Correlation-based OTDR for in-service monitoring of 64-split TDM PON

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Abstract: We demonstrate that the correlation-based optical time domain reflectometer (OTDR) can be used for the in-service monitoring of the 64-split time-division-multiplexed passive optical network (TDM PON). To achieve this objective, we superimpose a pseudo noise (PN) sequence having a modulation depth of ~40% to the downstream signal and utilize it for the correlation detection. However, the use of such a large PN sequence can seriously deteriorate the performance of the downstream receiver. Thus, we apply 8B/10B encoding to the downstream signal, and then filter out the PN sequence at the downstream receiver by using a high-pass filter. As a result, the power penalty caused by the use of a large PN sequence is reduced to an acceptable level (<3 dB), while the dynamic range of this correlation-based OTDR is increased to ~30 dB. We then evaluate the performance of the proposed OTDR in the fiber link similar to the optical distribution network of the 64-split TDM PON. The results show that this OTDR can detect both the reflective and non-reflective events occurred in the feeder fiber as well as the reflective events in the drop fibers even in the 64-split TDM PON.

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References and links
1. R. Heron, “Next generation optical access networks,” in Proc. of Access Networks and In-house Communications 2011, paper AMA2.
1. Introduction

During the last decade, the time-division-multiplexed passive optical network (TDM PON) has been massively deployed all around the world [1]. However, to minimize the downtime of these networks, we should be able to detect and localize any fiber failures in the outside plant without delay. At present, the conventional optical time domain reflectometer (OTDR), which measures the loss traces in the transmission fiber by transmitting short optical pulses and analyzing their backscattering signals, is typically used for this purpose [2–4]. However, this technique can be too expensive for the in-service monitoring of the TDM PON, since it requires not only an additional high-power light source at the optical line terminal (OLT) for the generation of the OTDR pulse, but also the installation of a blocking filter at every optical network unit (ONU) to prevent the saturation of the downstream receiver by the OTDR pulse. In addition, the intense OTDR pulse can cause a penalty on the signal’s performance through Raman scattering [5, 6]. To solve these problems, we have recently proposed a new OTDR based on the correlation detection [7]. Since this technique utilizes the downstream signal itself as a probe signal (instead of using the intense OTDR pulse operating at the supervisory wavelength), there is no need to use an additional light source at the OLT or a blocking filter at every ONU. However, the dynamic range of this correlation-based OTDR depends highly on the statistical property of the downstream signal, and, as a result, it is difficult to detect the Rayleigh backscattered signals. In this paper, we overcome this limitation by utilizing the pseudo-random noise (PN) sequence superimposed on the downstream signal [8]. Since we use a PN sequence having superior correlation characteristics to the downstream signal such as the maximum-length sequence (MLS), the background noise level is drastically reduced. Our objective is to further improve the dynamic range of this correlation-based OTDR to ~30 dB, so that it can be used for the in-service monitoring even in a 64-split TDM PON [9]. For this purpose, we need to increase the modulation depth of the superimposed PN sequence to ~40%. However, such a large PN sequence can seriously deteriorate the sensitivity of the downstream receiver. Thus, we apply 8B/10B encoding to the downstream signal and filter out the superimposed PN sequence at the downstream receiver by using a high-pass filter [10]. We then evaluate the performance of the proposed correlation-based OTDR using the fiber link similar to the optical distribution network of 64-split TDM PON. The results show that this OTDR can be used for the in-service monitoring of the non-reflective events (caused by the connector loss, bending loss, and splicing loss, etc.) as well as the reflective events in such a network.

2. Principle of operation and experiment

Figure 1 shows the schematic diagram of an OLT implemented with the proposed correlation-based OTDR. We modulated the downstream transmitter using a 2.5-Gb/s signal in non-return-to-zero (NRZ) format. For the correlation detection, we also superimposed an MLS PN sequence (length: 2^15-1, chip rate: 5 Mchip/s) to the downstream signal. The backscattered signal was detected by using a photodetector. After the detection, we removed the unwanted high-frequency components from this backscattered signal by using a low-pass filter (LPF) having a cut-off frequency of 4 MHz. The filtered signal was sampled at the rate of 10 Msample/s with 12-bit resolution. We then obtained the OTDR trace by calculating the cross-correlation function between the sampled signal and PN sequence.
Fig. 1. Schematic diagram of the correlation-based OTDR. The inset shows the electrical spectrum of the signal measured (A) at the input of the downstream transmitter, and (B) after the high-pass filter at the downstream receiver.

The operating principle of the correlation detection used in the proposed OTDR is similar to that used in the random cw lidar [11]. We denote the sampled voltages of the launched and backscattered signals by $\nu_0$ and $\nu_b$, respectively. Although both of these signals are noise-like, we can obtain the OTDR trace from the cross-correlation function between them [7, 8]:

$$q(t) = \langle \nu_0(t) \cdot \nu_b(t + \tau) \rangle = \eta \phi_s(\tau) \otimes R(\nu_s / 2) \otimes \xi(\tau)$$  \hspace{1cm} (1)

where $\otimes$ represents the convolution, $\phi_s$ is the autocorrelation function of the superimposed PN sequence, $R(z)$ is the distribution of the reflectivity, $v_c$ is the velocity of light in the fiber, and $\xi$ represents the response of LPF. When the MLS sequence is used for the correlation detection, $\phi_s$ has nearly an ideal delta-function shape with a low background noise level [7]. As a result, $q(t)$ can be considered as a replica of the distribution of the reflectivity, $R(z)$. However, in practice, there are various noise sources including the thermal noise of the photodetector. Nevertheless, since these noises are not correlated with the superimpose PN sequence, their effects can be averaged out by the cross-correlation operation, while the correlated components accumulate coherently. This indicates that the signal-to-noise ratio (SNR) can be improved if the PN sequence is sufficiently long (i.e., by providing the correlation gain [8]). Thus, by using a long PN sequence, we can obtain a clear OTDR trace even if the amplitude of the PN sequence is small. However, to detect both the reflective and non-reflective events in a 64-split TDM PON by using the proposed correlation-based OTDR, we must further increase its dynamic range. For this purpose, it is indispensable to use a large modulation depth for the PN sequence. However, the use of such a large PN sequence can

Fig. 2. Schematic diagram of the optical test link used to evaluate the performance of the proposed correlation-based OTDR in a 64-split TDM PON
seriously deteriorate the performance of the downstream signal. To solve this problem, we encoded the downstream signal with 8B/10B code. Since the low-frequency cutoff of the 8B/10B encoded 2.5-Gb/s downstream signal was ~70 MHz, we could easily filter out the superimposed PN sequence (5M chip/s) at the downstream receiver by using a high-pass filter. As a result, we could suppress the power penalty caused by the superimposed PN sequence to be less than 3 dB, even when its modulation depth was increased to 40%. Under this condition, the achievable dynamic range of the proposed OTDR was measured to be ~30 dB (which is similar to the maximum optical path loss of the 64-split TDM PON [9]).

3. Performance evaluation in 64-split TDM PON

To evaluate the performance of the proposed OTDR based on the correlation detection, we emulated the optical link of the 64-split TDM PON by using a 20.8-km long feeder fiber, a 1x4 coupler, four 13-dB optical attenuators, and four drop fibers of various lengths (1.57 km ~5.06 km), as shown in Fig. 2. The insertion loss of the 1x4 splitter was 6.6 dB. Thus, we could emulate the insertion loss of a 1x64 splitter (typically 20 dB ~21 dB) by using this 1x4 splitter together with 13-dB optical attenuators. The reflective events were emulated by using open connectors at the end of the drop fiber.

A distributed-feedback laser diode (DFB-LD) operating at 1550 nm was used for the downstream transmission. We set the bias current of this DFB-LD to be 40 mA. The optical power of the 2.5-Gb/s downstream signal launched into the feeder fiber was measured to be 3 dBm. We then evaluated the effect of the superimposed PN sequence on the performance of the downstream receiver by measuring the bit-error rate (BER) curves of the downstream signal. Figure 3 shows the results. When we did not use the 8B/10B encoding, the receiver sensitivity was seriously degraded (>5 dB) even if we set the modulation depth of the superimposed PN sequence to be only 10%. However, when we applied 8B/10B encoding to the downstream signal and filtered out the superimposed PN sequence at the ONU by using a high-pass filter (cut-off frequency: 4 MHz), this penalty was substantially reduced. For example, Fig. 3 shows the BER curves of the 8B/10B encoded downstream signal measured while varying the modulation depth of the superimposed PN sequence. The power penalty caused by the superimposed PN sequence was measured to be <3 dB (@ BER = 10^{-9}), even when we increased the modulation depth to 40%. Thus, we set the modulation depth of the superimposed PN sequence to be 40%. Then, we measured the cross-correlation function and took an average of 1,000 measured traces. The sampled data contained a period of PN sequence (i.e., 65,534 chips at 5 Mchip/s) and its duration was 13 ms. Thus, the measurement time was 13 sec.
Figure 4(a) shows the measured OTDR trace by using the proposed correlation-based OTDR. As shown in this trace, we could detect the discrete reflections caused by fiber connectors as well as the bending and splicing losses occurred in the feeder fiber. In addition, we could clearly identify the location of the remote node (RN) and 4 drop fibers. To verify these results, we measured the same OTDR trace by using a commercial OTDR (pulse width: 100 ns, measurement time: 3 minutes), as shown in Fig. 4(b). The measured fiber loss agreed well with the value obtained by using a commercial OTDR with an accuracy of $<$0.01 dB/km. We did not observe any effects of the fiber dispersion in the measured OTDR trace due to the slow chip rate of the PN sequence (5M chip/s) used in this experiment. The spatial resolution of this OTDR (determined by the chip rate) was measured to be 40 m. We also evaluated the effects of the downstream signal on the OTDR performance. For this purpose, we repeated the same OTDR measurement with and without using the downstream signal operating at 2.5 Gb/s (pattern length: $2^7-1$, $2^{15}-1$, $2^{31}-1$). However, there was no significant difference in the measured OTDR traces. Also, we did not observe any dependency on the pattern length. Thus, we concluded that the performance of the proposed correlation-based OTDR was not sensitive to the downstream signal.

4. Summary

We have improved the dynamic range of the OTDR based on the correlation detection to use it for the in-service monitoring of the 64-split TDM PON. For this purpose, we superimposed the MLS PN sequence to the downstream signal and increased its modulation depth to 40%. By using these techniques, we could increase the dynamic range of the proposed OTDR to...
~30 dB. However, such a large PN sequence could seriously degrade the sensitivity of the downstream receiver. Thus, to mitigate this problem, we applied 8B/10B encoding to the downstream signal and filtered out the superimposed PN sequence at the downstream receiver in the ONU by using an electrical high-pass filter. As a result, the power penalty caused by the superimposed PN sequence could be reduced to be <3 dB even when we increased its modulation index to 40%. We experimentally showed that the proposed OTDR based on the correlation detection could detect both the reflective and non-reflective events even in a 64-split TDM PON. Since the proposed technique acquires the OTDR trace by using the PN sequence superimposed to the downstream signal, it can be used for the fault monitoring without interrupting the service in such a network.