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Troubleshooting PON Networks Effectively with Carrier-Grade Ethernet and WDM-PON

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ABSTRACT

WDM-PONs have recently emerged to provide dedicated and separated point-to-point wavelengths to individual optical network units. In addition, the recently standardized Ethernet OAM capabilities under the IEEE 802.1ag standard and ITU-T Recommendation Y.1731, together with state-of-the-art optical time-domain reflectometry provide new link-layer and physical tools for the effective troubleshooting of WDM-PONs. This article proposes an integrated troubleshooting box (ITB) for the effective combination of both physical and link-layer information into an effective and efficient set of management procedures for WDM-PONs. We show its applicability in a number of realistic troubleshooting scenarios, including failure situations involving either the feeder fiber, one of its branches, or even Ethernet links after the ONU.

INTRODUCTION

Passive optical networks (PONs) have been proposed and standardized to open up the bandwidth capacity of access networks. At present, network operators have begun to deploy time-division multiplexing (TDM)-based PONs in high-density urban areas, while wavelength-division multiplexing (WDM) PONs are still in the stage of research and standardization.

Concerning TDM-PONs, current standards such as the Gigabit PON (International Telecommunication Union Telecommunication Standards Sector, ITU-T, G.984), the Ethernet PON (IEEE 802.802.3ah), and their recent enhancements XG-PON1 (ITU-T G.987) and 10G-EPON (IEEE 802.3av) use a $1 \times N$ passive splitter/combiner to divide the optical signal to all users in the downstream direction and aggregate the users' data in the upstream direction. TDM access sharing is required in the upstream direction to avoid collisions between users' data. On the other hand, for PONs based on WDM, the power splitter/combiner is replaced by a wavelength selective filter, usually an array waveguide grating (AWG), thus allowing a dedicated wavelength with symmetric bandwidth between each user and the central office.

Despite their differences, both types of PONs share a main drawback related to the high operational expenditures (OPEX) derived from their manually troubleshooting procedures, as follows. Typically, most vendor equipment offers proactive alarms related to physical and link-layer aspects such as link down, frame loss, or power level events. These alarms are often followed by a set of manual measurements launched by the network manager to detect and locate the failure, usually comprising fiber breaks or dirty connectors. In this light, the network manager must devote some time to manually connecting external measurement equipment with optical time-domain reflectometry (OTDR) capabilities to actually locate the failure and isolate it from the rest of the network. Such manual operational procedures cause high OPEX, and it would be desirable to make them automatic.

Indeed, the IEEE and ITU-T have standardized a number of operations, administration, and maintenance (OAM) procedures for Ethernet networks under IEEE 802.1ag [1] and ITU-T Y.1731 [2]. These mechanisms include the generation of loopback messages, measurements of packet delay or loss, and others at the Ethernet layer, which, in conjuction with the raw physical alarms provided by most vendor equipment and the OTDR measurements, can provide a means of automatically troubleshooting WDM-PON networks.

This article explores this idea of integrating troubleshooting information from multiple independent sources (equipment alarms, OTDR traces, and Ethernet OAM features) and further proposes an integrated troubleshooting box (ITB) for effective and proactive (i.e., without user intervention) management of failures in WDM-PONs. Thanks to this box, the network manager will be provided with accurate real-time information about the PON status, including the detection, isolation, and verification of failures upon their occurrence (Fig. 1).

The remainder of this article is organized as follows. We describe the troubleshooting capabilities of OTDRs at the optical layer. We review the Ethernet OAM mechanisms described in IEEE 802.1ag and ITU-T Y.1731 at the link layer. We propose the above-mentioned ITB device, which will integrate both physical and link-layer functionalities, and automatize the
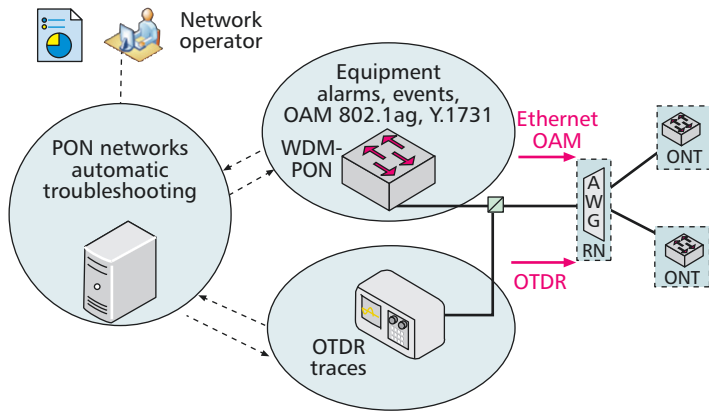
Figure 1. *Integrated troubleshooting box (ITB): architecture.*

process of detection, verification, and isolation of the failure. Finally, we conclude this article with a summary and discussion of its main contributions, along with future work worth investigation.

THOUBLESHOOTING WDM-PON NETWORKS AT THE OPTICAL LAYER

OTDR BACKGROUND

OTDR equipment allows fiber breaks to be detected and located with a very fine resolution, on the order of millimeters. Essentially, the OTDR equipment launches a very narrowband pulse into the fiber, and a response is then received back at the OTDR when any air-glass interface in the cable is detected. Typical examples of air-glass interfaces are due to fiber connectors or fiber breaks. The exact location of a fiber break can be inferred from the measured amplitude and delay of the response.

OTDR equipment can be applied to PONs for the detection of fiber breaks, in either the feeder or a branch. In TDM-PONs, the OTDR pulse can be tuned on either the same up/downstream wavelength (in-band OTDR, 1490/1310 nm) or a different one (out-of-band OTDR, typically at 1625 nm). In the former, hardware changes are required in both the optical line terminal (OLT) and optical network terminals (ONTs) to prevent the OTDR signal from affecting the traffic of non-faulty users. In the latter case, hardware changes are only required in the ONTs, basically to make them capable of reflecting the OTDR wavelength. In either case, significant hardware changes are required.

However, in WDM-PONs, the OTDR can be tuned on each user wavelength (in-band OTDR) with minimal hardware changes, only those involving the coupling of the OTDR equipment itself as shown in Fig. 1, which poses a clear benefit over TDM-PON troubleshooting.

Fiber breaks may occur in either the feeder section of the PON or a user's branch. In the case, all users will experience service disrup-, so the OTDR should detect the same prob-at exactly the same location in every elength. If the fiber break occurs in a branch, OTDR must be tuned to that particular

channel in order to detect the exact location of the break. Thanks to its WDM nature, the failure can be diagnosed without affecting other users of the WDM-PON.

Figure 2 shows two OTDR trace examples. The first trace gives an example of the expected measurement displayed by the OTDR under normal operation, whereas the second one exhibits the expected displayed figure under a fiber break. The y-axis depicts the signal strength vs. distance, shown in the x-axis. In the figure, we observe the attenuation due to Rayleigh scattering, AWG absorption, connector reflections, and a fiber break reflection.

LABORATORY FIELD TRIALS

Previous studies from Park *et al.* [3] and Kaiser *et al.* [4] have demonstrated the use of a tunable OTDR for in-service monitoring of fiber faults in an experimental unstandardized WDM-PON. In their experimental setup, they used a colorless WDM-PON-based wavelength-locked Fabry-Perot lasers with Broadband Light Sources (BLS) [5] on the C- and S-bands. The authors used a wavelength-locked Fabry-Perot laser, tuned by an L-band BLS, to emulate the tunable OTDR signal.

Our laboratory setup is very similar to those of [3, 4] but uses a standardized WDM-PON (ITU-T G.698.3 compliant [6])[1] and standard frequency grids rather than experimental WDM-PON technology. The OTDR equipment used in our experiment is also commercially available.

Two different test scenarios were set up for the experiments (Fig. 3). The first test was aimed at demonstrating basic AWG pass-through features of the OTDR, whereas the second one was focused on exploring the whole fiber path across the WDM-PON.

Test 1. AWG Pass-Through Tests — In Test 1, two 4-km fiber spools were assembled to build an 8-km trunk fiber at the output of the OLT and further connected to the common port of the AWG using SC/APC connectors (Fig. 3). In port 4 of the AWG, another 4-km fiber spool was connected but not terminated on any ONT. In fact, this branch fiber was terminated on another SC/APC connector.

No fiber was connected to any of the other 31 ports of the AWG for the following reason: Essentially, the OTDR equipment is very sensitive to external light sources. Hence, if other active ONTs at different wavelengths are connected in the laboratory setup, the OTDR would receive the power from all of them, hence masking the signal of interest on channel 4. This issue is typically solved by using appropriate filtering at the input of the OTDR, but this device was not available at the time of writing. For this reason, we decided not to connect any ONT to the other AWG ports.

The tuning accuracy of the OTDR, below 0.1 nm, allows for the selection of individual user wavelengths over the full C-band range, where channel spacing is approximately 0.8 nm. The OTDR was then tuned to the 1535.8 nm and 1536.6 nm wavelengths (channels 4 and 5 of the AWG). The two responses are displayed in Fig. 4. We conclude from the figures that both the
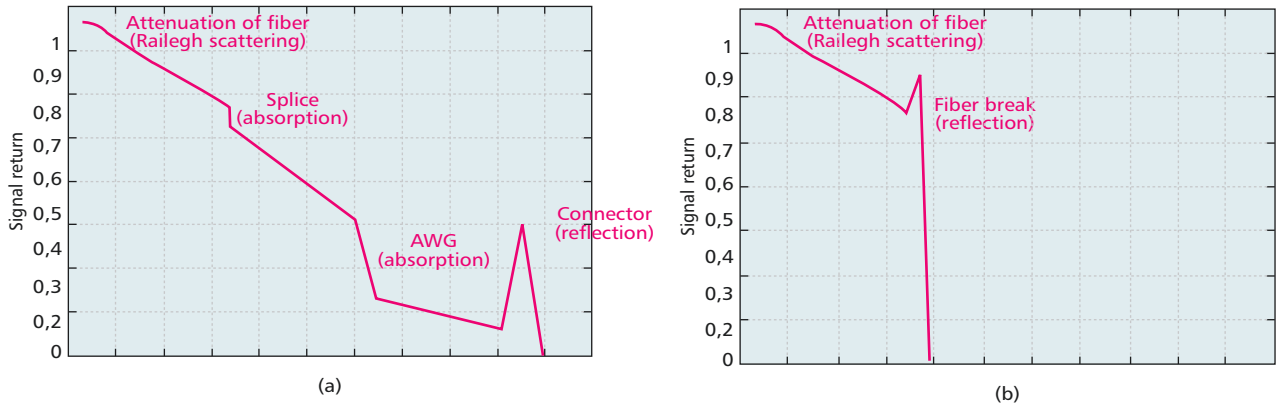
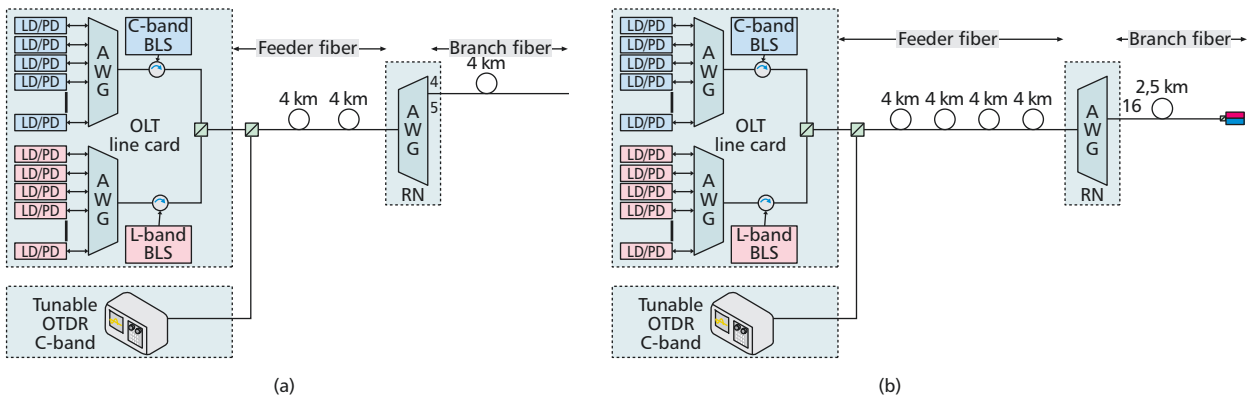**Figure 2.** *OTDR trace example: a) normal operation; b) fiber break.*

Figure 3. *Test setups: a) AWG pass-through; b) reach and termination test.*

feeder and branch fibers can be inspected, even with the large insertion loss introduced by the AWG (of 5.5 dB at most). Any AWG ports without a fiber can easily be identified from the OTDR response.

Test 2. Reach and Termination Tests — Test 2 takes one step further by increasing the trunk fiber length for up to 16 km, and terminating port 16 (instead of port 4) of the AWG with an unpowered ONT (Fig. 3). In this setup, the branch is 2.5 km long rather than 4 km as before. Again, all connections were performed with SC/APC connectors. The OTDR was then tuned to channel 16 (i.e., wavelength 1545.3 nm) showing the snapshots of Fig. 5.

The first snapshot shows the entire 18.5 km fiber length on a 20-km window view. The OTDR sensitivity is set to the maximum value (71 dB), but even so, the very large attenuation observed hides any details about the power drop at the AWG or the banch fiber section. The OTDR automatically switches to Rayleigh mode for this view.

In order to better see the details at the end of the fiber, the second snapshot of Fig. 5 provides a 50-m window view at the very end of the fiber (i.e., at 18.5 km). Sensitivity is now reduced to 42 dB, and the OTDR has automatically switched to the Fresnel mode for this zoomed-in view. The reflection produced by the ONT is now clearly evident. Both window size, sensitivity, and window position can be manually adjusted along the entire fiber length to identify and locate any fiber anomaly, including fiber breaks, dirty connectors, and so on.

CARRIER-GRADE ETHERNET OAM

In WDM-PONs, the point-to-point wavelengths between the OLT and the ONTs can, but not necessarily, carry Ethernet frames. In this case, the WDM-PON can leverage from the Ethernet carrier-grade capabilities, which can show multiple advantages for troubleshooting. The OAM features of Ethernet, specified in IEEE 802.1ag and ITU-T Y.1731, can be split into two main areas: fault management and performance monitoring.
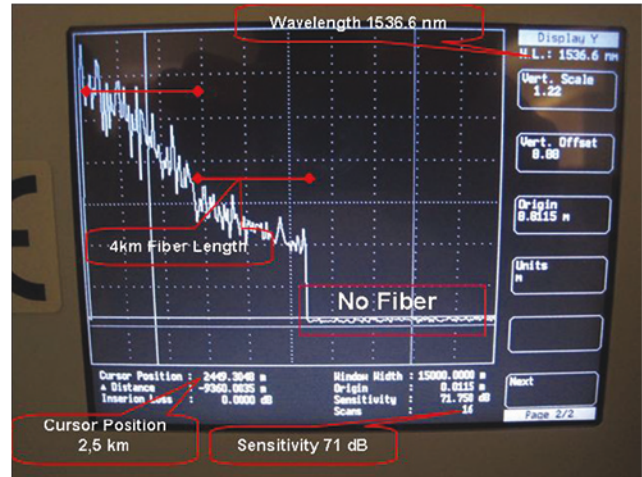
FAULT MANAGEMENT

Fault management is in charge of detecting and isolating failures, and reporting them to the network operator. To this end, it provides the following functionality.

Fault detection supported through the use of continuity check messages (CCMs). CCMs are periodically issued between two endpoints, for
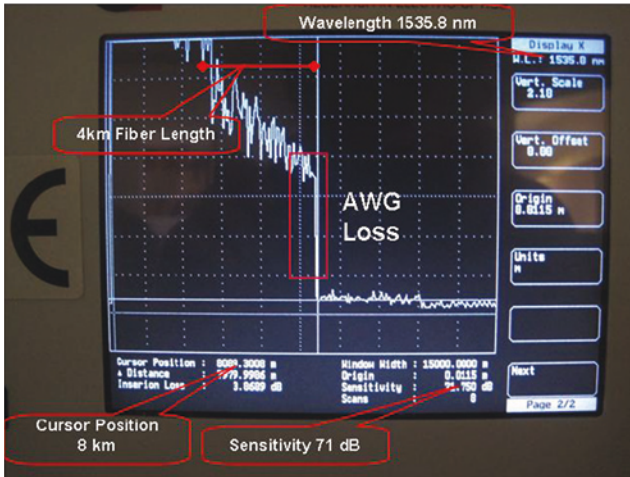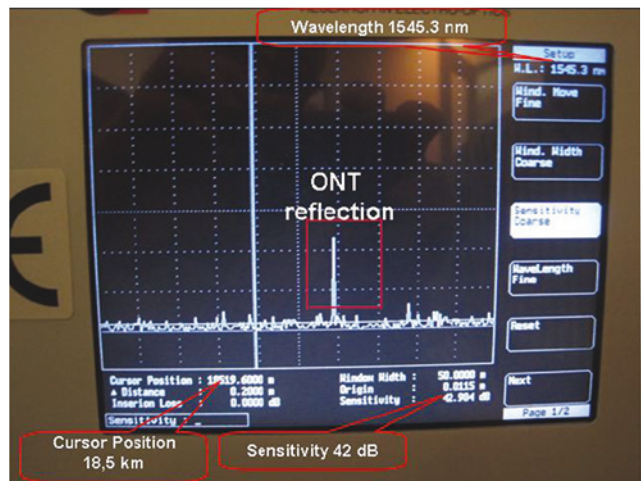
Figure 4. *OTDR snapshots for Test 1: a) OTDR snapshot (channel 4); b) OTDR snapshot (channel 5).*

Figure 5. *OTDR snapshots for Test 2: a) OTDR snapshot (channel 16); b) zoomed-in OTDR snapshot (channel 16).*

instance, every 10 ms (this value can be configured by the network manager). If three consecutive CCMs are not received, a failure is assumed to have occurred. At this point, an alarm is reported to the network management plane.

Fault notification: All devices supporting ITU-T Y.1731 can be configured to report alarm indication signals (AISs) to the network management plane upon failure suspicion, either after three lost CCMs or any other misbehaving event. At this point, the network manager should verify and isolate the failure, as explained next.

Fault verification, in charge of verifying that an actual failure has occurred. Under failure suspicion, the network manager can configure the device to send a loopback message (LBM) to a specific destination, which would answer with a loopback reply (LBR). Obviously, in the case of an actual failure, no reply would arrive back at the source. The key difference between fault detection and verification is that in the former,

the CCMs are periodically sent, whereas the LBMs have to be manually launched by the operator.

Fault isolation, achieved through the use of linktrace messages (LTMs) and linktrace reply (LTR) messages, also provided by the management plane. The network manager may configure a device to initiate an LTM toward an end node. In this case, each intermediate device along the source-destination path must reply with an LTR back to the source. This allows the network operator to detect the exact faulty link. In a nutshell, the LBM/LBRs are like ICMP pings, while the LTM/LTRs act as traceroutes at the Ethernet layer.

PERFORMANCE MONITORING

The ITU-T Y.1731 standard complements the fault management procedures defined in IEEE 802.1ag with extra performance monitoring features. Essentially, the network manager may

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decide to use the ETH-LM and ETH-DM fields inside the CCM frame to collect information regarding loss measurements (ETH-LM) or delay and delay variation information (ETH-DM). These two counters allow the network management plane to trigger alarms to the network operator when certain thresholds are exceeded.

These counters can be used to estimate useful metrics for the network operator such as frame loss ratio (FLR), frame delay (FD), and frame delay variation (FDV). This information is particularly valuable in real-time services since these require strict service level agreements (SLAs).

To conclude, Ethernet offers a comprehensive set of OAM tools with enhanced troubleshooting capabilities when combined with optical tests. The next section introduces the integrated troubleshooting box (ITB), which combines both approaches and further shows its applicability with a number of realistic use cases.

THE INTEGRATED TROUBLESHOOTING BOX

The ITB is a software module that brings together optical and link-layer troubleshooting. Figure 6 overviews the architecture of the ITB interoperating with the OLT and a tunable OTDR, and their interfaces. As shown, both OLT and OTDR support command line interfaces (CLIs) for third party provisioning by the ITB, although other typical interfaces such as NETCONF could be supported. In addition, the OLT exports alarms through Simple Network Management Protocol (SNMP), while the OTDR uses Secured FTP (STFP) to send its traces to the ITB.

In a real scenario, the OTDR should be properly connected to the WDM-PON for in-service measurements; that is, the OTDR signal must not be affected by users' traffic carried in other wavelengths. The following set of requirements are necessary for such in-service tests:

• Permanent low loss optical tap to be inserted into each line card for connecting the OTDR (point A in Fig. 6).
• A single tunable OTDR to be coupled to all line cards with an optical switch (point B). This way, the OTDR may take measurements in all line cards, but not simultaneously.
• A low pass filter (LPF) between the OTDR and the optical switch (point C) that isolates the OTDR from stray light.
• Disable the L-Band laser on the OLT line card associated with the channel under inspection.
• The OTDR must be able to be tuned on the L-Band (downstream band) for fiber testing.

The software module at the ITB runs the following algorithm (Fig. 7): Upon reception of one or many alarms, the OLT forwards these events to the ITB via SNMP. With this information, the ITB's first task is to determine whether or not the problem comes from the PON's feeder fiber or one of its branches. In the former case, the next action is to launch the OTDR measurement to effectively locate the failure position. In the
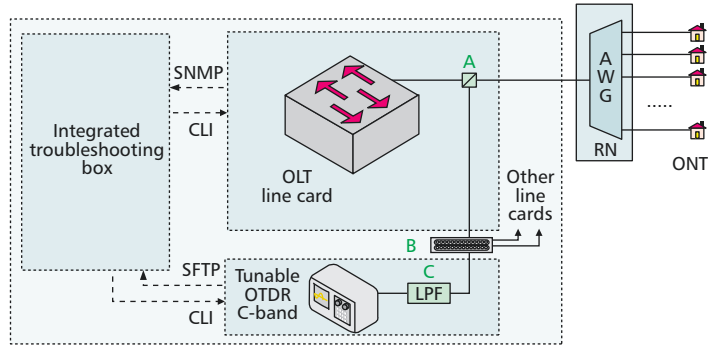

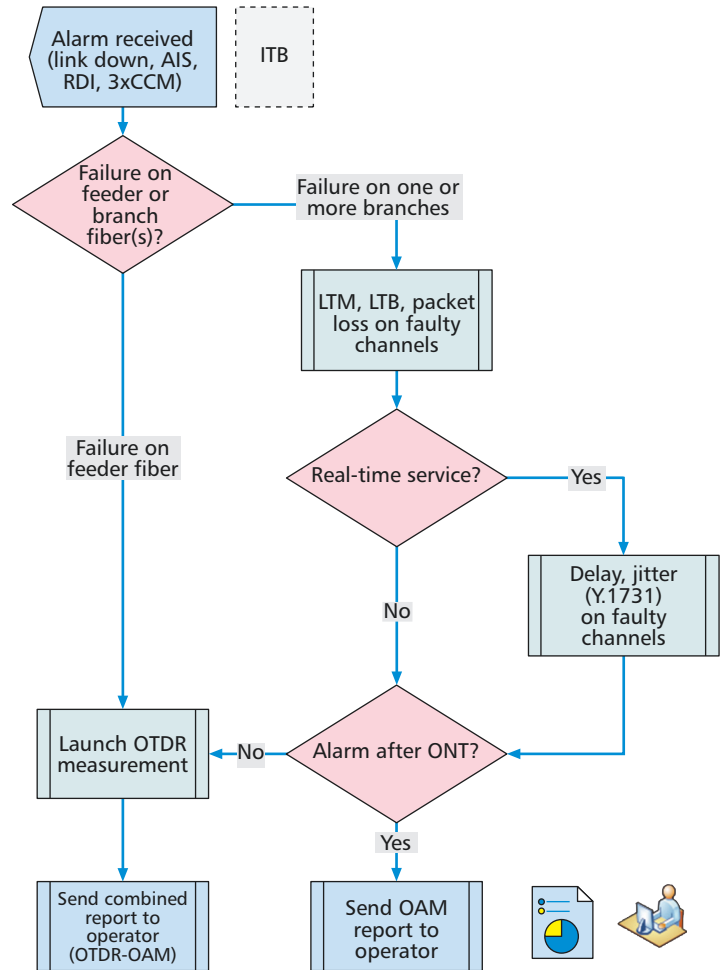**Figure 6.** *Integrated troubleshooting box and connectivity details.*

Figure 7. *The troubleshooting algorithm running on the ITB.*

latter case, the algorithm must combine Ethernet OAM measurements with the OTDR to identify and isolate the failure. Results of those tests are sent to the ITB using SNMP (OAM measurements from OLT) or SFTP (OTDR traces) and received by the operator. This information is of key importance for the operator to properly diagnose the failure.

As shown in Fig. 7, the troubleshooting algorithm starts with an alarm received from the

Essentially, the Ethernet OAM makes it possible to quickly identify either network failures or performance degradation, while the OTDR can further investigate the exact failure location at the physical level with a very fine resolution.
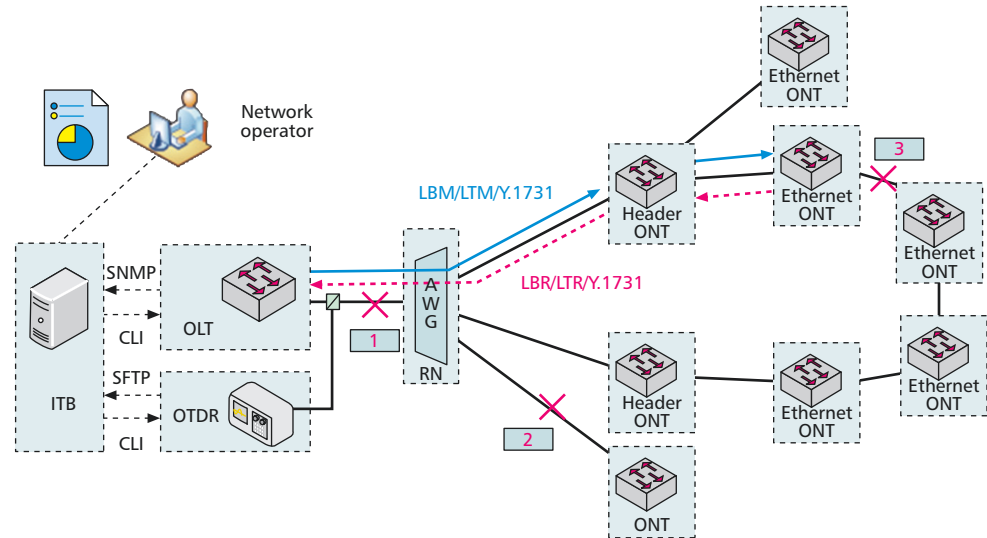
Figure 8. *Use cases 1, 2, and 3.*

OLT. There are many types of alarms and events, some of them are more important than others. For instance, an alarm related to OLT misconfiguration should be ignored by the ITB since it is not related to network failures, whereas an alarm associated with signal loss on a specific wavelength is particularly important. In this case, the following set of alarms should be considered by the ITB to initiate the troubleshooting procedure of Fig. 7: link down, AIS of 802.1ag, remote defect indication (RDI), or three missing CCMs on any wavelength. In addition, those events resulting from exceeding performance thresholds, such as bit error rate, delay, or jitter indications, should have been configured in advance by the network operator according to a specific SLA in order to be treated by the ITB.

The next section further explores the operation of the ITB in detail with a generic WDM-PON topology where two ONTs are connected in an Ethernet ring beyond the PON tree (Fig. 8). This configuration allows end-to-end Ethernet OAM tests across multiple ONTs.

USE CASE 1:
A FAILURE IN THE FEEDER FIBER

This first case (failure 1 in Fig. 8) considers a severe fiber problem in the feeder, namely fiber break or strong bending. In this case, the ITB is expected to receive several alarms involving all channels or most of them. The ITB infers from the multiple alarms that the problem affects the feeder fiber, so the next action is to find the exact failure location using the OTDR, as noted from Fig. 7. No Ethernet OAM measurement is needed since the failure is likely related to a physical issue.

USE CASE 2:
SINGLE FAILURE IN A FIBER BRANCH

In this case (failure 2 in Fig. 8), the ITB would receive a single alarm coming from a faulty channel. At this point, the ITB needs to decide whether or not this failure is after the ONT. For

this reason, the ITB must next launch LBM/LTM measurements on the faulty channel. In this case, no reply is received from the ONT, so the ITB understands that the failure is affecting a fiber branch of the PON. The final step is to launch the OTDR to identify the exact failure location inside the fiber branch.

In addition, the ITU-T Y.1731 performance measurements (jitter, delay) are encouraged if real-time services traverse this particular fiber branch.

USE CASE N3:
SINGLE FAILURE AFTER THE ONT

In this case, we consider a failure after the ONT (failure 3 in Fig. 8). The ITB behaves similarly as in case 2, except that the ONT would reply to the LBM/LTM measurements, hence diagnosing a problem after the ONT. Furthermore, thanks to the end-to-end nature of LTMs, the network operator is capable of isolating the exact failing link, since LBMs do not provide this information. Clearly, the OTDR does not need to be launched since it cannot traverse active elements. This troubleshooting use case finishes with an OAM report submitted to the network operator detailing the actual link failure.

SUMMARY, DISCUSSION AND FUTURE WORK

This article has shown the benefits of combining the recently standardized OAM features of carrier-grade Ethernet (IEEE 802.1ag and ITU-T Y.1731) together with current state-of-the-art OTDR equipment for effective troubleshooting of WDM-PON networks. Essentially, the Ethernet OAM makes it possible to quickly identify either network failures or performance degradation, while the OTDR can further investigate the exact failure location at the physical level at very fine resolution.

This article proposes an algorithm to bring

together these two historically-separated worlds, Ethernet OAM and physical measurements, into an integrated and effective troubleshooting tool to ease management of WDM-PON networks. This algorithm is capable of diagnosing different failure situations in a WDM-PON setup, including failures in the feeder fiber, one of its branches, or even after the ONT.

One of the main drawbacks of the proposed solution is related to the cost of the tunable OTDR and its associated filters required for in-service operations. Nevertheless, it is worth noticing that OTDR equipment is shared among a number of OLT line cards, each serving up to 32 ONTs in current deployments, but may reach 128 ONTs [7] and beyond in the near future. Hence, the total cost of the integrated solution would be shared among $N \times 128$ ONTs, where N refers to the number of OLT line cards per chassis, at present ranging between 8 and 16.

Concerning future work, the recently proposed software-defined networking (SDN) paradigm may be very well suited for a real implementation of the ITB [8]. SDN is a new paradigm where the control plane (in particular forwarding decisions and learning) is decoupled from the data plane. The research community has nade great progress toward the standardization of a unified management plane. For example, the Open Networking Foundation (ONF) has proposed a new protocol, called OF-Config [9], that defines a number of XML schemas for device management. In this light, future work will try to implement OF-Config as part of the ITB. An interesting research direction may also be to use these protocols instead of CLI to configure the OLT and the OTDR.

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ACKNOWLEDGMENTS

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BIOGRAPHIES

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