Time Transfer in a 1839-km Telecommunication Fiber Link Demonstrating a Picosecond-Scale Stability

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An implementation of high-precision time transfer over a 1839-km field fiber loop back link between two provincial capitals of China, Xi'an and Taiyuan, is reported. Time transfer stabilities of 6.5 ps at averaging time of 1 s and 4.6 ps at 40000 s were achieved. The uncertainty for the time transfer system was evaluated, showing a budget of 56.2 ps. These results stand for a significant milestone in achieving high-precision time transfer over a field fiber link spanning thousands of kilometers, signifying a record-breaking achievement for the real-field time transfer in both stability and distance, which paves the way for constructing the nationwide high-precision time service via fiber network.

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Applications of high-precision time and frequency have not only been playing an essential role in areas of fundamental physics research [1–3] and engineering technology, [4–6] but also been deeply involved in enormous fields associated with national economy and people's livelihood. As the ability of time transfer and synchronization determines the ultimate limit of the time and frequency applications, the construction of high-precision time and frequency transfer systems and improving the time transfer performances are always a crucial subject. Benefiting from the low loss, high reliability, and high stability of optical fibers, time transfer over fiber (TTOF) offers potentially superior performance over its satellite-based counterparts. Numerous groups have been conducting research on high-performance TTOF technology since as early as 2006, resulting in continuous breakthrough progress. [7–12] As of the present time, long-distance fiber-optic time transfer has been implemented both in laboratory fibers [13–17] and in field telecom fiber links. [18–21] Specifically, the TTOF demonstration in laboratory fibers has been extended to cover 2000 km distance. Remarkably, stabilities of less than 89 ps at an averaging time of 1 s and 23 ps at 10000 s have been achieved. [16] The TTOF in a field telecom fiber link of 1085 km was reported by our group in 2021, with the time transfer instability being 9.2 ps at 1 s and 5.4 ps at 40000 s. [21]

With the widespread popularization of fiber communication networks, TTOF technology has been regarded as the most precise ground-based timing method currently available. In 2021, the High Precision Ground-based Time Service System project was launched in China as a major national scientific and technological infrastructure, the construction of a nationwide fiber-optic time service network with a time transfer stability better than 100 ps is one of the main tasks. Recently, the fiber-optic time transfer over a 1839-km field fiber loop link was successfully accomplished. In this Letter, we report the time transfer performance achieved over this fiber link. Time transfer stabilities of 6.5 ps at an averaging time of 1 s and 4.6 ps at 40000 s were achieved. The stability of the simultaneously transferred 10 MHz frequency signal was measured to reach the level of 4.5×10^{-12}/s and 1.9×10^{-15}/10000 s. These results mark the first high-precision fiber-optic time transfer over the field fiber link beyond a thousand-kilometer level. This is a record-breaking achievement in both stability and distance, paving the way for providing high-precision time services through field fiber-optic networks across China.

The geographical distribution of this field fiber link is shown in Fig. 1. Starting from the station located at Chang'an campus of National Time Service Center in Xi'an, it passes through 3 relay stations in Shaanxi province (Weinan, Pucheng, Heyang) and 8 relay stations in Shanxi province (Hejin, Houma, Linfen, Huozhou, Jiexiu, Qixian, Yuci, Taiyuan), then turns back via another parallel fiber to the station in Xi'an. The fiber distances between adjacent stations are marked on the map. To implement the time transfer experiment, 23 devices were installed: the local device and the remote device were

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both installed at the local station of Xi'an. Each of the 10 relay stations between Xi'an and Taiyuan was installed with 2 relay/download devices. Only one relay/download device was installed at Taiyuan station.

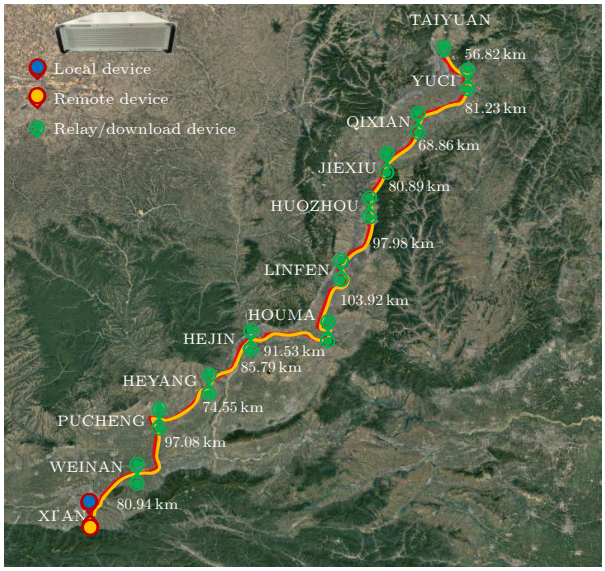

Fig. 1. Geographical distribution of the 1839-km field fiber link.

The implementation of high-precision long-distance fiber-optic time transfer was based on the method of dual-wavelength bidirectional time transfer in a single fiber.[21] All three types of devices are equipped with two customized single-mode Small Form-factor Pluggable (SFP) Transceiver modules, whose transmitting wavelengths are 1549.32 nm (C35) and 1548.51 nm (C36), respectively. Dense wavelength division multiplexers (DWDMs) are quipped 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. The working flow of each specific device is briefly depicted in Fig. 2.

The local device receives the standard time-frequency (T/F) signals (e.g., UTC-NTSC) in the forms of 1 PPS (pulse per second), 10 MHz frequency, 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 1 PPS and 10 MHz frequency, 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 forms of 1 PPS and 10 MHz frequency. 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.

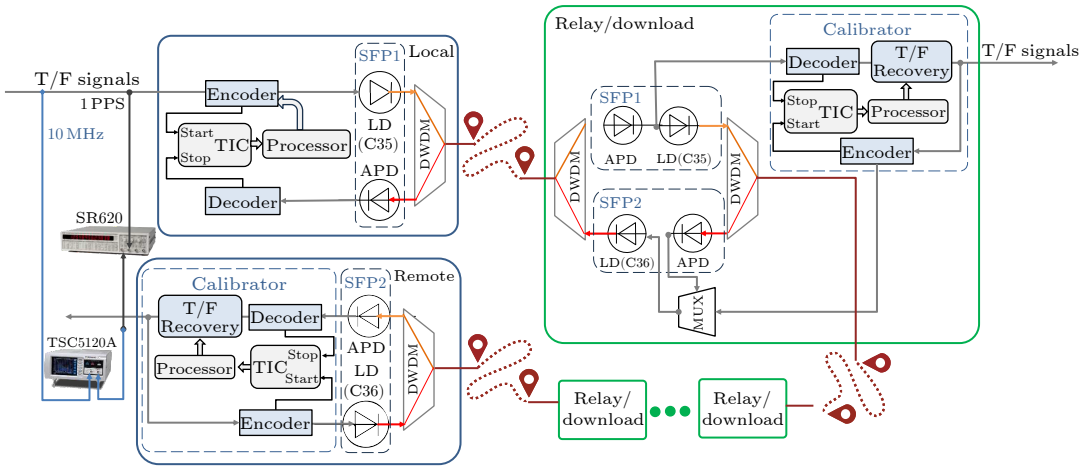

Fig. 2. Structural diagram of the local device, the remote device as well as the relay/download devices equipped in the distributed stations, with basic working principle of each specific device showing in the frames. For simplicity, only one SFP module is plotted for the local and remote device. T/F: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

In comparison with the previous version utilized in Ref. [21], the self-developed devices have been upgraded by adopting advanced hardware components and optimizing the electrical circuits. These modules adopt distributed feedback (DFB) laser diodes with excellent wavelength stability. The wavelength variation was monitored for a period of 24 h as the ambient temperature changed from 25 ℃ to 35 ℃, revealing only a slight peak-to-peak drift of 5 pm. In addition, avalanche photodiodes (APDs) are integrated in the modules, which offer better receiver sensitivity of down to −32.5 dBm due to their much lower noise current. 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. To further improve the performance of the whole system, temperature stabilization on the electrical circuit board was applied at 45 ℃. Furthermore, the system has in-band network management functionality. At the local site, it enables real-time monitoring of the operational status of all devices connected to the entire fiber optic link and the status of each fiber segment, which facilitates the fault alarm and maintenance.

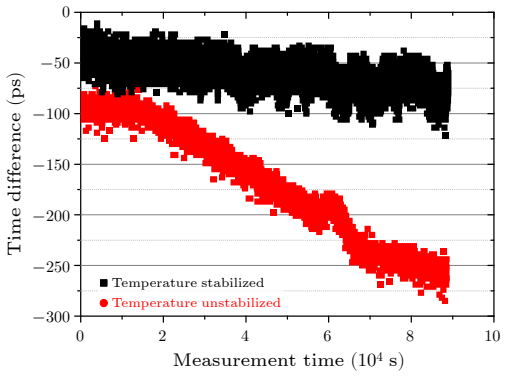

Fig. 3. Measured time difference between the short-connected local and remote devices under the high-low temperature cycle test from 25 ℃ to 35 ℃ during a period of 24 h.

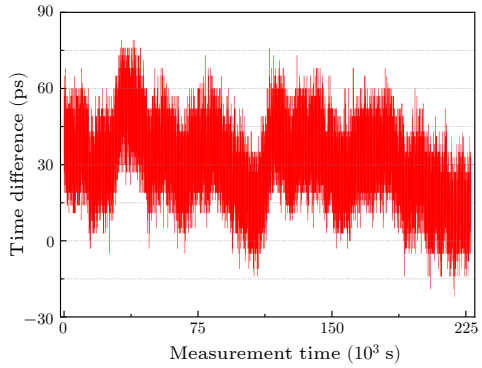

Fig. 4. Time difference of the 1839-km field fiber link over 63 h.

The thermal sensitivity of the self-developed device was evaluated by both placing the short-connected local and remote devices into the high-low temperature test-box, whose temperature was controlled to vary linearly from 25 ℃ to 35 ℃ during a period of 24 h. As depicted in Fig. 3, the observed time difference exhibits a minor temporal drift of 3.75 ps/K when temperature stabilization is activated. When temperature stabilization is deactivated, however, this drift increases to 15.7 ps/K.

To test the performance of the time transfer system, the time difference between the input PPS signal of the local device and the output PPS signal of the remote device was measured based on the same time and frequency reference, which is the so-called common clock difference (CCD) experiment. The commercial time interval counter, Stanford Research System (SRS) SR620, was utilized for the time difference measurement. Then the time difference measurement was made after connecting the local and remote devices into the 1839-km field fiber link. The data over 63 h of measurement are plotted in Fig. 4. The time difference results exhibit periodic variations, which is, we believe, mainly caused by changes in the environmental temperature. Upon analysis of the data, the average time difference was determined to be 30.1 ps, along with a fluctuation of 12.4 ps in standard deviation.

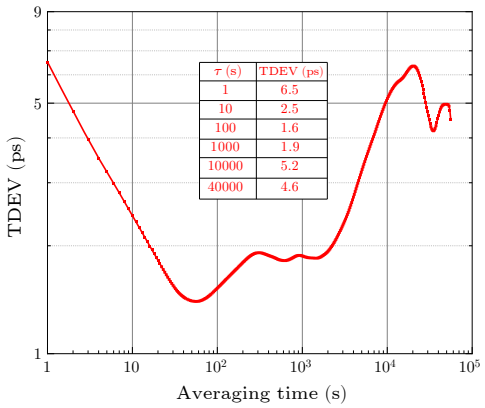

Fig. 5. Time deviation (TDEV) of the time signal transfer over the 1839-km field fiber link.

The stability of the transferred 1 PPS time signal was then analyzed by measuring the time deviation (TDEV) as a function of the averaging time. The outcome of this analysis is illustrated in Fig. 5, indicating time stabilities of 6.5 ps at 1 s, 2.5 ps at 10 s, 1.6 ps at 100 s, 5.2 ps at 10000 s, and 4.6 ps at 40000 s.

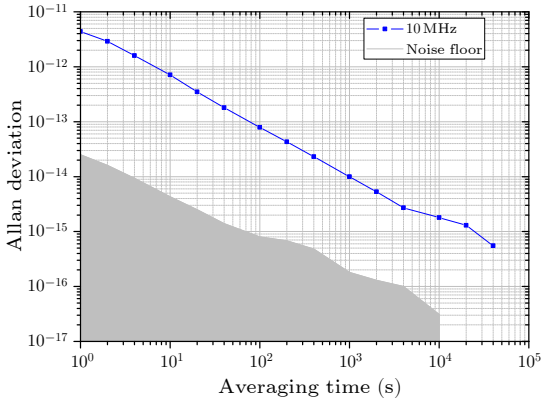

Fig. 6. Measured Allan deviation (ADEV) result of the accompanied 10 MHz frequency signal transfer over the 1839-km field fiber link.

The transfer stability of the accompanied 10 MHz frequency was also evaluated by comparing the 10 MHz frequency signals sent into the local device with those out of the remote device using the phase noise analyzer, Symmetricom TSC-5120A, for Allan deviation (ADEV) test. The result is shown in Fig. 6. One can see that frequency stability of 4.5×10^{-12}/s and 1.9×10^{-15}/10000 s was achieved.

In addition to the stability performance, the uncertainty of the time transfer system was also evaluated systematically in details. The main terms of the uncertainty budget are summarized in Table 1. The first term rep-

resents the uncertainty of the measured time differences based on the two-way time transfer system. From the long period of time difference measurements conducted over the 63 h, as shown in Fig. 4, it was evaluated as 12.4 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,[16] the used SFP transceivers would induce power-dependent delay. Benefiting from the symmetry of TWTT, most of such delay 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 to be less than 10 ps. In total, this term contributes an uncertainty of 33.2 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.[23] Such a non-reciprocal time delay can be evaluated by $\sum_i L_i D(\lambda_i - \lambda_{i+1})/2$, where L_i denotes the i-th fiber segment length between the adjacent i-th and $(i+1)$-th stations, $D \sim 17$ ps/nm/km is the dispersion of the single mode fiber, and $\lambda_i - \lambda_{i+1}$ denotes the wavelength difference between the two SFPs of the adjacent stations. Due to environmental variation, such as temperature, experienced by the fibers and SFPs, as well as the measurement errors in determining parameters like the dispersion coefficient, fiber length and optical wavelengths, the non-reciprocal time delay variation should be considered even after calibration. By monitoring the single-path time delay over the 1839-km fiber, a peak-to-peak variation of less than 120 ns was observed, which infers an average fiber temperature variation of smaller than 2 ℃. It has been investigated that the single-mode fiber dispersion has a thermal sensitivity of 4.5×10^{-3} ps/(nm·km·K)[23] and a dispersion slope of 0.1 ps/(nm^2·km).[24] The measurement precision of the fiber length and dispersion were estimated to be 0.1 m/km and 0.13 ps/(nm·km),[21] respectively. The typical magnitude of wavelength fluctuation for individual SFPs, resulting from thermal sensitivity and measurement error, was no more than 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 41.96 ps. The uncertainty from the polarization mode dispersion (PMD) effect was calculated with the typical coefficient of PMD, ~ 0.05 ps/$\sqrt{\text{km}}$.[25] The uncertainty introduced by the Sagnac effect correction was estimated to be 9.2 ps by adopting the approach outlined in Ref. [26], utilizing the knowledge of 24 positions along the fiber path between Xi'an and Taiyuan, along with the longitude, latitude, and elevation variances of each position.

All in all, the combined uncertainty for the time transfer system over the 1839-km field fiber was estimated to be 56.2 ps.

Table 1. Uncertainty budget for TWTT over the 1839-km field fiber link.

Uncertainty source	Uncertainty contribution (ps)	Uncertainty type
Time difference measurement	12.4	A
TIC	7.07	B
SFPs	33.2	B
FPGA	1.2	A
EVDL	1.4	A
Non-reciprocity from fiber	41.96	A&B
PMD	2.1	B
Sagnac	9.2	B
Combined uncertainty	56.2	

In summary, we have reported the implementation of high-precision time transfer over a long-haul field fiber link reaching a record distance of 1839 km. The time transfer stability has been achieved to be always better than 7 ps in the whole range of averaging time, with the uncertainty evaluated as 56.2 ps. This work constitutes a key component for constructing the nationwide high-precision fiber-optic time service network in China.

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