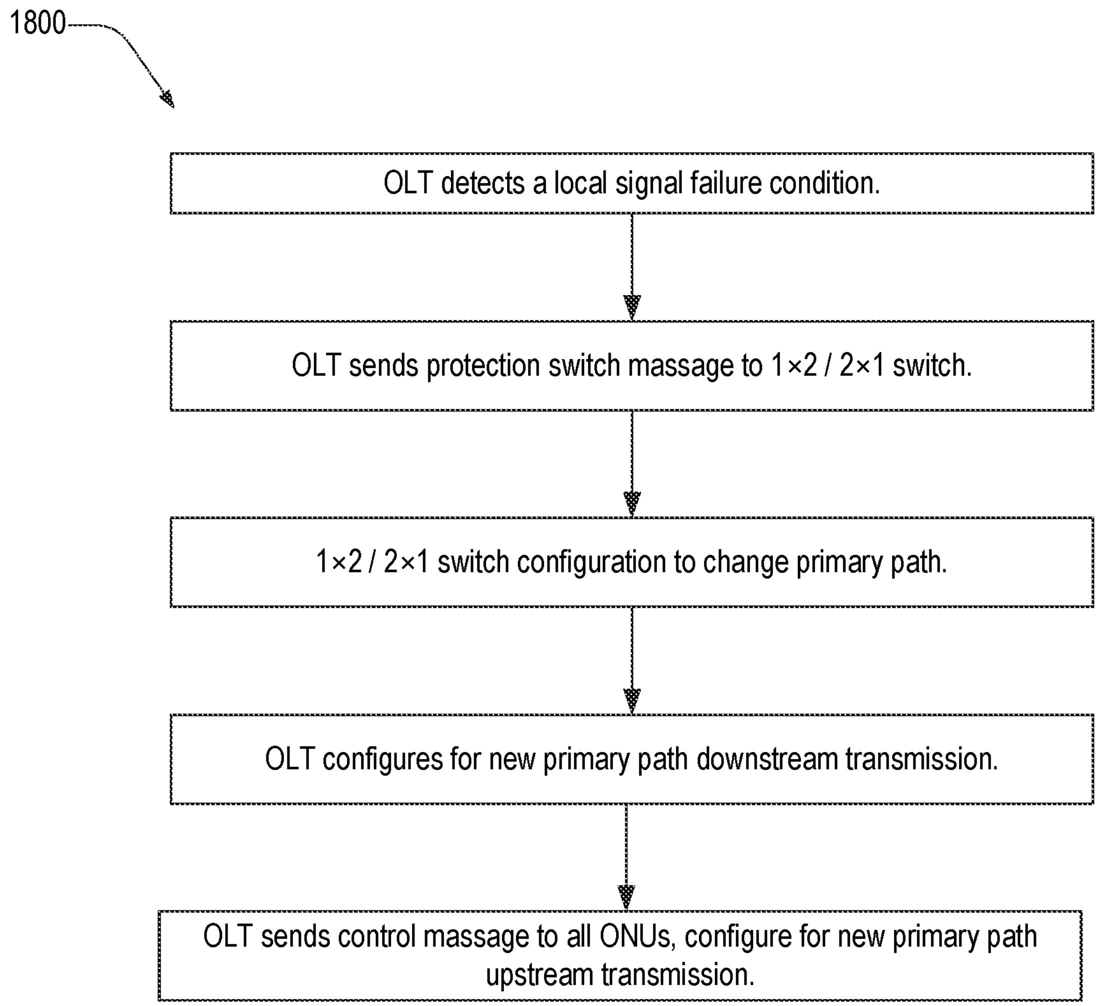

1800
OLT detects a local signal failure condition.
OLT sends protection switch massage to 1×2 / 2×1 switch.
1×2 / 2×1 switch configuration to change primary path.
OLT configures for new primary path downstream transmission.
OLT sends control massage to all ONUs, configure for new primary path upstream transmission.

FIG. 18

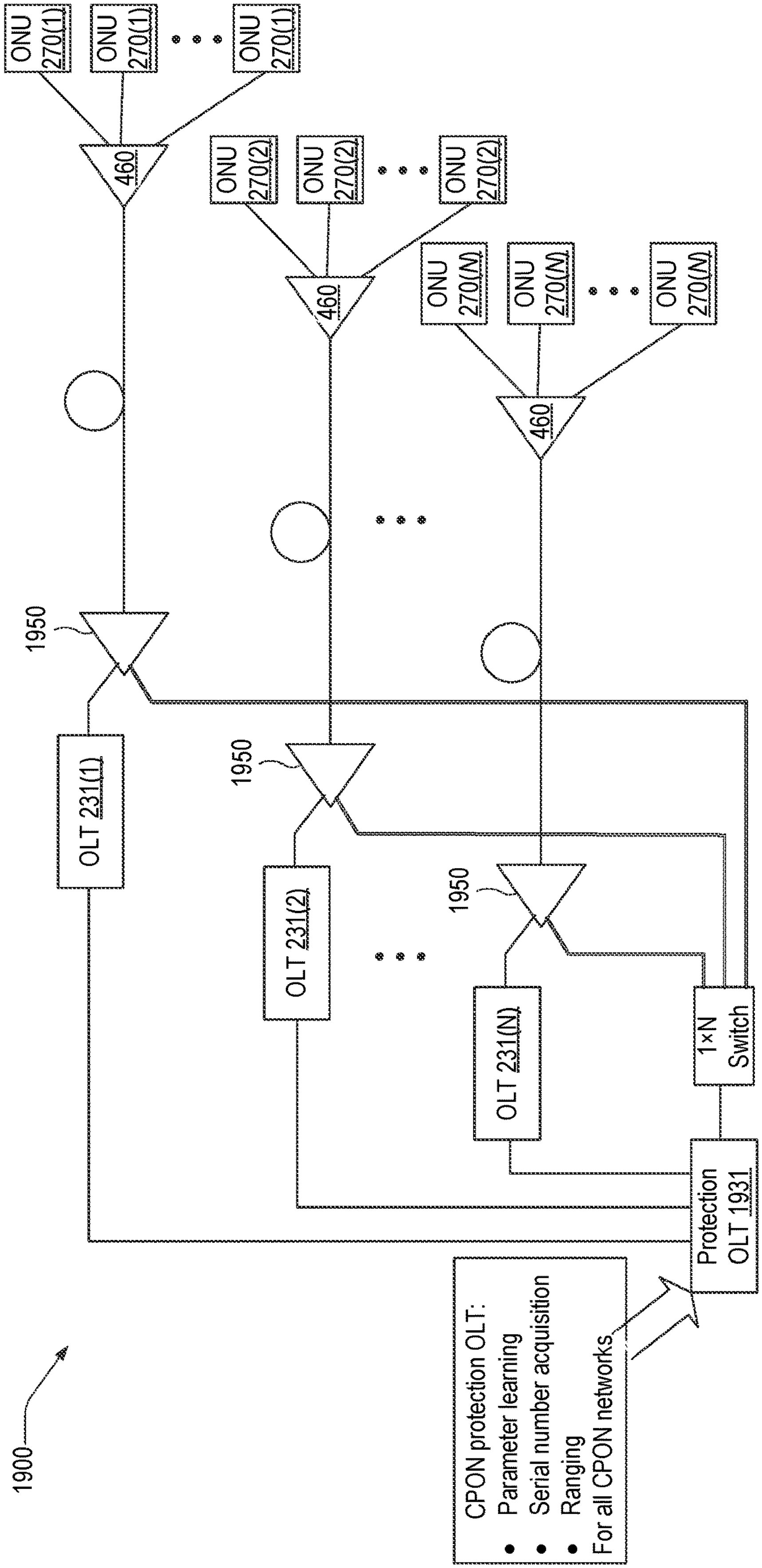
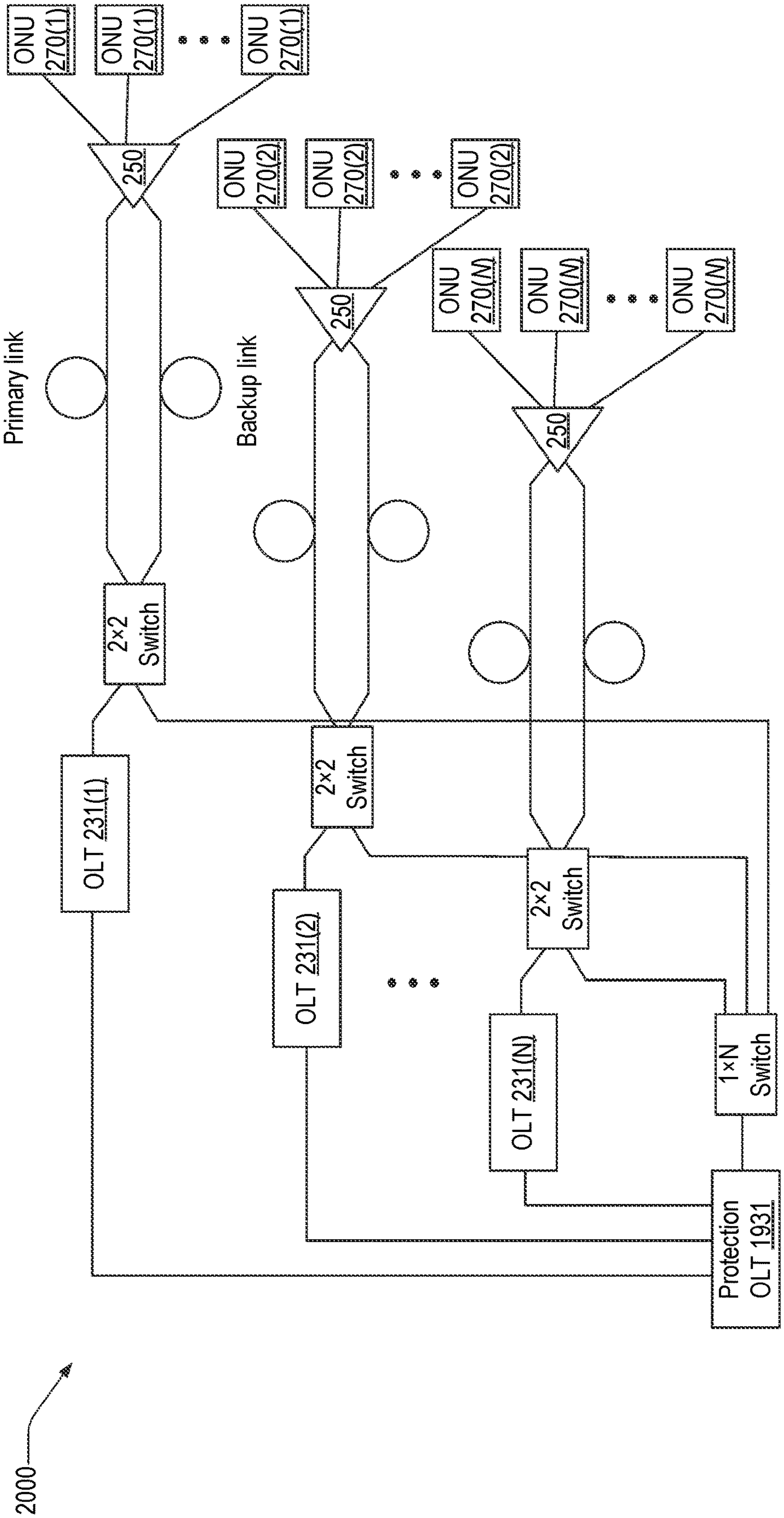

1900
ONU 270(1)
ONU 270(1)
ONU 270(1)
460
ONU 270(2)
ONU 270(2)
ONU 270(2)
460
ONU 270(N)
ONU 270(N)
ONU 270(N)
460
1950
1950
1950
OLT 231(1)
OLT 231(2)
OLT 231(N)
1×N Switch
Protection OLT 1931
CPON protection OLT:
• Parameter learning
• Serial number acquisition
• Ranging
For all CPON networks

FIG. 19



2000
ONU 270(1)
ONU 270(1)
ONU 270(1)
250
ONU 270(2)
ONU 270(2)
ONU 270(2)
250
ONU 270(N)
ONU 270(N)
ONU 270(N)
250
Primary link
Backup link
2×2 Switch
2×2 Switch
2×2 Switch
OLT 231(1)
OLT 231(2)
OLT 231(N)
1×N Switch
Protection OLT 1931

FIG. 20

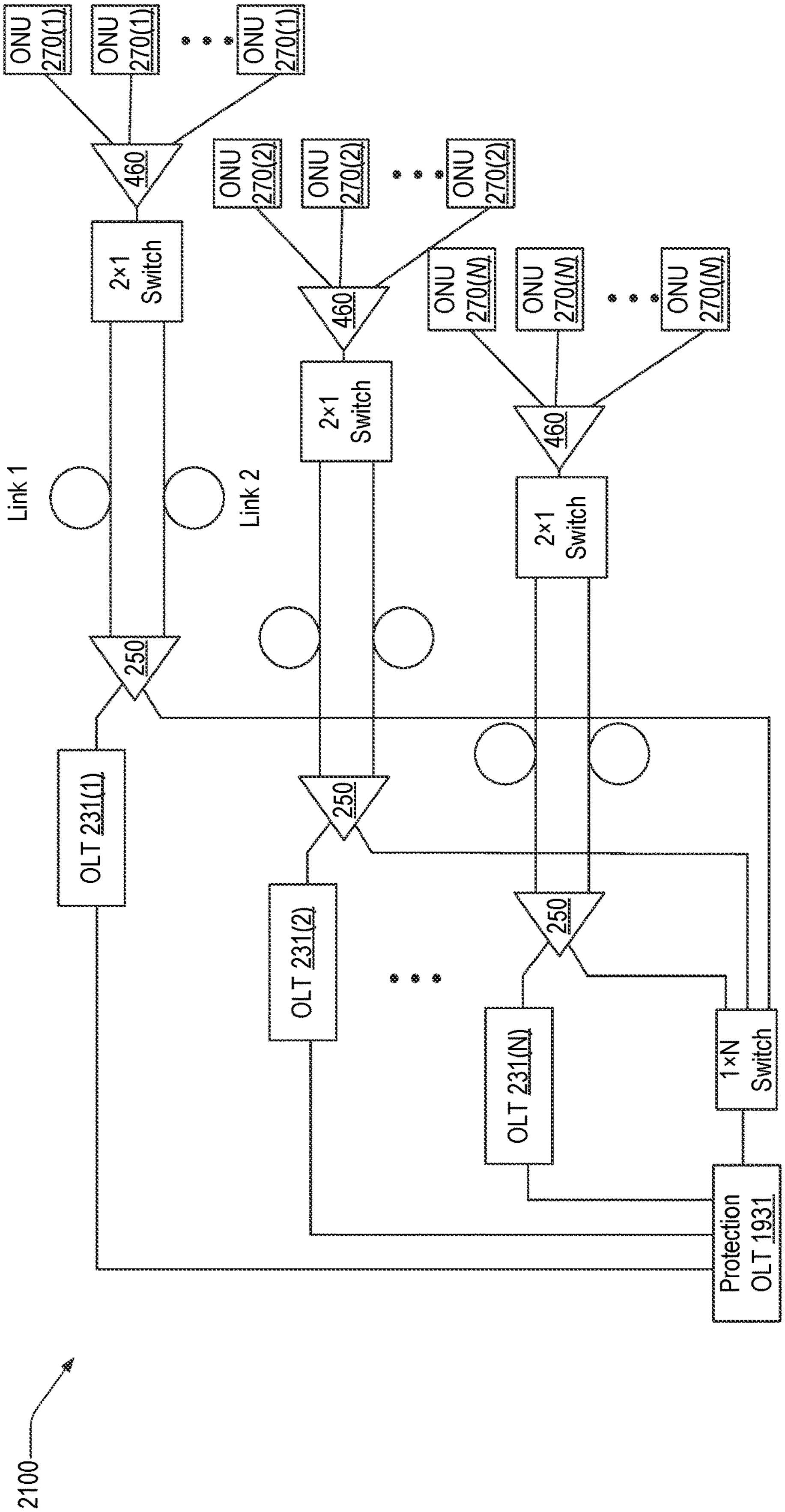

ONU 270(1)
ONU 270(1)
ONU 270(1)
460
2×1 Switch
Link 1
Link 2
250
OLT 231(1)
ONU 270(2)
ONU 270(2)
ONU 270(2)
460
2×1 Switch
250
OLT 231(2)
ONU 270(N)
ONU 270(N)
ONU 270(N)
460
2×1 Switch
250
OLT 231(N)
1×N Switch
Protection OLT 1931
2100

FIG. 21

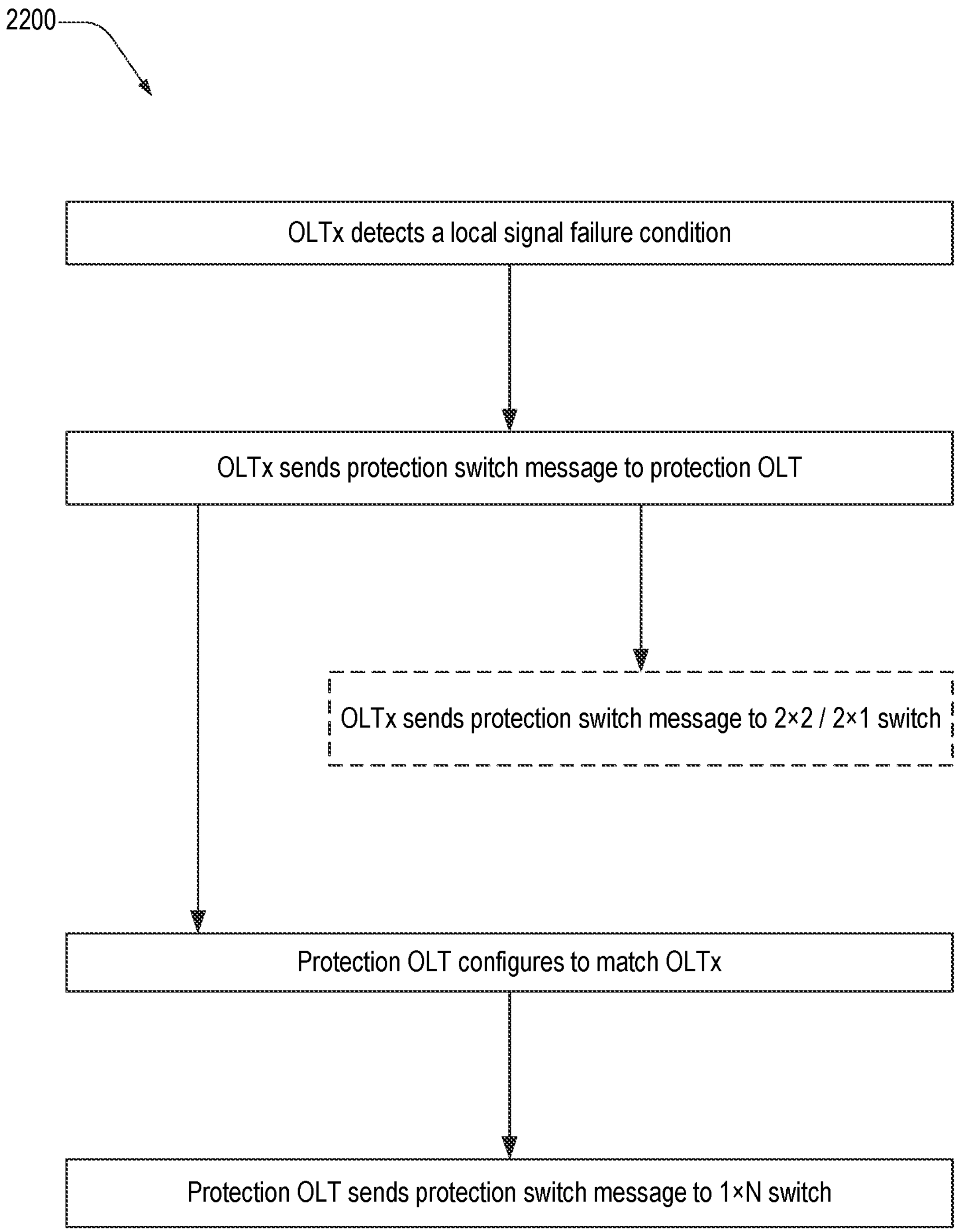

2200
OLTx detects a local signal failure condition
OLTx sends protection switch message to protection OLT
OLTx sends protection switch message to 2×2 / 2×1 switch
Protection OLT configures to match OLTx
Protection OLT sends protection switch message to 1×N switch

FIG. 22

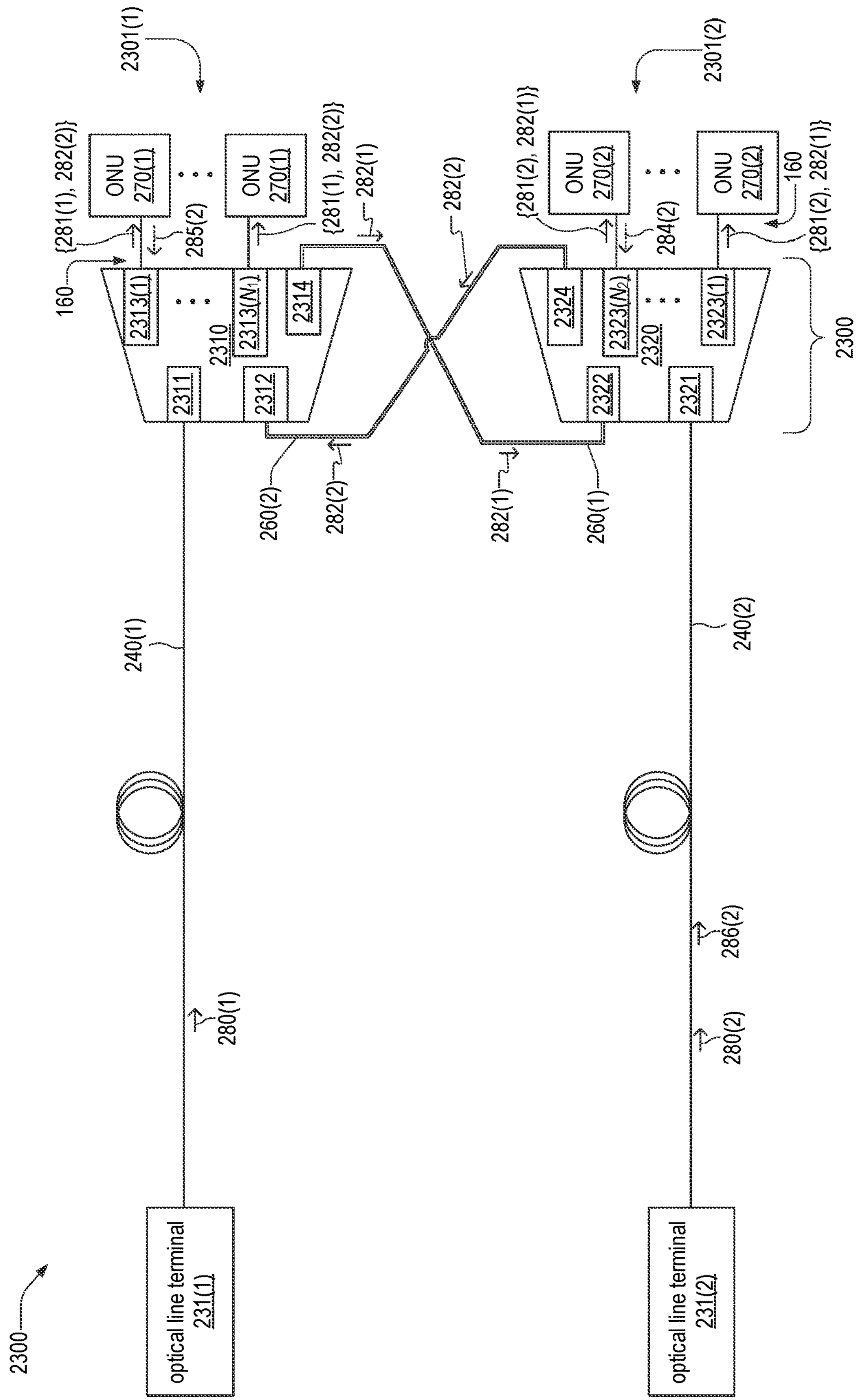

2300
2301(1)
2301(2)
ONU
270(1)
ONU
270(1)
ONU
270(2)
ONU
270(2)
{281(1), 282(2)}
{281(1), 282(2)}
{281(2), 282(1)}
{281(2), 282(1)}
285(2)
284(2)
160
160
282(1)
282(2)
2313(1)
2313(N1)
2314
2310
2311
2312
2324
2323(N2)
2323(1)
2320
2322
2321
2300
260(2)
282(2)
282(1)
260(1)
240(1)
240(2)
286(2)
280(1)
280(2)
optical line terminal
231(1)
optical line terminal
231(2)

FIG. 23

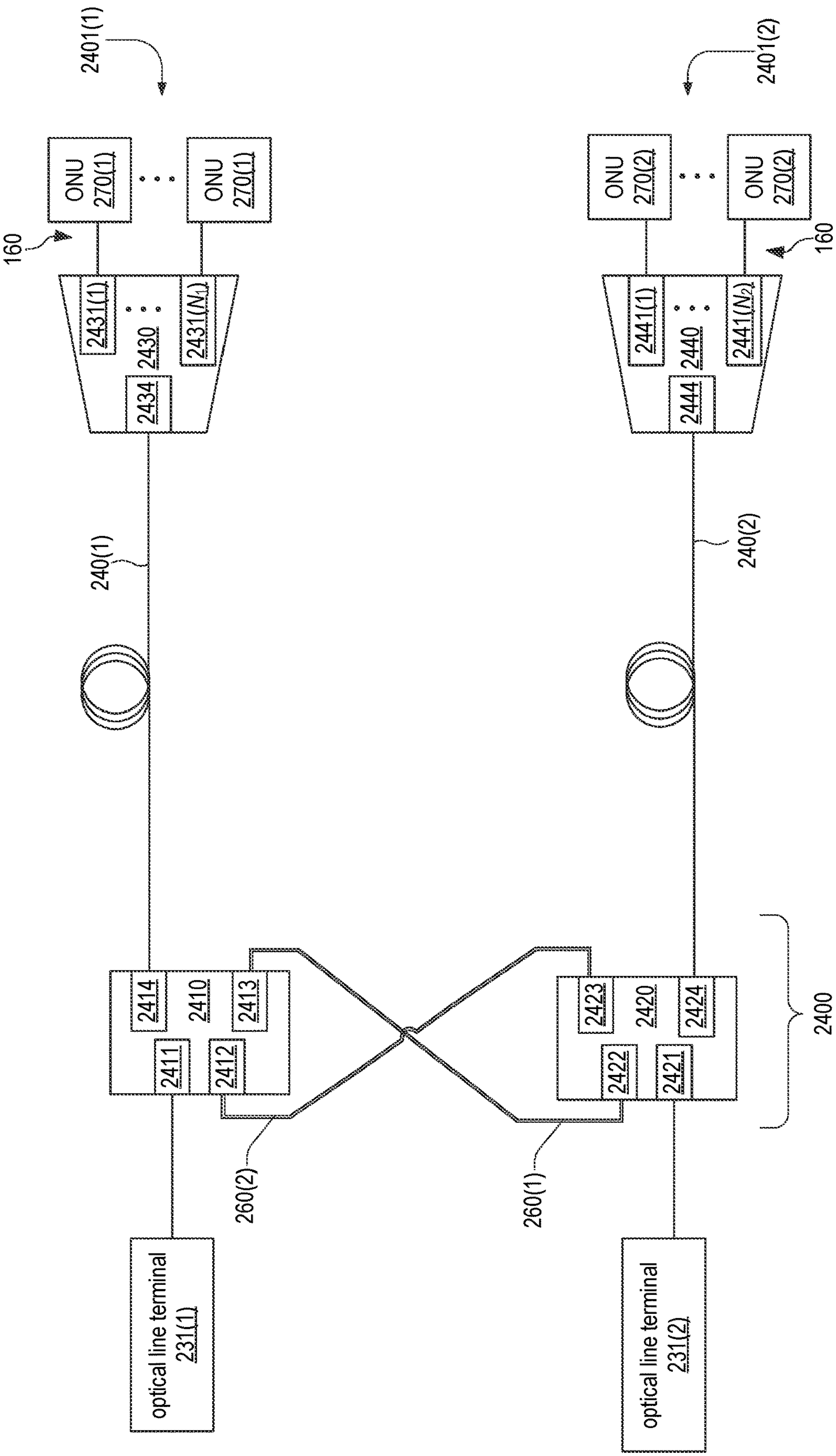
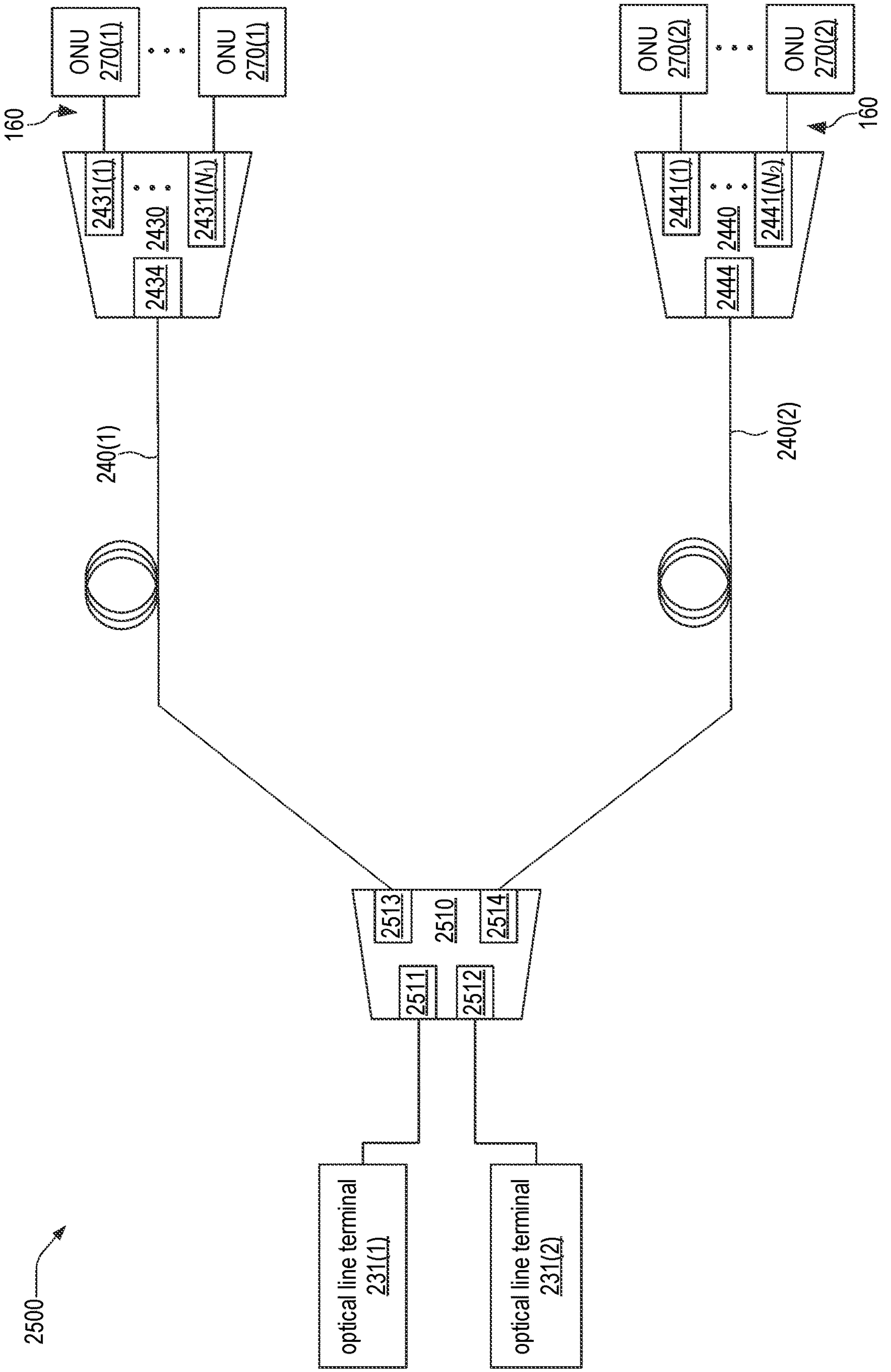

2401(1)
2401(2)
ONU 270(1)
ONU 270(1)
ONU 270(2)
ONU 270(2)
160
160
2431(1)
2431(N_1)
2430
2434
2441(1)
2441(N_2)
2440
2444
240(1)
240(2)
2414
2410
2413
2411
2412
2423
2420
2424
2422
2421
2400
260(2)
260(1)
optical line terminal 231(1)
optical line terminal 231(2)

FIG. 24



2500
optical line terminal 231(1)
optical line terminal 231(2)
2511
2512
2510
2513
2514
240(1)
240(2)
2434
2430
2431(1)
2431(N1)
2444
2440
2441(1)
2441(N2)
160
ONU 270(1)
ONU 270(1)
160
ONU 270(2)
ONU 270(2)

FIG. 25

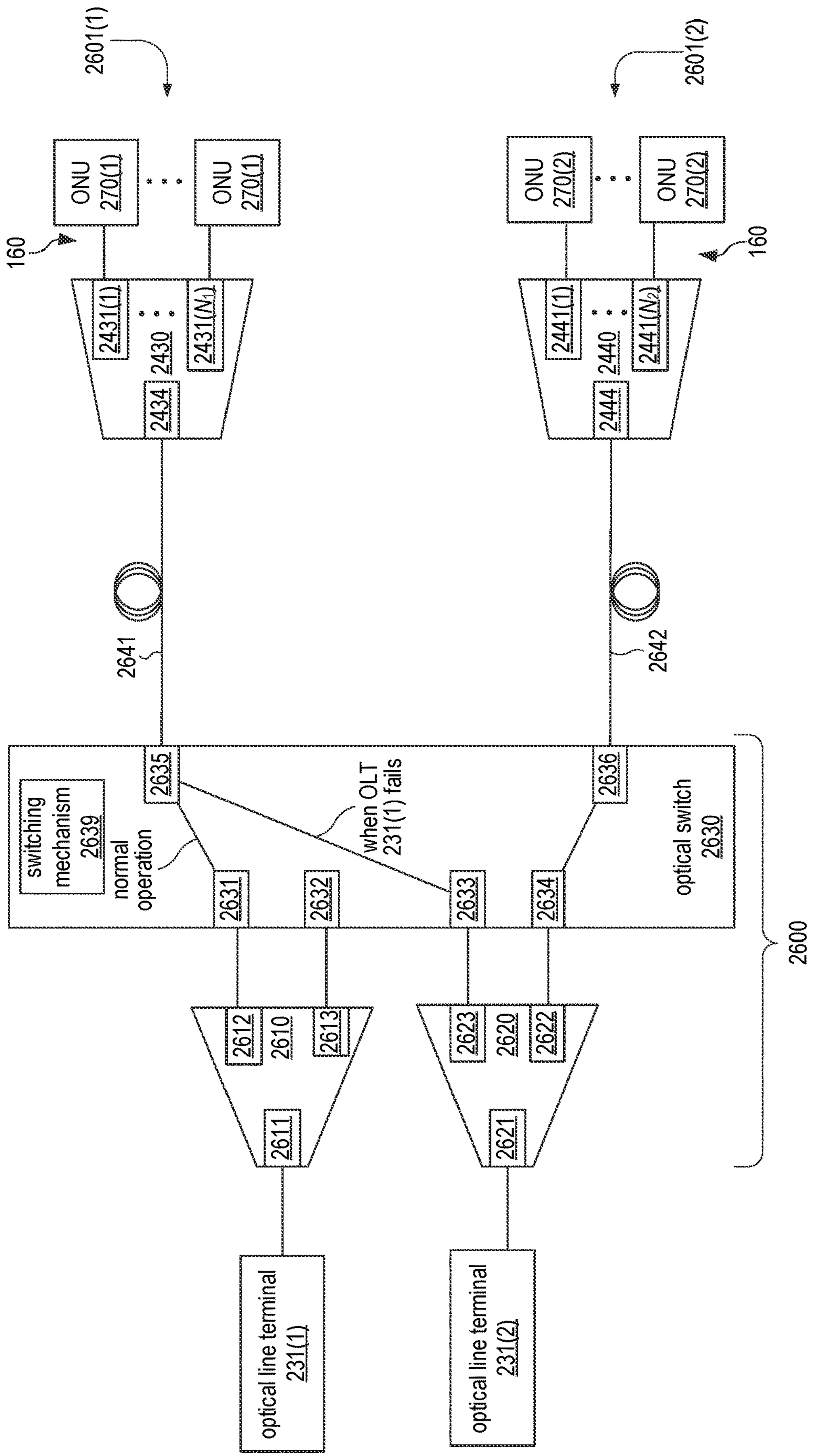

2601(1)
2601(2)
160
160
ONU 270(1)
ONU 270(1)
ONU 270(2)
ONU 270(2)
2431(1)
2431(N1)
2430
2434
2441(1)
2441(N2)
2440
2444
2641
2642
switching mechanism 2639
normal operation
when OLT 231(1) fails
optical switch 2630
2631
2632
2633
2634
2635
2636
2612
2613
2610
2611
2623
2622
2620
2621
2600
optical line terminal 231(1)
optical line terminal 231(2)

FIG. 26

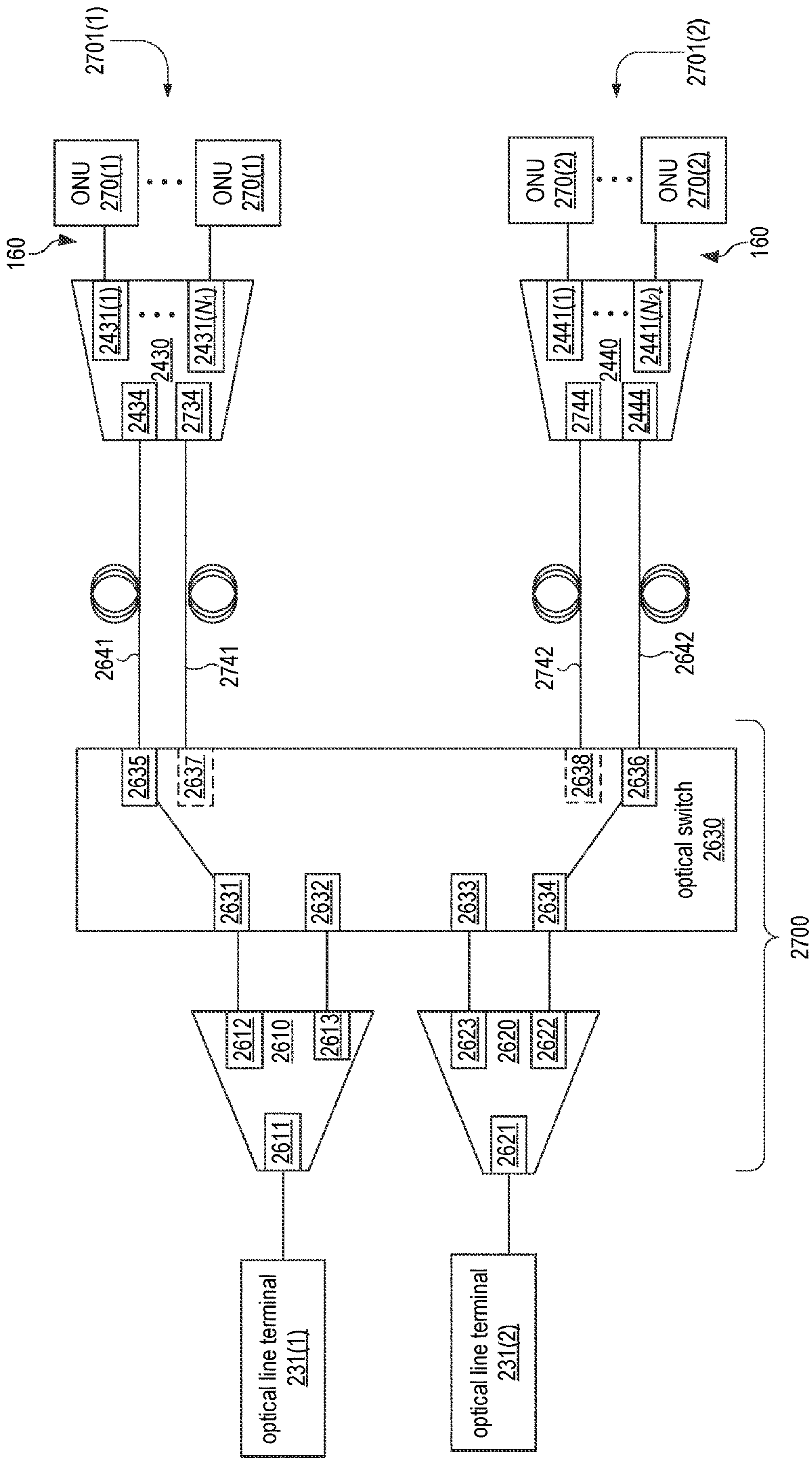
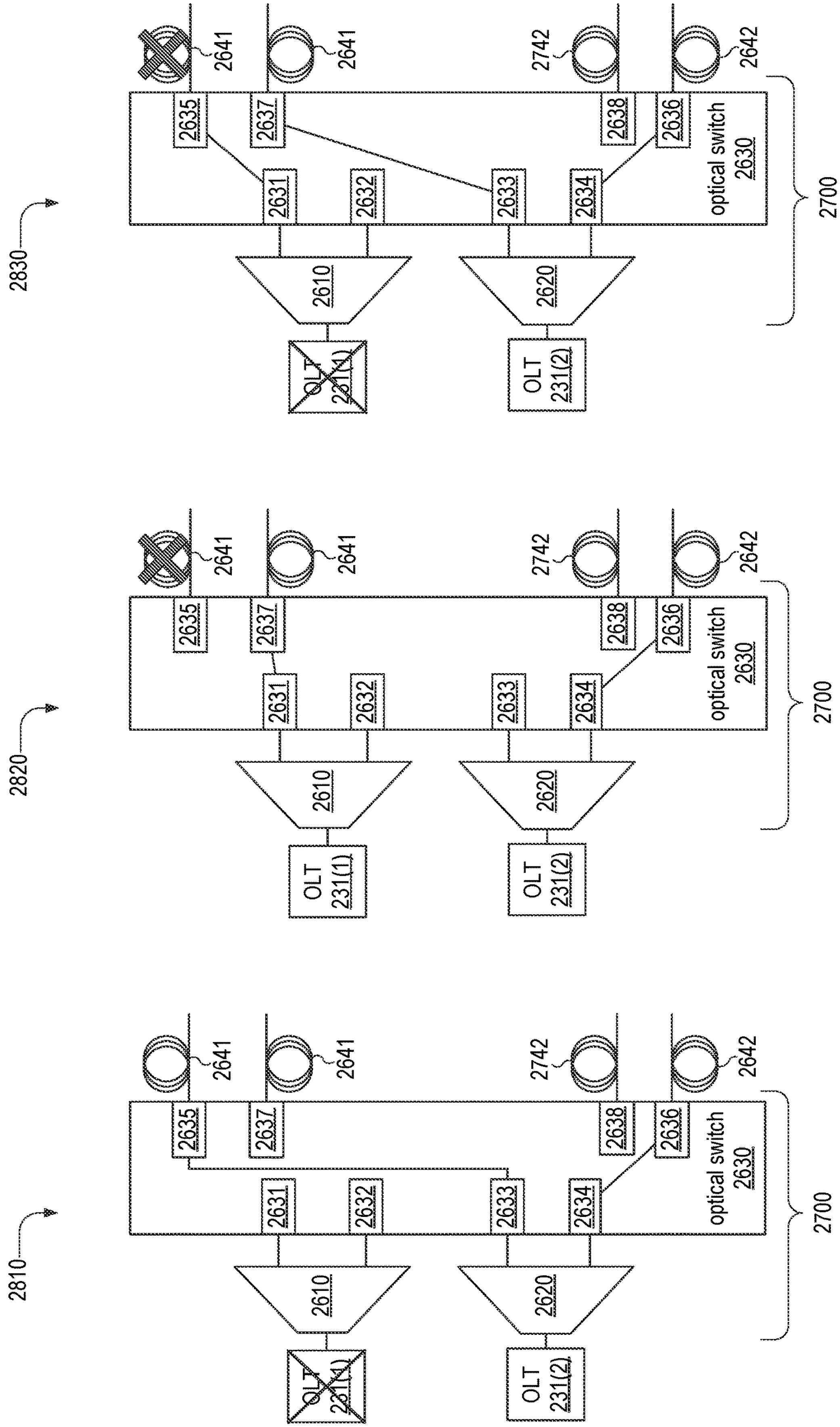

2701(1)
2701(2)
ONU 270(1)
ONU 270(1)
ONU 270(2)
ONU 270(2)
160
160
2431(1)
2431(N1)
2430
2434
2734
2441(1)
2441(N2)
2440
2744
2444
2641
2741
2742
2642
2635
2637
2638
2636
optical switch 2630
2631
2632
2633
2634
2700
2612
2610
2613
2611
2623
2620
2622
2621
optical line terminal 231(1)
optical line terminal 231(2)

FIG. 27



2830
2820
2810
2641
2742
2642
2635
2637
2638
2636
2631
2632
2633
2634
optical switch
2630
2610
2620
OLT
231(1)
OLT
231(2)
2700

FIG. 28

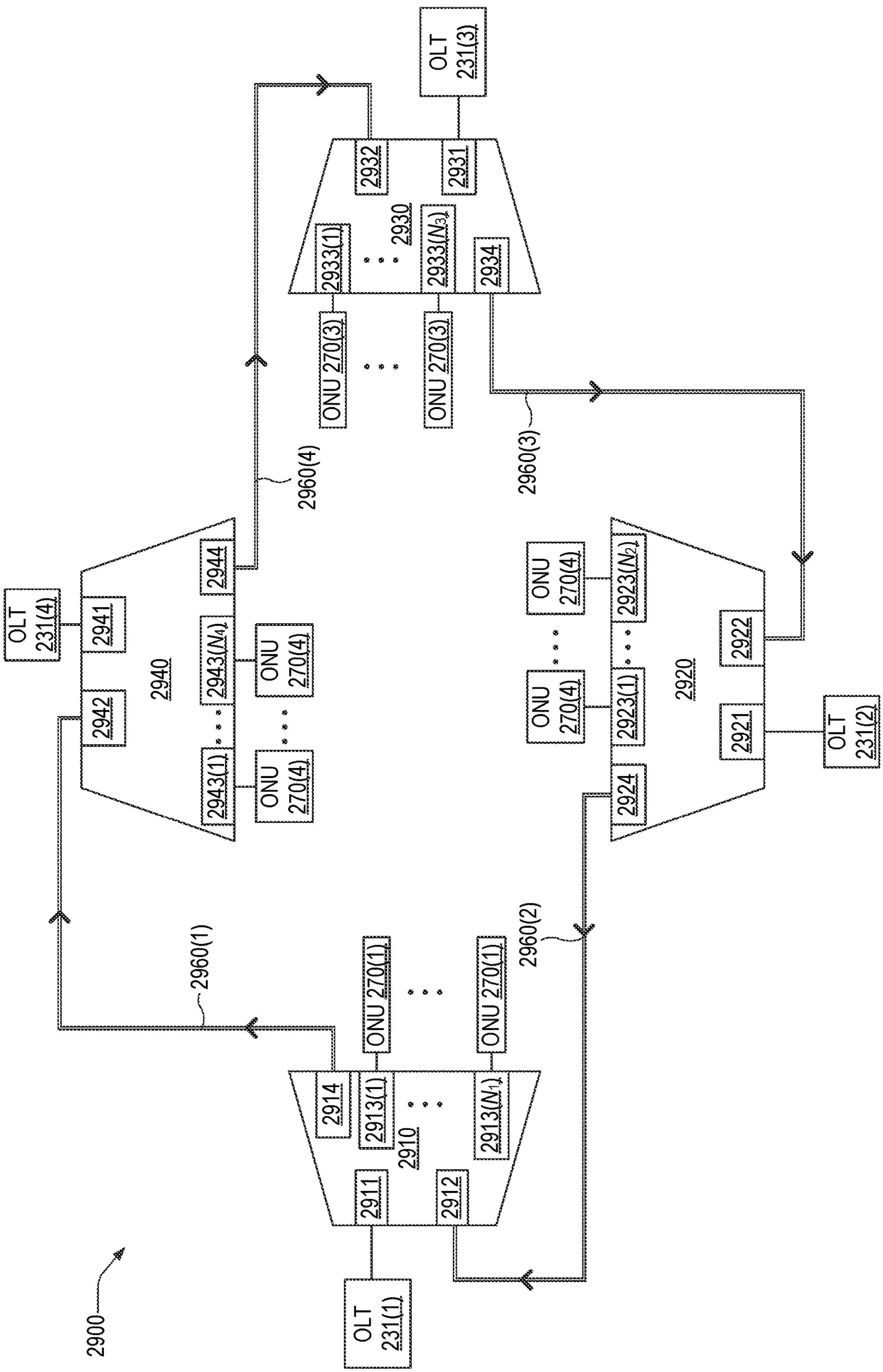

2900
OLT 231(1)
2911
2912
2910
2914
2913(1)
2913(N_1)
ONU 270(1)
ONU 270(1)
2960(1)
2960(2)
OLT 231(4)
2941
2942
2940
2943(1)
2943(N_4)
2944
ONU 270(4)
ONU 270(4)
2960(4)
OLT 231(3)
2931
2932
2930
2933(1)
2933(N_3)
2934
ONU 270(3)
ONU 270(3)
2960(3)
OLT 231(2)
2921
2922
2920
2923(1)
2923(N_2)
2924
ONU 270(4)
ONU 270(4)

FIG. 29

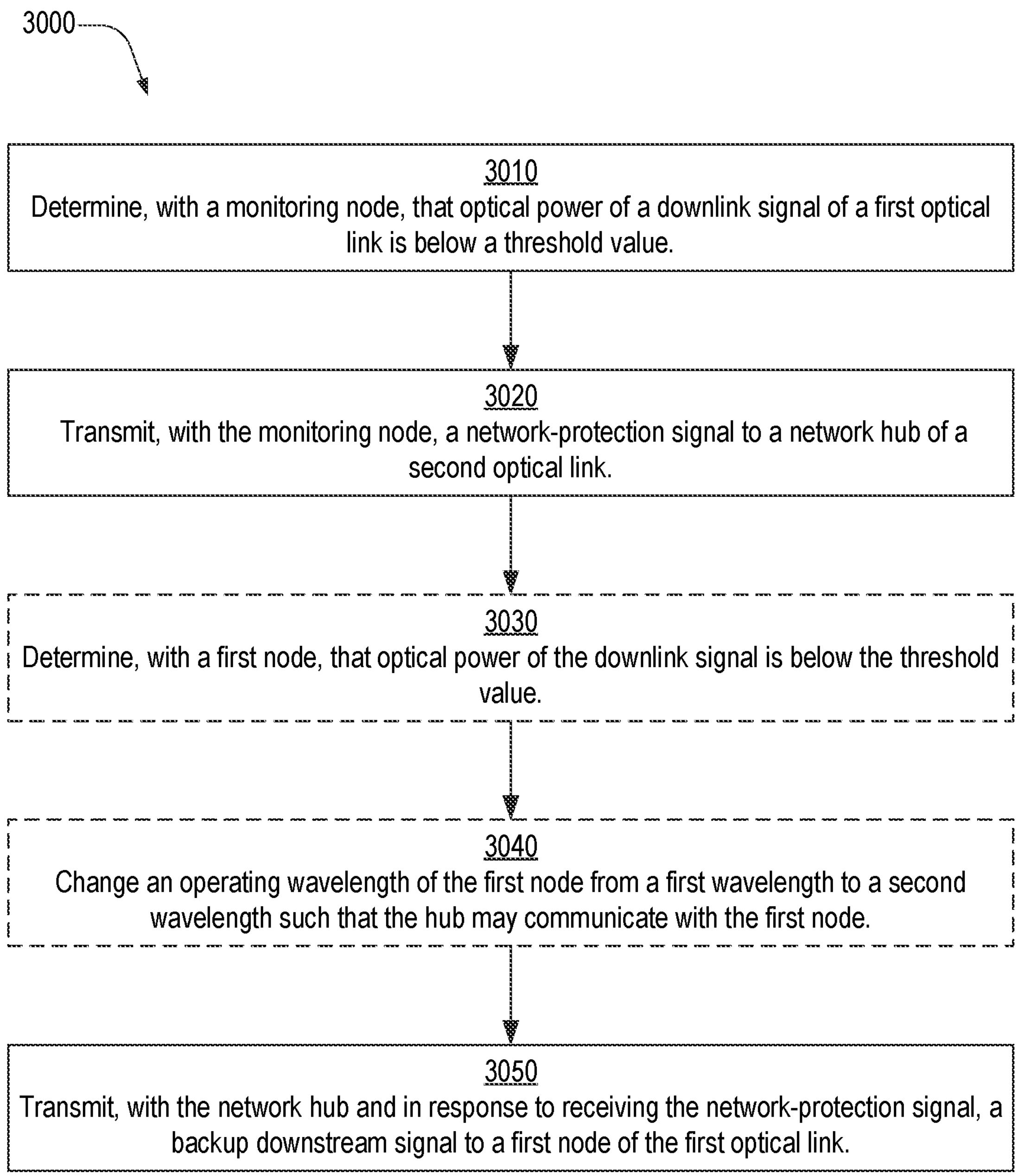

3000
3010
Determine, with a monitoring node, that optical power of a downlink signal of a first optical link is below a threshold value.
3020
Transmit, with the monitoring node, a network-protection signal to a network hub of a second optical link.
3030
Determine, with a first node, that optical power of the downlink signal is below the threshold value.
3040
Change an operating wavelength of the first node from a first wavelength to a second wavelength such that the hub may communicate with the first node.
3050
Transmit, with the network hub and in response to receiving the network-protection signal, a backup downstream signal to a first node of the first optical link.

FIG. 30

REDUNDANCY LINKS, RESILIENCY ARCHITECTURES, AND PROTECTION METHODS FOR PASSIVE OPTICAL NETWORKS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 63/247,437, filed Sep. 23, 2021, U.S. Provisional Application No. 63/247,879, filed Sep. 24, 2021, and U.S. Provisional Application No. 63/278,988 filed Nov. 12, 2021. The disclosure of each of these applications is incorporated herein by reference in its entirety.

BACKGROUND

Today, the cable industry is rolling out plans for providing 10-gigabit-per-second symmetrical speeds, lower latencies, enhanced reliability, and better security to the end users in a scalable manner. A suite of key advances in cable and optical technologies will enable such a 10G platform, including deeper fiber penetration, flexible and modular intelligent fiber nodes, spectrum expansion and DOCSIS® 4.0 technologies, all-IP services, and multi-layer network function virtualization.

FIG. **1** shows a schematic of a distributed access architecture (DAA) **100** designed to deliver high-speed data and video to support a variety of services. DAA **100** includes a primary headend **110** (depending on the network architecture also known as, for example, a core, head office, primary distribution center, etc.), an optical fiber ring network **120**, a secondary hub **130**, optical fiber link **140**, aggregation nodes **150**, drop fibers **160**, child nodes **170**, and connections **180** (such as coaxial cables, fiber line, twisted pair, and could be a wireless connection such as a directional or non-directional wireless signal). Each optical fiber link **140** may be a feeder fiber. In embodiments, optical fiber ring network **120** is one or more of a mobile network and a cellular network, such as 3G, 4G, 5G, and successor generations, or any cellular network that complies with standards set by the 3^{rd} Generation Partnership Project (3GPP). Other embodiments may support communications systems such as ground portions of satellite systems such as geostationary orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellite systems.

Headend **110** may serve as the primary signal/content sources from satellite/microwave antennas, core/metro networks, and due to its central location may also serve as the interconnection points with other service providers. Typically, headend **110** is connected to a few hubs (e.g., secondary hubs **130**) with optical fiber ring network **120**. Because of the fundamental shift from centralized architecture to distributed architecture, where the RF is all generated at a Remote PHY Device (RPD) or Remote MAC/PHY Device (RMD) for more Service Group (SG) with fewer customers each, an aggregation node **150** is needed for multiple child nodes for residential, business, and cellular backhaul services. The distance between secondary hub **130** and aggregation node **150** may be less than 80 km, and the distance from the aggregation node **150** to each child node **170** may be less than 3 km.

Available digital options connecting the hub **130**, aggregation nodes **150**, and child nodes **170** include intensity-modulation and direct-detection (IM-DD) technology and coherent optical solutions. In IM-DD case, multiple 10G optical links can be multiplexed by using DWDM, with each

aggregation node **150** being an optical pair of Mux/Demux. This technology is a mature technology and can be an initial approach. Coherent optics, on the other hand, can significantly increase the spectral efficiency and address the IM-DD limitation on the capacity scaling challenge through enabling a capacity of 100 Gbps or higher on a single wavelength at a much longer transmission distance.

This common transport platform operates over a typical point-to-multipoint (P2MP) topology, also called a tree or trunk-and-branch topology. In such network, there are two common ways for digital optical technology selection based on the principle of splitting the signal. The two methods are called active optical networks (AON) or passive optical networks (PON). In an AON approach, hub **130** would send a single 100-Gbps or 200-Gbps coherent optical signal to an aggregation node **150** (at a distance of up to 80 km), which would in turn terminate the optical link and generate multiple 10 Gbps links using low cost grey optics that only need to reach a few kilometers. The aggregation node may be one of several different types of electrically powered network devices: a router, a switch, or a muxponder. In contrast, a PON uses optical splitters, which require no electrical power in aggregation node, to send the signal to each child node **170**. Given the requirements of operational simplicity, network reliability, and future capacity demand and statistical gain per child node **170**, PON architecture is favored, especially coherent PON (CPON) is more attractive because ultra-high data rate per wavelength over a much longer transmission distance with much higher split ratio. Similar to other PON architectures, CPON would comprise of an Optical Line Terminal (OLT) in the hub and Optical Network Units (ONU) at each child node directly, where the CPON ONU would be connected to the different edge devices for different use cases.

With more and more activities being carried out online, ensuring a reliable broadband network connectivity has become critical to operators to provide an uninterrupted access service to consumers (business and residential end users), especially for emerging applications in remote patient monitoring, telerobotic surgery, autonomous cars, home security and other fields. With the optical fiber playing more important role of cable broadband access network and with the transmission rate of fiber channels continuing to improve, especially for coherent PON transport, a significant loss of data service interruptions will occur once there is a single fiber network failure. To meet service level agreement (SLA) and provide the appropriate level of access connection availability, fault management, namely preplanned protection, and dynamic restoration, within access portion of optical fiber network becomes more significant for reliable service delivery and business continuance.

Currently, there are a large number of optical protection and restoration architectures for network survivability implemented in the backbone and metro networks. However, present cable optical access networks are mostly poorly protected or not protected at all. Unlike the backbone, in the access, the types of signals on an optical carrier have very diverse characteristics, have different values and need to be treated differently in case of failures. With the convergence of multiple services and the increasing capacity of coherent PON transport in access networks, eliminating access network vulnerability is pivotal for operators to ensure a reliable Internet connection to consumers.

SUMMARY OF THE EMBODIMENTS

The motivation for embodiments disclosed herein is to design novel resilient schemes and develop cost-efficient protection technologies in the context of CPON transport as the common platform for universal aggregated services.

In a first aspect, a redundancy link includes a first optical splitter and a second optical splitter. The first optical splitter includes (i) a first hub-side port that optically couples to a first optical line terminal, a first hub-side failover-mode port, (iii) a first plurality of node-side splitter-ports each optically coupled to the first hub-side port and the first hub-side failover-mode port, (iii) a first failover-mode port coupled to the first hub-side port. The second optical splitter includes (i) a second hub-side port that optically couples to a second optical line terminal, a second hub-side failover-mode port optically coupled to the first failover-mode port, (iii) a second plurality of node-side splitter-ports each optically coupled to the second hub-side port and the second hub-side failover-mode port, (iii) a second failover-mode port coupled to the second hub-side port.

In a second aspect, a redundancy link includes a first fiber-optic component and a second fiber-optic component. The first fiber-optic component includes (i) a first hub-side port that optically couples to a first optical line terminal, (ii) a first hub-side failover-mode port, (iii) a first node-side failover-mode port optically coupled to each of the first hub-side port and the first hub-side failover-mode port; and (iv) a first node-side port optically coupled to each of the first hub-side port and the first hub-side failover-mode port. The second fiber-optic component includes (i) a second hub-side port that optically couples to a second optical line terminal, (ii) a second hub-side failover-mode port optically coupled to the first node-side failover-mode port, (iii) a second node-side failover-mode port optically coupled to the first hub-side failover-mode port, the second hub-side port, and the second hub-side failover-mode port, and (iv) a second node-side port optically coupled to each of the second hub-side port and second hub-side failover-mode port.

In a third aspect, an optical network includes a hub-side optical splitter. The hub-side optical splitter includes a hub-side splitter-port **A01** that optically couples to a first optical line terminal, a hub-side splitter-port **A02** that optically couples to a second optical line terminal, a node-side splitter-port **A03** optically coupled to each of the splitter-ports **A01** and **A02**, and a node-side splitter-port **A04** optically coupled to each of the splitter-ports **A01** and **A02**.

In a fourth aspect, network resiliency architecture includes a first optical splitter, a second optical splitter, and an optical switch. The first optical splitter including a hub-side splitter-port **A01** that optically couples to a first optical line terminal, a node-side splitter-port **A02** optically coupled to hub-side splitter-port **A01**; and a node-side splitter-port **A03** optically coupled to hub-side splitter-port **A01**. The second optical splitter including a hub-side splitter-port B**01** that optically couples to a second optical line terminal, a node-side splitter-port B**02** optically coupled to the hub-side splitter-port B**01**; and a node-side splitter-port B**03** optically coupled to the hub-side splitter-port B**01**. The optical switch including (a) four inputs port each optically coupled to a respective one of splitter-ports **A02**, **A03**, B**02**, and B**03**; (b) a first output port that optically couples to a first aggregation node of an optical network; and (c) a second output port that optically couples to a second aggregation node of an optical network.

In a fifth aspect, a network protection method includes determining, with a monitoring node, that optical power of a downlink signal of a first optical link is below a threshold value; and transmitting, with the monitoring node, a network-protection signal to a network protection connected hub of a second optical link. The method also includes transmitting, with a second optical hub and in response to receiving the network-protection signal, a backup downstream signal to a first node of the first optical link; and changing an operating wavelength of the first node from a first wavelength to a second wavelength such that the second hub may communicate with the first node.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** shows a schematic of distributed access architectures (DAA) designed to deliver high-speed data and video to support a variety of services.

FIGS. **2** and **3** are respective schematics of a first CPON protection design under normal operation and when a fiber link is down, in an embodiment.

FIGS. **4** and **5** are respective schematics of a second CPON protection design under normal operation and when an optical line terminal is down, in an embodiment.

FIGS. **6** and **7** are respective schematics of a third CPON protection design under normal operation and when an optical line terminal is down, in an embodiment.

FIG. **8** is a schematic of the protection design of FIG. **2** operating to protect OLT and feeder fibers in P2MP coherent access networks, in an embodiment.

FIG. **9** is a schematic of an experimental demonstration of the protection design of FIG. **2** operating in FIG. **8**, in an embodiment.

FIGS. **10** and **11** are schematics of a P2MP coherent network architecture during normal operation and protection operation respectively, in an embodiment.

FIGS. **12-15** are plots of measured optical spectra and bit-error rates of an embodiment of P2MP coherent network architecture of FIG. **10**.

FIG. **16** is a schematic of a protection design that includes a hub-side optical switch, in an embodiment.

FIG. **17** is a schematic of a protection design that includes a node-side optical switch, in an embodiment.

FIG. **18** is a flowchart illustrating a protection switching method applicable to protection designs of FIGS. **16** and **17**, in an embodiment.

FIG. **19** is a schematic of a 1:N CPON protection design, in an embodiment.

FIG. **20** is a schematic of a protection design, which features redundancy design for both OLTs and the trunk fiber links, in an embodiment.

FIG. **21** is a schematic of a CPON protection design, which features a combination of 1:N and 1+1 protection configurations, in an embodiment.

FIG. **22** is a flowchart illustrating an embodiment of a protection switching process that is applicable to CPON protection designs of FIGS. **19-21**.

FIG. **23** is a schematic of a first redundancy link in a use scenario in which it includes, and connects, components of two optical networks, in an embodiment.

FIG. **24** is a schematic of a second redundancy link in a use scenario in which it includes, and connects, components of two optical networks, in an embodiment.

FIG. **25** is a schematic of an optical network that includes a hub-side optical splitter, in an embodiment.

FIG. **26** is a schematic of a first network resiliency architecture that includes, and connects, components of two optical networks, in embodiments.

FIG. **27** is a schematic of a second network resiliency architecture that includes, and connects, components of two optical networks, in embodiments.

FIG. **28** illustrates network resiliency architecture of FIG. **27** in three network failure scenarios, in embodiments.

FIG. **29** is a schematic of a coherent passive optical network that includes redundancy links of FIG. **23** implemented in a ring topology, in an embodiment.

FIG. **30** is a flowchart illustrating a network protection method that may be executed by the redundancy link of FIG. **23**, in an embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

1. Protection Designs for Coherent Passive Optical Networks

FIG. **2** is a schematic of a passive-optical-network (PON) protection design **200**, hereinafter protection design **200**, coupled between two coherent passive optical networks **201(1)** and **201(2)**. CPON **201(1)** includes an optical line terminal (OLT) **231(1)**, a passive optical splitter **250(1)**, and an optical fiber link **240(1)** coupled therebetween. CPON **201(2)** includes an OLT **231(2)**, a passive optical splitter **250(2)**, and an optical fiber link **240(2)** coupled therebetween. OLTs **231** may be part of a secondary hub, such as secondary hub **130**. Herein, an element in the figures denoted by a reference numeral suffixed by a parenthetical numeral is an example of the element indicated by the reference numeral. For example, optical fiber link **240(2)** is an example (2) of optical fiber link **240**.

While only two OLTs **231(1,2)** are shown in FIG. **2**, the design principle can be applied to more than two OLTs. Under normal operation, the OLTs **231(1)** and **231(2)** operate at different wavelengths, i.e., λ_1 λ_2 and λ_2, respectively. These wavelengths are carrier wavelengths. Passive optical splitter **250**(*k*) has a 2×(N+1) configuration where N represents the number of ONUs **270**(*k*) coupled to passive optical splitter **250**(*k*), where k equals either one or two in this example. At least one ONU **270** may be a coherent ONU. Herein, normal CPON fiber links are shown as single lines, whereas protection fiber links are shown as double lines.

Protection design **200** includes passive optical splitters **250(1)** and **250(2)** and protection fiber-optic links **260(1)** and **260(2)**. Compared with standard optical splitters in a PON network, which usually have a 1×N configuration, the extra input and output ports on the optical splitters allow extra network protection by connecting two adjacent splitter nodes via protection fiber-optic links **260**. While FIG. **2** illustrates passive optical splitters **250(1)** and **250(2)** as being in different optical networks, passive optical splitters **250(1)** and **250(2)** may be in the same optical network without departing from the scope hereof.

A length of optical fiber link **240** may be between one kilometer and three hundred kilometers long. Optical fiber link **240** is an example of optical fiber link **140**. A length of protection fiber-optic link **260** may be between fifty meters and five kilometers.

Passive optical splitter **250** may be part of, or function as, an aggregation node of CPON **201**. It is also noted that the extra output can be one of regular outputs to one of the ONUs. Under normal operation, a downstream signal **280(1)** from OLT **231(1)** at wavelength λ_1 is sent to ONUs **270(1)**, whose local oscillators are tuned to λ_1 to receive the downstream signal, and also transmit an upstream signal at λ_1 to OLT **231(1)**. Similarly, a downstream signal **280(2)** from OLT **231(2)** at wavelength λ_2 is received by ONUs **270(2)** with local oscillators tuned to λ_2. ONUs **270(2)** transmit upstream signals at λ_2 to OLT **231(2)**.

Passive optical splitter **250(1)** splits signal **280(1)** to yield (a) signals **281(1)**, which propagate to ONUs **270(1)**, and (b) a downstream redundancy signal **282(1)**, which propagates to ONUs **270(2)** via protection fiber-optic link **260(1)** and passive optical splitter **250(2)**. Under normal operation, ONUs **270(2)** will not detect downstream redundancy signal **282(1)**, which has wavelength λ_1, because ONUs **270(2)** are tuned to wavelength λ_2.

Similarly, passive optical splitter **250(2)** splits signal **280(2)** to yield (a) signals **281(2)**, which propagate to ONUs **270(2)**, and (b) a downstream redundancy signal **282(2)**, which propagates to ONUs **270(1)** via protection fiber-optic link **260(2)** and passive optical splitter **250(1)**. Under normal operation, ONUs **270(1)** will not detect downstream redundancy signal **282(2)**, which has wavelength λ_2 because ONUs **270(1)** are tuned to wavelength λ_1.

A splitting ratio of passive optical splitter **250** may be in the range from 95:5 to 50:50. While passive optical splitter **250** is illustrated as a single component, any passive optical splitter **250** disclosed herein may include two or more cascaded optical splitters.

In embodiments, three phases including parameter learning, serial number acquisition, and ranging in the activation process are implemented in the initial learning parameter phase for both CPONs **201(1)** and **201(2)**. Each OLT **231(1)** may store information of both its normal link ONUs **270(1)** and its protection link ONUs **270(2)** with the wavelength as the identifier. Similarly, each OLT **231(2)** may store information of both its normal link ONUs **270(2)** and its protection link ONUs **270(1)** with the wavelength as the identifier. Furthermore, all the ONUs in this protection domain (ONUs **270**) may acquire the operational parameters that are needed in the upstream transmission in this phase as well. An example of the initial activation process is included in FIG. **2**. This activation process and information stored in ONUs **270** and OLT **231**, as described in this paragraph, is applicable to embodiments of subsequent protection designs, network architectures, and resiliency architectures disclosed herein.

Each OLT **231** may include a coherent transceiver, and each ONU **270** may include a coherent transceiver. The advantage of a coherent transceiver is that the respective operating wavelengths of both its transmitter and local oscillator are adjustable. This enables ONUs **270**(*m*) of CPON **201**(*m*) to receive signals from the OLT **231**(*n*) of the CPON **201**(*n*) when either an OLT **231**(*m*) or an optical fiber link **240**(*m*) malfunctions, where either m=1 and n=2, or m=2 and n=1. FIG. **3** illustrates an example where m=1 and n=2.

In FIG. **3**, optical fiber link **240(1)** is down, OLT **231(2)** transmits a backup downstream signal **286(2)**, and the upstream transmission wavelengths of ONUs **270(1)** are subsequently changed accordingly. When optical fiber link **240(1)** is down, signal **280(1)** (at wavelength λ_1) is no longer available, and CPON **201(1)** is operating at wavelength λ_2. In response to ONUs **270(1)** detecting that signal **280(1)** is not present or attenuated to a predetermined value, each ONU **270(1)**, previously operating at wavelength **11**, switches its operating wavelength to wavelength λ_2, for both transmitters and local oscillators. OLT **231(2)**, which is running at wavelength λ_2, will now provide downstream signals and receive upstream signals from all the ONUs.

In embodiments, when OLT **231(1)** or fiber link **240(1)** malfunctions, one or more ONUs **270(1)** or **280(2)** initiate the above-described protection scheme by transmitting a network-protection signal to OLT **231(2)**. When either OLT **231(1)** or fiber link **240(1)** malfunctions, the optical power of downstream redundancy signal **282(1)** decreases. By sending signal **281(1)** to ONUs **270(1)**, network protection design **200** enables ONUs **270(1)** to monitor the status of CPON **201(1)**. Similarly, by sending signal **282(1)** to ONUs **270(2)**, network protection design **200** enables ONUs **270(2)** to monitor the status of CPON **201(1)**.

In embodiments, an ONU **270(2)** monitors the optical power of downstream redundancy signal **282(1)**. When this optical power decreases below a predetermined threshold, this ONU **270(2)** transmits network-protection signal **284(2)** to OLT **231(2)**, which causes OLT **231(2)** to send backup downstream signal **286(2)** to ONUs **270(1)**. The wavelength of network-protection signal **284** (2) equals wavelength λ_2.

In embodiments, one or more ONUs **270(1)** initiate the above-described protection scheme by transmitting a network-protection signal **285(2)** to OLT **231(2)**. The wavelength of network-protection signal **285** (2) equals wavelength λ_1. ONU **270(1)** monitors the optical power of downstream redundancy signal **282(1)**. When the optical power of signal **282(1)** decreases below a predetermined threshold, this ONU **270(1)** transmits, via protection fiber-optic link **260(2)**, network-protection signal **285(2)** to OLT **231(2)**, which causes OLT **231(2)** to send backup downstream signal **286(2)** to ONUs **270(1)**.

The number of ONUs **270** that can be protected is dependent on the optical power budget for each OLT **231**. Passive optical splitter **250** may provide different splitting power level for at least one of its protection ports, to which a protection fiber-optic link **260** is coupled. Protection design **200** may include optical amplifiers **262** for increasing the power level of the redundancy signal, and hence enhance the power budget of protection design **200**.

While protection design **200** offers network redundancy and service backup when either the OLT **231** or optical fiber link **240** is down, it requires fiber connection between two adjacent splitter nodes. Depending on the distance between the splitter nodes, this design may introduce extra fiber deployment cost.

An alternative CPON protection design is shown in FIGS. **4** and **5**, where a PON protection design **400** does not require fiber connection between splitter nodes. In protection design **400**, two OLTs **231** located in the same central office are connected by a pair of passive optical splitters **450**. Optical splitter **450** may be a $M_1 \times M_2$ optical splitter, where each of M_1 and M_2 is at least two. As in protection design **200**, OLT **231(1)** operates at wavelength λ_1 and supports, via optical splitters **460**, multiple ONUs **270(1)** running the same wavelength. Similarly, OLT **231(2)** and corresponding ONUs **270(2)** operate at wavelength λ_2. When OLTs **231** and ONUs **450** include coherent transceivers, both OLTs **231** and all ONUs **270** receive the two wavelengths simultaneously, but detect only the wavelength that their respective local oscillators are tuned to. Protection design **400** offers redundancy and protection to ONUs **270**. Optical splitter **460** may be part of, or function as, an aggregation node of an optical network that includes one OLTs **231**.

When an OLT malfunction occurs, e.g., as shown in FIG. **5** where OLT **231(1)** is down, OLT **231(2)** (running at wavelength λ_2) sends a backup downstream signal **586(2)** to ONUs **270(1)**. ONU **270(1)** sends a In response to receiving signal **586(2)**, each ONU **270(1)** changes its upstream transmission wavelength to wavelength λ_2. As wavelength λ_1 is no longer available, now ONUs **270(1)** that were previously operating at wavelength λ_1 is now switched to wavelength λ_2, for both transmitters and local oscillators. In this scenario, OLT **231(2)** provides downstream signals and receive upstream signals from all ONUs **270**. As in protection scheme **200**, an ONU **270(1)** or an ONU **270(2)** may initiate the above-described protection scheme by transmitting a network-protection signal **285(2)** or **284(2)**, respectively, to OLT **231(2)**.

Protection designs **200** and **400** use passive optical splitters **450** as the key components to provide network redundancy. Although passive optical splitters are typically lower in cost compared to analogous active components, and do not require active power sources, which make them suitable devices for optical distribution networks (ODNs) in PON, they usually introduce excess optical insertion loss. The insertion loss associated with the passive splitters reduces link power budget is undesirable under certain scenarios where link budget is already tight.

FIGS. **6** and **7** are schematics of a CPON protection design **600**. The configuration and working principle are similar to protection design **400**, the major difference being that each passive splitters **450(1, 2)** are replaced by a respective optical switches **650(1, 2)**. Switch **650** is an $N_1 \times N_2$ switch, where each of N_1 and N_1 is greater or equal to two. Under normal operation, the backup ports (each labeled by a cross) are closed, and OLTs **231(1)** and **231(2)** connected to the ONU **270(1)** and **270(2)**, respectively. Note that since the backup ports are closed during normal operation, both OLTs **231** and corresponding ONUs **270(1, 2)** may operate at the same wavelength λ, e.g., when both OLTs **231** are located in the same central office. OLTs **231** and ONUs **270(1, 2)** may operate at different wavelengths without departing from the scope hereof.

Compared with protection designs **200** and **400** that feature passive optical splitters, CPON protection design **600** offers lower insertion loss and thus higher link budget by using optical switches **650**, and also allows the network running at the same wavelength which can potentially simplify hardware in the optical transceivers. Although optical switches are more expensive than passive splitters, switches **650** may be located in the central office such that their cost can be shared among multiple ONUs **270**.

When an OLT malfunction occurs, for example, as shown in FIG. **7** where OLT **231(1)** is down, the two backup ports on the optical switches **650** are turned on. In this scenario, OLT **231(2)** provides a downstream signal to each ONU **270(1)**, which had been supported by OLT **231(1)**, and also receive upstream signal from ONUs **270(1)**. OLT **231(2)** and all ONUs **270** remain operating at wavelength λ in this scenario.

2. Point-to-Multipoint Coherent Technology

The ever-increasing demand for bandwidth has been driven by continuing growth of data intensive applications such as 5G Xhaul, HD-video stream, cloud services, and internet of things (IoTs) over the past decade. As a cost-effective solution, passive optical network (PON) based on power splitting has been extensively studied and widely adopted in today's optical access networks. Among various access technologies, point-to-multipoint (P2MP) coherent technology is considered as a future-proof solution for next-generation 100G-class PON, thanks to its high sensitivity and powerful digital equalization of fiber transmission impairments.

As PON data rate evolving towards 100 Gb/s/λ, more traffic and bandwidth will be carried by the network, protection of key components becomes unprecedently important. Emerging applications in the field of remote health monitoring, telerobotic surgery, autonomous cars, home security and other fields require uninterrupted access service to the end user. Today, existing PON protection schemes usually require complex optical switches and control units, or redundant devices such as optical line terminals (OLTs) and backup fiber links, which can increase the deployment cost significantly. As a result, although there are many optical protection and restoration architectures implemented in the backbone and metro networks, the present optical access networks are mostly poorly protected or not protected at all. Developing a cost-effective protection scheme is critical to the success of future P2MP coherent network for supporting various traffic needs.

Another major hurdle for large-scale adoption of P2MP coherent network in the access networks is the prohibitively high cost associated with the existing long-haul coherent optics. High quality light sources such as external cavity lasers (ECLs) dedicated for coherent transmitters and local oscillators contribute a large portion of the overall cost. For short-haul applications, these expensive devices can be replaced by alternative solutions based on optical frequency comb and optical injection locking (OIL) of low-cost Fabry-Perot laser diodes (FP-LDs).

We disclose herein a mutually protected P2MP coherent network architecture employing optical frequency comb, OIL, and remote optical carrier delivery. The mutual protection of critical parts such as OLT and feeder fibers in two adjacent P2MP coherent networks can be realized by connecting the passive nodes without requiring complex switching devices or redundant OLTs. The combined use of optical frequency comb and OIL greatly reduces the number of high-cost lasers in a P2MP coherent network system, the mechanism of remote optical carrier delivery also ensures fast service restoration without requiring wavelength switching for all optical network units (ONUs). System performance and functionality of the protection mechanism have been verified through downstream and upstream transmission of 100 Gb/s data rate coherent signals (from both discrete components and commercial coherent optics) through 50 km single mode fiber (SMF) link and cascaded splitters (2×2+1×32) in both normal operation and protection mode.

2.1 Example P2MP Protection Designs

FIG. **8** shows the high-level schematic of protection design **200** operating to protect OLT and feeder fibers in P2MP coherent access networks **801**(**1**) and **801**(**2**). Leveraging the high power budget and the wavelength tunability of coherent optics, two adjacent P2MP coherent networks can provide protection to each other by connecting the passive nodes. Under normal operation, P2MP coherent networks work at different wavelengths, i.e., λ_1/λ_2 (downstream/upstream) for the upper P2MP coherent network, and λ_3/λ_4 for the lower P2MP coherent network.

Although P2MP coherent networks **801**(**1**) and **801**(**2**) are interconnected, by running at different wavelengths the two networks will not interfere with each other. When a feeder fiber or an OLT breakage occurs, i.e., if OLT **231**(**1**) or optical fiber link **240**(**1**) is down, protection activation signals are sent to all ONUs **270**(**1**). In such a scenario, all ONUs **270**(**1**) that were previously operating at λ_1/λ_2 are switched to λ_3/λ_4, for both transmitters and local oscillators. OLT **231**(**2**), which is running at λ_3/λ_4, provides downstream signals and receive upstream signals from all the ONU **270**.

As in the implementation of protection design **200** in FIG. **2**, protection design **200** in FIG. **8** may be extended to protect respective optical links of more than two networks. The protection port and the regular splitting port can be designed in a flexible way with asymmetric splitting ratios to accommodate different network configurations and application scenarios. Also, as in FIG. **2**, prior to operation, both OLTs **231** and all ONUs **270** may acquire operational parameters for both coherent networks during ranging process.

Protection of a PON is quantitatively evaluated by its availability, the fraction of time the system or service behaves as intended. For a given system, its availability $A=1-\Sigma_i^N \mathrm{MTTR}_i/(\mathrm{MTBF}_i+\mathrm{MTTR}_i)$, where MTBR defines mean time between failures, and MTTR is the mean time to restore or repair. A goal of the industry is to achieve 99.999% availability, which equivalent to a system being unavailable less than 5.25 minutes in a year. Table 1 shows statistical failure in time (failure frequency in 10^9 hours: $\mathrm{FIT}=10^9/\mathrm{MTBF}$) and MTTR for PON components, as documented in ITU-T Rec. G.Sup51 and J. Chen, et al., in IEEE Commun. Mag, 48(2), 56-65, 2010. Based on the parameters in Table 1, an unprotected PON can only have an availability of 99.973%, far from the industrial goal of 99.999%. With protection scheme **2000** as implemented proposed in FIG. **8**, the MTTR of the feeder fiber and OLT can be significantly reduced, from several hours down to minutes.

TABLE 1

Failure Rates and repair time for PON Components

	FIT	MTTR
OLT	2500	8 hrs.
ONU	256	8 hrs.
Feeder Fiber	50 km × 200/km	24 hrs.
Drop Fiber	2 km × 200/km	24 hrs.
Splitter	100	8 hrs.

As a proof of the concept, we start with testing the mutual protection scheme using commercially available products. FIG. **9** shows an experimental setup **900** that includes OLTs **931**(**1**) and **931**(**2**), passive nodes **950**(**1**) and **950**(**2**), optical circulators **965**, and a plurality of ONUs **970**. Each OLT **931**, passive node **950**, and ONU **970** is a respective example of OLT **231**, passive optical splitter **250**, and ONU **270**. Passive node **950** includes a pair of cascaded optical couplers/splitters. For clarity of illustration, FIG. **9** denotes an element-pair **960** that includes one circulator **965** and one ONU **970**.

Each OLT **931** and ONU **970** includes two commercial C-form-factor pluggable-digital coherent optics (CFP2-DCO) modules (operating the mode of 100 Gb/s date rate). Each CFP2-DCO module is one of CFP2-DCO 1, CFP2-DCO 2, and CFP2-DCO 3, as shown in FIG. **10**. CFP2-DCO 1 is tuned to wavelength λ_1 (1548.12 nm) and CFP2-DCO 2 is tuned to wavelength λ_2 (1548.52 nm) for downstream and upstream transmission under normal operation, where CFP2-DCO 3 is used at protection device and tuned to λ_1/λ_2 for downstream and upstream protection operation. Initial test using commercial devices verified the functionality of the mutual protection scheme.

However, changing upstream and downstream operating wavelengths of all ONUs is still challenging and time consuming, as most of today's commercially available coherent optics are not optimized for fast wavelength switching. Faster service restoration may be provided by a P2MP coherent network protection scheme based on optical frequency comb and remote delivery of optical carriers via an OIL process. Without requiring ONU-wavelength switching, the mutual protection between two P2MP coherent networks can be achieved by tuning an optical filter or wavelength selective switch (WSS). The proposed protection scheme can reach 99.999% availability, with i.e., 50-ms

MTTR for OLT and feeder fiber. With this design, one can exceed the 99.999% goal by adding ONU/drop fiber redundancy. Herein, we focus on the OLT and feeder fiber protection. The proposed design can also be applied in the hub/central office (CO) for OLT protection only, depends on requirements for different application scenarios.

2.2 Experimental Setup and Results

FIGS. **10** and **11** are schematics of a P2MP coherent network architecture **1000** during normal operation and protection operation, respectively. Network architecture **1000** includes an optical frequency comb generator **1032**, a wavelength-selective switch (WSS) **1034**, OLTs **1030**(**1**, **2**), single-mode fibers **1040**(**1**, **2**) passive nodes **1050**(**1**, **2**), protection fiber-optic links **260**(**1**) and **260**(**2**), ONUs **1070** (**1**), and ONUs **1070**(**2**). Each OLT **1030**, passive node **1050**, and ONU **1070** is a respective example of OLT **231**, passive optical splitter **250**, and ONU **270**. Protection fiber-optic links **260** connect passive nodes **1050** is in protection design **200**.

On the OLT side, comb generator **1032** includes an ECL, a phase modulator, and a Mach-Zehnder modulator. Comb generator **1032** generates an optical frequency comb **1033** by modulating the output of the ECL with the phase modulator followed by the Mach-Zehnder modulator. In this example, both modulators are driven by a 25-GHz RF signal. Four of the comb tones (λ_1: 1563.46 nm, λ_2: 1563.86 nm, λ_3: 1564.26 nm, λ_4: 1564.66 nm), after amplification, are filtered out by WSS **1034** with 50-GHz channel spacing to match ITU-T 50-GHz frequency grid. In OLT **1030**(**1**) of the upper P2MP coherent network, λ_1 is fed into a coherent driver modulator (CDM) (3-dB bandwidth of 40 GHz) to generate downstream signals. We use 30-GBd DP-QPSK signal targeting 100 Gb/s data rate. An optical coupler **1036**(**1**) splits the λ_2-signal in two: one is utilized as the local oscillator (LO) to detect upstream signals; the other is combined with downstream signals via an optical coupler **1037**(**1**) and sent downlink through single-mode fiber **1040** (**1**) as an optical carrier for upstream signal generation. In this example, single-mode fibers **1040** are 50-km long. Each passive node **1050** includes a 2×2 passive splitter cascaded with a 1×32 passive splitter, where the 2×2 splitter provides interconnection between the two P2MP coherent networks.

On the ONU side of the link, the remote delivered optical tone (**22**) is filtered out by a tunable optical filter (TOF) and used as the seed light to generate upstream optical carrier via OIL. The OIL slave laser is a FP-LD, with seed light injected into its cavity via an optical circulator. The generated optical carrier at λ_2 is then sent to a CDM for upstream signal transmission. The downstream signals are mixed with a local oscillator at λ_1 and detected by an integrated coherent receiver (ICR). The obtained radio frequency (RF) signals for the I/Q components are sent into an optical modulation analyzer acquired at 80GS/s and processed offline with a MATLAB program. Downstream and upstream signals at the OLT and the ONU side are routed by corresponding optical circulators.

The lower P2MP coherent network operates in the same way as the upper P2MP network, with λ_3 for downstream and λ_4 for upstream transmission, and includes optical couplers **1036**(**2**) and **1037**(**2**). When network failure occurs, i.e., when OLT **1030**(**1**)/single-mode fiber **1040**(**1**) is down as shown in FIG. **11**, downstream signal at λ_1 will be provided by OLT **1030**(**2**), and upstream carrier frequency will be changed to λ_4. In this scheme, wavelength adjustment of all ONUs **1070** is not required, and network protection can be achieved via fast switching of WSS **1034**.

FIGS. **12**-**15** are plots of measured optical spectra and bit-error rates of an embodiment of P2MP coherent network architecture **1000**. FIG. **12** shows an optical spectrum of a generated optical frequency comb centered at 1563.86 nm with 25-GHz spacing between adjacent tones. The optical frequency comb is an example of optical frequency comb **1033**. FIG. **13** shows the spectrum of our downstream signals (λ_1 and λ_3) coupled with the two remote-delivered optical carriers after OIL (λ_2 and λ_4). FIGS. **14** and **15** show bit-error-rate (BER) performance versus received optical power (ROP) for the 30-GBd DP-QPSK coherent signal with constellation diagrams, for downstream and upstream transmission, respectively. The test was performed using a variable optical attenuator (VOA) to adjust the received optical power at the coherent receiver. For reference, staircase hard-decision (HD) forward error correction (FEC) threshold (BER=4.5×10^{-3}) and concatenated soft-decision (SD) FEC threshold (BER=1.2×10^{-2}) are plotted as horizontal lines labeled HD and SD, respectively. Results for system under normal operation and protection mode, for both back-to-back (B2B) and 50 km fiber link are included. From the results, system performances under normal operation and protection mode are very similar, no significant penalty has been observed.

2.3. P2MP Conclusion

FIGS. **8**-**15** and the associated description demonstrate embodiments of a mutually protected P2MP coherent network architecture without requiring complex switching components, or redundant fiber and OLTs. With this scheme, system complexity and response time for network protection are greatly reduced. The combination of optical frequency comb and OIL also significantly reduces the number of high-cost ECLs in the P2MP system. Remote optical carrier delivery ensures fast service restoration without requiring wavelength switching for all ONUs. System performance and functionality of the protection mechanism have been verified through downstream and upstream transmission of 100 Gb/s date rate coherent signals through a 50-km SMF link and cascaded splitters (2×2 plus 1×32), in both normal operation and protection mode.

3. Point-to-Multipoint Coherent Technology

With continuing increase of traffic and bandwidth being carried by CPONs, ensuring a reliable and robust connectivity has become critical to network operators. Emerging applications in the field of remote health monitoring, telerobotic surgery, autonomous cars, home security and other fields require uninterrupted access service to the end user. Although there are many existing optical protection and restoration architectures in the backbone and metro networks, the present cable optical access networks are poorly protected. In this invention, we proposed multiple protection schemes targeting optical access networks that are adopting coherent PON technologies.

3.1 Example CPON Protection Designs

FIGS. **16** and **17** are schematics of protection plans in a CPON network with one CPON OLT and multiple CPON ONUs. The protection is mainly targeted to provide redundancy to the trunk fiber, which is the segment that connects the OLT and remote passive splitting node.

FIG. **16** shows a schematic of a protection design **1600** for CPON network protection with trunk fiber redundancy design in a 1:1 configuration. Under normal operation, the traffic is sent to the ONUs over the primary link. No traffic or only low priority traffic is sent over the backup link. When the primary link fails, all traffic will be switched to the backup link. A 1×2 optical switch is utilized to select the optical path for the optical distribution network (ODN).

Three phases including parameter learning, serial number acquisition and ranging in the activation process are implemented in the initial learning parameter phase for the CPON OLT, for both the primary and the backup link. On the other hand, each ONU will acquire operational parameters for both the primary and the backup link upstream transmission. In the initialization process, OLT should have the parameters of backup link stored in its table. When the switch takes action, the round-trip time (different delay between primary and backup links) is automatically adjusted. When the primary link fail is detected, the OLT sends control signal to the optical switch via in-band control or a separate supervisory channel.

In FIG. **17** is a schematic of a protection design **1700**, which is a 1+1 configuration design for a CPON network with one OLT and multiple ONUs. Similar to the 1:1 configuration, the 1+1 design also features two fiber links as redundancy and protection of the trunk fiber link. In this design, the downstream signal from the OLT is split into two paths by a passive optical splitter, the traffic is sent over two parallel paths. On the other side of the network, a 2×1 optical switch will select signal from one of the two fiber links based on signal quality and transmission performance. Different from the 1:1 configuration, in this 1+1 design downstream signal is always transmitted in parallel in both fiber links. Initial OLT configuration evaluates signal transmission performance on fiber link 1 and 2 and makes a decision on switching to the link with better signal quality for a normal operation condition. The ONUs also acquire operational parameters for both link 1 and link 2 upstream transmission. The switch can be controlled by the OLT through in-band control. The trade-off for the 1+1 design compared with the 1:1 design is that it requires an intelligent device that performs switching at an intermediate location that needs powering.

FIG. **18** is a flowchart illustrating a protection switching method **1800**, for when failure occurs on the normal transmission paths of protection designs **1600** and **1700**. For the 1:1 and 1+1 configurations, the switching process is similar. First the OLT detects the link failure, after a hold-off time interval, the OLT will send a protection switch message to the 1×2 optical switch (1:1 configuration) or the 2×1 optical switch (1+1 configuration). The 1×2 or the 2×1 optical switch will then reconfigure itself to change the optical path. The OLT will switch to the configuration for the alternative path transmission. Eventually the OLT will send a control message to all the ONUs, the ONUs will configure to the new optical path for upstream transmission. Note that the alternative path information is stored in the ONUs during the initial configuration process, when a link fails, the ONUs can be switched to the alternative path configuration immediately, without requiring of accessing the new path from scratch.

FIG. **19** is a schematic of a 1:N CPON protection design **1900**. In this design, there are N OLTs **231** in the same central office, or in proximity, and each of the N OLTs supports a respective CPON network. An extra OLT, designated as a protection OLT **1931**, provides redundancy and protection to each of the N OLTs **231**. Protection OLT **1931** is connected to all the CPON networks via a 1×N optical switch and N optical splitters (2×1 configuration). Each CPON network includes a 2×1 passive optical splitter **1950**, an input port thereof being connected to protection OLT **1931**. Protection OLT **1931** is also connected to the other OLTs via separate respective OLT interconnects.

Protection design **1900** provides redundancy and protection to the OLTs. Initially, protection OLT **1931** is configured for all the CPON networks it will potentially support. Under normal operation, the 1×N optical switch is closed, and each OLT supports only its corresponding CPON network. When one of the OLTs detects malfunction, this OLT stops transmitting downstream traffic, and sends a protection switching message to protection OLT **1931**. Protection OLT **1931** is then configured to support the corresponding CPON network and send a switching message to the 1×N switch. The 1×N switch will open the corresponding port, and then protection OLT **1931** transmits downstream traffic to the CPON network.

Each CPON network of FIG. **19** includes a plurality of ONUs **270**. The settings of ONU **270** may be stored in a controller working with protection OLT **1931**. In this case, protection OLT **1931** need not learn, through a lengthy initialization and ranging process, the settings of the new set of ONUs that is serving. When a link fails the specific settings can be passed along to protection OLT **1931**. In a highly integrated system where multiple OLTs are integrated together the OLT transmitter functionality could be decoupled from the OLT processing functionality. This would make the redundancy scheme presented here more seamless.

Protection design **1900** provides redundancy to the OLTs, but not to trunk fiber links. FIG. **20** is a schematic of a protection design **2000**, which features redundancy design for both OLTs **231** and the trunk fiber links. This design utilizes a combination of 1:N and 1:1 protection configurations. In addition to the 1:N design which protects OLTs **231**, 1:1 redundancy links in each of the CPON networks are added to protect the trunk fiber links. Protection OLT **1931** is connected to each CPON network via a 1×N optical switch and a corresponding 2×2 optical switch. The operating process is similar to the 1:N configuration, with an addition of protection switching message sent to the 2×2 optical switch. The process will be discussed in more details in FIG. **22**.

FIG. **21** is a schematic of a CPON protection design **2100**, which features a combination of 1:N and 1+1 protection configurations, offers protection to both OLTs **231** and trunk fiber links. In addition to the 1:N design which protects the OLTs **231**, 1+1 redundancy links in each of the CPON networks are added to protect the trunk fiber links. Protection OLT **1931** is connected to each CPON network via a 1×N optical switch and a corresponding 2×1 passive optical splitter. Switching between the primary and the backup links is done by the 2×1 optical switches. The operating process is similar to the 1:N configuration, with an addition of protection switching message sent to the 2×1 optical switch.

FIG. **22** is a flowchart illustrating a protection switching process **2200** that is applicable to CPON protection designs **1900**, **2000**, and **2100**. When one of the OLTs (OLTx) detects malfunction, this OLT will stop transmitting downstream traffic, and send a protection switching message to protection OLT **1931**. For CPON protection designs **2000** and **2100**, protection OLT **1931** will send a switching message to either the 2×2 optical switch (for protection design **2000**), or the 2×1 optical switch (for protection design **2100**). Protection OLT **1931** is then configured to match OLTx and support the corresponding CPON network. Protection OLT **1931** will also send a switching message to the 1×N switch. The 1×N switch will open the corresponding port, then protection OLT **1931** will transmit downstream traffic to the CPON network.

FIG. **23** is a schematic of a redundancy link **2300** in a use scenario in which it includes, and connects, components of optical networks **2301(1)** and **2301(2)**, which include OLTs

231(1) and 231(2) respectively. Redundancy link 2300 includes passive optical splitters 2310 and 2320, which are part of optical network 2301(2) and 2301(2), respectively. Protection design 200, passive optical splitter 250(1), and passive optical splitter 250(2) are respective examples of redundancy link 2300, optical splitter 2310, and optical splitter 2320. FIG. 23 illustrates signals 280, 281, 282, 284, 285, and 286 introduced in the discussion of protection design 200 of FIGS. 2 and 3. Protection design 200 is an example of redundancy link 2300, these signals serve the same function in redundancy link 2300 as they do in PON protection design 200.

Optical splitter 2310 may be part of, or function as, an aggregation node of optical network 2301(1). Optical splitter 2310 includes (i) a hub-side splitter-port 2311 that optically couples to OLT 231(1), a hub-side splitter-port 2312, (iii) a plurality of node-side splitter-ports 2313(1-N_1) each optically coupled to the hub-side splitter-ports 2311 and 2312, (iii) a failover-mode port 2314 coupled to hub-side splitter-port 2311. Failover-mode port 2314 may also be optically coupled to hub-side splitter-port 2312. In embodiments, port 2314 is not optically coupled to 2312, such that ONUs 270(1) do not receive multipath signals derived from signal 282(1).

Optical splitter 2320 may be part of, or function as, an aggregation node of optical network 2301(2). Optical splitter 2320 includes (i) a hub-side splitter-port 2321 that optically couples to OLT 231(2), a hub-side splitter-port 2322 optically coupled to the failover-mode port 2314, (iii) a plurality of node-side splitter-ports 2323(1-N_2) each optically coupled to hub-side splitter-ports 2321 and 2322, (iii) a failover-mode port 2324 coupled to hub-side splitter-port 2321 and to hub-side splitter-port 2312. Failover-mode port 2324 may also be optically coupled to hub-side splitter-port 2322. In embodiments, port 2324 is not optically coupled to port 2322, such that ONUs 270(2) do not receive multipath signals derived from signal 282(2).

In embodiments, redundancy link 2300 includes protection optical-fiber links 260(1) and 260(2). Protection optical-fiber link 260(2) is coupled between hub-side splitter-port 2312 and failover-mode port 2324. Protection optical-fiber link 260(1) is coupled between hub-side splitter-port 2322 and failover-mode port 2314. Redundancy link 2300 may include at least one of OLTs 231(1) and 231(2).

FIG. 24 is a schematic of a redundancy link 2400 in a use scenario in which includes, and connects, components of optical networks 2401(1) and 2401(2). Redundancy link 2400 includes fiber-optic components 2410 and 2420, which are part of optical networks 2401(1) and 2401(2), respectively. Protection designs 400 and 600 are examples of redundancy link 2400.

Fiber-optic component 2410 includes (i) a hub-side port 2411 that optically couples to OLT 231, (ii) a hub-side port 2412, (iii) a node-side port 2413 optically coupled to each of hub-side ports 2411 and 2412; and (iv) a node-side port 2414 optically coupled to each of hub-side ports 2411 and 2412. Fiber-optic component 2420 includes (i) a hub-side port 2421 that optically couples to OLT 231(2), (ii) a hub-side port 2422 optically coupled to node-side port 2413, (iii) a node-side port 2423 optically coupled to the hub-side ports 2412, 2421, and 2422, and (iv) a node-side port 2424 optically coupled to each of the hub-side ports 2421 and 2422.

In embodiments, each of fiber-optic components 2410 and 2420 is a passive optical splitter, such as passive splitter 450. FIG. 4. In such embodiments, node-side ports 2413 and 2414 are fixedly coupled to each of hub-side ports 2411 and 2412, and node-side ports 2423 and 2424 are fixedly coupled to each of hub-side ports 2421 and 2422.

In embodiments, each of fiber-optic components 2410 and 2420 is an optical switch, such as switch 650, FIG. 6. In such embodiments, node-side port 2413 and node-side port 2414 are switchably coupled to each of hub-side ports 2411 and 2412, and node-side port 2423 and node-side port 2424 are switchably coupled to each of the hub-side ports 2421 and 2422.

Each of fiber-optic components 2410 and 2420 may be a multi-cast optical switch. In such embodiments, during normal operation, hub-side splitter-ports 2411 and 2421 are coupled to respective node-side ports 2414 and 2424. When OLT 231(2) fails, hub-side splitter-port 2411 is optically coupled to both node-side ports 2413 and 2414. Similarly, when OLT 231(1) fails, hub-side splitter port 2421 is optically coupled to both node-side ports 2423 and 2424 simultaneously.

Redundancy link 2400 may include at least one of protection fiber-optic link 260(2) optically coupling hub-side port 2412 to node-side port 2423, and protection fiber-optic link 260(2) optically coupling hub-side port 2422 to node-side port 2413. Redundancy link 2400 may include at least one of OLTs 231(1) and 231(2).

Optical network 2401(1) includes OLT 231(1), fiber-optic component 2410, and an optical splitter 2430, of which optical splitter 460 is an example. OLT 231(1) is optically coupled to hub-side port 2411. Optical splitter 2430 may be part of, or function as, an aggregation node of optical network 2401(1).

Optical splitter 2430 includes a plurality of node-side splitter-ports 2431, N_1 in number, and a hub-side splitter-port 2434. Hub-side splitter-port 2434 is optically coupled to node-side port 2414 and to each splitter-port 2431. Optical network 2401(1) may include optical fiber link 240(1), which optically couples node-side port 2414 to hub-side splitter-port 2434. Optical network 2401 may also include ONUs 270(1) each coupled to a respective node-side splitter-port 2431, e.g., by a respective optical fiber 160.

Optical network 2401(2) includes OLT 231(2), fiber-optic component 2420, and an optical splitter 2440. OLT 231(2) is optically coupled to hub-side port 2421. Optical splitter 2440 may be part of, or function as, an aggregation node of optical network 2401(2). When OLTs 231(1) and 231(2) may operate at the same wavelength, e.g., when they are located in a same central office, or OLTs 231(1) and 231(2) may operate at different wavelengths, e.g., when they are located in different central offices.

Optical splitter 2440 includes a plurality of node-side splitter-ports 2441, N_2 in number, and a hub-side splitter-port 2444. Hub-side splitter-port 2444 is optically coupled to node-side port 2424 and to each splitter-port 2441. Optical network 2401(2) may include optical fiber link 240(2), which optically couples node-side port 2424 to hub-side splitter-port 2444. Optical network 2401(2) may also include ONUs 270(2) each coupled to a respective node-side splitter-port 2441, e.g., by a respective optical fiber 160.

FIG. 25 is a schematic of an optical network 2500 that includes a hub-side optical splitter 2510. Optical network 2500 may also include at least one of node-side optical splitter 2430, node-side optical splitter 2440, OLTs 231, ONUs 270(1), and ONUs 270(2). When included, optical splitters 2430 and 2440 are part of, or function as, respective aggregation nodes of optical network 2500.

Hub-side optical splitter 2510 includes a hub-side splitter-port 2511 that optically couples to OLT 231(1), a hub-side splitter-port 2512 that optically couples to OLT 231(2), and node-side splitter-port **2513** and **2514**. Each of splitter-ports **2513** and **2514** are optically coupled to both splitter-ports **2511** and **2512**. When optical network **2500** includes optical splitter **2430**, node-side splitter-port **2513** is optically coupled to hub-side splitter-port **2434**, e.g., by optical fiber link **240(1)**. When optical network **2500** includes optical splitter **2440**, node-side splitter-port **2514** is optically coupled to hub-side splitter-port **2444**, e.g., by optical fiber link **240(2)**.

During a normal mode of operation, optical network **2500** operates at both wavelengths λ_1 and λ_2. For example, OLTs **231(1)** and **231(2)** operate at wavelengths λ_1 and λ_2, respectively, and each ONU **270** receives signals from both OLTs **231**. When both OLTs **231** are functioning properly, transceivers of ONUs **270(1)** and **270(2)** are tuned to wavelengths λ_1 and λ_2, respectively. When one OLT is down, OLT **231(1)** for example, each ONU **270(1)** tunes its transceiver to wavelength λ_2, such that optical network **2500** operates at wavelength λ_2 only.

FIG. **26** is a schematic of a network resiliency architecture **2600** in a use scenario which includes, and connects, components of optical networks **2601(1)** and **2601(2)**. Resiliency architecture **2600** includes an optical splitter **2610**, an optical splitter **2620**, and an optical switch **2630**. Optical network **2601(1)** includes OLT **231(1)**, optical splitter **2610**, optical link **2641**, optical splitter **2430**, and ONUs **270(1)**. Optical network **2601(2)** includes OLT **231(2)**, optical splitter **2620**, backup optical link **2742**, optical splitter **2440**, and ONUs **270(2)**.

Primary optical link **2641** couples the output port **2635** to optical splitter **2430** at hub-side splitter-port **2434**. Primary optical link **2642** couples output port **2636** to optical splitter **2440** at hub-side splitter-port **2444**. Primary optical links **2641** and **2642** may be part of resiliency architecture **2600**.

Splitters **2610** and **2620** are part of optical networks **2601(1)** and **2601(2)**, respectively. Optical splitter **2610** includes a hub-side splitter-port **2611** that optically couples to an OLT **231(1)**, a node-side splitter-ports **2612** and **2613**, each of which are optically coupled to hub-side splitter-port **2611**. Optical splitter **2620** includes a hub-side splitter-port **2621** that optically couples to an OLT **231(2)**, a node-side splitter-ports **2622** and **2623**, each of which are optically coupled to hub-side splitter-port **2621**.

Optical switch **2630** includes input ports **2631-2634** and output ports **2635** and **2636**. Input ports **2631-2634** are optically coupled to splitter-ports **2612**, **2613**, **2623**, and **2622**, respectively. Output port **2635** optically couples to optical splitter **2430**. Output port **2636** optically couples to optical splitter **2440**. Optical splitter **2430** may be part of, or function as, an aggregation node of optical network **2601(1)**. Optical splitter **2440** may be part of, or function as, an aggregation node of optical network **2601(2)**.

Optical switch **2630** includes a switching mechanism **2639** that routes an optical signal from one of input ports **2631-2634** to one of output ports **2635** and **2636**. Switching mechanism **2639** may include at least one of (i) microelectromechanical mirrors, (ii) a liquid-crystal polarizer, (iii) a liquid-crystal-on-silicon beam steerer, and (iv) tunable optical resonators.

FIG. **26** denotes an optical network **2601(2)**, which includes resiliency architecture **2600**, OLTs **231**, node-side optical splitters **2430** and **2440**, and optical links **2641** and **2642**. Primary optical link **2641** couples the output port **2434** to hub-side splitter-port **2434**. Primary optical link **2642** couples output port **2636** to hub-side splitter-port **2444**.

When OLTs **231** and optical links **2641** and **2642** are properly operating, both OLTs **231** operate at the wavelength at which each of ONUs **270(1)** and **270(2)** are tuned. In such a normal state of operation, optical switch **2630** is configured such that input ports **2631** and **2634** are coupled to output ports **2635** and **2636** respectively, such that ONUs **270(1)** and ONUs **270(2)** receive signals from OLTs **231(1)** and **231(2)**, respectively.

When one of OLTs **231** fails, OLT **231(1)** in the example shown in FIG. **2600**, optical switch **2630** is configured such that (i) input port **2633** is coupled to output port **2635** and (ii) as in the normal mode, input port **2634** is coupled to output port **2636**. In embodiments, when OLT **231(1)** fails, switching mechanism **2639** couples input port **2633** to output port **2635**. Similarly, when OLT **231(2)** fails, optical switch **2630** is configured such that (i) input port **2631** is coupled to output port **2635** as in the normal mode and (ii) input port **2632** is coupled to output port **2636**. In embodiments, when OLT **231(2)** fails, switching mechanism **2639** couples input port **2632** to output port **2636**.

FIG. **27** is a schematic of a network resiliency architecture **2700** in a use scenario which includes, and connects, components of optical networks **2701(1)** and **2701(2)**. Network resiliency architecture **2700** and networks **2701** are similar to resiliency architecture **2600** and networks **2601**, where differences include: (i) optical splitters **2430** and **2440** have additional node-side splitter-ports **2734** and **2744** respectively, and (ii) optical switch **2630** includes additional output ports **2637** and **2638**. Output port **2637** optically couples to optical splitter **2430** at port **2734**, and output port **2638** optically couples to optical splitter **2440** at port **2744**. Resiliency architecture **2700** may also include primary optical links **2641** and **2642**, and backup optical links **2741** and **2742**. Backup optical link **2741** couples output port **2637** to optical splitter **2430** at a hub-side splitter-port **2734**. Backup optical link **2742** couples the output port **2636** to optical splitter **2440** at hub-side splitter-port **2744**.

FIG. **28** illustrates network resiliency architecture **2700** in three network failure scenarios **2810**, **2820**, and **2830**. In scenario **2810**, OLT **231(1)** has failed, such that the output port **2635** does not receive a signal from input port **2631** as it does under normal operation, shown in FIG. **27**. In this scenario, optical switch **2630** configured such that (i) input port **2633** is coupled to output port **2635**, such that ONUs **270(1)** receive downlink signals from OLT **231(2)**.

In scenario **2820**, optical link **2641** has failed, such that ONUs **270(1)** cannot receive a signal from hub-side splitter-port **2434** of node-side optical splitter **2430**. In this scenario, optical switch **2630** configured such that (i) input port **2631** is coupled to output port **2637**, such that ONUs **270(1)** receive downlink signals from OLT **231(1)** via backup optical link **2641**.

In scenario **2830**, both OLT **231(1)** and optical link **2641** have failed. In this scenario, optical switch **2630** configured such that (i) input port **2633** is coupled to output port **2637**, such that ONUs **270(1)** receive downlink signals from OLT **231(2)** via backup optical link **2641**.

FIG. **29** is a schematic of a coherent passive optical network **2900** (hereinafter CPON **2900**), where redundancy link **2300** of FIG. **23** is implemented in a ring topology. CPON **2900** includes optical splitters **2910**, **2920**, **2930**, and **2940**, each of which is an example of optical splitters **2310** and **2320**. Optical splitters **2910**, **2920**, **2930**, and **2940** include: (i) respective hub-side splitter-ports **2911**, **2921**, **2931**, and **2941**, which are examples of hub-side splitter-port **2311**; (ii) respective hub-side splitter-ports **2912**, **2922**, **2932**, and **2942**, which are examples of hub-side splitter-port **2312**, (iii) respective node-side splitter-ports **2913**(**1**-N_1), **2923**(**1**-N_2), **2933**(**1**-N_3), and (iv) **2943**(**1**-N_4) each of which are examples of a node-side splitter-port **2313**; and which are examples of failover-mode port **2314**.

CPON **2900** also includes N_1 ONUs **270(1)** each coupled to a respective node-side splitter port **2913**, N_2 ONUs **270(2)** each coupled to a respective node-side splitter port **2923**, N_3 ONUs **270(3)** each coupled to a respective node-side splitter port **2933**, and N_4 ONUs **270(4)** each coupled to a respective node-side splitter port **2943**.

CPON **2900** also includes optical fiber links **2960(1-4)**, each of which are examples of protection fiber-optic link **260**. Optical fiber link **2960(1)** connects ports **2914** and **2942**, such that OLT **231(1)** serves as a backup OLT for OLT **231(4)**. Optical fiber link **2960(2)** connects ports **2924** and **2941**, such that OLT **231(2)** serves as a backup OLT for OLT **231(1)**. Optical fiber link **2960(3)** connects ports **2934** and **2922**, such that OLT **231(3)** serves as a backup OLT for OLT **231(3)**. Optical fiber link **2960(4)** connects ports **2944** and **2932**, such that OLT **231(4)** serves as a backup OLT for OLT **231(3)**.

FIG. **30** is a flowchart illustrating a network protection method **3000**, which may be executed by redundancy link **2300** of FIG. **23**, in an embodiment. Method **3000** includes steps **3010**, **3020**, and **3050**. Method **3000** may also include at least one of steps **3030** and **3040**.

Step **3010** includes determining, with a monitoring node, that optical power of a downlink signal of a first optical link is below a threshold value. Optical links **240(1)** and **240(2)** are examples of the first and second optical links, respectively. In a first example of step **3010**, the monitoring node is an ONU **270(1)**, which determines that the optical power of signal **281(1)** is below a threshold value. In a second example of step **3010**, the monitoring node is an ONU **270(2)**, which determines that the optical power of signal **282(1)** is below a threshold value.

Step **3020** includes transmitting, with the monitoring node, a network-protection signal to a network hub of a second optical link. In a first example of step **3020**, the monitoring node is one of ONUs **270(1)**, which transmits network-protection signal **285(2)** to OLT **231(2)**, which is the network protection connected hub in this example. In this first example, the network-protection signal has a wavelength equal to the first wavelength, and the monitoring node is part of the first optical link. In a second example of step **3020**, the monitoring node is one of ONUs **270(2)**, which transmits network-protection signal **284(2)** to OLT **231(2)**, which is the network protection connected hub in this example. In this second example, the network-protection signal has a wavelength equal to the second wavelength, and the monitoring node is part of the second optical network

Step **3050** includes transmitting, with the network optical hub and in response to receiving the network-protection signal, a backup downstream signal to a first node of the first optical link. In an example of step **3050**, OLT **231(2)** transmits backup downstream signal **286(2)** to at least one ONU **270(1)**.

Method **3000** may include step **3030** when the carrier wavelengths of the downlink signal and the backup downstream signal equal a first wavelength and a second wavelength, respectively. Step **3030** occurs before step **3050**, and includes determining, with the first node, that optical power of the downlink signal is below the threshold value. In an example of step **3030**, an ONU **270(1)** determines that the optical power of signal **281(1)** is below a threshold value.

Step **3040** includes changing an operating wavelength of the first node from a first wavelength to a second wavelength such that the second hub may communicate with the first node. In an example of step **3040**, at least one ONU **270(1)** changes its operating wavelength from wavelength λ_1 to wavelength λ_2.

When the first node, introduced in step **3050**, is the same as the monitoring node of step **3010**, and when the downlink signal and the backup downstream signal have different wavelengths, steps **3010** and **3030** are identical. An example of such a scenario is when the downlink signal is downstream signal **280(1)** and an ONU **270(1)** is both the monitoring node and the first node. In this scenario, when the monitoring node executes step **3010**, step **3030** is also executed, and the downlink signal's optical power need only be determined once.

Changes may be made in the above methods and systems without departing from the scope of the present embodiments. It should thus be noted that the matter contained in the above description or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. Herein, and unless otherwise indicated, the phrase "in embodiments" is equivalent to the phrase "in certain embodiments," and does not refer to all embodiments. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A redundancy link comprising:

a first optical splitter including (i) a first hub-side port that optically couples to a first optical line terminal, (ii) a first hub-side failover-mode port, (iii) a first plurality of node-side splitter-ports each optically coupled to the first hub-side port and the first hub-side failover-mode port, and (iv) a first failover-mode port that is coupled to the first hub-side port and distinct from the first hub-side failover-mode port; and

a second optical splitter including (i) a second hub-side port that optically couples to a second optical line terminal, (ii) a second hub-side failover-mode port optically coupled to the first failover-mode port, (iii) a second plurality of node-side splitter-ports each optically coupled to the second hub-side port and the second hub-side failover-mode port, and (iv) a second failover-mode port that is coupled to the second hub-side port and distinct from the second hub-side failover-mode port.

2. The redundancy link of claim **1**, further comprising a first protection optical-fiber link coupled between the first hub-side failover-mode port and the second failover-mode port.

3. The redundancy link of claim **2**, further comprising a second protection optical-fiber link coupled between the second hub-side failover-mode port and the first failover-mode port.

4. The redundancy link of claim **1**, further comprising the first optical line terminal operating at a first wavelength.

5. The redundancy link of claim **4**, further comprising the second optical line terminal operating at a second wavelength that differs from the first wavelength.

6. A redundancy link comprising:

a first fiber-optic component including (i) a first hub-side port that optically couples to a first optical line terminal, (ii) a first hub-side failover-mode port, (iii) a first node-side failover-mode port optically coupled to each of the first hub-side port and the first hub-side failover-mode port; and (iv) a first node-side port optically coupled to each of the first hub-side port and the first hub-side failover-mode port; and a second fiber-optic component including (i) a second hub-side port that optically couples to a second optical line terminal, (ii) a second hub-side failover-mode port optically coupled to the first node-side failover-mode port, (iii) a second node-side failover-mode port optically coupled to the first hub-side failover-mode port, the second hub-side port, and the second hub-side failover-mode port, and (iv) a second node-side port optically coupled to each of the second hub-side port and the second hub-side failover-mode port.

7. The redundancy link of claim **6**,

the first fiber-optic component being a passive optical splitter, wherein the first node-side failover-mode port and the first node-side port is fixedly coupled to each of the first hub-side port and the first hub-side failover-mode port.

8. The redundancy link of claim **7**,

the second fiber-optic component being a passive optical splitter, wherein the second node-side failover-mode port and the second node-side port is fixedly coupled to each of the second hub-side port and the second hub-side failover-mode port.

9. The redundancy link of claim **6**, wherein:

the first fiber-optic component being an optical switch, the first node-side failover-mode port and the first node-side port is switchably coupled to each of the first hub-side port and the first hub-side failover-mode port; and

the second fiber-optic component being an optical switch, the second node-side failover-mode port and the second node-side port is switchably coupled to each of the second hub-side port and the second hub-side failover-mode port.

10. The redundancy link of claim **6**, further comprising an optical fiber optically coupling the first hub-side failover-mode port to the second node-side failover-mode port.

11. The redundancy link of claim **10**, further comprising an additional optical fiber optically coupling the second hub-side failover-mode port to the first node-side failover-mode port.

12. An optical network comprising: the redundancy link of claim **6**, wherein the first optical line terminal being optically is coupled to the first hub-side port, and the second optical line terminal is optically coupled to the second hub-side port.

13. An optical network comprising:

the redundancy link of claim **6**; and wherein

a first node-side optical splitter includes a first plurality of node-side splitter-ports and a first hub-side splitter-port optically coupled to the first node-side port and to each of the first plurality of node-side splitter-ports.

14. The optical network of claim **13**, further comprising an optical fiber optically coupling the first node-side port to the first hub-side splitter-port.

15. The optical network of claim **13**, further comprising:

a second node-side optical splitter including a second plurality of node-side splitter-ports and a second hub-side splitter-port optically coupled to the second node-side port and to each of the second plurality of node-side splitter-ports.

16. The optical network of claim **15**, further comprising an optical fiber optically coupling the second node-side port to the second hub-side splitter-port.

17. A network protection method, comprising:

determining, with a monitoring node, that optical power of a downlink signal of a first optical link is below a threshold value;

transmitting, with the monitoring node and via a first protection optical-fiber link, a network-protection signal to a network hub of a second optical link; and

transmitting, with the network hub and in response to receiving the network-protection signal, a backup downstream signal to a first node of the first optical link;

the first protection optical-fiber link being part of a redundancy link that includes:

a first optical splitter including (i) a first hub-side port that optically couples to a first optical line terminal, (ii) a first hub-side failover-mode port, (iii) a first plurality of node-side splitter-ports each optically coupled to the first hub-side port and the first hub-side failover-mode port, and (iv) a first failover-mode port that is coupled to the first hub-side port and distinct from the first hub-side failover-mode port; and

a second optical splitter including (i) a second hub-side port that optically couples to a second optical line terminal, (ii) a second hub-side failover-mode port optically coupled to the first failover-mode port, (iii) a second plurality of node-side splitter-ports each optically coupled to the second hub-side port and the second hub-side failover-mode port, and (iv) a second failover-mode port that is coupled to the second hub-side port and distinct from the second hub-side failover-mode port,

wherein the first protection optical-fiber link is coupled between the first hub-side failover-mode port and the second failover-mode port.

18. The network protection method of claim **17**, the downlink signal and the backup downstream signal having a respective first wavelength and a second wavelength, and further comprising, before transmitting the backup downstream signal:

determining, with the first node, that optical power of the downlink signal is below the threshold value.

19. The network protection method of claim **18**, further comprising:

changing an operating wavelength of the first node from the first wavelength to the second wavelength such that the network hub may communicate with the first node.

20. The network protection method of claim **17**, the downlink signal and the backup downstream signal having a respective first wavelength and a second wavelength and, in said step of transmitting the network-protection signal, the network-protection signal having a wavelength equal to the second wavelength.

21. The network protection method of claim **17**, the monitoring node and the second optical link being part of a same optical network.

22. The network protection method of claim **17**, the downlink signal and the backup downstream signal having a respective first wavelength and a second wavelength and, in said step of transmitting the network-protection signal, the network-protection signal having a wavelength equal to the first wavelength.

23. The network protection method of claim **17**, the monitoring node and the first optical link being part of a same optical network.

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