Redundant and Secure Time and Frequency Transfer through Fiber-Optic Networks for Quantum Applications and PNT beyond GNSS

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ABSTRACT

We present results on fiber-optic time and frequency distribution techniques that add scalability, security and reliability to existing methods. This includes ultrastable optical frequency distribution to multiple users with enhanced immunity to noise using code-division multiple access (CDMA). The CDMA scheme also opens up the possibility of encrypted ultrastable frequency distribution with more than 19 digits of relative frequency accuracy. In addition, we report on an extension of CERN's White Rabbit (WR) protocol for integrated Gigabit optical Ethernet and sub-nanosecond time distribution via optical networks. Through software modifications made to off-the-shelf WR switches, we created redundant optical timing ports, thus allowing the system to synchronize to multiple reference (atomic) clocks instead of just one. We show that such a modified WR switch can be used to combine the signals from multiple reference clocks into a virtual network timescale that can outperform any of the individual clocks. These concepts may find use in positioning, navigation and timing (PNT) as well as (quantum) network applications that require reliable frequency and time sources independent of GNSS, but with performance similar to or better than GNSS.

1.0 INTRODUCTION

Fiber-optic methods for long-distance time transfer with uncertainties below 1 ns [1,2] and optical frequency transfer (OFT) with more than 19 digits of accuracy [3,4] have existed for more than one decade, enabling such diverse applications as differential gravitational potential measurements via optical clocks [5], seismic sensing [6], terrestrial PNT beyond GNSS [7], and various quantum network technologies [8,9]. OFT through optical fibers is also expected to enable a future re-definition of the SI second based on optical atomic clocks [10]. In the field of OFT, the scalability of many-user networks has been considered by several authors (e.g. [4,11-13]), while encryption is to our knowledge yet to be addressed.

A topic closely related to the SI second is the realization of coordinated universal time (UTC), which currently takes place primarily through satellite-based comparisons of atomic timescales at national metrology institutes (NMIs). NMIs adjust their local timescales UTC(k) at intervals of days to weeks to track the 'paper timescale' UTC [14]. Fiber-optic time transfer methods [1,2] (for which we will take WR as an example) may have a transformative impact on the future realization of UTC for several reasons. First, WR enables clock comparisons and time distribution with residual errors at the level of a few 0.1 ns, one order of magnitude smaller than the errors associated with satellite time-transfer methods. Second, clock comparisons through WR can be performed quasi-continuously at a rate >1 Hz and with single-shot timing jitter of <10 ps. Third, with WR being a fully networked and digital system, clock comparison data can be made available within 1 s, limited only by CPU processing time and network latencies. These features may facilitate a GNSS-independent, network-based 'virtual' realization of UTC, computed on a second-to-second basis, and with UTC(k) timescales being steered to UTC at similarly short time intervals.

Here, we present preliminary results of a project that exploits CDMA for efficient and scalable optical frequency distribution through branched, many-user networks (Sec. 2). The use of CDMA methods may also enable encryption of signals for OFT, a capability that to our knowledge has not been demonstrated before. In Sec. 3 we present a modified WR network which can compare, process and combine signals from multiple reference (atomic) clocks, thus realizing an average time signal that is more stable and accurate, and which offers reliability through redundant clocks and timing links. Our results are relevant to the Symposium as they represent steps towards a secure GNSS-independent PNT infrastructure that will also enable quantum (network) applications [8,9], topics of strategic interest for defense and security.

2.0 EXPERIMENTS AND RESULTS

2.1 Code-Division Multiple Access Optical Frequency Distribution

2.1.1 Setup

In OFT, random optical path length variations of the fiber are sensed by propagating coherent light from an ultrastable laser through the fiber and back, and letting it interfere with the laser output on a photodetector. The interferometric signal is used for compensation of path length variations with servo bandwidths of < 1 MHz [3,4]. Serial multi-user links have been realized using various methods [4,11]. Methods for branched networks were demonstrated in [12,13]. The method of [12] makes use of sensing and compensation equipment at the (remote) user location, using a single ultrastable laser as a common optical frequency source (Figure 1a). This method, however, requires the upstream wave coming from each node to be frequency shifted by a unique amount, and at least 1 MHz away from shifts applied to waves associated with other nodes, in order to avoid cross talk between these waves at a given node's photodetector. This constitutes a frequency-division multiplexing method that could support tens to hundreds of nodes [12], but which requires careful network design and on-site hardware changes if the network needs to be reconfigured.

As shown schematically in Figure 1b, we overcome node-to-node cross talk by frequency-hopping (FH) the upstream wave over several values, following a pseudorandom sequence (PRS) that is unique to each node ('spreading'). Each node 'de-spreads' the round-trip interferometric signal in the electrical domain by correlating it with a version of its local PRS that is time-shifted to compensate for the round-trip delay. Electric signal contributions by other optical waves arriving at the node's photodetector, be they intermediate reflections of the upstream wave, or waves transmitted by other nearby nodes with other PRSs, will be suppressed owing to unmatched time delays and low cross correlation of the various PRSs used.

In our experiments we deployed a two-node network with two 10 km parallel branches (Figure 2a). Identical hardware is used in both nodes. Signal spreading is achieved through PRSs of length 50, imprinted onto the optical wave's frequency using an acousto-optic modulator. The PRS consists of 2-µs-long FH symbols represented by 10 frequency levels, spaced by 0.5 MHz. De-spreading takes place in the electrical domain, by first beating the round-trip wave with the original wave at a photodetector, and mixing the resulting beat-note signal with the appropriately time-shifted FH PRS.

2.1.2 Results

Figure 2b shows the relative frequency stability obtained at node B under various conditions. First, tests without modulation were conducted (similar to the approach of Schediwy et al. [12]). Switching on node A is found to slightly degrade the frequency stability at node B. Next, the modulation for CDMA was enabled (while node A was switched off). In this case the frequency stability in node B improves substantially as reflections of the upstream wave at intermediate components and connections in the fiber link have FH sequences whose delay does not match the full round-trip delay, and their effect on the link stabilization system is therefore suppressed. Switching on the CDMA unit of node A adds some frequency instability. To simulate the effect adding of more nodes, we inserted a bidirectional erbium-doped-fiber amplifier (EDFA) in branch A with a single-pass gain factor, *G*, where *G*=31 is equivalent to the optical power that would be received in node B in a network containing many tens of nodes (Figure 2a,c).

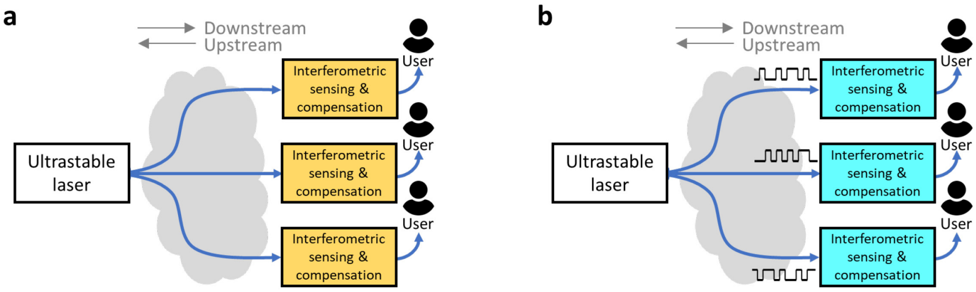

Figure 1: (a) Schematic depiction of the branched multi-user OFT network reported in [12]. Note that in this scheme, the downstream wave arriving from the ultrastable laser is frequency shifted at the user node, then sent back to the ultrastable laser (upstream wave), where it is partially reflected by a Faraday mirror (not shown) close to the ultrastable laser output. This reflected beam forms a second downstream wave, which ultimately is detected and used for interferometric sensing (b) Schematic depiction of the CDMA multi-user OFT network presented here, where the upstream optical waves are modulated using pseudorandom FH sequences.

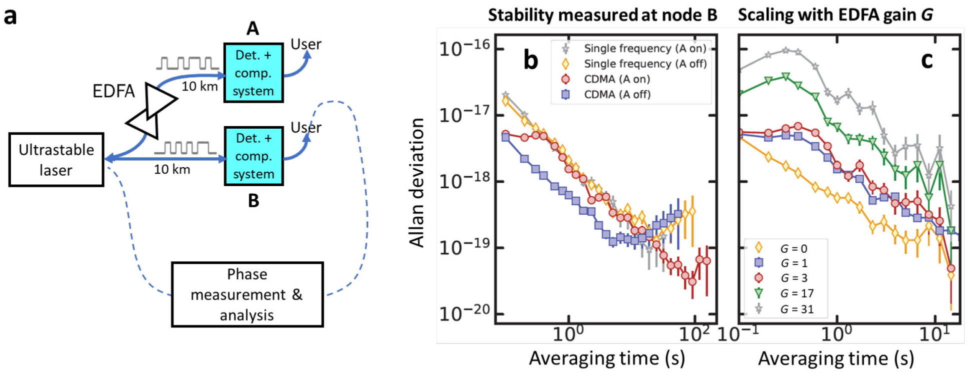

Figure 2: (a) Layout of the CDMA test network. (b) Frequency stability at node B for various test cases. (c) Frequency stability at node B versus EDFA gain.

2.2 Clock Comparisons and Clock Ensembling using White Rabbit

2.2.1 Setup

We used four arbitrary waveform generators (AWGs), synchronized to the same common phase and frequency produced by reference atomic clock, each with pre-programmed frequency noise and phase drift (Figure 33a,b). We thus mimic an ensemble of four clocks whose deviations from 'absolute time' (produced by the atomic clock) are known. Each AWG acts as a local reference clock that synchronizes one WR switch (WRS), while each of the WRSs transfers the time and frequency of its reference clock through fiber-optic Ethernet links to a fifth WRS (WRS5) using the WR protocol. WRS5, syntonized to WRS1, runs a modified version of the WR software which enables quasi-simultaneous (digital) phase measurements at four WR ports. WRS5 computes the average of the four phases, ϕ_{av}, and steers the 'timescale' phase of its output ports, ϕ_{ts}, to the value of ϕ_{av}. This may be considered a WR-based timescale based on an ensemble of four clocks, where a basic timescale algorithm runs inside the CPU of WRS5, and the timescale is realized at its output ports (the fiber-optic ports as well as the electrical 1 PPS/10 MHz outputs of WRS5).

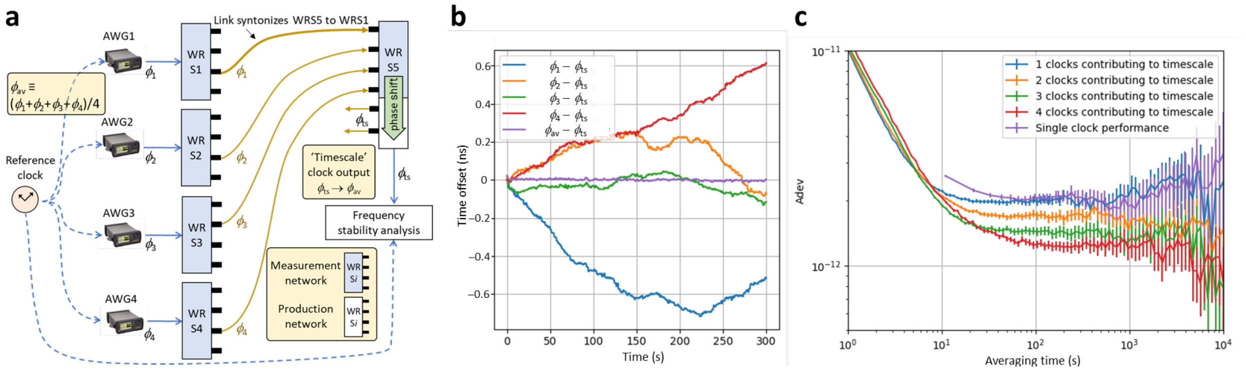

Figure 3: (a) Elementary WR-based timescale based on an ensemble of four clocks. Electrical connections are in blue, fiber-optic Ethernet connections in yellow. (b) Clock-versus-timescale phase differences. (c) Output frequency stability of WRS5 versus clock ensemble size.

2.2.2 Results

Figure 3b shows that the timescale output phase ϕ_{ts} tracks the (known) average clock phase ϕ_{av} with residual errors in the low picoseconds. Figure 3c illustrates the improvement in frequency stability that is achieved by adding more clocks (AWGs) to the ensemble. Here it should be noted that the AWG noise is intentionally chosen so as to contain only flicker FM much larger than the noise added by the WR links. This leads to flat Allan deviation curves for averaging of times beyond 50-100 s that can be easily compared. At short averaging times (< 10 s) the stability is limited by the white PM noise of the WR system itself. The WR short-term stability is seen to degrade somewhat when more clocks are added. This is caused by the current software implementation of the phase averaging at WRS5, which reduces the per-port phase measurement rate as more ports are being read out. It might also explain why at longer averagering times, the stability improvement is less than the factor $1/\sqrt{N}$ that is naively expected for an ensemble of N clocks.

2.2.3 Timescale Algorithms

In addition to the hardware timescale mentioned above, we are developing software timescale algorithms for generating an ensemble time in WR networks. Several types of algorithms have been published [15,16], which demonstrate advantages of timescale ensembles. The stability of the ensemble can be better than all member clocks at all averaging times, thus providing better predictability and holdover. The ensemble can detect a variety of clock anomalies and mitigate their effects. Finally, a timescale algorithm continuously estimates the offset of each member clock from ensemble time, enabling rapid fail-over in the case of a clock failure. We will be publishing results from software timescale algorithms in WR in the future.

3.0 DISCUSSION AND CONCLUSION

Our work shows that CDMA methods in combination with FH modulation of ultrastable optical carrier waves can be used for OFT through branched, multi-user networks. A proof-of-principle demonstration indicates that frequency stability below 10^{-16} at 1 s of averaging is possible for networks with many tens of nodes. The CDMA code might be optimized further to improve the OFT performance. Compared to existing methods for OFT through branched networks, our approach has the advantage that identical hardware can be used in all nodes, since all node-specific (re)configurations can be made remotely in software. The feasibility of FH-CDMA for OFT suggests that it may be possible to encrypt also the common ultrastable reference laser, so that it can be used to deliver $\sim 10^{-19}$ frequency stability *only* to authenticated network users who are in possession of the modulation code. Apart from time and frequency purposes, possible applications include encrypted distribution of optical carrier waves that can facilitate quantum communication [8,9].

In addition, we have demonstrated a basic implementation of a timescale based on an ensemble of four clocks, where WR is used to compare the phases of all clocks, digitally implement an elementary timescale algorithm, and realize a timescale output signal. More advanced timescale algorithms for WR are being developed. Our implementation offers redundant reference clocks and redundant WR connections, and naturally leads to a network infrastructure that can be divided into a ‘time measurement network’ (blue WR switches in Figure 3a) and a ‘time production network’ (represented by the white WR switch ports in Figure 3a, and any other WR gear that might be connected to them). This concept of WR-based timescales may find use in reliable and precise realizations of UTC, large-scale terrestrial PNT systems with performance beyond GNSS [7], and quantum communication [8,9], topics of strategic interest for defense and security.

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