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WDM-Based Fiber-Optic Time Synchronization Without Requiring Link Calibration

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ABSTRACT In this paper, we propose a fiber-optic time synchronization technique based on the bidirectional wavelength division multiplexing (WDM) transmission over a fiber link. The effect of fiber dispersion on the uncertainty of the system is effectively suppressed by properly allocating the forward and backward wavelength maps. Thus, only an initial easy-to-implement calibration in a back-to-back configuration instead of multiple complicated link calibrations is required. To compensate the propagation delay fluctuations, a large-dynamic-range time pre-compensator with high precision is implemented at the local site, enabling a time signal at the remote site is accurately synchronized with the clock at the local site. Our experiments demonstrate that stabilities in terms of time deviation (TDEV) of less than 29.8 ps at 1s and 5.2 ps at 10^4s and the clock difference of less than 28 ps can be achieved for the fiber link up to 200 km.

INDEX TERMS Optical fiber, time synchronization, wavelength division multiplexing, metrology.

I. INTRODUCTION

High precision fiber-optic time synchronization has attracted extensive research interest over the last two decades in the applications of metrology, telecommunication, navigation and atomic timescales development, where time deviation with the order of pico-second are required, because of fiber-optic's unique advantages of broad bandwidth, low attenuation, and immunity to electromagnetic interference, etc [1]–[3]. The fiber link subjected to the temperature variations and mechanical perturbations, however, leads to the propagation delay of fiber links with the fluctuations, and hence introduces fluctuated delay into the transferred time signal [4]. In order to mitigate this effect, bidirectional time transfer schemes over the single fiber (two-way and round-trip) have been proposed and experimentally demonstrated [5]–[9].

To suppress the effect of Rayleigh backscattering on the bidirectional transferred signal timing jitter, bidirectional wavelength-division multiplexing (WDM) schemes have been widely adopted [10]–[16]. However, unlike frequency dissemination, not only stability but accuracy is also a very vital index for time synchronization. Therefore, the existing WDM based schemes require a high precision link calibration procedure to determine the bidirectional delay asymmetry of the fiber link arose from the chromatic dispersion and its temperature-dependent delay variations for different wavelengths in the forward and backward directions. The fiber link calibration can be performed by employing the empirical value of the chromatic dispersion coefficient or refractive indexes of the corresponding fiber [10], [11]. In practical applications, however, the urban fiber links are often connected by several different sections, which are typically supplied by different companies, resulting in the inaccurate empirical value for the field-deployed fiber links. Another method of the link calibration, based on the measurement of the chromatic dispersion of the whole fiber link in filed by shifting laser wavelengths, may enhance the synchronization accuracy [17]. However, the calibration method is complicated, and recalibration is necessary for any change of fiber links, which will increase the operation and maintenance cost.

In this paper, we propose a fiber-optic time synchronization scheme based on the bidirectional wavelength division multiplexing (WDM) transmission without requiring any complex optical-fiber link calibrations. The effect of the fiber dispersion on the uncertainty of the system is effectively suppressed by properly allocating the bidirectional wavelengths. Time synchronization between the local and remote sites is realized by a large-dynamic-range time pre-compensator.

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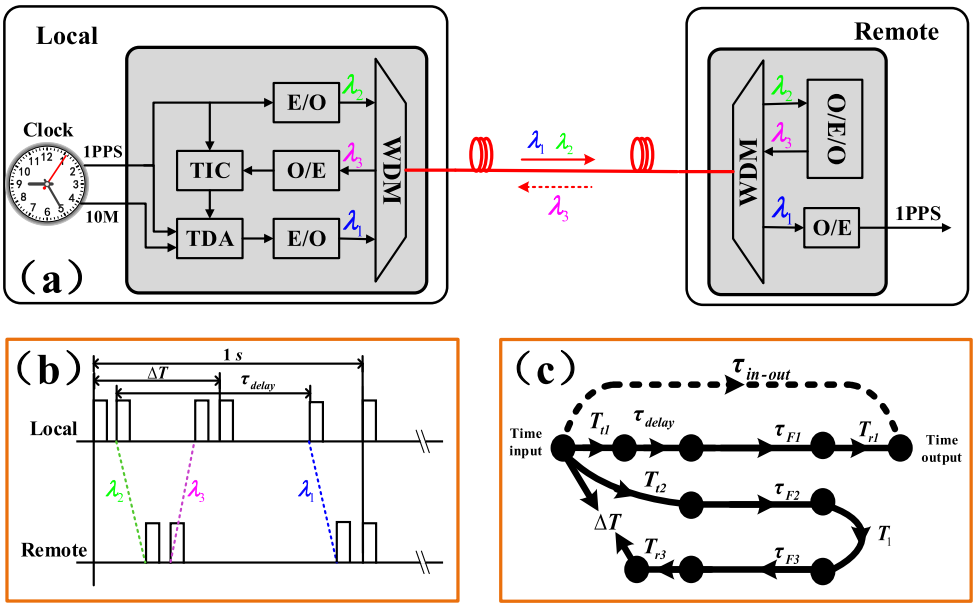

FIGURE 1. (a) Diagram of the proposed time synchronization scheme over a point-to-point fiber link based on the wavelength-division multiplexing technique, (b) The operation sequence flow, (c) The timing model of the scheme. TIC: time interval counter, TDA: time delay adjuster, WDM: wavelength division multiplexer, E/O: electrical-optical converter, O/E: optical-electrical converter, O/E/O: optical-electrical-optical converter.

The experimental results show that uncertainty of less than 28 ps can be reached with the proposed scheme for the fiber link up to 200 km which is consistent with the theoretical analysis, and stabilities in terms of time deviation (TDEV) can be less than 29.8 ps at 1 second and 5.2 ps at 10^4 seconds.

II. PRINCIPLE

Figure 1(a) illustrates the diagram of the proposed time synchronization scheme. The operation sequence flow is shown in Fig. 1(b). The time signal (1PPS, one-pulse-per-second) at the local site is sent to the remote site over an optical carrier with a wavelength of λ_2 via an optical fiber. At the remote site, the received time signal is then returned to the local site on a wavelength of λ_3 over the same fiber after processing with the optical-electrical-optical (O/E/O) conversion. The time difference between the local 1PPS and the received one at the local site is measured by a time interval counter (TIC), which is then used to control the time delay adjuster (TDA) to pre-compensate the propagation delay fluctuations introduced by the optical fiber. The pre-compensated time signal is sent to the remote site over another optical carrier with a wavelength of λ_1 to obtain a time synchronized signal at the remote site.

The timing model indicating the time delay of each part is shown in Fig. 1(c). T_{t1} (T_{t2}) and T_{r1} (T_{r3}) are the sending and receiving delays of the time signal at the local (remote) site, T_1 denotes the O/E/O conversion delay at the remote site; Considering the propagation delays of electronic circuits, internal cables, optical to electrical conversion and electrical to optical conversion, we can take the fluctuations of the delays (i.e. $T_{t1}, T_{t2}, T_{r1}, T_{r3}, T_1$) as constants. $\tau_{F1}, \tau_{F2}, \tau_{F3}$ are the forward or backward propagation delays in the fiber link for different wavelengths, τ_{delay} is the pre-compensation delay of the time signal achieved by TDA, ΔT represents the measured time difference by TIC, τ_{in-out}, indicated by the dashed arrow, is the time difference between the local clock and the output at the remote site, which should be one second when the remote site is exactly synchronized with the local site.

The system is initially calibrated by connecting the local site and the remote site with a short optical fiber (2m). In this situation, time synchronization between the local site and the remote site is achieved by adjusting the pre-compensation delay in TDA to make τ_{in-out} to be one second. Thus, we have,

$$\Delta T^0 = T_{t2} + \tau^0_{F2} + T_1 + \tau^0_{F3} + T_{r3}, \tag{1}$$
$$\tau^0_{in-out} = 1 = T_{t1} + \tau^0_{delay} + \tau^0_{F1} + T_{r1}, \tag{2}$$

where τ^0_{delay} and ΔT^0 represent the pre-compensation delay and the measured time interval achieved by TIC, τ^0_{F1}, τ^0_{F2} and τ^0_{F3} represent the propagation delays of the short fiber link in this back-to-back configuration for different wavelengths, respectively.

Similarly, when the local site and the remote site are connected by a fiber link with a length of L, we can have,

$$\Delta T^L = T_{t2} + \tau^L_{F2} + T_1 + \tau^L_{F3} + T_{r3}, \tag{3}$$
$$\tau^L_{in-out} = T_{t1} + \tau^L_{delay} + \tau^L_{F1} + T_{r1}, \tag{4}$$

where τ^L_{delay} and ΔT^L represent the pre-compensation delay and the measured time difference countered by TIC, τ^L_{F1}, τ^L_{F2} and τ^L_{F3} represent the propagation delays of the fiber link L for different wavelengths, respectively.

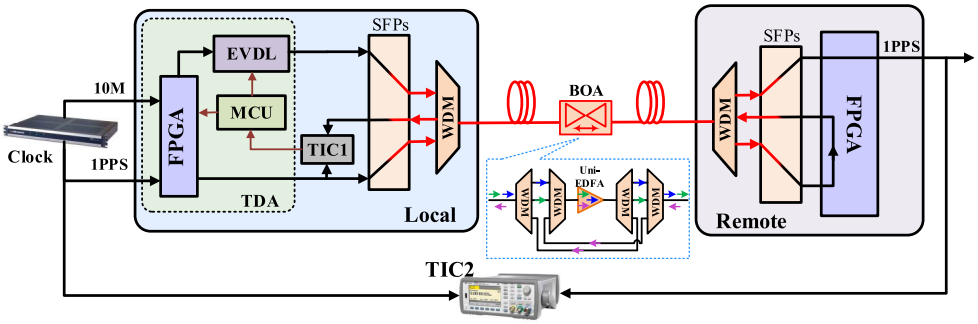

FIGURE 2. Experiment setup for the proposed time synchronization scheme. The inset shows the structure of the bidirectional optical amplifier (the transmission time for wavelength paths in blue, green and pink of the BOA are equal). TDA: time delay adjuster, FPGA: field programmable gate array, MCU: micro control unit, SFP: small form-factor pluggable transceiver, EVDL: electronic variable delay line, TIC: time interval counter, WDM: wavelength division multiplexer, BOA: bidirectional optical amplifier, Uni-EDFA: unidirectional erbium doped fiber amplifier.

From Eq. 1-4, we can obtain,

$$\tau^L_{in-out} = \tau^0_{in-out} + \frac{\Delta T^L - \Delta T^0}{2} + \left(\tau^L_{delay} - \tau^0_{delay}\right) + \left(\tau^L_{F1} - \frac{\tau^L_{F2}+\tau^L_{F3}}{2}\right) + \left(\frac{\tau^0_{F2}+\tau^0_{F3}}{2} - \tau^0_{F1}\right), \quad (5)$$

Considering that τ^0_{F1}, τ^0_{F2} and τ^0_{F3} are equal virtually in the back-to-back configuration, the fifth term on the right-side of Eq. 5 can be ignored. The forth term mainly comes from the wavelength difference between the forward and backward directions in the fiber link L. When the gaps among the three wavelengths are narrow enough, for example, 0.4 nm or 0.8 nm for the WDM optical transmission standards [18], the chromatic dispersion coefficients for the three wavelengths are considered to be equal and can be expressed by D. Thus we have,

$$\left(\tau^L_{F1} - \frac{\tau^L_{F2} + \tau^L_{F3}}{2}\right) = LD\left(\lambda_1 - \frac{\lambda_2 + \lambda_3}{2}\right). \quad (6)$$

From Eq. 6, we can see that the forth term in Eq. 5 can also be neglected when $\lambda_1 - (\lambda_2 + \lambda 3)/2 = 0$, and Eq. 5 can be simplified into

$$\tau^L_{in-out} = 1 + \frac{\Delta T^L - \Delta T^0}{2} + \left(\tau^L_{delay} - \tau^0_{delay}\right). \quad (7)$$

As illustrated in Eq. 7, time synchronization between the local site and the remote site can be achieved by adjusting τ^L_{delay} to make $\tau^L_{in-out} = 1$ s according to the known values of ΔT^0, τ^0_{delay} and ΔT^L. One can also see that the time synchronization in the case is independent of the length and the chromatic dispersion coefficient of the optical fiber link. In other words, the proposed scheme, in addition to suppressing backscattering, can achieve time synchronization without requiring link calibration by selecting pre-defined wavelengths.

III. EXPERIMENT APPARATUS AND RESULTS

The experiment setup for the proposed scheme is illustrated in Fig. 2. At the local site, the 1PPS time signal from a Rb clock is encoded into a time code in a field programmable gate array (FPGA) as proposed in [19], and injected into the fiber link through a WDM module with the assistance of a small form-factor pluggable transceiver (SFP) with a wavelength of $\lambda_2 = 1548.52$ nm. At the remote site, a SFP is used to detect the time signal over the wavelength of λ_2, and send it back over the same fiber link with a wavelength of $\lambda_3 = 1550.12$ nm by a direct optical-electrical-optical conversion. The time interval between the local input 1PPS and the returned back one at the local site is determined by TIC1. A micro control unit (MCU) is used to control the time pre-compensation delay adjustment according to the values of ΔT^0, τ^0_{delay} and ΔT^L. The pre-compensator consists of a large range adjustable delay and a small range adjustable delay with a high resolution implemented in FPGA and EVDL (electronic variable delay line), respectively, similar with the one adopted in [11]. The large time delays with a resolution of 8 ns are implemented in the FPGA with a working clock of 125 MHz synchronized to the 10 MHz frequency reference of the Rb clock. The EVDL has a tuning rang of 10.6 ns in a 10 ps resolution. The pre-compensated 1PPS time signal is transferred to the remote site over a wavelength of $\lambda_1 = 1549.32$ nm. Note that the three wavelengths employed here satisfy conditions to neglect the forth term in Eq.5, and Eq.7 can be used. To evaluate the synchronization performance, another TIC2 is used to measure the time interval between the 1PPS of the local clock and the synchronized time signal output at the remote site.

Figure 3 shows the measured clock difference between the local and remote sites in a 50 km fiber link over 80000 seconds with and without synchronization, respectively. For the case without synchronization (i.e. one way transfer), the measured clock difference varies within a range of about 6 ns around an average of about 239381.307 ns. On the contrast, the measured clock difference over the fiber link with synchronization varies around 12 ps with a peak-to-peak value of less than 252 ps, indicating that time synchronization between the local and remote sites has been successfully achieved. Time synchronization can extend to 100 km without requiring optical amplification

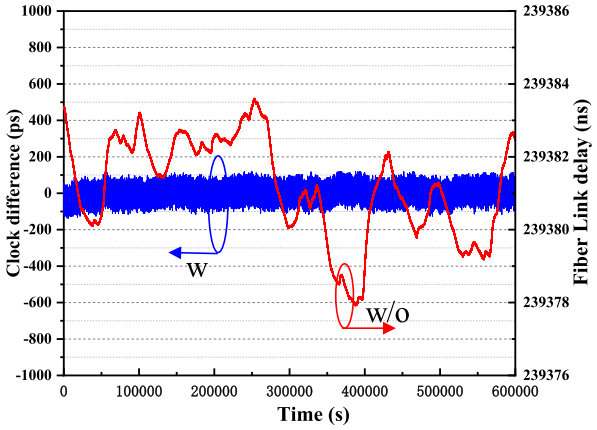

FIGURE 3. Measured clock differences over 50 km fiber link with/without time synchronization.

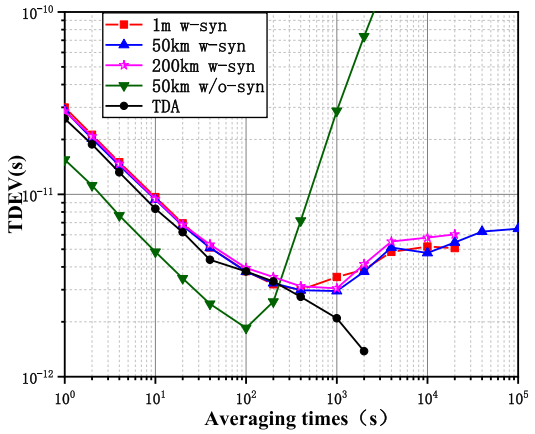

FIGURE 4. Measured stability in terms of TDEV with and without time synchronization for different fiber link lengths. As a comparison, the stability of TDA for time delay pre-compensation is also shown.

in the fiber link. We also verified the performance of the system in 200 km optical fiber link by employing a wavelength-division bidirectional optical amplifier (BOA) as proposed in [20], shown in the inset of Fig. 2. In order to guarantee the bidirectional symmetry of the BOA, the time delay differences among the three optical fiber paths are precisely adjusted by the optical tunable delay lines with a precision of 0.01 ps.

The measured stabilities in terms of TDEV over 1 m, 50 km and 200 km fiber links with time synchronization are shown in Fig. 4. As a comparison, the stability of the propagation delay of 50 km fiber link without synchronization is also presented. The result of 1 m can be regarded as the noise floor of our experimental apparatus. One can see that the stabilities of both 50 km and 200 km synchronized links are less than 29.8 ps at one second and 5.4 ps at 10^4 seconds and close to the noise floor. The long-term stabilities are significantly improved compared to the 50 km non-synchronized link, which indicate that the time delay fluctuations of the optical fiber is well compensated. It is important to note that the short-term (1-100 s) stability of the synchronized links, even in the back-to-back configuration, is mainly limited by that

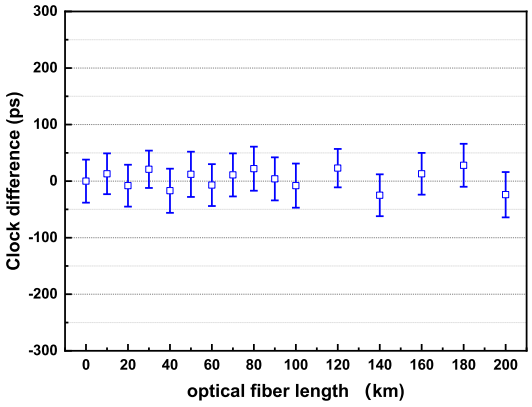

FIGURE 5. Measured clock difference for different fiber link lengths.

of the added TDA for pre-compensation (see the dotted curve in Fig.4), and is worse than that of the non-synchronized link. TDA with higher stabilities is required for improving the short-term (1-100 s) stability of the synchronized links.

The clock differences over various fiber lengths are shown in Fig. 5. In these measurements, after the initial calibration with a short fiber, no link calibration operation is performed for the different fiber link lengths. We can see that the the maximum mean clock difference is less than 28 ps for the fiber links up to 200 km, demonstrating that the proposed scheme is able to realize high-accuracy time synchronization without requiring link calibrations.

IV. UNCERTAINTY ANALYSIS

The main terms of the uncertainty budget for the proposed time synchronization scheme are summarized in Tab. 1. Here, type A uncertainty is evaluated by the statistical analysis of series of experiment observations, while type B uncertainty is data collected from non-experiment, such as data sheets, calibration reports and journal articles, etc [21], [22].

The first term results from the initial calibration in the back-to-back time synchronization configuration. A standard deviation of the clock difference of 30.55 ps is determined for 200 independent measurements, which indicates a type A uncertainty of 2.16 ps [21]. The second term is coming from TIC for determining the round-trip propagation delay. The type B uncertainty of TIC used in the experiment is 20 ps.

The third and forth terms denote the uncertainty originating from the time pre-compensation delay adjustment, which consists of the delay implemented in FPGA and in EVDL. To effectively evaluate this uncertainty coming from FPGA, we control FPGA to achieve the time delay from 0 to 1 s in a 0.1 s step and examine the differences between the measured time interval and the expected one. The evaluation result is shown in Fig. 6(a), and a type A uncertainty of 5.12 ps is obtained. Similarly, the uncertainty coming from EVDL is evaluated by adjusting the delay from 0 to 8 ns in a 1 ns step (shown in Fig. 6 (b)), and a type A uncertainty of 10.12 ps is acquired. Meanwhile, the resolution of 10 ps is another type B uncertainty source for EVDL. Conseqently, a combined uncertainty is 14.23 ps for the delay in EVDL.

TABLE 1. Uncertainty budget for the proposed time synchronization scheme.

Uncertainty source	Coefficient	Estimated value	Uncertainty contribution (ps)	Uncertainty type
Calibration	1	2.16 ps	2.16	A
TIC	1	20 ps	20	B
Counting delay	1	5.12 ps	5.12	A
Delay by EVDL	1	14.23 ps	14.23	A&B
Wavelength difference	DL^*	4.3 pm	$4.3 \times 10^{-3} DL$	A
Dispersion coefficient	$0.8^2 L$	0.1 ps/nm^2/km	$0.064L$	B
PMD	$\sqrt{3}\sqrt{L}$	0.05ps/$\sqrt{}$km	$0.05\sqrt{3}\sqrt{L}$	B
Sagnac effect	1	1.2	1.2	B

* The units of D and L are ps/nm/km and km, respectively.

TABLE 2. The theoretical uncertainty and the measured clock difference.

Fiber length (km)	10	50	100	180	200
Theoretical uncertainty (ps)	±25.2	±25.7	±27.1	±30.7	±31.8
Measured clock difference (ps)	13	12	-8	28	-24

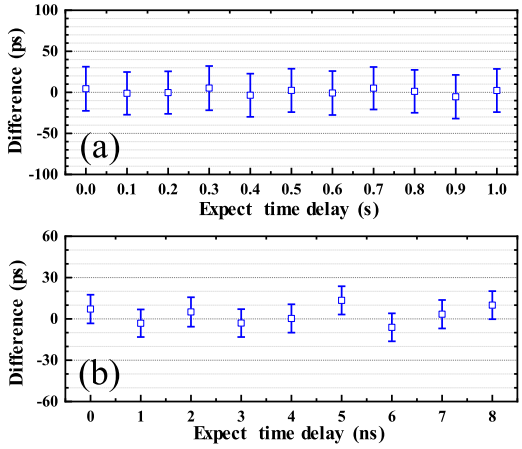

FIGURE 6. Time difference between the measured delay and the expected value implemented in FPGA (a) and in EVDL (b).

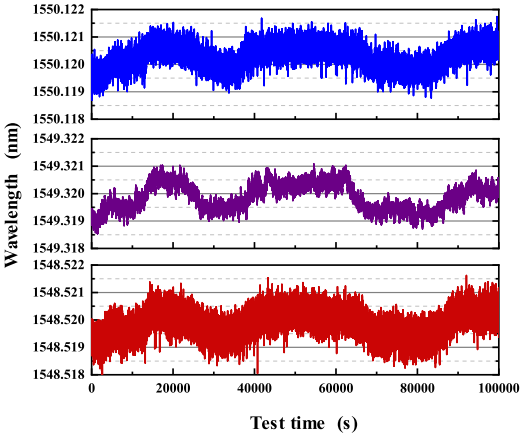

FIGURE 7. Measured wavelengths of the three SFP transceivers.

This part uncertainty can be reduced by employing higher precision EVDLs.

The wavelength-difference dependent fiber chromatic dispersion is another source of the uncertainty [23]. In practice, the wavelengths of SFPs cannot be completely accurate and stable for the limitation of the practical manufacture technique and the temperature variations. Figure 7 shows the wavelengths of the three employed SFP transceivers measured by an optical wavelength meter with a resolution of 0.1 pm. It can be seen that the wavelengths vary within a range of 3.5 pm in 100000 seconds. Since the wavelength variations of the three SFPs are independent, the overall contribution is 4.3 pm ($\sqrt{3.5^2 + (3.5/2)^2 \times 2}$, according to Eq.6), resulting in an uncertainty of $4.3 \times 10^{-3} DL$ ps for the fiber length of L km. Moreover, another uncertainty source comes from the approximation that the chromatic dispersion coefficients of the three wavelengths, D, are equal. An uncertainty of $0.064L$ ps will be introduced for a dispersion slope of 0.1 ps/nm^2/km which exceeds the values of most commercial fibers and represents the worse case [24].

The uncertainty from the random polarization mode dispersion (PMD) is calculated with the coefficient of 0.05ps/$\sqrt{}$km [22]. The last term represents the uncertainty introduced by the Sagnac effect concerning the impact of the Earth's rotation. The uncertainty from the correction of the Sagnac effect is less than 1.2 ps for any two sites connected with the fiber link of 200 km when the position uncertainty is better than 1 km of any point located on the earth, which can be achieved thanks to the global positioning system (GPS) [25].

The uncertainty caused by the bidirectional optical amplifier (BOA) is negligible since the time delay differences among the three wavelength paths are precisely controlled with a precision of 0.01 ps.

According to above analysis, the calculated combined uncertainty for the proposed time synchronization scheme over different fiber lengths without any fiber link calibration is summarized in Table 2. One can see that the uncertainty increases slightly with the extension of fiber links and still no more than 31.8 ps for the fiber links up to 200 km. The measured clock differences over different fiber links

after synchronization are also listed. It can be seen that all the measured clock differences are within the calculated uncertainty.

V. CONCLUSION

In summary, we propose and implement a fiber-optic time synchronization scheme without the need of fiber link calibrations and only a calibration in the back-to-back configuration is required. With the proposed scheme, a time signal (PPS) can be obtained at the remote site, which is synchronized with the one of the local site. Different factors related to the uncertainty of the time synchronization system are investigated in detail and full uncertainty budgets for the system are calculated. The results illustrate that the mean clock difference of less than 28 ps and the stabilities in terms of TDEV of less than 29.8 ps at one second and 5.2 ps at 10^4 aeconds can be achieved for the fiber links up to 200 km.

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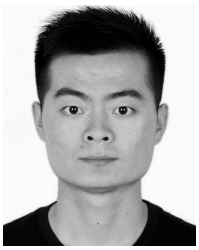

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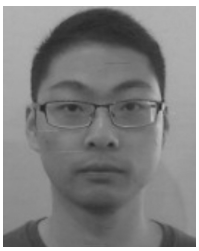

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