Design of a of a survivable multi-wavelength photonic access network

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***Abstract*—This paper investigates the design of protection schemes in an extended access network. The network is modeled as a stack of quasi independent logical Passive Optical Networks (PONs), each operating the IEEE Ethernet Passive Optical Networks (EPON) protocol. The dynamics of the network operation when protection schemes are employed are presented and discussed.**

Keywords- EPON;WDM PON; Protection Switching; OLT; ONU

I. INTRODUCTION

The BBPhotonics project looks into the design of an extended access network. The proposed access network will be a reconfigurable and resilient photonic multi-wavelength network. The extended network is expected to cater to multiple communities which are geographically spaced out. The paper presents the design of the network and discusses the dynamics when protection restoration techniques are implemented in such a network. Section II introduces the network design. Section III details the implementation options for protection mechanisms. Section IV discusses the operation of the network under conditions when the protection schemes come into play. Section V concludes the paper with directions for future work and discussions.

II. NETWORK ARCHITECTURE

A. Physical Design

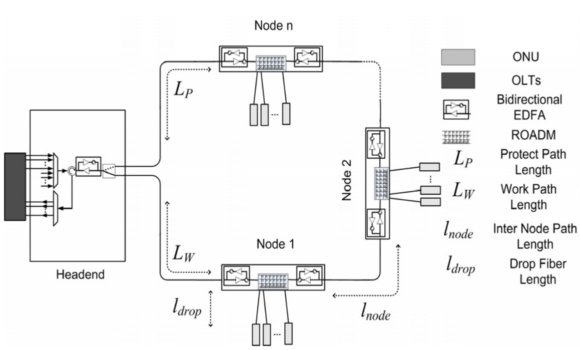

Figure 1 . Schematic of BBPhotonics Networks

Fig. 1 illustrates the network schematically. The drop fiber connection from the Head End (HE) to the first Remote Node (RN) is presumed to be 20 km. The inter RN spacing is again taken to be nominally 20 km. The drop fibers from the RN to the Customer Premises Equipment (CPE), which also houses the Optical Network Unit (ONU), is taken as 5 km. The motivation for the parameters so chosen is to provide a region wide access network with a central office location housing the HE. The Reconfigurable Optical Add Drop Multiplexer (ROADM) is based on micro-ring resonator technology [1] and the device gives the flexibility to have, add/drop any wavelength from/towards any port, to drop and continue, to drop only and to add only, configurations. Each RN will nominally support up to 256 ports thus enabling the connection of up to that many CPEs. It is proposed to have at least four such RNs thus allowing for up to a total of 1024 CPEs for the whole network

B. Network Topology

The logical network topology retains the tree architecture like classical Passive Optical Networks (PONs). Fig. 2

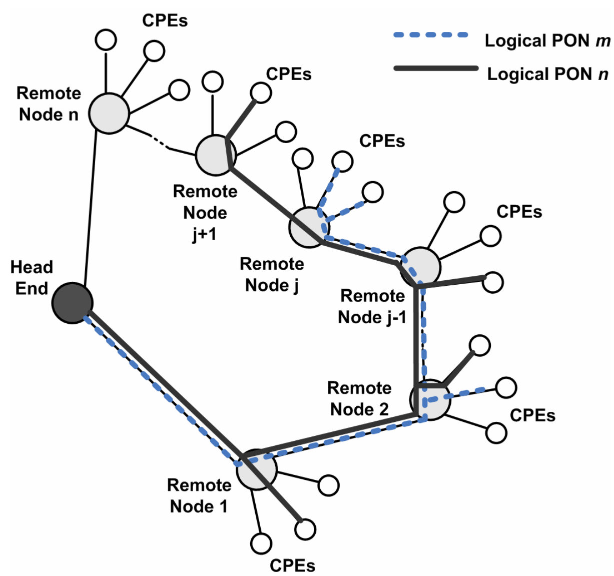

Figure 2 . Logical connection between HE and CPEs, two logical PONs are illustrated

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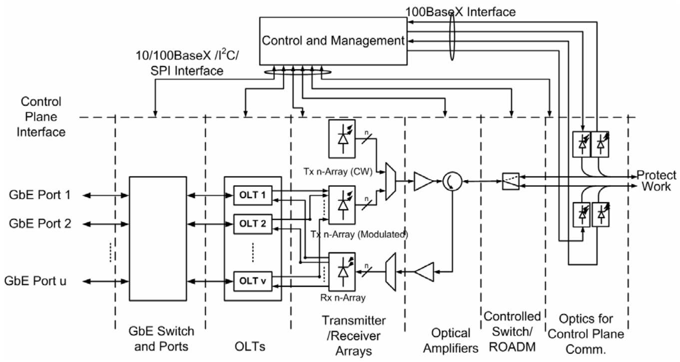

Figure 3 . Schematic Details of the Head End (HE)

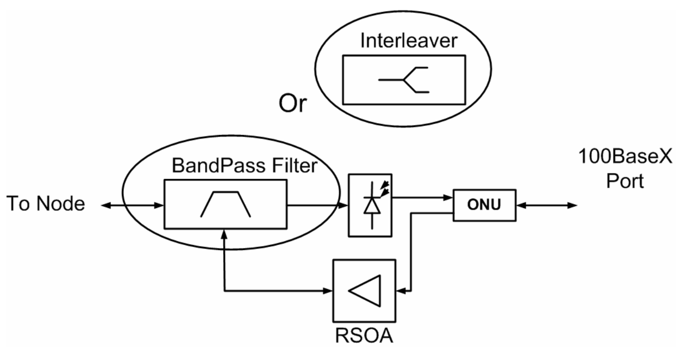

Figure 4 . Schematic Details of Customer Premises Equipment (CPE)

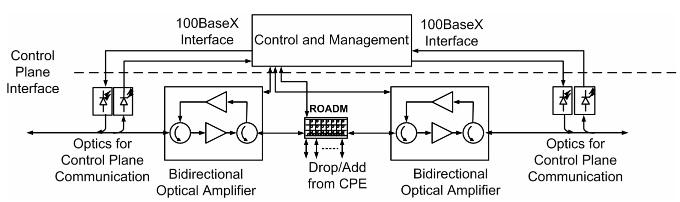

Figure 5 . Schematic Details of the Remote Node (RN)

illustrates the logical connectivity between the HE and a set of CPEs connected to diverse RNs. Each RN has two or more fiber connections and thus each such RN has fiber connectivity for up to a single fiber break. Each wavelength pair is supporting a PON like network, thus the network can be viewed as a superposition of ten (which is the number of wavelength pairs used) logical PONs.

The RN ports can drop/add selected wavelength pairs towards the CPEs. Each such group of CPEs on a single wavelength pair are part of a logical PON. The add/drop wavelength associated with each CPE can be changed dynamically thus associating the CPE with another PON. The reason to do so is to optimize the bandwidth distribution of the aggregate network to make more bandwidth available per logical PON when there is more demand from a user [2]. There is no logical constraint to the number of CPEs that can be associated in a single logical PON. There however would be

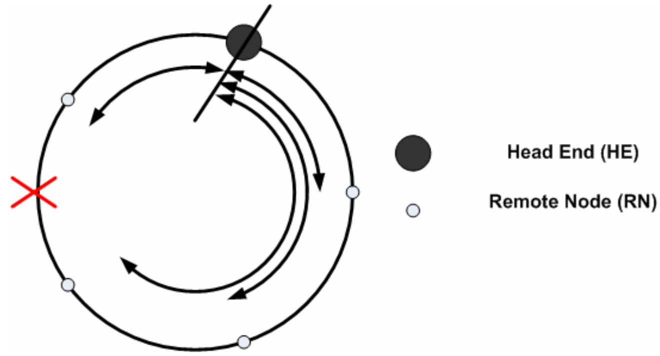

Figure 6 . Connectivity between the HE and RN for a single fiber break

physical constraints on the number of CPEs can be supported and this needs to be determined.

III. Implementation Options

The schematic detail of the HE is illustrated in Fig. 3. The HE will support a Gigabit Ethernet (GbE) Switch with ports towards the WAN and ports towards the access network which will connect to individual Optical Line Termination Units (OLTs). The OLTs will have 100 GHz ITU-T gridded optical interfaces with each OLT operating on a unique wavelength pair. The use of the GbE switch would allow for switching traffic towards/from any OLT and hence for switching traffic on a logical PON.

The schematic detail of the CPE is illustrated in Fig. 4. The ONUs are wavelength agnostic. Depending on the wavelength pair added/dropped towards the CPE by the RN, the ONUs are associated with unique OLTs.

Fig. 5 illustrates the detail of the RN. The RN and the HE will be provided with an out of band control and communication channel based on 1310/1490 nm optics and 100BaseX communication [3].

The network will have active elements which while allowing for dynamic re-configurability and an increase in the network span also increase potential failure points. To increase the resiliency of the network, redundancy is included in the network design. The redundancy in the network is viewed at two different levels, the first is at the physical level between the HE and the RNs and the second is at the logical level between the OLT and individual ONUs.

A. Head End to Remote Node Communication

The HE-RN communication link is an important part of the communication channel. Any failure in this communication channel will cause a widespread network outage. Each RN will be provided with multiple fiber connectivity. The HE can establish communication with each RN through two diverse fiber connections. The simplest way to do so is to use a controlled optical splitter at the HE which will route the normal work communication from the HE to the CPEs in the counter clock wise direction and receive communication from the CPEs to the HE in the clockwise direction. In the event of a fault, the optical power will split according to (1) and communication established in both directions as illustrated in Fig. 6 for up to a single fiber break.

$$P_{work}: P_{prot} :: i: n\text{-}i. \tag{1}$$

n: Number of RNs used
i: RN number after which the fault occurs
P_{work}: Optical Power launched in Work direction (HE to wards CPE)
P_{prot}: Optical Power launched in Protect direction (HE to wards CPE)

The use of a controlled splitter does not optimize on the provisioning of lightpaths, under normal work conditions the entire work communication is counter clockwise for the downstream communication and clockwise for the upstream communication. The HE design can also incorporate the ROADM instead of a controlled splitter. This allows for provisioning lightpaths such that the sum of the distance traversed from the HE to CPEs is minimized (2) subject to no physical constraints in provisioning the lightpath. The shortest path to every CPE from the HE can be selected. Fig. 7 illustrates the use of a ROADM to establish communication between HE and CPE through the shortest paths when there is no failure and Fig. 8 for the same case with a single fiber break.

$$D = \sum \sum l_{ij}^{\min} \forall l_{ij} \tag{2}$$

l_{ij} : Provisionable Lightpath between HE and j th CPE on i th RN
D: Sum of distance traversed from HE to all CPEs

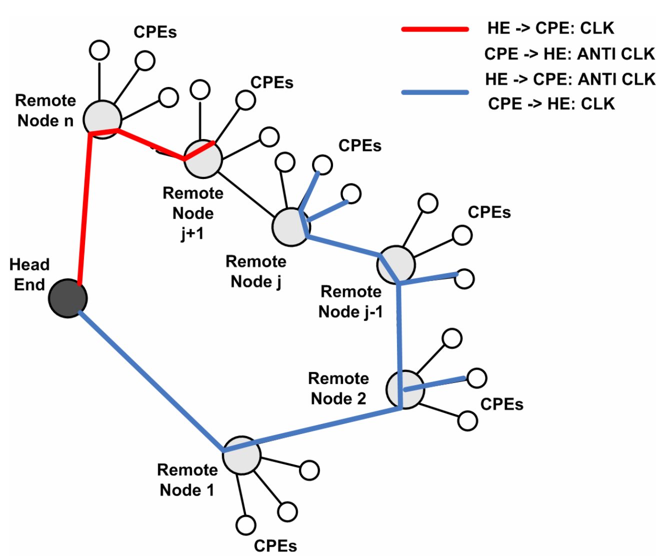

Figure 7 . HE with ROADM communicating with CPEs using shortest path to CPE

B. OLT to ONU Communication

The OLT-ONU link will be established over the physical network with each OLT being associated with a number of ONUs. The network design does not provide for redundancy in the final link between the RN and the CPE. This is not because it is not technically feasible to do so but because any such redundancy in the link is adding to cost which is borne by a single user. If a user desires additional redundancy which might be the case with commercial users, two or more CPEs can be used in a single premises with an additional switch with port aggregation. Fig. 9 illustrates the network as a two stage switch. The data link level connectivity between the WAN interface and an end user using two CPEs for redundancy is illustrated in Fig. 10. This configuration also allows for more provisionable bandwidth to such users.

IV. Operation under protection switching

Protection switching at the physical level creates new dynamics for the operation of the EPON protocol at the data link level. The HE will monitor the HE-RN link condition on a continual basis. This will be done at two levels, at the IP level (IP Connectivity) and at the physical level (Physical Connectivity). The IP connectivity is proposed to be implemented by pinging the RNs both in the clock wise and counter clockwise directions. An IP Connectivity failure would occur if there is any failure in receiving repeated ping messages, this could be due to break in physical communication or because of any software failure at the RNs and/or the HE. The physical connectivity to the RNs will be monitored by the signal detect from the Control and Management (C&M) communication channels based on 1310/ 1490 nm optics and from the signal detect on the upstream receivers. A Physical Connectivity failure would occur because of any impediment in establishing a physical lightpath to the RN. The HE will declare a link failure if the C&M receiver declares an LOS and if no upstream transmission is

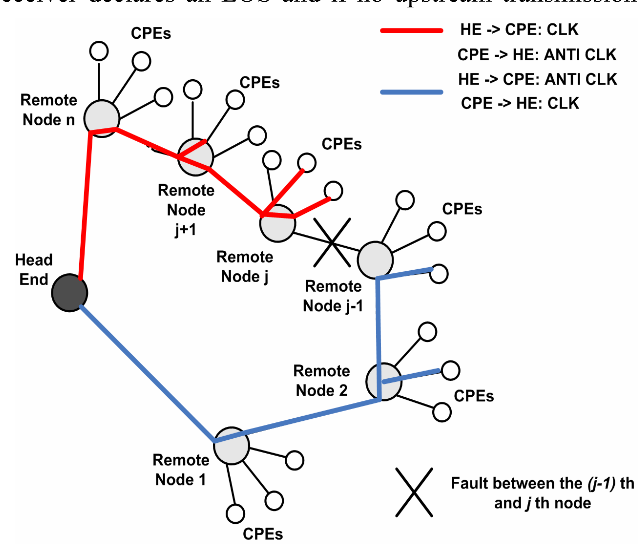

Figure 8 . HE with ROADM communicating with CPEs using shortest path to CPE after a single fiber break

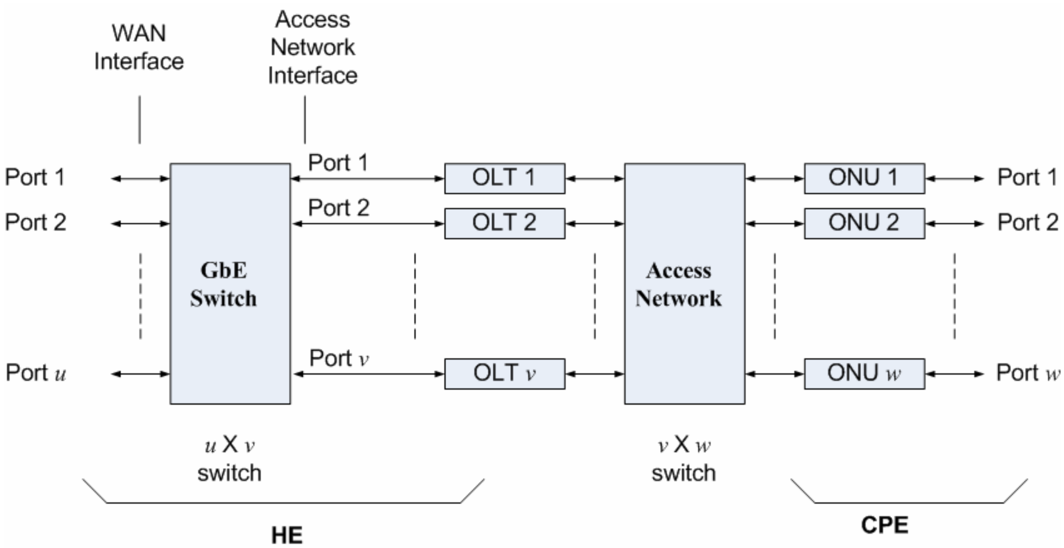

Figure 9 . Schematic visualization of the network as a two stage switch

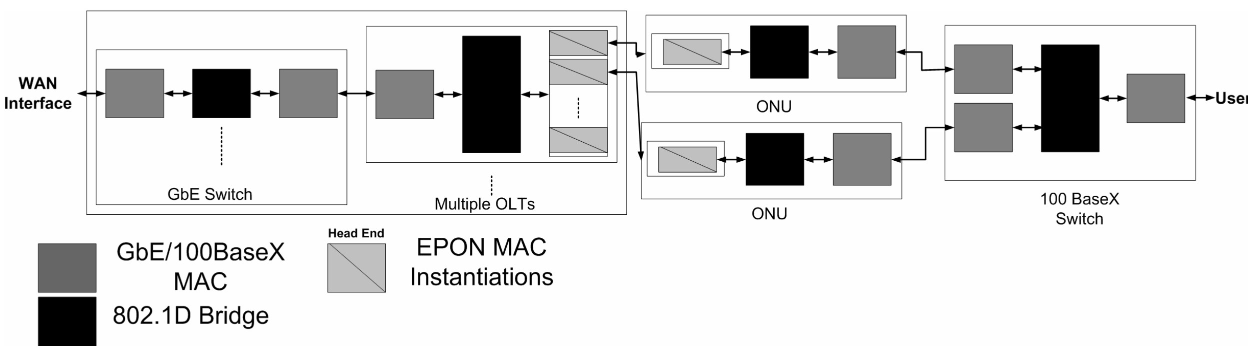

Figure 10 . User connection with WAN with redundancy in CPEs

detected on wavelengths which have ONUs associated with them.

The RN will declare a link failure if there is a Loss of Signal (LOS) declaration by both the C&M receiver and the tap signal at the Inline Amplifier (ILA). This introduces redundancy in checking for link failures. If only the C&M transceiver fails or the ILA tap detector fails then a link failure condition will not be generated. If the RN determines a link failure it will communicate the condition with the HE in the direction away from the fault location. The location of the link failure can be uniquely determined for up to a single fiber break. The transition of the HE under fault conditions is illustrated by means of a simplified state transition diagram in Fig. 11. The state diagram illustrates transitions with events, the unmarked transitions are forced transitions which occur once the actions intended to be performed in a particular state are completed.

If there is an ILA degradation then this would put a physical limitation on the number of ONUs that can be supported per wavelength. This would depend on the exact physical parameters of the network and the devices. In this

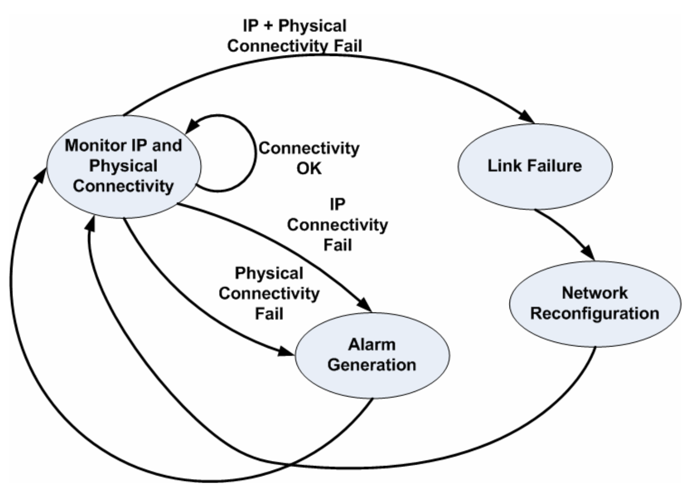

Figure 11 . Simplified state diagram for HE to monitor for link health and initiating restoration

situation the RNs would be re-configured to do add/drop towards ONUs which can be physically supported by the network. To achieve a graceful shutdown of the ONUs which cannot be supported, the OLTs will be triggered to de-register such ONUs. If there is a catastrophic failure of the ILA without sufficient time to have graceful shutdown of the ONUs then this would emulate link failure condition for some or all the ONUs. If the ROADM fails, the device itself being passive will stop add/drop towards some of the ONUs connected to it. This again emulates a link failure condition for such ONUs.

ONUs determine a Loss of Signal (LOS) when no optical signal is received or if the received optical power is less than the threshold. The LOS condition alone does not de-register the ONU [4]. An ONU is de-registered under two conditions, one if it is explicitly de-registered by the associated OLT or if an *mpcp_timeout* occurs. The *mpcp_timeout* occurs if no Multi Point Control Protocol Data Units (MPCPDU) messages are received. There are five such defined MPCPDU messages; *GATE, REPORT, REGISTER_REQ, REGISTER* and *REGISTER_ACK*. Of these only the *GATE* and the *REGISTER* messages flow from the OLT to the ONU. An *mpcp_timeout* occurs if no such messages are received by the ONU for at least 1 s [4].

This gives a window of opportunity of 1 s to restore the link. If it is possible to have physical connectivity with the ONU, this would give enough time to configure the network to re-establish communication. The problem the ONU would now face is that the restored path length could be different from the original work path and thus the Round Trip Travel (RTT) times to the OLT will be different from what the work path had. This creates problems for the TDM operation in the upstream direction because the pending grants that the ONU retains were calculated with a different RTT parameter.

There are two ways to mitigate the problem once traffic is restored to such ONUs; one is to de-register the ONUs after a fault and then float a *Discovery* round to enable re-registration and the other is to simply flush existing grants and re-allocate grants based on the new RTT parameters. For the described network there are only two RTT parameters possible for fixed CPEs, this is so because there are two diverse fiber paths from the OLT to the ONU. In principle it is possible to maintain a parameter table for every OLT-ONU mapping for both the RTTs. This would mean that the operation can start as soon as the pending grants are flushed. Practical implementation of the same could be a challenge with commercially available OLT and ONU equipment. This line of work will be investigated in future. Meanwhile the first option will be exercised for achieving restoration.

At the OLT a fault condition would trigger de-registering of associated ONUs and floating of a discovery round. The *Discovery* window floated has to be more than the RTT for the farthest link. For the described network parameters the RTT

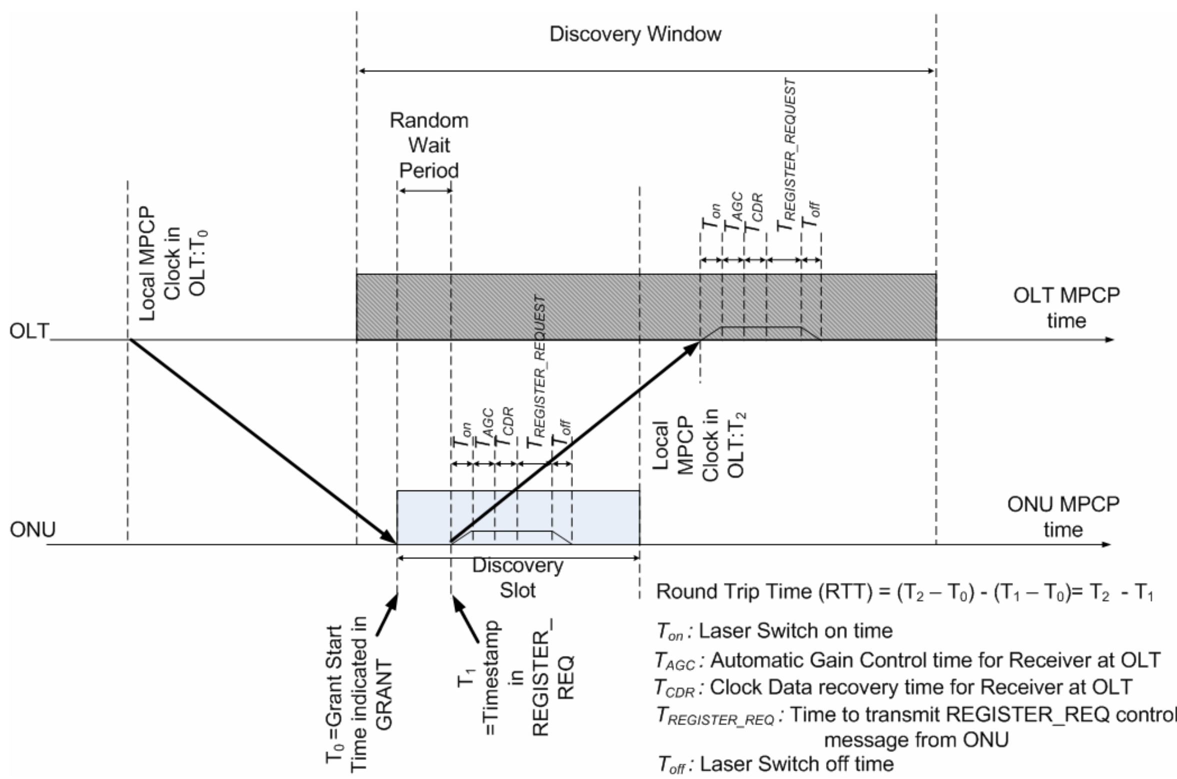

Figure 12 . Discovery process in an EPON

will be of the order of 800 µs. It can be shown that there exists an optimum *Discovery* slot size depending on the number of contending ONUs [5]. For a nominal value of 128 contending users this about 950 µs. Hence the optimum *Discovery* window is the sum of the *Discovery* slot and the maximum RTT which is 1.75 ms. The traffic disruption because of the new *Discovery* round is the sum of this window and the reconfiguration time. The over all disruption occurs from the time the network is re-configured, the ONU de-registered, subsequently re-registered to the first opportunity for the ONU to start transmission. The earliest it can start is when the first *GATE* message is sent to the ONU. The reconfiguration is estimated to be of the order of tens of milliseconds. The exact value is not known at the time of writing the paper. It should be possible to have a sub 200 ms restoration time for the network, this in itself is not a major limitation as this restoration time should ensure no significant network outage [6]. Fig. 13 illustrates the time diagrams to illustrate the traffic disruption that can be expected at the ONU after a fault restoration.

V. FUTURE WORK AND DISCUSSIONS

A schema for a resilient extended photonic access network is presented. The network is viewed as a stack of quasi independent PON like networks and the dynamics of the OLT, ONU in the proposed network are described. The physical implementation aspects of the protection schemes will be investigated and quantified. Work will include a techno-commercial evaluation of the alternative redundant network architectures to propose a cost effective implementation scheme. The network performance during implementation of protection schemes will be characterized by means of studying the effect of switching on user applications

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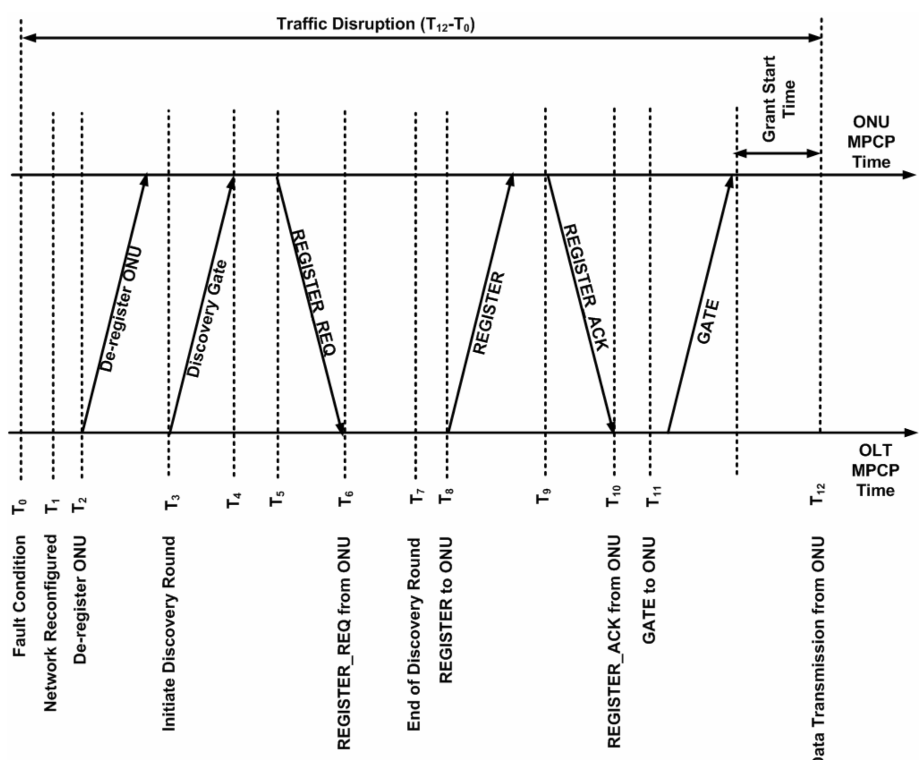

Figure 13 . Traffic disruption time line for an ONU