Fiber-based multiple-access frequency synchronization via 1f–2f dissemination*

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Considering the reference frequency dissemination requirements of the Square Kilometre Array telescope (SKA) project, on the basis of the 1f–2f precision frequency synchronization scheme, we propose and demonstrate a fiber-based multiple-access frequency synchronization scheme. The dissemination reference frequency can be recovered at arbitrary nodes along the entire fiber link. It can be applied to antennas close proximity to the SKA central station, and will lead to a better SKA frequency synchronization network. As a performance test, we recover the disseminated 100-MHz reference frequency at an arbitrary node chosen as being 5 km away from the transmitting site. Relative frequency stabilities of 2.0×10^{-14}/s and $1.6\times10^{-16}/10^{4}$s are obtained. We also experimentally verify the feasibility of a frequency dissemination link with three access points.

Keywords: Square Kilometre Array, frequency synchronization, fiber, multiple-access

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1. Introduction

Fiber-based time and frequency dissemination techniques, due to their properties of high precision, low loss, isolation to electro–magnetic interference, and ubiquitous availability, have been greatly developed recently. Besides to further improve their dissemination stability,[1–7] more and more efforts have been focused on extending their application area.[8–20] To realize ultra-long distance or even over continental frequency dissemination, the cascaded frequency dissemination schemes were demonstrated.[8–11] To improve the accessibility of the stable time and frequency signal, multiple-access time and frequency dissemination schemes were proposed and demonstrated.[12–15] An ultra-stable RF-over-fiber transport technique is used to ensure the tracking and communications capabilities of the deep station network.[16] A fiber-based timing signal synchronization technique is used to ensure a high angular resolution of the large high altitude air shower observatory (LHAASO) project.[17] Driven by the objective to construct a time and frequency synchronization network, especially, in the applications of radio telescope array, different topological time and frequency dissemination schemes have been demonstrated.[18–20] In the meantime, new challenges spring up.

As a typical example of a radio telescope array, the SKA project has a strict requirement on the reference frequency synchronization between hundreds of antennas in the first phase of SKA (SKA1). More specifically, in order to ensure the SKA imaging fidelity, the reference frequency from the central clock located at the central station should be disseminated to every antenna via fiber links. Consequently, a synchronization network with star-shaped topology will be established.[21] Aiming the requirements of SKA, in 2015, we proposed and demonstrated a 1f–2f reference frequency dissemination scheme which features phase noise compensation performed at the client site.[18] While, specific to the practical application, some supplement techniques can further simplify the complication of the frequency dissemination system. In the SKA1, take the mid-frequency aperture array (SKA1-MID) for example, it consists of 197 antennas as scheduled. Some of these antennas will be arranged in a moderately compact core with a diameter of 1 km, some others will be randomly placed but thinning at the edges within a radius of 4 km, and the remaining will be situated on three spiral arms which extend out to a radius of 80 km from the center, as shown in Fig. 1. Through analyzing the array configuration data, there are approximately 78% of the antennas arranged in a radius up to 4 km.[22] For these densely distributed antennas, we propose and demonstrate a fiber-based multiple-access frequency synchronization scheme as a supplement of the foregoing 1f–2f scheme. Using the multiple-access scheme, the disseminated reference frequency can be recovered at arbitrary nodes along the entire fiber link without degrading the frequency stability. For the SKA frequency synchronization network, after achieving precision frequency synchronization for the antennas (22%) along the three spiral arms with the 1f–2f scheme, the antennas (78%) inside the dense core can be synchronized

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by the proposed multiple-access scheme. In this way, the SKA frequency synchronization network will be dramatically simplified.

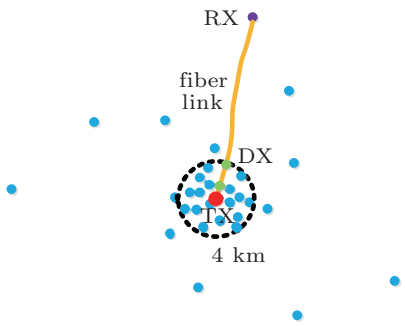


Fig. 1. (color online) Schematic diagram of the mid-frequency aperture array configuration in SKA1 and a certain frequency dissemination fiber link. The blue points represent the distributed antennas. TX: the transmitting site represented by the red point. RX: the receiving site represented by the purple point. DX: the download site represented by the green point.

In this paper, as a performance test, we set up a 55-km frequency dissemination fiber link and recover the 100-MHz disseminated frequency signal at the download site (DX) which is 5 km away from the transmitting site (TX). Relative frequency stabilities of 2.0×10^{-14}/s and $1.6\times10^{-16}/10^{4}$s for the download reference frequency are obtained. Furthermore, considering the approximately 3:1 (78%:22%) relationship between the antennas inside and outside the dense core, a frequency dissemination link with three DX access points is also demonstrated.

2. Methods

The schematic diagram of fiber-based multiple-access frequency synchronization via the 1f–2f dissemination scheme is shown in Fig. 2. The TX and RX are almost the same as those in Ref. [18], except that the TX here just has one dissemination channel. The 5-km and 50-km fiber spools are connected via a 2×2 fiber coupler (coupling ratio 80:20). At the DX site, the forward and backward dissemination signals can be coupled out from the fiber link, and the 100-MHz disseminated frequency can be recovered. For the convenience of phase stability measurement, the entire system is placed in the same lab.

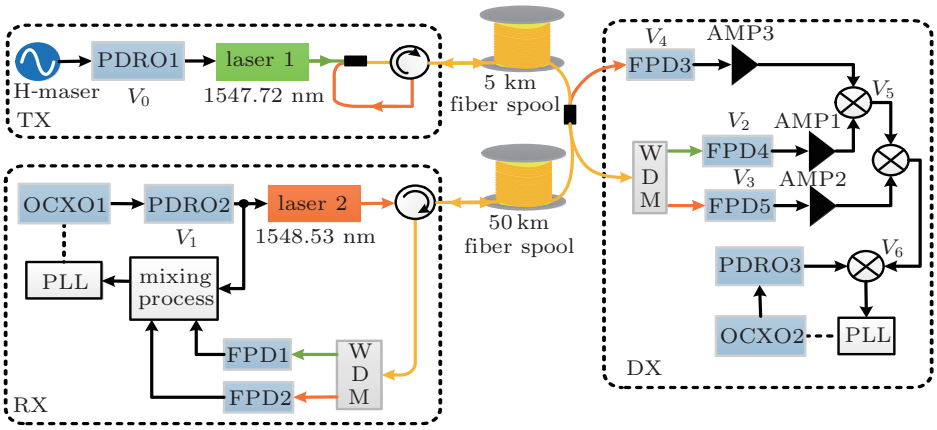


Fig. 2. (color online) Schematic diagram of the fiber-based multiple-access frequency synchronization via the 1f–2f dissemination scheme. OCXO: oven-controlled crystal oscillator. PDRO: phase-locked dielectric resonant oscillator. WDM: wavelength-division multiplexer. FPD: fast photodiode. AMP: high-linearity amplifier. PLL: phase-locked loop.

At the TX site, 100-MHz reference frequency from a hydrogen maser (H-maser) is converted to 2 GHz using a phase-locked dielectric resonant oscillator (PDRO1). Without considering its amplitude, the 2-GHz signal can be expressed as $V_0 = \cos(\omega_0 t + \phi_0)$. The V_0 is used to modulate the amplitude of a 1547.72-nm diode laser (laser 1) and disseminates from TX to RX. At the RX site, a 1-GHz PDRO2 is phase locked to a 100-MHz oven-controlled crystal oscillator (OCXO1), and can be expressed as $V_1 = \cos(\omega_1 t + \phi_1)$. The V_1 is used to modulate the amplitude of a 1548.53-nm diode laser (laser 2) and disseminates via the route from RX to TX and back. The one-way disseminated 1547.72-nm laser light and roundtrip disseminated 1548.53-nm laser light are separated from each other by a wavelength-division multiplexer (WDM) and then detected by two fast photodiodes (FPD1 and FPD2), respectively. These two signals are frequency mixed with each other, and the generated error signal is used to control the phase of the OCXO1. When the phase-locked loop (PLL) is closed, OCXO1 is phase locked to the 100-MHz reference frequency signal at TX with the relationship of $\phi_0 = 2\phi_1$.

On the basis of the above synchronous link, using a 2×2 fiber coupler, the 1548.53-nm laser light transmitting forward and backward as well as the 1547.72-nm laser light transmitting forward in the fiber link can be coupled out. The 1547.72-nm and 1548.53-nm forward transmitting laser lights are separated from each other by a WDM and detected by FPD4 and FPD5, respectively. We can obtain

$$V_2 = \cos(\omega_0 t + \phi_0 + \phi_{\rm pa}), \quad (1)$$

$$V_3 = \cos(\omega_1 t + \phi_1 + 2\phi'_{\rm pa} + \phi'_{\rm pb}). \quad (2)$$

Here, ϕ_{pa} is the accumulated phase fluctuation of the 2-GHz signal during the 5-km fiber dissemination, ϕ'_{pa} and ϕ'_{pb} are the accumulated phase fluctuations of the 1-GHz signal during 5-km and 50-km fiber dissemination, respectively. The 1548.53-nm backward transmitting laser light is detected by FPD3. The received signal can be written as

$$V_4 = \cos(\omega_1 t + \phi_1 + \phi'_{pb}). \tag{3}$$

Considering the one way phase fluctuation of the 2-GHz frequency signal is the same as the round-trip accumulated phase fluctuation of the 1-GHz frequency, there is a relationship of $\phi_{pa}=2\phi'_{pa}$. Through mixing signals V_2 and V_4, the up-conversion signal can be expressed as

$$V_5 = \cos\left[(\omega_0+\omega_1)t + \phi_0 + \phi_1 + \phi_{pa} + \phi'_{pb}\right]. \tag{4}$$

Then V_5 is mixed with V_3, the down-conversion signal can be expressed as

$$V_6 = \cos(\omega_0 t + \phi_0). \tag{5}$$

We can see the recovered frequency signal V_6 does not contain the phase fluctuation term, namely the reference frequency is recovered at DX. To reduce the impact of the higher harmonics of the 1-GHz signal, we use customized high-linearity amplifiers (AMP1, AMP2, and AMP3) and high-linearity mixers (Marki T3-03) in the above frequency mixing procedures.

3. Results

In order to obtain the dissemination stability of the whole synchronous link, the phase difference between the 100-MHz reference signal and the 100-MHz signal from phase-locked OCXO1 is measured by a phase detector. The measured phase difference is recorded by an 8-1/2 digital multimeter (Keithley 2002). After analyzing the phase difference using the commercial frequency stability analysis software "stable 32", we can get the relative frequency stability between these two 100-MHz signals. Figure 3 shows the experimental results. When the PLL is closed, relative stabilities of 2.6×10^{-14}/s and $1.2\times10^{-16}/10^4$s are achieved. While, for the free running dissemination link, relative stabilities are 4.9×10^{-13}/s and $7.1\times10^{-14}/10^4$s, respectively.

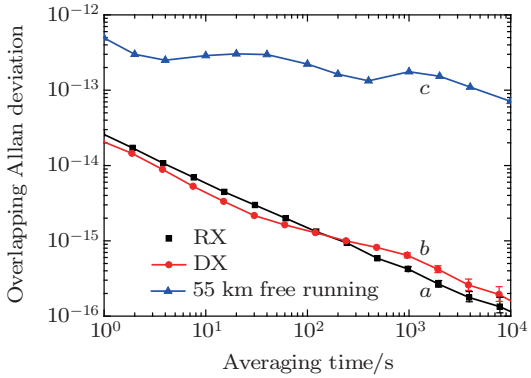


Fig. 3. (color online) Measured frequency dissemination stabilities. Curve *a*: The result of the recovered frequency signal at RX. Curve *b*: The result of the recovered frequency signal at DX. Curve *c*: The result of free running dissemination via 55-km fiber link.

To measure the relative frequency stability of the download signal, we can directly compare the recovered 2 GHz with V_1 and measure their phase difference. In order to make the results consistent with the measurement above and more convincing, a 100-MHz OCXO2 is phase locked to V_6. We measure the relative frequency stability between the recovered 100-MHz (from OCXO2) and the 100-MHz reference signal (from H-maser), and obtain the frequency dissemination stabilities of 2.0×10^{-14}/s and $1.6\times10^{-16}/10^4$s.

4. Extended experimental system and results

As previously mentioned, if each frequency dissemination fiber link between the SKA center station and the antenna on the spiral arm can include three DX access points (inside the dense core) respectively, the SKA1-MID reference frequency synchronization network can be dramatically simplified. Therefore, we carry out a frequency dissemination experiment with three DX access points and demonstrate the feasibility and practicality of the multiple-access frequency synchronization scheme.

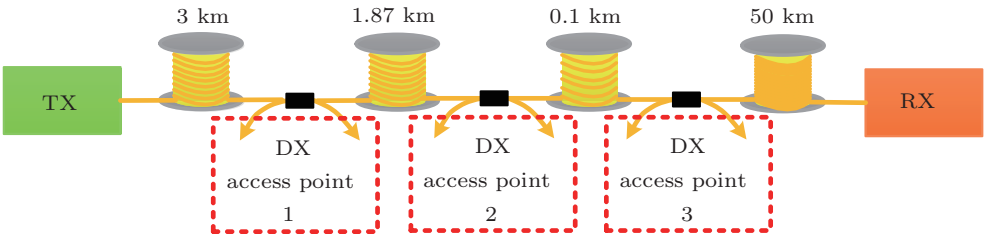


Fig. 4. (color online) Schematic diagram of the frequency synchronization link with three DX access points.

The experimental setup is shown in Fig. 4. DX access point 1 is set 3 km away from TX. Forward and backward transmitting laser lights are coupled out by a 2×2 fiber coupler (coupling ratio 80:20). The same structures apply to the other two access points with 1.87-km and 0.1-km fiber spools connected to the preceding point respectively. The RX is set

50 km away from DX access point 3. Considering the insertion loss and the 80:20 coupling ratio of the 2×2 fiber coupler, each fiber coupler will cause 1.2-dB power loss to the one way disseminated laser light in the main fiber link. Three fiber couplers will cause 3.6-dB power loss to the laser light disseminated one way in the main fiber link. Due to restrictions of experiment devices, we use the same frequency multiple-access setup (DX block of Fig. 2), and successively download the 100-MHz dissemination reference frequency signals at all three DX access points, respectively. Figure 5 shows measured relative stabilities of the recovered 100-MHz frequency signals at three DX access points and RX compared with the 100-MHz reference frequency signal (H-maser) of TX. It can be seen that, at the three DX access points, results are distributed in the range of $(2.0 \pm 0.3)\times10^{-14}$/s and $(1.8 \pm 0.2)\times10^{-16}/10^4$s which is consistent with that of the previous frequency dissemination experiment with one DX access point (red line of Fig. 3). The relative stabilities of the recovered frequency signal at RX are 3.2×10^{-14}/s and $1.5\times10^{-16}/10^4$s. They are slightly worse than the previous results (black line of Fig. 3). It is mainly caused by the power decrease of received laser lights at RX induced 2×2 fiber couplers. Nevertheless, the results still well meet the reference frequency synchronization requirements of SKA.

In practical applications, the working environment of the frequency dissemination system is more complicated. Firstly, the laid fiber link normally has larger attenuation than a fiber spool with the same length. According to the extended experiment, the 3.6-dB power loss caused by the fiber coupler does not greatly affect the dissemination stability. Cooperating with optical amplifiers, the frequency dissemination stability would be slightly affected. Secondly, according to the conditions of the SKA site, ambient temperature fluctuation is a big challenge to the proposed system, especially to the out-of-loop components. Consequently, a temperature controlled system is required for these out-of-loop components, which is what we will do in the future.

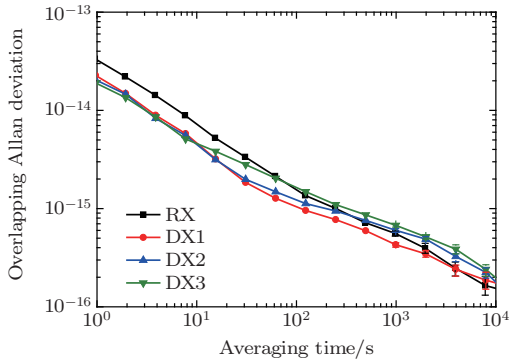


Fig. 5. (color online) Measured relative frequency stabilities of recovered frequency signals at RX and three DX access points.

5. Conclusion

Specific to the practical application of reference frequency synchronization in the SKA, we propose and demonstrate a fiber-based multiple-access frequency synchronization scheme. Using this method, the disseminated reference frequency can be recovered at arbitrary nodes along the entire fiber link. In the SKA1, the aperture array configuration features the majority of antennas located in a dense core and the others positioned away from the core. In consideration of these features, combining this multiple-access frequency synchronization scheme with the existing 1f–2f reference frequency dissemination scheme can construct a simplified SKA frequency synchronization network.

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