Precise measurement method of optical fiber length based on timestamp technique

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Abstract: A measurement method of optical fiber length using timestamp technique is demonstrated. Based on IEEE1588 precise clock synchronization protocol, the principle that time delay asymmetry on two path results in synchronization time deviation is used, and the difference between two-path delays could be deduced by measuring the synchronization time deviation reversely. Then the length of optical fiber on one path could be calculated if that on the other path is known. Due to the fact that the path of Sync and Delay_Req message is symmetric, the optical pulse dispersion and the asymmetry of photoelectric detector performance on two paths are averaged by exchanging two optical fibers. The time difference between master and slave clocks is eliminated by sharing the same time base. At last, the lengths of two single-mode optical fibers are measured with the uncertainty of 0.578 m for 3 227.722 m and 0.758 m for 25 491.522 m, respectively. Thus this method has high precision and long range.

Key words: timestamp; fiber length measurement; time synchronization

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For fiber optical communication and fiber optical sensing research, measuring fiber length precisely and feasibly becomes more and more important. The common method is optical time domain reflection (OTDR)[1-2]. This method is single end and non-destructive, but there are some measurement errors such as the front end positioning deviation, receiving deviation and the blind zone. The schemes of optical frequency domain reflectometer (OFDR)[3-4] and optical coherent domain reflectometer (OCDR)[5-7] can eliminate the front end positioning deviation and receiving deviation, and have high resolution. But they have trade-offs in range and sensitivity, and have high demand on laser source.

1 Main research work

In this paper, a method using timestamp is proposed to overcome the above disadvantages. The bidirectional measurement technology of IEEE1588 precision time synchronization protocol[8] is used to eliminate the front end positioning deviation and receiving deviation. The separation of optical sending signal and receiving signal is adopted to avoid blind area. High precision hardware timestamp technology[9-11] is utilized to make the measurement more precisely. Besides, this method has long range because the signal is based on Ethernet and it has long transmission distance and easy relay. In the experiment, the optical fibers with lengths of 3 227.722 m and 25 491.522 m are measured with uncertainty of 0.578 m and 0.758 m, respectively. Comparing the length result with that issued by National Communications Metrology Station (NCMS), the deviation between ours and NCMS's is within the uncertainty.

1.1 Measurement principle and design of experimental apparatus

The experimental apparatus is shown in Fig. 1.

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Time synchronization protocol analyzer with the model of XG7050 (SN: 007050140536) is used as master and slave clocks, and two optical fibers with the same length of 1.039 m are used to connect the master and slave clocks. The master and slave clocks share the same time base to eliminate their time deviation. At the same time, the clock is set to free state to avoid the jitter introduced by global navigation satellite system (GNSS) taming.

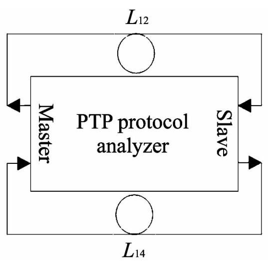

Fig. 1 Schematic of optical fiber length measuring apparatus

The principle of picture transfer protocol (PTP) is shown in Fig. 2.

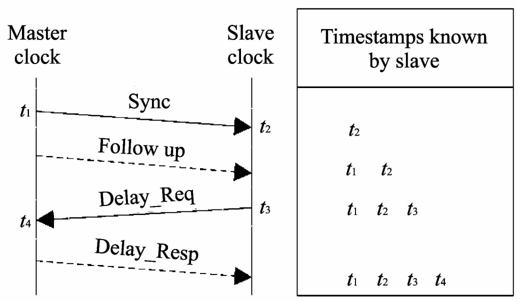

Fig. 2 Schematic of PTP

The time deviation between the slave and master clocks is

$$\Delta = \frac{(t_2 + t_3) - (t_1 + t_4) + (T_{L_{32}} - T_{L_{12}})}{2}, \quad (1)$$

where t_1 is the time when master clock sends Sync packet to slave clock, and t_2 is the time when slave clock receives this packet. t_3 is the time when slave clock sends Delay_Req packet to master clock, and this packet is used to calculate the reverse transmission delay. t_4 is the time when master clock receives the Delay_Req packet. $T_{L_{12}}$ and $T_{L_{34}}$ are path delays of L_{12} and L_{34}, respectively.

Due to $L_{12} = L_{34} = L$, the time deviation between the slave and master clocks is

$$\Delta = \frac{(t_2 + t_3) - (t_1 + t_4)}{2}. \quad (2)$$

Since master and slave clocks share the same time base and their transmission path is short, the measurement error caused by chromatic dispersion can be ignored. So the time deviation mainly depends on the timestamp accuracy of master and slave clocks.

First, L_{12} is replaced by L_x, as shown in Fig. 3.

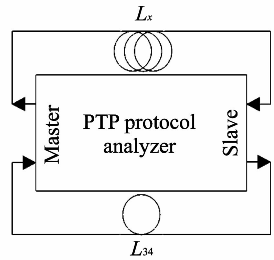

Fig. 3 L_{12} is replaced by L_x

It can be obtained as

$$\Delta_1 = \frac{(t_2 + t_3) - (t_1 + t_4) + (T_L - T_{L_x})}{2}. \quad (3)$$

In order to eliminate the asymmetry of optical pulse dispersion and photoelectric detector's performance in bidirectional measurements, L_{34} is replaced by L_x for the other measurement on the basis of Fig. 1, as shown in Fig. 4.

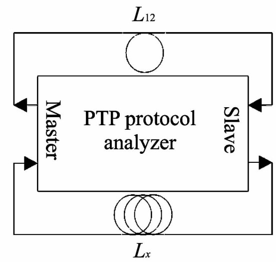

Fig. 4 L_{34} is replaced by L_x

It can be obtained as

$$\Delta_2 = \frac{(t_2 + t_3) - (t_1 + t_4) + (T_{L_x} - T_L)}{2}. \quad (4)$$

The following formula can be obtained by subtraction of Eqs. (4) and (3), that is

$$\Delta_2 - \Delta_1 = T_{L_x} - T_L = \frac{L_x - L}{\frac{c}{n}}, \quad (5)$$

where c is the speed of light, and n is the index of refraction. And then

$$L_x = (\Delta_2 - \Delta_1)\frac{c}{n} + L. \quad (6)$$

1.2 Experiment and results

The sending frequency of PTP analyzer's Sync and Delay_Req packet is set to 1 Hz, and the time deviation between the slave and master clocks is also calculated one time per second. While $L_{12} = L_{34} = L = 1.039$ m, the time deviation is recorded for 13 437 s, as shown in Fig. 5.

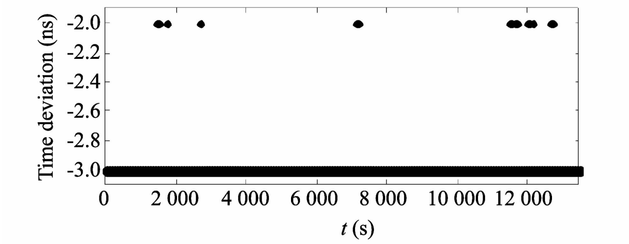

Fig. 5 Time deviation of slave and master clock using 1.039 m fiber at 1 550 nm

From the above figure, it can be obtained that the average time deviation is −2.999 ns, which represents the inherent deviation of the PTP analyzer. The resolution is 1 ns and standard deviation is 0.027 ns.

Then G.655 optical fiber with the length of $L_x = 25\ 487.3$ m and refractive index of $n = 1.46$ at 1 550 nm is measured in the experiment. Adding fiber jumper of 2.111 m on both ends, the total length of fiber is 25 491.522 m calibrated by NCMS with uncertainty of 1 m.

The configuration of PTP is the same as above. First, L_{12} is replaced by L_x, as shown in Fig. 3. Time deviation is measured for 108 s as shown in Fig. 6. From the above figure, it can be obtained that the average time deviation Δ_1 is −62 075 ns and standard deviation is 0 ns.

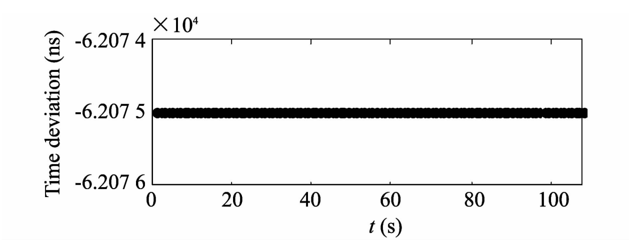

Fig. 6 Time deviation of slave and master clocks on condition that L_{12} is replaced by L_x with length of 25 491.522 m

Second, L_{34} is replaced by L_x, as shown in Fig. 4. The configuration of PTP is also the same. Time deviation is measured for 129 s as shown in Fig. 7.

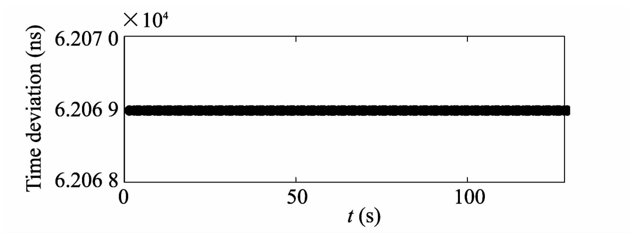

Fig. 7 Time deviation of slave and master clocks on condition that L_{34} is replaced by L_x with length of 25 491.522 m

From the above figure, it can be obtained that the average time deviation Δ_2 is 62 069 ns and standard deviation is 0 ns.

Substituting results into Eq. (6), it can be obtained that $L_x = 25\ 492.433$ m.

In order to verify the universality of this measurement method, G.652 optical fiber with the length of $L_x = 3\ 223.5$ m and refractive index of $n = 1.46$ at 1 310 nm is also measured. Adding fiber jumper of 2.111 m on both ends, the total length is $L_x = 3\ 227.722$ m calibrated by NCMS with uncertainty of 1 m. The configuration of PTP is also the same. L_{12} is replaced by L_x firstly, and the time deviation between the slave and master clocks is measured for 174 s as shown in Fig. 8. It can be obtained that the average time deviation Δ_1 is −7 867 ns and standard deviation is 0 ns.

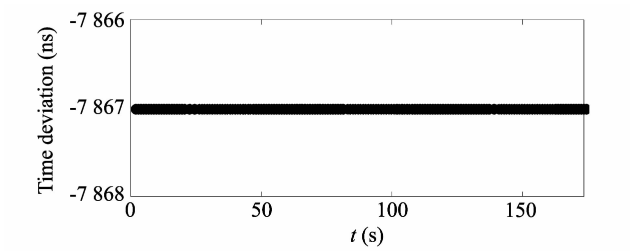

Fig. 8 Time deviation of slave and master clocks on condition that L_{12} is replaced by L_x with length of 3 227.722 m

Then L_{34} is replaced by L_x and time deviation is measured for 362 s, as shown in Fig. 9. It can be obtained that the average time deviation Δ_2 is 7 853.006 ns and standard deviation is 0.074 ns.

According to the above measurement results and Eq. (6), it can be obtained that $L_x = 3\ 228.943$ m. The deviation between ours and NCMS's is 1.221 m.

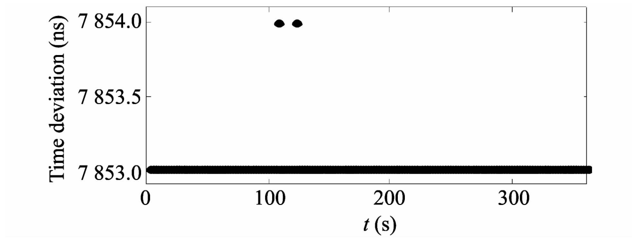

Fig. 9 Time deviation of slave and master clocks on condition that L_{34} is replaced by L_x with length of 3 227. 722 m

2 Analysis of measurement uncertainty

The uncertainty of time deviation Δ in the experiment mainly depends on the time deviation between master and slave clocks, time base error, dispersion[12], detection error of photoelectric detector and measurement resolution.

For measuring the optical fiber length of 25 492. 522 m, the master and slave clocks share the same time base, so the time deviation between master and slave clocks can be ignored. Since the time base is not tamed by the GNSS, there will be time base error in the measurement. The time base is measured as -1.18×10^{-10}, so the uncertainty due to time base error is −0. 118 ns within one second. Single mode small formfactor pluggables (SFP) optical module is used as light source in the experiment, and its spectrum width at −20 dB is about 1 nm. The attenuation coefficient of fiber is 0. 191 dB/km, and it can be obtained that the attenuation is 4. 869 dB. Thus the uncertainty due to narrowing of optical pulse's width is about 0. 5 ns. The dispersion coefficient is 17 ps/(nm • km), so the uncertainty due to dispersion is 0. 433 ns. The error of photoelectric detector is very small, so it can be ignored. The measurement resolution is 1 ns, so the uncertainty due to measurement resolution is 0. 5 ns. The larger one between measurement repeatability and resolution is adopted. Δ_1 and Δ_2 has the same measurement errors, as shown in Table 1.

Table 1 Influence factors in Δ_1 and Δ_2, while 25 492. 522 m optical fiber is measured

Influence factors	Value (ns)
Time base	0. 118
Attenuation	0. 5
Dispersion	0. 433
Resolution	0. 5

Based on the above influence factors, it can be obtained that the uncertainty ($k=2$) of time deviation Δ is 3. 690 ns. As the speed of light and refractive index is known, it can be obtained that the length measurement uncertainty ($k=2$) of 25 492. 522 m is 0. 758 m. Comparing the measurement result L_x with that of NCMS, it can be obtained that the deviation between ours and NCMS's is 0. 911 m. The sum of this uncertainty and that of NCMS is 1. 758 m. Because 0. 911 m is less than 1. 758 m, the measurement error is within uncertainty.

For measuring the optical fiber length of 3 227. 722 m, Δ_1 and Δ_2 have the same measurement errors, as shown in Table 2. Based on these influence factors, it can be obtained that the uncertainty ($k=2$) of time deviation Δ is 2. 817 ns and the measurement uncertainty ($k = 2$) of 3 227. 722 m is 0. 578 m.

The sum of this uncertainty and that of NCMS is 1. 578 m. Since 1. 221 m is less than 1. 578 m, the measurement error is within uncertainty.

Table 2 Influence factors in Δ_1 and Δ_2, while 3 227. 722 m optical fiber is measured

Influence factors	Value (ns)
Time base	0. 118
Attenuation	0. 5
Dispersion	0. 055
Resolution	0. 5

3 Conclusion

This paper presents a method to measure optical fiber length using timestamp technique. The method is high precise and dead zone is free. The principle that the difference between two-path delays could be deduced by measuring the time deviation between the slave and master clocks is adopted to calculate the length of optical fiber. The optical pulse dispersion and the asymmetricity of photoelectric detector performance on two paths are eliminated by exchanging two optical fibers. Sharing the same time base is used to eliminate the time difference between the master and slave clocks. The state of the clock is set to free to avoid the jitter introduced by GNSS taming. Besides, the bidirectional measurement is on separate path, so the dead zone is free. Finally, the lengths of two single-mode optical fibers are measured with the uncertainties of 0.578 m for 3 227.722 m and 0.758 m for 25 491.522 m. The measurement results are compared with that of NCMS. It can be concluded that the measurement error is within uncertainty. This method could be useful in the measurement of optical fiber length and calibration of optical fiber length measurement device.

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基于时间戳技术的光纤长度精确测量方法

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摘　要： 本文提出了一种基于时间戳技术的光纤长度测量方法。利用 IEEE1588 精密时间同步协议的线路时延不对称导致同步时间偏差的原理，测量同步时间偏差，反推线路时延差。并通过一路已知长度的参考光纤，计算得到被测光纤的长度。同时利用时间同步协议的同步信号和延时请求信号测量机理对称的特点，交换来回两线路上的光纤，来均衡此两线路上光脉冲色散和光电探测器性能的不对称性。将客户端和服务器至于同一时基，来消除同步时间偏差中客户端和服务器时钟不一致的影响。最后利用该方法测量了两根长度为 3 227.722 m 和 25 491.522 m 的单模光纤，不确定度分别为 0.578 m 和 0.758 m。故此测量方法精度高且范围大。

关键词： 时间戳；光纤长度测量；时间同步

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