Time Transfer Through Optical Fiber over 166km on Two Telecommunication Network Fibers

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***Abstract*—This article achieves a comparison of optical fiber time transfer systems on different optical fibers on the same route over a 166km long on-site fiber optic link. This article provides new ideas and methods for high-precision fiber optic time transfer comparison and indicator verification. When conducting time transfer with different wavelengths on the two telecommunication network fibers, the system adopts a bidirectional time comparison method. It needs to consider factors such as dispersion to further eliminate uncertainty in the fiber optic transmission process, to achieve extremely high precision time synchronization and clock source comparison. This article uses 8 optical fiber time transfer devices, starting from the National Time Service Center in Lintong, on two different optical fibers on the same path, passing through Xi'an and Xianyang to reach Tongchuan City. And the fiber dispersion self-correction scheme is used in the system. The experimental measurement results show that the fluctuation is 24 ps in standard deviation. The peak-to-peak value of fluctuation is 69 ps, and the transfer stability TDEV is 7 ps@1s.**

Keywords*—*time transfer, optical fiber, comparison method, different paths

I. INTRODUCTION

The accuracy of atomic clocks is constantly becoming more precise, as in [1]. The ability of time transfer and synchronization determines the ultimate limit of the time and frequency of atomic clocks application. So it is necessary to develop high-precision fiber optic time transfer technology that matches its accuracy, as in [2-3]. Benefitting from the low loss, high reliability, and high stability of optical fibers, time transfer over fibers (TTOF) offers potentially superior performance and exhibits superior transmission performance. Multiple groups and researchers have conducted research on high-performance TTOF technology and have achieved many results and progress in the laboratory, as in [5]. Accurate timing should not be limited to laboratories, but also to engineering and practical applications, as in [6]. When conducting time transfer with different wavelengths on the two telecommunication network fibers, the system adopts a bidirectional time comparison method. When the time and frequency signals reach the user site, compare the time difference between the signals output by two different remote devices. It needs to consider factors such as dispersion to further eliminate uncertainty in the fiber optic transmission process, to achieve extremely high precision time synchronization and clock source comparison, as in [7-9]. The TTOF in a field telecom fiber link of 1085 km was reported by the authors' group in 2021, with the time transfer instability being 9.2 ps at 1 s and 5.4 ps at 40000s, as in [4]. An implementation of high-precision time transfer over an 1839 km field fiber loop backlink between two provincial capitals of China, Xi'an and Taiyuan, is reported in [10].

Due to the high performance of fiber optic time transfer, it reaches the ps level. So it is difficult to choose a better method to directly measure and measure time transfer performance. The above experiments are all based on the loopback method implementation. The loop comparison method can explain some issues. For example, the signal output from the last remote end that is returned to the local end is synchronized with the local end time. However, it cannot be fully proven that the synchronization accuracy of intermediate sites must meet the same requirements and indicators. Therefore, this article continues to explore new methods for verifying indicators at different levels. This article selects optical fibers with different routes and compares the signals output by different devices at the same site. This article chooses the same path but not the same optical fiber. Compare the signals output by different devices on the same site. This demonstrates the consistency of the equipment and the consistency of time synchronization accuracy across different optical fibers. Finally, conduct uncertainty analysis on the system.

II. THE GEOGRAPHICAL DISTRIBUTION

This article uses 8 optical fiber time transfer devices, starting from the National Time Service Center in Lintong, on two different optical fibers on the same path, passing through Xi'an and Xianyang to reach Tongchuan City.

The geographical distribution of this field fiber link is shown in Fig. 1. Starting from the station located at the Lintong campus of the National Time Service Center, it passes through 2 relay stations in Shaanxi province (Xi'an and Xianyang)， then reaches the Tongchuan station via another parallel fiber. The fiber distances between adjacent stations are marked on the map. To implement the time transfer experiment, 8 devices were installed: the 2 local devices were both installed at the station of Lintong. Each of the 2 relay stations between Lintong and Tongchuan was installed with 2 relay/download devices. While 2 remote devices were installed at Tongchuan station.

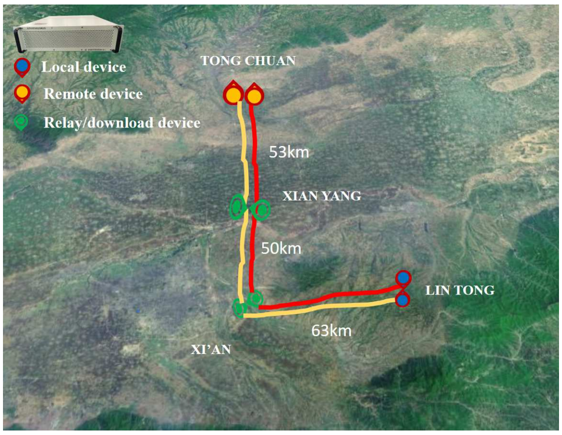

Fig. 1 Geographical distribution of the 166 km field fiber link.

The fiber optic model for the field line adopts single-mode G.652D. The distance from Lintong to Xi'an is 63 kilometers. And the loss of two fiber optic are both 24 dB. The distance from Xi'an to Xianyang is 50km, and the loss of one fiber optic is 16dB, while the loss of the other is 17 dB. The distance from Xianyang to Tongchuan is 53km, and the loss of one fiber optic is 11 dB, while the loss of the other is 12 dB. Perform a summary calculation, and the total loss of one link is 51 dB. The other line has a total loss of 53 dB. The total length of both lines is 166km.

III. Structural Diagram and Explanation

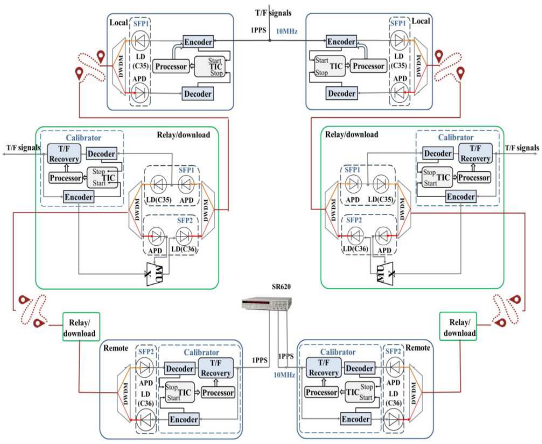

Fig. 2 The structural diagram of the local device, the remote device as well as the relay/download devices equipped in the distributed stations, with the basic working principle of each specific device showing in the frames. For simplicity, only one SFP module is plotted for the local and remote device. T/F: time-frequency, LD: laser diode, PD: photo diode, TIC: time interval counting module, MUX: multiplexer.

Based on the dual-wavelength two-way time transfer (TWTT) in the two-fiber method, the high-precision long-distance fiber-optic time transfer was implemented. The working flow of each specific device is briefly depicted in Figure 2. The local device receives the standard time-frequency (T/F) signals (e.g., UTC-NTSC) in the forms of 1PPS, 10MHz frequency, and IRIG-B time code, then encodes them into optical signals for downward fiber transmission. At the same time, it detects the upward transferred optical signals and decodes the carried T/F signals. Via the subsequent manipulation of time interval counting (TIC) and processing, the reference-dependent time delay is extracted and fed into the encoder. The remote device detects the optical signals from the downward fiber transmission and outputs the transferred T/F signals in 1PPS, 10MHz frequency, and IRIG-B forms after being corrected for the fiber transfer delays via the module combinations of TIC, processor, and T/F signal recovery. For the relay/download devices, they are used to detect the transmitted optical signals from the upward (downward) fiber link and manipulate regeneration of the optical signals before forwarding them to the downward (upward) fiber link. Meanwhile, the standard T/F signals can be decoded from the detected optical signals and output in the forms of 1PPS, 10MHz frequency, and IRIG-B time code. With the help of an electrical time-division multiplex (MUX), the recovered T/F signals can be uploaded onto the optical signals for upward fiber transmission as well. All the three types of devices are equipped with two optical transceivers based on single-mode SFP modules, whose working wavelengths are 1549.32 nm (C35) and 1548.51 nm (C36). Dense wavelength division multiplexers (DWDMs) are equipped at the input/output optical ports of all the devices, and the optical connections between the adjacent devices follow the rule that the optical signal along the downward link is at the wavelength channel of C35, while that along the upward link is at C36. All the devices are self-developed and their performances have been enhanced from the previous version [4] through the integration of more advanced hardware components. The additional time delay of each device is pre-calibrated to the picosecond level before being installed along the fiber route. The asymmetrical time delay caused by the dispersion associated with the wavelength difference between the uplink/downlink lasers can be calibrated onsite with the fiber dispersion self-correction scheme. Furthermore, the system is equipped with in-band network management functionality. At the local site, it provides real-time visibility into the operational status of all devices connected to the entire fiber optic link and the status of each fiber segment, which facilitates fault alarm and maintenance. Finally, the time interval measurement device SR620 was used to measure and compare the time signal output at the Tongchuan Station using two different optical fibers and two matching remote devices.

IV. Experimental Result

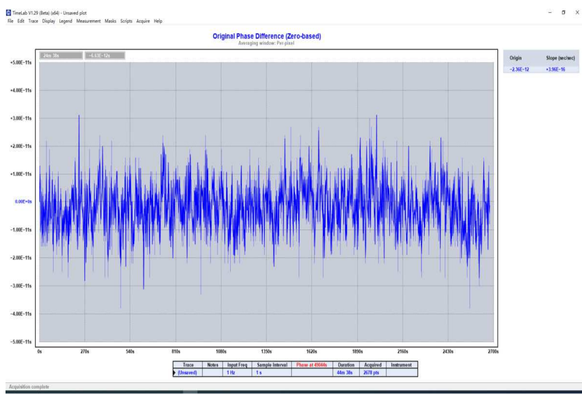

Fig. 3 Measured time difference of the 166 km fiber link over the 2700s

Then the time difference measurement was made after connecting the 2 remote devices to the 166km of field fiber link at Tongchuan station. The data over 2700s of measurement are plotted in Fig.4. As clearly seen, the time difference results exhibit a stable output. The experimental measurement results show that the fluctuation is 24 ps in standard deviation. The peak-to-peak value of fluctuation is 69 ps.

Fig. 4 TDEV of time transfer over the 166 km field fiber link.

The stability (TDEV) result of time transfer over the 166 km field fiber link. The stability of the transferred PPS signal was then analyzed. The outcome of this analysis is illustrated in Fig. 4, indicating time stabilities of 7.0 ps at 1 s, 3.7 ps at 10 s, 1.8 ps at 100 s, and 1.1 ps at 400 s.

TABLE I. UNCERTAINTY BUDGET OVER THE 166 KM FIBER LINK

Uncertainty source	Uncertainty contribution (ps)	Uncertainty type
Time difference measurement	24	A
TIC	7.07	B
SFPs	12.2	B
FPGA	1.2	A
EVIL	1.4	A
Non-reciprocity from fiber	9.1	A&B
PMD	0.64	B
Sagnac	1.0	B
Combined uncertainty	29.4	

In addition to the stability performance, the uncertainty of the time transfer system was also evaluated. The main terms of the uncertainty budget are summarized in Table 1. The first term represents the uncertainty of the measured time differences based on the two-way time transfer system. From the long period difference measurements conducted over the 2700s, which was shown in Fig. 4, it was evaluated as 24 ps. The second term is from the TICs in the local and remote devices for determining the two-way time differences. Considering the type-B uncertainty of each TIC is 10 ps and the TWTT scheme contributes a coefficient of $1/\sqrt{2}$, it leads to an uncertainty of 7.07 ps. According to the literature, as in [10], the used SFP transceivers would induce power-dependent delay. Benefitting from the symmetry of TWTT, most of such delays caused by the received power variation in the uplink can be canceled by that in the downlink. With the output optical power variation of individual SFPs being kept within 2 dB, the uncertainty induced by each SFP transceiver can be estimated at less than 10 ps. In total, this term contributes an uncertainty of 12.2 ps. The fourth and fifth terms represent the uncertainty arising from the precision of the T/F signal recovery unit's time delay compensation. These terms encompass the delay counting uncertainty of the embedded FPGA and the delay adjusting uncertainty of the subsequent electrical variable delay line (EVDL). A type-A uncertainty coming from FPGA was determined to be 1.2 ps by examining the differences between the measured time interval and the expected one under the condition of controlling the FPGA to serially generate a time delay ranging from 0 to 1 s in a 0.1 s step [22]. Similarly, the uncertainty coming from EVDL was evaluated by adjusting the delay from 0 to 200 ps in a 10 ps step, and a type-A uncertainty of 1.4 ps was acquired. Another origin of uncertainty is the non-reciprocal time delay variation associated with chromatic dispersion in the fiber link and wavelength differences. By monitoring the single-path time delay over the 166 km fiber, as in [10], the typical magnitude of wavelength fluctuation for individual SFPs, resulting from thermal sensitivity and measurement error, was estimated around 5 pm. Involving all these fluctuation components into the assessment, the non-reciprocal time delay variation associated with chromatic dispersion for each segment of the fiber can be evaluated. Summarizing the contributions from each segment, the non-reciprocal time delay variation for the total fiber link was determined to be 9.1 ps in 166km. The uncertainty from the polarization mode dispersion (PMD) effect was calculated with the typical coefficient of PMD, ~0.05 ps/$\sqrt{\text{km}}$, as in [11]. The uncertainty introduced by the 166km PMD is 0.64 ps. Based on the differences in longitude, latitude and elevation, a software algorithm is constructed to evaluate the effect and calculate the uncertainty of Sagnec. The uncertainty introduced by the Sagnac effect correction was estimated to be 1.0 ps, which can be achieved thanks to the global positioning system. All in all, the combined uncertainty for the time transfer system over the 166 km field fiber was estimated at 29.4 ps.

V. CONCLUSION

This article uses 8 optical fiber time transfer devices, starting from the National Time Service Center in Lintong, on two different optical fibers on the same path, passing through Xi'an and Xianyang to reach Tongchuan City. For the first time, the fiber dispersion self-correction scheme is used. And two different optical fiber paths are compared using the comparison method to achieve an on-site comparison of optical fiber time transfer systems on different optical fibers on the same route over a 166km long on-site fiber optic link, which can provide time tracing services for the cesium clock group of Tongchuan. The experimental measurement results show that the fluctuation is 24 ps in standard deviation. The peak-to-peak value of fluctuation is 69 ps, and the transfer stability TDEV is 7 ps@1s. This article provides new ideas and methods for high-precision fiber optic time transfer comparison and indicator verification.

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