



IEEE 1588 based time synchronization system for a seafloor observatory network^{*}

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Abstract: An IEEE 1588 based application scheme was proposed to achieve accurate time synchronization for a deep seafloor observatory network based on the communication topological structure of the Zhejiang University Experimental and Research Observatory. The principles of the network time protocol (NTP) and precision time protocol (PTP) were analyzed. The framework for time synchronization of the shore station, undersea junction box layer, and submarine science instrument layer was designed. NTP and PTP network signals were decoded by a PTP master clock on a shore station that receives signals from the Global Positioning System and the BeiDou Navigation Satellite System as reference time sources. These signals were remotely transmitted by a subsea optical–electrical composite cable through an Ethernet passive optical network. Accurate time was determined by time synchronization devices in each layer. Synchronization monitoring experiments performed within a laboratory environment indicated that the proposed system is valid and has the potential to realize microsecond accuracy to satisfy the time synchronization requirements of a high-precision seafloor observatory network.

Key words: Seafloor observatory network, Junction box, IEEE 1588, Time synchronization

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1 Introduction

Development of marine science and technology has increased the focus on construction of cabled seafloor observatory networks for marine scientific research. The most important function of a seafloor observatory network is to provide undersea scientific instruments (SIs) with connectors for power and communication through junction boxes (JBs) from a shore station (SS) through subsea optical–electrical composite cables. Such a network enables remote operation, real-time observation, and/or sampling of physical, chemical, and biological specimens in oceans, as well as development of hydrothermal solutions and observation and evaluation of micro-organisms on the seabed, water flow, plate movement,

and plate deformation under the seafloor, and other objects and processes of interest (Chen *et al.*, 2012a).

Time synchronization is an essential function of the Zhejiang University Experimental and Research Observatory (ZERO). Sensor data collected at different locations must be timestamped for analysis and correlated with other events and data sources located anywhere from a few meters to thousands of kilometers away (Lentz and Lécroart, 2009). For some observations, low timestamp accuracy is adequate, whereas for other observations such as acoustic or seismic signals, sub-millisecond precision levels are necessary (del Rio *et al.*, 2012) to obtain an accurate estimate of disasters such as earthquakes, storms, submarine volcanic eruptions, and tsunamis. The IEEE 1588 “precision clock synchronization protocol for networked measurement and control systems” is a new standard introduced in 2002. Its applications and enhancements have been widely used in industrial applications such as robotics, sensor networks

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(Ferrari *et al.*, 2008), wireless applications, computer numerical control systems (Zhang *et al.*, 2008), and electric power industries (Lixia *et al.*, 2009), but rarely in ocean exploration. The application of precision timing in a seafloor observatory network has been previously studied (Lentz and Lécroart, 2009; Kanazawa *et al.*, 2011; Månuel *et al.*, 2012). The design and realization of a time synchronization system based on the ZERO framework plays a significant role in the synchronous control and reliable operation of submarine JB's as well as on real-time monitoring and conjoint data analysis of undersea SIs.

Here we present an IEEE 1588 based time synchronization system that can supply pulse per second (PPS), network time protocol (NTP), and precision time protocol (PTP) signals with varying degrees of precision. These signals are sent to JB's and to appropriately designed SIs used within ZERO. An experimental setup was built in the laboratory to evaluate system performance. Conservative limits for precision are derived from the results.

2 Overview and the synchronization method of a seafloor observatory network

The ZERO seafloor observatory network consists of an SS, a JB layer, and an SI layer. The primary concerns in this type of framework are as follows: (1) Seawater attenuation does not allow the Global Positioning System (GPS) or BeiDou Navigation Satellite System (BDS) signals to directly reach the sea bottom. Thus, primary reference clocks in the SS layer are very important to the entire network and sub-microsecond accuracy is necessary. (2) The JB is a seafloor transfer station for delivery, conversion, distribution, and management of power and communication signals (Chen *et al.*, 2013). This component has a lower demand for synchronization accuracy and is designed with millisecond accuracy. (3) Because of the diversity of connected SIs, diverse accuracy classes of time synchronization signals are needed. Fig. 1 shows the structure of the ZERO time synchronization system.

2.1 Construction of the time synchronization system

The reliability and accuracy of a clock that a user client may provide may be limited for various reasons,

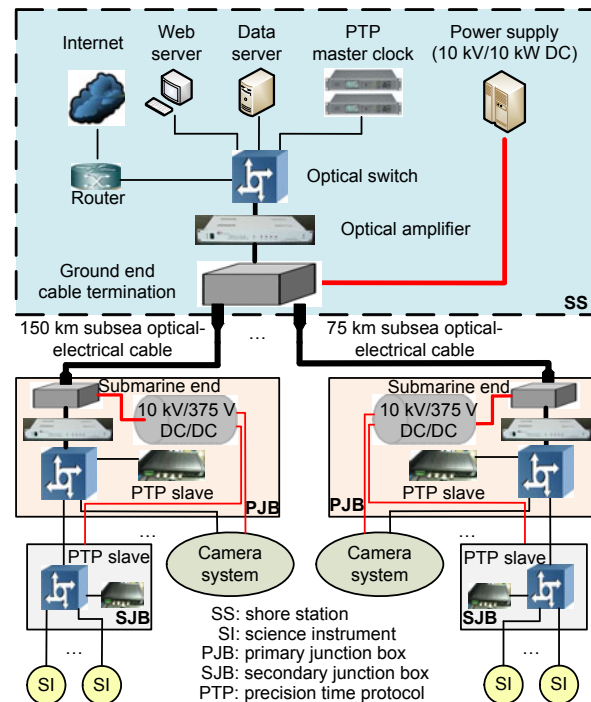


Fig. 1 Structure of the ZERO time synchronization system

such as its time synchronization method, hardware circuit, and software design. This limitation is a technical bottleneck in the time synchronization process in many application areas. Various available synchronization protocols provide different approaches to time synchronization but all follow two general models: (1) the client sends a request to a server and the server responds with its current time, or (2) the server sends messages to a group of or all clients (Refan and Valizadeh, 2011). Research on network time synchronization focuses mainly on NTP and PTP (Sun *et al.*, 2010). NTP provides millisecond accuracy in local area networks without hardware support, is widely used in the Internet, and is suitable for situations with large propagation delays (Ying, 2012). On the other hand, PTP represents a synchronization method for distributed systems which can guarantee a higher degree of synchronization among the clocks of different system elements (López *et al.*, 2010). The PTP specified in IEEE 1588 is capable of synchronizing distributed clocks with an accuracy of less than one microsecond (Wang and Long, 2010) with appropriate hardware support.

Considering system costs and the diversity of SIs, both the NTP and IEEE 1588 protocols are applied. The PTP master clock on the SS receives satellite

signals from both GPS and BDS and acts as a sufficiently accurate time source. A 150 km subsea optical–electrical composite cable originating from the SS lies on the seafloor and branches into many primary junction boxes (PJBs) via branching units (Chen *et al.*, 2012b). Electric cables are used to connect secondary junction boxes (SJBs) or camera systems to PJBs. SIs are connected to SJBs with waterproof or contactless connectors (Li *et al.*, 2010). Thus, abundant power and high bandwidth are provided to all PJBs, SJBs, and SIs. PTP slaves in PJBs, SJBs, and SIs communicate with the PTP master clock to achieve time synchronization. To meet the requirement of microsecond accuracy, the use of ordinary switches or routers should be avoided (Moreno-Muñoz *et al.*, 2013). All network transmission equipment must support IEEE 1588.

2.2 Basic introduction of NTP and PTP

NTP was proposed in 1985 by David L. Mills (University of Delaware) and subsequently became known as NTP Version 0 (Mills, 2003). NTP has been updated to Version 4 since then. A client/server work mode is generally employed to determine dual clock difference and network transmission delay based on round-trip NTP packets between a client and its server. Time synchronization accuracy is usually measured in milliseconds and varies with changes in network structure, network load, and operating systems (OS). Detailed content can be sought from RFC5905 (Mills *et al.*, 2010).

In contrast to the NTP protocol, PTP measures clock deviation and network latency mainly through four types of message packets: Sync, Follow_Up, Delay_Req, and Delay_Resp messages. The message delivery process is shown in Fig. 2.

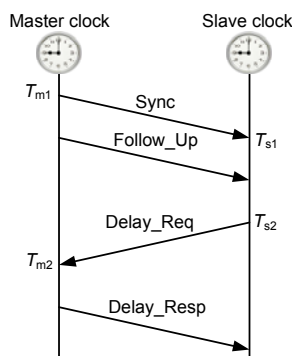


Fig. 2 Synchronization principle of the precision time protocol (PTP)

The master sends a Sync message to the slave and then records the accurate time of its local system clock (T_{m1}). The slave receives the Sync message and records the accurate time of its local system clock (T_{s1}). Finally, the master sends a Follow_Up message that contains T_{m1} . The offset between the master and the slave is given by

$$\text{Offset} = T_{s1} - T_{m1} - \text{Delay}. \quad (1)$$

The slave sends a Delay_Req message to the master and then records the accurate time of its local system clock (T_{s2}). The master receives the Delay_Req message and then records the accurate time of its local system clock (T_{m2}). Finally, the master sends a Delay_Resp message that contains T_{m2} . The delay between the master and the slave is given by

$$\text{Delay} = T_{m2} - T_{s2} + \text{Offset}. \quad (2)$$

Eqs. (1) and (2) yield

$$\text{Offset} = \frac{(T_{s1} - T_{m1}) - (T_{m2} - T_{s2})}{2}, \quad (3)$$

$$\text{Delay} = \frac{(T_{m2} - T_{s2}) + (T_{s1} - T_{m1})}{2}. \quad (4)$$

Sync and Follow_Up messages are typically sent periodically (the default period is 2 s, and the period of the master clock applied in ZERO is 1 s and can be adjusted from 1/64 s to 64 s), similar to the time offset correction discussed by Milevsky and Walrod (2008). By contrast, Delay_Req and Delay_Resp messages are sent randomly because changes in network delay are negligible due to the stability of the network architecture and minimal changes in the network load. In 2008, the announce message was defined for the best master clock service in IEEE 1588 v2 (Han and Jeong, 2010).

2.3 Uncertainty of the proposed time synchronization system

The synchronization accuracy of the proposed time synchronization system is affected by many factors, and most can be ascribed to the following causes: uncertainty of crystal oscillators inside the clocks, uncertainty of the master clock, uncertainty of the communication network, uncertainty of the slave clock, and uncertainty of the SIs to recover timing signals.

2.3.1 Uncertainty of crystal oscillators

High-precision time synchronization cannot be achieved without high-quality crystal oscillators (Loschmidt *et al.*, 2008). The quality of a crystal oscillator depends greatly on its frequency stability. Analysis of the noise characteristics of a crystal oscillator can provide insight regarding control of the frequency source and thus the accuracy of the oscillator. The time-domain characterization of the short-term frequency stability of a highly stable oscillator is usually derived from the Allan variance. The theoretical equation of the generalized Allan variance is as follows:

$$\sigma^2(N, T, \tau) = \lim_{m \rightarrow \infty} [\sigma^2(N, T, \tau)]_m, \quad (5)$$

where N is the sampling number of each group, T is the sampling period, τ is the sampling time which can range from milliseconds to months or years according to the application, and m is the group number. At present, the Allan variance on the particular condition of $N=2$, $T=\tau$ is defined as the short-term stability of a crystal oscillator, where

$$\sigma_y^2(\tau) = \lim_{m \rightarrow \infty} \frac{1}{m} \sum_{i=1}^m \frac{1}{2} (f_{j+1} - f_j)^2. \quad (6)$$

The greater the number of measurements, the more accurate the stability result will be. For most frequency sources, both random walk noise and flicker frequency noise exist. During its actual operation, the quality of a crystal oscillator usually depends on its running time, temperature, pressure, electromagnetic interference, and other factors, while the first two factors are dominant. Furthermore, different crystal oscillators applied in different clocks at different nodes (SS, SJB, and PJB) may also cause greater deviation in clock synchronization. Maintaining the consistency of the crystal oscillators in both master clocks and slave clocks should help to improve the overall network synchronization.

2.3.2 Uncertainty of the master clock

Serving as the master time reference for the seafloor observatory network, the PTP master clock receives GPS/BDS signals to achieve overall time synchronization. Uncertainties related to the satellite error, signal transmission error, and signal reception

error are unavoidable. The signal reception error depends on the noise rejection capability of the antenna and on the internal time delay. In the former, the performance and installation conditions of the antenna should be carefully considered. In the latter, the hardware circuit, software algorithm, and the crystal oscillator in the master clock have a significant impact on signal delay (Ferrari *et al.*, 2011).

2.3.3 Uncertainty of the communication network

The uncertainty of the communication network consists of propagation uncertainty and forwarding uncertainty.

Propagation uncertainty is usually caused by several factors such as asymmetry of the physical link, asymmetry of the uplink and downlink data rates, and network structure changes. One of the assumptions of IEEE 1588 is that the network path between the master clock and slave clock is symmetrical, a condition that can be met through reasonable design of the network topology. However, network jitters occur in the actual process of synchronization, such as the jitter caused during the process of hardware time stamping, and these errors are usually on the order of tens of microseconds. One way to reduce jitter is to boost the clock frequency (Loschmidt *et al.*, 2008). The waterproof connectors, contactless connectors, and other dedicated cables applied in the network can also introduce uncertainty in the signal transmission.

Forwarding uncertainty occurs when data goes through the network devices; the heavier the traffic in the network, the larger the forwarding delay and jitter will be. The transparent clock (TC) defined in IEEE 1588 v2 can reduce this source of uncertainty.

2.3.4 Uncertainty of the slave clock

As is the case with the master clock, the uncertainty of a slave clock relies greatly on the hardware circuit, software algorithm, and crystal oscillator. The hardware circuit and software algorithm help to continuously analyze the transmission delay of PTP packages, thereby reducing the overall uncertainty. Furthermore, a dedicated circuit can ensure highly accurate time synchronization in case of loss of communication with the master clock.

2.3.5 Uncertainty of SIs in recovering a timing signal

Diverse time synchronization methods may be necessary because of diversity of the connected SIs.

Some SIs cannot directly realize time synchronization through communication with the master clock. To achieve a high accuracy, they use signals in the form of PPS, IRIG-B, 10 MHz, RS232, or RS422 from the slave clocks placed in the SJBs. Uncertainties occur during signal transmission through dedicated wires, signal conditioning by hardware circuits, and signal recognition by SIs. High-quality shielded wires, elaborately designed circuits, optimized software algorithms, and optimum CPU performance of SIs can reduce these uncertainties.

For the time synchronization system applied in ZERO, the SIs can reach very high time synchronization accuracy by applying an estimation parameter $T_u(t)$ to the time provided by GPS/BDS:

$$T_u(t) = c_1 m_1(t) + c_2 \varepsilon_2(t) + c_3 s_3(t) + c_4 \mu_4(t), \quad (7)$$

where $m_1(t)$ is the uncertainty of the master clock, $\varepsilon_2(t)$ is the uncertainty of the communication network, $s_3(t)$ is the uncertainty of the slave clock, $\mu_4(t)$ is the uncertainty of the SIs to recover the timing signal, and c_1, c_2, c_3, c_4 are the corresponding coefficients.

3 Experimental setup

When NTP and PTP protocols are introduced into a seafloor observatory network, the reliability, stability, security, and scalability of the time synchronization system must be considered. Highest attention must be directed toward a low-cost, anti-interference, and redundant design.

In May 2000, the United States canceled the selective availability policy to improve the accuracy of civilian GPS positioning after the success of a technology test for 'partially shielding the GPS signal'. GPS satellite signals were found to be possibly controlled at any time in arbitrary regions with the proper equipment. In October 2012, China successfully sent the 16th BeiDou satellite into its scheduled transfer orbit, and successfully completed the full construction of the BDS constellation for the Asia-Pacific region. A recent report showed that BDS can reach a timing accuracy of 50 ns (Jin, 2013), indicating that BDS is a cost-effective approach for precise timing applications (Ye, 2011). From the perspective of security, both GPS and BDS signals are applied in the time synchronization system for ZERO.

The stable operation of a JB is based on accurate control and monitoring of signals and environmental factors such as current, voltage, leakage, temperature, and humidity. The real-time performance of these signals is important for the timely control of a JB. Once a JB breaks down, normal operation of the entire network will be affected, thus incurring high maintenance costs (Li et al., 2012). To ensure that precision time signals remain stable and accurate after long-distance transmission through deep sea optical-electrical composite cables, PJBs and SJBs should be considered in the design of time synchronization systems.

Human observation and monitoring of deep oceans is assisted by SIs. SIs therefore play an important function in marine science development, resource exploration, disaster prevention, and environmental protection. Accurate timestamps for a variety of environmental signals acquired by SIs can significantly contribute to data processing and analysis on land. The diversity of SIs requires that a system should be able to provide diverse time synchronization signals.

A time synchronization system was established in this study taking into account the above considerations. PPS, NTP, and PTP signals are provided across the entire network. For each JB, an embedded PC configured with an IEEE 1588 slave is used to supply the specific time. Considering the total costs as well as the redundant space and accuracy requirements for SIs, various time synchronization methods can be used: (1) For observations with low timestamp accuracy requirements, an NTP network signal can be used for millisecond time synchronization. (2) For observations with high timestamp accuracy requirements, two approaches are available: the use of a PTP network signal for microsecond time synchronization and the placement of a PTP slave in SIs to provide time synchronization signals in the form of PPS, IRIG-B, 10 MHz, RS232, RS422, etc.

To verify the overall performance of the system, an experiment has been set up in the laboratory (Fig. 3). The experimental setup includes the SS, optical amplifiers, optical switches, Ethernet switches, embedded PCs, a PPS slave clock, and a PPS distribution amplifier that can expand a PPS signal to eight signals while maintaining its accuracy. The PTP master clock can synchronize to the GPS directly or synchronize to BDS through a BeiDou module, and a

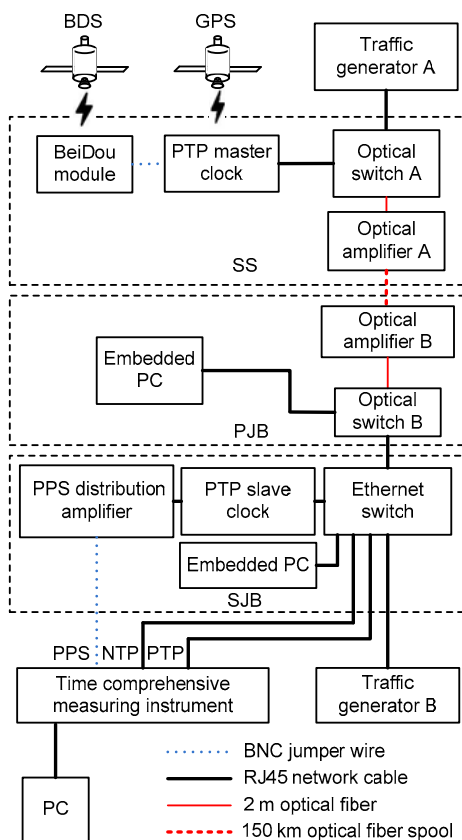


Fig. 3 Precision time protocol (PTP) experimental setup
 SS: shore station; PJB: primary junction box; SJB: secondary junction box; PPS: pulse per second; NTP: network time protocol; BNC: bayonet nut connector

high-quality oven controlled crystal oscillator (HQ-OEXO from Meinberg, Germany) with frequency stability of 1×10^{-12} is used by the master clock to maintain synchronization accuracy. An oscilloscope (TDS-3014C from Tektronix, USA), a comprehensive time measuring instrument (TimeAcc-007 from TITAN, China), and three computers are used. One PC runs a MATLAB application from MathWorks to analyze all the data stored in the TimeAcc-007. The time accuracy error of the TimeAcc-007 is within 50 ns of the Universal Time Coordinate (UTC). The other two PCs act as traffic generators. Fig. 4 shows the physical framework.

4 Experimental results

4.1 Real-time comparison of PPS

The PPS signal is an electrical signal most commonly used to test time synchronization performance

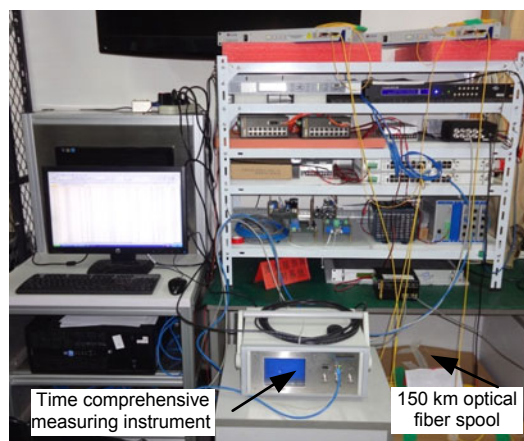


Fig. 4 Physical framework of the time synchronization system

in distributed systems. The rising edge of a PPS signal indicates the rollover of the UTC second precisely, with an accuracy generally ranging from several nanoseconds to a few microseconds (Ouellette *et al.*, 2011).

The time delay among the three PPS signals (PTP master clock, PTP slave clock, and PPS distribution amplifier) was measured (Fig. 5). The real-time measurement result of the time delay between the master and slave clocks is -460 ns. This value may vary over time. On the other hand, the time delay between the PTP slave clock and PPS distribution amplifier is 150 ns. This value should be constant because signal processing latency in the PPS distribution amplifier never changes.

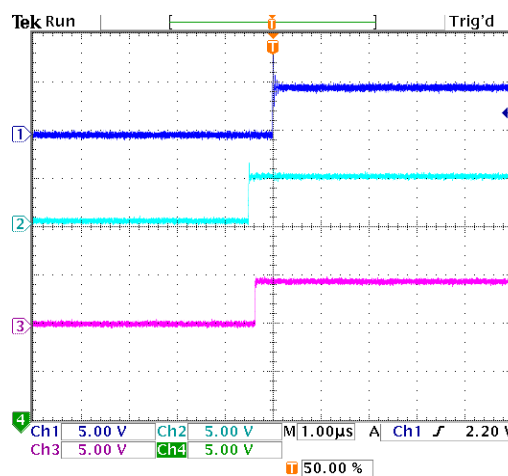


Fig. 5 Curves of pulse per second (PPS) signals used to evaluate time delays
 Ch1: PTP master clock; Ch2: PTP slave clock; Ch3: PPS distribution amplifier

4.2 Long-term time synchronization performance of NTP

To evaluate the long-term time synchronization performance of an NTP network signal, TimeAcc-007 was used. Three tests were set up, and the results are shown in Fig. 6. We took 20000 samples for each test to ensure stability. Table 1 summarizes the results obtained for the NTP network signal delay. Delays with missing GPS have a mean value of approximately 15.19 μs with a standard deviation of 86.22 μs . Delays with receiving GPS have a mean value of approximately $-9.83 \mu\text{s}$, with a standard deviation of 11.69 μs . Missing GPS may not cause an NTP signal to drift, but the jitter is significantly higher than that in the other two situations.

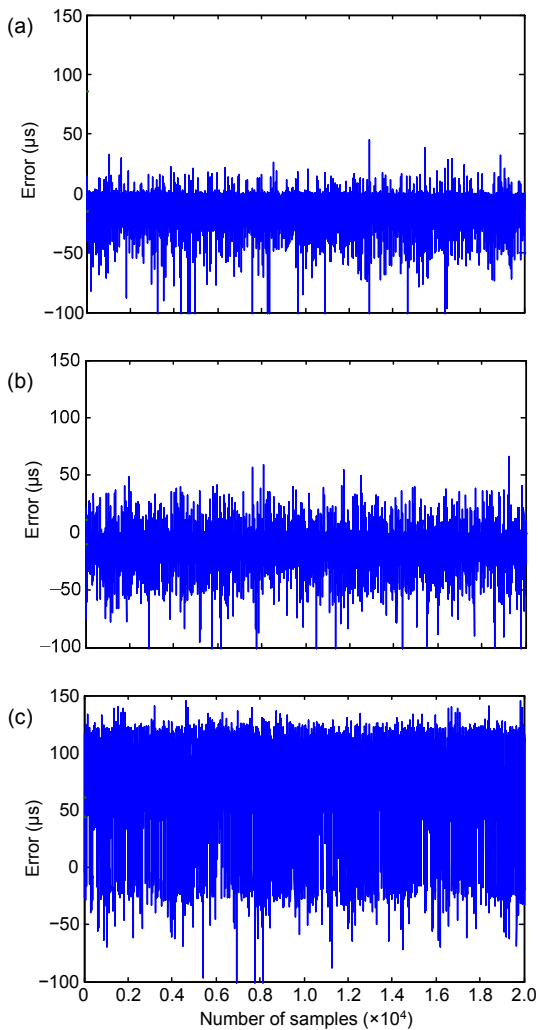


Fig. 6 NTP network signal measurement in the condition of missing GPS (a), receiving GPS without traffic (b), or receiving GPS with 100-Mb traffic (c)

Table 1 Results of NTP network signal delay

Condition	Mean (μs)	Standard deviation (μs)
Missing GPS	15.19	86.22
Receiving GPS without traffic	-9.83	11.69
Receiving GPS with 100-Mb traffic	60.98	44.45

Fig. 6c shows that the delays in the condition of receiving GPS with 100-Mb traffic have a mean value of approximately 60.98 μs with a standard deviation of 44.45 μs , which is larger than that in the other two situations. This observation can be attributed to the significant influence of payload on NTP time delay—a larger payload results in a greater delay. Although precision less than 100 μs has been measured, most NTP slaves can achieve only millisecond precision because the implementation of NTP is purely based on software. Thus, timestamps are being recorded at the application level, where large fluctuations occur between the application level and the physical connection in the NTP slave. Moreover, serious measurement errors can arise, and these may affect timing quality and offset calculation (Neagoe *et al.*, 2006). NTP also adjusts the local clock of a slave by calling the system application programming interface (API) function, thereby indicating errors from a few milliseconds up to a few hundred milliseconds which may occur depending on the performance of the computer OS (Carta *et al.*, 2011). A massive survey of the NTP protocol in the global Internet revealed that most NTP clocks are within 21 ms of their synchronization sources and all are within 29 ms on average (Neagoe *et al.*, 2006).

4.3 Long-term time synchronization performance of PTP

The long-term time synchronization performance of PTP was tested under four conditions: missing GPS, receiving GPS through ordinary switches, receiving GPS through IEEE 1588 switches without traffic, and receiving GPS through IEEE 1588 switches with 100-Mb traffic. The results are shown in Figs. 7–9. Fig. 7 shows that in the case of missing GPS, the PTP network signal drifts by 4 μs for every 20000 s (sampling period: 1 s), representing a drift of approximately 2×10^{-10} s/s, i.e., 17.28 μs per day. This value may be reduced if we use a crystal oscillator with frequency stability higher than 1×10^{-12} .

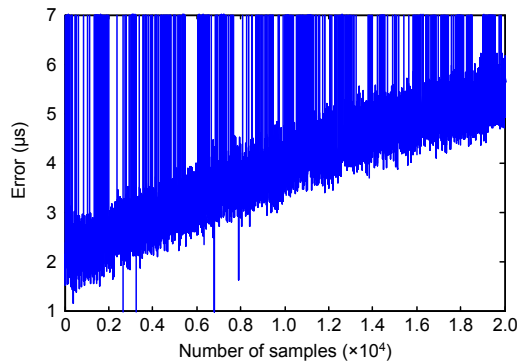


Fig. 7 PTP network signal measurement in the condition of missing GPS

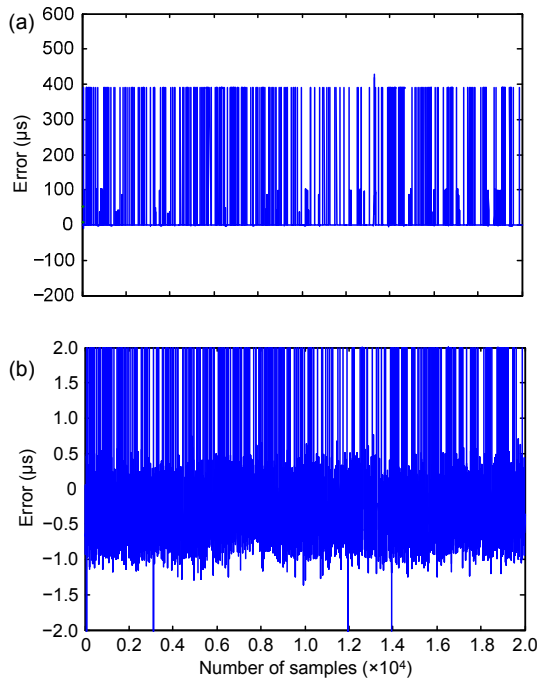


Fig. 8 PTP network signal measurement in the condition of receiving GPS through ordinary switches
(a) Total view; (b) Partial view

A comparison between Figs. 7 and 8b shows that the PTP network signal does not drift when the GPS/BDS satellite signals are received. A comparison between Figs. 8a and 9a shows that the time synchronization accuracy significantly increases when IEEE 1588 switches in the transparent clock mode are used. The residence time in switches can be measured for the correction of clock offset in this mode. Meanwhile, given that residence time is determined by the local clock, a certain deviation is unavoidable. Thus, any necessary adjustment and compensation

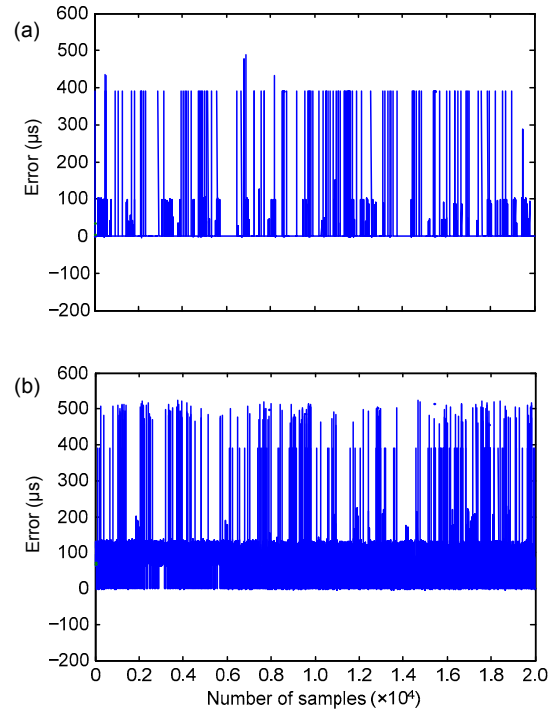


Fig. 9 PTP network signal measurement in the condition of receiving GPS through IEEE 1588 switches without traffic (a) or receiving GPS through IEEE 1588 switches with 100-Mb traffic (b)

methods should be applied to the calculation of residence time.

Fig. 9b shows that the time synchronization accuracy is affected by congested traffic conditions because network delay may exhibit a large deviation from real-time conditions when network traffic increases significantly within a short time. Moreover, packet loss occurs more often as network traffic increases. Although PTP is defined based on the assumption that network delays are symmetrical, in networks with large traffic load where asymmetry of paths is attributed mainly to asymmetrical queuing delays, the assumption of symmetrical paths is difficult to satisfy (Du *et al.*, 2011). These asymmetrical conditions can also contribute to large delays and offsets. However, a real network for distributed measurement and control is generally managed to maintain the traffic load at a level where packet loss seldom occurs (Han and Jeong, 2010), so the main delay effects occur from asymmetrical queue delays. A summary of the results obtained for PTP network signal delay is shown in Table 2. Delays when using ordinary switches have a mean value of

approximately 8.28 μs with a standard deviation of 54.21 μs . Delays when using IEEE 1588 switches without traffic have a mean value of approximately 4.40 μs with a standard deviation of 35.19 μs . The delay is worse when 100-Mb traffic is applied to the network. The mean value of the delay is approximately 73.00 μs with a standard deviation of 68.79 μs .

Table 2 Results obtained for PTP network signal delay

Condition	Mean (μs)	Standard deviation (μs)
Receiving GPS, ordinary switches	8.28	54.21
Receiving GPS, IEEE 1588 switches, no traffic	4.40	35.19
Receiving GPS, IEEE 1588 switches, 100-Mb traffic	73.00	68.79

4.4 Long-term time synchronization performance of PPS

Three tests were set up to evaluate the long-term time synchronization performance of a PPS signal under different conditions. The results are shown in Fig. 10.

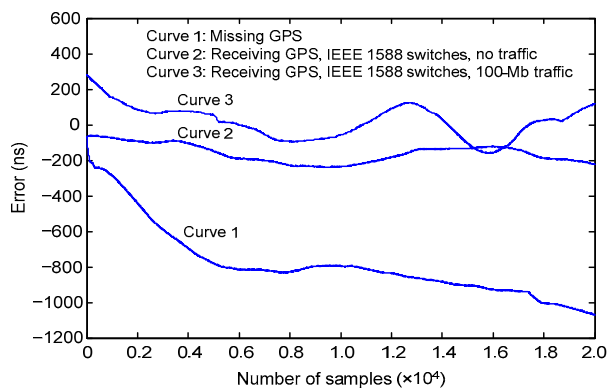


Fig. 10 Pulse per second (PPS) measurements under different conditions

Curve 1 shows that the PPS signal delay drifts over time in the case of missing GPS. The clock drift is 1 μs for every 20000 s (sampling period: 1 s), and represents a drift of approximately 5×10^{-11} s/s. This value is ideal because the HQ-OCXOs inside both the master and slave clocks can maintain clock accuracy (e.g., they drift in a similar manner, eliminating the offset). A crystal oscillator with higher frequency stability results in a lower drift.

The results obtained for PPS signal delay measurement are shown in Table 3. Delays in the condition of receiving GPS through IEEE 1588 switches without traffic have a mean value of approximately -160.31 ns with a standard deviation of 51.44 ns. The mean value of time delay is 16.17 ns with a standard deviation of 90.70 ns when the 100-Mb network load is added.

Table 3 Results of PPS signal delay

Condition	Mean (ns)	Standard deviation (ns)
Receiving GPS, IEEE 1588 switches, no traffic	-160.31	51.44
Receiving GPS, IEEE 1588 switches, 100-Mb traffic	16.17	90.70

The cumulative distribution function of the PPS offset is shown in Fig. 11. Evidently, 100-Mb traffic affects both signal delay and signal jitter as some PTP frames are unable to reach their destination.

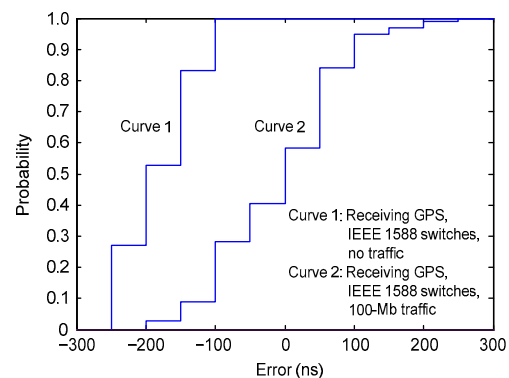


Fig. 11 Cumulative distribution function of the pulse per second (PPS) offset

Although the PPS signal is decoded by a PTP slave and synchronized to a PTP master through IEEE 1588, a significant difference is observed when the results of PTP and PPS are compared. Given that the measured PTP network signal is from an Ethernet switch in an SJB, and not even a simple filter is applied on the received messages, packet loss significantly affects the time synchronization accuracy of the PTP network signal. On the other hand, the measured PPS signal is generated by a PTP slave that has an HQ-OCXO to maintain time accuracy, and software is used to filter the received messages.

5 Conclusions

An IEEE 1588 based time synchronization system is proposed and developed for ZERO. The overall structure is designed to provide PPS, NTP, and PTP time synchronization signals for the entire network. GPS and BDS satellite signals can be directly or indirectly received by the PTP master clock. Long-term laboratory experiments have been conducted to verify time synchronization accuracy. When practically applied, precision may vary with practical network architecture changes, type and amount of network transmission equipment, properties of electric connectors, real-time traffic load, etc. Experimental results showed that the proposed system, which is the foundation of the time synchronization system for ZERO, is valid and can achieve microsecond accuracy. More experiments are currently underway to enable future observations that provide significantly greater precision. Future research can be conducted in the following areas: working mode of the clocks (boundary or transparent clocks), time synchronization interval, error compensation through hardware and software methods, and design symmetry of the communication system. Additional tests should be performed to assess the overall performance when applying these techniques.

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