Novel Monitoring Technique for Passive Optical Networks Based on Optical Frequency Domain Reflectometry and Fiber Bragg Gratings

Kivilcim Yüksel, Marc Wuilpart, Véronique Moeyaert, and Patrice Mégret

***Abstract*—An efficient monitoring method having a very short measurement time (a few seconds) is proposed. The equal-length branches can be effectively monitored, but also the information of temperature at any place in the network can be obtained. The feasibility of this technique is experimentally demonstrated.**

***Index Terms*—Optical layer; Monitoring; OFDR; PON; Sensing**.

I. INTRODUCTION

Fiber-to-the-x (where x is for home, building, curb, or node) technology using passive optical networks (PONs) is the most promising way to provide high-quality broadband access. In PONs, there are only passive elements between the optical line terminal (OLT) and the customer premises. A single optical fiber carries the whole traffic to a remote node, where the signal is split by a passive optical coupling device into separate fibers that run to the individual optical network units (ONUs) or optical network terminations (ONTs). Even though PON architecture is expected to lower the operation and maintenance expenses compared with solutions involving active devices, there is still a possibility for the operators to save a significant amount of operation and maintenance expenses by implementing efficient and simpler operation and maintenance processes on the physical infrastructure. It is clear that the development of reliable monitoring systems is required for the practical implementation of such networks. In today's PON networks the physical infrastructure is usually not entirely visible to the network management system. A physical layer monitoring strategy should therefore be viable and easily integrated into the network management system [1,2].

Several physical layer monitoring solutions based on optical time domain reflectometry (OTDR) have been proposed in the literature [3]. However, implementation of OTDR into tree-structured PONs brings several challenges: the lack of dynamic range to monitor the infrastructure after the splitter, a long measurement time due to averaging necessary to obtain a suitable OTDR trace and (in some solutions) repetition of the measurement on a large number of ONTs, and the reflection dead zone that makes it impossible to distinguish the monitoring reflection peaks from two similar-length branches [4].

Monitoring solutions based on optical frequency domain reflectometry (OFDR) recently appeared in the literature as an alternative approach [5,6]. These solutions require, however, either a very coherent laser source to reach an adequate measurement range (a few tens of kilometers) [5] or some complicated modulation schemes superimposed on the downstream data signal [6]. A very recent monitoring strategy based on interferometric devices placed at the ONTs relaxes the requirement on the linewidth of the light source [7]. However, this solution detects only the breaks (or disconnects) in the network. As an alternative approach, generation of a test signal by way of a self-injection-locked reflective semiconductor optical amplifier located at each ONU was proposed [8]. This approach, however, requires a protocol extension, and therefore is not directly applicable to all PON protocols.

In this paper, we describe a new monitoring method for PONs using an OFDR at the OLT and interferometer units (IF units) at the network terminals (ONU/ONT, fiber distribution hub, or network access-drop

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terminals). Each IF unit includes a uniform fiber Bragg grating (FBG) and creates a beat term (a peak) on the OFDR trace, which is used to check the integrity of the corresponding branch. Analyzing the beat terms of all branches allows an easy distinction of the faulty branch after the splitter. 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, our method fits well the *demarcation point* monitoring concept introduced by Hehmann and Pfeiffer [9] without the problems of power supply that they mentioned.

In addition to the easy determination of the faulty branch, the system directly measures the temperature in the network terminals such as ONU/ONT, fiber distribution hub, or network access terminals. Temperature measurement is realized by using the temperature sensitivity of the FBG's spectrum inside the IF units. We apply simple signal processing steps on the OFDR trace to deduce the Bragg wavelength shift of each FBG located in each IF unit. This information in turn gives the temperature evolution of the interferometer device's position.

In today's PON systems, temperature can be measured by the transceiver modules and used in combination with other physical parameters to detect aging effects to both optimize the economics of the components' (e.g., lasers) useful life span and reduce maintenance activities [9]. However, the physical layer parameters measured at all active components (ONT/ONU) should be collected at the OLT, which requires a software extension at the subscriber side together with some modifications of signaling protocols [9]. Moreover, in the outside-plant equipment, temperature measurement is not available to be used for monitoring functions to strengthen operation and maintenance tasks.

To the best of our knowledge, this is the first time that a surveillance system provides information about the physical parameters of the active as well as the passive network terminals in a fully optical manner. This functionality provides the monitoring system with the capability of foreseeing the evolution of temperature in the network terminals before some unexpected environmental conditions (such as high temperature or freezing due to an open remote terminal port) create severe consequences. As the measurements are realized in the physical layer, the method is readily applicable to all PON protocols without any software or protocol modifications in the transmission system.

The proposed method uses simple, mass-produced, passive components at the subscriber side (a simple interferometer device including an FBG). The measurement range is not limited by the coherence length of the light source, and the measurement time is much shorter than OTDR-based solutions. Finally, it can be used for networks with branches of equal length and can be easily tailored for different multiplexing schemes without disturbing the transmission system by the monitoring functions.

II. Principles of the Monitoring System

Figure 1 shows the schematic of a PON architecture implementing the proposed monitoring system. An OFDR unit is used at the OLT side and interrogates the interferometer units (IF units) located at the ONUs/ONTs side and at any other critical points (e.g., outside-plant distribution cabinet, fiber distribution hub, drop terminal) of the network.

The OFDR unit launches into the network a frequency-modulated continuous-wave signal (monitoring signal 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 that depends on the group delay difference between the signal paths of the IF unit. The optical frequency of the probe signal must be swept linearly in time. However the tunable laser source (TLS) inside the OFDR module shows unavoidable deviations from linear sweep during the measurements that can, however, be compensated [10]. The PON is further equipped with wavelength selective couplers to separate (combine) the wavelength range swept by the OFDR (represented by a single symbol $\Delta\lambda_m$ in Fig. 1) from the downstream or upstream information signal.

The composite signal, which includes the sum of the responses (beating signals) from all the 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 vi-

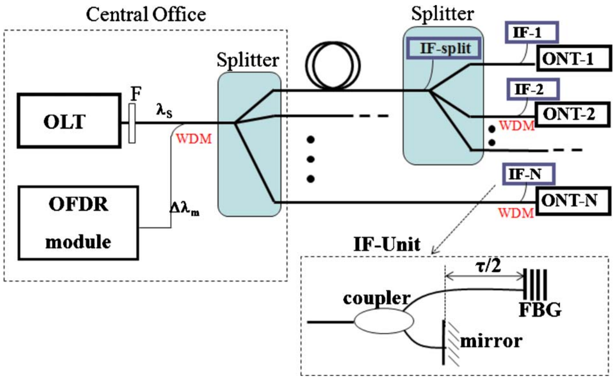

Fig. 1. (Color online) Optical functions present in the PON with the proposed monitoring method. (IF, interferometer unit; WDM, wavelength division (de)multiplexer; F, filter).

sualized in this way allow the integrity of the network to be checked. If one (a group) of the distribution branches fails, the corresponding IF-unit peak (group of peaks) on the OFDR trace will be influenced. For instance, the related peaks will disappear if some of the distribution branches are broken or disconnected.

By using properly designed IF units, in addition to determining the faulty branch in the network, one is also capable of measuring the ambiance temperature of the network location (ONU/ONT, fiber distribution hub, or network access-drop terminals) containing the IF unit. The key element to realize this functionality is the FBG used in the IF units as represented in Fig. 1. It can be shown that discrete reflections on the OFDR trace created by FBGs in the IF units are related to the FBGs' reflection spectra. Indeed, the reflection spectrum of each FBG modulates a sinusoidal function with a unique beat frequency. Therefore, the reflection spectrum of each FBG can be obtained by bandpass filtering the signal in the frequency domain around each beat frequency with a sufficient bandwidth. Then, an inverse fast Fourier transform (IFFT) on this selected portion can be used to recover the complex reflection spectrum of each grating independently from the others [11,12]. One should note that, after the IFFT process, the reflection coefficient of the FBGs can be mapped from the time scale to the wavelength scale under the condition that the wavelength of the laser source is swept linearly in time as schematically represented in Fig. 2. Finally, from the estimation of their Bragg wavelength and from their temperature characteristics, the temperature is deduced for each FBG in the network. These steps are depicted in Fig. 3.

Using Fig. 3, one can also see that our method equipped with IF units at the splitter positions provides the monitoring system with supplementary information about the location of the fault. For example, if the reflection peaks of a group of users (e.g., from IF-X to IF-N in Fig. 3) disappear, then the reflection peak of the IF unit located at the second-level splitter location (e.g., IF-3 in Fig. 3) gives the information on whether the break is before the splitter or in the drop cable after the splitter serving this group of subscribers even if the corresponding ONTs are not in operation.

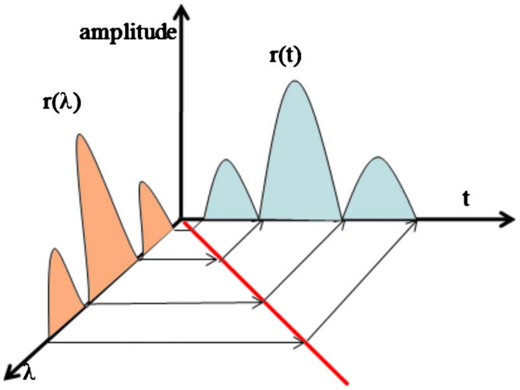

Fig. 2. (Color online) Mapping of the amplitude reflection coefficient as a function of wavelength into the amplitude reflection coefficient as a function of time under the condition that the wavelength of the TLS is swept linearly in time.

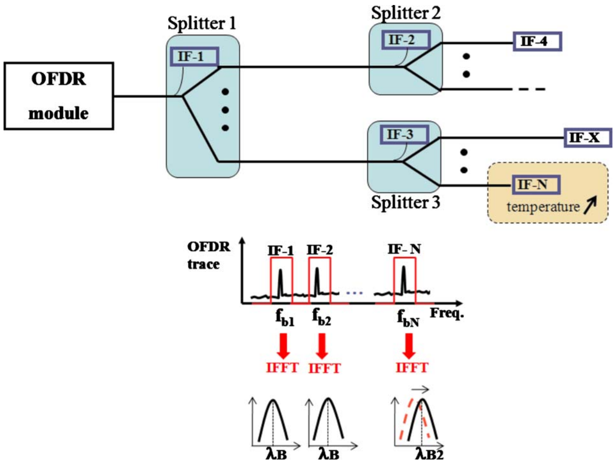

Fig. 3. (Color online) Operation principles for temperature sensing.

Additional information on the temperature evolution at the splitter location in some cases facilitates finding the origin of the fault (e.g., a temperature increase due to an open door of a distribution cabinet).

III. Experimental Validation

A demonstration of the concept using an eight-branch network was realized with the experimental setup depicted in Fig. 4. The setup comprises the OFDR module, a feeder fiber, a power splitter, distribution fibers, and three IF units.

The OFDR unit includes a tunable laser source whose frequency is swept continuously in time, a balanced photodetector, a data acquisition card (DAQ in Fig. 4) used to take the measurement points at the photodetector output, and a signal processing unit [10]. In place of the TLS, other types of sweepable

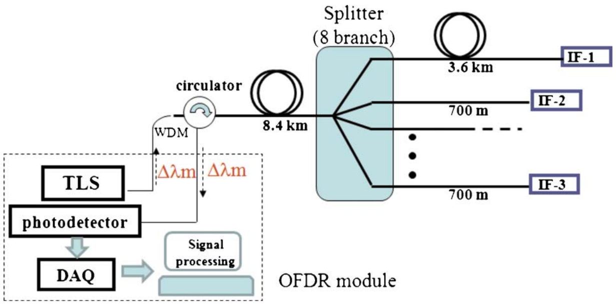

Fig. 4. (Color online) Experimental setup.

light sources can be used [7]. The nominal tuning rate (γ) of the TLS is set to about 3 THz/s. The wavelength of the TLS is swept on about a 2.5 nm sweep span over a 100 ms sweep time. The wavelength range is centered on 1583 nm, which is located outside the wavelength bands used for the data and is allocated for future use in PON protocols. The dynamic of the OFDR is good enough that the beat terms from IF units are not influenced by the location of the IF unit (the distance between the OFDR module and the IF unit in the network) over the classical distance range for PONs (20 km).

The 1×8 splitter is located at 8.4 km from the OFDR module. Three distribution fibers (3.6 km, 700 m, and 700 m) are connected to the IF units. The unwanted reflections from five unused output ports of the splitter are avoided by a proper termination.

The IF units used are Michelson-type interferometers having a uniform FBG in the test arm and a broadband reflector in the reference arm. The group delay mismatch between both arms of the IF units are 4.0 ns (τ_1), 4.6 ns (τ_2), and 8.0 ns (τ_3) for IF-1, IF-2, and IF-3, respectively. The beat frequencies created by IF-1, IF-2, and IF-3 can be expressed as $f_{bi}=\gamma\tau_i$, where γ is the optical frequency chirp rate and τ_i is the optical group delay difference of the ith IF unit. This equation gives the calculated beat frequencies as 11.9, 13.7, and 23.6 kHz for IF-1, IF-2, and IF-3, respectively. The order of magnitude of the path length distances of the IF units varies from 40 up to 80 cm. This range is far below the coherence length of the TLS (having a linewidth of 150 kHz).

The gratings used in the experiments were inscribed with hydrogenated single-mode fiber in our clean room facilities by using the phase-mask technique. The gratings in all the IF units are identical and are characterized by a Bragg wavelength of 1583.7 ±0.2 nm at room temperature, a small reflectivity below 10%, and a physical length of 2 mm. Even if all FBGs are written with identical process in order to have the same characteristics, slight variations in terms of Bragg wavelength may occur. Each grating is therefore characterized by an individual temperature calibration slope (using our demodulation technique). Once this is done before the installation of IF units inside the network, the slight variations between FBGs do not affect the temperature measurements during network maintenance.

As an example, Fig. 5 shows the experimental evolution of the Bragg wavelength as a function of temperature obtained by our interrogation system comprising an OFDR and a single IF unit (IF-2). The FBG in the IF unit was exposed to temperatures (within 0.1°C) between room temperature and 100°C with a 10°C step. The slope computed on the linear fit (or grating sensitivity) of the evolution is equal to 10.06 pm/°C.

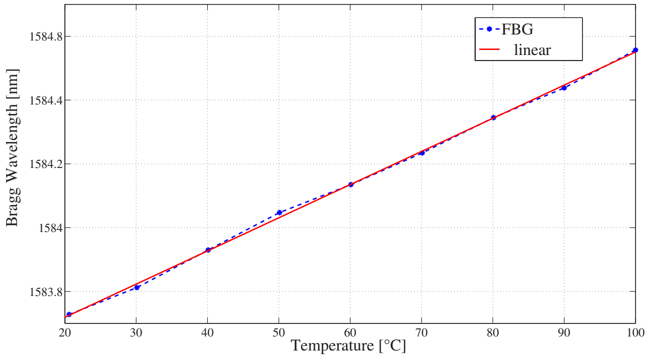

Fig. 5. (Color online) Evolution of demodulated Bragg wavelength as a function of temperature for IF-2.

In order to explain our detection methodology, let us detail one faulty case example. In this scenario, IF-2 is subject to a temperature of 50°C and branch 1 is disconnected. A reference OFDR trace is taken when there is no fault in the network, and IF units are subject to room temperature (21.5°C). The composite signal, which includes the sum of the beating signals from all the IF units, is shown in Fig. 6. Another measurement is taken for the faulty case. The composite signals in the time domain are converted into the frequency domain in order to observe the beat frequencies. Figure 7 compares the OFDR spectra for the reference and the faulty cases. The reflection peak related to IF-1 disappears, indicating a fiber break or a disconnection in branch 1 of the distribution part of the network. One should also note that in our method each IF unit has a unique frequency component (beat frequency). This means that the reflected signal from each IF unit can be distinguished from the others even if the IF units are located at the same distance

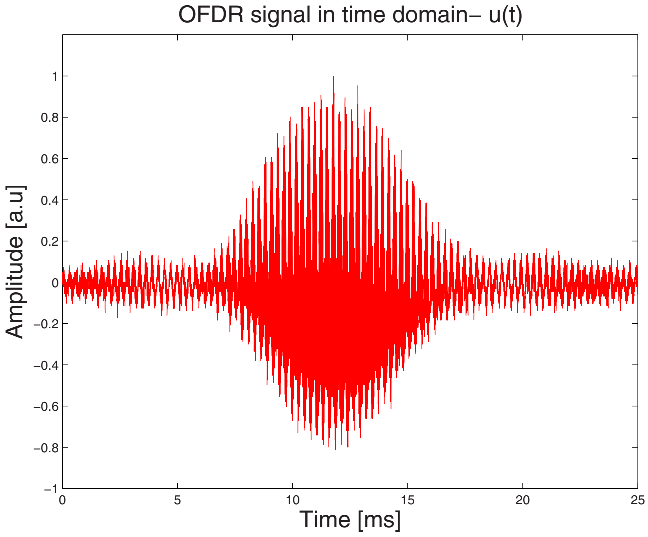

Fig. 6. (Color online) OFDR signal in time domain.

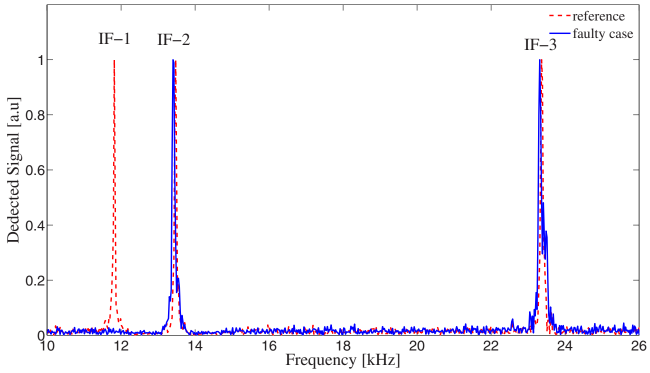

Fig. 7. (Color online) Detected OFDR spectra for the reference and faulty cases.

from the central office. In other words, the faulty branch can be distinguished even if the branches have equal lengths when properly designed IF units are placed in the fiber ends at the subscriber side.

The temperature changes on all the IF units (except IF-1, which is disconnected) are interrogated by applying bandpass filtering and the IFFT. In order to recover the reflection spectrum of each FBG, the OFDR spectrum is bandpass filtered around the corresponding beat frequency, and the selected portion is inverse Fourier transformed. The changes in the Bragg wavelength can then be recorded for each FBG. The reflection spectrum of the FBG inside the IF-3 does not change between the reference measurement and the test measurement performed after the faults were introduced into the network. However, the shift in the Bragg wavelength is clearly seen on the demodulated reflection spectrum of the FBG used in the IF-2 (Fig. 8). This wavelength shift is equal to 290 pm, which corresponds to a 29 °C temperature change. The real temperature difference on the IF-2 between the first and the second measurement was 28.5 °C (50.0 °C–21.5 °C). Then the measurements were repeated 10 times with the IF-2 subject to 50 °C. These repeated measurements gave a standard deviation of 0.5 °C on the measured temperature.

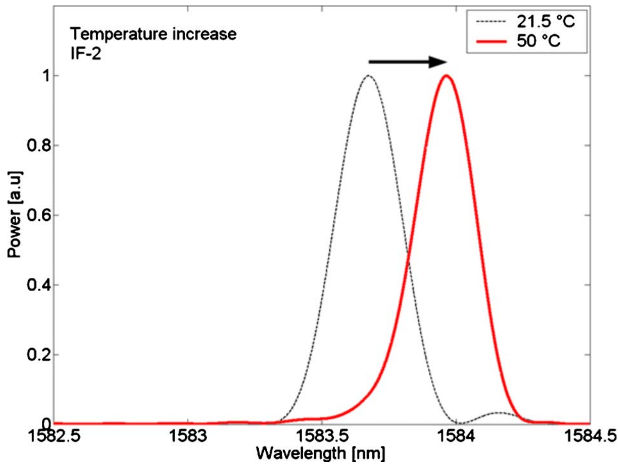

Fig. 8. (Color online) Demodulated reflection spectra for the FBG inside the IF-2 for the reference and faulty cases.

Detection of faulty branches and measurement of the temperatures of all IF units takes only a few seconds (100 ms TLS scan time plus signal processing), and this measurement time does not increase with the number of IF units.

The width of the bandpass filters applied to the reflection peaks in our experiment (shown in Fig. 7) is about 200 Hz, which means that for the given γ (3 THz/s), a number of 128 IF units can easily be allocated over about a 26 kHz electrical bandwidth. The electrical frequency band used can be tailored by changing the chirp rate.

IV. CONCLUSION

An efficient monitoring method was proposed and applicability was demonstrated. The main advantage of the method is that it provides the information of temperature at any place in the network, which improves the preventive maintenance capability. The measurements give 0.5 °C standard deviation on a measured temperature. The proposed solution is applicable for any kind of multiplexing scheme (TDM, WDM) without the need of any protocol extension and without disturbing the transmission system. Moreover, measurement time is considerably short (a few seconds) compared with OTDR methods.

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