Comparative Analysis of Different NG-PON2 Protection Types Based on FDM

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Abstract—Resilience of a Passive Optical Network is the capacity to recover quickly from its failures and to resume back to its services soon after the failure condition. Resilience becomes a very important technique during the critical conditions of failure especially in the upcoming Next Generation-Optical Networks stage2 (ITU-T G. 989.2) when the network grows in high density, high speed and high data rate. Hence in this article, we have proposed a Fault Detection Module (FDM) and implemented in the NG-PON2 protection architecture for 2048 high-end subscribers using 2048 splitter for an extended reach of 100 Km Optical fiber distance. ITU-T G.984.1 outlines certain topologies for achieving redundancy. The proposed design is investigated and the simulation results shows that the protection architecture with proposed FDM exhibits low Total Round Trip Propagation Loss for ITU G. 655.D corning LEAF fiber, low Network Connection Availability of 0.9997 achieved for Type B protection which is exclusively required for business service providers when compared with all other protection types without FDM.

Index Terms—International Telecommunication Union-Telecommunication (ITU-T), Next Generation-Passive Optical Networks Stage 2 (NG-PON2), Total Round Trip Propagation Loss (TRPL), Network Connection Availability (NCA) and Network Connection Unavailability (NCU)

I. Introduction

In today's world, we have a huge demand for bandwidth applications as the number of subscribers increasing day by day. The solution to meet the increase in demand is Passive Optical Networks (PON). If the demand is not met properly while having a fault in the network, protection and restoration of the service have to be done. The connection request is made for protection with respect to path length in a heavily loaded TWDM-PON network.

No protection connection is considered for short path length. Shared path protection is used for moderate path length. Dedicated path protection is considered for long path length. A WDM-PON metro access network is proposed for Four level protection using a single ring which is highly reliable and reconfigurable for the proposed design of flexible distribution node [1]. A DWDM-PON FTTH channel is designed and investigated by varying the dispersion rates and by varying the LED power rates in the presence of non linearity'service without any amplifier and with a constant channel spacing of 100 GHz to achieve a maximum reach. The simulated results obtained shows a better BER < 10^{-10} and Q factor of 6.16 for the above design [2].

A novel Multi-Hop bypass-Based Protection (MHBP) scheme is proposed in dense urban areas, providing protection to ONUs against DF failures, which reduces the number of backup DFs in 100 Km LR-PON [3]. A WDM-PON network is proposed in remote nodes and designed for heavy data traffic and providing protection and securing mechanism by utilized only passive optical components. The aim is to optimize the optical power budget constraints in WDM-PON network [4].

For long reach, Google Fiber has proposed a variant in wavelength-routed TWDM-PON in today's network. An automated protection switching is designed against fiber failures by avoiding back up OLTs and by using splitter and EDFAs to provide the secondary path [5].

A WDM network is designed and investigated for link failure in mesh topology by providing a sparse traffic grooming as a survivability approach by means of using combiner queueing model to calculates the probability of call request and to reduce the blocking probability as well as reducing the number of call dropping [6]. Two proposed LR-PON architectures were designed to use the idle backup OLTs to serve the users requesting for high bandwidth and providing protection to users to ensure the reliability under failure conditions and heavy traffic in case.

It gives low average buffer size, less average cycle time, average packet delay, and more reliability to traffic than the general LR-PONs[7]. A new NG-PON2 is designed for 2048 users using TWDM-PON architecture for long reach of 100 Km using three EDFA optical amplifiers. The amplifier emission noise power and saturation power of optical amplifier and splitter losses are simulated and evaluated. The design is analyzed for Quality of service parameter [8].

A proposed techno-economics study was done in regions for large number of users, but the cost increases when using protection strategies is the drawback. XG-PON performs well when the bit rate increases up to hundreds of Mb/s in non-protected scenarios, the most suitable technology, in protected scenarios is NG-PON2 when the bit rate demand approaches 1 Gb/s [9]. A novel ring-based WDM-PON is proposed to reduce the optical beat interference noise induced by Rayleigh

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backscattering by using the orthogonal coding scheme. The novel technique requires fewer Bragg gratings and no band filter, so the proposed scheme cost is less [10].

Two methods of Type B protection systems are introduced for fast protection switching under 50 ms. The N:1 and 1:1 scheme is suitable for high-density cost-effective services and high-reliability business services [11]. Network geometric model and corresponding software is modelled by a reliability growth, these two models, is captured by a Markov cost model and solved by simulations showing clients failure versus downtime [12]. LR-PON designed with large split ratio for long reach, the protection mechanisms become a major consideration, as a single mode fiber failure could disrupt the services for thousands of users.

The software-defined network control plane is proposed to manage the dual-homed N: M protection switching and traffic rerouting with restoration times of 40 and 80 ms, respectively [13]. The protection mechanism is designed with switches to protect the network from the Multi-faults of fiber links. The signals propagates in different fiber rings to reduce the influence of Rayleigh backscattering. Space division multiplexing technology is adopted to reduce the loss and crosstalk of signals [14].

The feeder fiber are more subjected to failures in longer reach design therefore for resiliency purposes, a dual-homed architecture is proposed. An N:1 protection mechanism to reduce backup OLTs in a resilient dual homed LR-PON is deployment. The problem is modelled as an integer linear program for solving Irish and UK network deployments [15]. WDM mesh network is designed for power saving and resource efficiency with the proposed dynamic power aware shared path protection algorithm. It reduces the blocking probability by energy saving, it improves sharing spare capacity [16].

Design of downlink/uplink unicast 8 channel of each 2.5 Gb/s and one 10 Gb/s broadcast channel with the use of the cyclic property of arrayed waveguide grating with reflective capabilities of the fiber Bragg grating which produces colourless operation in TWDM-PON. The maximum allowable power budget loss for the network is about 36.5 dB with the receiver sensitivity for all ONUs obtained is 29.83 dBm [17]. The proposed algorithm is evaluated for three different topologies and it shows the low blocking probability for long path length topology. It also exhibits a low wavelength occupancy ratio. It provides better low blocking probability without any service interruption [18].

This article describes the survivability using dedicated and shared protection algorithm to compute multicast and multi-domain level protection in passive optical networks. They provide inter-domain and intra domain level protection using the Dijkstra algorithm for computing the optical network tree. It provides a low blocking percentage and high resource efficiency [19]. PON offers more bandwidth to huge users with higher scalability for longer reach with combined TDM and WDM multiplexing in access topology. They also designed the system for OFDM and Ultra-Dense WDM are operated over tree topology. Efficient utilization of resources has resulted from the three different optical access networks. Spectral efficiency improvement is achieved which results in power and cost savings [20].

This paper address the protection and restoration method for reliable data traffic. They designed an optical burst switching network for guaranteed data transmission. This scheme resulted in better QoS in a high-speed network with minimum loss rate. It improves the network resource sharing and the channel utilization with the reserved backup link channels [21]. Here they have designed a TDM-PON and OFDM-PON using power splitter. An analysis is being done both for OOK in TDM-PON and OFDM signal in OFDM-PON. The experiment is carried out for 10 Gb/s NRZ PRBS signal. Better BER is obtained for the signal to crosstalk ratio of 7.7 dB. The CW injection from an ONU produces a severe power penalty in the upstream OFDM signal. The new scheme preserves the idling optical power at ODN to maintain passiveness of the optical splitter with a 1% reduction in power [22].

TWDM–PONs increase the fault detection and super fast restoration of services to users. They use sleep/doze mode optical network terminal to detect and switching against multipoint failure in TWDM-PON network. The analysis is done for maximum split ratio and maximum reach using Type A, Type B and Type C architecture. The reliable detection methods limit the maximum total fiber link to be deployed. Establishment of survivability in a TWDM-PON comes at the penalty of increased cost per user[23]. It investigates about the multiple fault restorability in WDM networks and mainly discusses the survivable routing and wavelength assignment algorithm in wavelength-routed all-optical WDM networks, which is very efficient for networks with multiple failures when varying loads are applied to nodes. The analysis is done for 14 nodes and 21 links for a varying load which results in low blocking probability [24].

Protective measures are discussed to avoid interference between a certain wavelength of present and next generation PONs. Separation of signaling is done using wavelength blocking filters for GPON and NG-PON. Proper filtering increases the bandwidth, their allocation schemes of a long pass and short pass filter placed in ONUs offers eight times increased bandwidth[25]. A restoration schemes against failure is proposed in the Light Path Line (LPL) which is applied in the tree and ring topologies by means of a protection unit called End User protection Unit (EUPU) designed by means of optical switch and optical coupler, so that the signal find the alternative path in case of failure in specific line. The results are analyzed for output power, Q factor for different coupling ratios and for different receiver sensitivity [26].

It explains the art of the NG-PON2 architecture and provides the solutions by considering wavelength, cost, traffic and bandwidth with the consistency of splitter based ODNs. It provides an access solution for 10 Gb/s in NG-PON2 for 10000 users. It also serves for 10 Tbps in terms of switching capacity in OLT backplanes [27]. Switches and ring topology based protection mechanism using TWDM-PON were realized and resilience is provided for multiple failures in the network.

The protection is made for total 10 Km with 5 Km feeder fiber and 5 Km distribution fiber using one ring and double ring architecture. They calculated the unavailability for splitter switches and fiber. A switch is placed in front of each ONU in case of failure to make intelligent protection [28]. They proposed the protection scheme for coexistence from TDM-PON to TWDM-PON. A cost-effective method of power budget, recovery time and connection availability are estimated. It provides a low-cost architecture and gives a better performance which is relevant to future access solutions [29].

The paper proposed a new architecture for redundancy and analyzed the performance in WDM-PON in terms of cost and availability. The efficiency of the redundancy is estimated from each optical component [30]. This article represents a solution for protection by providing hardware accelerated in Spur and Ring topology LR-PON by estimating fast switching time of 14 ms and finding the location of failure automatically [31]. This article explains about the LR-PON in ring topology for 100 Km and provides protection in WDM network.

Optical encoders are provided to monitor the information. Cross talk and loss of signal is reduced by applying space division multiplexing. It prevents multiple failures in fiber links to provide high availability, reliability and low-cost protection mechanism [32]. Protection and restoration method are proposed in ONU and used with the access control system module as a solution. They have simulated for different levels of protection and restoration scheme and analyzed for different number of split ratio to showcase its performance [33].

The paper proposes sustainable 1 Gb/s capacity NG-PON2, even though the standards are offering 100 Mb/s. They focus on investments on securement of the existing plant to increase the overall efficiency. They analyzed about the co-existence and co-operation between operators and generations as the main concern [34]. A cost-effective FTTH-PON system is designed successfully and demonstrated for 24 man hours with an access control system with a combination of software and hardware protection schemes for fiber fault identification. The solution improves the live fiber service and reduces the maintenance cost and restoration time [35].

The rest of the paper is organized as follows. The section 2 discusses different survivable architectures types. Section 3 gives details about the investigation study of network parameters needed for different survivability architectures. The simulation is performed and the performance is evaluated in section 4. The next Section 5 talks about the conclusion and finally the reference.

II. Materials and Methods

A. Proposed Design of NG-PON2 Protection Architectures Types with FDM

The conventional PON almost adopts the tree topology to provide point to multi-point connection. The incoming signal from the OLT is sent through the optical fiber to RN where an optical splitter is used to split the signal for different ONUs by the distribution fiber. In the standard NG-PON2, we have 4 different types of protection architecture, as suggested by ITU-T G.983.1. with a proposed additional feature of Fault Detection Module(FDM) which uses the downstream signal for simultaneous operation of carrying the data and monitoring the fault detection, instead of depending upon the upstream signal. These architecture provides a different level of protection in different parts of the NG-PON2 network. They are majorly classified as Type A, Type B, Type C and Type D. Type D is once again classified as Type D Full protection and Type D Partial protection. This section discusses the protection operations and functions mechanism involved in the following different types of protection architecture with and without FDM.

- Unprotected NG-PON2 Architecture
- Type A Protection Architecture with FDM
- Type B Protection Architecture with FDM
- Type C Protection Architecture with FDM
- Type D Architecture with FDM (Full protection)
- Type D Architecture with FDM (Partial protection)

B. Unprotected NG-PON2 Architecture

Fig. 1 shows the unprotected NG-PON2 architecture designed for 2048 subscribers using 2048 way splitter, where N refers to 2048 ONU's [5]. The novelty here in the architecture is designed for 120 Km with 100 Km feeder fiber called Working Fiber (WF) and with 20 Km distribution fiber. The data can be transmitted at the rate of 10 Gbps both in down/upstream directions. The proposed operating wavelength is 1544 nm in the upstream direction and 1596 nm in the downstream direction with 100 GHz channel spacing respectively. Since the network distance is designed for Extended Reach of 120 Km, we have placed a three number of EDFA optical amplifier. One optical amplifier viz. OA_1 works as a booster amplifier and is placed after the Optical Line Terminal (OLT) and other two optical amplifiers namely OA_2 and OA_3 are placed before the optical power splitter (1xN PS) present in Remote Note (RN). The output signal from the OLT is split to 2048 optical Network Units (ONUs) by using the distribution fiber. The active components are placed in the CO and ONU. The Optical Distribution Unit (ODU) remains passive in nature, even though optical amplifiers are used.

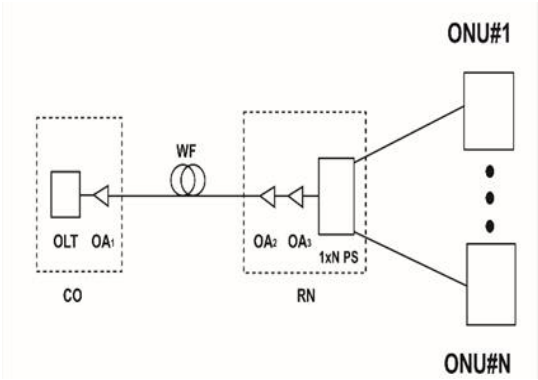

Fig. 1. Unprotected NG-PON2 Architecture

In the unprotected architecture, it performs only the normal operation, neither the components used nor the feeder fiber employed is unprotected. During the time of either the fiber fault or component fault, the total network fails to operate. So to prevent this unavoidable situation we are implementing protection techniques for NG-PON2 according to the literature of ITU Std. G. 989.1[36]. But the drawback in the conventional protection NG-PON2 is, it provides protection only manually and the second drawback is that no monitoring system is present. Last, but not least, in our research article, we are using the separate downstream wavelength for transiting the data and for fault monitoring purpose, which is the advantage over the conventional protection techniques. This is implemented by using the proposed FDM.

C. Type A Protection Architecture with FDM

Type A protection with FDM architecture is shown in Fig. 2. The NG-PON2 architecture remains the same, when the fault occurs in WF, the protection is given to the PF by duplicating the feeder fiber called Protection Fiber (PF). Here only the feeder fiber is protected. Both the WF and PF are placed between the CO and the RN. Here the PF is separated and installed from the WF which is parallel to the OLT through an Optical Switch (OS). The OS is connected to an optical coupler (CO) (1x2) to the WF and the other end to Tx monitor. The OS connects both the WF and the PF to a remote node via a 2 EDFA optical amplifiers OA_1 and OA_2 respective and further to the optical splitter (1xN).

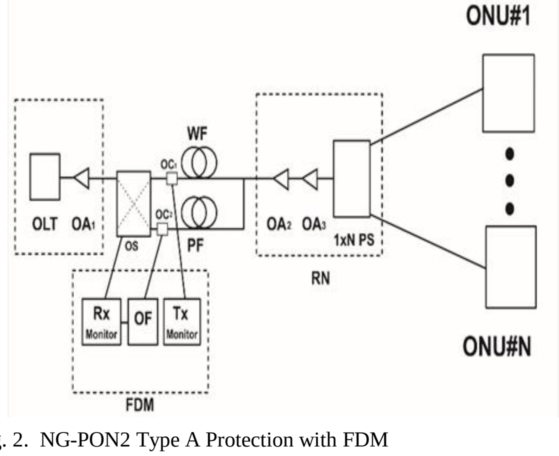

Fig. 2. NG-PON2 Type A Protection with FDM

Under the normal operation the OS is in BAR state and in feeder fiber failure it is in CROSS state. The transmitter monitor connected to the OLT adds a λ_D to the fiber. The λ_D travels as Fault detection wavelength signal through the power splitter and it reflects a fraction of signal to the Rx monitor. If the WF is cut, the proposed FDM checks for the λ_D and automatically triggers the OS into CROSS bar state, thereby rerouting all the traffic and providing protection to the fiber.

The proposed FDM is placed immediately after the CO. Here a new wavelength introduced called λ_D, called the Fault detection wavelength is selected other than the used downstream/upstream wavelength which is used to monitor the fault in the fiber. Survivability is achieved by means of proposed FDM which has an advantage of (a) which detects the absence of λ_D and also it checks the λ_{DS} (downstream signal) (b) to redirect the traffic from the WF to the PF. The proposed FDM block consists of Optical filters (OF) which are tuned to λ_D and Receiver (Rx) Monitor which is highly sensitive and has high responsivity with fast fault detection and finally Transmitter (Tx) Monitor, which continuously monitor the transmitter light source (λ_D). These two monitors are used since they have high sensitivity to be reliably applied for high propagation losses topologies.

D. Type B Protection Architecture with FDM

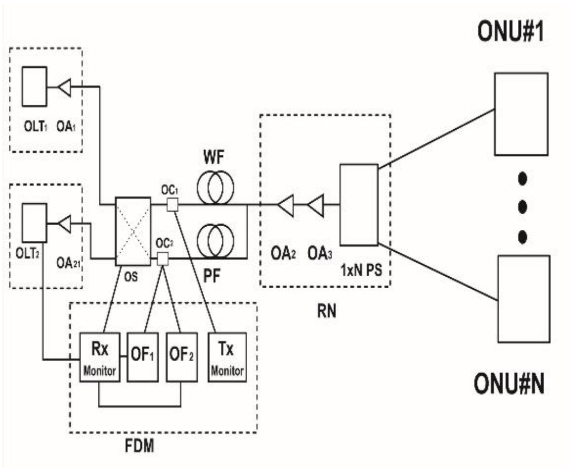

Fig. 3. NG-PON2 Type B Protection with FDM

In this Type B, protection is provided to both the fiber and the device as it detects both fiber and device failure. Particularly the Feeder fiber and the OLT (OLT_1) equipment is protected from fault. Here the OLT equipment is duplicated called as the backup OLT (OLT_2) and the feeder fiber is also duplicated as PF. The OLT_2 and the PF are physically separated from OLT_1 and WF. By duplicating the OLT_2 the cost of ONU is reduced. It works similar to Type A in case of fiber fault where the downstream signal $\lambda_{DS.}$ But in case of OLT_1 fault, the standby OLT_2 is triggered and resumes the data into WF. The Rx monitor in proposed FDM is connected to OS and OLT_2 to detect the absence of λ_{DS} from OLT_1 failure, by automatically switching the OS in the CROSS bar state to ower up OLT_2. Protection against multipoint failure is achieved. This is shown in Fig. 3. Survivability in Type B is achieved by means of proposed FDM which has an advantage of switches and couplers (a) which detects the absence of λ_D and also λ_{DS} (downstream signal)(b) to redirect the traffic from the WF to the PF (c) the device/equipment fault is detected and monitored the λ_D and also λ_{DS} and using the protection switches in proposed FDM design, the traffic is diverted from an affected path to protected path.

E. Type C Protection Architecture with FDM

In Type C, complete protection with FDM is provided to the fiber, OLT device and the ONU device. Particularly the feeder fiber and not only the OLT (OLT_1) equipment is protected from fault, but also the ONU is also protected from fault. Here the OLT equipment is duplicated as a standby OLT (OLT_2) and the feeder fiber is also duplicated as PF. In addition, the optical splitter at the Remote Node is also doubled. This is shown in fig 4. Both the primary and secondary equipment's are normally working and the switching time is also very fast and they are geographically separated.

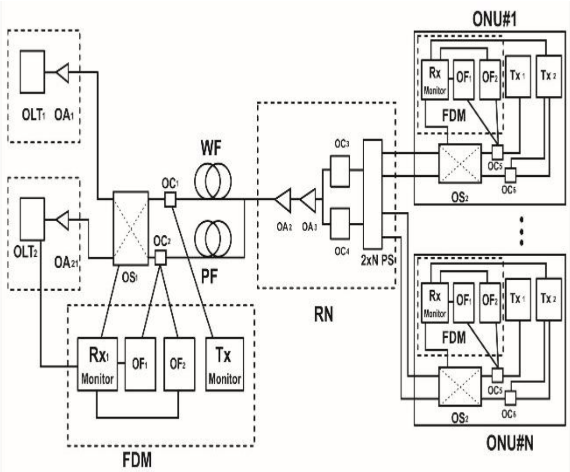

Fig 4 NG-PON2 type C protection with FDM

In the remote node two additional optical couplers (OC_1 and OC_2) to provide a physical connection between primary and backup to provide the optical loopback to CO. Two optical splitters (PS_1 and PS_2) are additionally used to connect to 2048 ONUs through two different distribution fibers. An additional proposed FDM is added to each ONU, it resumes the same function as above as in the case of OLT. It provides a centrally controlled protection via PS, distribution fiber and ONU transceiver. If PS or distribution fiber is failed, the OS switches from BAR state to CROSS bar state to detect the λ_D and to provide the protection and switches from Tx_1 to Tx_2.

F. Type D Protection Architecture with FDM (Full Protection)

Here in the Type D Architecture with FDM (Full Protection) as shown in Fig. 5. Duplicates the equipment OLT and ONU, feeder fiber, splitter and distribution fiber followed by the amplifier we have a two number of a coupler, followed by the 2 no. of duplicated power splitter (1XN). Here the OLT equipment is duplicated as a standby OLT (OLT_2) and the feeder fiber is also duplicated as PF. In addition, the optical splitter at the Remote Node is also doubled. Here 1+1 protection is provided. Both the primary and secondary equipment's are normally working and the switching time is also very fast and they are geographically separated.

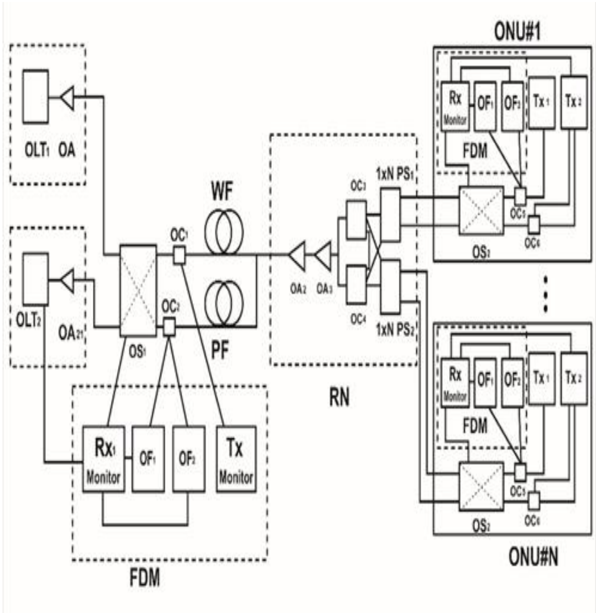

Fig. 5. NG-PON2 Type D Protection with FDM (Full Protection)

In the remote node two additional optical couplers (OC_1 and OC_2) to provide a physical connection between primary and backup to provide the optical loopback to CO. Two optical splitters (PS_1 and PS_2) are additionally used to connect to two N no. of ONUs through two different distribution fibers. An additional proposed FDM is added to each ONU, it resumes the same function as above as in the case of OLT. It provides a centrally controlled protection via PS, distribution fiber and ONU transceiver. If PS or distribution fiber is failed, the OS switches from BAR state to CROSS bar state to detect the λ_D and to provide the protection and switches from Tx_1 to Tx_2.

G. Type D Protection Architecture with FDM (Partial Protection)

Type D Architecture with FDM (Partial Protection) is shown in Fig. 6. Duplicates the equipment OLT and the feeder fiber. Followed by the amplifier we have a two number of coupler followed by the duplicated Power splitter(1XN). Here the OLT equipment is duplicated as a standby OLT (OLT_2) and the feeder fiber is also duplicated as PF. In addition, the optical splitter at the Remote Node is also doubled. Both the primary and secondary equipment's are normally working and the switching time is also very fast and they are geographically separated. The normal operation is from OLT to OC_1 and PS to ONU. If any fault in WF or OLT_1 the path is protected by means of proposed FDM to PF and data is routed to via OC_2 to PS.

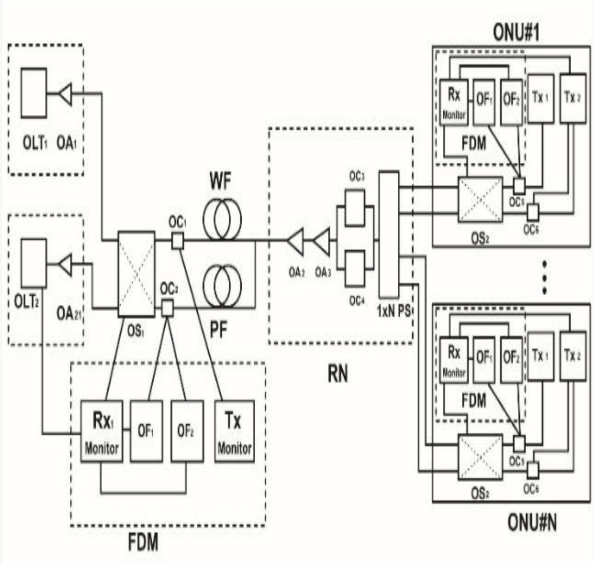

Fig. 6. NG-PON2 type D protection with FDM (partial protection)

In the remote node, two additional optical couplers (OC_1 and OC_2) to provide a physical connection between primary and backup to provide the optical loopback to CO. Optical splitter (PS) are additionally used to connect to N no. of ONUs through two different distribution fibers. An additional proposed FDM is added to each ONU, it resumes the same function as above as in the case of OLT. It provides a centrally controlled protection via PS, distribution fiber and ONU transceiver. If PS or distribution fiber is failed, the OS switches from BAR state to CROSS bar state to detect the λ_D and to provide the protection and switches from Tx_1 to Tx_2. Table I. summarizes the place of fault occurrence and the protection provided to corresponding place.

TABLE I: SUMMARIZES OF THE PROTECTION TYPES

PROTECTION TYPE	**FAULTY PLACE**	**PROTECTION PROVIDED**
A	Feeder Fiber	Feeder Fiber
B	Feeder Fiber and OLT	Feeder Fiber and OLT
C	Feeder fiber, OLT, ONU	Feeder fiber, OLT, ONU
D (Full protection)	Feeder fiber, OLT, ONU	Feeder fiber, OLT, ONU
D(Partial protection)	Feeder fiber, OLT, ONU	Feeder fiber, OLT, ONU

III. MATHEMATICAL MODEL ANALYSIS

In this section we have derived mathematical formulas for investigating the following parameters including all the different types of NG-PON2 protection architecture with FDM. The results are also discussed.

- Probability of Propagation Loss
- Probability of Network Connection Availability and
- Probability of Network Connection Unavailability

A. *Mathematical Model Derivation for Round Trip Propagation Loss*

In NG-PON2 network designed for protection architecture with FDM for 2048 splitter and 100 Km, our aim is to detect the faults in the device or fiber using the Fault Detection Module (FDM). To determine that, the input optical powers of λ_D must be operated less than -51 dBm the sensitivity limit of the monitoring module [32]. Input specifications used are listed in Table II. For each survivable architecture, the typical insertion loss values of all contributing components/fiber are listed in Table III. Equations from (1) - (12) below describe the insertion losses incurred by λ_D, as functions of fiber loss and passive splitter loss Total Roundtrip Propagation Loss is estimated for different types of survivable architecture and is compared with unprotected architecture.

TABLE II: INPUT SPECIFICATIONS

Specifications/ Parameters	ITU-T G.652	ITU-T G.655	Corning LEAF Fiber
wavelength	1565 to 1625 nm	1565 to 1625 nm	1565 to 1625 nm
Attenuation (α)(dB/Km)	0.5	0.4	0.25
Optical launch Power	+6 dBm	+6 dBm	+6 dBm
Power margin	3 dB	3 dB	3 dB
Fiber Attenuation	0.25 to 5 dB / Km	0.25 to 5 dB / Km	0.25 to 5 dB / Km
Splitter ratio	1: 2048	1: 2048	1: 2048
ONU Power	-51 dBm	-51 dBm	-51 dBm

For the Type A with FDM survivable architecture, λ_D traverses the entire network for 100 Km from OLT to ONU through (1x2048) passive splitter twice, incurring a TRPL is calculated as follows:

$$L_{A,\ \lambda D} = 16.5 + 2(L_F + L_{PS}) \tag{1}$$

The first term on RHS is calculated from the values of the components listed in Table III.

TABLE III: SUMMARIZES THE INSERTION LOSS INCURRED BY EACH COMPONENT

Insertion loss dB)	Type A (λ_D)	Type B (λ_{DS})	Type B (λ_{DS})	Type C (λ_M, CO)	Type C (λ_M, ONU)	Type C (λ_{DS}, ONU)	Type D (λ_{DS}, ONU)	Type D (λ_{DS}, ONU)	Type D (λ_{DS}, ONU)
SW_1	0	0	1.5	0	0	1.5	0	0	0
SW_2	0	0	0	0	0	1.5	0	0	0
OF	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Connectors	1	1	1	1	1	1	1	1	1

1 x 2 Coupler	0	3	3	3	0	0	0	0	0
1 x 3 Coupler	0	0	0	9.54	4.77	4.77	0	0	0
20:80 Coupler	14	14	7	14	14	7	14	14	14
80:20 Coupler	0	0	0	0	0	0	0	0	0
Splitter size N:16	14	14	14	14	14	14	14	14	14
Splitter size N:4	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3

To detect feeder fiber fault for Type B with FDM architecture is that λ_D transverse the entire network for 100 Km from OLT to ONU through the RN (1x 2048) passive splitter twice incurring a TRPL of:

$$L_{B,\ \lambda D} = 19.5 + 2(L_F + L_{PS}) \quad (2)$$

In Type B to detect the fault in CO, λ_{DS} transverse traverses the entire network for 100 Km from OLT to ONU, through the RN (1x 2048) passive splitter twice, incurring a TRPL of:

$$L_{B,\ \lambda DS} = 15 + 2(L_F + L_{PS}) \quad (3)$$

In Type C, λ_D and λ_{DS} are detected at Central office for feeder fiber and coupler faults, λ_D traverses the entire network for 100 Km from OLT to ONU, the coupler twice with a TRPL of:

$$L_{C,\lambda D}\ (CO) = 29.04 + 2(L_F) \quad (4)$$

As far as Type C, λ_D is detected at the ONU which traverses the entire network for 100 Km from OLT to ONU through the coupler, RN (1x 2048) passive splitter, feeder fiber and distribution fiber once, incurring a TRPL of:

$$L_{C,\ \lambda D}\ (ONU) = 21.27 + L_D + L_{DF} + L_{RN} \quad (5)$$

These architecture have combined effect of fast detection and speedy recovery time in case of single and multipoint failure. In Type C to detect failures λ_{DS} in ONU is detected as it is transverse across two optical switches, coupler, passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{C,\ \lambda DS}\ (ONU) = 20.17 + L_D + L_{DF} + L_{RN} \quad (6)$$

In Type D Full protection to detect failures λ_{DS} in ONU is detected as it is transverse the entire network for 100 Km from OLT to ONU, across two optical switches, coupler, RN (1x 2048) passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{DFP,\ \lambda D\,(CO)} = 30.54 + 2(L_F) \quad (7)$$

In Type D Full protection to detect failures λ_{DS} in ONU is detected as it is transverse across two optical switches, coupler, passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{DFP,\ \lambda D\,(ONU)} = 22.7 + (L_{FD} + L_{DF} + L_{RN}) \quad (8)$$

In Type D Full protection to detect failures λ_{DS} in ONU is detected as it is transverse across two optical switches, coupler, passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{DFP,\ \lambda DS\,(ONU)} = 20.17 + 2\left(L_F + {L_{DF}}^2 + {L_{RN}}^2\right) \quad (9)$$

In Type D partial Protection to detect failures λ_{DS} in ONU is detected as it is transverse the entire network for 100 Km from OLT to ONU, across two optical switches, coupler, RN (1x 2048) passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{DPF,\ \lambda D\,(CO)} = 30.54 + 2\left(L_D + {L_{RN}}^2\right) \quad (10)$$

In Type D partial Protection to detect failures λ_{DS} in ONU is detected as it is transverse the entire network for 100 Km from OLT to ONU, across two optical switches, coupler, RN (1x 2048) passive splitter, feeder and distribution fiber one time, having TRPL of:

$$L_{DPF,\ \lambda D\,(ONU)} = 22.7 + 2(L_D + L_{RN}) \quad (11)$$

In Type D partial Protection to detect failures λ_{DS} in ONU is detected as it is transverse transverse the entire network for 100 Km from OLT to ONU, across two optical switches, coupler, RN (1x 2048) passive splitter, feeder, and distribution fiber one time, having TRPL of:

$$L_{DPF,\ \lambda DS\,(ONU)} = 20.17 + 2(L_D + L_{RN}) \quad (12)$$

B. Mathematical Model Derivation for Network Connection Availability

In this section we are analysis the Network Connection Availability using the above architecture from figure no (2-6), here we investigated the impact of device and fiber failure, assuming both the WF and PF are having the same length of 100 Km. Here we have derived and compared the equations for Connection Availability for unprotected and protection with FDM schemes.

For unprotected NG-PON2, the probability of an intact connection between the CO and any random ONU_j is given by equation (13)

$$P_{ONUj,\text{OLT}} = (1 - P_{OLT})\,(1 - P_F)\,(1 - P_{RNPS})\,(1 - P_{d,j})\,(1 - P_{ONU}) \quad (13)$$

where P_{OLT}, P_F, P_{RNPS}, Pd, j, P_{ONU} denote the probability of failure in the device OLT, feeder fiber, remote node, jth distribution fiber and ONU. For Types A protection with FDM, the probability of intact connection between OLT and jth ONU is derived and given by the equations from (14)

$$P_{ONUj,A} = (1 - P_{OLT})\,(12 - P_F^2)(1 - P_{RNPS})(1 - P_d)\,(1 - P_{ONU}) \quad (14)$$

where P_{OS}, P_C, denotes the probability of failure in the optical splitter and coupler.

For Types B protection with FDM, the probability of intact connection between OLT and jth ONU is derived and given by the equations from (15)

$$P_{ONUj,B} = (1-P_{OLT}^2)(1-P_{OS})(1-P_C^2)(1-P_F^2)(1-P_{RNPS})(1-P_d)(1-P_{ONU}) \quad (15)$$

For Types C protection with FDM, the probability of intact connection between OLT and jth ONU is derived and given by the equations from (16)

$$P_{ONUj,C} = (1-P_{OLT}^2)(1-P_{OS})^2(1-P_C^2)(1-P_F^2)(1-P_{RN\,CO}^2)(1-P_{RNPS}^2)(1-P_{D,j}^2)(1-P_{ONU}^2) \quad (16)$$

For Types D full protection with FDM, the probability of intact connection between OLT and jth ONU is derived and given by the following equations from (17)

$$P_{ONUj,D,FP} = (1-P_{OLT}^2)(1-P_{OS})^2(1-P_C^2)(1-P_F^2)^2(1-P_{RN\,OC}^2)(1-P_{RNPS}^2)^2(1-P_{D,j}^2)^2(1-P_{ONU}^2)^2 \quad (17)$$

For Types D partial protection with FDM, the probability of intact connection between OLT and jth ONU is derived and given by the following equations from (18)

$$P_{ONUj,D,PF} = (1-P_{OLT}^2)(1-P_{OS})^2(1-P_C^2)(1-P_F^2)^2(1-P_{RN\,OC}^2)(1-P_{RNPS}^2)(1-P_{D,j}^2)(1-P_{ONU}^2) \quad (18)$$

C. *Mathematical Model Derivation for Network Connection Unavailability*

The probability of network Connection availability is studied in Session 3.2. Now in this session we have derived and investigated the probability of Network Connection Unavailability. This is expressed by the formula

Network Connection Unavailability (NCU) = 1 - Network Connection Availability (19)

IV. Results and Discussion

The protection types have been successfully implemented using FDM to NG-PON2 network using 2048 splitter for long reach application with fault detection method in the above section. Their corresponding mathematical model has also been described in the next section. The all protection types are investigated to reduce the round trip loss and make the network to be very effective in terms of giving more bandwidth to the end users and to check the probability of connection availability and the corresponding network connection unavailability.

A. *Performance Analysis of Probability of Propagation Loss*

Firstly we will discuss the performance of the round trip propagation loss by using the above equations from (1-12) The corresponding graphs are calculated using the values listed in Table II and III and also shown below. The significance of each and every protection technique along with the graph is also discussed.

1) Probability of propagation loss for ITU G.652.A single mode fiber

The comparison of Total Round Trip Propagation Loss provided by using the industrial single mode fiber no. ITU G.652.A is shown in below Fig. 7. We have used the above architecture from fig no (2-6) and table no II and III values, to investigate and calculated the TRPL using the above equations from (1-12) and plotted using the bar chart. Here We used ITU.G.652A SMF with maximum attenuation loss considered of 0.25/Km. For Type A, Type B_1 and B_2 around 100 dB, the TRPL is found to be almost equal. DF_3 has the moderate TRPL of 68 dB and DP_1 is almost closer to DF_3 of 69 dB along with DP_3. DF_2 has the moderation TRPL loss of 114. The lowest TRPL loss is provided by C_2, and followed by C_3 and DF_2. When compared with all other protection types

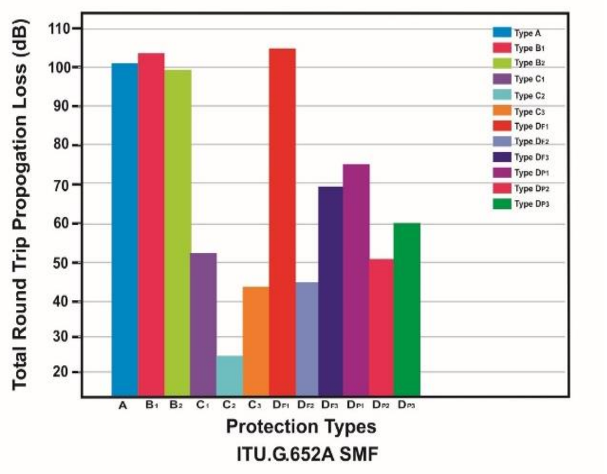

Fig. 7 Comparison of performance of RTPL for different protection Types using ITU G.652. A single mode fiber

2) Probability of propagation loss for ITU G.652.D single mode fiber

The comparison of Total round trip propagation loss provided by using the industrial single mode fiber no. ITU G.652.D for survivable is shown in Fig. 8. We have used the above architecture from fig no (2-6) to investigate and calculated the TRPL loss using the above equations from (1-12) and plotted using the bar chart. In this highest loss is offered by DF_1. Next, the highest TRPL is provided by B_1, A, B_2 and DF_3. Moderate losses are provided by C_3, DF_2 and DP_3. The lowest loss is provided by C_2 type of architecture.

3) Probability of propagation loss for ITU G.655.D single mode fiber

The Total round trip propagation loss provided by using the industrial single mode fiber no. ITU G.655.D Corning LEAF fiber for survivable is compared with other types and si shown in Fig. 9. We have used the above architecture from fig no (2-6) to investigate and calculated the TRPL loss using the above equations from

(1-12) and plotted using the bar chart. In this highest loss is offered by DF_3 and DP_1. Next, the highest TRPL is provided by DF_3, C_1, B_1, B_2 and. Moderate losses are provided by DF_2 and DP_3. The lowest loss is provided by C_3 type of architecture.

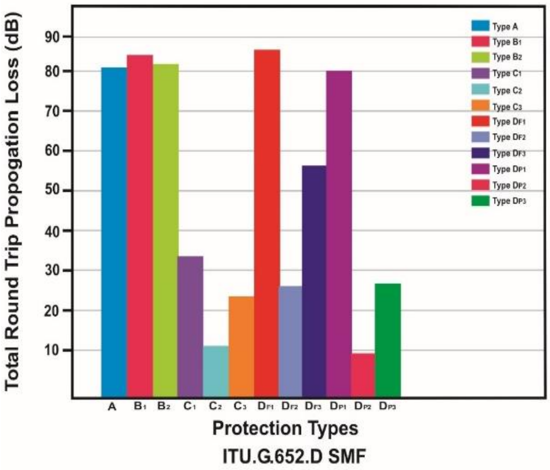

Fig 8. Comparison of Performance of RTPL for different Protection Types using ITU G.652. D Single Mode Fiber

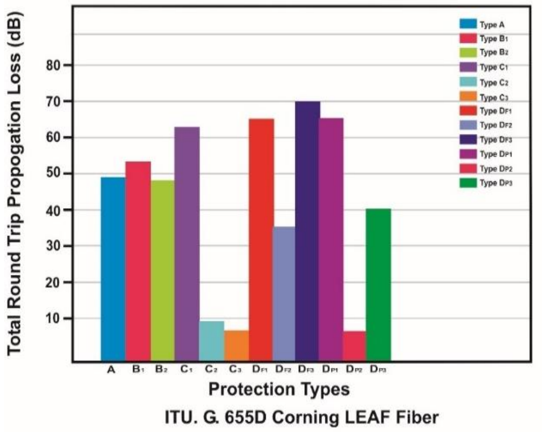

Fig 9. Comparison of Performance of RTPL for different Protection Types using ITU G.655. D Single Mode Fiber Corning LEAF Fiber

B. *Performance Analysis of Network Connection Availability*

Secondly we will discuss the performance of network connection availability by using the above equations from (13-18). The corresponding bar charts are calculated using the values listed in Table II and III and also shown below. The significance of each and every protection technique along with the graph is also discussed. The Probability of successful connection is discussed for various coupling ratios, which in turn is related to the switching speed of the network.

1) Probability of successful connection for coupling ratio 80:20

Fig 10. Shows about the Probability of successful connection for each and every protection schemes. Here we have used a coupler of 80 % and 20 % for providing switching connection. All protection types are compared with the unprotected type NG-PON2. Here Type A provides the highest connection probability of 0.98 and Type B provides the next highest connection probability of 0.97 and Type D_1 full protection provides the least protection of 0.91. The unprotected type gives the connection probability of 0.90 only.

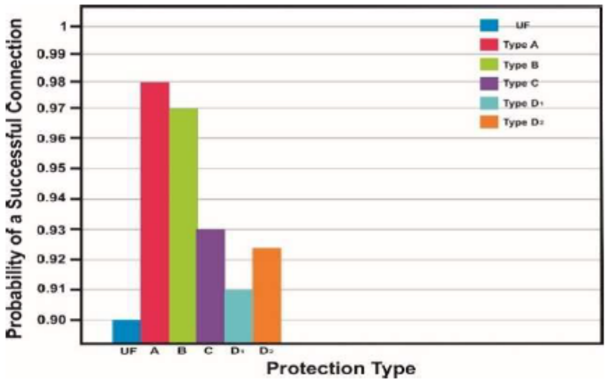

Fig. 10. Comparison of probability of successful connection for different Protection Types using coupling ratio of 80:20

2) Probability of successful connection for coupling ratio 90:10

Fig 11 shows about the probability of successful connection for each and every protection schemes. Here we have used a coupler of 90 % and 10 % for providing switching connection. All protection types are compared with the unprotected type of NG-PON2. Here Type A provides the highest connection probability of 0.995 and Type B provides the next highest connection probability of 0.9945 and Type D_1 full protection provides the least protection of 0.989. The unprotected type gives the connection probability of 0.91 only.

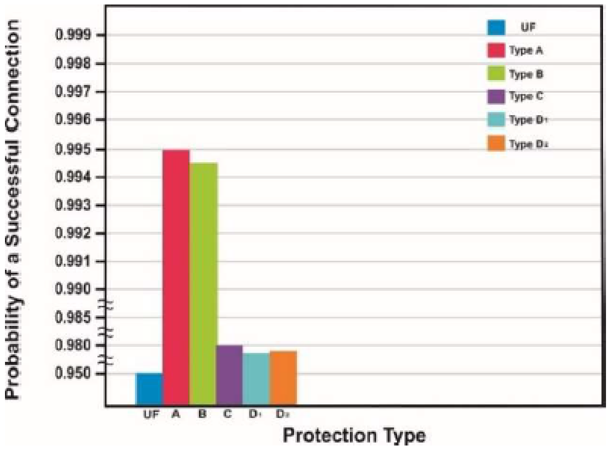

Fig. 11. Comparison of probability of successful connection availability for different Protection Types using coupling ratio of 90:10

3) Probability of successful connection for coupling ratio 95:05

Fig. 12. Shows about the probability of successful connection for each and every protection schemes. Here we have used a coupler of 95 % and 05 % for providing switching connection. All protection types are compared with the unprotected type NG-PON2. Here Type A provides the highest connection probability of 0.999 and Type B provides the next highest connection probability

of 0.9988 and Type D_1 full protection provides the least protection of 0.9964. The unprotected type gives the connection probability of 0.98 only.

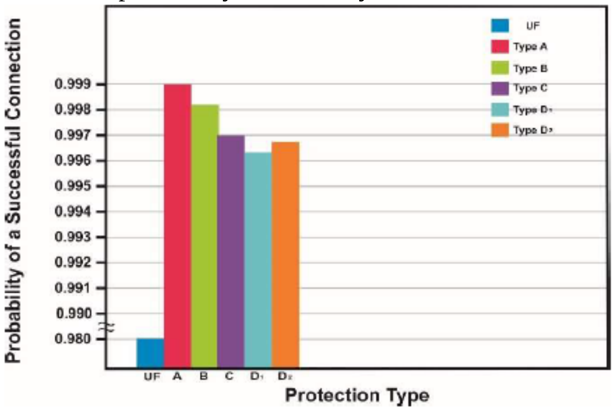

Fig 12. Comparison of probability of successful connection availability for different Protection Types using coupling ratio of 95:05

4) Probability of successful connection for coupling ratio 98:02

Fig. 13. Shows the probability of successful connection for each and every protection schemes. Here we have used a coupler of 98 % and 02 % for providing switching connection. All protection types are compared with the unprotected type of NG-PON2. Here Type B provides the highest connection probability of 0.9997 and Type D_1 full protection provides the least protection of 0.9991 the unprotected type gives the connection probability of 0.980 only.

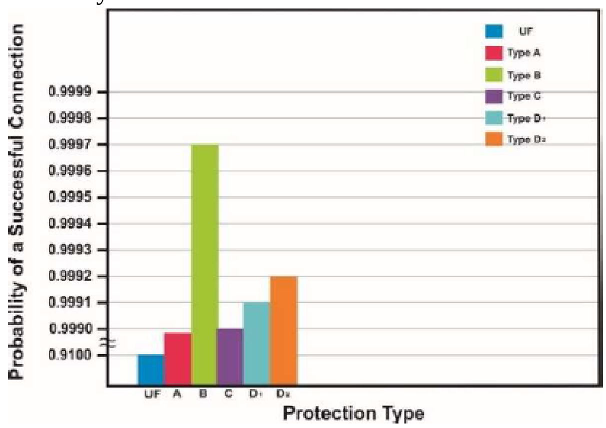

Fig 13. Comparison of probability of successful connection for different Protection Types using coupling ratio of 98:02

C. *Performance Analysis of Network Connection Unavailability*

Using the above equation no.19, we have plotted the bar graphs for connection unavailability which is shown in below figure. It is also compared with the unprotected fiber.

1) Probability of connection unavailability for coupling ratio 80:20

Fig. 14 shows the analysis of connection unavailability when coupler ratio of 80% and 20 % is used. The NCU is highest for unprotected fiber. When comparing with other types, Type A has the highest probability of 0.028 failure and D_1 and D_2 has the least probability of 0.2 and 0.3 failure respectively.

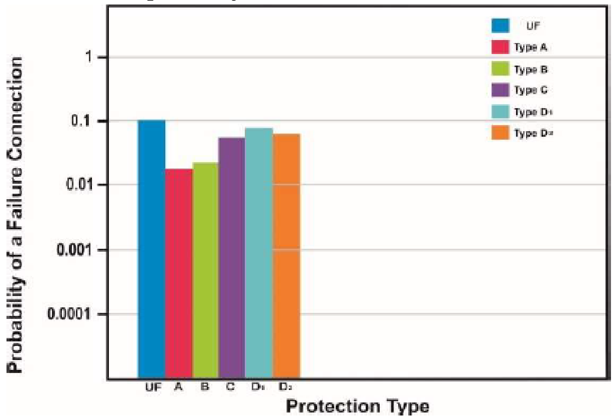

Fig. 14. Comparison of probability of failure connection for different Protection Types using coupling ratio of 80:20

2) Probability of connection unavailability for coupling ratio 90:10

Fig 15 shows the analysis of the highest connection unavailability when coupler ratio of 90% and 10 % is used. The NCU is highest for unprotected fiber when comparing with other types, Type A have the highest probability of 0.0055 failure and D_1 has the least probability of 0.02 failure.

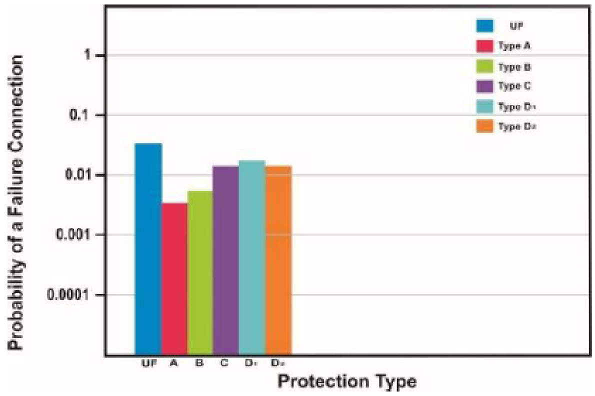

Fig. 15. Comparison of probability of failure connection for different Protection Types using coupling ratio of 90:10

3) Probability of connection unavailability for coupling ratio 95:05

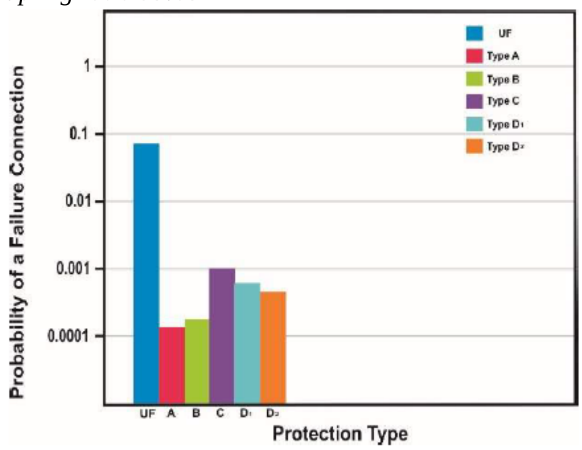

Fig. 16. Comparison of probability of failure connection for different Protection Types using coupling ratio of 95:05

Fig. 16 shows the analysis of the highest connection unavailability when coupler ratio of 95% and 5 % is used. The NCU is highest for unprotected fiber. When comparing with other types, Type A has the highest probability of 0.001 failure and D_1 has the least probability of 0.002 failure.

4) Probability of connection unavailability for coupling ratio 98:02

Fig. 17 shows the analysis of the highest connection unavailability when coupler ratio of 98% and 02 % is used. The NCU is highest for unprotected fiber. When comparing with other types, Type A has the highest probability of 0.00019 failure and B has the least probability of 0.001 failure.

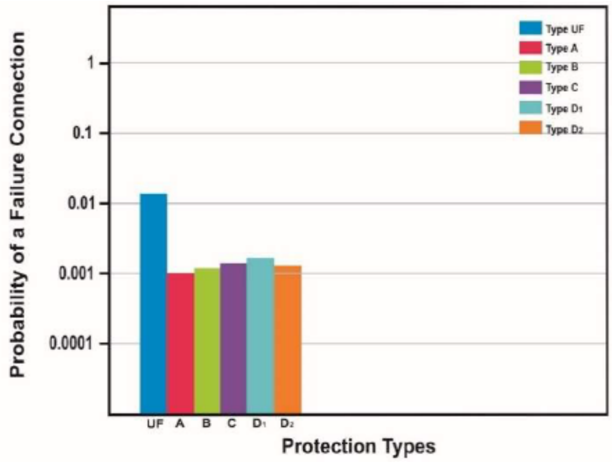

Fig 17.Comparison of probability of failure connection for different Protection Types using coupling ratio of 98:02

V. Conclusions

In this article, we have analyzed the four types of Survivable NG-PON2 architectures which highly uses a Fault Detection Module. These architecture has been analyzed for various dimensions in term of Total round trip propagation loss and network connection availability and network connection unavailability. Here Type A and Type B has the least TRPL while comparing with other types of architecture. When coming for connection availability, taking all types of coupler configuration into consideration Type B gives the best performance to the nearer value of 0.9997. When discussing the network connection unavailability within the survivable architectures Type A has the lowest probability of unavailability.

Conflict of Interest

“The authors declare no conflict of interest".

Author Contributions

Prof S. Rajalakshmi conducted the research with mathematical modeling and analyzed the data. She has also wrote the above research article paper. Prof Dr. Shankar has gone through the technical aspects of the research article and verified the data. He has also done the review of the paper and edited the writing style and technical content of the paper. All The authors had approved the final version of the research article.

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