Energy Efficiency and Cost Optimization of OTDR Supervision Systems for Monitoring Optical Fiber Infrastructures

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***Abstract*—A new optical fiber supervision architecture based on Multi-Wavelength Optical Time Domain Reflectometer (OTDR) and hybrid active/passive fiber-optic cross-connect system (FOCS) using Wavelength Division Multiplexing (WDM) multiplexer-demultiplexers is reported. The results of our study show that up to 60% cost reduction and 50% energy savings can be obtained using a 4 wavelengths OTDR-based supervision system. Experimental validation of the architecture is also reported.**

Keywords-Optical Time Domain Reflectometer (OTDR); Wavelength Division Multiplexing (WDM); optical fiber, optical supervision.

I. Introduction

In today's Passive Optical Network (PON) systems, the physical infrastructure is not entirely visible to the Network Management System (NMS). As a direct consequence, a physical failure is not detected before creating service outage in upper layers, which in turn may lead to tremendous loss in business for the operators. These arguments have been gaining importance as the warranty on the quality of the infrastructure becomes a deciding factor in the strongly competitive market place [1]. The aim of preventive maintenance is to detect any kind of deterioration in the network that can cause suspended services and to localize these faults in order to avoid specially trained people deployed with dedicated and often expensive equipments, which increases operation-and-maintenance expenses (OPEX).

PON infrastructure does not only suffer from accidental damages and environmental effects (e.g. water penetration in splice closures) but are also subject to a lot of changes after the network is installed and activated. As an example, the optical access network may not be initially fully loaded; subscribers would be turned up, possibly over an extended period of time [2]. Hence, network operators should continuously be aware if a change noticed by its monitoring system is service oriented or indeed a fault. So, the existing maintenance methods in PONs [3] need to be updated.

The most common maintenance tool employed for troubleshooting in long-haul, point-to-point fiber optic links is an Optical Time Domain Reflectometer (OTDR).

OTDR measurements can also be applied to PON systems, and there are three main approaches for doing that:

- Using dark fibers accompanying the feeder fibers of PONs, physically bypassing the first level of splitting up to the second level splitting. The efficiency of this approach relies on the gathering of information from active elements [4] and the fact that PON fibers can probabilistically share a high percentage of the same fiber cable infrastructure.
- Performing in-line measurements inside each PON fiber infrastructure by multiplexing an OTDR signal inside each PON feeder fiber at the Central Office, using Wavelength Division Multiplexers. In this approach, the OTDR signal is generated by an external optical source at a different wavelength than data signals.
- Performing in-line measurements inside each PON fiber infrastructure by generating the OTDR signal inside the PON transceiver at the OLT.

The management of the optical layer in PON systems is being standardized in [5].

The in-line measurements using the integrated OTDR signal inside the PON data transceiver is a challenging approach [6] whose implementation depends on the transceiver implementation and the physical media dependant layer of a particular PON technology. Even though GPON and EPON standards are completely closed, and XG-PON1 is on its way, no commercial product has appeared up to now for those systems; the technological uncertainty of XG-PON2 and NG-PON2 makes even more difficult the commercial adoption of this approach for PON supervision in a massive way.

On the other hand, external OTDR approaches, either using dark fibers or by multiplexing the OTDR signal inside the PON feeder fibers by using WDMs is an already commercially available tool.

Central Offices (CO) with PON technologies can typically cover between 10 to 50 thousand homes passed (HP), and even higher in Long-Reach PON scenarios [7]. For a splitting ratio of 1:64, this means that there would be required up to 800 PON interfaces from a single CO. Additional fibers used for metro and core systems must also be considered.

In order to share the cost of OTDR measurement equipment between all these PON interfaces, fiber switches are typically used, thus launching the OTDR pulses on a selected fiber at a certain time either in a periodic way (preventive measurement) or on demand (after a detected

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alarm), switching to other fibers when required. Fiber Optic Cross-Connected Systems (FOCS) are used to address this need.

The most suitable optical fiber switching technologies for FOCS implementations are Micro-Electro-Mechanical (MEM) switches [8] and opto-mechanical switches [9], being both types active elements which require power supply for operating.

The OTDR implementation inside PON transceivers is a very interesting proposal, but suffers from a high uncertainty due to both technological challenges and slow standardization advances, thus being difficult to have a commercial solution and massive deployment able to address the current and mid-term supervision requirements of FTTx network operators.

Regarding the existing external OTDR approaches,

- they lack of efficient scalability as more fibers are deployed requiring to be monitored as FTTx services become to be massively deployed. As new FTTx feeder fibers are deployed smoothly, a large number of active switches are required increasing the power consumption of the system.
- they require a high number of fibers or electrical supply points to be installed in order to increase the number of test ports of a OTDR supervision system. If a new active switch is installed close to fibers under test, a new electrical supply is required. If the same active switch is installed close to an already available electrical supply, longer fiber links are required to deliver the test signal to the fibers to be monitored.
- they have the risk of blocking a fiber connection in case of power supply failure at a certain switching stage of the fiber-optic cross-connects.

In this paper, we propose a new approach for optical fiber infrastructure supervision from Central Offices, using Tunable/Multiple-Wavelength OTDR and Wavelength Division Multiplexing (WDM) techniques, see Fig. 1, by employing hybrid switching elements which combine active and passive elements, see Fig. 2.

II. Proposed Multi-Wavelength OTDR Supervision System

Instead of having a single wavelength operating OTDR, we propose to use N different wavelengths and WDM passives in the FOCS. By tuning the OTDR wavelength, the WDM passives combined with optical switches will deliver the test signal to the desired fiber under test, which may be part of the PON, metro and/or long haul fiber transmission operator infrastructures.

The proposed solution relies on two key factors:

- OTDR wavelength tunability. The OTDR pulses can be launched at different wavelengths, all of them within the legacy waveband already established for fiber monitoring. In the case of in-line monitoring, this can be the U-band (1625-1675nm) for access systems [10], and any available channel of the employed wavelength grid in WDM metro/core systems. Dark fiber supervision can be performed using arbitrary wavelengths.
- Wavelength multiplexer-demultiplexer filters at some stage/s of the FOCS. The OTDR pulses are delivered to a selected fiber in a passive and inherent way depending on the wavelength of the OTDR. At certain parts of the optical fiber switching system, wavelength demultiplexing of OTDR signals is used as a fiber selection mechanism, instead of mechanically moving input fiber to a desired fiber output or using MEM switches.

A. *Supervision NMS operation*

The Supervision NMS communicates with the local management system in the CO for monitoring the M fibers of the system. The local management system is a local subsystem performing as interface for the NMS to obtain measurements on specific fibers, thus configuring the OTDR as well as all the switches in all the stages to prepare an optical path for delivering the test signal to a specific fiber to test. The local management should link the inventory information to the physical interconnections of the fiber ports of the different switching stages between them, and with the M fibers under test.

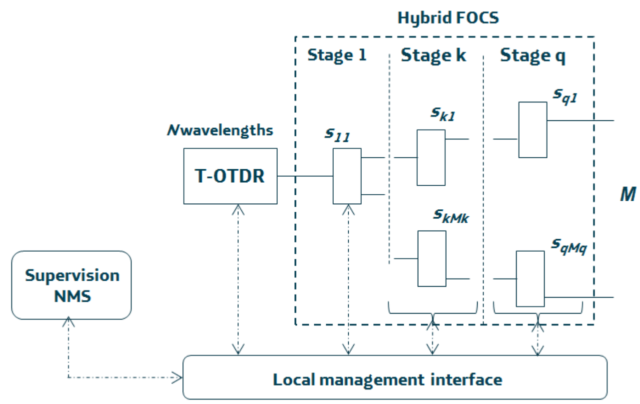

Figure 1. Proposed hybrid Fiber Optic Cross-Connect System (FOCS) for OTDR fiber supervision. T-OTDR: Tunable Optical Time Domain Reflectometer.

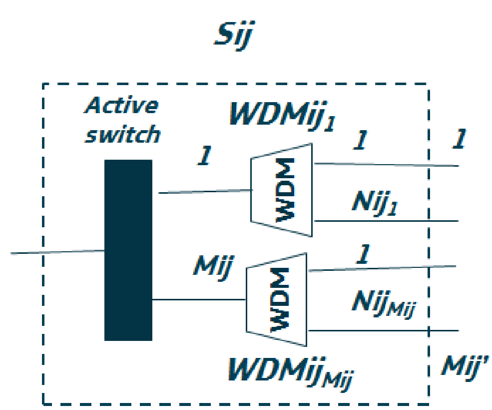

Figure 2. Generic architecture of the proposed hybrid switching element sij.

B. Switching elements description

We propose a hybrid switch element sij design, reducing the active switching components and/or using optical wavelength multiplexer-demultiplexers WDMijk, see Fig. 2.

At each of the Mij ports of the active switch, a 1xNijk WDM (k=1...Mij) passive is used. The number of output ports of sij is:

$$Mij' = \sum Nijk\ (k=1...Mij). \quad (1)$$

This configuration allows two relevant advantages:

- FOCS WDM passive scalability: An increased number of ports (Mij>Mij) can be achieved in a passive and cost-effective way by increasing each sij output port of an active switch with Nijk ports (Nijk $\geqslant$1).
- Reduced active components in switching elements sij. In case that an increase in the number of output ports is not desired for a particular FOCS design, it is possible to reduce the value of Mij and use WDM filters to keep the total number of desired outputs. This allows a reduction in the cost and energy consumption of the switching elements in the FOCS.

The proposed hybrid switching elements can also be implemented in a totally passive way (without active switch). In that particular case, an active switch is completely replaced by a passive wavelength multiplexer-demultiplexer.

Fiber selectors sij can either replace a design with less active elements while keeping the same number of fiber outputs (M) for system cost and power consumption reduction, or they can increase the number of output fibers in a cost effective way using the WDM scalability approach of the invention without increasing the power consumption.

The WDM filters may slightly increase the insertion loss of the OTDR signal through the FOCS with regards to active switches, see Tab. 1. Nevertheless this should not be considered a restriction in most cases, as the loss of dynamic range of OTDR will not be very significant compared with the total range (~40dB) or could be compensated with an increased measurement time (more averaging) or wider test pulses.

TABLE I. TYPICAL INSERTION LOSSES IN COARSE WDM (C-BAND) WITHOUT CONNECTORS

#channels	Active switches	Thin Film Filters (TFF) WDM
2	0.5-1.5	1.4-1.8
4	0.6-1.7	1,6-2.0
8	0.6-1.7	1.8-2.5
16	0.6-1.7	3.8-4.5
32	0.6-1.7	4.8-5.5
40	0.6-2.3	5.2-6.0

III. CAPITAL EXPENDITURE (CAPEX) AND POWER EFFICIENCY ANALYSIS OF A 4 WAVELENGTHS OTDR AND FOCS DESIGN

In this section, a conventional FOCS implementation using a single wavelength OTDR and active switches is compared with the proposed alternative approach using a 4 wavelength OTDR (N=4) and 1x4 ports multiplexers/demultiplexers (Nijk=4) design example, see Fig. 3.

The comparative analysis has been performed for different number of fibers under test (16 to 1024). For each number of test fibers, the proposed FOCS uses an active switch with a 4 times lower number of outputs that in a conventional system, and adds ports in groups of 4 by cascading 1x4 WDMs. In the case of GPON and EPON deployments, the proposed approach can be deployed as any already available PON supervision solution with external OTDR, using commercial triplexers in the Central Office, which combine optical data and OTDR signals.

TABLE II. COST AND POWER MODEL PARAMETERS

Element	Cost (a.u.)	Power Cons. (W)
1-wavelenth OTDR	1.00	40
4-wavelengths OTDR	2.09	40
Active switch 1x4	0.82	0.6
Active switch 1x8	1.12	0.6
Active switch 1x32	3.21	2.8
Active switch 1x64	5.22	5.8
4-channels Mux/Demux	0.04	0.0

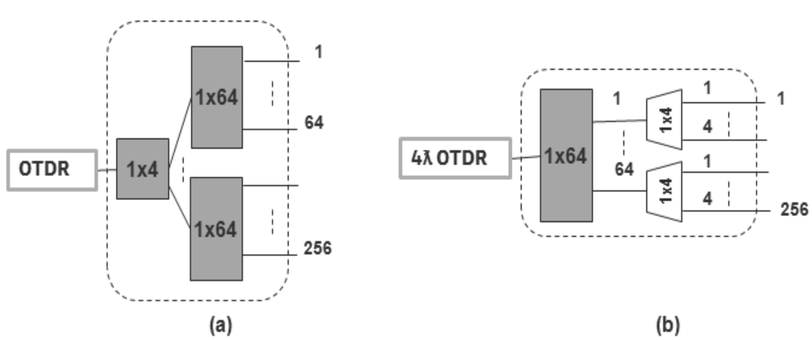

Figure 3. Centralized OTDR supervision system (a) with active FOCS and (b) proposed system with hybrid FOCS (4 wavelengths) for 256 supervision fibers.

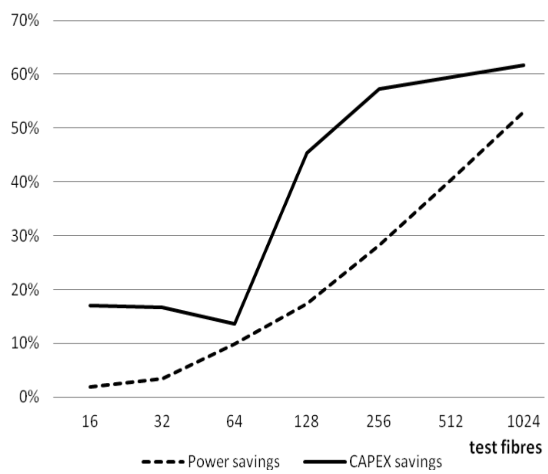

Figure 4. Savings (%) of proposed system versus number of test fibers with regards to a single wavelength supervision system.

Table II shows the values of the parameters used in the cost and power model employed for the cost and energy efficiency analysis. Due to the high cost of active switches with regards to passive Mux/Demuxes, reducing by 4 times the number of ports allows to significantly reduce the total cost, even adding a large number of Mux/Demux components. The use of passive components for fiber switching also achieves a relevant power consumption reduction.

As shown in Fig. 4 (dashed line), the proposed 4 wavelengths system can save up to 50% of power consumption of a conventional FOCS with a single-wavelength OTDR. For a number of test fibers smaller or equal than 64, the CAPEX savings keep below 20% due to the impact of the high cost of the OTDR with regards to the total system CAPEX. For a number of test fibers higher that 64, the proposed WDM FOCS with Multiple-Wavelength OTDR can save more than 20% and up to 62% of the total system CAPEX.

The penalty of the OTDR dynamic range is typically reduced around 1.0 dB, which is a very low value compared with the total dynamic range (~41dB) of the considered OTDR modules.

IV. EXPERIMENTAL VALIDATION

In order to experimentally validate the principle of concept of the proposed Multi-Wavelength OTDR supervision system, a laboratory setup has been prepared emulating a Central Office monitoring four Single Mode Fiber (SFM 10/125μm) coils, whose lengths are 10027m (L1), 19850m (L2), 24330m (L3) and 40216m (L4).

The Multi-Wavelength OTDR system has been implemented using a CWDM OTDR module with $\lambda 1$=1551nm, $\lambda 2$=1571nm, $\lambda 3$=1591nm and $\lambda 4$=1611nm selectable nominal center wavelengths for measurements.

A Coarse WDM TFF multiplexer-demultiplexer operating in the same four CWDM channels of the OTDR module was employed as a totally passive fiber switch (s11, M11=1, N111=4, see Fig. 2). All fiber connectors were SC/APC type. Maximum insertion loss of the CWDM TFF mux/demux is 2.0 dB according to its specifications datasheet.

In the management system database, the supervision wavelengths $\lambda 1$, $\lambda 2$, $\lambda 3$, $\lambda 4$ are assigned to fibers L1, L2, L3 and L4, respectively, by connecting the corresponding ports of the CWDM TFF multiplexer-demultiplexer to each fiber.

TABLE III. MEASURED TRANSMISSION LOSSES OF A 4 CHANNELS CWDM MUX/DEMUX TFF

Wavelength (nm)	Measured Transmission Loss (dB)
1551	0.67
1571	0.67
1591	1.45
1611	1.38

Successful measurements using 100ns pulses and 30s of acquisition time were obtained using the novel Multi-Wavelength OTDR supervision architecture. Clear traces with 0.18dB/km propagation loss were obtained, see Fig. 6.

For L1 and L2, the end of fibers was measured at around 10 km and 20 km, as expected.

At L3 and L4, high connection losses of 7.7 dB and 3.8 dB were detected at 20km from the Central Office. These losses generally appear when dirty connections appear at intermediate Central Offices along an optical path. End of fibers L3 and L4 were also clearly detected at around 24.3 and 40.2 km from the Central Office, as expected.

In order to evaluate the loss of dynamic range in the OTDR due to the transmission loss of the 4-channel CWDM multiplexer-demultiplexer, an alternative setup using a 20 km fiber coil connected to the OTDR module, followed by the CWDM multiplexer-demultiplexer and a cascaded 20km fiber coil at each output port was employed.

The obtained traces are shown in Fig. 5, where the connection losses at 20km correspond to the transmission loss of the 4-channel WDM multiplexer-demultiplexer.

The transmission losses are shown in Table III with values close to typical specifications and well below the maximum loss of 2 dB of the CWDM TFF mux/demux. The reduction of less than 1.5 dB of the OTDR dynamic range is negligible with regards to an obtained range of around 20 dB in the measurements, even with only 30 seconds of acquisition time, and being 41 dB the maximum dynamic range of the CWDM OTDR module.

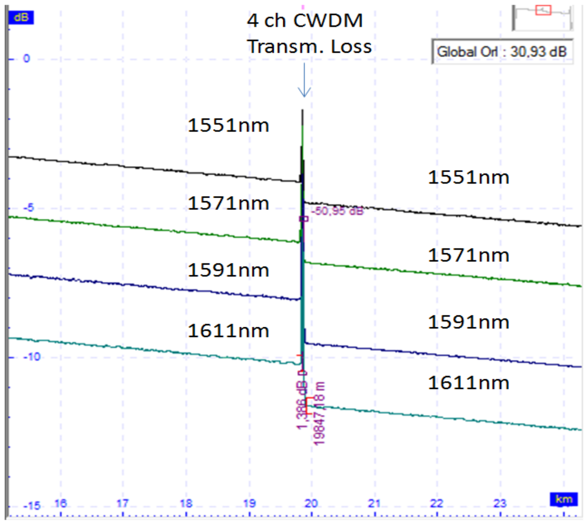

Figure 5. Measurement of transmission loss of the 4channels CWDM.

V. SUMMARY AND CONCLUSIONS

A new reflectometric system and FOCS approach has been presented for physical layer supervision of fiber optic infrastructures from the Central Offices, with high potential for CAPEX savings and energy efficiency.

It is based on the use of Tunable or Multi-Wavelength OTDR measurement equipment and WDM components used as passive fiber switches. By selecting the operating wavelength of the OTDR, the test signal can be delivered to a desired fiber under test of the network operator fiber infrastructure.

Compared to external OTDR solutions with a single wavelength, already available in the market, the proposed approach keeps the same architecture and maintenance processes than the existing products, being the additional feature a selectable OTDR operating wavelength assigned to different test ports in an automatic way.

The proposed approach enhances energy and cost efficiency of fiber infrastructure supervision systems, what can be especially interesting in the case of massive PON deployments with in-line reflectometry for physical layer supervision, which have a high number of fiber under test (>64). In the case of in-line OTDR PON supervision, the standard waveband is the U-band [10], so U-band passive components and U-band Multi-Wavelength or Tunable OTDRs should be used. The U-band is specified for monitoring purposes when communication wavelength band extends up to the L-band, thus the proposed approach is compatible not only with GPON and EPON, but even with emerging XG-PON deployments and, in the future, with NGPON2 systems and beyond.

In the case of using reserved dark fibers attached to PON fiber infrastructure for supervision, there is no restriction in the waveband.

For a number of channels of the WDM mux-demuxes higher than 16, the insertion losses of the OTDR test signal may be increased more than 3 dB with regards to a totally active fiber switching approach, so it is recommended a design of the hybrid FOCS employing filters with a lower number of output ports, unless the reduction of the dynamic range can be afforded by the monitoring system.

The overall power consumption of the system is reduced because the FOCS is partially implemented in a passive way. Switching cost is also reduced because a lower number of active elements is required.

The system advantages increase with the number of fibers under test. The most suitable use case is a massive PON deployment with in-line external OTDR supervision, but the proposed system is also applicable to any supervision system using dark fiber or metro-core systems with vacant channels.

In a PON scenario with 10 million Homes Passed and 256 ports FOCS (610 Central Offices), it is estimated that a 4 wavelength OTDR plus a hybrid FOCS system can save several tenths M€ of CAPEX.

From the energy efficiency perspective, energy savings are in the range of 100 MWh/year in the same deployment scenario.

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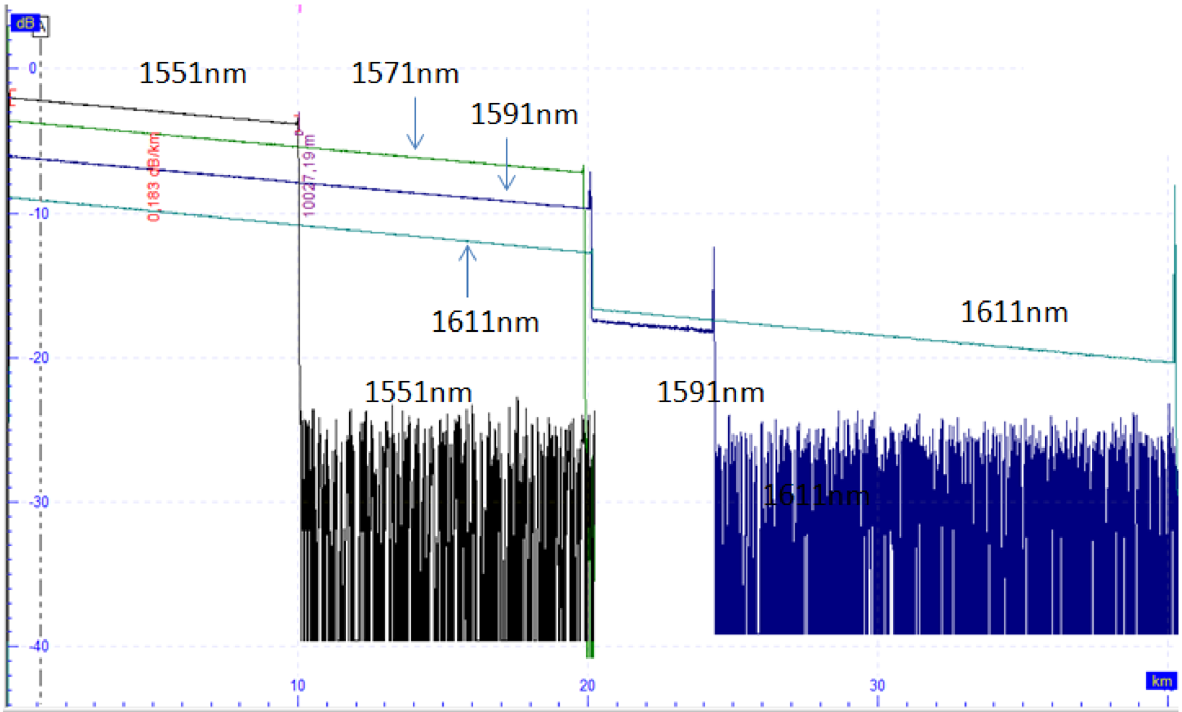

Figure 6. Traces corresponding to the four supervision fibers obtained from the CO with the Multi-Wavelength OTDR and the CWDM passive mux/demux as FOCS.