Automatic protection, restoration, and survivability of long-reach passive optical networks

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Abstract—The long-reach passive optical network (LR-PON) can potentially deliver future bandwidth intensive services to a significantly higher number of customers at a lower unit cost of bandwidth. Carrying substantially higher traffic over increased distances as compared to conventional PONs, the survivability of these networks is a key feature that must be addressed to ensure end-to-end network reliability. Further, as these networks are optically amplified to extend its coverage, measures to detect and remove hazardous high power exposure at the fiber break are also critical. Here, we propose, experimentally demonstrate, and characterize a simple automatic protection switching scheme that exploits the use of a highly-sensitive and fast-response protection module to achieve traffic diversion onto the protection path within 12 ms for all customers. The protection module provides an additional flexibility of activating amplifier shutdown within 2 ms of failure detection, thereby removing the hazard at the fiber break. We also perform numerical analyses of LR-PON survivability based on the probabilistic nature of fiber link failures, for conventional traffic services as well as for peer-to-peer sharing over the LR-PON. Our results highlight that the level of improvement in survivability from optical protection in an LR-PON is dependent on the probability link failure of each stage of the network.

Keywords—long-reach passive optical network; network restoration; network survivability; and optical protection.

I. INTRODUCTION

The evolution of conventional passive optical networks (PONs) into long-reach (LR) PONs is currently underway in the anticipation of delivering a rich mix of conventional as well as emerging bandwidth-intensive services, such as Internet Protocol (IP)-based video services. LR-PONs are considered by service providers as a potential solution to significantly reduce the unit cost of bandwidth [1]-[2]. Reaching spans of up to 100 km, such networks consolidate optical metro and access into a single integrated network, resulting in significant savings in power consumption, capital expenditure, and operational expenditure from lower numbers of network interfaces and elements [1]. LR-PONs are also suitable for overcoming the high cost associated with sparsely distributed customers in rural areas [3]. As these networks are envisioned to carry high capacity links over an extended coverage area and split ratio [4]-[6], measures to detect and rectify hazardous high power exposure from fiber failures, and subsequent amplifier shutdown, are critical. Depending on the location of the fiber cut, this could potentially lead to Class 4 laser radiation exposure. Hazardous exposure is further exacerbated in optically-amplified networks employing wavelength division multiplexed (WDM) technology for future-proofing in which the amount of optical power per fiber link is significantly increased. In a WDM LR-PON, different wavelengths are multiplexed at the central office (CO) and transmitted simultaneously through a feeder fiber to a WDM demultiplexer which is typically an arrayed waveguide grating (AWG). The AWG separates the multiplexed channels into individual wavelengths channels. Each of these wavelength channels are then further power split into multiple distribution fibers that connect to optical network units (ONUs) that reside at customer premises.

While protection and restoration mechanisms for both conventional PONs and LR-PONs do exists [7]-[13], our work is focus on experimentally investigating and demonstrating the survivability of optically amplified extended-reach networks. Existing research into LR-PON survivability is mainly accomplished through simulations. In this work, we propose the use of partial optical-layer protection in combination with a simple automatic protection switching scheme that exploits the use of a highly-sensitive and fast-response protection module to achieve traffic restoration within 12 ms for all customers. The protection module provides an additional flexibility of activating automatic pump laser shutdown (APLS) within 2 ms of failure detection, thereby removing the hazard at the fiber break. To our knowledge, this is the first time a protection switching and APLS scheme has been experimentally demonstrated for a LR-PON with response times well within standard requirements. Another distinctive feature of the proposed scheme is that the fiber plant is completely passive, further improving the cost-savings of the LR-PON. All active components that require power and cooling management are restricted to the central office (CO). In Section II, the operating principles of the automatic protection switching and APLS scheme are discussed, together with an example of a network architecture in which the scheme may be deployed. In Section III, results from our proof-of-concept demonstration are presented. Measurements which highlight the response time of our prototype protection module and APLS scheme to be well within the standard requirements,
are also discussed. In Section IV, results from our survivability analyses as a function of fiber failure probability for various types of connectivity within the network are presented.

II. PRINCIPLE OF OPERATION

Fig. 1 illustrates the schematic of a distributed Raman amplified LR-PON implementing the proposed protection switching and APLS scheme. Of all choices of optical amplification, distributed Raman amplification is chosen due to the fact that the amplifier could be easily tailored to provide a flat optical gain bandwidth which spans a wide wavelength amplification region that exceeds common optical amplifiers [3], [6], [14]. All active components, including the pump lasers of the Raman amplifier and protection module are located at the CO, thereby maintaining a purely passive outside plant. To facilitate network survivability in a cost-effective way, partial optical layer protection through dual fiber links is selected over full PON duplication where every major component of the plant is duplicated. It should be noted that although dual-fiber links are already specified for dual-parented unamplified gigabit PONs with a second headend in the ITU-T Recommendation G.984 [15], our scheme relies only on the physical layer to achieve a much faster traffic diversion onto the protection path. Referring back to the LR-PON architecture in Fig. 1, the CO is connected to an AWG through an optical switch that feeds a dual-fiber link, establishing primary and protection paths all the way to the optical splitter. At each optical splitter, an optical loopback via direct connection of two optical splitter ports facilitates the reflection of continuous downstream signal, i.e. monitoring signal, back to the CO. Under normal operating conditions, the optical switch is in BAR state with downstream and upstream signal transmissions traversing the primary path whilst the monitoring signal traverses the protection path that is connected to the protection module. Under protection operating conditions, the optical switch is in CROSS state, removing the hazardous exposure at the point of failure and diverting all transmissions onto the protection fiber.

The protection module (schematically shown inset of Fig. 1) monitors the integrity of the primary path by detecting the presence and absence of the reflected monitoring signal. A transimpedance front-end, designed with high gain to amplify the incoming optical signal, is followed by a low pass filter (LPF). The LPF has a bandwidth that is much lower than the bit-rate of the incoming signal due to the fact that its primary function is of packet detection rather than of data recovery. The LPF is followed by a two-stage voltage amplifier and finally a decision circuit with hysteresis to prevent oscillations in the output from noise. In the event of a fiber failure, the module senses the absence of the monitoring signal and triggers the optical switch into CROSS state. The reduced bandwidth of the protection module results in much higher sensitivity than a data receiver, which is essential for high optical link loss such as that exhibited by LR-PONs. In our experiments, the measured sensitivity of the protection module was -50.5 dBm with false triggering observed for received optical powers below that value.

The protection module can also be utilized to control the amplifier interlock of the Raman pump lasers to facilitate APLS. According to the IEC60825-2 standard for safety of optical transmission systems, automatic laser shutdown mechanisms must be fully engaged < 3 seconds (restricted area, e.g. CO) and < 1 second (unrestricted area, e.g. external plant) of fiber/device/connector failure [16]. CO-located Raman pump lasers therefore restricts accidental hazardous exposure from the failure of pump lasers to a confined environment, thus relaxing the APLS shutdown time.

III. PROOF-OF-CONCEPT DEMONSTRATION

A. Experimental Setup

Fig. 2 shows a simplified experimental setup to verify the characterization and demonstration of the automatic protection switching and APLS scheme. Due to the unavailability of optical components, we demonstrate a single wavelength 32 split LR-PON configuration. In our numerical analyses, we extend this configuration by 32 wavelengths, hence a 1024 ONU supported LR-PON. At the CO, a distributed feedback (DFB) laser is directly modulated with a 2^{31}-1 pseudorandom bit sequence (PRBS) non-return-to-zero (NRZ) data from a bit-error-rate testset (BERT) at 1.25 Gb/s. The downstream signal (λ₀ = 1534.2 nm with ~1 mW average output power) is combined with Raman pump light via a coarse WDM filter. The pump lasers comprise two 1450 nm grating stabilized lasers which polarized outputs are multiplexed together. The combined light first traverses an optical switch and an external passive plant comprising a 50 km of feeder fiber link, a 2×32 optical splitter implemented with an optical loopback, and a 20 km distribution fiber link. The optical loopback reflects a
fraction of the continuous downstream signal, i.e. monitoring signal, into a second 50 km feeder fiber link. The output from the protection module controls the TTL input of the optical switch. At each ONU, an optical circulator directs downstream signals towards the receiver whilst upstream signals are launched into the passive plant from a VCSEL. The VCSEL ($I_{\text{bias}} = 5.9 \text{ mA}$, $\lambda_U = 1531.1 \text{ nm}$, average output power of $\sim0.5 \text{ mW}$) was directly-modulated with $2^{31}-1$ PRBS NRZ data at 1.25 Gb/s from a second BERT. For data recovery of both backscattered light before detection using a 2.5 Gb/s avalanche photodiode, tuned to $\lambda_D$ was used to filter out the reflected monitoring signal from the combined spectra of Raman pump lasers and upstream signal. Shown inset are the measured symmetrical Raman gain profiles of the upstream and downstream signals at varying pump powers. In our experiments, a pump power of $\sim260 \text{ mW}$ was chosen to optimize optical link budget with an achieved 6.75 dB Raman gain at the 1530 nm region, limited by the output wavelength of the low-cost, uncooled, and low power consumption ONU transmitter used in our experiments. Nevertheless, higher gains of up to 10 dB can be achieved in the 1550 nm region as observed from the insets of Fig. 2. If transmitters of higher output power and of appropriate wavelengths are employed, network reach, coverage and customer numbers can be increased beyond that demonstrated in our experiment.

B. Network Performance Measurements

Bit error ratio (BER) measurements of the downstream and upstream signals of the experimental setup in Fig. 2 are plotted in Figs. 3(a) and 3(b), respectively. Downstream signals which originate at the CO are transmitted to ONUs, where as upstream signals which originate from an ONU are transmitted to the CO. In Figs. 3(a) and 3(b), we compare back-to-back (B2B) BER measurements taken without transmission fiber to that taken with fiber transmissions under normal (BAR state) and protection (CROSS state) operations. BER measurements of transmissions through a conventional PON without optical layer protection were also performed to study the impact of the reflected monitoring signal on signal transmissions. Using the standard measurement of BER $<10^{-9}$ to represent error-free transmission, both downstream and upstream BER measurements indicate minimal penalty for transmissions of signals on the protection path as compared to the primary path, i.e. 0 dB for downstream signals and 0.2 dB for upstream signals. Results also indicate minimal impact of the reflected monitoring signal on signal transmissions on the primary and protection paths, i.e. 0.2 dB for downstream signals and 0.4 dB for upstream signals.

C. Response Time Measurements

The response time of the protection module, optical switch and automatic pump laser shutdown (APLS) mechanism were also measured to ensure that these times were well within the
specified standard values. These measurements were made using the experimental setups shown in Fig. 4(a) and 4(b), respectively. In both setups, the burst packet driver and transmitter generates a series of optical packets that are fed into the protection module. These optical packets represent the monitoring signal that is to be detected by the protection module. Whenever an optical packet is detected, both optical switch and amplifier interlock are at default positions. However, the protection module will detect the absence of an optical packet as a fiber failure and will subsequently switch the optical switch to CROSS state and/or activate APLS.

Fig. 5(a) compares the measured oscilloscope traces of an incoming trailing edge of an optical packet to the resulting protection module output. Results show that the protection module transitions from ‘1’ to ‘0’ within a fast response time of ≈524 ns. Fig. 5(b) compares the oscilloscope traces of the protection module, primary path output and protection path output. Upon a ‘1’ to ‘0’ transition of the protection module output, signals are switched from the primary to the protection path, showing a fast response time of 10.5 ms. Considering the worst case scenario where fiber failure occurs just outside the CO, the total protection switching time is measured to be < 12 ms (= 0.5 ms roundtrip propagation delay + 524 ns protection module response time + 10.5 ms optical switch response time).

In practice, the protection module will provide an additional flexibility of activating APLS upon detecting a fiber failure, thereby removing the hazardous exposure at the fiber break. We measure APLS response time using the setup in Fig. 4(b). We compare the oscilloscope traces of the protection module output at its ‘1’ to ‘0’ transition (representing fiber failure) to that at the output of the photodetector. A ‘1’ to ‘0’ transition from the protection module output deactivates the amplifier interlock, thereby turning off the pump lasers. Without amplification, the signal at the photodetector is measured to have smaller amplitude, as shown in Fig. 6(a). A detailed measurement at the ‘1’ to ‘0’ transition as depicted in Fig. 6(b), show an APLS response time of 1.15 ms. Considering the worst case scenario where fiber failure occurs just outside the CO, a fast APLS activation response time of < 2 ms (= 0.5 ms roundtrip propagation delay + 524 ns protection module response + 1.15 ms optical switch response) can be achieved.

IV. SURVIVABILITY ANALYSIS

In this section, we perform numerical analyses of the survivability of LR-PONs based on the probabilistic nature of link failures. We begin by considering an LR-PON with a three stage tree topology as shown in Fig. 1, and we analyze its ONU connectivity as a function of increasing fiber link failure probability. Referring to Fig. 1, the stages of the network are defined as follows: Stage 1 is between the CO and the AWG, Stage 2 is between the AWG and each optical splitter, and finally Stage 3 is between the optical splitter and each ONU. In our analyses, it is assumed that all fiber links, including protection fibers that reside within the same stage have identical failure rates. Denoting the probability that a given fiber link fails by $p_1$, $p_2$, and $p_3$, for Stages 1, 2, and 3, respectively, the probability that ONU $i$ is connected to the
OLT, is therefore expressed by:

\[ P_{\text{ONU},0} = (1 - p_1)(1 - p_2)(1 - p_3) \]  

(1)

With the implementation of a second feeder fiber to provide optical protection in Stage 1, the probability that ONU \( i \), where ONU \( i \), is connected to the OLT is given by:

\[ P_{\text{ONU},1} = (1 - p_1^2)(1 - p_2)(1 - p_3) \]  

(2)

where \( p_1^2 \) denotes simultaneous link failure probability of both feeder fibers of Stage 1. When optical protection is extended through to Stage 2, as shown in Fig. 1, the probability that ONU \( i \), where ONU \( i \), is connected to the OLT is given by:

\[ P_{\text{ONU},2} = (1 - p_2^2)(1 - p_2^2)(1 - p_3) \]  

(3)

where \( p_2^2 \) is the simultaneous link failure probability of both distribution fibers of Stage 2.

In the interest of peer-to-peer sharing within local communities [17], the expected number of fault-free connections, \( L \), between any pair of ONUs of the LR-PON was also analyzed using (4), (5) and (6) for the corresponding network scenarios: a) no optical protection; b) Stage 1 optical protection and c) Stages 1 and 2 optical protection, respectively. In our calculations, the total number of supported ONUs, \( N \) is 1024, a practical value chosen based on the allowable power budget from our experimental setup.

\[ L_0 = \sum_{i=1}^{N} \sum_{j=1}^{N} \left(1 - p_1\right) \left(1 - p_2\right)^2 \left(1 - p_3\right)^2 - \sum_{i=1}^{N} \left(1 - p_1\right) \left(1 - p_2\right)^2 \left(1 - p_3\right)^2 \]  

(4)

\[ L_1 = \sum_{i=1}^{N} \sum_{j=1}^{N} (1 - p_1^2)(1 - p_2\)^2 \left(1 - p_3\right)^2 - \sum_{i=1}^{N} (1 - p_1^2)(1 - p_2\)^2 \left(1 - p_3\right)^2 \]  

(5)

\[ L_2 = \sum_{i=1}^{N} \sum_{j=1}^{N} (1 - p_2^2)(1 - p_2^2\)(1 - p_3\)^2 - \sum_{i=1}^{N} (1 - p_2^2)(1 - p_2^2\)(1 - p_3\)^2 \]  

(6)

The improvement in network survivability from deploying partial optical protection can be observed from Figs. 7 and 8. The actual level of improvement is dependent on the fiber failure probability of each stage, which in turn is dependent on a number of factors, most notably fiber length and how the fiber is deployed, i.e. underground versus aerial fiber. To provide a simple example, Fig. 7 plots \( P_{\text{ONU},i} \) as a function of fiber failure probability where \( p_1 = p_2 = p_3 \). In this case, regardless of the exact value of fiber failure probability, the probability of a fault-free OLT-ONU connection increases by 10% with the deployment of Stage 1 optical protection. With Stage 1 and 2 protection, the increase is a further 11%. When calculations were repeated for the case with decreasing fiber failure probability whereby \( p_1 = 10p_2 \) and \( p_1 = 100p_3 \), then the probability of a fault-free OLT-ONU connection increases by 10% with Stage 1 optical protection as compared to the case without optical protection. With Stage 1 and 2 protection, the increase is only a further 1%. This small improvement in OLT-ONU connectivity is attributed to the fact that for the chosen probabilities of \( p_1 > p_2 > p_3 \), the values calculated from (1), (2) and (3) are most dependent on Stage 1 of the network.

The expected number of fault-free connections between ONUs, \( L \), as a function of fiber failure probability where \( p_1 = p_2 = p_3 \), is depicted in Fig. 8. As the probability of link failure increases, the expected number of intact ONU-ONU connection deviates from an ideal network with no failures where \( p_1 = p_2 = p_3 = 0 \). For such an ideal network, \( L \) is calculated to be 1047550 and is represented by the dashed horizontal line in Fig. 8. At \( p = 10^{-5} \), a network with no fiber

**Fig. 7 Probability of ONU \( i \) being connected to OLT.**

**Fig. 8 Expected number of ONU-ONU connections.**
protection has approximately 10 intact ONU-ONU connections less than the ideal case. At $p = 0.1$ this value has exponentially increased to 428981, or equivalently 42% less than the ideal case. With Stage 1 optical protection, the number of intact ONU-ONU connections is 10% higher than when no protection is implemented. With Stages 1 and 2 optical protection, the improvement is 33% higher than when no protection is implemented, thus improving overall network survivability and approaching the ideal network scenario. Again, the actual level of improvement in $L$ is dependent on the fiber failure probabilities of each stage of the network. For the case with decreasing link probabilities, i.e., $p_1 > p_2 > \ldots > p_n$, optical protection in the first stage is adequate to provide sufficient survivability. As for the case with increasing link probabilities, i.e., $p_1 < p_2 < \ldots < p_n$, protection of all stages leading up to that with the highest probability of failure is necessary to provide sufficient survivability.

V. CONCLUSION

The long-reach PON is emerging as a future-proof and cost-effective approach to enable network operators and services providers to deliver a rich mix of conventional and emerging IP-based video services. As compared to conventional PONs, LR-PONs face significant challenges in providing network survivability whilst ensuring hazardous exposure is redirected away from the point of failure within a small timeframe. In this regard, network survivability in guaranteeing end-to-end reliability to an increased number of customers over an extended coverage area is critical. In this work, we have proposed a cost-effective automatic protection switching and amplifier shutdown scheme that is based on a low-cost, highly-sensitive, and fast-response protection module. We have successfully demonstrated the proposed scheme in a completely passive LR-PON and in conjunction with our prototype protection module. Our measurements show failure detection and recovery times that are well within standard requirements. Further, bit-error-rate measurements indicate negligible penalty for transmission of signals in the protected path. Our numerical analyses of LR-PON survivability based on the probabilistic nature of fiber link failures, confirms the beneficial impact of partial optical protection for conventional traffic services and peer-to-peer traffic over the LR-PON. The exact level of improvement in survivability is dependent on the probability of link failure at each stage of the network.

REFERENCES