4-antenna Distributed Receiving System for Broadband Signal Transmission and Combination

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Abstract: We demonstrate a stable distributed receiving antenna system for broadband signal transmission and combination. A simple remote structure, a large link compensation range, and improved signal SNR have been achieved simultaneously with 4 remote ends.
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1. Introduction

Compared with a centralized single antenna structure, the distributed receiving system with multiple smaller antennas has a larger effect aperture, better detection performance, and higher flexibility [1]. This concept has been used in the Atacama large millimeter array (ALMA) project for deep space exploration [2] and has been demonstrated in distributed radar systems [3]. In such a system, the signal from a single source is first detected by different antennas from different remote ends. Then these separate signals are transmitted to the local end for further processing and combination, enhancing the SNR of the received signal. Generally, more remote antennas and a larger distance between different antennas result in a larger effective aperture and better detection performance. The distance is usually in the order of kilometers or even farther, making the optical fiber the only possible transmission media. However, it also brings challenges to signal transmission from the remote ends to the local end, because any delay fluctuation induced by the transmission fiber link can distort the signal quality, making it more difficult for signal combination. One solution is to convert the received signal to a digital signal at the remote end with an analog to digital converter. Yet it will dramatically increase the complexity of the remote end, also leading to extra delay variation of the signal. Thus, many approaches have been proposed to compensate for the link length variation, such as electrical delay lines [4], fiber stretchers [5]. However, they all have a limited compensation range, which is not suitable for long-haul transmission with large environmental variations.

In this letter, we propose and demonstrate a highly stable distributed receiving antenna system with 4 remote ends. The core idea is to first transfer a stable local oscillator (LO) signal to the remote end for signal down-conversion, and this LO is then transferred back to the local end to generate a sampling clock carrying the link variation information. Therefore, the delay variation of the transmitted signal has been canceled out when it is sampled in the ADC by the jittered clock. The stability of the LO signal reaches 0.0083 rad and the delay variation of the transmitted signal is 7.8 ps. Finally, the signals from 4 remote ends have been combined with well-designed algorithms, and 5.2 dB signal SNR improvement has been achieved. With a simple remote end structure and large link length compensation range, the proposed approach is highly desired in distributed detection systems where high link stability is required.

2. Principle

For a distributed system, the key technique is to first transmit the signal detected by each independent remote antenna back to the central station and then combine them for signal enhancement. To achieve this, we propose a stable LO-based solution as shown in Fig. 1. Firstly, we transfer a stable LO signal from the local end to the remote end by controlling an intermediate frequency voltage-controlled oscillator (VCO) with a phase-locked loop (PLL) [6]. At the remote end, the received broadband signal is down-converted by this highly stable LO signal, which can lower the requirements for the backhaul transmission. Then the stable LO signal is transmitted back together with the received signal along the same optical fiber link. The returned LO is then processed to generate a sampling clock for an analog-digital converter (ADC). Since the LO and the broadband signal experience the same timing jitter induced by the link, the timing jitter of the transmitted broadband signal will be canceled out during the ADC sampling. The 4 sampled digital signals are then processed in a computer. A well-designed time delay estimation algorithm is first used for aligning the beginning of the 4 signals with different transmission delays. Finally, after estimating and correcting the phase difference, the 4 signals are combined with an enhanced SNR. By transferring and stabilizing a single frequency signal as the LO at the remote end and then transferring it back as the sampled clock at the local end, the received broadband signal can be stably transmitted back to the local end without any real link compensation even under large environmental perturbations. Meanwhile, since the sampling and processing are realized in the local end, the proposed approach has a relatively simple remote end, inducing less phase variation of the signal out of the control loop. The two advantages make it an ideal candidate for next-generation distributed systems.

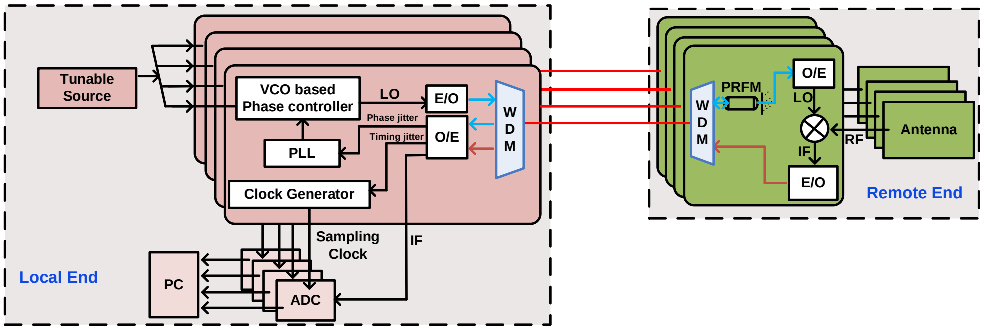

Fig. 1. The principle of the proposed distributed receiving system.

3. Experiment and results

Fig 2 shows the experimental setup of the proposed distributed receiving system with 4 remote ends. For each channel, a 1550 nm laser is divided into two branches. One branch is modulated with an LO signal in a Mach-Zehnder modulator (MZM1). This single-frequency LO signal is generated by modulating a tunable source with a 10 MHz VCO via a single sideband (SSB) modulator. The other branch is modulated directly with the tunable source in the MZM2 as a reference signal. The optically carried LO signal passes through a polarization beam splitter (PBS) and a wavelength division multiplexer (WDM) successively and is then injected into the single-mode fiber of 20 to 25 km. After fiber transmission, it is first frequency shifted by an acousto-optic frequency shifter (AOFS) and then reflected to the local end by a partial reflective Faraday mirror (PRFM). Its phase fluctuation induced by the link length variation is transferred to an intermediate frequency by a dual-heterodyne phase-error transfer (DHPT) module [7] and detected by a phase-frequency detector (PFD). A 10-MHz rubidium clock is used as the frequency reference of the PFD. Then the phase error signal goes through a loop filter and drives a VCO to compensate for the link length fluctuation. Meanwhile, the phase-varied VCO signal is also used to generate a jittered clock whose phase variation is equal to the link length variation. At the remote end, the signal from the X-band signal generator is first down-converted in a mixer with the LO signal from the photodetector (PD) and is then modulated on the light from another laser with a different wavelength. It is coupled into the optical fiber through a WDM and is then transmitted to the local end. After being separated with another WDM, it is detected by a PD and is then sampled in the ADC with the jittered clock. Finally, the 4 received digital signals are combined with a well-designed algorithm in a computer.

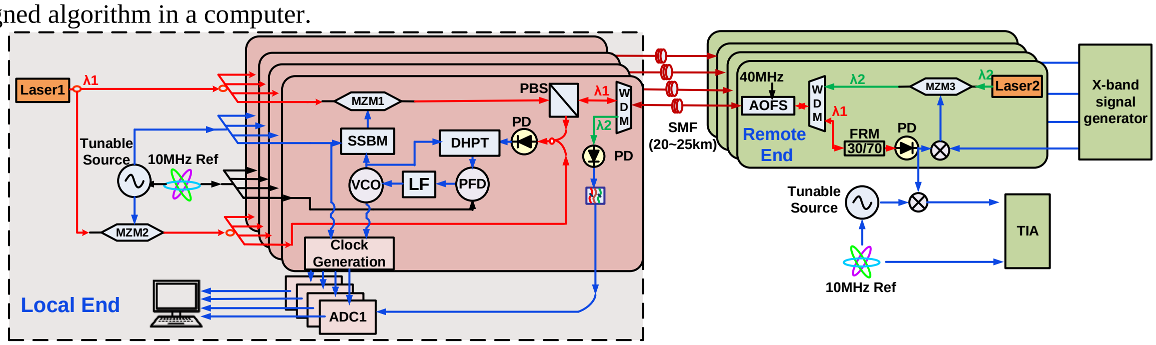

Fig. 2. The experimental setup of the proposed distributed receiving system.

The stability of the LO signal directly determines the stability of the whole system, which has been first measured. Since it is difficult to directly measure the phase variation of a high-frequency signal, the LO signal is first mixed with the same tunable source as in the local end to generate a 10 MHz IF signal, whose phase variation is the same as the original LO signal. A time interval analyzer (TIA) is adopted to measure the delay jitter of this IF signal by comparing the time difference of every zero-crossing point pair of the IF signal and the 10 MHz reference clock signal. The 10 GHz LO phase drifts at the remote ends under locking and unlocking states are shown in Fig. 3(a). The root-mean-square (RMS) values of the phase drift are merely 0.0096 rad, and 0.0083 rad for locked link 1 and link 2, respectively, while the unlocked link 1 has a phase drift as high as 10.2 rad, proving the validity of the precise feedback phase control of the LO. Then the stability of the broadband signal transmission with the jittered sampling clock is evaluated. To accurately measure the delay variation of the link, a binary phase-shift keying signal with a 400 MHz carrier frequency and a 20 MHz bandwidth is directly modulated on the light and is transmitted back through the fiber link together with the LO signal. This broadband signal is then sampled in the ADCs with the jittered clocks carrying the timing jitter of the link. The timing jitters between every two links are obtained by calculating the group delay slope of the two links' cross-correlation spectrum. As shown in Fig. 3, the relative timing jitter between link 1 and link 2 is 8.3 ps, and the jitter between link 1 and link 3 is 7.8 ps. Considering that the link length variation is at the order of nanosecond even under 1-degree temperature variation, the link has been successfully stabilized for the broadband signal transmission.

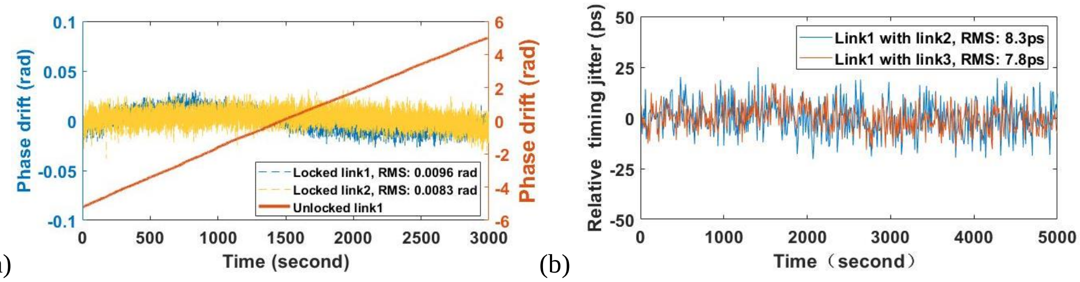

Fig. 3. Stability of the (a) LO signal at the remote end and (b) the transmitted received signal at the local end.

After the verification of the phase stability of the LO signal at the remote end and the delay stability of the received signal at the local end, the 4 transmitted signals from 4 different remote ends are combined in a computer with a well-designed algorithm to evaluate the signal combining performance. The received signal is a 10.3 GHz single frequency signal, which is down-converted to 300 MHz with a 10 GHz LO. It is sampled at the local end within 3 minutes. The SNRs of each received signal and the combined signal are shown in Fig. 4. It is clearly observed that the SNR is increased by 5.2 dB over the average SNR and 2.1 dB over the best channel. Note that the SNRs of the 4 received signals are different due to the different transmission distance and receiver noise. Here, we only demonstrate a single frequency signal for combination, but the system can support any signals with different bandwidths and center frequencies if a proper LO signal and ADCs are adopted. Further SNR improvement, channel performance equalization, and noise suppression will be demonstrated in future work.

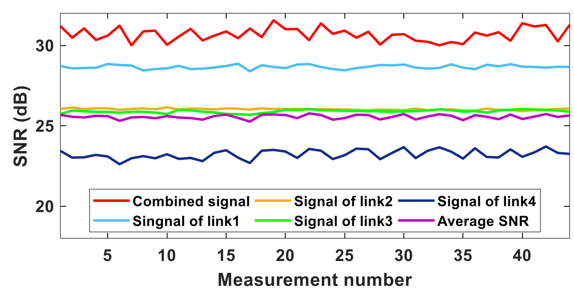

Fig. 4. The SNRs of each received signal and the combined signal.

4. Conclusion

We have demonstrated a highly stable distributed receiving antenna system with 4 remote ends. By stabilizing a single frequency signal as the LO at the remote end and as the jittered clock at the local end, a broadband signal detected by 4 remote ends is stably transmitted to the local end and combined for SNR enhancement. The stability of the LO signal reaches 0.0083 rad and the delay variation of the signal is 7.8 ps, leading to an SNR increase by 5.2 dB over the average SNR and 2.1 dB over the best channel. The proposed scheme can find its versatile applications in the next-generation distributed detection system where signal phase stability is highly required.

5. Reference

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