Correlation-Based OTDR for High-Resolution Monitoring in Passive Optical Networks

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Abstract: Utilizing correlation detection and comical optical transceivers, we detected <-58 dBm reflection signals with <10 cm spatial resolution in typical PON scenarios. Optical power monitoring and fault diagnosis are accomplished through analyzing the correlation results.

1. Introduction

Driven by the growing number of Fiber-to-the-Home (FTTH) users and bandwidth-demanding mobile services, effective and efficient monitoring of the fiber infrastructure has become essential for optical access network maintenance in passive optical networks (PONs). Physical layer monitoring often relies on the optical time-domain reflectometer (OTDR) to monitor the optical power and locate the faults of fiber links [1]. However, the tasks become challenging when dealing with multiple branches after the splitter due to the weak overlapping reflections. Various methods have been developed to enhance the OTDR. In [2], branch links are sequentially combined in pairs to serialize the OTDR traces from multiple branches, but this approach suffers from severe power loss and is unsuitable for established PON networks. In [3], a machine learning (ML) based approach is proposed for diagnosing and locating the events from OTDR traces, whereas the limited spatial resolution of OTDR (typical ~1m) hinders the analysis of details. In [4], an In-Service OTDR approach superimposes pseudo-random noise (PN) sequences on the downstream signals and detects the back-reflected signals using correlation detection, but this approach requires an additional filter to isolate low-frequency signals at the user end, and the low rate of the PN sequence limits its spatial resolution.

In this paper, we propose a high-resolution monitoring technique for PON networks using correlation detection. Instead of utilizing ultrashort pulses, we transmit ultra-long PN sequences as probing signals and apply correlation detection to identify the back-reflected signals, thus significantly enhancing the signal-to-noise ratio (SNR) of the probing signal. Furthermore, the round-trip time of the reflected signal can be measured from the shift of correlation peaks, and the time resolution is determined by the duration of each PN bit, so high-speed transmission improves the location precision. Experimental results demonstrate the high-sensitivity detection and high-resolution location in typical PON scenarios (32 customers with a 20 km feeder). The method is capable of identifying extremely weak reflections (<-58 dBm) from connectors with a spatial resolution of less than 10 cm. Through analyzing the amplitude changes in correlated peaks, optical power monitoring and fault location of the PON can also be achieved.

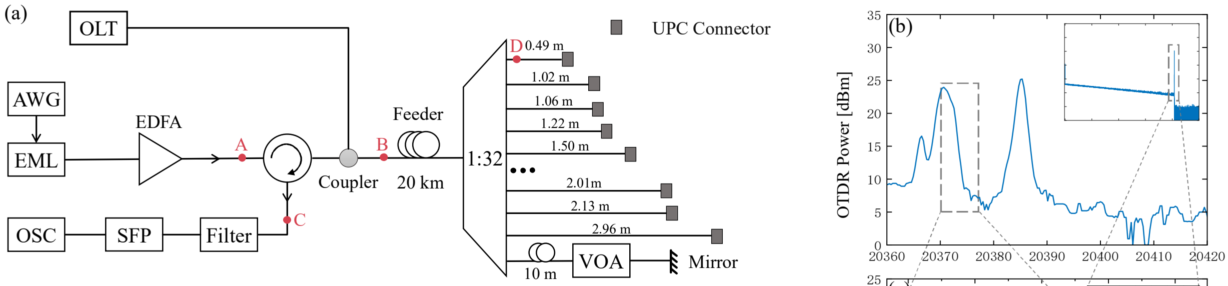
2. Principle

The direct sequence spread spectrum method employs a spread spectrum sequence to expand the signal spectrum for transmission, while at the receiving end, the same sequence is used for dispreading and restoring the transmitted signal. Utilizing PN sequences instead of pulse signals enables the retrieval of weak signals from the noise after dispreading. The spread spectrum gain is expressed as: $\Delta SNR_{spread} = 10\,log_{10} N$, where N is the expansion factor of the spread spectrum code [5]. This indicates that the longer PN sequence used for spreading operations, the higher the SNR obtained. Averaging is another commonly used noise reduction method. When periodic signals are aligned and averaged, the noise is suppressed, thus improving the SNR. The noise reduction gain is expressed as: $\Delta SNR_{average} = 10\log_{10}\sqrt{M}$, where M is the expansion factor by the number of averaging times [6].

Based on the excellent self-correlation characteristics of PN sequences, significant correlation peaks are only formed when the receiving sequence aligns precisely with the sending sequence. Consequently, the round-trip time of the reflected signal can be measured by the shift of the correlation peak. In theory, the time resolution is determined by the duration of each PN bit, and the positioning graduation is given by: $\Delta D = ct/2$, where c represents the propagation rate of light in the fiber and t represents the duration of each PN bit. Therefore, with a PN sequence transmitted at a rate of 3.125 GS/s, the spatial resolution achieves 3 cm.

3. Experimental Demonstration

Fig. 1 (a) shows the setup of the proposed high-resolution monitoring system. The monitoring module is a typical intensity modulation-direct detection (IM-DD) system: the electroabsorption modulated laser (EML) modulates the PN sequence generated by the arbitrary waveform generator (AWG) onto the optical carrier; the probing optical signals are amplified by an erbium-doped fiber amplifier (EDFA) and then enter the optical distribution network (ODN) network. The probe signal reflects off the joints and open connectors and returns to the monitor module. An optical circulator and optical filter separate the back-reflected signal, which is detected by a small form-factor pluggable plus (SFP+) and recorded by a digital phosphor oscilloscope (DPO, Tektronix 73304D) for offline processing. For convenience and cost reduction, commercial optical devices are used: the transmitter is a 40 Gbps EML operating at a wavelength of 1559.79 nm, a spectrum reserved for cable television (TV) in the IEEE 802.3av standard. The receiver utilizes a 10 Gbps optical module (10G-1550 nm-80 km-SM-SFP+) for photoelectric detection, featuring a receiving sensitivity of -24 dBm and a high gain limiting amplifier for converting weak signals into 0/1 levels. The AWG (Tektronix 7122C) cyclically sends a PN sequence of length 2^{17}-1 (Generate polynomial as G (x)=x^{17}+x^{14}+1) at a rate of 3.125 GS/s, while the oscilloscope (OSC) samples at 12.5 GS/s. To improve the SNR of the probing signal, we choose an appropriate EDFA gain to resist the attenuation without causing excessive Rayleigh scattering. The power at each monitoring point is shown in Fig. 1.



Location	Power(dBm)
EDFA gain	8.17
Point A	10.10
Point B	6.13
Point C	-31.13
Point D	-15.53

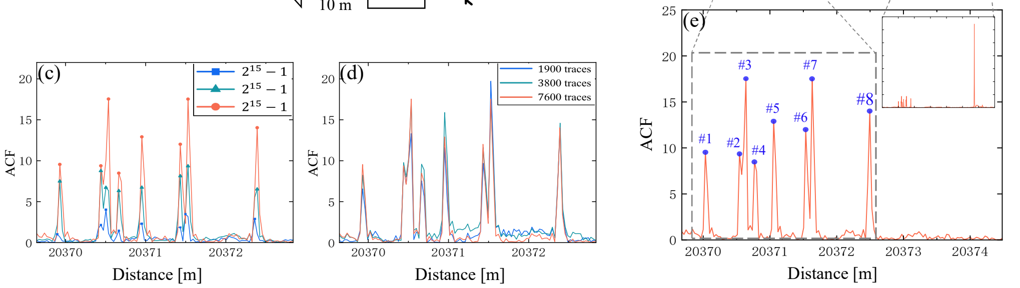


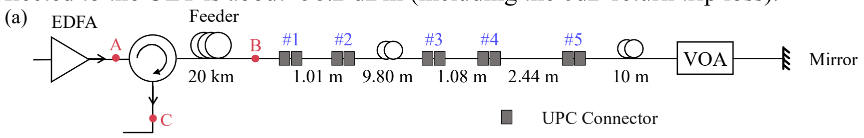
Fig. 1: (a) Experimental setup for detecting the open UPC connectors. (b) OTDR trace measured. (c) ACF of reflected signals with different PN lengths. (d) ACF of reflected signals with different average times. (e) ACF of reflected signals after 1:32 PSC.

We first detect the ultra-polished connectors (UPC) in a typical Ethernet passive optical network (EPON) scenario (32 customers with a 20 km feeder). Optical fiber patch cords with unequal lengths are connected at each branch as open connectors, one is 10 m in length with a 30% reflection film on its end face, generating a strong reflection signal for synchronizing the cyclic signal. All reflected signals fall within a single detection cycle.

After resampling and averaging, the received signals perform cross-correlation with the transmitted PN pattern, the auto-correlation function (ACF) results are shown in Fig.1(e). The correlation peaks indicate the signals reflected by each open connector, the arrival order and the time interval can be identified according to their length difference. Even when the length difference between branch 2 and branch 3 is 6 cm, their correlation peaks can be accurately identified as expected. For comparison, Fig.1(b) shows the conventional OTDR traces, the OTDR operates with a scanning wavelength of 1550 nm and pulse width of 5 ns, and the reflected signals from each branch are difficult to distinguish. The impact of PN sequence length and the number of averaging times in the detection signal are also analyzed. Theoretically, doubling the length of the PN code can bring the spreading gain by 3 dB, and averaging 4 more times can increase the SNR by 3 dB. The correlation peaks observed in Figs. 1(c) and 1(d) confirm the improvement: longer PN codes yield higher correlation peaks, while more average times lead to lower noise levels.

Sequentially, Fig. 2(a) illustrates the process of probing connectors after the feeder, where amplified signals pass through a 20 km single-mode fiber (SMF) and optic fiber patch cords in series. The PN sequence with a length of 2^{20}-1 (Generate polynomial as G (x)=x^{20}+x^{17}+1) and the detected signal are averaged 4000 times for higher SNR. As is shown in Fig.2(c)(d), each connector can be distinguished by the position of cross-correlation peaks, while the

OTDR traces hide the details. According to [6], we assume the optical return loss of UPC is 55 dBm, thus the probing signal reflected to the OLT is about -58.2 dBm (including the 6dB return trip loss).



Location	Power(dBm)
EDFA gain	5.95
Point A	7.87
Point B	2.81
Point C	-26.68

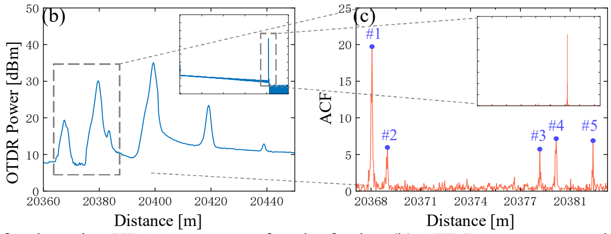
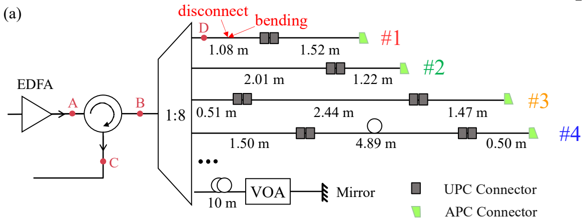


Fig. 2: (a) Experimental setup for detecting UPC connectors after the feeder. (b) OTDR trace measured. (c) ACF of correlation detection.

Finally, the connectors on each branch are monitored. As is shown in Fig. 3(a), the amplified signals pass through the 1:8 splitter, and the jumpers with different lengths are connected in series for 4 branches, with the power at each monitor point listed. We employed the PN sequence of length 2^{20}-1 and averaged the detected signal 2000 times. The cross-correlation peak is shown in Fig. 3(b), where 10 peaks indicate connector reflections on different branches. When branch 1 is disconnected, the correlation results are shown in Fig. 3(c). When branch 1 incurs ~1 dB attenuation due to bending, its peak value reveals a significant reduction, as is shown in Fig. 3(d). The correlation peak values of fixed connectors reflect the disconnection and optical power changes in each branch.



Location	Power(dBm)
EDFA gain	21.65
Point A	23.50
Point B	22.83
Point C	-28.26
Point D	-11.56

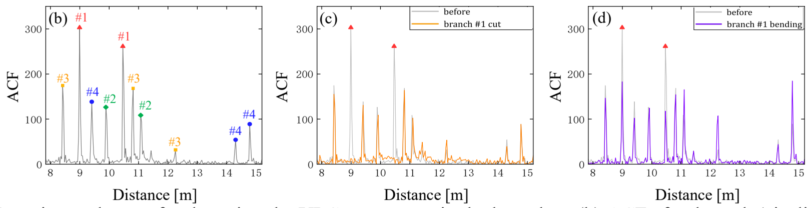


Fig. 3: (a) Experimental setup for detecting the UPC connectors in the branches. (b) ACF after branch 1 is disconnected. (c) ACF after branch 1 is bent.

4. Conclusion

We experimentally demonstrate a high-resolution monitoring approach in the PON, which sends ultra-long PN sequences as probing signals and detects weak reflection based on correlation progress. This method achieves high-sensitivity detection and high-resolution ranging. By analyzing the amplitude changes of correlated peaks, optical power monitoring and fault location of the PON can be achieved.

5. Acknowledgements

This research is supported by the National Key Research and Development Program of China (2022YFB2903303).

6. References

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