Mechanical threat monitoring over telecommunication fiber cables using distributed acoustic sensing without distributed amplification

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***Abstract*—We report the results of monitoring the digging threat in telecommunication fiber cables using distributed acoustic sensing without distributed amplification. The system successfully detected different excavator actions in a 101-km fiber cable with high accuracy.**

***Index Terms*—distributed acoustic sensing, ϕ-OTDR, fiber cable monitoring.**

I. Introduction

The advancement of telecommunication technology has led to the extensive deployment of fiber optic cables underground. As a result of chaotic fiber optic cable path planning and casual construction, communication fiber optic cables are often damaged during external construction excavation, which significantly impacts the quality of telecommunication service and can lead to significant losses, particularly in private network services. Therefore, it is of great importance for operators and users to receive timely warnings regarding the risks associated with fiber optic cables and to rapidly repair the damage incurred [1]. At present, the safety of fiber optic links is usually ensured by manual patrol, but this method is costly, inefficient, and has poor real-time performance.

Distributed acoustic sensing (DAS) based on phase-sensitive optical time-domain reflectometer (ϕ-OTDR) is a highly promising long-range strain sensing technique that has been applied in oil and gas pipeline monitoring, perimeter security, etc. In ϕ-OTDR, the external vibration will change the phase of the Rayleigh backscattered signal, and it is a linear response [2]. By detecting the backscattered signal and demodulating the phase, the system can monitor and locate the dynamic strain. Utilizing the dark fiber present in fiber optic cables as the sensing medium, the DAS technology can monitor cable links while avoiding interference with communication services, enabling compatibility between sensing and communication functions [3]. The distance of a single span in the optical backbone network is about 80$\sim$100 km, and optical relaying is commonly achieved using erbium-doped fiber amplifiers (EDFA). In the absence of distributed amplification, the sensing range of ϕ-OTDR is typically limited to 50$\sim$80 km due to weak Rayleigh backscatter [4]. Consequently, achieving end-to-end monitoring of the entire optical cable link with inline amplification requires additional optimization of the signal-to-noise ratio (SNR) of the sensing system.

In this paper, we present the results of a field trial aimed at monitoring excavator activities in telecommunication cables. After optimizing the SNR of the ϕ-OTDR system, we have successfully achieved excavator behavior monitoring with high accuracy over a distance of 101 km. The field trial effectively confirms the feasibility of utilizing ϕ-OTDR in backbone networks.

II. SNR Optimization in ϕ-OTDR

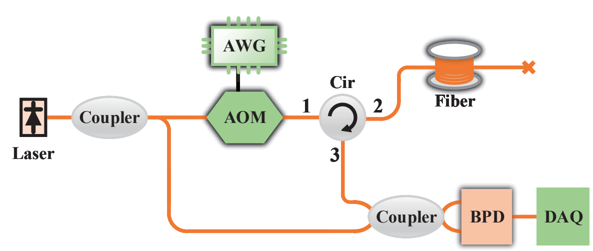

Fig. 1. Basic setup of ϕ-OTDR.

Figure. 1 shows a typical ϕ-OTDR setup with coherent detection. A narrow-linewidth laser operates as the light source. An arbitrary waveform generator (AWG) generates electrical pulses to drive an acoustic optic modulator (AOM) to produce optical probe pulses. The probe pulses enter the fiber through a circulator (Cir) when the backscattered signal enters the receiving side from the opposite direction. Then, coherent detection is achieved using an optical coupler and a balanced detector (BPD). Finally, a digital acquisition card (DAQ) is used for data capture.

To improve the SNR for longer sensing distance, it is important not only to increase the signal power but also to reduce the system noise power [5]. These include: (a) Using an ultra-narrow linewidth laser to reduce the phase noise; (b) Improving the extinction ratio of the AOM and the circulator; (c)

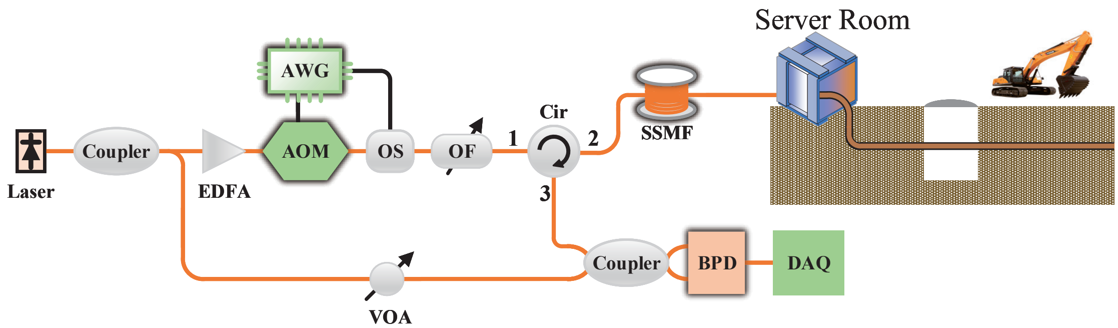

Fig. 2. Experimental setup.

Optimizing the power of probe pulses and oscillator light; (d) Using low-noise power detector and high-resolution analog-to-digital converter; (e) Reducing the amplified spontaneous emission (ASE) noise if EDFAs are used in the system.

III. Experimental Setup

Based on the previous analysis, we optimized the SNR of the ϕ-OTDR system and conducted outdoor excavator vibration monitoring using both indoor optical fiber and underground fiber optic cable. The experimental system setup is depicted in Fig. 2. The system utilizes a fiber laser with a linewidth of 100 Hz and a central wavelength of 1550.12 nm. An EDFA is used to amplify optical power, and it is positioned before the AOM to enhance the extinction ratio and avoid transient effects. To eliminate ASE noise generated by the EDFA, a 50-GHz bandwidth optical filter (OF) is employed. Additionally, an optical switch (OS) controls the on/off state of the probe pulse to further improve the extinction ratio of the transmitter. An AWG produces linear frequency modulation (LFM) pulses with a pulse width of 16 μs and a frequency range of 170 MHz to 230 MHz. To prevent modulation instability while maintaining sufficient signal power, the peak power of the optical probe pulse entering the fiber is 19 dBm. A variable optical attenuation (VOA) is used for controlling the local oscillator light power. A DAQ with 14-bit resolutions is used for data acquisition. The fiber under test consists of two segments: the indoor segment, which includes four spools of optical fiber, each containing 25 km of standard single-mode fiber (SSMF), and the outdoor segment, which comprises a buried fiber optic cable about 700 meters. The two segments are fused in the server room, with a total length of 101.3 km. The fiber span is probed with a probing rate of 900 Hz, subjected to the fiber length. Limited by the storage space, 100 signal traces are captured for each test, corresponding to a single measurement time of 0.1 seconds. These sampled signals are instantly processed on a computer, and the signal traces are demodulated by phase detection [6]. Six sub-bands are used for the inner-pulse frequency-division method and rotated-vector-sum method to improve the effect of fading elimination. To further mitigate fading noise and improve the SNR, signal intensity traces after the fading elimination and phase traces before phase difference are smoothed using a sliding average algorithm with a 10-m distance window. And the gauge length is 10 m.

IV. Results of Field Trial

We apply different artificial disturbances near the fiber cable well and monitor the link status in real time using the indoor ϕ-OTDR system. These perturbations include tapping on the fiber optic cable, excavator walking, excavator digging, etc. Fig.3 (a) shows the environment of the fiber cable well, and the burial depth is approximately 1.5 meters. Fig. 4 shows the signal power trace after fading elimination. It can be seen that the optimized system can obtain an SNR of 14 dB at the far end of 101 km.

(a) **(b)**

Fig. 3. (a) Top view of the cable well, (b) Scene of excavator digging.

Figure.5 depicts the detected phase standard deviation (STD) trace when the well is undisturbed. However, due to the operation noise from large equipment and fans, a significant peak appears near 100.5 km in the trace. Between 100.6 km and 101.3 km, the STD is relatively small, indicating that the buried fiber cable is stable. We set a judgment threshold of 1 radian. If the STD of any position exceeded this threshold, we concluded that there was a disturbance at that location. To investigate the detection performance, we conducted 50 tests under an undisturbed environment. For all 50 tests, the phase STD remained below 1 radian, indicating that no false judgments were made.

Then, we apply an external disturbance by tapping the fiber optic cable. Fig. 6 shows the phase STD traces detected by the system. It is clear that a 3 rad peak appears at 101.95 km, i.e., the perturbation causes an increase in the STD. Considering the full width at half maximum (FWHM) of the peak, the

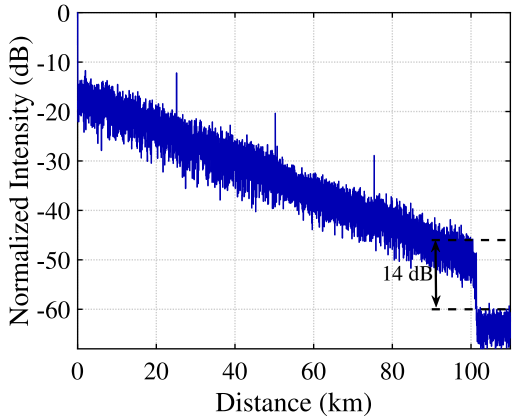

Fig. 4. Signal trace after fading elimination.

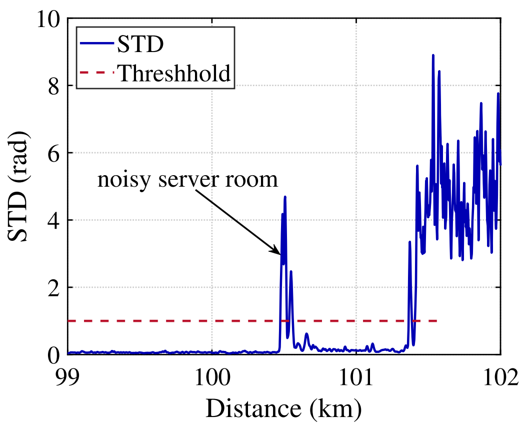

Fig. 5. STD trace near the cable well without disturbance.

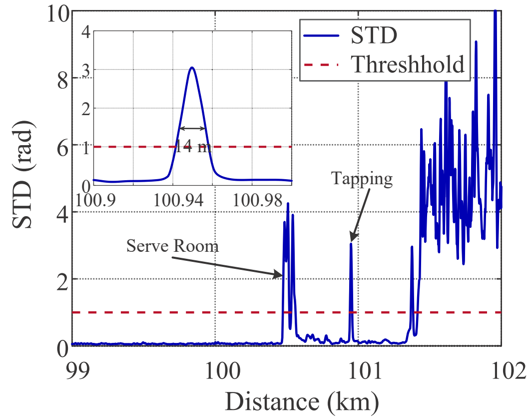

Fig. 6. STD trace near the cable well under tapping.

spatial resolution is about 14 m in the inset. The spatial resolution declines due to the inner-pulse frequency-division method and sliding average algorithm, but it is completely in the range of human audiovisual distance, which hardly affects the monitoring of fiber optic cable protection.

With the same system configuration, to verify the ability of the system to detect the excavator, we changed the external disturbance to an excavator under construction, as shown in Fig. 3 (b). By comparing with the threshold, the system successfully detected significant disturbances when the excavator was walking and digging near the fiber optic cable well. We conducted a total of 180 tests, and the detailed results are presented in Table.I. While the false negative rate for detecting the tapping is only 2.5%, it is 6% and 9.9% for walking and digging, respectively. The increase in error rate when monitoring the excavator is attributed to the short duration of individual sampling and the specific timing of the sampling slots when the machinery is running slowly causing the change in vibration is less than the threshold. By measuring multiple times over a longer duration, the error rate can be further reduced.

TABLE I
DETECTION PROBABILITY

Condition	Total Num	Error Num	Error rate
static state	50	0	0
tapping cable	40	1	2.5 %
excavator walking	50	3	6 %
excavator digging	30	3	9.9 %

V. Conclusion

We show the feasibility of ϕ-OTDR in detecting and localizing vibration in buried fiber cable over 101 km without distributed amplification. The SNR-optimized system successfully detected the threat of excavators in telecommunication cables with only inline amplification. The results show high accuracy in detecting actions of the excavator, like walking and digging, and the false positive rate is zero. The trial also shows the way for a per-span vibration monitoring of telecommunication networks.

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