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Survivable architectures for time and wavelength division multiplexed passive optical networks

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ABSTRACT

The increased network reach and customer base of next-generation time and wavelength division multiplexed PON (TWDM-PONs) have necessitated rapid fault detection and subsequent restoration of services to its users. However, direct application of existing solutions for conventional PONs to TWDM-PONs is unsuitable as these schemes rely on the loss of signal (LOS) of upstream transmissions to trigger protection switching. As TWDM-PONs are required to potentially use sleep/doze mode optical network units (ONU), the loss of upstream transmission from a sleeping or dozing ONU could erroneously trigger protection switching. Further, TWDM-PONs require its monitoring modules for fiber/device fault detection to be more sensitive than those typically deployed in conventional PONs. To address the above issues, three survivable architectures that are compliant with TWDM-PON specifications are presented in this work. These architectures combine rapid detection and protection switching against multipoint failure, and most importantly do not rely on upstream transmissions for LOS activation. Survivability analyses as well as evaluations of the additional costs incurred to achieve survivability are performed and compared to the unprotected TWDM-PON. Network parameters that impact the maximum achievable network reach, maximum split ratio, connection availability, fault impact, and the incremental reliability costs for each proposed survivable architecture are highlighted.

1. Introduction

The use of optical fiber technology in the access segment and in backhauling wireless networks has proven to be the most practical yet future-proof solution against the exponential growth of Internet traffic [1]. In terms of access segment, the standardization of second generation passive optical network (PON) systems with aggregate upstream and downstream capacities up to 10 Gbps has recently been finalized by both ITU-T (i.e. NG-PON1) and IEEE (i.e. 10GE-PON) [2,3]. Beyond 10 Gbps, major carriers have indicated that the following requirements be addressed when choosing the next technology solution: (a) concurrent support of legacy, new, and mobile backhaul services; (b) reuse of existing optical distribution network (ODN); (c) flexible bandwidth upgradeability and management; (d) support of high bandwidth/capacity and customer base; (d) optimized technology combinations in terms of cost, performance and energy savings; and (e) implementation of *non-intrusive fault diagnostics with rapid restoration of services* [4]. In addressing these requirements, the Full Services Access Network (FSAN) group has selected the time and wavelength division multiplexed PON (TWDM-PON) as the technology solution for NG-PON2 [5].

A baseline TWDM-PON architecture is schematically shown in Fig. 1. The optical line terminal (OLT) comprises M transceivers, the remote node comprises a passive splitter, and each ONU comprises a tunable transceiver [6]. The use of tunable transceivers in ONUs allow each to transmit on any of the M upstream wavelengths on the C-minus band and receive on any of the M' downstream wavelengths on the C band. A TWDM-PON therefore operates as multiple concurrent TDM-PONs, all sharing the same ODN. Unlike the conventional hybrid TDM/WDM PON whose remote note can house active elements such as optical amplifiers, wavelength multiplexers/demultiplexers, and wavelength switches [7], the ODN in a TWDM PON must strictly retain the passive nature of a power split TDM-PON. All active equipment are located only at the OLT and ONUs. For example, to support an increased network reach and customer base in a TWDM-PON, optical amplifier(s) are deployed only at the OLT [6]. Recent proof-of-concept demonstrations of TWDM-PONs have used thermally tuned DFB ONUs [6] and current bias tuned VCSEL ONUs [8] as tunable transmitters at the ONU. The VCSEL ONU is considered in this work due to the two following reasons: energy-efficiency and ONU fault detection. Wavelength tuning of a VCSEL ONU through current biasing does not require the use of thermoelectric cooling and heating, thereby improving energy-efficiency of the ONU [8]. In the active mode,

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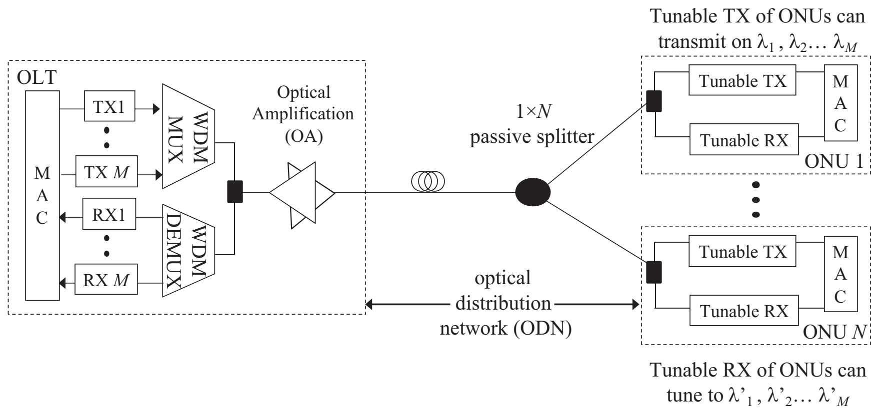

Fig. 1. Baseline architecture of time and wavelength division multiplexed passive optical network (TWDM-PON). Optical distribution network is completely passive with active components deployed only at the OLT and ONUs [8].

the VCSEL ONU consumes 80% less power than a comparable DFB ONU [9]. Further, the high reflectivity of the top distributed Bragg reflector (DBR) mirror of VCSEL ONUs is exploited to detect ONU failures [10,11], as will be discussed in Section 2.

As TWDM-PON deployments are to service increased network reach and customer base, providing resilience against fiber/equipment failure through fault detection and subsequent protection switching is an important consideration in the design of the network. Protection switching of the affected signals onto the protection path also prevents hazardous high-power laser exposure at the fiber breaks [11]. One commonly deployed fault monitoring and detection scheme is the optical time domain reflectometry (OTDR). This technique can be implemented offline, but because offline troubleshooting can lead to traffic interruptions and delays in service restoration, in-line OTDR monitoring using a separate light source located at the U band (~1625–1675 nm) is much preferred [12]. Applying OTDR, either offline and in-line, to a TWDM-PON is, however, unreliable and ambiguous. This is due to the fact that the power splitting ODN of a TWDM-PON will cause the backscattered signals from distribution fiber branches to overlap, thus making individual backscattered signals indistinguishable and subsequently the location of the distribution fiber faults unidentifiable.

Survivability in conventional TDM-PONs and WDM-PONs of typically 10–20 km has been extensively explored and is well documented in the literature, e.g. [13–15]. Many of these exploit the use of a combination of optical switches and fiber/equipment redundancy. These architectures are mostly based on four basic recommended configurations in the ITU G.983.1 [16]. Note that though these basic configurations have been recommended, the ITU-T does not specify the actual fault monitoring and protection scheme to be used, leaving the decision to the network operator. Survivability in hybrid TDM/WDM PONs is also a well-researched topic [7,17,18]. Unlike TWDM-PONs, the ODN of a hybrid TDM/WDM PON may be implemented with active elements, e.g. optical amplifiers, wavelength multiplexers/demultiplexers, and wavelength switches, to improve reach, customer numbers, and bandwidth flexibility. As with the conventional TDM-PON, varying degrees of fiber/equipment duplication are implemented to achieve survivability in a hybrid TDM/WDM PON. A glaring inefficiency in these existing schemes when applied directly to a TWDM-PON lies in the assumption that the absence of upstream transmissions at the central office can be used to activate the LOS alarm, and subsequently trigger protection switches. This technique can lead to erroneous LOS alarm activations when used in conjunction with sleep/doze mode ONUs, as per NG-PON2 recommendation for achieving energy efficiency. During idle periods, the sleep/doze mode ONUs will transition from active into either sleep or doze mode in which no upstream data will be transmitted. Hence, the absence of upstream signals at the central office *cannot* be used in TWDM-PONs as a true indication of LOS.

In this work, three survivable architectures for TWDM-PONs are proposed to address the shortcomings of existing schemes, as discussed above. The proposed architectures do not need to rely on upstream transmissions to indicate LOS, instead using either the downstream signals or a CW monitoring light for such a purpose. Each of the proposed architecture exploits highly sensitive monitoring modules with fast-response fault detection and subsequent protection switching times. The modules used in this work require very low levels of monitoring input power (<-50 dBm) for operation [11]. Due to high optical losses associated with increased network reach and customer numbers, monitoring modules that are able to reliably detect faults at low optical input powers are critical to the survivability of the network. Using the sensitivity of the monitoring module as a performance limit on reliable fault detection, the maximum network reach and split ratio for each of these proposed architectures are investigated. Depending on the degree of redundancy, the proposed architectures are able to protect against multipoint failures. Survivability analyses, considering connection availability and fault impact, are also performed. Results highlight that the probability of an intact connection between the central office to ONU and the number of these intact connections are strongly dependent on the degree of protection and network parameters such as deployed fiber length and split ratio. Finally, the incremental reliability cost incurred by implementing backup fiber/equipment in exchange for improved reliability performance is evaluated for each of the proposed architectures and compared to an unprotected TWDM-PON. Results highlight that backup fiber/equipment that is shared amongst ONUs do not significantly contribute to the incremental reliability cost per user whereas backup fiber/equipment dedicated to each ONU dominates the incremental reliability cost per user.

2. Survivable TWDM-PON architectures

Fig. 2(a)–(c) illustrate the three types of architectures, namely Types A, B, and C, proposed specifically for survivable TWDM-PONs. For illustrative purposes, all architectures are connected to *N* ONUs. The architectures shown in Fig. 2(a)–(c) are analogous to the basic configurations recommended by the ITU-T but with an *added advantage* of a loopback feature which allows the monitoring and downstream signals to be used for simultaneous fault detection, rather than relying on upstream signals to activate the LOS alarm. Active components that are added to the architectures