

Chapter 36

Simple Precise Time Signal Delivery Over Fiber Link Scheme

Yitang Dai, Zhongle Wu, Tianpeng Ren, Feifei Yin, Kun Xu, Jintong Lin and Geshi Tang

Abstract The capability of transferring time signal to remote locations with high stability and accuracy for synchronization is crucial for many important occasions, involving very long-baseline interferometry, coherent radio telescope arrays, modern particle accelerator, and the Deep Space Network. The widely used satellite methods of time and frequency transfer are unable to preserve the stability delivered by modern timekeeping sources. To meet these high stability requirements, optical fiber link has been used to transfer frequency and time reference, which however still suffers from mechanical perturbation and temperature variation along the link and degrades the phase stability at the remote end. Over the past decade, researchers mainly focused on the frequency dissemination, and the transfer stability is now sufficient for most frequency standards. However, the time signal transfer stability is far below frequency reference, which is typically at the nanosecond accuracy level. We propose and demonstrate a stable time signal delivery scheme over fiber link utilizing frequency stabilization technology. In the scheme, we utilizing the frequency reference to compensate the link-length variation, and the total transfer delay is kept constant. Precise time signal is regenerated at the remote end. The fiber link we used in this paper is 10-km, and the long-term fiber delay variation is more than 800 ps. We obtain a time deviation of 40 ps at 1-s and falling to 2.3 ps at 1,000-s averaging time for time transfer. The time delay resolution of scheme is 1 ps, and the compensation range is in direct proportion with the fiber length. The proposed scheme shows a potential ability to

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precisely transfer time signal and frequency reference simultaneously, which is very suitable for long range time and frequency transfer.

Keywords Time and frequency delivery · Fiber link · Time deviation

36.1 Introduction

Current research on microwave frequency references and optical atomic clocks offers the potential to produce frequency references with short-term instabilities of a few parts in 10^{16} for a 1 s averaging time [1]. These highest precision atomic clocks are usually very complex and not portable, maintained by certain laboratories, with very limited access. The ability to remotely transfer time signal and frequency reference to remote locations without introducing any additional instability is of greatly needed for many important occasions, such as the test of fundamental physical principles, development of next-generation accelerator-based x-ray sources, long-baseline coherent radio telescope arrays, and the accurate mapping of the Earth's geoid [2]. For example, in the Atacama Large Millimeter Array (ALMA) radio astronomy project, the local oscillator reference signal arriving at remote antennas with a maximum path length up to 18 km must be stabilized under one picosecond, in order to achieve the unprecedented sensitivity and angular resolution [3, 4].

The widely used satellite methods of time and frequency transfer are unable to preserve the stability delivered by modern timekeeping sources. To meet these high stability requirements, optical fiber link has been used to transfer frequency and time reference, which however still suffers from mechanical perturbation and temperature variation along the link and degrades the phase stability at the remote end. Over the past decade, researchers mainly focused on the frequency dissemination, and the transfer stability is now sufficient for most frequency standards. Different frequency transfer schemes based on fiber links have been proposed and demonstrated, basically two types [5]. The first one is in-loop tunable delay lines, such as the piezoelectric fiber stretcher or motor-driven tunable optical delay line. The second type is that the frequency standard at the center station is phase-tuned so that the phase at the remote end is stable, such as a voltage-controlled oscillator (VCO) or a cavity-length-changeable passively mode-locked laser. However, these schemes are not suitable for long range time signal transfer. For the first type, due to the large temperature-dependent delay variation of standard fiber, RF delivery over tens of kilometers requires a significant tunable range which will beyond the dynamic range of tunable delay lines. For the second type, because time signal is a wide-band signal, the VCO can only compensate single-frequency signal. Therefore, the time signal transfer stability is far below frequency reference, which is typically at the nanosecond accuracy level.

Recently, a time synchronization at 50 ps precision level was demonstrated in a frequency transfer fiber link [6], however, the time compensation and frequency compensation are achieved separately. Reference [7] fulfilled the joint stable time and frequency transfer in the same transmission path, but the time delay resolution is limited by the delay-locked loop integrated circuit.

In this paper, we propose and demonstrate the extension of our frequency transfer scheme [6] to the time transfer capability. We use the frequency reference to stabilize the time signal. Precise time signal and frequency reference are simultaneously regenerated at the remote end of fiber link. By utilizing the fiber's inherent chromatic dispersion, link-length variation caused by the environment variation are compensated. As the delay fluctuation of the fiber link is corrected, the time signal and the frequency signal are stabilized at the same time. In a 50-km fiber link, we obtain a time deviation of 2.1 ps (for time transfer) and an Allan Deviation of 1.42×10^{-15} (for frequency transfer) at 1,000-s averaging. The time delay resolution of scheme is 1 ps, and the compensation range is in direct proportion with the fiber length, which is very suitable for long range time and frequency transfer.

36.2 Principle

The proposed time signal transfer scheme is illustrated in Fig. 36.1. The stable transfer scheme consists of a large tunable-range optical delay and a regular phase detector. Rather than acting directly on the optical length of the fiber link like a broadly proposed optical compensation system, the scheme takes advantage of the chromatic dispersion in optical fiber. Utilizing the fiber's inherent chromatic dispersion, link-length variation caused by the environment change are compensated. As the delay fluctuation of the fiber link is corrected, the frequency signal can be stably transferred to the remote end. Because the time signal follows the same transmission path as the frequency signal, its delay is also stabilized by the system. Therefore, stable time can be regenerated at the remote end.

The radio frequency signal to be transferred is also regarded as a calibration signal. At the center station, the calibration frequency reference signal RF_1 and time signal are modulated on the optical carrier which comes from a computer-controlled tunable laser diode (TLD) via a Mach-Zehnder modulator (MZM), where the time signal is BPSK modulated by RF_2 . Assume that the initial wavelength of the optical carrier is λ_0 . After the modulator and an optical circulator, the optical signal is injected into the standard single mode fiber (SMF) spool which is located at the laboratory. The fiber delay fluctuation that results from the environment variation is τ . At the remote end, part of the optical signal is transferred back to the center station through the same fiber link via a Faraday rotator mirror (FRM). The round-trip transmitted optical signal is detected by a fast photo detector which recovers the calibration signal. The recovered calibration signal is filtered out and compared to the original frequency reference signal through an

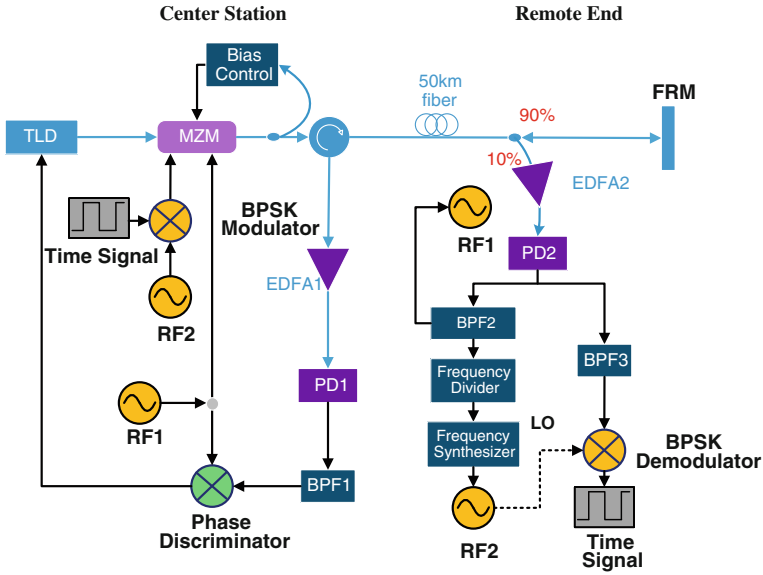


Fig. 36.1 Simple precise time signal delivery over fiber link scheme

electronic phase detector. Phase error signal is extracted which contains twice the phase perturbation of the fiber link under the assumption that the forward and backward propagations through the same fiber link experiences the same time delay. The output of the phase detector is then used to alter the wavelength of the tunable laser by a computer. The wavelength of the tunable laser is shifted using a classic proportional—integral-derivation (PID) algorithm according to the round—trip phase fluctuation. By tuning the wavelength of the TLD to λ we can get the following equation:

$$D \cdot L \cdot (\lambda - \lambda_0) + \tau = 0 \tag{36.1}$$

where D is the dispersion factor of the fiber and L is the length of the fiber.

The whole scheme acts as a long phase locking loop. After the loop is locked, at the remote end, the other part of the optical signal is filtered and recovered by a photo detector. The RF_1 is filtered out. This is the stably transferred frequency reference. We frequency divide this signal to synthesize RF_2 to demodulate the time signal. The stabilized time signal as well as frequency signal can be regenerated at the remote end.

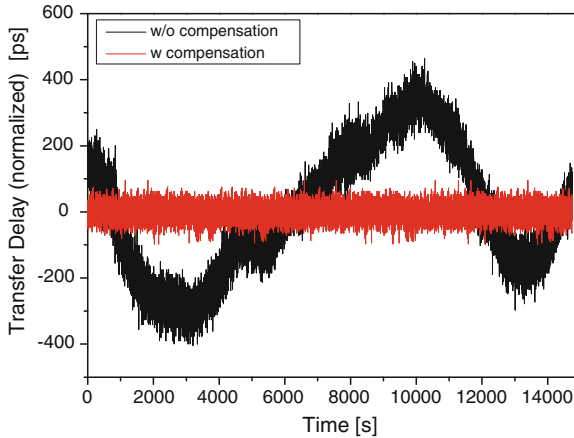


Fig. 36.2 Measured transfer delay of the time signal without (*black*) and with compensation (*red*)

36.3 Experiment and Results

36.3.1 Time Stability

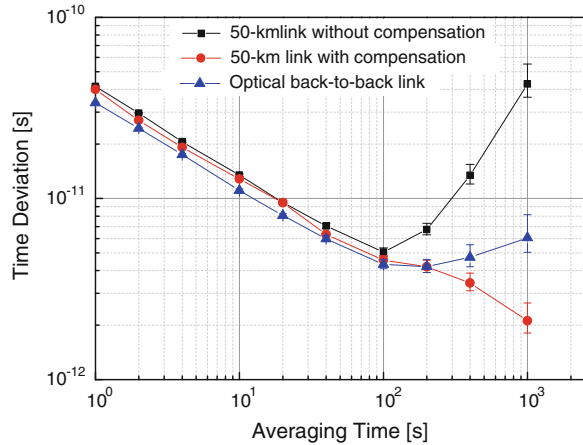
A proof-of-concept experiment is carried out and the setup is shown in Fig. 36.1. In the experiment, because we do not have an atomic clock, the frequency reference is synthesized by an analog signal generator and is set at 1,210 MHz. The time signal is generated by an arbitrary waveform generator. It generates an output square wave signal with an 8.4 ns rise and fall time and a 0.1 % duty ratio at a rate of 1.2 kHz. The tunable wavelength range of our TLD is from 1,525 to 1,568 nm and the minimum $\Delta\lambda$ is about 1 pm. A modulator bias-controller is used to lock the MZM at quadrature point.

Experimentally, we compare the time signal delivery stability without and with the proposed fluctuation compensation. In the uncompensated delivery, the wavelength of the optical carrier is fixed at 1,550 nm while the other conditions remain the same as those in the compensated situation.

In the experiment, we measure the time delay fluctuations of our system. In 15,000 s measuring time, the temperature changes more than 5° in the laboratory. Time transfer delay of the time signal is measured 1-s a time with a time interval counter and shown in Fig. 36.2. During the whole 15,000 s recording time, the uncompensated time transfer delay (normalized) is as large as 800 ps (shown in Fig. 36.2, black line). When the wavelength tuning driven by the PID phase tracking is on, the time transfer delay is about ± 50 ps (shown in Fig. 36.2, red line). We can see with compensation, the time delay is independent with temperature change. The time transfer delay suppression ratio will be greater for larger fiber length fluctuation.

The time deviation calculated from the transfer delay measurement is shown in Fig. 36.3. In the compensated link, the time deviation is monotonically decreasing

Fig. 36.3 Time deviation of time signal transfer with and without compensation. *Black square* 50 km without compensation; *red circle* 50 km with compensation; *blue triangle* optical back-to-back link transfer

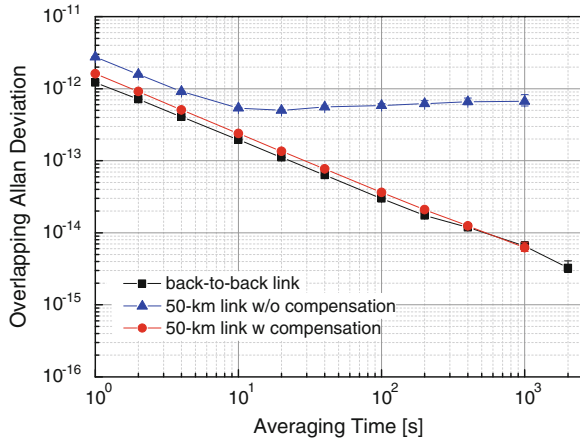


with averaging time, while the uncompensated link is not. The short-term jitter of the time signal, measured in a 1-s period, was 40 ps, which is similar with the uncompensated one. For averaging time of 1,000-s, the time deviation fall to 2.3 ps, whereas for uncompensated situation, it reached back to 50 ps. The time deviation of time signal reference was also measured. The time deviation of compensated link is approaching to that of the reference signal. This shows that the compensation scheme ensures the time signal preserving the stability in the long-term transfer. In our formal work [3], we measured the frequency transfer stability in a 54-km fiber link. A 0.854 ps root mean square time jitter is achieved after compensation. The time signal transfer is expected to achieve this accuracy level if we use better time interval measurement equipment. The proposed scheme shows a potential ability to precisely transfer time signal and frequency reference simultaneously.

36.3.2 Frequency Stability

Next, we examined the frequency transfer capability of our system. We measured the frequency stability with and without compensation. The Allan Deviation calculated from a 15,000-s measurement is shown in Fig. 36.4. The Allan Deviation of the compensated link was monotonically decreasing with averaging time, from 1.12×10^{-12} at 1-s falling to 1.42×10^{-15} for an averaging time of 1,000-s. The uncompensated link was even worse, and was degraded by the fluctuation. We also measured the optical back-to-back stability of our system. In this test, the 50-km fiber was replaced by a 1-m fiber, and the other situation remained the same. We can see the degradation introduced by the time signal, and the Allan Deviation of the compensated link is almost the same with the optical back-to-back stability.

Fig. 36.4 Allan deviation of frequency signal transfer with and without compensation



36.4 Conclusion

In conclusion, we have presented a scheme allowing time and frequency simultaneously transfer in a fiber link with active compensation of the propagation delay. The scheme takes advantage of the chromatic dispersion in optical fiber, and the time signal and frequency reference are stabilized at the remote end at the same time. We have demonstrated a stability of the time signal transfer over 50-km fiber with a time deviation around 40 ps at 1-s and 2.3 ps for 1,000-s averaging. We have also tested the performance of our frequency transfer. We obtained an Allan Deviation of about 1.42×10^{-15} for an averaging time of 1,000-s. The compensation range is in direct proportion with the fiber length, which is very suitable for long range time and frequency transfer. It may have important applications in radio astronomy.

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