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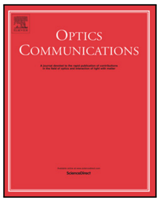

Stable radio frequency dissemination in a multi-access link based on passive phase fluctuation cancellation

Guochuan Tong, Tao Jin *, Hao Chi, Xiang Zhu, Tianhao Lai, Dong Li, Lulu Zuo

College of Information Science and Electronic Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, 310027, China

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ABSTRACT

We propose and experimentally demonstrate a novel scheme of stable radio frequency (RF) dissemination in a multi-access radio-over-fiber (ROF) link. Unlike the active compensation scheme based on a phase-locking loop, the proposed scheme provides fast responses and infinite dynamic ranges with a passive phase fluctuation cancellation (PPFC) approach. In our experiment, a 2.5-GHz signal is steadily distributed to a remote end through an arbitrary user site in a 25-km optical fiber link. The stability of the recovered signals at the user site and the remote end are evaluated. By using the phase correction scheme, the peak–peak phase excursion is reduced from 140 to 4 ps at the user site and 160 to 4 ps at the remote end, respectively. The achieved relative residual frequency instabilities are $1.4117 \times 10^{-16}/10^4$ s and $1.6503 \times 10^{-16}/10^4$ s at the user site and the remote end, respectively.

1. Introduction

High-stable radio frequency (RF) transfer is of great need in a large number of applications such as deep space networks [1], high precision clock standard distribution [2] and multi-antenna array systems [3]. Optical fiber is considered to be an ideal medium for a radio-frequency (RF) transmission with the least phase variation due to its low loss, large bandwidth and immunity to electromagnetic interference. However, transmission of RF signals over fiber suffers from severe phase fluctuations due to random temperature changes and mechanical vibrations. In order to realize the stable RF dissemination over fiber, the environment-induced phase fluctuation should be canceled out. Two types of schemes have been proposed to improve the stability of signal transmission. One is an active phase compensation scheme [4–6], in which a phase compensator, such as a piezo-driven optical stretcher [7], a voltage-controlled oscillator (VCO) [8] or a microwave delay module [9], is controlled according to the phase error. The real-time phase correction can be achieved at the cost of complex circuits for rapid acquisition and compensation of the phase fluctuation. In addition, the phase error compensation capability is limited by the phase adjustment range of the compensator. The other is a passive phase compensation scheme based on frequency mixing [10–12], which involves neither phase discrimination nor dynamic tracking, and can provide fast responses and infinite dynamic ranges.

Almost all the above schemes are applied to "point-to-point" transmission systems. A stable RF signal transmission can be established from one central station to one remote site. However, the limited accessibility limits their further applications in multi-access communication systems. The scheme of stable RF dissemination is needed to provide multiple user support. In Ref. [13], a wavelength-division multiplexing (WDM) technique is used to realize a "point-to-multipoint" signal transmission. At the local site, the signal is broadcasted to the users, and the optical carriers are reflected from all user sites. The reflected signals from the different user sites share a common transmission link, and can be distinguished from each other through different wavelengths. The main drawback of this scheme is the use of multiple wavelengths, which will greatly increase the complexity of the system. In addition, the laser instability will affect the effectiveness of the scheme. In Ref. [14], a multiple-access frequency dissemination system based on an ultra-stable optical comb is proposed, in which a mode-locked-laser (MLL) is used as an optical voltage control oscillator to compensate for the phase noise. However, the mode-locked laser itself is much more complicated to implement. Unlike the schemes for tree-shaped "point-to-multipoint" transmission systems, in the method proposed in Ref. [15], the phase-noise compensation function is applied at the receiving site, which makes this method suitable for use in any star-shaped topology frequency dissemination applications. However, the complexity of the system is inevitable because the method develops from the "point-to-point" active phase compensation scheme.

In this letter, we propose and demonstrate a novel approach for multi-access stable RF dissemination based on passive phase correction.

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* Corresponding author.
E-mail address: jint@zju.edu.cn (T. Jin).

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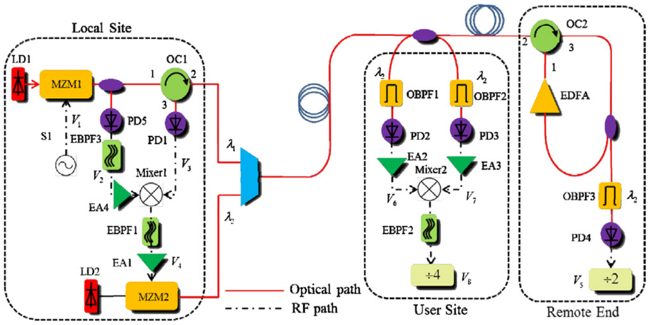

Fig. 1. Schematic diagram of the proposed multi-access stable radio frequency delivery system based on passive phase correction scheme. LD: laser diode, MZM: Mach–Zehnder modulator, WDM: wavelength-division multiplexing, SMF: single mode fiber, OC: optical circulator, EDFA: erbium-doped optical fiber amplifier, PD: photodetector, OBPF: optical band pass filter, S: radio frequency source, EA: electric amplifier, EBPF: electric bandpass filter.

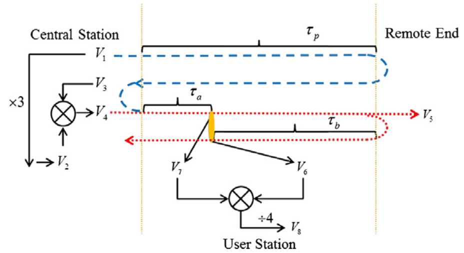

Fig. 2. The principle of the automatic phase stabilization scheme.

At the local site, a phase-conjugated signal is generated by mixing the standard signal and the round-trip signal. At an arbitrary user site in the optical link, the forward phase-conjugation signal and the backward probe signal are tapped and mixed to derive a stable signal.

2. Operation principle

The schematic diagram of the proposed passive phase correction scheme is shown in Fig. 1. Our goal is to transmit a standard RF signal at a local site to an arbitrary user site and a remote end via single-mode fiber (SMF) with stabilized phase. At the local site, an optical carrier from a laser diode (LD1) with a wavelength of λ_1 is modulated by a Mach–Zehnder modulator (MZM1) driven by a standard RF signal with angular frequency ω_s. Part of the optical signal (10%) is photoelectrically converted, and fed into an electric bandpass filter (EBPF3) centering at $3\omega_s$ to generate a triple-frequency signal. Other optical signal is transmitted to the remote end through a long length of fiber. The optical signal at the remote end is amplified by an erbium-doped optical fiber amplifier (EDFA) to compensate for the link loss and sent back to the local site. The returned optical signal is detected by PD1 and mixed with the triple-frequency signal. The mixed signal is bandpass filtered to obtain a phase-conjugated double-frequency signal and amplified before driving MZM2. An extra laser with a wavelength of λ_2 is used as another optical carrier to carry the phase-conjugated signal to the remote end once more. The signals with the two different wavelengths of λ_1 and λ_2 are transmitted over the same optical fiber link and suffer from the same phase fluctuations, which ensures the automatic elimination of the phase drift of the RF signal photoelectrically converted from the optical signal with the wavelength of λ_2 at the remote end. At the arbitrary user site, two optical signals are partially extracted from the backward and the forward transmitted lights through a 2 × 2 optical coupler, respectively. When the two extracted signals are mixed in a RF mixer after being bandpass-filtered at the center wavelength λ_2 to eliminate the signals at the wavelength λ_1, photoelectrically converted and amplified, respectively, the phase drift of the RF signal is also eliminated automatically.

Fig. 2 shows more clearly the relationship between all the signals in the phase stabilization scheme. The dashed blue and the dotted red lines represent the signals from LD1 and LD2, respectively.

The standard signal at the local site and its triple-frequency signal can be expressed as:

$$V_1 = \cos\left(\omega_s t + \varphi_1\right), \tag{1}$$

$$V_2 = \cos\left(3\omega_s t + \varphi_2\right), \tag{2}$$

where the standard frequency ω_s is the angular frequency of $V_1 \cdot \varphi_1$ and φ_2 denote the initial phases of V_1 and V_2, respectively. Because the signal V_2 is the third harmonic of the signal V_1, the initial phase difference between them, $\varphi_2 - \varphi_1$, is constant. For the sake of simplicity, all signal amplitudes in this letter have been normalized.

Because the delay variation of fiber is much slower than the transmission time of signals, the difference between the forward and the backward transmission delays is negligible. The round-trip signal V_3 detected by PD1 is given by

$$V_3 = \cos\left[\omega_s\left(t - 2\tau_p\right) + \varphi_1\right], \tag{3}$$

where τ_p is the delay variation due to mechanical and thermal fluctuations of the fiber when the optical signal transmits from the local site to the remote end.

The signal after Mixer1 and EBPF1 at the local site can be written as

$$V_4 = \cos\left[2\omega_s\left(t + \tau_p\right) + \varphi_2 - \varphi_1\right], \tag{4}$$

and is a phase-conjugated double-frequency signal. At the remote end, the RF signal after PD4 and a divided-by-two frequency divider can be expressed as

$$V_5 = \cos\left[\omega_s t + \left(\varphi_2 - \varphi_1\right)/2\right]. \tag{5}$$

It can be seen from Eq. (5) that the delay fluctuation induced by the fiber link is eliminated.

At an arbitrary user site, two tapped signals after being filtered and photoelectrically converted can be denoted as

$$V_6 = \cos\left[2\omega_s\left(t - \tau_b\right) + \varphi_2 - \varphi_1\right], \tag{6}$$

$$V_7 = \cos\left[2\omega_s\left(t + \tau_p - \tau_a\right) + \varphi_2 - \varphi_1\right], \tag{7}$$

where V_6 and V_7 are the signals extracted from the backward and the forward transmitted waves, respectively. τ_a is the delay fluctuation from the local site to the user site and τ_b is the delay fluctuation from the user site to the remote end. Obviously, $\tau_a + \tau_b = \tau_p$. The signal V_6 is mixed with V_7 to generate an up-conversion signal after EBPF2. Finally, a stable RF signal can be obtained after a divided-by-four frequency divider at the user site.

$$V_8 = \cos\left[\omega_s t + \left(\varphi_2 - \varphi_1\right)/2\right]. \tag{8}$$

It is obvious from Eq. (8) that the delay variation from fiber has been canceled.

3. Results and discussions

A proof-of-concept experiment was carried out to verify the proposed technique. Two DFB lasers with wavelengths of 1543.34 nm and 1550.12 nm are used as optical carriers. At the local site, a standard RF signal at 2.5 GHz is generated by a microwave generator (KEYSIGHT E8267D). The RF signal at 7.5 GHz is filtered out by EBPF3 with a center frequency of 7.5 GHz and is amplified by an RF amplifier (EA4). A 25-km SMF is connected between the local site and the remote end. An arbitrary user site is set at 5 km away from the local site.

To test the performance of the system, we measure the phase drifts at the user site and the remote end over 15,000 s of continuous operation.