Monitoring in the Physical Channels of Optical Access Networks

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Abstract: This research concerns the issues of monitoring in the physical channels optical access networks. This is relevant because automated diagnostic and monitoring systems in passive optical networks (PONs) are not available at the moment. The authors discuss the technique for monitoring physical channels of the tree topology in PONs by Brillouin optical time domain analysis (BOTDA) using end reflections. The paper analyses the main factors affecting the transmission and mechanical characteristics of the optical fiber, presents the results of the comparative analysis of optical fiber deformation measurement methods, and justifies the application of the technique based on the principles of Mandelstam-Brillouin scattering. Also, it provides the theoretical basis and the calculated relations, which allow us to evaluate the main functional capabilities of BOTDA reflectometry. The feasibility of monitoring the physical channels of the tree topology of the optical access network by Brillouin analysis in the time domain using end reflections is evaluated.

1 INTRODUCTION

To date the number of users of fiber to the home (FTTH) services is growing rapidly, and telecom operators are striving to reduce the maintenance costs related to a huge amount of optical equipment. To provide FTTH services in an optical access network, they commonly employ a passive optical network (PON) which decreases the requirements for the optical cable and the provider's maintenance equipment. However, there is a problem of diagnostics due to remote monitoring of PON parameters.

Conventional Optical Time Domain Reflectometer (OTDR) has already found its practical application as a remote testing technology. Nevertheless, when an optical splitter is installed in the access network, backscattering signals from the branched fibers behind the splitter overlap on the backbone fiber. Therefore, it is problematic to identify a malfunction in a single branch of a tree topology with several splitters and subscriber nodes from the central office using OTDR. In this regard, the reduction of maintenance operations carried out by remote OTDR testing remains limited. On the other hand, most commonly used FTTH networks use PONs with an external splitter. So, this substantiates the urgency to develop remote testing technology outside of the splitter for the needs of the telecommunications industry. This work aims to increase the scalability and reliability of fault detection technique in optical fiber, and make it compatible with a branched topology. In addition, we apply the basic principle to communication networks and refine the performance of monitoring systems in the mode of remote testing of PON subscribers' facilities. This paper is the first to describe the distributed optical sensing technology for a branched topology, designed to improve the scalability of connection and reliability of optical sensor systems. When conducting probing in an extended network, monitoring can be continued using other branches, even if one of them is broken. In addition, by adding optical splitters to the network, one can easily expand the detection area at any time.

2 BASIC REQUIREMENTS FOR THE MONITORING SYSTEMS

Telecom operators impose the following requirements for monitoring systems [1]:

- the ability to detect and locate faults in each branch of the distributed network;
- the ability to automatically collect information about the parameters of the physical environment, there is no need for technical specialists to visit the site and the user of telecommunication services is not involved;
- the demarcation function which allows the operator to distinguish between their responsibility and the responsibility of the client;
- no active components in the field between the central office and the client's facilities;
- system’s reliability which is ensured by the system’s ability to perform its necessary functions for a certain period of time;
- scalability as the ability of the monitoring method to smoothly process changes in the net-work infrastructure;
- the monitoring technique should be applicable to available deployed networks without changing the network infrastructure;
- cascading of remote nodes should not represent an obstacle for the monitoring system;
- notification time defined as the time between the occurrence of a fault and its detection should be as short as possible;
- the cost of the monitoring system, which is a critical characteristic for any service operator;
- complexity of feasibility and practical implementation;
- independence from the client as it facilitates service and increases clients’ satisfaction.

Monitoring systems based on the principles of Mandelstam - Brillouin scattering meet the above requirements to a greater extent.

3 FUNDAMENTALS OF BRILLOUIN OPTICAL TIME DOMAIN ANALYSIS (BOTDA)

An optical measurement method using Brillouin scattering is a method that uses the linear dependence of the Brillouin frequency shift (BFS) on temperature change or deformation. To determine BFS, the peak frequency of the Brillouin gain spectrum (BGS), observed with the help of the fit function, is used. Brillouin scattering is the inelastic scattering of photons by acoustic phonons. The Brillouin frequency shift is determined by (1)

$$\nu_{\text{B}} = \frac{2nV_A}{\lambda_u}, \quad (1)$$

where V_B is the Brillouin frequency shift; n is the refractive index of the core material; V_A is acoustic wave velocity; λu is the wavelength of the pump light.

For an optical fiber made of silica (refractive index n = 1.45), at the speed of sound V_A = 5.96 km/s, the frequency shift caused by Brillouin scattering in the wavelength band 1.55 microns is approximately 11.1 GHz [2].

Brillouin measurement methods track the linear increase in BFS that occurs with an increase in temperature [3] or tensile deformation [4]. This dependence is due to the dependence of the acoustic velocity in the optical fiber on temperature and deformation.

Equations (2) and (3) express the dependence of BFS on temperature and tensile strain, respectively.

$$\nu_{\text{B}}(t) = \nu_{\text{B}}(t)[1 + C_t(t - t_r)] \quad (2)$$

$$\nu_{\text{B}}(\varepsilon) = \nu_{\text{B}}(0)[1 + C_s\varepsilon] \quad (3)$$

Here t is the temperature, t_r is the initial temperature, and ε is the tensile strain.

C_t and C_s are linear coefficients for temperature and strain changes of 1.10 MHz/°C and 0.0483 MHz/με, respectively, at a wavelength of 1553.8 nm [5].

Since temperature and strain changes cannot be measured separately, the change in BFS $\delta\nu_B$ is sometimes expressed by (4)

$$\delta\nu_{\text{B}}(t, \varepsilon) = C_t\delta t + C_\varepsilon\delta\varepsilon. \quad (4)$$

Here, δt and $\delta\varepsilon$ represent temperature changes and deformations, respectively. In practice, a reference optical fiber or reference data is prepared to compensate for changes in temperature or deformation that are not intended for measurement.

To determine BFS, a fit is applied to the resulting BGS. BGS has a form that can be approximated by the Lorentz function with a central frequency ν_B and a spectrum width at 0.5 relative to the maximum $\Delta\nu_B$. In the case of a quadrature fit, the measurement error of BFS can be estimated using (5) [6].

$$\sigma_\nu(z) = \frac{1}{SNR(z)}\sqrt{\frac{3}{4}\delta * \Delta\nu_{\text{B}}} \quad (5)$$

Here *SNR(z)* is the signal-to-noise ratio (SNR) of the BGS peak in the z coordinate, and δ is the frequency sampling step ($\delta << \Delta\nu_B$).

Equation (5) shows that the detectable minimum change in BFS decreases inversely with the SNR of the measured BGS distribution and increases as the square root of the frequency sampling step δ.

Brillouin Optical Time Domain Analysis (BOTDA) measures the intensity of Brillouin scattering as a function of time. When the photodetector response rate is high enough, the spatial resolution corresponds to the width of the pump light pulse.

The spatial resolution δz is expressed by (6) [7]

$$\delta z = \frac{vW_u}{2} \quad (6)$$

Here v is the group speed of light in the optical fiber, and W_u is the pulse width of the pump light. The spatial resolution of a standard BOTDA is limited to 1 m.

This is due to the fact that the phonon lifetime is about 10 ns, and it is difficult to implement a pump pulse width of less than 1 m.

To measure BFS along a sensitive fiber, it is necessary to obtain the BGS distribution as a frequency dependence of the Brillouin gain intensity.

Figure 1 shows the diagram of a typical BOTDA system.

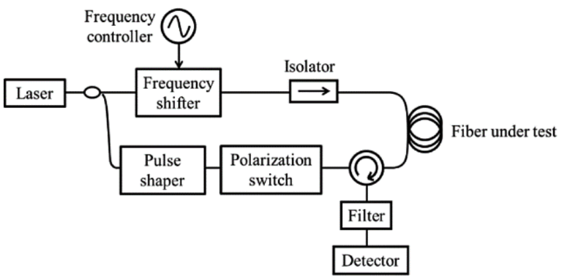

Figure 1: Diagram of a typical system of BOTDA.

The laser output signal is separated by a connector to form a pump light and a probe light. As a rule, the pump light is a pulsed light, and the probing light is launched from the opposite side using a continuous beam. The Brillouin interaction occurs during the collision of test beams in the tested fiber.

To generate a Brillouin interaction between the test beams, the frequency of the probing light is lowered using an optical frequency converter BFS (approximately 11 GHz at a wavelength of 1.55 microns). The pump light is generated by a pulse generator, such as an electro-optical modulator, an acousto-optical modulator, or a semiconductor optical amplifier.

To eliminate the polarization dependence of the Brillouin gain, a polarizing scrambler or polarization switch is turned on in the optical path of the pumping or probing light. Rayleigh scattering of pump light, which is an unnecessary component of the signal, can be eliminated by using an optical filter with a narrow line width, such as Bragg fiber lattice (FBG). The distribution of the gain spectrum by Brillouin can be obtained using the abovementioned measuring system.

4 FUNDAMENTALS OF END REFLECTIONS ASSISTED BRILLOUIN ANALYSIS (ERA-BA)

There has recently been proposed End-reflection-assisted Brillouin analysis (ERA-BA), which is able to measure the individual characteristics of branched fibers based on BOTDA [9]. ERA-BA measures the characteristics of branched fiber by analyzing the Brillouin gain caused by the collision between the pump pulse and the probing pulse reflected from the far end of the split. The ERA-BA branched fiber measurement technique allows remote testing of all optical access networks that include branched fibers, and significantly reduces the number of *in situ* operations. We can expect this technique to provide high-quality maintenance of extremely large network facilities at low cost and with a small workforce.

Figure 2 is a schematic illustration showing the principle of ERA-BA operation [8].

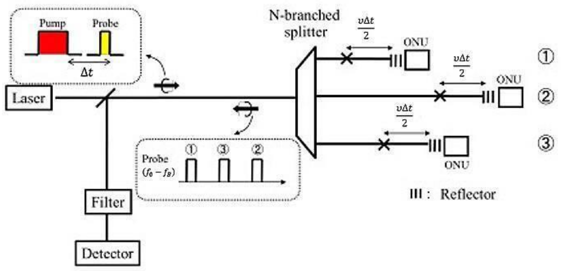

Figure 2: Schematic illustration of the ERA-BA principle.

ERA-BA is an optical measurement technique that measures the characteristics of each branched fiber from the backbone fiber side. Here, the characteristics are optical losses, as well as temperature changes and deformations. The characteristics of the branched fiber are measured using Brillouin gain analysis using a collision between a pump pulse and a probing pulse returning from the far end of the branch. The dependence of the Brillouin gain impact on the pump power is useful for measuring losses in branches. Meanwhile, BFS which varies with temperature and strain changes is measured to identify an optical fiber with a branched fiber topology.

To provoke a collision of test pulses in the branched fibers, we need an optical filter that reflects the test pulse at the far end of the branched fiber. The pump pulse is triggered after a probing pulse with a time delay Δt for collision at the position $v\Delta t/2$ from the far end. The distribution can be measured by sequentially changing the time delay Δt. To generate long–range reflection in the available access network efficiently, we can use a test light cut-off filter, as recommended in ITU-T L.66 [10].

On the other hand, for probing with a branched fiber, we can use an FBG filter or a full reflection filter designed for the wavelength of the probe.

The difference in the time of the return of the flyback probing pulses caused by the different lengths of the branched fibers is used to determine the signals from the branched fiber. To identify the branched fibers, we at least should know the difference in the branch length δL, expressed by (7). This is referred to as branch identification resolution.

$$\delta L = \frac{\nu W_r}{2}, \tag{7}$$

where W_r is the width of the probing pulse.

For telecommunication networks, since the branched fiber lengths randomly differ by several meters, the target performance of fiber identification resolution should be equal to or greater than this value.

For branched fibers identification, the difference in the lengths of the branches can be arbitrarily set using an additional delay fiber. The spatial resolution can be determined by (7) using the pump pulse width, as in the conventional BOTDA.

To describe the configuration, let the lengths of the branches with respect to the shortest branch be $0<t_1<t_2$, –, $<t_{N-1}$. And the t_i values are written in terms of the roundtrip times to the end of each branch. The total branched sensing range is assumed to be T.

The technology proposed here uses a series of probe pulses and a single pump pulse instead of a single pair of probe and pump pulses. The probe beam consists of a series of pulses with a pulse width of $\Delta tpro$, a repetition interval of ΔT, and a train length that nearly equals the entire sensing range, T. A single pump pulse with a Brillouin frequency shift (BFS) accompanies the probe pulse train with an interval of Δt after the last probe pulse. The probe pulses are reflected by the end reflectors in each branch, and the m-th probe pulse collides with the pump pulse and acquires the Brillouin gain at a distance of $vg(\Delta t+m\Delta T)/2$ from the end reflectors in every branch, where vg is the light velocity and m is an integer (0). The entire range, T, can be analyzed by scanning Δt from 0 to ΔT (instead of scanning the entire range, T).

To determine the Brillouin gains yielded in the branches individually, the probe pulses, which are recombined at the splitter, must not overlap each other. In other words, the probe pulses from different branches must be located in different time slots. Probing pulses from the branches should be in different time intervals. We can implement this by changing the optical length of the fiber. To increase the data collection rate, we propose a fiber sensor design that employs different BFS fibers for the feeder and branched fibers. Since no Brillouin interaction occurs on the feeder fiber, the test beam repetition rate (data collection rate) is decided solely by the roundtrip time of the longest branched fiber (excluding the roundtrip time of the feeder fiber). Additionally, in terms of pump depletion, the effect does not occur in feeder fiber. To benefit from the use of different BFS fibers in the sensing fiber topology, the difference between the BFSs of the feeder and branched fibers should be designed to be sufficiently wider than the expected BFS change caused by temperature or strain.

5 CONCLUSIONS

Operators of telecommunication services still do not have at their disposal automated diagnostic and monitoring systems in passive optical networks, which would improve the maintenance efficiency, increase operational reliability and safety of company’s optical networks. Nevertheless, the analyzed technique for monitoring physical channels of the tree topology in a passive optical network by BOTDA using end reflections sufficiently meets the criteria for fiber optic cable maintenance to test the fiber of access networks ITU–T L.66, (2007) in service. Here we have proposed a new measurement technique that provides high-speed monitoring with greatly simplified equipment settings. The possibility of practical application of this technique for in telecommunications is proved. It can be implemented as a loss distribution measurement technology for branched fiber PONs without making any changes to the network configuration. According to the authors, further development in the field of fiber optic sounding would be the study of limiting functionality, the metrological substantiation of technical requirements for the main components and the creation of a metrological support system for monitoring systems.

REFERENCES

[1] M. Rad, K. Fouli, H. Fathallah, L. Rusch, and M. Maier, “Passive Optical Network Monitoring: Challenges and Requirements,” IEEE Communications Magazine, vol. 2, no. 49, pp. S45-S52, Feb. 2011.

[2] G.P. Agrawal, “Nonlinear Fiber Optics,” 4th Edition, Academic Press, 529 p., 2007.

[3] T. Kurashima, T. Horiguchi, and M. Tateda, “Thermal Effects on Brillouin Frequency Shift in Jacketed Optical Silica Fibers,” Appl. Opt., vol. 29, no. 15, pp. 2219-2222, 1990.

[4] T. Horiguchi, T. Kurashima, and M. Tateda, “Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers,” IEEE Photon. Tech. Lett., vol. 1, no. 5, pp. 107-108, 1989.

[5] T. Horiguchi, T. Kurashima, and M. Tateda, “Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers,” IEEE Photon. Tech. Lett., vol. 1, no. 5, pp. 107-108, 1989.

[6] M. Soto and L. Thévenaz, “Modeling and Evaluating the Performance of Brillouin Distributed Optical Fiber Sensors,” Opt. Express, vol. 21, no. 25, pp. 31347-31366, 2013.

[7] T. Horiguchi, K. Shimizu, T. Kurashima, M. Tateda, and Y. Koyamada, “Development of a Distributed Sensing Technique Using Brillouin Scattering,” J. lightw. Technol. vol. 13, no. 7, pp. 1296-1302, 1995.

[8] H. Takahashi, F. Ito, C. Kito, and K. Toge, “Individual Loss Distribution Measurement in 32-branched PON Using Pulsed Pump-probe Brillouin aAalysis,” Opt. Express, vol. 21, no. 6, pp. 6739-6748, 2013.

[9] F. Ito, H. Takahashi, K. Toge, and C. Kito, “End reflection assisted Brillouin measurement for PON monitoring,” OECC2013, pp. MS2-1, 2013.

[10] “Optical Fibre Cable Maintenance Criteria for In-service Fibre Testing in Access Networks,” ITU-T L. 66, 2007.