All-Digital Radio-Frequency Signal Distribution Via Optical Fibers

Magnus T. L. Hsu, Yabai He, Daniel A. Shaddock, Richard B. Warrington, and Malcolm B. Gray

Abstract—We present a radio-frequency (RF) signal distribution system via optical fibers. We utilize an all-digital platform that encompasses a phase-locked loop, numerically-controlled oscillator, and fiber phase noise cancellation system. Our system achieves a fractional frequency transfer stability of 4×10^{-13} at 1 s and 6×10^{-17} at one day for the distribution of RF signals over 70 km of optical fiber. We demonstrate that this performance can be achieved with standard crystal oscillators. Our system is scalable, configurable, and flexible, allowing distribution of signals at different frequencies while maintaining over two orders of magnitude of the fiber phase noise suppression.

Index Terms—Digital signal processing (DSP), field programmable gate array (FPGA), optical fibers, phasemeter, radio-frequency (RF) signal distribution.

I. INTRODUCTION

THE development of ultra-accurate optical clocks has revolutionized frequency metrology to the level of parts in 10^{-18} [1]. To complement the development of ultra-accurate clocks, high stability frequency distribution and comparison techniques are required for the benchmarking of these clocks. Clock comparison across large distances traditionally uses satellite techniques such as two-way transfer or Global Navigation Satellite System signals [2], [3]. However, noise processes inherent to these techniques require long averaging times (e.g. days) to match the stability of the clocks, imposing practical limits to the sensitivity of ultra-accurate clock comparison. Recently, optical fiber based clock comparisons have been demonstrated by a number of laboratories, using either radio frequency (RF) [4]–[6] or optical frequency comparisons [7]–[11]¹. The benefits of the fiber based technique are the relatively low phase noise of optical fibers and the ability to use existing telecommunications fiber infrastructure [12]–[15].

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¹State-of-the-art radio frequency distribution systems have achieved stabilities of parts in 10^{-18} , whilst optical frequency distribution have achieved stabilities of parts in 10^{-20} for integration times over one day.

Fiber phase noise tends to be negligible at short time scales (e.g. seconds) but increases at longer time scales (e.g. hours), due to thermal effects. However, the fiber phase noise can be subtracted via a return trip measurement, within a closed-loop feedback system that stabilizes a slave to a master oscillator. RF signal distribution over optical fiber has numerous applications including precise synchronization for accelerators and antenna arrays, for example in long baseline radio astronomy.

Current schemes for RF signal distribution via optical fibers rely on stabilization based on analog electronics. In this letter, we demonstrate an all-digital system based on a Field-Programmable Gate Array (FPGA) platform. The benefits of the all-digital system are timing coherence, long-term stability, scalability and versatility, whereby gains and filters can be optimized for the particular application. We configure our system to operate using different RF frequencies in its distribution chain, to reduce cross-talk errors due to spurious optical and electronic reflections. Using standard quartz crystal oscillators for both master and slave systems, we demonstrate a fractional frequency transfer stability of 6×10^{-17} over a day, through 70 km of optical fiber.

II. EXPERIMENTAL SETUP AND RESULTS

RF signals that are amplitude modulated onto an optical field and injected into optical fibers suffer from phase noise due to the changing path length of the fiber, or equivalently the changing time of flight Δt , due to thermal and mechanical noise sources along the fiber. The added RF noise due to the fiber is given by

$$\phi_{f_{\text{mod}}}^F = 2\pi \Delta t f_{\text{mod}}, \quad (1)$$

where f_{mod} is the frequency of the RF amplitude modulation signal. To avoid $\phi_{f_{\text{mod}}}^F$ degrading the slave oscillator stability, we implement the round trip fiber noise subtraction scheme shown in Fig. 1. The RF signal from the slave laser is sent through the fiber to the master, acquiring fiber phase noise, $\phi_{f_{\text{mod}}}^F$. At the master, this phase noise is negated using digital signal processing operations and imposed onto the outgoing master RF signal. This RF signal is then sent through the same fiber back to the slave, acquiring additional noise $\phi_{f_{\text{mod}}}^F$. Due to the negation at the master, the forward and reverse $\phi_{f_{\text{mod}}}^F$ terms subtract at the slave. This enables the slave to track the master oscillator free from fiber phase noise.

In order to improve orthogonality between the forward and reverse RF signals, we use two different RF frequencies: 20 MHz for the master-to-slave and 15 MHz for the slave-to-master signals. Eq. (1) shows that the fiber phase noise added

Fig. 1. Schematic of our all-digital RF distribution system. OC: optical circulator. PLL: phase-locked loop. NCO: numerically-controlled oscillator. Master f and slave f are the nominal frequencies of the respective master and slave oscillators. Frequency multipliers: 1/3, 1/4, 3, and 4.

to the RF signal is linearly proportional to the RF modulation frequency f_{mod} . To subtract the forward and reverse fiber phase noise, we normalize the phase signals to 5 MHz nominal frequency at both master and slave.

Our RF signal distribution system was implemented using two separate FPGA systems² with different local clock oscillators. The master system uses a telecommunications-grade fiber-coupled diode laser operating at 1550 nm. The laser was fed through an optical circulator to a fiber spool. The incoming slave laser was detected from the reflection port of the optical circulator using a high bandwidth photodetector. The slave signal was sampled using an analog-to-digital converter (ADC)³, and sent to a digital phase-locked loop (PLL). The PLL produced a frequency correction signal corresponding to the phase of the slave, ϕ_{15}^S MHz, and fiber phase noise, ϕ_{15}^F MHz, given by ϕ_{15}^S MHz + ϕ_{15}^F MHz. The frequency correction signal was then negated and divided by 3, to match its frequency with the nominal frequency of the master (i.e. 5 MHz). The corresponding phase signal is given by $-(\phi_{15}^S$ MHz + ϕ_{15}^F MHz). The frequency correction signal was added to the master nominal frequency to yield a frequency error signal for subsequent feedback control of the slave, with a corresponding phase given by ϕ_{5}^M MHz - $(\phi_{15}^S$ MHz + ϕ_{15}^F MHz), where the master phase is ϕ_{5}^M MHz. The frequency error signal was multiplied by 4 and input to a numerically-controlled oscillator (NCO) to produce a 20 MHz RF signal via a digital-to-analog converter (DAC) for amplitude modulation onto the master laser. The phase of the outgoing 20 MHz master signal is thus given by

$$\phi_{20}^{M \rightarrow S} = \phi_{20}^M \text{ MHz} - \phi_{20}^S \text{ MHz} - \phi_{20}^F \text{ MHz}. \quad (2)$$

²National Instruments PXI-7954R, using Virtex-5 LX110 FPGA.

³National Instruments NI-5781, with 100 MS/s dual channel 14-bit inputs and 100 MS/s dual channel 16-bit outputs.

Fig. 2. Noise spectral density of (i) electronic implementation of the RF distribution system and (ii) electronic noise floor of the phasemeter.

The slave system had the same optical configuration as the master. The incoming master laser was detected on the reflection port of the slave optical circulator. The signal on the incoming master laser is the error signal for feedback control of the slave oscillator. This signal was digitized using an ADC and sent to a digital PLL with detected phase given by

$$\begin{aligned} \phi_{20}^{\text{det}} \text{ MHz} &= (\phi_{20}^M \text{ MHz} - \phi_{20}^S \text{ MHz} - \phi_{20}^F \text{ MHz}) + \phi_{20}^F \text{ MHz}, \\ &= \phi_{20}^M \text{ MHz} - \phi_{20}^S \text{ MHz}, \end{aligned} \quad (3)$$

where the return trip subtracts the fiber phase noise. The frequency correction signal from the PLL was then divided by 4, to match the frequency with the nominal frequency of the slave (i.e. 5 MHz) and added to the slave nominal frequency to produce a frequency error signal for steering of the slave NCO. Subsequently the slave NCO produced a 15 MHz RF signal via a DAC for modulation onto the slave laser for distribution back to the master.

For diagnostic purposes, a 15 MHz master oscillator output was derived and used for comparison with the 15 MHz slave oscillator signal. In addition, the uncompensated fiber phase noise for a single pass through the fiber spool was extracted at the output of the master PLL.

We now quantify the noise performance of our RF signal distribution scheme by analyzing the noise spectral density as a function of frequency, given in Fig. 2. The electronic noise performance of our dual-channel differential phasemeter system [16], when driven with identical RF signals, is given by trace (ii), achieving 0.3 $\mu\text{rad}/\sqrt{\text{Hz}}$ sensitivity above 0.1 Hz. Trace (i) shows the noise performance of a purely electronic implementation of the RF signal distribution system with the optical components in Fig. 1 replaced by direct electrical connections between master and slave. Phase noise performance of 1 $\mu\text{rad}/\sqrt{\text{Hz}}$ above 0.5 Hz is achieved for the stabilization between the slave and master systems.

We characterize the stability of our RF distribution scheme using the Allan deviation, shown in Fig. 3. The stability of the independent master and slave oscillators is given in trace (i),

Fig. 3. Fractional frequency stability as a function of averaging time for (i) comparison of independent master and slave oscillators without stabilization, (ii) phase noise through 70 km of optical fiber, master and slave oscillators disciplined using the stabilization scheme through (iii) 70 km and (iv) 70 m of optical fiber, (v) electronic closed-loop stabilization of the master and slave oscillators, and (vi) phasemeter noise floor.

typical of quartz oscillators. Trace (vi) shows the stability floor of our differential phasemeter. White noise timing jitter between the two ADCs results in an Allan deviation of 1×10^{-14} at 1 s, averaging down over time as τ^{-1} . The electronic implementation of our RF distribution system, shown in trace (v), demonstrates greater noise at longer time scales, attributable to ADC and DAC noise. Trace (iv) shows the closed-loop RF distribution system through 70 m of optical fiber, whereby electronic-to-optical and optical-to-electronic conversions couple in optical shot noise and detector dark noise that further degrade the stability compared to trace (v). The closed-loop system operating over 70 km of optical fiber, given in trace (iii), has approximately 20 dB of optical attenuation and reduced PLL bandwidth to maintain round trip closed loop stability. Trace (ii) shows the one-way open-loop fiber phase noise through 70 km of fiber, typical of fibers with similar lengths [6].

Our phasemeter enables a fractional frequency stability measurement of $\sim 4 \times 10^{-19}$ over a day. We utilize this low-noise phasemeter to implement an all-digital RF signal distribution system through 70 km of optical fiber with a stability of 6×10^{-17} over a day, as shown in trace (iii). The fiber noise suppression, given by the difference between traces (ii) and (iii), is approximately two orders of magnitude for time scales of a day. Our RF stabilization results have been achieved with two FPGA systems operating on standard quartz crystal oscillators. The stability of our closed-loop RF distribution system is 4×10^{-13} at 1 s, comparable to typical

commercial masers. However, for time scales longer than 5 minutes, the transfer system is significantly more stable than typical masers.

III. CONCLUSION

Our RF distribution system provides simple, scalable, and convenient distribution of reference RF frequencies at high precision. The master oscillator can be readily disciplined to a high-stability reference, such as a caesium clock or hydrogen maser, to provide absolute frequency stability to the system. The system, therefore, supports a wide variety of applications in science and metrology, including distributed antenna arrays for radio astronomy, such as the proposed square kilometer array.

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