Passive Optical Network Monitoring: Challenges and Requirements

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ABSTRACT

As PONs carry increasing amounts of data, issues relating to their protection and maintenance are becoming crucial. In-service monitoring of the PON's fiber infrastructure is a powerful enabling tool to those ends, and a number of techniques have been proposed, some of them based on optical time-domain reflectometry. In this work we address the required features of PON monitoring techniques and review the major candidate technologies. We highlight some of the limitations of standard and adapted OTDR techniques as well as non-OTDR schemes. Among the proposed optical-layer monitoring schemes, we describe our novel optical-coding-based reflection monitoring proposal and report on recent progress. We end with a discussion of promising solution paths.

INTRODUCTION

Since the emergence of the passive optical network (PON) as a crucial access technology, a considerable amount of research has focused on fundamental design issues such as resource allocation [1]. PON technologies are constantly advancing toward increased capacity, embodied primarily by high-speed time-division multiplexing (TDM) PONs and wavelength-division multiplexing (WDM) PONs. In addition, important advances have been achieved to extend PON reaches, hence multiplying their subscriber counts. As a consequence, PONs are destined to carry huge amounts of traffic in the near future. The search for practical and cost-effective survivability and maintenance mechanisms is therefore becoming key to the continued development of viable PON solutions.

The standardization of PON survivability mechanisms started within the broadband PON (BPON) standardization effort. International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) G.983.1 described a set of four PON protection configurations that were subsequently narrowed down to two protection schemes in ITU-T Recommendations G.983.5 (BPON) and G.984.1 (Gigabit PON), Type B and Type C protection. Type B protection duplicates both the feeder fiber and optical line terminal (OLT) interface and uses an N:2 splitter at the remote node (RN), where N is the number of supported optical network units (ONUs). The Type B configuration hence offers protection only against the failure of the OLT interface equipment or a cut in the feeder fiber. In contrast, Type C duplicates the whole PON network infrastructure, including ONU and OLT interfaces, as well as the splitter, thus providing additional protection against ONU equipment failures. EPON has no standardized protection scheme but may adopt Type C protection through the adaptation of Ethernet protection switching defined in ITU-T G.8031 [2]. In both Type B and C protection configurations, automatic protection switching is typically triggered by layer 2 alarms related to the loss of signal intensity or quality. This has two important consequences [3]. First, the physical PON infrastructure is not entirely visible to the network management system (NMS) for fault management operations. Second, failures within the fiber plant are likely to entail service disruption before being detected, leading to revenue losses and customer dissatisfaction.

Due to the high capital expenditures incurred by the deployment of such protection mechanisms, operators have resorted to troubleshooting and restoration once faults are detected [4]. Troubleshooting is an important network maintenance function that involves locating and identifying any source of fault in the network. The above-mentioned ITU-T protection configurations make no specific provisions to identify and localize faults within the optical infrastructure and defer the task to maintenance standards (L series). ITU-T L.53 (2003) is the first standard to specifically address the maintenance of PONs by recommending the use of optical time-domain reflectometry (OTDR)-based techniques for troubleshooting.

Whether it is for survivability or maintenance

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purposes, there is a growing need for the monitoring of the PON fiber plant. PON monitoring technology automatically identifies and localizes faults of the in-service PON optical infrastructure. In doing so, it provides the NMS with enhanced optical infrastructure visibility in real time, thus speeding up the detection and localization of faults. Monitoring avoids the operational expenditures (OPEX) and large service restoration times of offline troubleshooting, thus enabling wider service differentiation and stronger QoS guarantees. In addition, it paves the way to potentially enhanced physical layer protection mechanisms.

Accordingly, PON monitoring has been receiving increasing attention, and a variety of proposals have emerged [3, 5]. To accommodate the demand for monitoring technology, the ITU-T L.66 (2007) Recommendation 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 such as OTDR testing, loss testing, and power monitoring (i.e., monitoring a proportion of the signal power).

Note that PONs need to be tested during installation to ensure that all fiber links and components are properly installed and working. Therefore, link characterization and diagnosis during network installation is also of great importance and can easily be performed using one of the aforementioned testing methods. However, there is a growing need to monitor fiber link failures and degradations without disturbing ongoing services. In this article we focus on the monitoring of in-service live PONs (i.e., after installation), where a service interruption due to monitoring is not permissible.

In this article we review and compare the major optical-layer PON monitoring proposals, and address advantages and challenges of the monitoring techniques for deployment of high-capacity PONs. In the next section we enumerate the desired features and major requirements of in-service PON monitoring techniques. We then briefly review the basic principles of OTDR for point-to-point monitoring, and outline the challenges and limitations of standard OTDR in PON (point-to-multipoint) applications. Non-OTDR-based techniques are then addressed. We particularly focus on two recently proposed techniques: Brillouin frequency shift assignment and optical-coding (OC)-based reflection monitoring. We also address in detail the advantages and disadvantages of each of the mentioned techniques in PONs. Finally, we discuss promising solution paths before concluding in the final section.

REQUIRED FEATURES OF PON MONITORING TECHNOLOGIES

GENERAL REQUIREMENTS

By definition, an effective monitoring technology should be able to both detect a fault and provide the NMS with useful information for root cause analysis. Useful monitoring information enables technicians to perform fast network repair, hence increasing PON reliability and reducing operational expenses.

The most important issue in PON monitoring technology is *cost*, including capital expenditure (CAPEX, i.e., the initial cost of the monitoring technology per customer) and operational expenditure (OPEX, i.e., the cost of system maintenance). The reason is that the PON market is highly cost-sensitive, especially for the components not shared between customers, such as distributed monitoring nodes. Therefore, an expensive technology, even though it may provide in-service full visibility of the optical infrastructure to the network operator, may not be interesting for PON applications. Consequently, the monitoring technology requires simple design, fabrication, and implementation procedures to minimize the cost.

Capacity, in terms of the number of PON branches or distribution fibers that can be simultaneously monitored, is the second desired feature. Candidate monitoring technologies should be able to support at least the maximum split-ratio of current PON standards (e.g., 1:128 for ITU-T G.984 GPON). Accommodating larger split-ratios increases the number of supported customers, thus amortizing the expenses of the service provider and generating higher benefits. The monitoring technology should thus be *scalable* in order to enable seamless and continuous upgrades of the PON infrastructure (i.e., PON capacity, reach, and customer base) at low costs. The *simplicity* of the monitoring architecture and components directly affects the cost, and is hence an important requirement. In addition, as for any maintenance and protection mechanism, *reliability* is primordial. Furthermore, to operate in-service, the desired monitoring technology should act *transparently* to the data band signals such as the L and C bands. Therefore, strict isolation between the data band and monitoring signals is required.

AUTOMATIC AND CENTRALIZED MONITORING

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Both centralized and distributed approaches have been proposed for monitoring the fiber link quality of a PON [3–5]. In distributed (decentralized) monitoring strategies, active modules are placed inside the ONUs to measure performance and report to the NMS. These modules periodically evaluate the uplink for a specific fiber branch and may be implemented electronically at the ONU.

Although the distributed approach effectively identifies fiber link degradation, it is ineffective when there is an interruption in the fiber link (e.g., a fiber cut) as it requires the real-time collaboration of ONUs. For instance, a missing monitoring signal at the NMS can be interpreted as the result of either a fiber fault or an electronic malfunction at the ONU. While the operator may take advantage of information on link quality provided by the ONU, the case is strong for a separate, independent, and rapid indicator of whether the fault occurred in the client's or the operator's domain. Therefore, a centralized automatic monitoring technology is highly desirable for PON applications.

OPTICAL TIME DOMAIN REFLECTOMETRY

Optical-time-domain-reflectometry-based monitoring has been implemented for the first time for optical carriers in long-distance transmission systems. OTDR is an efficient way to characterize an optical link while accessing only one end, as appropriate for point-to-point links. It operates as follows. The OTDR equipment launches a short light pulse into the fiber and measures the backscattered light. *Rayleigh* scattering and *Fresnel* reflections are the physical causes of this scattering behavior [4]. Due to the measured power at the OTDR receiver, a trace of the power vs. the distance may be computed, representing the impulse response of the link under test, as shown in Fig. 1. This trace can be used to extract information about link faults, including fiber misalignment, fiber mismatch, angular faults, dirt on connectors, macro-bends, and breaks. These faults are usually referred to as *events* on the OTDR trace. For instance, the jumps in Fig. 1 correspond to the insertion loss of different network components, whereas the power reflection peak at 40 km indicates the Fresnel reflections at the fiber-air interface, signifying the fiber end. After the fiber end, no backscattering is detected, and the trace drops to receiver noise levels.

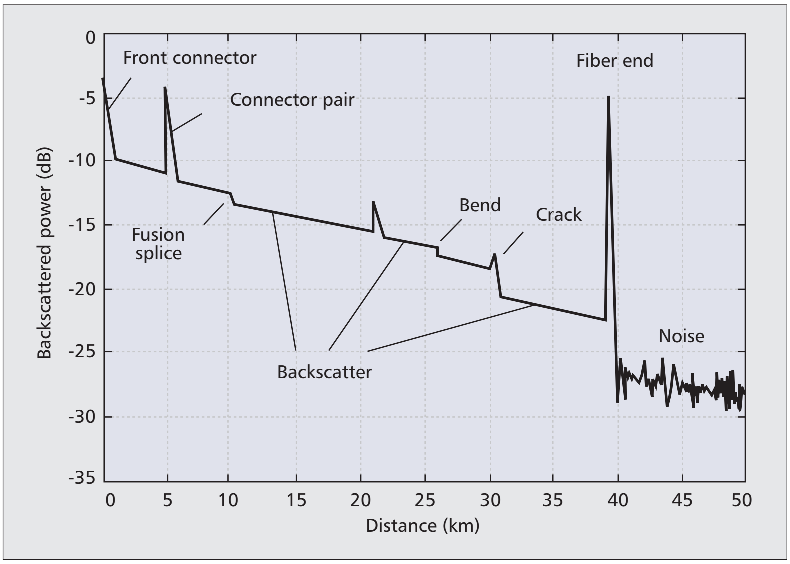

Figure 1. *Typical trace of OTDR of a fiber link.*

CHALLENGES OF STANDARD OTDR FOR PON

While providing automatic monitoring and full characterization of the fiber link, OTDR is ineffective for PON point-to-multipoint (PMP) networks [3–6]. This is because a branch backscattering signal in a PON can be partially or totally masked by other branch signals. For PONs, the total power measured by the OTDR is a linear sum of all powers coming from different branches. Useful information can be extracted from the global backscattering trace when returns from individual branches are separated in time. Otherwise, extracting the desired information from the OTDR trace may require considerable offline signal processing, or simply be impossible.

OTDR analysis for a branched network compares the backscattering trace with reference returns acquired under controlled conditions. A simulator interprets any deviation from the reference signals [7, 8]. The accuracy of such software depends on the quality of the simulator as well as the uncertainties in both the measured traces and the simulated return based on reference measurements. In the event of equidistant branch terminations, the challenge is severe. As the network size increases, analysis complexity increases, leading to less reliable monitoring.

In addition, the huge loss by passive splitters, typically located at the remote node (RN), leads to a significant drop in measured power. For example, a 1:32 splitter at the RN leads to 15 dB loss in the total backscattered light from each branch. The RN then resembles a fiber end, and no useful information can be extracted beyond the RN. In traditional OTDR, losses higher than 3–7 dB are identified as end-of-fiber. However, it is reported that by modifying the OTDR analysis, testing can be performed through splitters with losses up to 20 dB. This type of OTDR is usually referred to as *PON-tuned OTDR* [6].

MODIFIED OTDR SOLUTIONS

Reference Reflector — In order to reduce PON OTDR analysis complexity, a variety of solutions have been proposed to distinguish individual fiber branches. The most well-known technique is the use of reference reflectors (RR-OTDR) [5] assigned to each fiber branch to render it distinguishable from others in the total measured OTDR trace.

The principle of the reference reflectors is illustrated in Fig. 2. A reflector can be realized by different methods [5]. It could be wavelength selective and inserted in the input of the ONU connector to act as a stop filter. It also could be a non-wavelength-selective reflector placed on a separate tap (lower part of Fig. 2). Note that the reflectors at each fiber end are identical, and all reflect the same wavelength, each producing a reflection for its corresponding branch. To distinguish between the branches, it is critical to adjust the fiber lengths in each branch to avoid temporal overlapping. In this way a single OTDR return will have each branch return located in an isolated time interval.

By monitoring the stability and level of reflections from reference reflectors placed at each fiber branch end, the integrity of a specific branch can easily be investigated. The OTDR is exploited for a full characterization of the corresponding fiber branch. The shift in the power level of the reference reflection for a desired branch provides useful information for the OTDR trace analysis. Checking the stability of the strong reflection (located well above the noise level) is faster and easier than analyzing the OTDR trace, and these reflectors are often used as a first fault indicator in most OTDR-based techniques.

In RR-OTDR, the choice of the fiber lengths requires an important trade-off between OTDR sensitivity and resolution. The required fiber length is proportionally related to the transmitted OTDR pulse width as well as the relative distances between the customers. While for very short pulses small fiber lengths are required, the OTDR sensitivity is very poor, limiting allowable splitter size at the RN. For longer pulses, sensitivity improves. However, significantly long delay lines are required, leading to lower OTDR accuracy and larger *dead zones* (i.e., the area of an OTDR trace where events are not distinguishable).

The NMS requires updated information on the customer distribution in the network; otherwise, customer relocations cause false alarms. The RR-OTDR scheme does not scale well with large network sizes. In fact, due to the huge splitter loss at the RN, it is difficult to extract useful information from the OTDR trace beyond the RN. In addition, as the network size increases, the selection of an optimal delay line becomes more challenging, and the complexity of the OTDR trace increases.

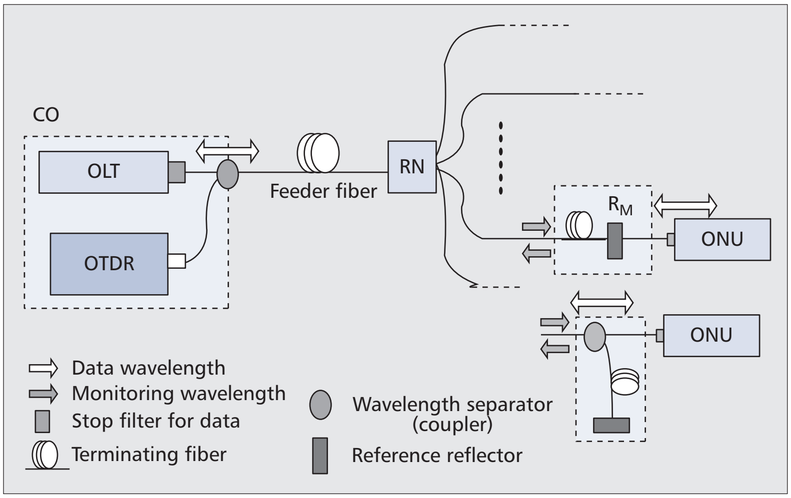

Figure 2. *Use of a reference reflector for OTDR-based automatic monitoring of PONs.*

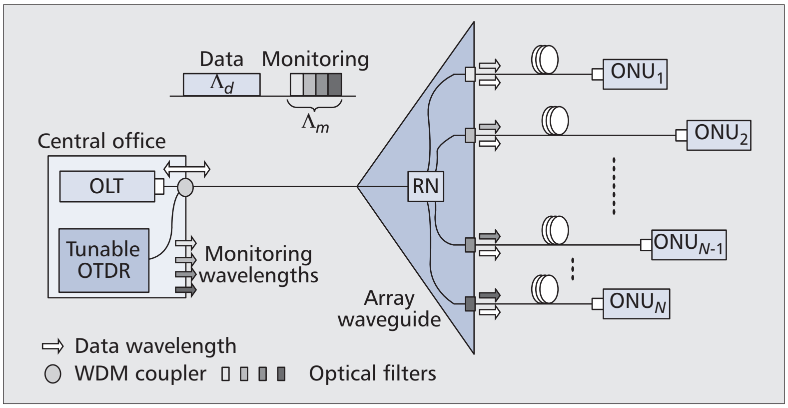

Figure 3. *OTDR for PON via one monitoring wavelength per ONU.*

Multi-Wavelength Approach — One other simple approach would be employing a multiwavelength source and an arrayed waveguide grating (AWG) at the RN. This reduces the PON monitoring problem to point-to-point link characterization, as illustrated in Fig. 3. In this case the tunable multiwavelength OTDR source should be very stable for reliable monitoring. Isolation between the monitoring and data signals will be more strict than single-wavelength OTDR. In addition to its high cost, this technique also has limited capacity due to practical limitations and very poor spectrum efficiency [9]. Its scalability is hence very low. Nevertheless, this approach provides a centralized monitoring system that enables the NMS to both detect and localize faults.

Electronic Solutions — Note that the functionality of an OTDR device can be implemented within the ONU at the customer side [10]. This approach, known as *embedded OTDR*, leverages the electronics at the ONU for a cost-efficient solution, such that embedded OTDR within the ONUs becomes an integral part of the monitoring network. In this scheme the monitoring segment transmits an OTDR trace from the ONU upon request of the NMS at the CO when the corresponding ONU is idle over the upstream channel. Therefore, this solution relies on in-band upstream signaling. As mentioned earlier, this solution is inadequate when a fiber cut happens, as all data and control channels linking the NMS to the ONU are disrupted.

Critical Issues for the Use of OTDR in PONs

As the basic equipment for the above automatic test systems, OTDR requires suitable technical characteristics. The most important performance characteristics of OTDR-based techniques are *spatial resolution*, *dynamic range*, *dead zone, wavelength stability*, and *minimum sensitivity* [4–7]. Adequate performance requirements should be met for an OTDR to be an effective monitoring solution for future PONs. For instance, as the splitting ratio increases, larger dynamic ranges are required. Increasing the transmitted pulse width is not an efficient solution, as it decreases the spatial resolution and enlarges the dead zone of the OTDR. Also, the launched power is limited due to nonlinear effects. Generally, the capacity of OTDR-based techniques are limited to tens of customers, and system scalability is a serious concern. Recall that although cost is an important issue, it is not critical since the OTDR is shared among network clients.

The leakage of the monitoring power from the U band to the data band (C and L) may cause performance degradation for data commu-

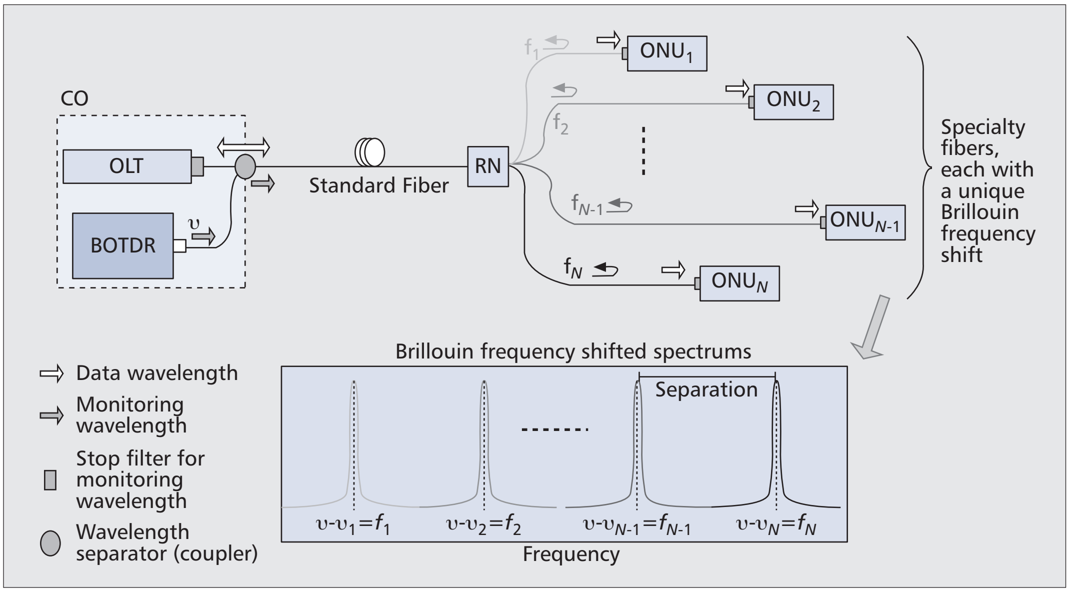

Figure 4. *Performance monitoring based on Brillouin frequency shift assignment.*

While the ITU recommendations propose the U band for monitoring applications, the behavior of passive components is not very well investigated for this wavelength regime. Due to the continuous advancement in related fields, OTDR-based techniques are expected to become more reliable in the future.

nications. Hence, strict isolation between the data and monitoring bands is required. As a result, optical sources with very high sideband suppression ratios and optical filters with high insertion losses are required [11]. Other critical issues for OTDR-based monitoring are the use of optical selectors, filters, reflectors, and WDM devices. These devices should be cost- and dimension-effective (i.e., low cost and high density) in order to be able to monitor a large amount of fibers in future access networks. While the ITU Recommendations propose the U band for monitoring applications, the behavior of passive components is not very well investigated for this wavelength regime. Due to the continuous advancement in related fields, OTDR-based techniques are expected to become more reliable in the future.

NON-OTDR-BASED TECHNIQUES

A variety of non-OTDR techniques have been proposed recently for the monitoring of link quality in a PON. In this article we focus on two of the most interesting, Brillouin frequency shift assignment (BFSA) and OC-based PON monitoring, and address their challenges and advantages.

BRILLOUIN FREQUENCY SHIFT ASSIGNMENT

This technique uses Brillouin-based OTDRs (BOTDRs) at the CO [11] and deploys specialty fibers in the distribution segment of the PON, as shown in Fig. 4. Each fiber branch is hence distinguished by a unique Brillouin frequency shift as a signature, and is called an *identification fiber*.

To monitor an individual fiber in a PON, an optical pulse with center frequency ν is launched through the network from the CO using a BOTDR. After the RN, subpulses are passed through different identification fibers, each of which scatters a unique pre-assigned Brillouin frequency. A specific identification fiber is then selected by monitoring the spectrum of the received signal. The frequency shifts are designed to have disjoint spectra for different branches. By observing peaks at center frequencies $f_k = \nu - \nu_k$, as shown in Fig. 4, the status of the identification fiber is monitored. Furthermore, by measuring the filtered backscattered optical signal for a specific branch, BOTDR achieves a unique trace that is identical to the trace provided by traditional OTDR in a point-to-point link. In principle similar to the multi-wavelength OTDR approach, this centralized technique provides a unique OTDR trace for each fiber branch that lies beyond the RN. Hence, it is capable of both detecting and localizing a fault at any branch of a PON.

While providing a centralized and complete characterization of the identification fibers, the BFSA technique imposes significant design challenges for the network infrastructure. This technique requires the identification fibers to be manufactured with different physical characteristics that generate and return different Brillouin frequencies. Each identification fiber, while scattering a unique Brillouin frequency shift, should naturally also operate as a data link to satisfy the data transmission requirements of PONs. In addition to involving high CAPEX, this technique has a dramatic impact on existing fiber network infrastructures, as new fibers have to be designed and all existing distribution fibers replaced. As the capacity of the network increases, so does the number of required identification fibers. This leads to more strenuous constraints on the required frequency shifts, implying the use of more advanced manufacturing technology with higher cost and complexity. This technique is hence not simply scalable and has yet to demonstrate its capability for the monitoring of currently deployed PONs with standard splitting ratios (e.g., GPON with 64 and 128 branches). Furthermore, the use of specialty fiber for subscriber drop cables adds substantially to the cost of network deployment, especially when the subscriber take rate (i.e., the anticipated number of subscribers) is low. Due to the aforementioned

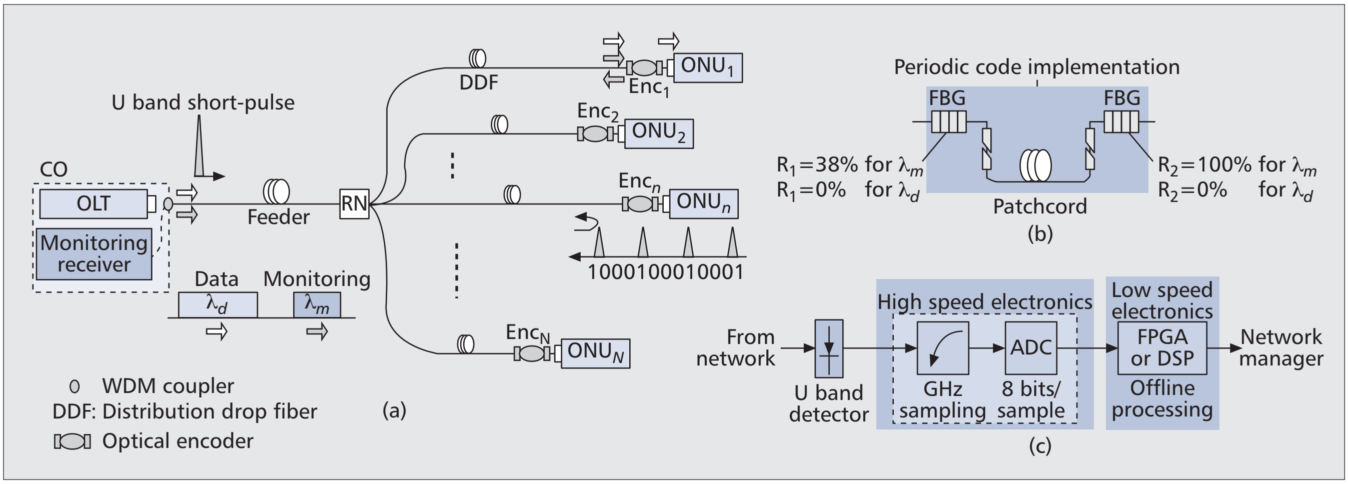

Figure 5. *OC-based PON monitoring: a) architecture; b) encoder; c) receiver for monitoring.*

reasons, this technique is very unlikely to be adopted commercially.

OPTICAL-CODING-BASED PON MONITORING

OC exploits signal-coding techniques (inspired by optical code-division multiplexing) for control- and management-layer signaling operations. In OC-based PON monitoring, passive out-of-band encoders (Enc_n) are placed at the extremity of each PON distribution fiber to identify and monitor it, as shown in Fig. 5a [12]. The data and monitoring signals occupy separate wavelength bands (Λ_d and Λ_m, respectively) consistent with emerging standards. An optical source at the CO transmits the out-of-band pulses downstream; an optical or electronic receiver at the CO processes the aggregate upstream reflected signal.

The encoders both reflect and imprint a unique code (i.e., specific to the PON branch) on the source pulses. Waveband separators split the data and monitoring wavebands at the ONU and the OLT. Alternatively, a combination of in-line encoders and monitoring band-stop filters may be used at the branch termination points prior to the ONUs, as is the case for RR-OTDR. The use of simple fiber Bragg gratings (FBGs) directly inscribed at the termination of drop fibers may be regarded as a particular case of OC-based PON monitoring. Although the simplest approach, the use of FBGs as wavelength reflectors shares the low scalability and bandwidth efficiency drawbacks of the multiwavelength technique described earlier. Nevertheless, the use of in-fiber FBGs is particularly attractive since it reduces monitoring power losses by removing the requirement for waveband separators at the termination of drop fibers.

While several encoders and receivers have been proposed, the most cost-effective and high-performance solution that has emerged is a combination of periodic codes [13] and an electronic receiver [14], illustrated in Figs. 5b and 5c. Periodic codes were developed exclusively for this application, and have low loss, low-complexity hardware, and good performance. Previously proposed encoders based on optical orthogonal codes exhibited much lower performance for this application [13].

A particularly attractive feature of this solution is the self-configuring nature of the network. Encoders are installed at the drop fiber ends without concern for the fiber length from the remote node, unlike RR-OTDR. Signal processing at the receiver differentiates returns even for remarkably similar fiber lengths (within meters). Customer relocations can be accommodated without a re-allocation strategy based on previous installations.

One of the challenges in evaluating any monitoring solution is predicting system capacity as it varies with the specific topology of the PON, whether legacy or greenfield. Simulations of specific topologies can be performed; however, they do not probe the generality of the solution. Statistical examinations of topologies can provide outage probabilities for the monitoring system in general.

Several research topics remain to bring this technology to the marketplace. Compact low-cost periodic encoders are essential. While previously proposed fiber delay lines are simple, mass production is problematic. An integrated solution for the encoder would reduce both cost and bulk. Signal processing challenges also remain to increase the coverage capability of the decoding algorithm. A reduced complexity maximum likelihood receiver has been proposed in [14], but is nonetheless suboptimal and may leave room for performance improvement.

The use of time- or wavelength-domain reflectors to identify PON branches, as in the reference-reflector and wavelength-based OTDR approaches, may be treated as particular cases of OC-based PON monitoring [15]. Compared to wavelength-domain reflection monitoring, code-domain reflection monitoring trades its more complex reflectors for higher scalability and bandwidth efficiency. Compared to time-domain reflection monitoring, it avoids the use of delay lines to differentiate branch fiber lengths and offers potentially higher scalability, particularly in the context of future long-reach PON (LR-PON) applications. Moreover, the extension of OC-based monitoring to LR-PONs may be facilitated through the use of in-line reflectors [15]. However, this places additional strain on the more stringent power budgeting constraints of code-domain monitoring.

OC-based monitoring does not require forklift upgrades of the PON distribution infrastructure, as does BOTDR. Consequently, the design of simplified and more cost-effective encoder and system architectures is a promising research direction [13]. Although OC-based monitoring does not offer complete fault localization (only fault identification on the branch), it is potentially more scalable than BOTDR. Therefore, it is well suited as a component within a hybrid solution, discussed in the next section.

SOLUTION PATHS TO SCALABLE COST-EFFECTIVE PON MONITORING

Our review of proposed optical-layer PON monitoring technologies reveals two distinct and complementary monitoring principles: standard reflectometry and the use of dedicated reflectors at the termination points of distribution fibers. While reflectors are capable of speedy identification of faulty distribution fibers, they lack any accurate fault localization capability. Conversely, whereas standard reflectometry methods are inefficient for distribution fibers, they are capable of yielding highly accurate fault localization in point-to-point settings. In addition, adapting standard reflectometry techniques for PON applications is neither economical nor practical, particularly due to their lack of scalability to larger PON sizes. In contrast, fault detection via the monitoring of reflected signals is potentially simple, cost-effective, and reliable.

Therefore, we expect that comprehensive monitoring methods will integrate both the aforementioned monitoring principles. To do so, it is necessary to break the monitoring procedure into two separate steps, whereby fault detection and the identification of faulty distribution fiber is carried out in real time through reflection monitoring, and precise fault localization is implemented subsequently through OTDR.

In currently deployed PONs, the implementation of reflection-based monitoring will enable faster troubleshooting, as they will allow the NMS to exclude customer equipment malfunctions as the cause for a loss of signal while indicating the faulty distribution fiber. Technicians equipped with high-resolution OTDR can thus be dispatched immediately for exact fault localization and root cause analysis. Hence, fiber plant degradation may be detected long before transmission errors occur or services fail. In future PON deployments where protection is expected to play an increasing role, reflection-based monitoring may be integrated with the protection schemes as triggers for implemented APS mechanisms, leading to reduced downtimes and higher quality of service.

CONCLUSIONS

Cost effectiveness and scalability are among the major requirements for in-service monitoring of PON fiber infrastructures. OTDR requires costly architectural enhancements to deliver fast automatic fault localization in PON tree topologies. In this work we review some of the most promising OTDR- and non-OTDR-based proposals for PON monitoring, and address the practical challenges facing their potential deployment. Rather than being exclusive, OTDR and alternative technologies such as reflection-based monitoring are complementary. Therefore, hybrid techniques should be investigated as promising solutions for delivering the maintenance and protection functionalities required by current and next-generation PONs. OC-based methods are particularly attractive to implement reflection monitoring in the context of increasing PON sizes.

Hybrid techniques should be investigated as promising solutions for delivering the maintenance and protection functionalities required by current and next-generation PONs. OC-based methods are particularly attractive to implement reflection monitoring in the context of increasing PON sizes.

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