Wang *et al.*
*EURASIP Journal on Advances in Signal Processing* (2023) 2023:45
https://doi.org/10.1186/s13634-023-01010-5

EURASIP Journal on Advances in Signal Processing

RESEARCH **Open Access**

# Stable frequency transfer for clock synchronization for telecom networks

Xiaocheng Wang[1,2*], Qiaoni Han[3], Yupeng Li[1] and Liang Han[1]

*Correspondence: xcwang@tjnu.edu.cn

[1] Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin 300387, China
[2] Key Laboratory of System Control and Information Processing, Ministry of Education, Shanghai, China
[3] School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China

**Abstract**

A stable and reliable clock synchronization system that transfers reference clocks to nodes is essential for telecom networks. Mainly, the clock synchronization of telecom networks is carried out through satellite links. However, for the evolving ubiquitous wireless communications, especially in some harsh environments, such as underground and trenches, the satellite-based clock synchronization scheme bears inevitable obstacles, which may cause strategic risks for the telecom networks, since no control and manipulation can be imposed on the satellite systems. Therefore, to ensure the robust operation of telecom networks with performance guarantees, some auxiliary means are desirable to assist clock synchronization that is solely based on satellite links. In this article, we report a phase-stabilized frequency signal transmission on branching optical fiber for clock synchronization for telecom networks. Particularly, the phase fluctuation due to optical carriers separation link and fiber link is compensated by a feedback network, which employs a high-precision voltage-controlled oscillator in the phase-locked loop to drive the acousto-optic frequency shifter for fast phase correction. Furtherly, the factors that cause performance limitations of the frequency distribution system are analyzed. Eventually, the experiment results obtained show that a stabilized fiber-optic frequency transfer scheme can be used as a reliable method for clock synchronization with high accuracy.

## 1 Introduction

It is of great significance to synchronize with the reference clock sources in many areas of human activity. Generally, these highly stable clock sources are operated and maintained by specialized laboratories and central stations. Then, the stable reference sources are transmitted to remote locations or nodes with traceability. Therefore, clock synchronization is the basis of many commercial and scientific applications, e.g., in navigation, telecommunication, astronomical, and physical experiments. At present, the operation of global navigation satellite systems (GNSS) and telecommunication networks are two typical applications of high-precision time and frequency transmission [1], and each of them has ambitious requirements regarding accuracy, availability, and security.

Currently, mobile telecom networks are operated according to the long-term evolution-advanced (LTE-A) standard, where time-division duplex (TDD) operation, mobile location-based services, and single-frequency network-based multi- and

© The Author(s) 2023. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

broadcast applications services all require precise clock synchronization. To meet the requirements of synchronization accuracy for large-scale telecom networks, each node performs local clock synchronization according to a superior hierarchy element located closer to the primary clock, and thus, a hierarchical and layered synchronization network is formed [2]. Especially, at the core level of telecom networks, the highest accuracy synchronization equipment is used, which is responsible for passing down the network reference clock along the hierarchy. Therefore, the stability and accuracy of the clock synchronization at the core level of the telecom network play a key role in the entire network synchronization system.

The International Atomic Time (TAI) is determined by comparing the atomic clocks of different laboratories around the world. From TAI, one obtains coordinated universal time (UTC), which is the basis of today's world time system with 24 time zones. In the existing telecommunication network and the next-generation network, the clock signal is required to be highly synchronized with the UTC. Mainly, the clock synchronization of the core level of the telecom networks is realized by satellite links, which have the advantages of convenient access, wide coverage, and long dissemination distance. However, due to the geometrical distance, ionosphere, and troposphere disturbances, the delay of the signal received from the satellite fluctuates randomly over time and is not constant. To suppress such effects, where both parties operate dedicated GNSS timing receivers, measure the time delay between the local clock and the space clock of the individual GNSS satellites, and then correct the propagation delay [3]. In other words, in the telecom industry, it is a common practice to directly achieve clock synchronization at the core level of the network through a GNSS signal that is in good agreement with UTC.

However, the clock synchronization at the core level of the telecom network through a local GNSS receiver may cause strategic risks for the network system, because they cannot control and manipulate the satellite transmission system. In particular, in some harsh environments, such as underground and trenches communication networks, the low signal-to-noise ratio (SNR) of the received GNSS signal causes the clock synchronization accuracy to decrease or even fail. In addition, in the strong electromagnetic interference and shadow-fading environment, the accuracy of the satellite-based clock synchronization will also go down. Besides, the synchronization accuracy of these core network nodes is stringent, generally on the order of nanoseconds or even higher, which is a challenging task.

Therefore, to provide highly stable and reliable clock synchronization for the telecom networks, an additional level of synchronization hierarchy is desirable, to monitor and supervise the real performance of the highest-level equipment. An example of such a network is shown in Fig. 1, where the integration of the fiber optic clock transfer technique into the telecommunication infrastructure will do great help to the clock synchronization of telecom networks in enhancing performance and becoming independent of GNSS signals. The integration method is to use dense wavelength division multiplexing technology to assign frequency signals and data signals to different frequency channels for transmission. Moreover, differing from the ordinary GNSS time transfer, the fiber-optic clock distribution is an online service and can

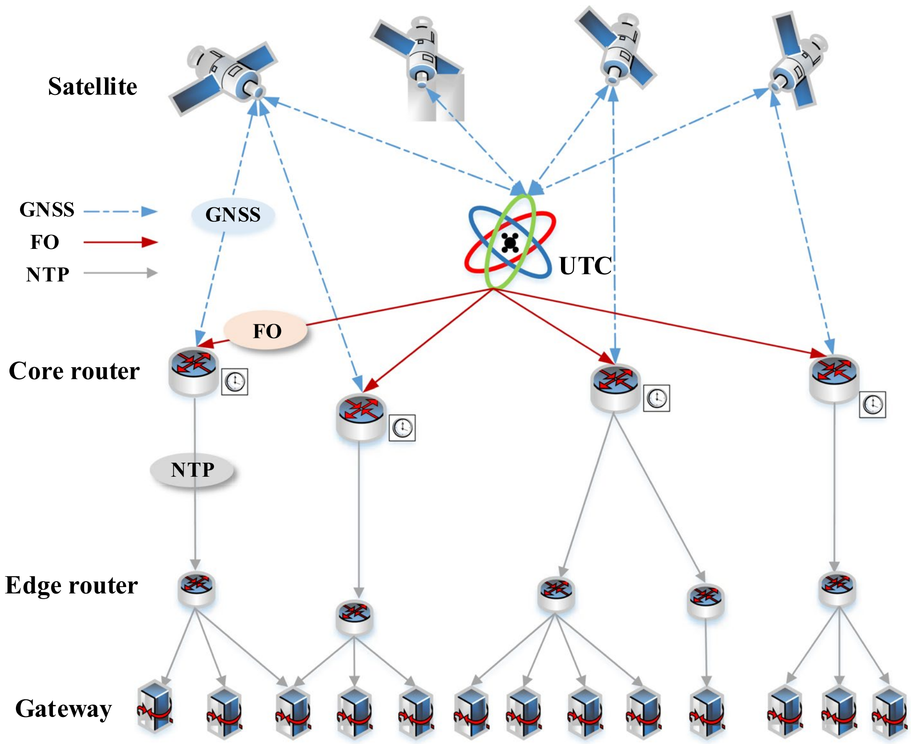


**Fig. 1** The clock synchronization of a telecom network. GNSS, global navigation satellite systems; FO, fiber-optic; NTP, network time protocol; UTC, coordinated universal time

distribute stable frequency and accurate time signals to a remote location without the need for the operation of the clock at the remote site.

With the rapid development of atomic clocks and optical communication technology, it has been shown that optical fiber has the potential to disseminate stable clock signals over long distances due to its low attenuation, high reliability, and immunity to electromagnetic interference [4]. The common optical fiber clock transmission refers to the electrical clock signal that is transferred to the optical domain through light intensity modulation. At the receiver nodes, the modulation is back-converted to the electrical domain by direct detection of the intensity of received light using a photodiode.

However, due to environmental perturbations on fiber links, the transmission delay over optical fiber varies, which may degrade the synchronization accuracy of the receiver nodes. The external environment perturbations mainly come from the fiber temperature variations, and possibly by some varying mechanical tensions which cause changes in the external pressure [5]. Generally, the transmission delay of the signal in the optical fiber can be expressed as $\tau = (L \cdot n)/c$, where $L$ is the fiber length, $n$ is the group refractive index, and $c$ is the velocity of light in vacuum. For example, when the external temperature of the optical fiber changes $\Delta T$, then the transmission delay of the fiber link varies $\Delta\tau_T = 1/c \cdot \left[\left(n\Delta T \partial L/\partial T\right) + \left(L\Delta T \partial n/\partial T\right)\right]$, where the first term and the second term on the right side are the deformations of the fiber length and the change of the refractive index of the fiber with temperature variation, respectively. Similarly, the length of the fiber and the refractive index of the fiber will also change with the external pressure. The delay variation of the optical fiber link is related to the laying method and the surrounding environment. For example, an optical fiber buried deep in the ground may be affected by vibrations caused by underground transportation facilities and changes in soil temperature. The literature has reported that [6], for the 6 km fiber buried in the ground within two months, the transmission delay variations of the fiber reached 2 ns when the outside temperature changed by about 20 °C. That is, if this fiber is used to transmit a microwave signal of 10 GHz, the phase shift will be as high as 40 π. Therefore, to realize highly stable frequency signal transmission at core network nodes, real-time compensation must be carried out for the transmission delay variation of the optical fiber link.

The cesium atomic clocks are generally used in laboratories around the world to compare clocks to obtain UTC. At present, the long-term frequency stability of cesium clocks can achieve a $1 \times 10^{-15}$ level. Therefore, the frequency stability of the optical fiber transmission system is required to be better than the frequency stability of the cesium atomic clock, to ensure that the stability of the signal does not deteriorate after transmission.

## 2 Related works

The round-trip correction mechanism is one of the methods to achieve signal synchronization through pre-phase compensation [7–9]. The following describes its principle with frequency signal. Assuming that the initial phase of the frequency signal is $\varphi_o$, it first passes through a controllable phase compensator for phase pre-compensation $\varphi_c$. Denoting that the phase jitter caused by the delay variation of the optical fiber is $\varphi_v$, the phase $\varphi_r$ of the signal transmitted to the remote end via the optical fiber can be expressed as $\varphi_r = \varphi_o + \varphi_c + \varphi_v$. At the remote end, part of the signal is transmitted back to the local end through the same optical fiber link, ignoring the nonlinearity and non-reciprocity of the optical fiber, the forward and backward transmission signals will experience the same transmission delay [10]. Therefore, the signal transmitted back to the local end will experience twice the transmission delay, that is, twice the phase jitter is introduced, then the phase $\varphi_b$ of the returned signal can be expressed as $\varphi_b = \varphi_o + 2(\varphi_c + \varphi_v)$. Then, the local frequency signal is used as the reference signal and the returned signal is phase-detected to obtain the error signal $\varphi_e$, which drives the phase $\varphi_c$ of the compensation module so that the error signal is zero, that is, $\varphi_e = \varphi_c + \varphi_v = 0$. It can be seen that the phase $\varphi_r$ of the remote end signal is independent of the phase fluctuation induced by the fiber link, $\varphi_r = \varphi_o + \varphi_c + \varphi_v = \varphi_o$, and the phase of the remote signal is synchronized with the phase of the local signal.

The method of signal synchronization by the round-trip delay correction mechanism includes passive phase conjugate compensation and active adjustable delay line or phase pre-compensation. By conjugating the phase of a round-trip signal and its triple frequency signal, the output signal of the mixer will be immune to the fluctuation in the fiber link at the remote end [11–13]. It can achieve infinite phase compensation because of its open-loop scheme that avoids the use of phase detection and tunable compensation devices. Unfortunately, establishing such a passive compensation system for high-frequency distribution is difficult due to the bandwidth limit of electronic devices. Besides, serious harmonic interference between different frequency signals also needs to be paid attention to. So far, previous studies on this technique have demonstrated the stabilized distribution for frequencies lower than 10 GHz.

Apart from the passive compensation methods, the active phase compensation method based on a tunable optical true delay line, which is composed of a piezoelectric fiber stretcher and a temperature controlled fiber spool, has been widely adopted [14, 15]. Its frequency-independent compensation enables the distribution of high-frequency references directly. Nonetheless, the small compensation range and slow response of the fiber stretcher would limit the system's loop bandwidth and applications in long-distance distribution whose delay suffers large and fast variations. An alternative method that uses voltage-controlled oscillators (VCOs) for phase-drift correction enables phase stabilization with an infinite compensation range and fast response [16–18]. However, it is difficult to detect and compensate the phase error of a high-frequency signal (millimeter-wave or terahertz wave) precisely since traditional electronic approaches suffer from the limited frequency range of phase detection and the insufficient phase control accuracy of compensation.

The performance evaluation of the frequency and time signal transmission system is mainly characterized by the stability of the signal [19]. In the frequency domain, phase noise is used to characterize the stability of the signal. To reflect the signal phase spectrum more directly, the phase noise of one of the sidebands is analyzed, that is, the single-sideband phase noise is used to describe the phase noise. In terms of the time domain, the Allen deviation is used to evaluate signal stability.

## 3 Methods

### 3.1 Innovations

To enhance the clock synchronization performance for the core level of telecom networks, we carry out frequency signal stable transmission through a branching optical fiber, where the performance of the GNSS-based synchronization scheme is limited. After the frequency signal is transmitted through the optical fiber, the phase of the signal is jittered due to the transmission delay variation, i.e., $\delta\varphi = \omega \cdot \delta\tau$. If the transmission frequency $\omega$ is increased, it is equivalent to providing a higher gain for the measurement of phase fluctuations. In addition, the increase in gain by increasing the transmission frequency can in turn weaken the influence of other noises, such as laser phase noise, and indirectly reduce the system's requirements for other noises, thereby increasing the sensitivity of signal phase detection. Note that the fundamental phase noise limitations imposed by shot noise and thermal noise do not depend on the frequency of the transfer signal, and therefore the resulting instability and timing jitter limitations can be improved by the use of a higher frequency [4].

Phase detection and phase correction are two key technologies to realize stable signal transmission. However, the traditional methods based on intensity modulation and direct detection have low sensitivity, and the frequency supported by the phase detector is limited to tens of GHz, which cannot meet the phase detection requirements of high-frequency signals. On the other hand, high-speed photoelectric conversion can also cause amplitude-phase conversion noise to deteriorate the accuracy of detection. To solve this problem, we proposed a dual-heterodyning phase error transfer (DHPT) scheme to detect the phase error of the millimeter-wave signal induced by the fiber delay variation and applied an acousto-optic frequency shifter (AOFS) to cancel the phase noise, respectively [20]. The terminal user only needs to convert the received high-frequency signal into the required frequency range through down-conversion and other means. Furthermore, the theoretical analysis reveals the relationship between the system instability and the frequency of the transmitted signal, which testifies to the potential high stability obtained thanks to the higher frequencies of the transmitted signals [21].

In this article, we present the simultaneous dissemination of the terahertz signals to multiple independent remote sites on a branching optical-fiber network. The transmitted terahertz wave signal over the fiber link is obtained by extracting two optical carriers from an optical frequency comb. The phase fluctuation due to the optical carrier separation link and fiber link is compensated by a feedback network, which includes a phase-locked loop (PLL) and a fast response AOFS. The phase noise within the loop bandwidth is effectively suppressed; thus, the high phase-stable terahertz signal is achieved at the remote end. The results obtained show that the frequency transmission based on optical fiber can achieve high precision clock synchronization, which can be used for accurate clock synchronization for the core level of telecom networks. Besides, the factors that cause the performance limitations of the photonic terahertz signal distribution system are further analyzed.

### 3.2 The proposed stable terahertz signal distribution system

In this section, we will introduce the proposed terahertz signal stable distribution on branching optical-fiber networks in detail. The schematic diagram of the terahertz wave distribution on branching optical-fiber networks is shown in Fig. 2. An optical frequency comb generator (OFCG) based on a Fabry–Perot electro-optic modulator [22] with 2.5 GHz free spectral range is driven by a 25 GHz microwave synthesizer, which produces a low phase noise OFC with a 25-GHz frequency interval and more than a 10-THz spectral span. The microwave synthesizer is synchronized to a Rubidium reference. The Rubidium clock is synchronized with the standard time scale assigned by UTC.

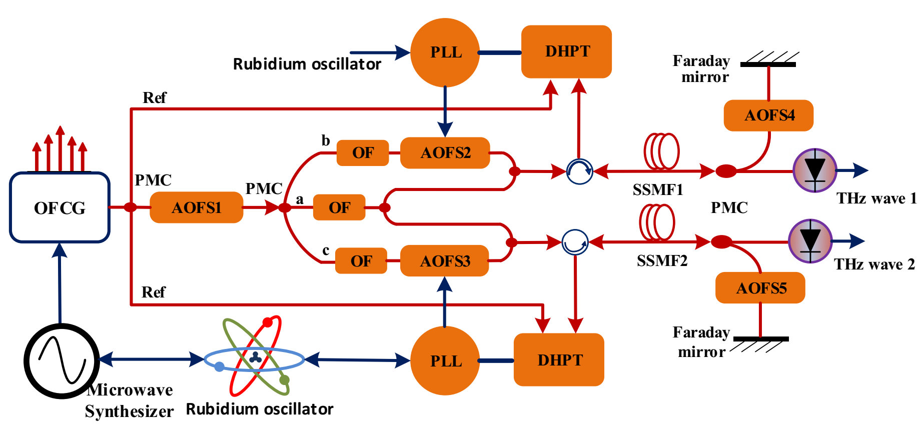


**Fig. 2** The schematic diagram of the terahertz wave distribution on branching optical-fiber networks. OFCG, optical frequency comb generator; PMC, polarization maintained coupler; OF, optical filter; AOFS, acousto-optic frequency shifter; PLL, phase-locked loop; DHPT, dual-heterodyne phase error transfer; SSMF, standard single-mode fiber

The OFC is divided into three branches by passing through polarization-maintained couplers (PMCs). The two branches are the reference for detecting the phase error induced by the optical carrier separation link and transmission fiber link. The last branch is frequency shifted by AOFS1, which is used to obtain two phase-locked optical carriers with terahertz frequency spacing. Then, the OFC shifted by AOFS1 is subdivided into three paths. Each optical carrier that generates a terahertz signal can be filtered out by an optical filter (OF), or replaced by a polarization-maintaining arrayed waveguide grating. To avoid homodyne mixing in the phase measurement of the two terahertz signals, the two optical carriers are shifted to different frequencies by AOFS2 and AOFS3, respectively.

The selected optical carriers from the OFC shifted by AOFS1 can be written as,

$$E_a(t) = \exp\left\{j[(\omega_1 + \omega_{\mathrm{IF1}})t + \varphi_1]\right\} \tag{1}$$

$$E_b(t) = \exp\left\{j[(\omega_2 + \omega_{\mathrm{IF1}} + \omega_{IF2})t + \varphi_2 + \varphi_{\mathrm{IF2}}(t)]\right\} \tag{2}$$

$$E_c(t) = \exp\left\{j[(\omega_2 + \omega_{\mathrm{IF1}} + \omega_{\mathrm{IF3}})t + \varphi_2 + \varphi_{\mathrm{IF3}}(t)]\right\} \tag{3}$$

where $\omega_1$ is the selected optical carriers' angular frequency, $\varphi_1$ is the initial phase. $\omega_{\mathrm{IF1}}$ is the angular frequency of the AOFS1 drive signal. The AOFS1 is driven by the rubidium reference clock. The $\omega_2$ is selected optical carriers' angular frequency, $\varphi_2$ is the initial phase. $\omega_{\mathrm{IF2}}$ and $\varphi_{\mathrm{IF2}}(t)$ are the angular frequency of the AOFS2 drive signal and its phase, respectively. $\omega_{\mathrm{IF3}}$ and $\varphi_{\mathrm{IF3}}(t)$ are the angular frequency of the AOFS3 drive signal and its phase, respectively. Both AOFS2 and AOFS3 are driven by the VCO and are used as part of the PLL to compensate for the phase fluctuations induced by the optical path. Since signal amplitude has a limited impact on the system, it is omitted for the sake of simplicity.

Since the frequency distribution of the proposed terahertz signal in the branch optical fiber network is two relatively independent systems, the working principle can be introduced by taking one of them as an example. The photonic terahertz signal is formed by coupling the filtered optical carriers through two different separate links and then transmitted to the remote via a fiber optic link. At the remote nodes, the photonic terahertz signal passing through the fiber link can be expressed as,

$$E_{\mathrm{THz}}(t) = \cos\{(\omega_2 - \omega_1 + \omega_{\mathrm{IF2}})(t) + \varphi_{\mathrm{IF2}}(t) - \varphi_v(t)\} \tag{4}$$

where $\varphi_v(t) = (\omega_2 + \omega_{\mathrm{IF1}} + \omega_{\mathrm{IF2}})\tau_b(t) - (\omega_1 + \omega_{\mathrm{IF1}})\tau_a(t) + (\omega_2 - \omega_1 + \omega_{\mathrm{IF2}})\tau_{\mathrm{link}}(t)$. The $\tau_{\mathrm{link}}(t)$ is the delay change of the transmitted optical fiber link due to external temperature and pressure. The $\tau_a(t)$ and $\tau_b(t)$ are time-varying transmission delays of the optical carriers due to the different separated paths. Therefore, it is necessary to compensate for the phase fluctuations caused by the optical fiber link and the carrier separation link to achieve stable transmission of the photonic terahertz signals.

In this paper, the round-trip correction mechanism is adopted for phase compensation. Then, the remote terahertz signal is power split into two branches by PMC. One is down-converted after being converted by the photo-detector (PD) and provided to the user, the other is frequency-shifted by an AOFS4 to avoid the Rayleigh backscattering and transmitted back to the local end through the same fiber link. Since the fiber delay changes slowly, the forward transmission time and the backward transmission time are the same. Then, the returned optical carriers exhibit double the one-way fiber-induced phase noise. Based on the proposed DHPT scheme, the phase fluctuation induced by the separated path and the optical fiber transmission delay variations is mapped onto an intermediate frequency (IF) signal $E_{\mathrm{IF}}(t)$,

$$E_{\mathrm{IF}}(t) = \cos\{(2\omega_{\mathrm{IF2}} - \omega_{\mathrm{Rb}})t + 2\varphi_{\mathrm{IF2}}(t) - 2\varphi_{v}(t) - \varphi_{\mathrm{Rb}}\} \tag{5}$$

where $\omega_{\mathrm{Rb}}$ is the angular frequency of the rubidium oscillator, and $\varphi_{\mathrm{Rb}}$ is its initial phase which is considered a constant. It should be noted that the phase of the IF $E_{\mathrm{IF}}(t)$ signal and the phase of the remote terahertz signal $E_{\mathrm{THz}}(t)$ are coherent.

Based on the phase-locked loop theory [23], the $E_{\mathrm{IF}}(t)$ signal is discriminated by a digital phase and frequency detector compared with the rubidium oscillator. Then, the error signal is integrated into a loop filter to control the phase of VCO. When the loop is locked, the steady-state error is zero. Then, the locked remote node's terahertz wave signal can be expressed as,

$$E'_{\mathrm{THz}}(t) = \cos[(\omega_2 - \omega_1 + \omega_{\mathrm{IF2}})t + N\varphi_{\mathrm{Rb}}] \tag{6}$$

where the number $N$ is determined by the frequency of the AOFS2 drive signal and the frequency of the rubidium clock reference. It can be seen that $E'_{\mathrm{THz}}(t)$ is independent of the phase fluctuation induced by the separated path and the optical fiber transmission delay variations. Thus, a high phase-stable terahertz signal is obtained at the remote core-level nodes.

## 4 Experiment results and analysis

In this section, the performance of the stable terahertz-wave signal distribution system will be analyzed and discussed through the experimental data collected by the instrument. The experimental setup and the phase measurement are shown in Fig. 3. The lengths of the local and two remote ends of the fiber branch network are 20.5 km and 21 km spooled standard single mode fiber (SSMF), respectively. Both the local and remote ends of the frequency distribution system are placed in the same laboratory to facilitate phase noise measurements. The continuous-wave laser (NKT-E15) operating at 1550 nm with less than 1 kHz linewidth is fed as a seed into the OFCG. The synchronous microwave synthesizer (E8267D) generates a 25-GHz signal and then launches

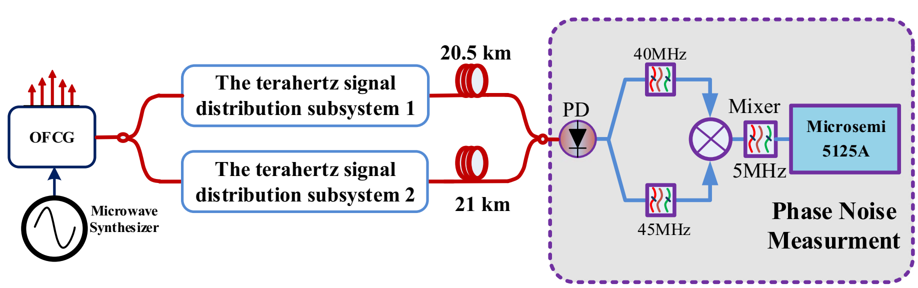


**Fig. 3** Experimental setup for the stable terahertz-wave signal distribution system and the phase measurement. OFCG, optical frequency comb generator; PD photo-detector

to drive the OFCG generating a low phase noise OFC with a 25-GHz frequency interval. The erbium-doped fiber amplifiers are applied after transmission to compensate for the power loss caused by the transmission link. Amplified spontaneous emission noise of the erbium-doped fiber amplifier (EDFA) is suppressed by an OF. To avoid Rayleigh backscattering, the returned signal is first passed through an AOFS and then returned to the local end through the same fiber link. To alleviate the polarization varying effect, the polarization tracker is used before the heterodyne detection.

In this paper, two frequency signals of the same local oscillator are transmitted to different remote ends through a branched optical fiber network to achieve clock synchronization between users. To verify the accuracy of the clock synchronization of the proposed frequency distribution system, it can be characterized by measuring the phase noise and frequency stability between the two frequency signals transmitted to the remote end. Then, the residual phase noise and the frequency stability of the proposed frequency distribution system are obtained by measuring the phase noise of the 5-MHz heterodyne beat note between the remote two terahertz signals with a phase-noise test set (Microsemi 5125A). Moreover, to guarantee that the residual phase noise measurements are taken under equal conditions, the same loop bandwidth of about 800 Hz is used. The loop bandwidth of the PLL is mainly determined by the length of the transmission link. A large bandwidth may cause loop instability; a small bandwidth may hinder the system's ability to suppress higher frequency link fluctuations. A large loop bandwidth may cause the phase-locked loop to fail to work and increase the instability of the system, while a small loop bandwidth will reduce the system's ability to suppress high-frequency phase noise.

Figure 4 shows the residual phase noise measurement of the phase-locked distribution system, the free running system (no round-trip correction mechanism, VCO locked to the rubidium oscillator), and a short fiber system (the spooled fiber link replaced

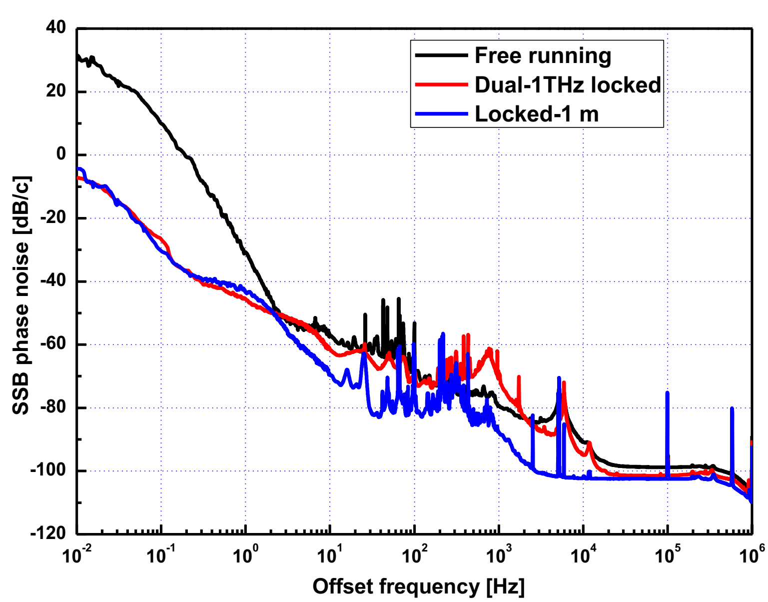


**Fig. 4** The residual phase noise of the terahertz signal distribution system in conditions of free-running spool fiber link, phase-locked spool fiber link, and phase-locked 1 m short fiber, respectively

with a 1-m fiber optic patch cord). The measurement shows that the residual phase noise between the two phase-locked terahertz signal distribution systems reaches −8 dBc/Hz and −45 dBc/Hz at 0.01 Hz and 1 Hz frequency offset from the carrier, respectively. Comparing the phase-locked system with the free-running system, we can see that the residual phase noise reduces phase noise by 15 dB at 1 Hz frequency offset and over 35 dB at 0.01 Hz frequency offset. It presents that the phase noise is effectively suppressed in the loop bandwidth. The noise suppression capability within the loop bandwidth is related to the ambient environment and may be more obvious in realistic scenarios than the slight changes in the laboratory. However, the delay self-heterodyne interferometric noise and the amplified spontaneous emission noise of the EDFA dominate the high-frequency part of the residual phase noise. Due to the use of optical attenuators in the short fiber system to ensure the same test conditions, the delay self-heterodyne interferometric noise causes other different noises at higher frequency components.

The long-term frequency stability of the distribution system is shown as an Allan deviation in Fig. 5. The relative frequency stability of the two terahertz signals distributed to the remote end by free-running is $1.45 \times 10^{-14}$ at 1000 s averaging time. While the phase-locked system improves its frequency stability by more than two orders of magnitude to $8.35 \times 10^{-17}$ at 1000 s averaging time. A plateau around the 3–30 s range should be caused by polarization mode dispersion (PMD). Meanwhile, due to the noise of the source signals and electronic components, and PMD, the frequency instability of the phase-locked system slightly exceeds that of the short fiber system. The long-term stability of the distribution system is dominated by the temperature sensitivity of the electronic components in the phase compensation feedback network. Moreover, based on the photonic-delay technique for phase noise measurement [24], the degradation of the delayed self-heterodyne characteristic will reduce the phase

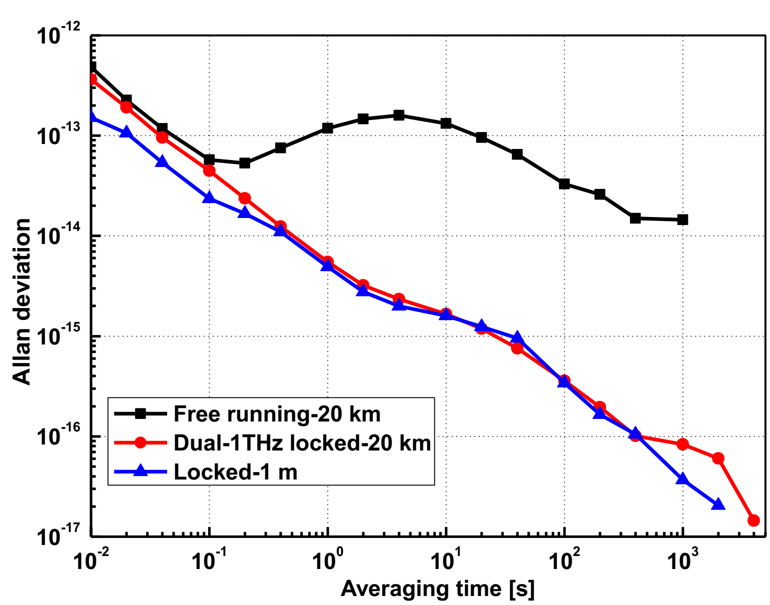


**Fig. 5** The relative frequency stability of the two terahertz signal distribution systems in conditions of free-running spool fiber link, phase-locked spool fiber link, and phase-locked 1 m short fiber, respectively

coherence between the microwave signal and its delayed signal, thus affecting the performance of the distribution system.

In the future, to improve the performance of photonic distribution systems, microwave synthesizers with lower phase noise and lasers with narrower line widths need to be employed to generate OFC. It is also crucial to optimize the noise floor of the optical fiber transmission system. In particular, reducing thermal noise and shot noise of optical and electrical components in the transmission system loop, as well as amplitude to phase noise and amplifier noise during signal processing.

## 5 Conclusion

In this article, to realize the robust and reliable clock synchronization for the core level of telecom networks, we report the idea of stable frequency transmission through branching optical fiber, which is an auxiliary or alternative method for clock synchronization based on the satellite link, whose accuracy may decrease or fail in harsh environments. However, the transmission delay varies due to environmental perturbation on fiber links, which may degrade the synchronization accuracy of the receiver nodes.

Then, we experimentally demonstrate the simultaneous dissemination of the terahertz signals to multiple independent remote sites on a branching optical-fiber network. Particularly, the phase fluctuation of the terahertz signal caused by the optical carriers separation link and the fiber link is identically transferred to an IF signal by using the DHPT scheme. Accordingly, a phase compensation system based on optical frequency tuning is adopted, which uses a high-precision VCO in the PLL to drive the AOFS for fast phase correction. Finally, compared with the free running situation, it can be seen that the residual phase noise of the phase-locked distribution system is reduced by 35 dB at 0.01 Hz frequency offset from the carrier, and the frequency stability of $1.45 \times 10^{-17}$ at 4000 s averaging time is achieved. The experimental results show that the fiber-based frequency transfer scheme can be used as a reliable method for clock synchronization for telecom networks.

**Abbreviations**

| | |
|---|---|
| GNSS | Global navigation satellite systems |
| LTE-A | Long-term evolution-advanced |
| TDD | Time-division duplex |
| UTC | Coordinated universal time |
| SNR | Signal-to-noise ratio |
| VCO | Voltage-controlled oscillators |
| DHPT | Dual-heterodyning phase error transfer |
| AOFS | Acousto-optic frequency shifter |
| PLL | Phase-locked loop |
| OFCG | Optical frequency comb generator |
| PMC | Polarization-maintained couplers |
| OF | Optical filter |
| PD | Photo-detector |
| IF | Intermediate frequency |
| SSMF | Standard single-mode fiber |
| EDFA | Erbium-doped fiber amplifier |

**Acknowledgements**
The authors would like to thank the handing associate editor and the anonymous reviewers for their valuable comments and suggestions for this paper.

**Author contributions**
XW proposed the method for the phase-stabilized frequency signal transmission on branching optical fiber. QH contributed to experimental data acquisition and literature review. XW wrote the majority of the manuscript. YL and LH revised the content. XW is the corresponding author of this paper. All authors read and approved the final manuscript.

**Funding**
This work was supported by the National Natural Science Foundation of China (NSFC) (62001327, 61803218, 61901301), the Scientific Research Project of Tianjin Educational Committee (2022KJ010), and the Foundation of the Key Laboratory of System Control and Information Processing, Ministry of Education (Scip202217, Scip202101).

**Availability of data and materials**
The authors state the data available in this manuscript.

## Declarations

**Ethics approval and consent to participate**
This work does not involve human participants, human data, or human tissue.

**Consent for publication**
This work does not contain any individual person's data in any form.

**Competing interests**
The authors declare that they have no competing interests.

Received: 30 August 2022 Accepted: 13 April 2023
Published online: 21 April 2023

**References**

1. D. Piester, M. Rost, M. Fujieda et al., Remote atomic clock synchronization via satellites and optical fibers. Adv. Radio Sci. **9**, 1–7 (2011)
2. L. Sliwczynski, P. Krehlik, J. Kolodziej et al., Fiber-optic time transfer for UTC-traceable synchronization for telecom networks. IEEE Commu. Standards Mag. **1**, 66–73 (2017)
3. F. Sivrikaya, B. Yener, Time synchronization in sensor networks: a survey. IEEE Netw. **18**, 45–50 (2004)
4. S.M. Foreman, K.W. Holman, D.D. Hudson, D.J. Jones, J. Ye, Remote transfer of ultrastable frequency references via fiber networks. Rev. Sci. Instrum. **78**, 021101 (2007)
5. A.H. Hartog, A.J. Conduit, D.N. Payne, Variation of pulse delay with stress and temperature in jacketed and unjacketed optical fibres. Opt. Quant. Electron. **11**, 265–273 (1979)
6. Ł. Śliwczyński, P. Krehlik, M. Lipiński, Optical fibers in time and frequency transfer. Meas. Sci. Technol. **21**, 075302 (2010)
7. L. Ma, P. Jungner, J. Ye, J.L. Hall, Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path. Opt Lett. **19**, 1777–1779 (1994)
8. X. Wang, Z. Liu, S. Wang, Y. Dong, W. Hu, Photonic radio-frequency dissemination via optical fiber with high-phase stability. Opt. Lett. **40**, 2618–2621 (2015)
9. N.R. Newbury, P.A. Williams, W.C. Swann, Coherent transfer of an optical carrier over 251 km. Opt. Lett. **32**, 3056–3058 (2007)
10. F. Narbonneau, M. Lours, S. Bize, A. Clairon, G. Santarelli, O. Lopez, C. Daussy, A. Amy-Klein, C. Chardonnet, High resolution frequency standard dissemination via optical fiber metropolitan network. Rev. Sci. Instrum. **77**, 064701 (2006)
11. Y. He, B. Orr, K. Baldwin et al., Stable radio-frequency transfer over optical fiber by phase-conjugate frequency mixing. Opt. Express **21**, 18754–18764 (2013)
12. W. Li, W. Wang, W. Sun, W. Wang, N. Zhu, Stable radio-frequency phase distribution over optical fiber by phase-drift auto-cancellation. Opt. Lett. **39**, 4294–4296 (2014)
13. L. Hu, R. Xue, X. Tian, G. Wu, J. Chen, All-passive multiple-place optical phase noise cancellation. Opt. Lett. **46**, 1381–1384 (2021)
14. O. Lopez, A. Amy-Klein, C. Daussy et al., 86-km optical link with a resolution of $2\times10^{-18}$ for RF frequency transfer. Eur. Phys. J. D: Atomic, Mol. Opt. Plasma Phys. EDP Sci. **48**, 35–41 (2008)
15. G. Marra, H.S. Margolis, D.J. Richardson, Dissemination of an optical frequency comb over fiber with $3 \times 10^{-18}$ fractional accuracy. Opt. Express **20**, 1775–1782 (2012)
16. M. Fujieda, M. Kumagai, S. Nagano, Coherent microwave transfer over a 204-km telecom fiber link by a cascaded system. IEEE Trans. Ultrason. Ferroelectr. Frequ. Control **57**, 168–174 (2010)
17. B. Wang, C. Gao, W. Chen et al., Precise and continuous time and frequency synchronisation at the 5 × 10–19 accuracy level. Sci. Rep. **2**, 556 (2012)
18. S. Wang, D. Sun, Y. Dong et al., Distribution of high-stability 10 GHz local oscillator over 100 km optical fiber with accurate phase-correction system. Opt. Lett. **39**, 888–891 (2014)
19. W. Riley and D. A. Howe Handbook of Frequency Stability Analysis. https://www.nist.gov/publications/handbookfrequency-stability-analysis.
20. X. Wang, D. Sun, Z. Liu, Y. Dong, and W. Hu, Stable fiber delivery of millimeter wave signal by fast phase compensation system. *Proc. Asia Commu. Photonics Conf. (ACP)*, (2014)

21. Z. Liu, W. Xie, W. Wei, N. Deng, Y. Dong, Theoretical analysis for fiber-optic distribution of RF signals based on phase-locked loop. Opt. Express **28**, 19851–19863 (2020)
22. E. Gordon, J. Rigden, The Fabry–Perot electrooptic modulator. Bell Syst. Tech. J. **42**, 155 (1963)
23. G. Hsieh, J. Hung, Phase-locked loop techniques. A survey. IEEE Trans. Ind. Electron. **43**, 609–615 (1996)
24. E. Rubiola, E. Salik, S. Huang, N. Yu, L. Maleki, Photonic-delay technique for phase-noise measurement of microwave oscillators. J. Opt. Soc. Am. B **22**, 987–997 (2005)


## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.


**Submit your manuscript to a SpringerOpen journal and benefit from:**

- ► Convenient online submission
- ► Rigorous peer review
- ► Open access: articles freely available online
- ► High visibility within the field
- ► Retaining the copyright to your article

**Submit your next manuscript at ► springeropen.com**