

Physical Layer Monitoring Techniques for TDM-Passive Optical Networks: A Survey

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Abstract— In order to enable new services that require high data rates over longer distances, the optical fiber substitutes the copper cable step by step in the access network area. Time division multiplexed-Passive optical network (TDM-PON) is a fast emerging architecture that uses only passive components between the customer and the central office. PON operators need a monitoring system for the physical layer to guarantee high service quality. This monitoring system is necessary during the fiber installation, final network installation testing, regular operation of the network, and for fault localization. First, in this paper, we present the motivations, requirements and challenges of TDM-PON monitoring. Second, we make an exhaustive review of the monitoring techniques and systems for TDM-PON, mostly proposed within the last five years. In our survey we include the approaches already available in the market even with limited performance and those still in research. Third, we make a detailed classification of all these approaches and qualitatively compare characteristics in a list of performance parameters and aspects. Finally, we outline open issues and future research perspectives in physical layer PON monitoring that may target higher performance, lower cost, or scalability to next generation PON architectures. This includes wavelength division multiplexing (WDM), TDM over WDM or long-reach PONs intended to extend the reach from 20 up to 100 km distances and beyond.

Index Terms—PON, FTTH, physical layer, fault detection, fault location, monitoring, OTDR, next generation access.

I. INTRODUCTION

Passive optical networks (PONs) are the most emerging class of fiber access systems in the world today. PON based Fiber-to-the-Home (FTTH) systems are progressively becoming reality while commercial deployments are reported worldwide [1], [2]. FTTH is a network technology that has been recognized as the ultimate solution for providing various communication and multimedia services. This deploys optical fiber cable directly to the home or business to deliver triple-play services, high speed internet access, digital cable television, online gaming, etc. [3]. This worldwide acceleration is largely due to both, the considerable decrease in capital expenditure (CapEx) of introducing FTTH connectivity, and its “future proof” nature in meeting ever

increasing user bandwidth requirements [4]. For instance, in February 2010, Google announced the plans to build an experimental Gbps FTTH network to households in North America for testing out new concepts in technologies and applications. Worldwide, FTTH/B (where B stands for building) subscribers attained 44 million at the end of June 2010 out of 121.4 million home already passed, according to a study by IDATE [5].

The time division multiplexing PON (TDM-PON), one among several architectures that can be used in FTTH networks, is widely chosen by operators and it is expected that the next generation 10Gbit TDM-PON will be the most promising system among several technologies [6]. According to *Alcatel-Lucent* [7], TDM PON bandwidth supply is growing faster than subscriber bandwidth demand. TDM-PON will deliver future ultra-high speed services far more efficiently than WDM-PON for years to come. Such architecture decreases the operational expenditure (OpEx) because there are no electronic components that are more prone to failure in the PON outside plant. Hence, there is no need for the operators to provide and monitor electrical power or maintain back-up batteries in the field. Important FTTH deployments have been carried out in North America, Europe, and Japan over the last decade. Starting from 1:1 (one fiber to one customer) in the early 1990s, passive splitter/combiner (PSC) together with TDM technologies have enabled up to 1:128 for the GPON standard (ITU-T G. 984.1) with forward error correction (FEC). In [8], the authors report a testbed with 1:256 PSC, and future extra large XL-PON systems are aimed at splitting factor of up to 1024 [9].

PON technologies are advancing to increase the data rate to 10 Gbps in parallel with increasing the number of customers to 128 and more. This huge amount of information carried by the PON needs a practical, cost-effective surveillance and management system which is a key factor to continue developing these networks. The International Standards Organization (ISO) categorized the network management (monitoring) functions into five generic categories: performance, configuration, accounting, fault, and security management [10]. In this paper, we discuss only fault management that occurs in the physical layer.

Long haul and metro networks use monitoring functions to test the operational status of point-to-point links (P2P). In contrast, a new challenge has been appeared in PON networks. The network now becomes a point-to-multipoint (P2MP) with passive optical splitter placed in the field. This network architecture introduces a new challenge for network testing

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which requires enhanced test and measurement techniques. In addition, these techniques must be capable of measuring the performance of a single bidirectional fiber link that carries three wavelengths simultaneously [10]. Therefore, PON physical layer fault monitoring has been receiving increasing attention in the last years where high numbers of proposals from researchers have emerged. This attention leads to the ITU-T L.66 (2007) Recommendation which standardizes the criteria for in-service maintenance of PONs. It reserves the U-band (1625–1675 nm) for maintenance and lists several methods to implement PON in-service maintenance functions.

In [11], the authors made a short review paper about physical layer monitoring focusing on optical coding techniques. They also addressed some of the challenges and requirements for monitoring PONs. In contrast, this extensive survey covers almost all the proposed or available in the market techniques to the best of our knowledge. We make very extensive comparison of all the reviewed techniques on a high number of required features and summarize them in a table to easily understand their differences and similarities. We investigate and propose some methods for integrating the physical layer monitoring techniques with the existing higher layer protocols. Furthermore, we discuss in this paper the open issues and some monitoring techniques proposed for next generation long-reach PON.

In Section II we study the TDM-PON architecture and challenges. Section III describes the importance of PON monitoring and the OTDR limits are discussed in Section IV. Section V outlines the measurements used to evaluate the monitoring systems performance. Physical layer monitoring techniques that have been proposed in the literature and those already available in the market are discussed in Section VI. Section VII describes the monitoring required features that should be adopted to satisfy the network operator and then compares the techniques discussed in VI based on these features. Section VIII investigates the higher layer protocols shortcomings to monitor PON and the possibility of integrating physical layer monitoring systems to higher layer protocols to completely monitor the PON. Open issues and research perspectives for monitoring PON are discussed in Section IX and we finally conclude in Section X.

II. TDM-PON ARCHITECTURE, OPERATION AND CHALLENGES

Fig. 1(a) shows a TDM-PON where an optical line terminal (OLT) located in the central office (CO) is connected via a PSC to multiple optical network units (ONUs) or multiple network terminals (ONTs) (one for each subscriber). The PSC located in the remote node (RN) allows a single point PON to be shared by many subscribers. Note that ONU implies a multiple subscriber-device and ONT is a special case of an ONU with a single customer. An ONU supporting FTTH has been commonly referred as ONT in ITU-T Recommendations like G.987. In this paper we use both terminologies interchangeably. The fibers between the PSCs and the ONTs on the customer site are called distribution and drop fibers

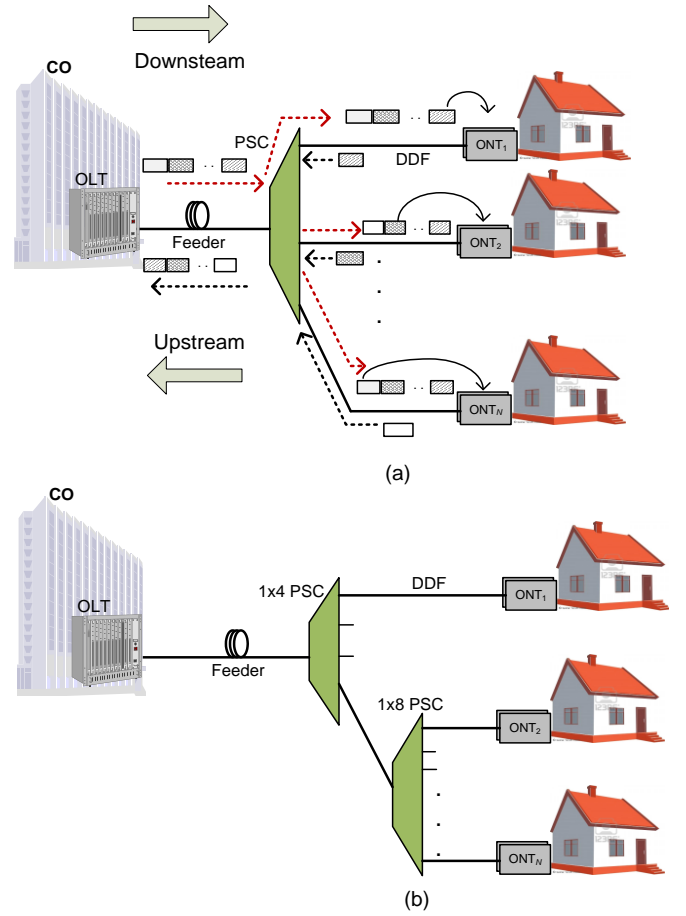


Fig. 1. TDM-PON: (a) Architecture and operation, (b) Cascaded architecture.

(DDFs).

In TDM-PON, the downstream signal is transmitted from the OLT. The later operates as a master for the network which controls the operation of the ONUs. It assigns a time slot for each ONU to upload its data and determines the amount of data to be uploaded by each ONU. When the downstream signal arrives the PSC, it splits this signal by power division to each optical branch (DDF), i.e. all ONUs receive the same downstream signal. Therefore, the downstream signal is encrypted by the OLT and each ONU can correctly decrypt only its specific data. In the upstream direction, each ONU transmits its data at a specific time slot scheduled by the OLT to avoid collision at the PSC.

There are two major standards for PON. Gigabit Ethernet PON (GEAPON) so called EPON written by IEEE as part of the Ethernet First Mile Project. EPON uses standard 802.3 Ethernet frames with symmetric 1 Gb/s upstream and downstream rates. It has 20 km span and supports 32 customers. In 2009, IEEE approved the 802.3av standard for EPON with 10 Gb/s rate. The other standard is Gigabit PON (GPON) that is written by ITU-T in its G.984 series. It has data rate up to 2.5 and 1.25/2.5 Gbps for downstream and upstream respectively. It theoretically supports 64 customers and 20 km span. GPON defines a protocol designed to support multiple services in their native formats. 10GPON is being standardized by ITU-T and FSAN for next generation of

PONs.

A PON may be designed with a single optical PSC, or it can have two or more PSCs cascaded together as shown in Fig. 1(b). Different ramifications of the PON can be done depending on the customers distribution. The splitting ratio can increase or decrease depending on the total loss budget between the OLT and the customer ONT. This budget must not exceed a certain value. The main contribution to the loss is generated by the PSC. Each 1×2^n PSC gives a power loss approximated by $3n$ dB. In the case of a PON with 32 users we have power reduction of at least 15 dB due to the PSC. Additional loss in the PON is generated by the fiber attenuation. According to ITU-T G.652, the maximum attenuation coefficients for G.652D fibers used for PONs are 0.4 and 0.3 dB/km at 1310 and 1550 nm respectively [12]. These losses limit the number of customers in the network where a threshold should be calculated from the loss budget to determine the capacity (number of customers) of the PON.

III. IMPORTANCE OF MONITORING PON

Since the TDM-PON architecture can accommodate a large number of subscribers, a fiber fault in any branch of the distribution fibers, or in the feeder, will cause the access network to be without benefit behind this fault. Any service outage in the network can be translated into financial loss in business for the service providers [13]. When a fault occurs, technicians must be dispatched to identify, locate and fix the failure. The time, labor and truck-roll for fault identification dramatically increase the OPEX and customer dissatisfaction and complaints [14].

Some service providers report that more than 80% of installed PON failures occurs within the first/last mile, i.e., within the distribution/drop segments of the network [15]. According to the cases reported to the Federal Communications Commission (FCC), more than one third of service disruptions are due to fiber-cable problems, and many of those disruptions have involved lifeline 911 services. Therefore, rapidly finding the cause of the disruption is critical for minimizing its effect [16]. The authors in [17] state that one requirement for the next NG-PON is monitoring and on demand checking of the condition of optical network independently from a PON system. It is desirable that such monitoring and checking be available regardless of the ONU is in service or even not connected. NG-PON systems would benefit from an ability to automatically and autonomously detect and locate network faults.

The optical fibers are subjected to the risk of fiber cut, break, fissure, aging, bending, etc. or fiber break caused by earthwork with excavators and other construction tools. Also bad fiber installation is a source of service disruption. Analyzing the fault sources in *Nippon Telegraph and Telephone Corporation* (NTT) company showed that wildlife like crows, squirrels and cicadas may cause damage to both underground fiber cables and aerial fiber cables [18].

All the requirements and issues mentioned above mean that the existing monitoring techniques need to be updated in

parallel to the rapid development of PONs. In addition to fault detection and localization in normal network operation, PON monitoring is also necessary during the installation with final test of the network. Monitoring the PONs reduces provisioning time, improves quality of service (QoS), attracts more customers and reduces maintenance cost.

IV. OTDR LIMITATIONS

Remote monitoring of fiber networks via standard Optical Time Domain Reflectometer (OTDR) technique is widely used in P2P technologies. OTDR is a powerful tool to characterize an optical fiber link. In addition to identifying and locating faults within a link, this instrument measures parameters such as fiber attenuation, length, optical connector, splice losses, etc. The OTDR operates fundamentally as radar. It injects a short light probing pulse to the link and measures the backward signals coming from the link under test. Fresnel reflections and Rayleigh scatterings are the source of these back signals. From these signals, the OTDR characterizes the link by computing the power versus the distance and produces a plot of trace as shown in Fig. 2. This trace can then be used to find any impairment in the link as bends, cracks, fiber misalignment, mismatch, dirty connections, etc. [10], [19].

OTDR has major limitations in tree-structured TDM-PONs, where all backward signals are added together at the RN location by the PSC, thereby making it difficult to differentiate between the branches' backward signals (see Fig. 2) [13], [20], [21]. Some leading companies in optical networks testing have manufactured physical layer monitoring products based on OTDR for PON. These companies include *NTT* [22], *Fujikura* (*FiMO* system) [23] and *JDSU* (*ONMS* system) [24]. Although these products use optical reflectors at the end of each branch to improve the OTDR detectability of faults, they still miss the capability to accurately detect and localize the faults. For example, the OTDR based monitoring system cannot differentiate between two or more branches that have the same or close fiber length. Hence, it assumes that the distribution fibers have necessarily different lengths, which is a serious problem. It is an expensive and complex requirement for the installation of FTTH networks. Even if this requirement is achieved, any repair in the network after

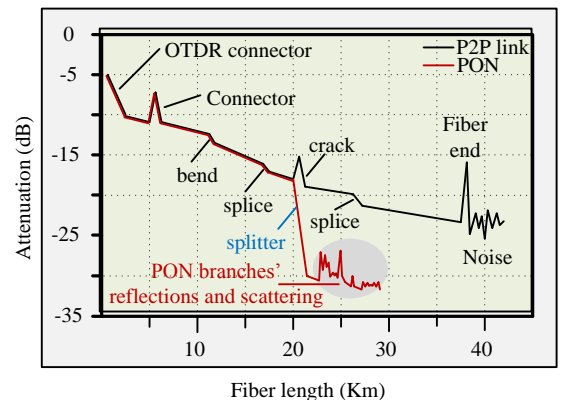


Fig. 2. Typical OTDR trace for point-to-point link and PON.

installation may induce a change in the fiber lengths, raising this problem again. Moreover, fiber lines in PONs have many connection points with only short distances between them. It requires the use of OTDR test equipment optimized for high resolution and short or zero dead zones [10]. Another consideration is that PONs contain PSC component with high insertion losses. For example, a 1x64 PSC introduces >21 dB loss in power. This increases the difficulty to detect a fault and requires high dynamic range (DR) at the OTDR. One technique to improve the DR of OTDR is to use Raman amplification [25] which is found to increase the dynamics by 16 dB but it does not solve the other problems mentioned above.

We find in the industry enhanced performance OTDRs made by different suppliers so called PON-optimized OTDRs [26]. To the best of our knowledge all of them try to increase the DR and reduce the dead zone but do not provide any solution for the aforementioned problems of detecting faults inside specific branches in the network.

V. PERFORMANCE MEASUREMENTS OF PHYSICAL LAYER MONITORING IN PON

Different measurements can be used to evaluate the performance of physical layer monitoring systems. These measurements are taken in time domain, spectral domain or both depending on the monitoring technique [19]. They include:

1. Peak power: power monitoring is the basic requirement for any monitoring system. The network management system (NMS) at the CO can determine the status of the physical layer by comparing the measured power with a reference value or threshold. Any variation in the peak power imposes damage or fault in the physical layer.
2. Average power: instead of making the measurement once, averaging is used to improve the measured signal. Any variation in this average power compared to a reference implies damage or fault in the physical layer.
3. Power spectrum: some physical layer monitoring techniques depend on measuring the power of the received identified frequencies. Monitoring the power for these frequencies determine the status of the physical layer.
4. Optical spectrum: some monitoring techniques monitor the

received wavelengths. A lost wavelength means that the specific branch is faulty or damaged.

5. Signal-to-noise ratio (SNR): measuring the SNR at the receiver is a common method to study the performance of a system.
6. Probability of false alarm (PFA): this parameter characterizes the receiver operation. An alarm is generated (false alarm) when there is no fault in the i^{th} branch but the receiver decides wrongly there is.
7. Probability of misdetection (PMD): similarly, this parameter characterizes the receiver operation. It describes the receiver probability to misdetect a fault in the network.
8. Region of Characteristics (ROCs): this is a design and performance measurement tool borrowed from radar applications, which illustrates the trade-off between the PMD, PFA and the SNR in the receiver.
9. Notification time: it determines the time required for the NMS in the CO to detect a fault in the network and notify the operator.

VI. PHYSICAL LAYER MONITORING TECHNIQUES

Many techniques have been proposed in the literature and others are available in the market for TDM-PON physical layer fault management. Each of which has its own advantages and disadvantages. Some of these techniques are already available in the market but with limited performance, and others are still under research. Research in this topic is motivated basically by both, performance of the technique and overall cost of the monitoring system. Indeed, the cost is very sensitive in access networks. Fig. 3 is a classification summarizing the different monitoring techniques. In the following, we discuss each technique showing its operation, advantages and drawbacks.

A. Single Wavelength OTDR based Techniques

(1) Upstream OTDR Measurement Technique

Many OTDR products developed to make upstream measurements from the ONU side are available in the market long time ago, e.g. FTB-7300E OTDR from EXFO Company [26] and T-BERD/MTS-4000 from JDSU Company [27]. This technique has the disadvantage of not being centralized where it may be necessary to convey a technician to the ONU side, in

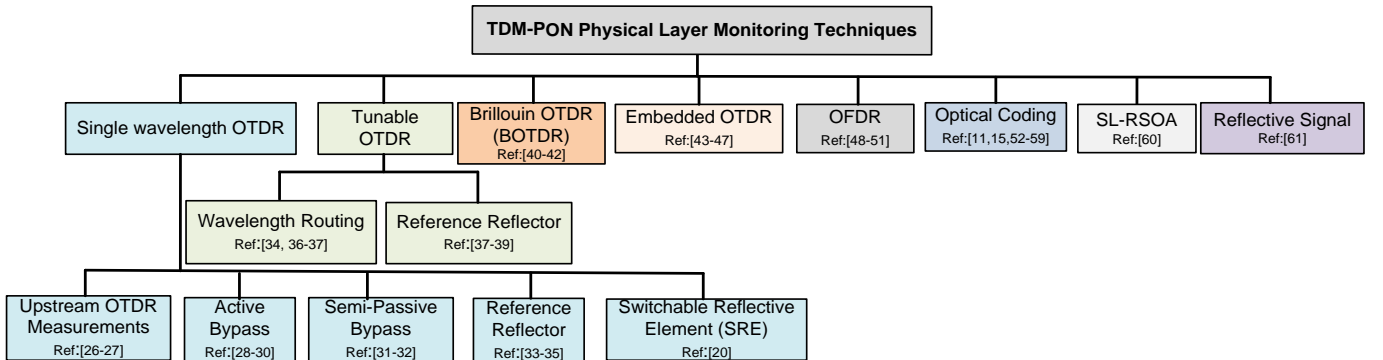


Fig. 3. TDM-PON physical layer monitoring techniques classification.

order to inject an OTDR pulse up to the CO and measure the backward light. This solution delays the maintenance and repair time of the network and increases the OpEx. Many researchers have worked on the development of centralized monitoring techniques, in order to reduce the cost induced by truck rolls and dispatching technicians in the field.

(2) Active Bypass Technique

In order to allow the analysis of the individual backscattering traces of the PON branches, active by-pass the PSC using optical selectors can be used [28]. In this technique, the optical branch under test is chosen by a control signal transmitted from the CO using copper wires in the same fiber cable. In normal operation, the monitoring signal is transmitted downstream with the data and then bypassed the PSC using WDM device as shown in Fig. 4. The backscattering from each branch is tapped (2%), monitored by a detector and transmitted to the control system. The control system compares the measured traces with a reference. When the reference and the measured trace of a specific branch dose not coincide, this means the branch is faulty. The feasibility of this technique is demonstrated for a PON using 1x16 PSC followed by 1x8 PSC (1x128 PON). The two PSCs introduce about 23 dB loss. The authors used EDFA enhanced OTDR for loss compensation.

Another approach is proposed in [29]. In this approach, the authors tap a part of the monitoring signal (1% of 1625 nm) to activate the monitoring and restoration system in the RN. This system consists of an optical switch, a microcontroller, an Ethernet module and a restoration scheme. When a fault occurs, the monitoring and restoration system in the RN will route the data signal to the protection line and sends the information to the CO using Ethernet connection. The authors in [29] and [30] reported a demonstration for this technique with 1x8 PON.

Although the techniques based on PSC-bypass can detect and localize the exact location of faults using active components at the RN, they have the drawback to require power supply in the field which is not consistent with the principle of passive optical networks. These active components are more prone to faults, hence increases operation and maintenance cost.

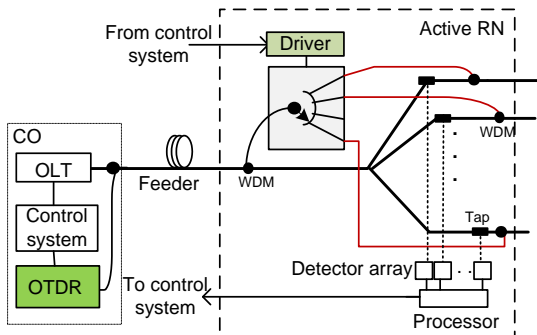


Fig. 4. Monitoring system based on active bypass.

(3) Semi-Passive Bypass Technique

Semi-passive bypass technique eliminates the need for power supply in the field. In this technique, the optical switch in the RN is powered by using high power optical signal transmitted remotely from the CO in parallel with the data and the monitoring signal through the same fiber (see Fig. 5) [31]. The optical switch selects one branch a time from the output of the PSC. The OTDR in the CO measures the backward light of the branch selected by the optical switch. These measurements are compared with a reference to determine the branch status. The authors investigated the feasibility of their technique for 1x32 PON using four monitoring ports, i.e., each set of eight branches of the PON are connected to one testing port. The results show the ability to detect a fault assuming that multiple faults cannot occur simultaneously.

This principle was enhanced in [32] in order to integrate a protection function to the monitoring system by using pair of fibers as shown in Fig. 6. The RN is assumed to be passive but a photovoltaic converter with control unit to control the operation of the switches is used. To reconfigure a specific switch, a high optical power signal with control information is transmitted from the CO to the RN. In the RN, the photovoltaic converts this optical power signal to electrical signal. Then a control unit uses this electrical signal to reconfigure the specific switch.

For preventive OTDR measurements (normal mode), the fiber branch that we want to test is selected by reconfiguring the switches both at the CO and RN. Also the 1xN switch for the OTDR is reconfigured remotely to this specific branch. In case of fiber fault (fault mode), the fault is detected both at the CO and ONT. Then the state of corresponding optical switch (SW_3) at the RN will be reconfigured remotely and simultaneously with the state of optical switch (SW_4) at the ONTs. This creates a new healthy path for the data. To find the exact fault location within this faulty branch, a path for OTDR signal is constituted by the 1xN switch to this branch. Then the NMS in the CO can find the fault location from the OTDR trace. This technique is demonstrated practically with 1x32 PSC. A Raman fiber laser is used in the CO to supply the power needed to drive the control unit and the optical switches at the RN. The restoration time when a fault occurs is found to be 680 ms.

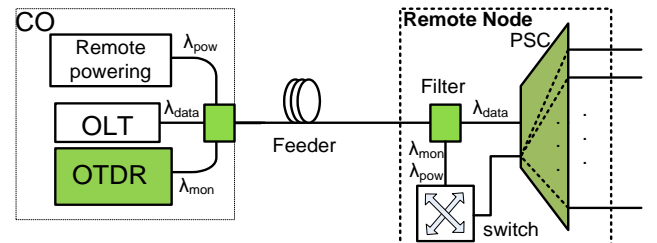


Fig. 5. Monitoring system based on semi-passive bypass.

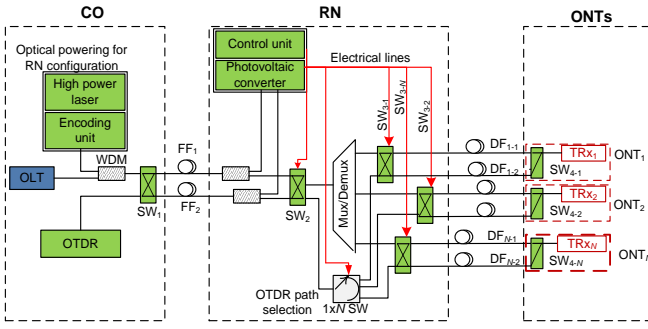


Fig. 6. Semi-passive bypass monitoring technique with protection.

Although the authors of the both proposed solutions consider their techniques as passive, we think they are not. We call them semi-passive because they use active components in the field. These are more susceptible to faults, hence increasing the OpEx. Moreover, they miss the demarcation function.

(4) Reference Reflector based Technique

Using OTDR in the CO and reflective element at the end of each branch will improve the DR of the OTDR. This allows detecting the presence and height variation of reference reflection peaks at the CO [33]. The reflectors can be implemented in different ways. For example, they can be wavelength selective reflectors inserted in the input connector at the ONU, acting as stop filters like fiber Bragg grating (FBG) which is made to reflect the OTDR wavelength in the U-band but pass all other data wavelengths with negligible insertion loss. Reflectors can also be mirrors set on a branch of a WDM device, as shown in the lower part of Fig. 7 [34].

The authors in [33] evaluated this experimentally using high resolution OTDR with less than 10 ns pulse width for 1x4 PON. The results showed that the technique can detect power peaks (branches' ends) with 31.5 dB DR. This peak detection is conditioned by using fibers that differ at least two meters in length. This requirement makes the technique inappropriate for the network operator [35]. In the inset of Fig. 7 we illustrate a typical OTDR trace with the peaks produced by the reference reflectors. The position of each peak shows the

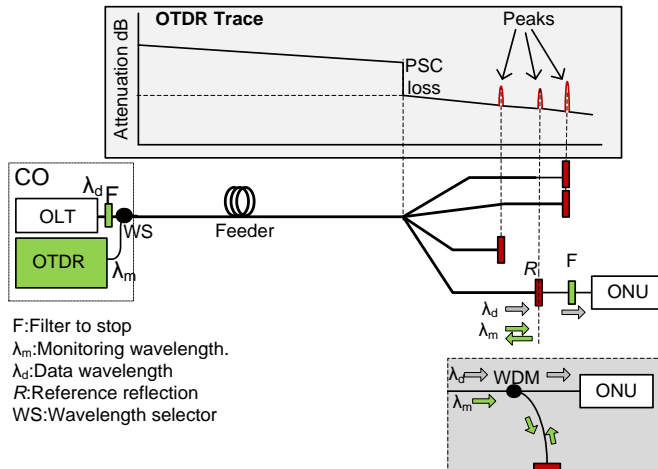


Fig. 7. Reference reflector based monitoring system.

distance of the respective ONT from the CO. It is clear that reflectors located close in distance will rise almost the same peak which confuses the network operator. Moreover, this technique cannot determine the exact fault location within the faulty branch because its specific information is mixed with those of other branches.

Although all the mentioned drawbacks of this technique, to the best of our knowledge, this technique is the one used today for PONs monitoring due to its simplicity and ease of implementation. This technique is available on the market from leading companies in optical networks testing and troubleshooting as JDSU, Fujikura and NTT.

(5) Switchable Reflective Element (SRE) based Technique

An alternative to reference reflector technique has been proposed that places a switchable reflective element (SRE) close to each ONU location, whose signature on the OTDR trace would identify the branch being monitored [20]. The SRE is colorless device which consists of an optical switch with a photodiode on one branch (non-reflective state; default state) and a mirror on the other branch (reflective state) as shown in Fig. 8. The position of the switch is controlled by the photodiode.

Each SRE is switched remotely from the CO by sending a downstream coded signal through the transmission line at 1625 nm. If the code received at the photodiode corresponds to the ONU address, the switch will be actuated and the SRE will turn to the reflective state. In the mean time, all other SREs will remain in the non-reflective position. During the monitoring, the SREs are thus successively remotely switched from the CO and consequently there is only one peak at a time on the OTDR trace.

To improve the DR of the OTDR that is highly degraded by the PSC, the authors implement Raman amplification. The pump laser wavelength is chosen so that the OTDR wavelength lies within the corresponding Raman gain bandwidth. The authors have further equipped the PON with interference filters (not shown in Fig. 8) allowing to suppress as much as possible the amount of backscattering light at the Raman laser wavelength. In [20], the authors used a pump source (Raman) and found that 870 mW was necessary to observe amplification. The setup uses 1x16 PON and an increase in the dynamic range after the PSC by 16 dB was observed. The authors showed that their technique can detect

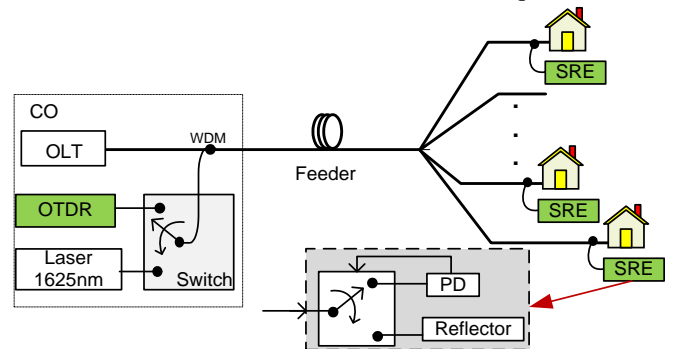


Fig. 8. PON monitoring based on switchable reflective element (SRE).

even faults with low power thanks to amplification.

Although this approach detects any faulty branch, it uses expensive optical switch with a photodiode at each branch end. In addition using active components in the field is contradictory with the passive network principle. Moreover, these active components are more prone to faults than passive components, hence increasing the network cost. Also this technique cannot localize a fault in a specific branch because the fault information is mixed with others coming from the other branches.

B. Tunable OTDR based Monitoring Techniques

Several techniques have been proposed in the past to monitor TDM-PON using tunable OTDR located at the CO, but these solutions have the common disadvantage of exploiting tunable laser or tunable filter at the CO that is used to be very expensive.

(1) Wavelength Routing based Monitoring Technique

In this monitoring scheme shown in Fig. 9, a different wavelength in the maintenance band is assigned to each branch of the optical network by a WDM device, located beside the PSC in the RN. Using a tunable OTDR is thus possible to observe the backscattering traces of the individual branches. This method is described in a 1994 patent [36] and demonstrated in [37]. The key component is the routing WDM which could be implemented in an integrated optic module including the PON PSC [34]. The authors in [37] carried out a field trial for this technique with 1x8 ATM-PON. Their results showed the ability of this technique to detect even minor faults in the fiber such as a loss lower than 1 dB.

Even if this technique can detect and localize faults in any branch, the capacity of the network is limited by the monitoring bandwidth since each branch has its own wavelength. Despite the technique was proposed long time ago, this never found success in the industry mainly because deploying WDM systems is complex and expensive.

(2) Reference Reflector based Monitoring Technique

In [37], the authors proposed to use wavelength selective reflectors at the end of each branch with tunable OTDR in the CO. The wavelength selective reflectors can be FBGs, each designed with specific wavelength that is used as an ID for the branch connected to it. These references will identify each branch by reflecting a specific wavelength from the transmitted broadband signal. At the CO, the reflected

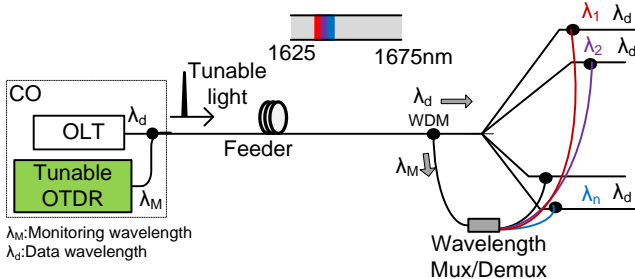


Fig. 9. PON monitoring based on wavelength routing.

wavelength of each branch is monitored and a fault can be detected from the presence or absence of this peak.

Fig. 10 shows the structure of the monitoring system. An FBG filter, fabricated by the phase-mask method is embedded in the connector ferrules. It can easily and economically replace the optical filter currently used in the testing systems without the need to reinstall the optical fiber cables on a user premise when services are changed [38], [39]. The authors carried out a field trial for this technique using 1x8 ATM-PON. They showed the ability of this technique to detect fiber impairments without need to add additional components in the RN. This makes it applicable for the current deployed PON.

However, this approach needs to assign one wavelength for each branch. This limits the capacity of the network to low number of customers. Also it uses tunable filter at the receiver, hence increases the network cost.

C. Brillouin OTDR (BOTDR) based Monitoring Technique

Researchers from NTT proposed in [40] to use Brillouin OTDR (BOTDR) based principle instead of conventional OTDR to monitor the network. This technique exploits the Brillouin frequency shift (BFS) to distinguish the backscattered signals from each branch. Specific BFS is assigned to each branch by controlling the dopant concentration in the branch core during fabrication process. When a test light is applied, the peak power of the BFSs (f_1, f_2, \dots, f_N) generated from the backscattering can be distinguished from each branch as shown in Fig. 11. If the peak power of a specific BFS changes from its initial level (reference), it can be inferred that its assigned branch is faulty. Then, the exact fault location within the faulty branch is determined by analyzing the trace of this branch at that specific BFS. The authors in [40] did more work about PON monitoring considering outside environment in [41], [42].

This technique is demonstrated experimentally with 1x8 PON. The monitoring pulse has 1650 nm wavelength with duration of 100 ns and peak power of 26 dBm. The monitoring signal is amplified using two stage amplifiers in the CO. Using signal averaging, the authors obtained 17.2 dB single way DR and showed the ability of their technique to characterize all the branches. Unfortunately, this approach requires manufacturing a different fiber for each customer. This calls for a dramatic change in current existing PON infrastructure making the CapEx extremely high.

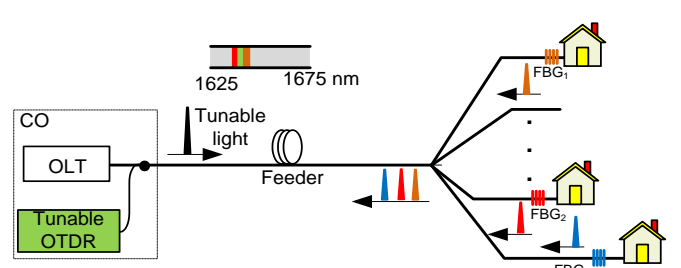


Fig. 10. PON monitoring based on using different reference reflectors.

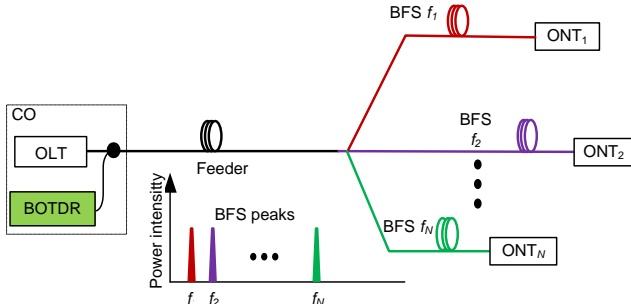


Fig. 11. BOTDR principle to monitor the PON.

D. Embedded OTDR based Monitoring Technique

In this technique, a mini OTDR is integrated into the ONUs [43], [44]. This eliminates the need to connect other separated test equipments to the network or using tunable OTDR at the CO. However, the integration of embedded fiber monitoring means into ONUs requires hardware modifications, particularly at the transceivers. This solution uses the upstream data laser (1310 nm) in the ONU to detect the reflections and scatterings from the branch connected to it.

There are two different transmission schemes in a PON system. The first is a continuous traffic in the downstream direction, and the second is burst mode traffic in the upstream direction. Hence, the authors in [45] proposed two different OTDR methods integrated in both the ONUs and OLT to completely monitor the network. The first is the modulated sine wave OTDR method for monitoring the feeder located in the CO side. The second is the pulse OTDR method for monitoring the network branches which is located in the ONUs side. In the upstream direction, the classic pulse OTDR method can be used in which the pulse signal, that has the same wavelength as the upstream data (1310 nm), is inserted between two data bursts, obeying the timing requirements of the data traffic. A waiting time is needed before sending the OTDR pulse to avoid interference between the backscattering signal from the last data packet and the OTDR pulse. The waiting time depends on the fiber length. The same timing requirement has to be taken into account before the next data burst can be sent after the OTDR pulse. The backscattering light from the OTDR pulse has to be detected completely before a new data packet can be sent to the OLT.

In the downstream direction, a continuous data stream is transmitted and no traffic interruptions are allowed. In this case, a sine wave is modulated on top of the downstream data traffic and the frequency of the sine wave is swept across a certain range of frequencies. The modulation index for the sine wave is 5 % to ensure that the data traffic is not severely affected by this method. The authors in [45] demonstrated their technique for 1x4 PON with FPGA for data processing and system control.

Although this technique eliminates the need to use expensive tunable OTDR, it interrupts upstream data transmission. Moreover, because this technique depends on ONU equipment for monitoring the branches, any ONU fault, relocate or turning OFF will confuse the NMS about the real

branch status where the information is missed from this ONU. In this case the operator cannot differentiate between ONU fault, fiber fault or even ONU switching OFF. For more reading about this technique, see [46], [47].

E. Optical Frequency Domain Reflectometer (OFDR) based Monitoring Technique

Monitoring solutions based on Optical Frequency Domain Reflectometer (OFDR) recently appeared in the literature as an alternative approach to detect any faulty branch in PONs [48]. The principle of OFDR for characterizing optical components using coherent detection is shown in Fig. 12 (a). The monitoring signal is swept in time and then transmitted toward the device under test (DUT). Then this signal is split into two paths, one probes the device under test and the other is used as a reference signal. The two signals (the reference signal returning from the reference mirror and the test signal returning from the reflection sites in the device under test) coherently interfere at the coupler. This interference signal contains the beat frequencies which appear as peaks at the network analyzer display after the Fourier transform of the time-sampled photocurrent.

To adapt OFDR for monitoring PON, some techniques are presented in the literature [49], [50] and [51]. In [51], the authors proposed using interferometer units (IF units) which can detect any faulty branch within PON. Each IF unit includes a uniform fiber Bragg grating (FBG) and a mirror as shown in Fig. 12(b) which creates a beat term (a peak) on the

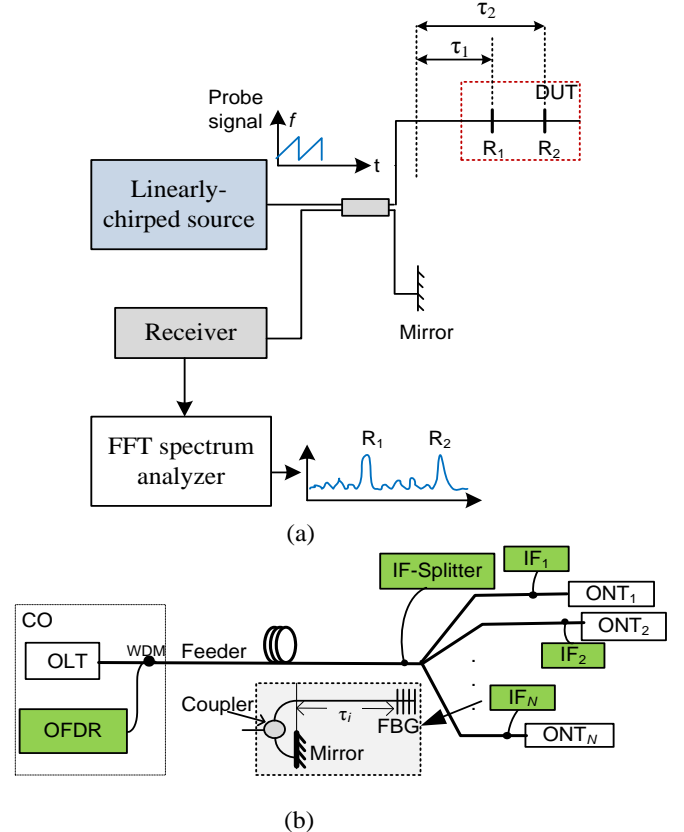


Fig. 12. (a) Operation principle of coherent OFDR, (b) Using IF units with OFDR for PON monitoring.

OFDR trace, that is used to check the integrity of the corresponding branch. The OFDR unit launches into the network a frequency-modulated continuous-wave signal (monitoring or probe signal) and measures the interference signals created by the IF units. Each IF unit creates a periodical beat signal (i.e. a reflection peak on the OFDR trace) with a unique beat frequency. This peak depends on the group delay difference between the signal paths of the IF unit. Each IF unit is designed with different fiber length (τ_i) between the coupler and the FBG shown in Fig. 12(b), which leads to unique group delay and then unique peak for each branch.

The composite signal, which includes the sum of the responses (beating signals) from all IF units, arrives at the OFDR unit, is electrically detected, and is converted into the frequency domain by using a fast Fourier transform algorithm. The beat frequencies visualized in this way allow the integrity of the network to be checked. If one of the distribution branches fails, the corresponding IF-unit peak on the OFDR trace will be influenced. For instance, the related peaks will disappear if some of the distribution branches are broken or disconnected. In addition to the detecting of the faulty branch, the IF units used at the subscriber side can be located before the customer premises equipment in order to determine whether a failure is within the users' home network or within the operator network. From this end, this technique fits well the demarcation point monitoring principle.

The authors demonstrated their technique with 1x8 PON where only three branches were connected to the PSC and the remaining ports were terminated. The results showed the ability to detect any faulty branch in addition to measuring the temperature at the FBG location. However, this technique fails in localizing the exact location of a fault within the faulty branch.

F. Optical Coding based Monitoring Technique

In [52], a modified optical code-division-multiplexing (OCDM) scheme for centralized monitoring of PONs is proposed for the first time. In this system, no active component is placed in the field and no intelligent module is embedded inside the customer's ONU. This approach uses optical encoders that generate pseudo orthogonal codes to identify each subscriber from the other. Hence there is no need to use OTDR at the CO to detect if there is a fault in any branch. Instead, a decoding system is placed at the CO to decode the signatures (codes) coming from the different branches. After decoding, the NMS takes a decision about the state of each branch. These passive encoders can be placed outside the home before the customer premises equipments as shown in Fig. 13 in order to determine whether a failure is within the users' home network or within the operator network. From this end, this approach fits well the demarcation point function without the need of power supply. The operator will no longer be confused between fiber and ONU faults. Recall that when a fiber fault occurs, the operator is responsible and this proposed technique allows troubleshooting without involving the customer. However, an

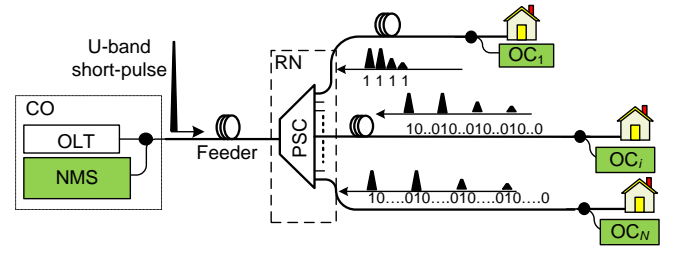


Fig. 13. Optical coding based monitoring system.

ONU fault, in most cases, depends on the customer himself.

Different types of passive optical encoders have been proposed for PON monitoring. Fig. 14(a) and Fig. 14(b) show two passive encoders that generate optical codes. The first uses time delay lines (TDLs) whereas the other uses FBGs with different reflectivities to generate optical code [15], [53]. To reduce the cost of the encoder, two other encoders shown in Fig. 14(c) and Fig. 14(d) have been proposed in [54], [55]. These encoders are called multi-level periodic encoders because they generate code that consists of a periodic sequence of subpulses; each of them has different power level.

Fig. 14(c) uses two FBGs with partial reflectivity for the first and 100% reflectivity for the second. When the monitoring signal arrives, a part of it is reflected back to the CO and other part continues its direction toward the 100% reflectivity FBG. The pulse will be reflected back and part of it will pass the first FBG creating the second subpulse in the code and the other part reflected back toward the 100% reflectivity FBG. This process continues creating a multi-level code. The performance of this encoder has been demonstrated experimentally in [56] for 1x4 PON and in [57] for 1x16 PON. Using a reduced complex algorithm with signal averaging (100 times), the system was able to decode and detect all the codes correctly. The encoder shown in Fig. 14(d) is proposed in [55] which uses a 100% reflectivity FBG and a ring of fiber. This encoder structure is simple and can create a periodic code with subpulses levels determined by adjusting the coupling ratio of the encoder.

To reduce the effect of interference on the received code coming from the encoders of the other customers for large capacity networks, 2D optical encoders are used as shown in Fig. 14(e) and Fig. 14(f). Fig. 14(e) uses BPFs to pass specific wavelength from the monitoring signal while Fig. 14(f) exploits FBGs with different wavelength reflectivities. These two encoders generate 2D codes. Hence, reduce the interference contribution from the interfering codes. See also [58] and [59] for more reading about optical coding for PON monitoring.

G. SL-RSOA based Monitoring Technique

The authors in [60] suggested a technique based on cavity mode analysis of self-injection locked reflective semiconductor optical amplifier (SL-RSOA). At each ONU, an upstream transmitter utilizing SL-RSOA can generate both upstream data signal and surveillance signal due to presence of external cavity. Both upstream data and surveillance signals from all ONUs can be detected simultaneously at the OLT by

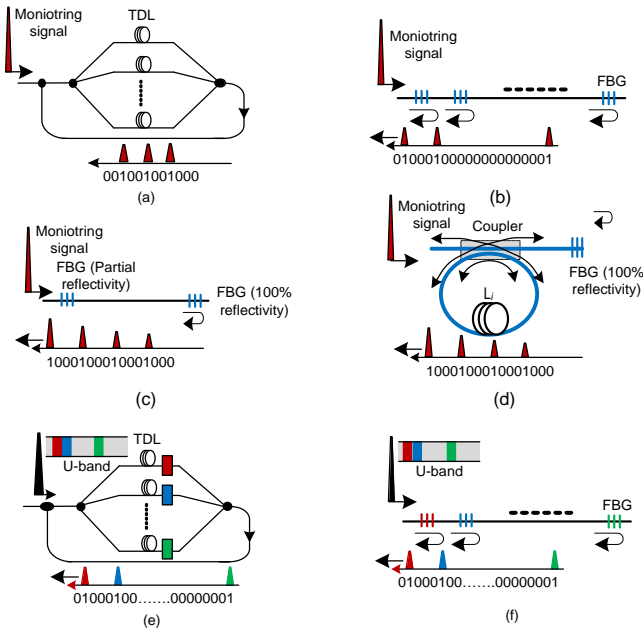


Fig. 14. Some types of passive optical encoders designed for PON monitoring.

assigning a distinct cavity mode frequency to each upstream transmitter.

The configuration of this technique is shown in Fig. 15. The cavity mode frequency is generated utilizing a coupler and FBG where a portion of amplified spontaneous emission (ASE) noise of the RSOA is coupled into the upper port of the 3 dB coupler and a slice of ASE spectrum at Bragg wavelength of FBG is reflected back, thereby locking the RSOA to the Bragg wavelength of the FBG. The presence of an external fiber cavity generates a train of cavity modes with a unique mode spacing corresponding to the cavity length (L_i). This unique cavity mode spacing serves to identify the respective ONU branch. The cavity mode spacing is given by, $f_k = c/2nL_k$, where c is the velocity of light in free space, n is the refractive index of the fiber and L_k is the cavity length of the k^{th} branch. An upstream transmitter can be realized by direct modulation of the SL-RSOA. The modulated signal along with train of cavity modes generated at each ONU are fed into the branch fiber and then to the feeder fiber through a PSC. At the optical line terminal (OLT), the signal is tapped using a 90/10 coupler and fed to a monitoring module where the signal is analyzed for cavity mode spacing frequency. The

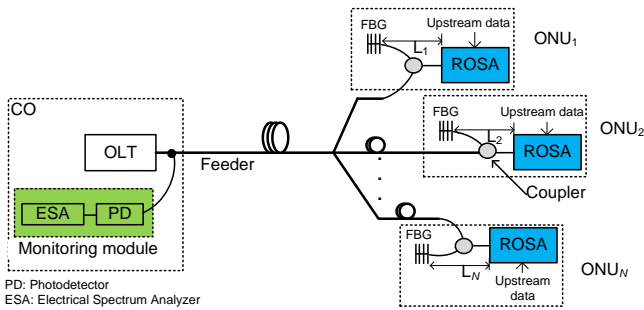


Fig. 15. SL-RSOA based monitoring system.

individual mode spacing can easily be differentiated by applying fast Fourier transform (FFT) algorithm on the radio frequency (RF) power spectrum. Each distinct peak in the output autocorrelation function is represented by an identification label. If a fault occurs on one of the branch fibers or one of the upstream transmitters fails, then the corresponding identification peak of ONU is suppressed in amplitude indicating the fault on the branch fiber.

For large number of customers more than 16, this simultaneous detection mechanism is not an attractive solution as it induces unnecessary power penalty on the upstream data traffic which is not desired. To reduce the influence of surveillance signals on the upstream data channel, the authors proposed to assign a time slot for each ONU to transmit its surveillance information. In this way, the MAC allocates a time slot for the surveillance signals and instructs the entire set of ONUs to transmit their surveillance signals within the allocated monitoring time slot. This eliminates the effect of surveillance signals on the upstream data. This technique is demonstrated for 1x4 GPON. The authors proposed an extension for GPON Transmission Convergence (GTC) protocol to accommodate the monitoring information by assigning a time slot so that the monitoring information can be transmitted from the ONUs to the CO without influence on the upstream data.

This approach, however, requires a protocol extension, and therefore is not directly applicable to all PON protocols. Also the principle of demarcation point is not possible here. Another important drawback of this technique is the gain competition that occurs between both upstream wavelengths (data and surveillance wavelengths) if achieved in the same time. This may induce high cross-talk between the data wavelength and monitoring wavelength.

H. Reflective Signal based Monitoring Technique

The authors in [61] proposed a monitoring system based on a micro-electromechanical system (MEMS) optical switch and an optical mirror placed close the customer location as shown in Fig. 16. The system works when a monitoring signal is transmitted from the CO. This signal is reflected back by a mirror and then modulated with signal when it passes the optical switch. The monitoring module will generate a signal pattern that consists of some pulses shifted in time. This pattern works as an ID for the branch connected to it. When the generated pattern is lost or received but attenuated, this means there is a problem with the assigned branch and OTDR is needed to determine the exact location of the problem

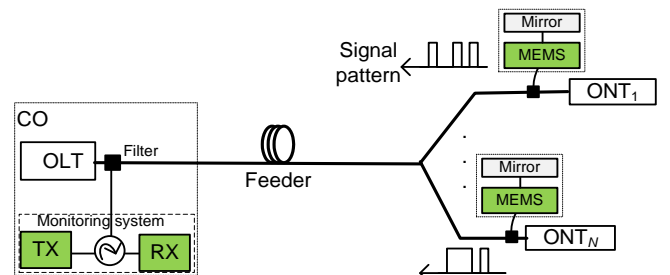


Fig. 16. Reflected signal based monitoring system.

source. The use of MEMS optical switch requires using a control signal (electrical signal) to control its operation which contrasts the principle of passive network.

VII. MONITORING REQUIRED FEATURES AND TECHNIQUES COMPARISON

To design a complete monitoring system that receives the consent of a network operator, the system should achieve some features. In the following, we will define 17 monitoring features.

1. *Centralized* monitoring system enables the NMS in CO to remotely and completely collect the monitoring information of the network without customer collaboration or collecting part of the information by the ONT.
2. The possibility to monitor the network *automatically* enables the operator to collect monitoring information and detect faults without dispatching technicians to the field. This feature reduces the network OpEx and measurement time.
3. It is desirable for the monitoring system to be *transparent* to the data in the C and L bands. Hence, data transmission and reception can work in parallel with the monitoring system without interruption.
4. Achieving the *demarcation function* is an important feature for any network operator. This function allows the operator to differentiate between his responsibility and that of the customer.
5. In principle, using *single wavelength* for network monitoring saves the bandwidth and decreases the cost of the system.
6. The ability to monitor high network *capacity* (64, 128 and beyond) makes the technique applicable for NG-PON.
7. *Fault detection* is the first objective of any monitoring system. It allows the NMS to identify which branch in the network is faulty.
8. The second objective is *fault localization*. This feature determines the exact location of a fault within the faulty branch. Hence, it decreases the OpEx.
9. Using *active components in the field* between the CO and the ONUs is inconsistent with the key principle of PONs. It also increases the OpEx because active components are more prone to faults than passive components.
10. The monitoring technique *cost* is a critical feature for any service operator. This is mainly because the PON market is cost sensitive especially for the components not shared by the customers (components between the PSC and the customers). Hence, the monitoring technique should be inexpensive even if it has full monitoring capability.
11. Another important feature is network *reliability* which is the ability of the system to perform its required functions for a specified period of time
12. Technique *complexity* limits its applicability. The technique should use simple components that are easy to design, manufacture and install. This ensures the

technique will be adopted by the industry. This includes for example, the constraint of using different fiber for each branch or fixing the length of each fiber branch. This constraint puts impractical limitations when it comes to real implementation.

13. *Scalability* feature is the ability of the monitoring technique to handle network infrastructure changes in graceful manner.
14. *Customer independence* is preferable because it makes the maintenance easier and improves customer satisfaction.
15. *Cascading* remote nodes (PSCs) should not be an obstacle for the monitoring system.
16. The monitoring technique should be *applicable for the networks already deployed* without need to modify the network infrastructure.
17. *Notification time* is defined as the time between fault occurrence and detection. This time should be as short as possible.

After we defined the features required by fully monitoring system, we summarize the different monitoring techniques in [Table I](#) based on the required features, providing the main advantages and drawbacks of each technique.

VIII. INTEGRATION OF PHYSICAL LAYER WITH OTHER SURVEILLANCE FUNCTIONS

Higher layer protocols and applications are widely used today by network operators to supervise access, metro and long haul transmission system. ITU-T G.984.2 (Amendment 2) and G.984.3 are two standards developed for GPON maintenance. ITU-T G.984.2 (Amendment 2) (2008) Recommendation describes some physical layer measurements to provide the G-PON system with a basic optical layer supervision capability. The method of obtaining these measurements is left to implementation choice. These measurements are based on monitoring the transceivers, i.e. active components (OLT and ONT). These include the transmitted and received power, temperature, voltage and laser bias current. The OLT and ONT communicate together allowing the operator to monitor, administrate and troubleshoot the network. For example, if the optical power level at the receiver is lower than a threshold, a message is sent to the opposite transmitter to increase the laser power.

G.984.3 (2008) Recommendation describes the operation, administration and maintenance (OAM) functions installed in the OLT and ONU. The alarms defined in this Recommendation include mechanisms to monitor the health and performance of the links and detect failures.

Although the measurements based on the active equipments (OLT and ONT) and the higher layer protocols provide a solution for physical layer monitoring and supervision in PON, their performance is still limited, insufficient and expensive for the network operator. Recall that one among the most important goals of ongoing research is to better optimize the finding of faults and avoid expensive dispatching of technicians and truck rolls in the field for each service

interruption. In the following, we highlight the major shortages of using active components measurements and higher layer protocols to monitor the PON's physical layer:

- 1- Technicians are required in the field to localize faults: faulty branches are detected from measuring the signal quality without determining their exact location. To localize the faults, technicians should be dispatched in the

Table I: Summary of monitoring techniques and their main advantages and drawbacks.

Advantages and drawbacks		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Monitoring Technique		Centralized	Automatic	Transparency	Demarcation function	Single wavelength	Capacity	Fault detection	Fault localization	Active components in the field	Cost	Reliability	Complexity	Scalability	Customer independence	Support PSC cascading	Applicable for currently deployed PON	Notification time
Single Wavelength OTDR	Upstream OTDR Measurement Ref: [26] - [27]	No	No	No	No	Yes	Low	No	Yes	No	High	Low	Low	No	No	Yes	Yes	Long
	Active Bypass Ref: [28] - [30]	Yes	Yes	Yes	No	Yes	High	Yes	Yes	Yes	Low	Low	Low	No	Yes	No	Yes	Med
	Semi-Passive Bypass Ref: [31] - [32]	Yes	Yes	Yes	No	Yes	High	Yes	Yes	Yes	Low	Low	Low	No	Yes	No	Yes	Med
	Reference Reflector Ref: [33] - [35]	Yes	Yes	Yes	Yes	Yes	High	Yes	No	No	Low	Low	Low	No	Yes	Yes	Yes	Short
	Switchable Reflective Element (SRE) Ref: [20]	Yes	Yes	Yes	Yes	Yes	High	Yes	No	Yes	High	Low	Med	Yes	Yes	Yes	Yes	Med
Tunable OTDR	Wavelength Routing Ref: [34], [36] - [37]	Yes	Yes	Yes	No	No	Low	Yes	Yes	No	High	High	High	No	Yes	Yes	Yes	Short
	Reference Reflector Ref: [37] - [39]	Yes	Yes	Yes	Yes	No	Low	Yes	Yes	No	High	High	Med	No	Yes	Yes	Yes	Med
Brillouin OTDR Ref: [40] - [42]		Yes	Yes	Yes	No	Yes	High	Yes	Yes	No	High	Med	High	No	Yes	Yes	No	Short
Embedded OTDR Ref: [43] - [47]		No	Yes	No	No	Data wavelengths	High	Yes	Yes	No	Med	Low	High	Yes	No	No	No	Med
OFDR+IF Units Ref: [48] - [51]		Yes	Yes	Yes	Yes	Yes	High	Yes	No	No	Low	Med	Low	Yes	Yes	Yes	Yes	Short
Optical Coding Ref: [11], [15], [52] - [59]		Yes	Yes	Yes	Yes	Yes	High	Yes	No	No	Low	Med	Low	Yes	Yes	Yes	Yes	Short
SL-RSOA Ref: [60]		No	Yes	Yes	No	RF frequencies	High	Yes	No	No	Low	Low	Med	Yes	No	Yes	No	Short
Reflective Signal Ref: [61]		Yes	Yes	Yes	Yes	Yes	High	Yes	No	Yes	High	Med	Low	Yes	Yes	Yes	Yes	Short

field to make OTDR measurements.

- 2- No preventive fault detection leads to error rate degradation and data loss: using higher layer protocols, fault detection is achieved by monitoring increasing the bit error rate (BER). In this case, the signal is already affected and none of the higher layer parameters can identify the main source of problem. Signal degradations between the transmitter and the receiver could be detected in an earlier stage before bit error detection and correction takes place. Therefore it is recommended that fault detection takes place at the layer closest to the failure, which is the physical layer for optical networks [62].
- 3- To use higher layer protocols, a special numerical algorithm and additional processor capacity at the endpoints of the network (OLT/ONUs) are required to collect data about the signal quality, process it and then transmit it to the central office to take decisions. This increases the complexity, cost and repairing time.
- 4- Higher layer protocols need to depend on the ONT equipments (which belong to the customer in some companies) in collecting monitoring information which is not preferred for the service provider.
- 5- In case of an ONU fault, relocating or switching off scenarios, the monitoring information from these terminals will be lost. This makes the CO confused about the real status of the branched fiber that is connected to the respective customer which can be taken as fiber cut whereas it is not. Then the service provider has to dispatch technicians to fix a problem that is under the customer responsibility. This induces loss of money for avoidable operation tasks.

For these reasons, using active equipments measurements

and higher layer protocols to monitor the physical layer of PONs is inefficient. However, an optical layer monitoring system can be integrated with the active equipments measurements and higher layer protocols to produce an efficient and complete monitoring system. This integration enables the service provider to monitor the active equipments in addition to the health characteristics of each fiber segment in the network. Table II shows some OLT alarms defined in G.984.3 Recommendation related to the physical layer. We can integrate these alarms with the gathered monitoring information collected by the physical layer monitoring system to end up with more effective monitoring system.

IX. PON MONITORING OPEN ISSUES AND FUTURE DIRECTIONS OF RESEARCH

This survey shows that PON still does not have full monitoring capability. Most of the monitoring techniques which are reliable and cost-effective misses the fault localization feature which is a very important task for any monitoring technique. This missed feature leads us to divide the monitoring procedure into two main steps. The first step is fault detection to determine the faulty branch among the different branches in PON. This should be achieved by using a reliable, cost-effective technique among the techniques discussed in this paper. The second step is accomplished by dispatching technicians to the faulty branch in the field and injecting an OTDR signal to exactly determine the location of the fault. However, dispatching technicians increases the OpEx of the network. Designing a centralized monitoring technique with full capability, i.e. a technique that perform fault detection and localization from the CO without need for dispatching technicians, is still an open issue for further

Table II: Some physical layer related alarms in ITU-T G.984.3 Recommendation and physical layer monitoring systems integration.

G.984.3 physical layer monitoring parameters		Integrated physical layer monitoring system parameters	
Alarm Type		Detection Condition in G.984.3	
		Expected role of physical layer monitoring system	
LOS _i	Loss of signal for ONU _i	No valid optical signal from the i^{th} ONU when it was expected during 4 consecutive non-contiguous allocations to that ONU.	Loss of signal could originate from a fault in the branch or another source (e.g. ONU _i itself faulty). The active measurements of OLT or higher layer protocols cannot determine the exact source of fault. Physical layer monitoring system can confirm if the specific branch is interrupted or there is another problem.
LOS	Loss of signal	The OLT did not receive any expected transmissions in the upstream (complete PON failure) for 4 consecutive frames.	There is no monitoring signal detected from any branch. Interruption of all ONUs signals is probable only when the fault occurs in the feeder or the RN. The OLT measurements or higher layer protocols cannot determine the exact source of fault. Physical layer monitoring system can determine if the loss is due to feeder problem or splitter problem.
SF _i	Signal fail of ONU _i	When the upstream BER of ONU _i becomes $\geq 10^{-Y}$, this state is entered. Y is configurable in the range of 3 to 8.	In this case, the OLT measurements or higher layer protocols cannot identify the cause of the BER degradation. Physical layer monitoring system will help the operator to fix the source if this originated from the fiber or the ONU _i itself.
SD _i	Signal degraded of ONU _i	When the upstream BER of ONU _i becomes $\geq 10^{-X}$, this state is entered. X is configurable in the range of 4 to 9, but must be higher than Y (the SF _i threshold).	Similarly, in this case, the OLT measurements or the higher layer protocols cannot identify the cause of the BER degradation. Our system will assist the operator to fix the source of the problem.

research.

Also our discussion showed the shortcoming for monitoring PON based only on the measurements taken by the active components or using higher layer protocols. Integrating the physical layer monitoring system with the measurements gathered by the active components and the alarms generated by the higher layer protocols will create more effective monitoring system. This integration needs more research work and standardization.

NG-PON with high bandwidth is a natural path forward to satisfy the demand for high data rate requirements and for network operators to develop further valuable access services. Increasing the number of customers up to 128, 256 and beyond, in addition to increasing the bandwidth up to multi-hundred Mbps (or Gbps) per customer is among the requirements of NG-PONs [17]. However, most of currently available or proposed monitoring techniques have constraints to approach this level of customers. For example, the reference reflector with tunable OTDR technique consumes the monitoring band by assigning one wavelength for each customer, hence it cannot support high capacity networks. Furthermore, the high splitting ratio (128, 256) introduces severe degradation to the monitoring signal which may lead to losing the monitoring information.

The NG-PON architecture includes TDM-PON, WDM-PON and hybrid TDM over WDM-PON. They all require to develop an adequate monitoring system that can be installed on any PON regardless of its architecture. Recently, there has been increasing interest in extended-reach networks which offer the potential to reduce bandwidth transport costs by enabling the direct connection of access networks and inner core networks, thereby eliminating the costs of the electronic interface between the access and the core/metro backhaul network. These networks are called long-reach passive optical networks (LR-PONs) [63], [64]. LR-PON extends the PONs span from the traditional 20 km span up to 100 km and beyond by exploiting optical amplifiers to composite for the large loss and WDM technologies to support more customers. The increased range and number of optical access-metro nodes, compounds the need for OAM technologies, particularly fault management. However, these under research networks come with some challenges for the current proposed or available in the market physical layer monitoring systems. These challenges include the high capacity in terms of number of customers, the large delay and high loss for the signal due to the long distance. Moreover, these networks have different architectures from the traditional PON. For example, in Ring-and-spur LR-PON shown in Fig. 17, a ring is used to connect the traditional TDM-PONs to the CO. This means that the monitoring system should be able to monitor this ring in addition to the traditional PON.

LR-PON requires installing some equipments in the field like erbium doped fiber amplifiers (EDFA), optical add drop multiplexers (OADMs) to route the signal and compensate for the huge signal loss. These devices are designed to work in the data C band only, which block the monitoring signals in the

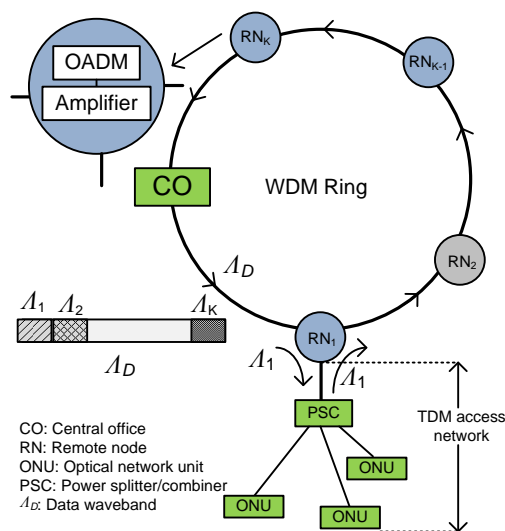


Fig. 17. Ring-and-spur LR-PON architecture.

recommended maintenance band (U-band). Moreover, amplification technology in the U-band is still unavailable at affordable cost in the market. These challenges require more research for suitable and efficient monitoring techniques to go in parallel with the fast emerging NG-PONs.

A recent work has been published in the literature for monitoring the physical layer in all-optical access-metro networks like LR-PON based on using passive components. In [65] and [66], the authors proposed using optical reflectors to monitor the whole network (metro and access). These reflectors are installed at the end of each branch, close to each ONU and also at the boundary of each optical device in the network like amplifiers to enable monitoring them. The authors in [67] and [68] suggested using optical encoders to monitor only the physical layer in metro ring of LR-PON instead of monitoring the whole network which has high reliability with low cost compared to monitoring the whole network that has high cost. In this scheme, the optical encoders are placed before and after each OADM in the metro ring. Hence, in addition to detecting the faulty segment of the ring, it can detect any faulty OADM. When a fault occurs, the system can recover in short time.

Using active components for monitoring the network is also proposed in [69] and [70]. In this approach, the authors proposes using optical switches and detectors in the OADMs. This enables the system to detect the fault immediately but it increases the network cost, more prone to fault and requires maintenance. The authors in [71] and [72] proposed using passive components in the RN which decreases the network cost but it may lead to false alarms. Both proposals can also protect the network after detecting the fault. Table III summarizes the different techniques for monitoring the LR-PON.

Table III: Summary of NG-PON monitoring techniques and their main advantages and drawbacks.

Monitoring Technique \ Advantages and drawbacks	Centralized	Automatic	Transparency	Demarcation function	Capacity	Fault detection	Active components in the field	Cost	Reliability	Scalability	Protection
Reflectors Ref: [65]- [66],	Yes	Yes	Yes	Yes	Large	Yes	No	Med	High	Yes	No
Optical coding in the ring Ref: [67] - [68]	Yes	Yes	Yes	No	Large	Yes	No	Low	High	Yes	Yes
Active components in RN Ref: [69]- [70]	No	Yes	Yes	No	Large	Yes	Yes	Med	Med	Yes	Yes
Passive components in RN Ref: [71]- [72]	Yes	Yes	Yes	No	Large	Yes with probability of false alarm	No	Low	Med	Yes	Yes

X. CONCLUSION

As the fiber progresses towards the home, TDM-PON maintenance is very important to develop a reliable network and to minimize the down time and OpEx. Although there is an increasing need to use efficient monitoring system for the physical layer in TDM-PONs, there is no standardized monitoring system that satisfies the requirements of PON operators till now. The lack of a centralized, comprehensive, efficient and inexpensive solution for the PON physical layer monitoring inspired this survey. We have presented the challenges, the motivations and the requirements for the physical layer monitoring system. We made a survey for the PON monitoring techniques and approaches that are proposed in the literature or available in the market to help develop and improve future research in this area. It was also intended to provide a big picture of the competing approaches for both industrial and academic research efforts. We have discussed their designs, operation, advantages and drawbacks. Our discussion showed that the PON is still missing a complete monitoring system. Different performance measurement tools were listed and explained. We have also reviewed the research perspectives for NG-PONs that support high data rate, large number of customers and longer spans. We have shown that most if not all of the current monitoring techniques have limitations to monitor the NG-PONs. Moreover, we have discussed some challenges and requirements for monitoring these networks.

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