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Impact of Fiber Duplication on Protection Architectures Feasibility for Passive Optical Networks

Waqas Ahmed Imtiaz, Javed Iqbal, Affaq Qamar,
Haider Ali and Sevia M. Idrus

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Abstract

Adaptability of high capacity passive optical network (PON) requires the provision of an efficient fault detection and restoration mechanism throughout the network at an acceptable cost. The readily adapted pre-planned protection strategy relies on component duplication, which significantly increases the cost of deployment for PON. Therefore, it is imperative to determine a suitable component that requires high redundancy and determine the impact of protection for that component on feasibility of PON. Five protection architecture including ITU-T 983.1 Type C, single ring, dual ring, tree- and ring-based architectures with hybrid star-ring topology at the optical distribution network (ODN), are considered to evaluate the impact of fiber duplication in terms of capital expenditure (CAPEX), operation expenditure (OPEX), reliability, and support for maximum number of subscribers. Reliability block diagram (RBD) based analysis shows that desirable 5 nines connection availability is provided by each protection architecture and utilization of ring topology avoids duplication of the fiber but effects the number of subscribers. Furthermore, it is observed that OF duplication at ODN is the main contributor to CAPEX. Collectively hybrid protection architectures provide efficient performance and proves to be a feasible solution for the deployment of survivable PONs at the access domain.

Keywords: passive optical network, protection, network topology, reliability, CAPEX, OPEX

1. Introduction

Exponential growth in Internet traffic has significantly increased the demand for high bandwidth connectivity at both business and residential premises. Internet service providers are deploying passive optical network (PON) at the access domain to provide the required capacity

in terms of reach, bandwidth, and the number of subscribers. In PON, all services are originated from an optical line terminal (OLT) at the central office (CO). End-face of the OLT is connected to a 15–20 km feeder fiber (FF) that extends the network toward the subscriber premises called optical distribution network (ODN). Remote node (RN) receives the FF at ODN, which houses a $1 : N$ bidirectional passive optical coupler (POC). N output ports from the POC are fed into short-branched distribution fibers (DFs) that connect the RN to individual optical network unit (ONU) transceiver modules [1].

PON has emerged as a promising candidate to resolve the last-mile bottle, owing to its significant advantages like:

- Support for high network capacity in terms of reach, bandwidth, and the number of subscribers due to a complete optical fiber (OF) path between OLT and ONU modules.
- Minimum capital expenditure (CAPEX) by sharing FF between OLT and multiple ONUs.
- Reduced operational expenditure (OPEX) through passive components at RN, which requires no power, minimum maintenance and planning.
- Smooth service upgradability with existing infrastructures.
- Highly scalable as new subscribers can easily join the network.
- High degree of flexibility, owing to the use of FF between OLT and multiple subscribers.

With the rapid increase in PONs capacity, fault detection and restoration at satisfactory costs have turned the network reliability to a new challenge for Internet service providers. Each subscriber is interested in seamless reception of maximum bandwidth at minimum possible cost. However, the conventional PON architecture has limited protection, which results in significant data loss at the event of failure in optical components including OF medium. Therefore, it is imperative to devise an architecture, which is capable of maintaining a seamless flow of upstream and downstream traffic at required capacity and acceptable costs for a common end subscriber [1, 2].

Two techniques are readily adapted to provide fault detection and restoration in PON, namely pre-planned and dynamic protection. The latter relies on fault detection and restoration through diagnosis at the higher levels and dynamically allocates resources at the event of failure. Such technique requires more time for traffic restoration between OLT and ONU modules, as upper layer recovery techniques usually utilize routing tables, topology recalculations, and slow convergence time. Yet there is no guarantee for fault restoration at the physical layer [1–3]. Therefore, for the facilitation of an effective and prompt fault detection and restoration, it is highly desirable to provide protection measures at the optical layer.

Pre-planned protection utilize an optical-layer approach by providing dedicated backup paths for components including OF medium. This type of protection is planned at the network design phase, owing to the fact that topology of PON remains same, and the proposed solution can address fault restoration at both feeder and ODN. This type of protection provides high reliability at minimum recovery time in the event of failures at both optical components and OF medium. However, path and resources duplication significantly elevates the CAPEX at the network deployment phase [4, 5]. Therefore, it is imperative to encompass the following considerations while designing a pre-planned protection architecture.

2. Consideration for PON protection planning

2.1. Network topology

Network topology significantly effects the design, redundancy, and deployment cost for the PON. Two common network topologies are used for the deployment of PON, namely tree and ring [1]. In tree topology, the optical signal sent from OLT is divided into N equal parts and delivered to designated ONU modules through respective DFs. Such deployment can provide the required bandwidth at desired number of subscribers; however, a single cut or failure at the feeder level can cripple the entire network by disconnecting the working OLT from ONU modules. Moreover, failure at the DF can also result in significant data loss and high customer dissatisfaction. Therefore, such topology requires the provision of redundancy at both levels of PON, which is achieved by duplicating the network components.

Ring topology is adapted to minimize the cost incurred by the provision of redundant paths in the conventional PON. It utilizes a single ring-based fiber that connects the OLT directly to all ONU transceiver modules. This significantly reduces the effect of fiber cuts or failures [6, 7]. Ring topology provides the required reliability at acceptable costs; however, use of the POC between OLT and individual ONU module introduces serious power budget issues, which effects network capacity in terms of the number of subscribers [4, 8, 9]. Besides the commonly used ring- and tree-based network architectures, hybrid topologies are readily adapted for the implementation of survivable PON at the access domain. These architectures utilize a combination of tree- and ring-based architectures with subsequent topologies such as tree-ring, tree-star, ring-star, and bus. Hybrid architectures have proved as a promising candidate to provide the required redundancy at desirable network capacity [10–14].

2.2. Resources to be protected

A typical PON primarily comprises two types of resources that require protection for efficient delivery of information between OLT and ONU modules, namely OF medium and optical components. Both significantly effect the flow of upstream and downstream traffic throughout the network. **Figure 1** shows connection availability for PON components based on **Table 1** [15]. It is observed that active and passive devices, such as OLT, ONU, POC, $X : N$ POC, and so on, provide desirable (5 nines) connection availability over the network lifetime, since the rate of failure for these components is significantly low. Furthermore, the mean time to repair (MTTR) for the in-house optical components is minuscule as compared to the on-field components like OF medium that constitutes a major portion of PON architecture and is more prone to failures as shown in **Figure 1**.

Therefore, OF paths require more attention as compared to other components of the networks, in order to ensure seamless transmission of information, minimize the loss of data, service interruption penalty cost, and PON downtime per year [4].

2.3. Number of subscribers

Number of subscribers refer to the amount of users that a PON can accommodate without compromising the reach and provision of nominal bandwidth. It is an important parameter

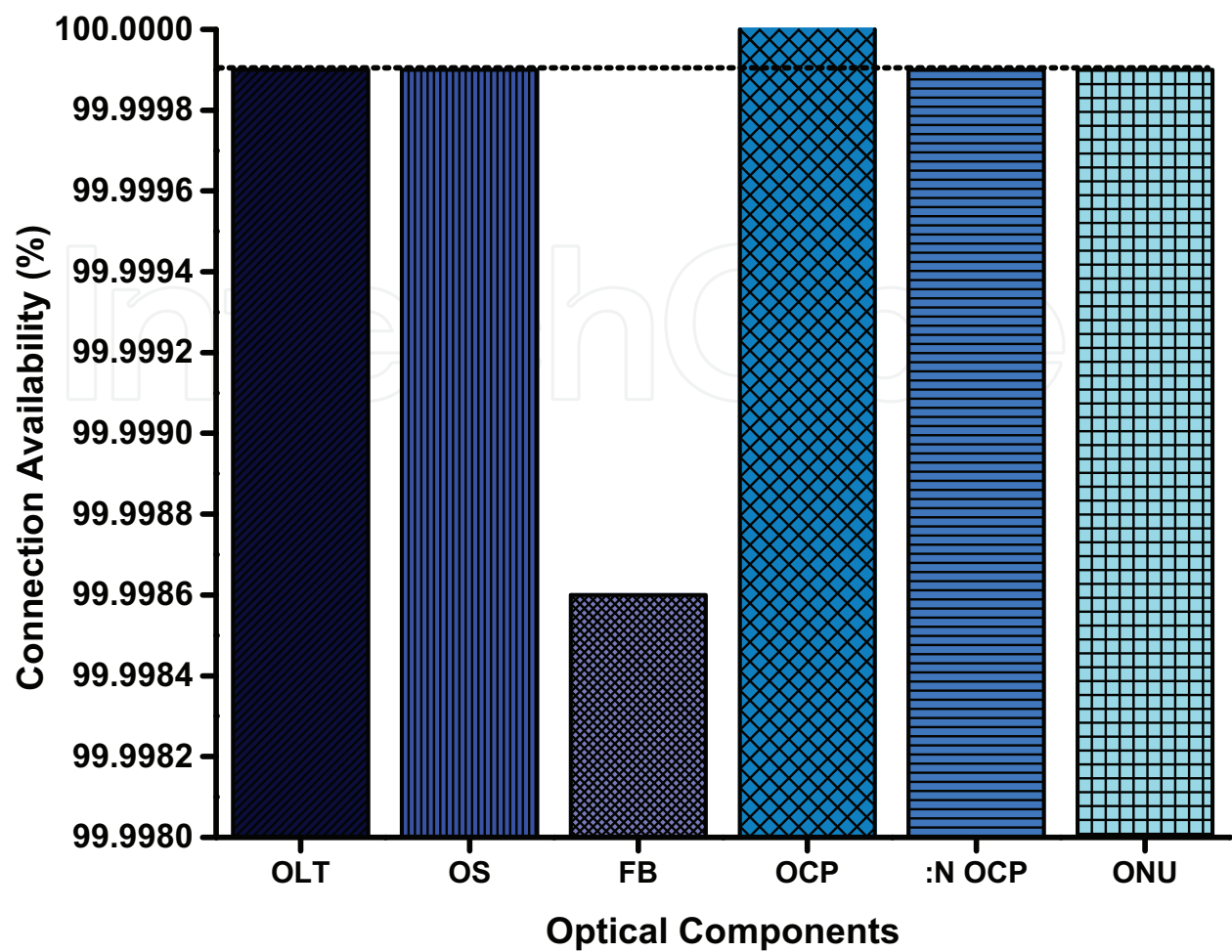


Figure 1. Connection availability of basic optical components in PON.

System components	Unavailability	Cost (\$)	Energy consumption
OLT	$5.12e^{-7}$	12100	20 W, 25 W (with EDFA), 2 W (standby)
ONU	$1.54e^{-6}$	350	1 W, 0.25 W (standby)
Optical circulator	$3e^{-7}$	50	
Optical switch	$1.2e^{-6}$	50	
1:2, 2:2 POC	$3e^{-7}$	50	
1:N, 2:N POC	$7.2e^{-7}$	800	
Fiber (\$/Km)	$1.3e^{-5}$	160	

Table 1. Components description, connection availability, and cost.

since it is directly associated with the extent and cost of the network. Number of subscribers is primarily effected by the type of topology at both feeder and ODN along with devices at the CO and RN. For example, a typical tree-star topology can accommodate more subscribers as compared to a conventional ring-based architecture due to the use of 1 : N POC. Whereas, the

latter utilizes symmetric Y, 1 : 2 or 2 : 2, POC per subscriber, which introduces a power-budget loss of -3 dBm in each symmetric POC, $P_{\text{POC}} = 10\text{Log}_{10}\left(\frac{1}{2}\right)$ [6, 16]. This significantly effects capacity of the network since nominal received power is required for high bandwidth communication. Therefore, it is imperative to consider these features at the network planning phase, so that the proposed PON can accommodate maximum number of subscribers at desirable capacity and cost.

2.4. Cost and complexity

Deployment/operational costs and feasibility of PONs primarily depend on complexity of the network architecture. For example, some protection mechanics utilize redundant transceivers at both OLT and ONUs, like ITU-T type C and D, in order to avoid 1 : 1 or 1 + 1 switching [17]. Although such techniques provide an abrupt recovery to maintain a smooth flow of information between OLT and ONU modules, they significantly elevate the deployment cost of the network. Since more CAPEX is spent on OLT duplication as compared to the 1 : 1 or 1 + 1 switching, a trade-off must be made between the cost and recovery time at the event of failure. Therefore, it is desirable to minimize the overall system complexity, without compromising the fault detection and restoration time.

3. Protection architectures for PON

Different protection architectures are proposed to facilitate fault detection and restoration in PON. This section discusses five pre-planned protection architectures, which vary in terms of topology, fiber duplication, and devices at both feeder level and ODN.

3.1. ITU-T 983.1 type C architecture

ITU-T 983.1 type C is a pre-planned protection architecture, which provides fault detection and restoration throughout the network with redundant components at both feeder and the distribution levels [17]. The basic type C PON is shown in **Figure 2**, where each component of the network is duplicated to ensure high connection availability and fast restoration time. OLT is placed at the CO and consists of two transceiver modules, where one acts as primary (OLT_p) and another is set as a secondary (OLT_s) module. Under normal mode of operation, OLT_p is responsible for originating and managing services across the network, whereas OLT_s activates in the event of failure at OLT_p module.

Each transceiver module at OLT is connected to a corresponding FF, namely primary (FF_p) and secondary (FF_s). Both fibers extend the network toward the subscribers' premises. Under normal mode of operation, OLT_p is connected to the FF_p. Two FFs are used to provide maximum connection availability and fast restoration time, such that FF_p is immediately replaced with FF_s in the event of failure. The span of each fiber is about 20 km for a standard PON. Both FFs terminate into RN, which serves as chases for two 1 : N POC modules connected with the corresponding FF at the input port and N DFs at the output port, respectively, where N represents the number of subscribers.

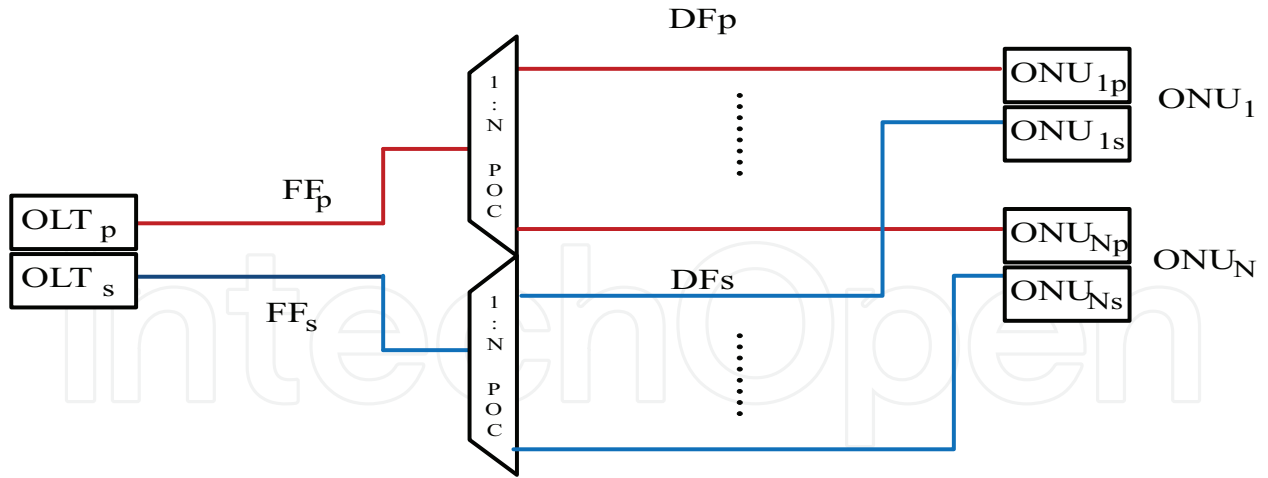


Figure 2. Type C protection architecture.

Consequently, a total of $2N$ DFs are utilized to provide the required protection at the ODN. DFs terminate into ONU with two transceiver modules, $(\text{ONU}_p, \text{ONU}_s)$, in order to facilitate abrupt fault detection and restoration. Type C protection architecture duplicates every component including OFs to provide abrupt fault detection and restoration. Furthermore, a two-fiber tree-based topology is laid at the feeder level, whereas a star-based topology is adapted to implement the $2N$ DFs at the ODN.

Number of subscribers in type C protection architecture can be determined through power budget analysis from OLT toward ONU module. Power budgeting in PON ensures an efficient communication between the transmitting and receiving modules. Moreover, it also determines the POC splitting ratio, which translates the number of subscribers in PON, respectively. If P_i represents the power loss across each component i , α is attenuation/km in the OF medium, and R_{sen} represents the receiver sensitivity, then the number of subscribers for type C protection architecture can be determined as:

$$P_T - P_{\text{OLT}} - \alpha P_{\text{FF}} - P_{\text{POC}} - \alpha P_{\text{DF}} - P_{\text{ONU}} - P_{\text{mis}} \geq R_{\text{sen}} \quad (1)$$

Equation (1) shows that major power loss occurs across the POC, which is determined by $P_{\text{OPC}} = 10\text{Log}_{10}(N)$, where N represents the number of subscribers or splitting ratio of $1:N$ POC. Therefore, to maintain received power $P_{\text{re}} \geq R_{\text{sen}}$, the value of N must be adjusted to facilitate extended reach, fault detection, and restoration along with high bandwidth connectivity. For example, when the transmitter power is 10 dBm, $\alpha = -0.25 \frac{\text{dB}}{\text{km}}$, $N = 128$, 25 km fiber, and $P_{\text{mis}} = -3$ dBm, the approximate power received at the PIN photo-diode will be $P_{\text{re}} = -20$ dBm. Consequently, for $R_{\text{sen}} = -25$ dBm, type C architecture can efficiently support 128 subscribers simultaneously accessing the medium.

3.2. Single ring architecture

In order to avoid extensive duplication of the OF medium at both feeder and ODN, ring-based topology is utilized to implement PON with desired connection availability and fault detection/

restoration between OLT and ONU modules [16]. The basic ring-based PON is shown in **Figure 3**, which contains OLT module at the CO. In order to avoid the high deployment cost of OLT module, this architecture employs a single unit, owing to the fact that failure per year of OLT module is minuscule [4, 18]. End-face of the OLT module is connected to a switching arrangement (SA_{CO}) that extends the OF medium in both clockwise (CW) and counter clockwise (CCW) directions. SA_{CO} serves as chases for a $1:2$ POC_{sa} , and $1:2$ OS_{sa} . POC_{sa} sends and receives the traffic for OLT module. Port 1 splits the optical signal toward the clockwise feeder ring (FR_{cw}), whereas port 2 extends the flow of traffic toward the counter clockwise FR (FR_{ccw}) through a $1:2$ OS_{sa} . This arrangement recovers the flow of information in case of failures at the FR. Under normal working conditions, OS_{sa} is at port a and both upstream and downstream traffic are carried on the FR_{cw} .

FR contains multiple ONU modules $\{ONU_n; n = 1, 2, 3 \dots N\}$, which are placed directly over the FR through individual RNs (RN_x) housing a $2:2$ $POC_{x,1}$ and a $1:2$ $POC_{x,2}$, respectively. Consequently, the total number of ONU modules is equal to RNs on the FR $X = N$. $POC_{x,1}$ is used to extend the FR to the neighboring ONU modules. Furthermore, it also connects individual ONU_n with FR through $POC_{x,2}$ and controls the flow of traffic in and out of the ONU module.

Network capacity in single ring-based architecture is significantly effected by the utilization of a single POC per subscriber. If N represents the number of RNs, then the total subscribers accessing the medium simultaneously can be determined by:

$$P_T - P_{OLT} - P_{POC_{sa}} - P_{OS_{sa}} - 2XP_{POC_{onu}} - P_{ONU} - P_{mis} \geq R_{sen} \quad (2)$$

X represents the number of RNs in Eq. (2), which is equal to ONUs N that can access the medium simultaneously. Consequently, for the transmitter power of 10, -3 dBm loss across the POC, $P_{mis} = -3$ dBm, 25 km fiber, and $R_{sen} = -25$ dBm, this architecture can scarcely support 16 subscribers simultaneously accessing the medium [6]. It is observed that fiber duplication is avoided at both levels through a ring-based structure; however, power drop across each POC

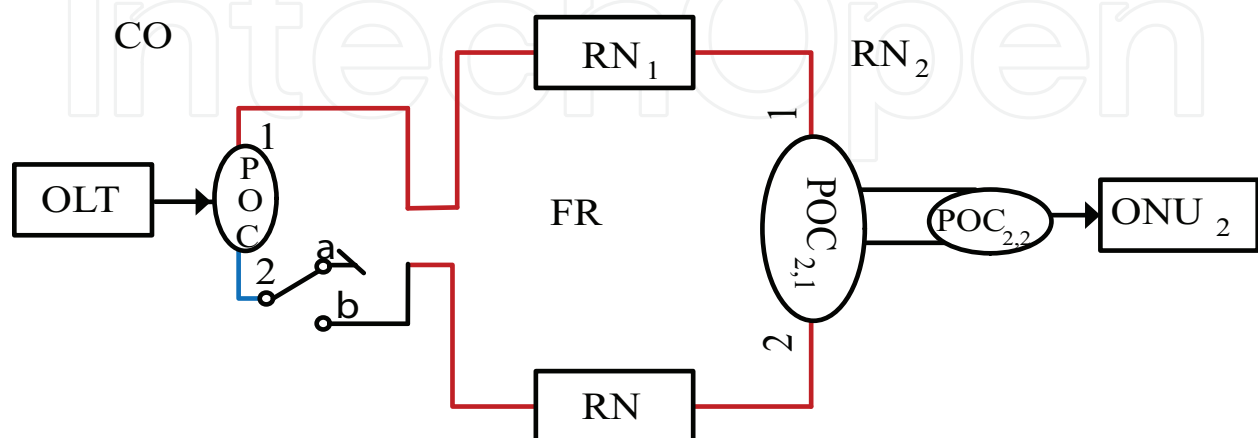


Figure 3. Single ring protection architecture.

introduces serious power budget issues. Consequently, capacity of the PON is effected. It is therefore imperative to utilize a topology that is capable of providing fault detection and restoration without compromising the network capacity and total cost.

3.3. Dual ring protection architecture

Dual ring PON avoids fiber duplication at the feeder level through a single ring-based fiber (FR) as shown in **Figure 4** [9]. Furthermore, several small rings are deployed at ODN to negate the power budget issue. CO contains a single OLT module, which is fed into an optical circulator (OC_{co}) and erbium-doped fiber amplifier (EDFA) module. To maintain passive nature of the PON, EDFA is placed inside the CO as shown in **Figure 4**. Switching arrangement SA_{co} is placed at end-face of the EDFA, which serves as chases for 1 : 2 POC_{sa} and 1 : 2 OS_{sa} . Port 1 of POC_{sa} splits the down-stream traffic towards FR_{cw} , whereas port 2 extends the flow of traffic towards the FR_{ccw} through a 1 : 2 OS_{sa} . In normal mode of operation, all traffic is carried through the FR_{cw} . However, OLT medium access control (MAC) layer flips the switch position when a failure occurs at the FR. This new position of the switch converts the ring-based fiber in two trees-based fibers carrying traffic in clock- and counter clockwise direction between the PoF.

Both FR_{cw} and FR_{ccw} are fed into multiple remote nodes forming several distribution rings (DRs) at the ODN. Each remote node $\{RN_x; x = 1, 2, 3 \dots X\}$ houses two 2 : 2 bidirectional POCs, namely $(POC_{x,1}, POC_{x,2})$ as shown in **Figure 4**. The former extends the FR from CW toward CCW direction and the latter carries the traffic from feeder toward the ODN and vice versa. End-face of $POC_{x,2}$ splits the incoming traffic into clock- and counter clockwise DRs (DR_{cw} and DR_{ccw}), respectively. Both DR_{cw} and DR_{ccw} are connected to individual ONU

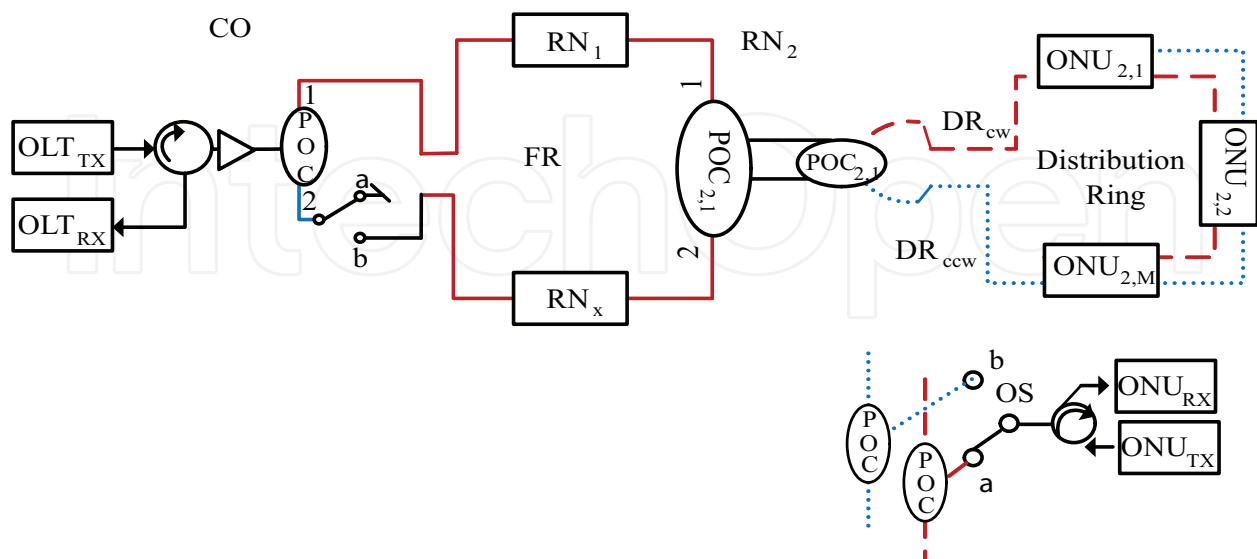


Figure 4. Dual ring protection architecture.

$\{\text{ONU}_{x,m}; m = 1, 2, 3 \dots M\}$ module through two 1:2 $\text{POC}_{\text{onu}_{x,m}}$ and $\text{OS}_{\text{onu}_{x,m}}$. Under normal working conditions, $\text{OS}_{\text{onu}_{x,m}}$ is at position a and all traffic is handled through DR_{cw} .

Dual ring architecture utilizes multiple rings at the distribution level to compensate the excessive power drop. Furthermore, EDFA is also employed at the CO to support high capacity transmission. Consequently, the power budget equation from OLT toward ONU module can be written as:

$$P_T - P_{\text{OLT}} - P_{\text{OC}_{\text{co}}} + P_{\text{EDFA}} - P_{\text{POC}_{\text{sa}}} - P_{\text{OS}_{\text{sa}}} - \alpha P_{\text{FR}} - 2XP_{\text{POC}_{\text{RN}}} - \alpha P_{\text{DR}} - MP_{\text{POC}_{\text{onu}}} - P_{\text{ONU}} \geq R_{\text{sen}} \quad (3)$$

Where X , in Eq. (3), represents the total number of RNs deployed at the FR and M represents the number ONUs per RN. Consequently, the total ONU modules accessing the medium simultaneously become $N = X \times M$. Now, at $P_T = 10$ dBm, 25 km fiber, and $P_{\text{edfa}} = 25$ dB, the maximum value of N that can be achieved is 72 with $X = 9$ and $M = 8$ [9]. It is observed that the dual ring architecture supports more ONU modules in comparison with the single ring architecture. Nevertheless, power drops in the ring topology at the distribution level limits the overall capacity of the network.

3.4. Tree-based hybrid protection architecture

This architecture employs a hybrid topology through combination of tree and star-ring architectures at the feeder and ODN, respectively. OLT is placed at the CO, which is fed into an OC_{co} , EDFA, and SA_{co} as shown in **Figure 5** [15]. SA_{co} consists of a 1 : 2 OS_{sa} , with port a connected to the FF_p , whereas port b is fed into FF_s . In normal working conditions, OS_{sa} is at port a and all upstream and down-stream traffic is sent and received through the FF_p . However, in case of failures or cuts at the FF_p , OLT MAC layer flips the switch position and resumes the flow of traffic through the FF_s .

Since a tree-based topology is adapted at the feeder level, the required protection is provided by duplicating the long-span fiber. End-face of both FF_p and FF_s terminates into RN that serves as chases for a 2 : N POC. Output of the 2 : N POC is connected to a series of dedicated DFs connecting N ONU transceiver modules as shown in **Figure 5**. In order to avoid extensive duplication of the DFs for protection, a ring-based topology is adapted by connecting intermediate ONU modules, respectively. Consequently, each ONU_n module, where $\{n = 1, 2, 3 \dots, N\}$, consists of 1 : 2 POC_n and 1:2 OS_n . Port 1 of the POC is connected to respective DF, whereas port 2 is fed into a 1:2 OS_n . Port 3 extends the DF toward a DR that provides the necessary protection in case of failure at the DF.

OS_n is used to connect OC_n and ONU_n with transmission media at the distribution level. Port "a" of OS_n connects ONU_n with the DF, whereas port "b" is used to connect ONU_n with the redundant DR in case of failure. Consequently, the required protection is achieved by avoiding the extensive duplication of the DFs. Under normal mode of operation, OS_n is at port "a" and all services are delivered through the DF, whereas in case of failure the affected ONU_n MAC

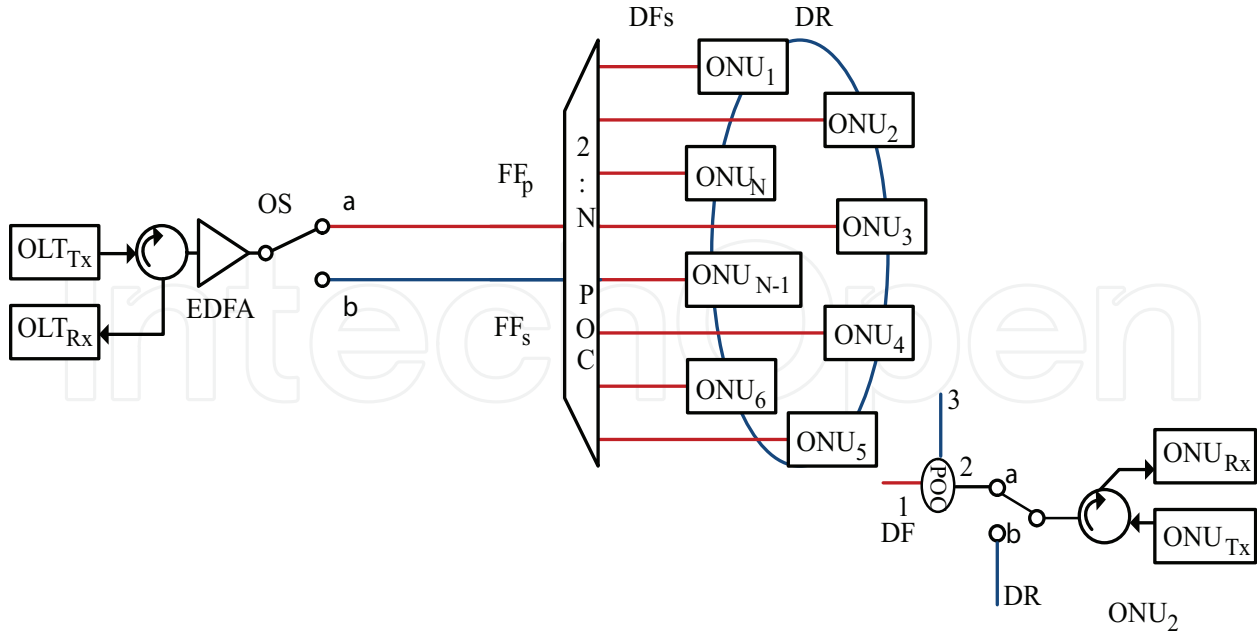


Figure 5. Tree-based hybrid protection architecture.

layer flips the switch position and transfers the flow of traffic to the DR between the adjacent ONU module.

The downstream power budget for tree-based hybrid protection architecture can be written as:

$$P_T - P_{OLT} - P_{OC_{co}} + P_{EDFA} - P_{OS_{co}} - \alpha P_{FF} - 10 \log_{10} N - \alpha P_{DF} - P_{POC_{onu}} - P_{OS_{onu}} - P_{OC_{onu}} - P_{ONU} \geq R_{sen} \quad (4)$$

It is observed from Eq. (4) that for $P_T = 10$ dBm, 25 km fiber, $P_{edfa} = 25$ dB, and $R_{sen} = -25$ dBm, the tree-based hybrid protection architecture can efficiently support 128 subscribers simultaneously accessing the medium [15].

3.5. Ring-based hybrid protection architecture

This architecture is formed by the combination of a single ring topology at the feeder level and a star-ring architecture at the ODN. A single OLT is placed at the CO, which is connected to an OC_{co} , EDFA, and SA_{co} as shown in Figure 6 [18]. This architecture utilizes a single ring-based fiber to provide the required high bandwidth connectivity and reliability at the feeder level. Port 1 and 2 of the POC_{sa} extend traffic toward the FR_{cw} and FR_{ccw} , respectively. A 1:2 OS_{sa} is connected with port 2 of the POC_{sa} to provide the required fault recovery in the event of failure. Port a of the OS_{sa} is connected to ground, whereas port b is fed into the FR_{ccw} . Under normal mode of operation, OS_{sa} is at port a and all traffic is sent and received through the FR_{cw} .

FR is implemented at each RN by combining FR_{cw} and FR_{ccw} through a special arrangement. This significantly reduces the power budget penalty and cost of the overall architecture. RN

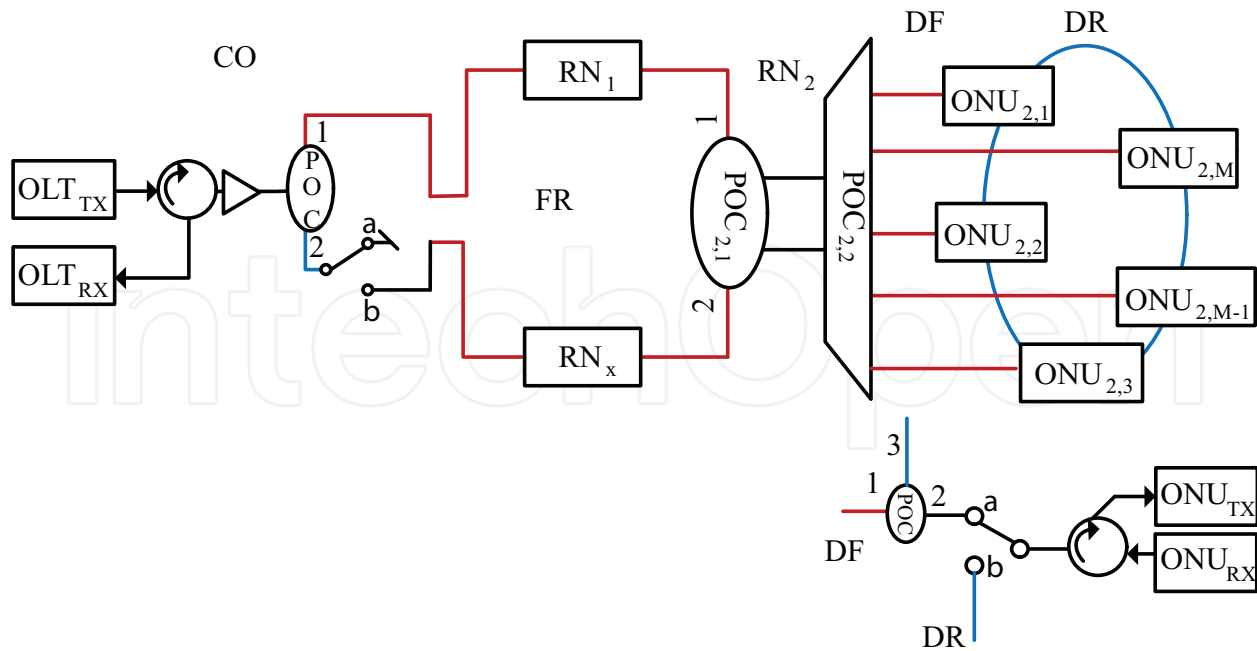


Figure 6. Ring-based hybrid protection architecture.

in the ring-based hybrid network $\{RN_x; x = 1, 2, 3 \dots X\}$ consists of two POCs, namely $(POC_{x,1}, POC_{x,2})$. Where $POC_{x,1}$ and $POC_{x,2}$ are bidirectional couplers with $2 : 2$ and $2:M$ ports respectively. FR is formed by connecting both CW and CCW paths through port 1 and 2 of the $POC_{x,1}$ as shown in **Figure 6**. $POC_{x,1}$ further extends the FR toward the ODN through a $2 : M$ $POC_{x,2}$, where M is the number of ONUs connected to each $POC_{x,2}$ through dedicated DFs. If X represents the total number of RNs deployed over the FR and M is the number ONUs per RN, then the proposed system can support a total of $N = X \times M$ ONUs.

ONU module, $\{ONU_{x,m}; m = 1, 2, 3 \dots M\}$, starts with a $1:2$ $POC_{x,m}$ with three ports as shown in **Figure 6**. Port 1 is used to connect each ONU to its dedicated DF, whereas port 2 is fed into $1:2$ $OS_{x,m}$. Port 3 is used to form a backup DR, which ensures immediate survivability of traffic between ONUs and OLT. Port a of the $OS_{x,m}$ connects $ONU_{x,m}$ with corresponding DF, under normal working conditions, and port "b" is fed into the DR.

The number of subscribers in ring-based hybrid protection architecture can be determined as:

$$P_T - P_{OLT} - P_{OC_{co}} + P_{EDFA} - P_{POC_{sa}} - P_{OS_{sa}} - \alpha P_{FR} - X P_{POC_{x,1}} - 10 \log_{10}(M) - \alpha P_{DF} - P_{POC_{onu}} - P_{OS_{onu}} - P_{OC_{onu}} - P_{ONU} \quad (5)$$

If N represents the total number of ONUs, then the value of X can be written as:

$$X \leq \frac{P_T - R_{sen} - 16.25 - 10 \log_{10} M + P_{EDFA}}{3} \quad (6)$$

Analysis of Eq. (6) shows that capacity of the network increases when more ONUs are placed per RN. Furthermore, it is observed that for $P_T = 10$ dBm, $P_{\text{edfa}} = 25$ dB, and $R_{\text{sen}} = -25$ dBm, the ring-based hybrid protection architecture can efficiently support 128 subscribers simultaneously accessing the medium [18].

4. Reliability analysis

Network reliability analysis is an important tool that is used to determine the overall connection availability for a given protection architecture. Reliability block diagrams (RBDs) are commonly used to determine the overall connection availability of PON, owing to its significant advantages like, accuracy, simplicity, visual impact, and flexibility. This section analyzes network reliability in terms of connection availability of the selected protection architectures through RBDs.

RBD represents each component including the OF medium as a functional block connected in series or parallel combination with adjacent blocks. Series and parallel connectivity represent the unprotected and protected components in protection architecture, respectively. The characteristic parameter of each RBD block is the asymptotic unavailability (U_i) of the components that represent their probability of failures. Consequently, if I represents the total number of components in PON, then overall connection availability A is given by:

$$A = 1 - \sum_{i=1}^I U_i \quad (7)$$

where U_i is determined by

$$U_i = 1 - \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad (8)$$

MTBF in Eq. (8) is the mean time between failures, which is used to represent the number of failures per million hours for an optical component [19]. MTTR represents the mean time to repair, which is the time required for reparation or replacement of faulty hardware modules [5, 20, 21]. In order to determine the overall connection availability for each architecture, RBDs with series and parallel combination of functional blocks are extracted as shown in **Figure 7**.

If $\sum_{i=1}^I U_i$ is the summation of i components unavailability in a protection architecture, then connection availability for each survivable PON can be written as:

$$A_{[C]} = 1 - \left[\left(U_{\text{OLT}} \times U_{\text{OLT}_{\text{pt}}} \right) + \left(U_{\text{FF}} \times U_{\text{FF}_{\text{pt}}} \right) + \left(U_{1:N \text{ POC}} \times U_{1:N \text{ POC}_{\text{pt}}} \right) + \left(U_{\text{DF}} \times U_{\text{DF}_{\text{pt}}} \right) + \left(U_{\text{ONU}} \times U_{\text{ONU}_{\text{pt}}} \right) \right] \quad (9)$$

$$A_{[\text{SR}]} = 1 - \left[U_{\text{OLT}} + U_{\text{POC}} + U_{\text{OS}} + \left(U_{\text{FR}} \times U_{\text{FR}_{\text{pt}}} \right) + U_{\text{POC}} + U_{\text{POC}} + U_{\text{ONU}} \right] \quad (10)$$

$$A_{[DR]} = 1 - \left[U_{OLT} + U_{POC} + U_{OS} + (U_{FR} \times U_{FR_{pt}}) + U_{POC} + U_{POC} + (U_{DR} \times U_{DR_{pt}}) + (U_{POC} \times U_{POC_{pt}}) + U_{OS} + U_{ONU} \right] \quad (11)$$

$$A_{[HT]} = 1 - \left[U_{OLT} + U_{OS} + (U_{FF} \times U_{FF_{pt}}) + U_{2:N POC} + (U_{DF} \times U_{DR_{pt}}) + U_{POC} + U_{OS} + U_{ONU} \right] \quad (12)$$

$$A_{[HR]} = 1 - \left[U_{OLT} + U_{POC} + U_{OS} + (U_{FR} \times U_{FR_{pt}}) + U_{POC} + U_{2:N POC} + (U_{DF} \times U_{DR_{pt}}) + U_{POC} + U_{OS} + U_{ONU} \right] \quad (13)$$

Figure 8 shows the overall connection availability of the selected protection architectures based on **Table 1**. It is observed that maximum 5 nines connection availability is provided by all architectures, owing to the efficient utilization of redundant components and OF medium throughout the network. Maximum connection availability is provided by type C protection architecture, which duplicates entire PON including OLT and ONU modules. Ring-based architecture at both feeder and ODN, which avoids the duplication of light-wave path, is also observed to provide the required availability. A single failure at the ring-based fiber converts

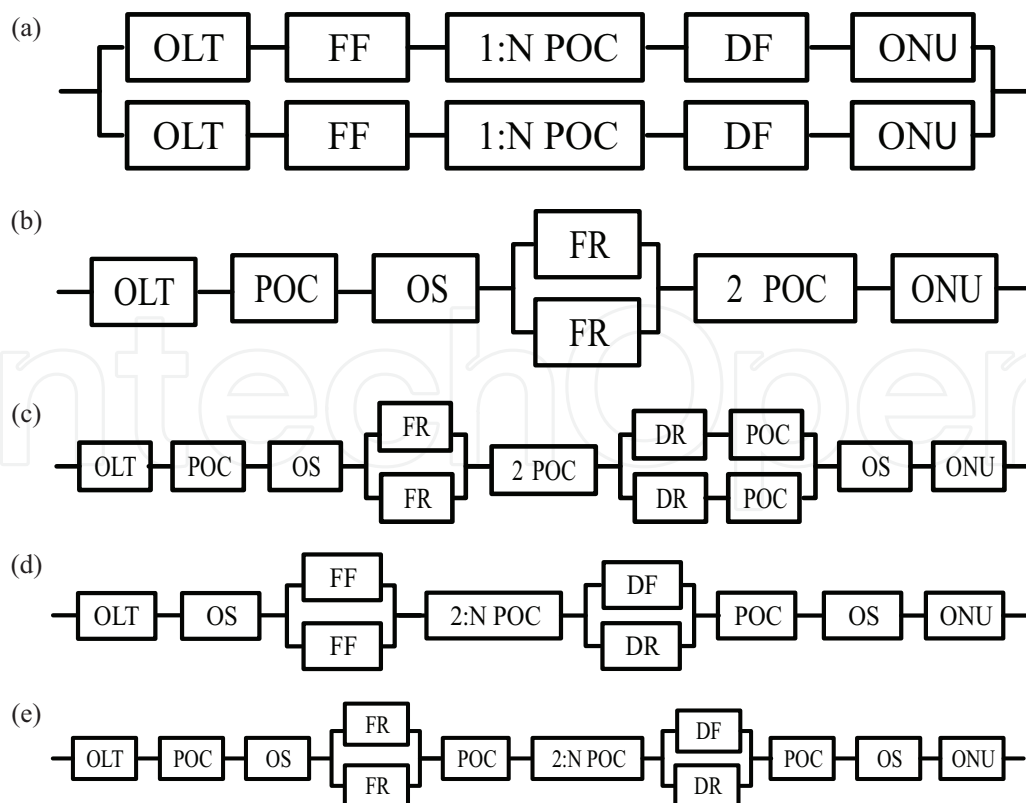


Figure 7. Reliability block diagrams for (a) type C, (b) single ring (SR), (c) dual ring (DR), (d) tree-based hybrid (HT), and (e) ring-based hybrid (HR) protection architectures.

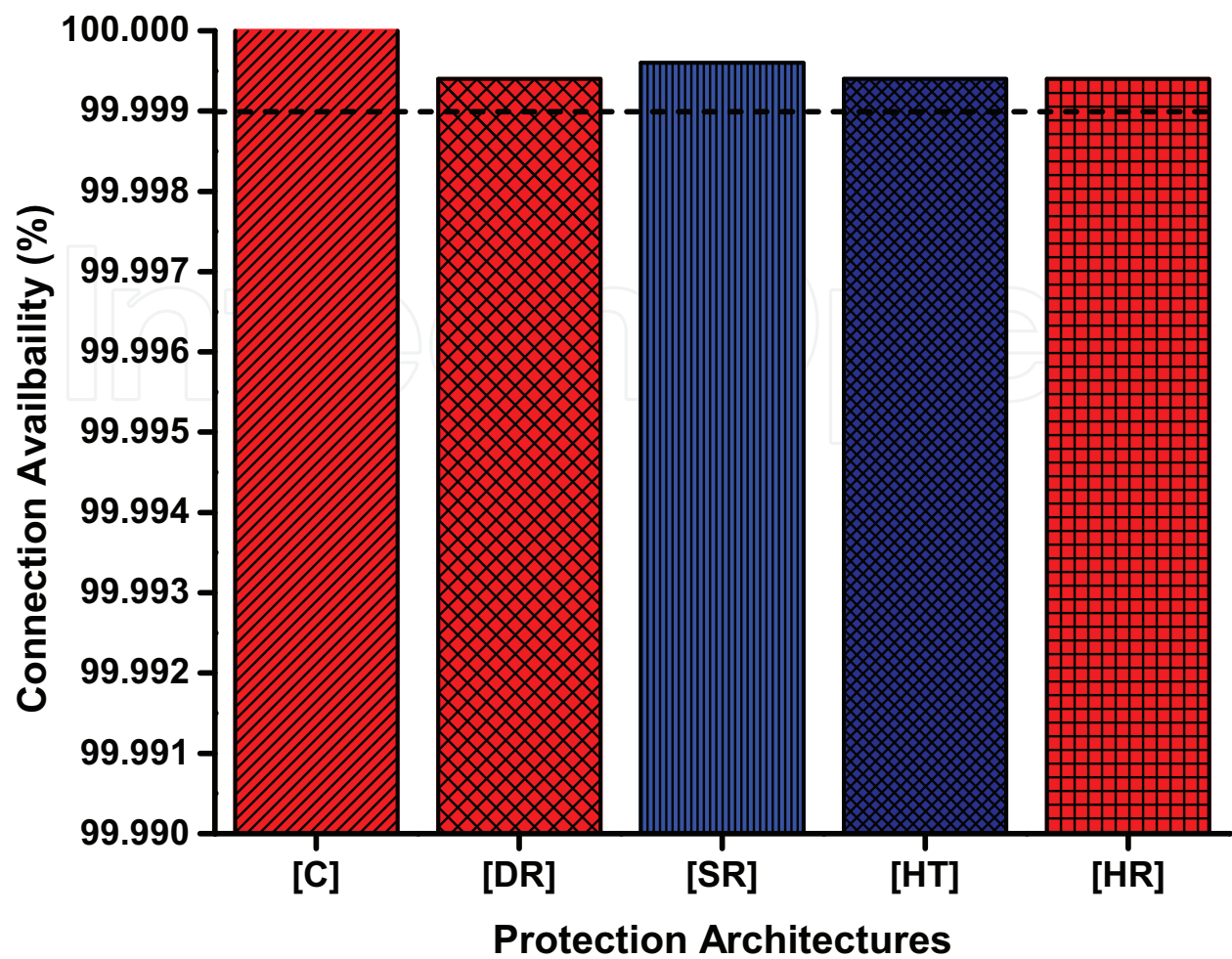


Figure 8. Overall connection availability of selected protection architectures.

the network into two tree-based architectures with the flow of traffic in both clockwise and counter clockwise directions. Thus, redundancy is achieved without duplicating the entire fiber. Furthermore, it is observed that desirable connection availability can be maintained without duplicating the transceiver modules, which further helps in reducing the overall cost of deployment for such architectures.

5. Cost analysis

Cost figures for protection architectures are an important parameter, showing the economic benefits for a common end user at the access domain. This section determines the overall expenditure for the selected architecture while using component costs in **Table 1**. Cost figures for PON can be categorized as CAPEX and OPEX. CAPEX includes the investment utilized for the deployment of PON at access domain and is calculated by computing the cost expenditure on network devices along with the OF infrastructure. OPEX includes the cost incurred on the network operations from the time of deployment till replacement by a new technology [4, 15, 22, 23].

OPEX primarily includes the cost required for repairing the faulty, failed equipment (including OF medium), service interruption penalty cost that is commonly applicable for business subscribers, and energy consumed by active components at transceiver modules of OLT and ONU. Reparation cost is determined by multiplying the total downtime/year with resources required to remove the fault, which includes the number of technicians along with their wages and miscellaneous charges. Service interruption penalties include the expenditure that is spent on the fine defined in service level agreement (SLA) between network operators and subscribers. Power consumption by each component is determined by multiplying the unit price of electricity with the sum of energy consumption of all active components over the network life span [15, 23].

Analysis is performed for residential customers only, and life span of each network is taken as 20 years. Furthermore, following specifications are considered for fair analysis of the selected protection architectures

- OLT can support 16, 32, 64, and 128 subscribers based on the type of adapted topology.
- Length of FF = 20 km, DF = 5 km, and DR = 1 km between adjacent nodes in selected architectures.
- EDFA cost is considered in dual ring, tree- and ring-based hybrid architectures.
- Digging cost for OF medium is ignored due to high variation.
- No service interruption penalty cost is considered.
- Repairing cost is 1000 \$/h.
- Per hour cost of electricity is taken to be 0.25 \$/kWh.

If N is the total number of ONUs in each PON and X represents the number of RNs in ring-based topologies at the feeder level, then the CAPEX equations (based on RBDs) for selected protection architectures can be written as:

$$C_C = (OLT + OLT) + (20 \times FF \times FF) + (2 \times 1 : N \text{ POC}) + (5 \times N \times DF \times DF) + (N \times ONU \times ONU) \quad (14)$$

$$C_{SR} = OLT + POC + OS + (25 \times FR) + (2X \times POC) + (N \times ONU) \quad (15)$$

$$C_{DR} = OLT + POC + OS + EDFA + (20 \times FR) + (2X \times POC) + (N \times DR_{cw}) + (N \times DR_{ccw}) + (2N \times POC) + (N \times OS) + (N \times ONU) \quad (16)$$

$$C_{HT} = OLT + OS + EDFA + (20 \times FF \times FF) + (2 : N \text{ POC}) + (5 \times N \times DF) + (N \times DR) + (N \times POC) + (N \times OS) + (N \times ONU) \quad (17)$$

$$C_{HR} = OLT + POC + OS + EDFA + (20 \times FR) + (X \times POC) + (X \times 2 : N \text{ POC}) + (5 \times N \times DF) + (N \times DR) + (N \times POC) + (N \times OS) + (N \times ONU) \quad (18)$$

Figure 9 shows the CAPEX for each protection architecture at different number of subscribers by referring to **Table 1**. It is observed that ring-based architecture requires minimum CAPEX when compared to conventional tree and hybrid techniques. However, due to the power budget and capacity limitations of single and dual ring-based architectures, their analysis is performed till 16 and 64 number of subscribers, respectively. Overall analysis shows that the deployment cost for each architecture decreases as the number of subscriber increases. It is evident from the fact that total cost incurred is distributed among the number of subscribers, which results in reduced CAPEX per user as the network capacity increases. Furthermore, it is shown that type C architecture requires the highest cost, for all subscribers, in comparison with other schemes due to the extensive duplication of optical components and OF medium throughout the network.

Figure 9 shows that hybrid protection architectures provide nominal performance, for all subscribers, in terms of the deployment cost as they avoid extensive duplication of the OF medium. **Figure 10** further elaborates the CAPEX required for the deployment of light wave path in type C, tree- and ring-based hybrid protection architectures for 128 subscribers in the

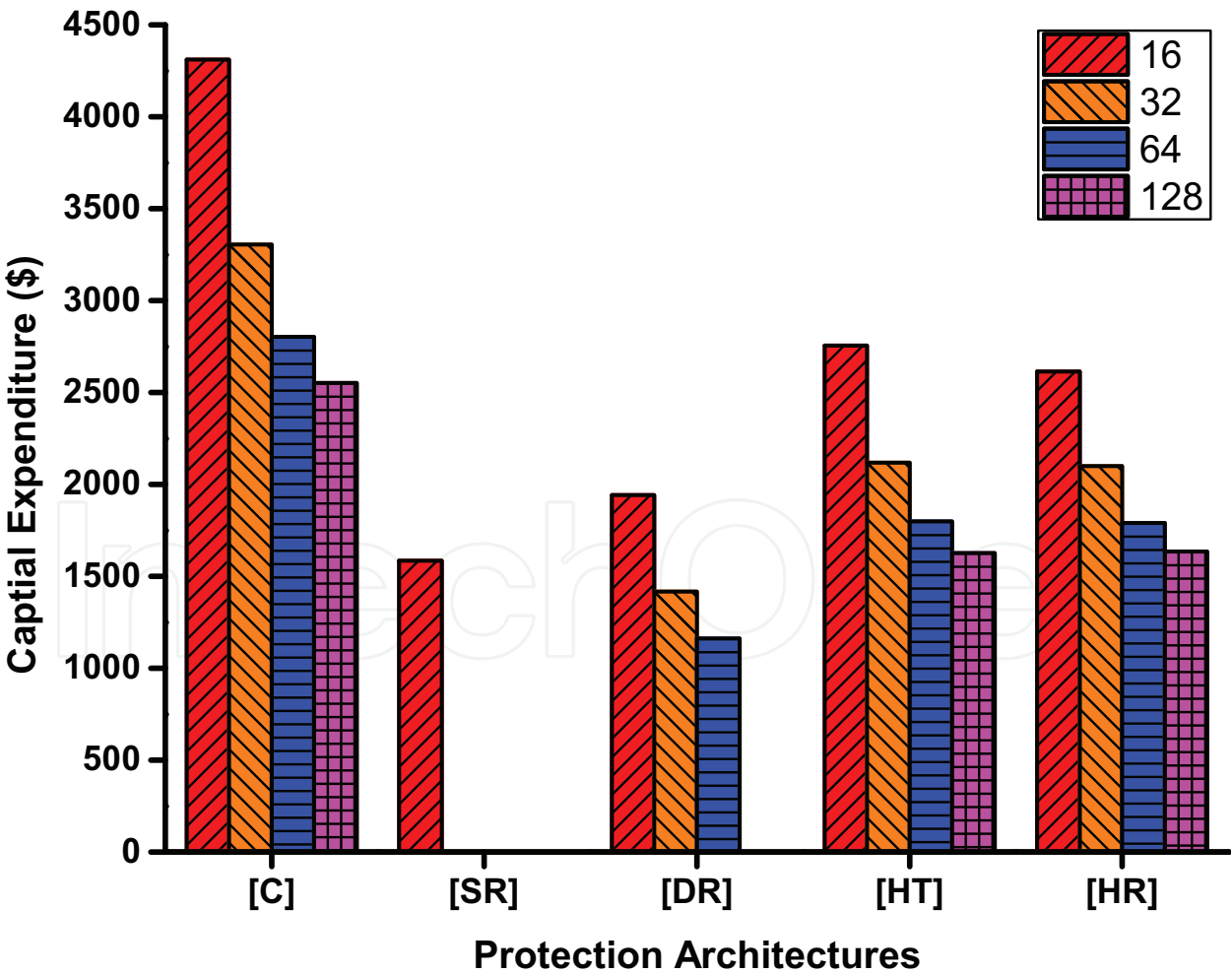


Figure 9. CAPEX at different number of subscribers.

network. It is observed that the main contributor for CAPEX, besides OLT module, is the DF as each subscriber requires a dedicated path for high speed connectivity. Furthermore, it is shown in **Figure 10** that type C requires the highest deployment cost for DFs due to the duplication of each fiber between RN and corresponding ONU module. On the other hand, the deployment of star-ring topology at ODN significantly reduces the CAPEX, on redundancy, for hybrid protection architectures.

It is also observed that the CAPEX in hybrid protection architecture varies with the type of topology at the feeder level. Since ring-based architecture requires multiple RNs, the cost of deployment increases with the number of subscribers due to increase in RNs. Consequently, tree-based hybrid architecture requires less cost when compared to ring-based scheme for 64 and 128 subscribers. However, the difference is minuscule.

Figure 11 shows the total expenditure for protection architectures with high network capacity in terms of the number of subscribers. It is evident from the fact that each architecture provides the desired connection availability, which significantly reduces their downtime/year. Hence, minuscule amount is spent on reparation cost over the network life span. Type C protection architecture requires highest OPEX due to the duplication of transceiver modules at both OLT

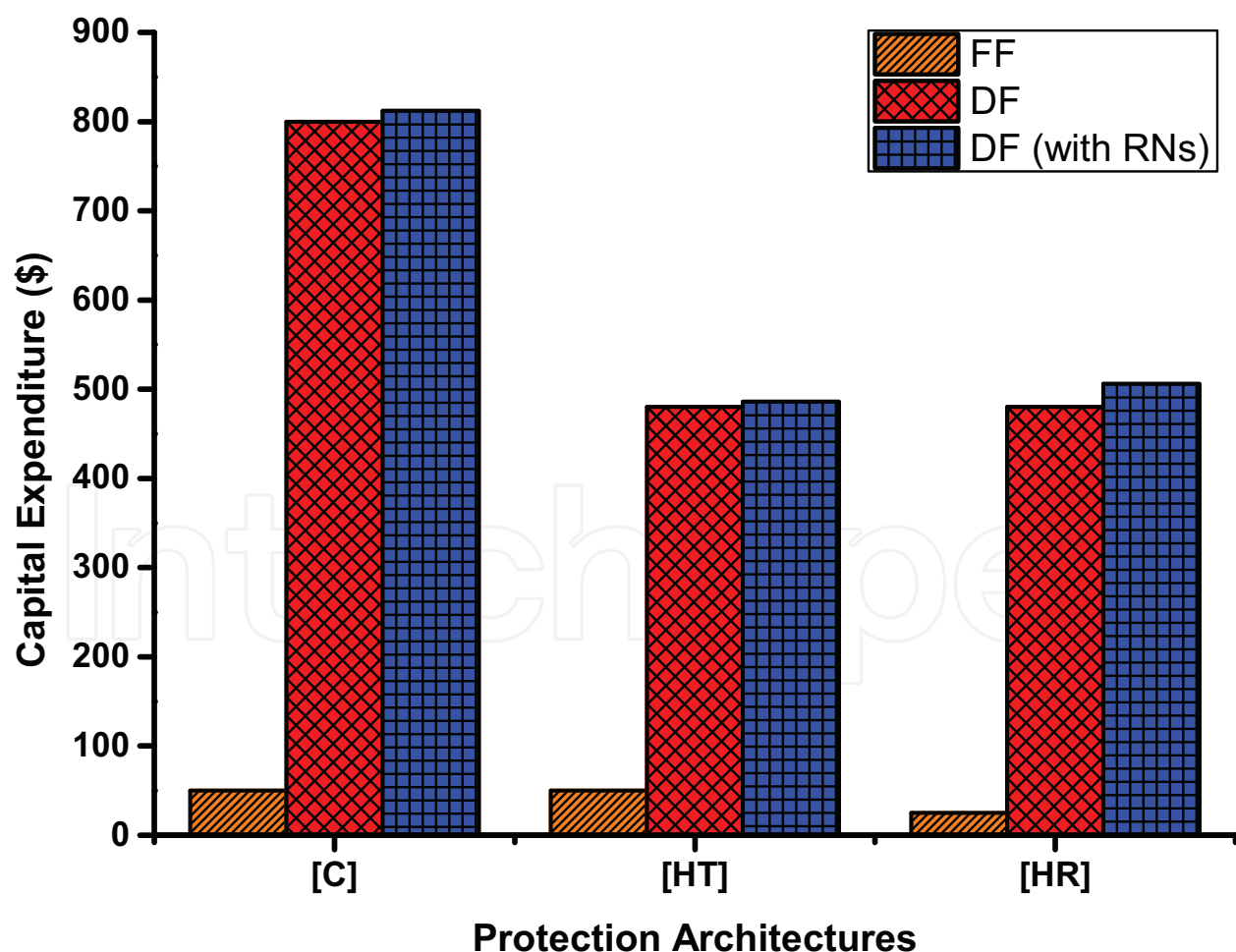


Figure 10. CAPEX for OF infrastructure at 128 subscribers.

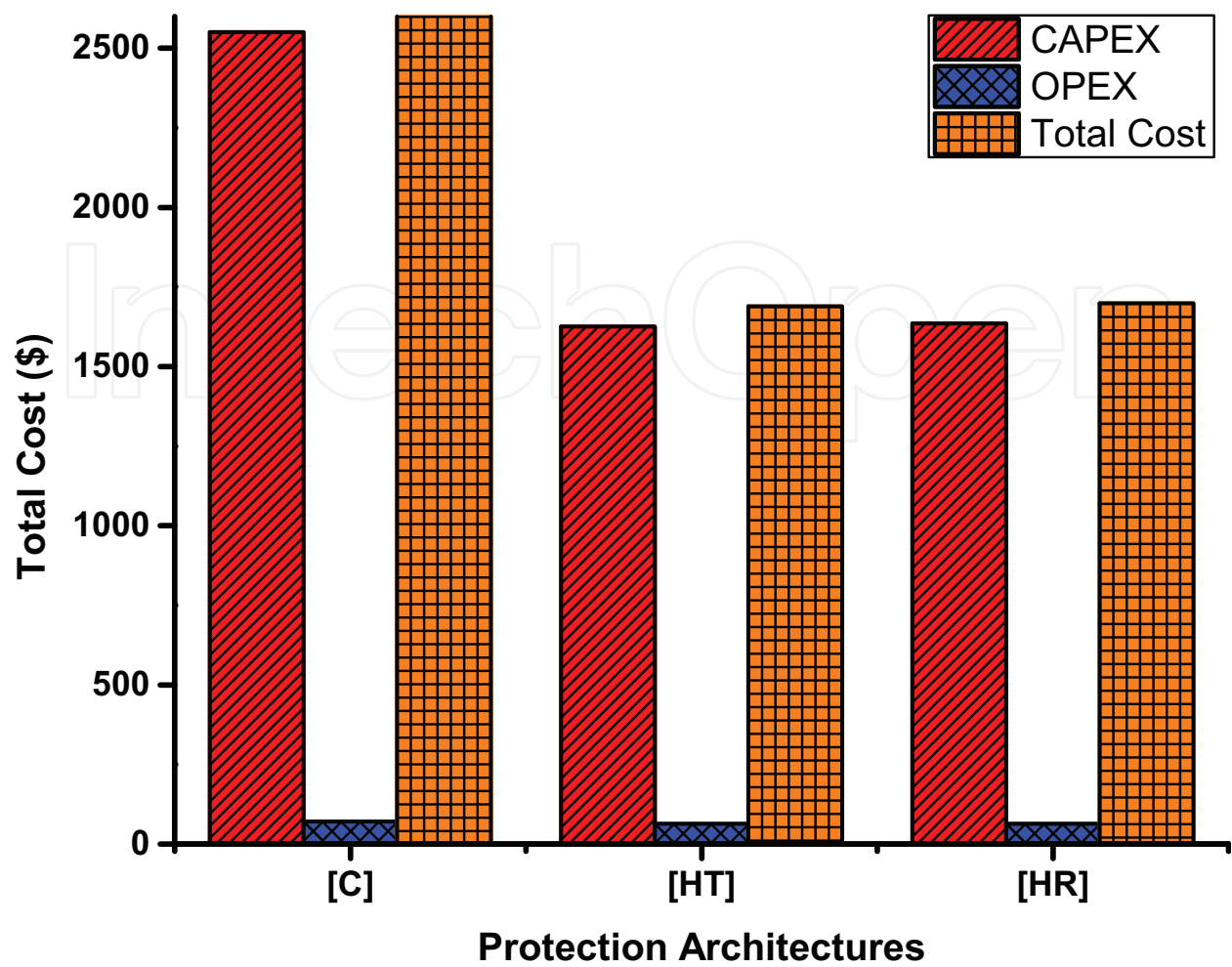


Figure 11. Total cost including CAPEX and OPEX at 128 subscribers.

and ONUs, which consumes more energy as compared to hybrid architectures with single OLT and ONU modules. Consequently, hybrid architecture requires minimum cost, collectively, as compared to the conventional protection scheme.

6. Conclusion

This chapter analyzes the effect of fiber duplication, for protection, on feasibility of PON. Increase in the capacity and adaptability of PON demands for an efficient fault detection and restoration mechanism, which is able to provide the required connection availability at minimum cost. Among all components in the PON, OF medium requires significant protection due to its high rate of failure. Furthermore, it is an on-field component and constitutes a major portion of PON; therefore, it is imperative to provide pre-planned redundant paths in order to ensure swift recovery of failures at the OF medium throughout the network. Five protection architectures are considered, which mainly emphasize on the type of topology laid through the OF medium at both feeder level and ODN. ITU-T 983.1 type C and single ring-based architectures are considered to encompass the conventional tree-star

and ring topology, respectively. For further analysis, dual ring architecture and tree- and ring-based hybrid protection architectures for PON are analyzed to study the effect of hybrid topologies on PON feasibility in terms of the number of subscribers, reliability, and cost. It is observed that ring-based architectures provide desirable connection availability without duplicating the OF medium; however, the use of multiple POCs to extend the FR significantly elevates the power budget issues. Consequently, the number of subscribers that can access the medium simultaneously is reduced. Hybrid topologies formed by the variation of tree, ring, and star topology provide nominal performance, in terms of all parameters, as compared to the survivable PONs based on conventional topologies. Furthermore, it is shown that duplication of the OF medium at the ODN network is more critical in comparison with the feeder level duplication. Nevertheless, both tree- and ring-based hybrid pre-planned protection architectures provide desirable network capacity and connection availability at minimum cost.

Author details

Waqas Ahmed Imtiaz^{1*}, Javed Iqbal², Affaq Qamar¹, Haider Ali¹ and Sevia M. Idrus³

*Address all correspondence to: w.imtiaz.1985@ieee.org

1 Abasyn University, Peshawar, Pakistan

2 Sarhad University of Science and Information Technology, Peshawar, Pakistan

3 Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Malaysia

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