A Sub-ps Stability Time Transfer Method Based on Optical Modems

Florian Frank, Fabio Stefani, Philip Tuckey, and Paul-Eric Pottie

***Abstract*— Coherent optical fiber links recently demonstrate their ability to compare the most advanced optical clocks over a continental scale. The outstanding performances of the optical clocks are stimulating the community to build much more stable time scales, and to develop the means to compare them. Optical fiber link is one solution that needs to be explored. Here, we are investigating a new method to transfer time based on an optical demodulation of a phase step imprint onto the optical carrier. We show the implementation of a proof-of-principle experiment over 86-km urban fiber, and report time interval transfer stability of 1 pulse per second signal with sub-ps resolution from 10 s to one day of measurement time. Prospects for future development and implementation in active telecommunication networks, not only regarding performance but also compatibility, conclude this paper.**

***Index Terms*— Demodulation, optical fiber communication, time dissemination.**

I. Introduction

RECENTLY, frequency comparisons of clocks by optical fiber links become a reality. Long-range comparisons of optical clocks and of atomic fountains have been recently demonstrated [1]–[3]. New tests of special relativity as a local Lorentz invariant were demonstrated using the ability of comparing a frequency difference between the optical clocks with unprecedented resolution [2], and it is likely expected that these tests will improve with the progress of optical clocks and the advent of clock's network [4]–[7]. One suspended question is how to achieve time transfer with sub-ps accuracy at continental scale.

The rapid progress made on optical clocks let us foresee the generation of much more stable time scales [8]–[11], potentially keeping time at the ps level over one day. Along with a future redefinition of the SI second, National Metrology Institutes (NMIs) will need the means for an accurate time scale comparison [12]. Also theoretical works predict that a relativistic effect could be detected with accurate sub-ps time transfer [13]. But state-of-the-art time comparisons as implemented today on a daily basis, as well as the calibration methods and definition of the origin of the epoch, severely lack resolution and accuracy. These questions stimulate the study, and novel methods have been investigated for several years either with fiber links [14]–[17] or in free space [18]–[20]. Advanced calibration methods were reported in [21]–[23]. The most impressive achievement was recently performed using femtosecond lasers and free-space propagation, with resolution below the femtosecond level, at a range of few kilometers [24]. The extension of such methods to longer ranges is still challenging.

Two-way methods implemented over the optical fiber links are another class of experiment with high potentiality. We focus here on the possibilities offered by fiber links since several NMIs in Europe are already connected by such fiber links, and offer prospects of reaching metropolitan, regional, and continental scales. Those links rely on the optical telecommunications network infrastructures, either over dedicated fibers (dark fiber) or over dedicated channels within active networks with parallel data traffic such as research and education networks.

Fiber link is a very promising candidate, as guided and bidirectional propagation can ensure excellent rejection of the propagation delay fluctuations and high signal-to-noise ratios.

For an optimal fiber noise rejection, those links are used in a fully bidirectional manner, and make use of various amplification and regenerating techniques to extend the range of fiber links to thousands of kilometers [25]–[28]. These techniques developed for the purpose of frequency transfer do not fit for accurate time transfer, as not only the delay fluctuation must be stabilized but also the one-way propagation delay must be accurately evaluated. This is very challenging for an optical fiber link since neither the physical length nor the optical index is a well-known quantity.

Cascaded fiber links were demonstrated to be compatible with high-resolution time transfer over a two-span 540-km fiber link with the parallel data traffic [14], but the extension of this technique over several spans is not straightforward, as they need the development of dedicated and remotely controlled instruments, with accurate time calibration abilities. Fiber Brillouin amplification, from their principle of narrowband amplification, limits the bandwidth of the modulation: an original method based on chirped frequency transfer has been demonstrated for synchronization and time transfer, but only using slow frequency ramps [29]. By contrast, erbium-doped fiber amplifiers have a wide amplification bandwidth and were successfully used over long ranges for the simultaneous time and RF frequency transfer [30]. It is interesting to note that Raman amplification also offers wide bandwidth of

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amplification and should offer the same compatibility [28]. The most recent review of methods for time and frequency transfer over fiber links is given in [31].

But at least, for fully bidirectional fiber links using coherent carrier, the asymmetries of the paths forth and back over hundreds of kilometers amount for less than 10 ps [14], [15]. To the best of our knowledge, the best accuracy budget was reported in [16]. Noticeably, a very promising method is also explored using optical frequency combs, for which an accuracy budget of 100 ps is reported [17].

Whatever the telecommunication layout, the principle of any accurate time transfer is to refer a time-modulated signal to a time scale and evaluate the uncertainty budget, including the contributions of instrumental delays, propagation delays, and eventually physical effects such as Sagnac terms.

If the propagation noise and propagation asymmetries can be very well suppressed, even at the price of using ultrastable carrier, a limiting factor arises from the instrumental delays, importantly at the modulation/demodulation stage. It was, for instance, a limiting factor in our previous experiment, where the SATRE modems were the dominant source of noise and inaccuracy [14]. So, we were interested in finding the new strategies where the optical methods can be used at their best, while keeping a practical and "reasonable" cost approach.

This "reasonable" cost approach is also motivated by a wide range of applications of so-called time transfer beyond the NMIs [32]–[35].

Indeed, time interval transfer, without knowledge of the static phase difference between two time scales, offers very interesting possibilities as a *universal* frequency transfer, since a time interval is not dependent of the carrier frequency. In a general concept for which a pulse per second (PPS) signal is delivered to the end user, the accuracy of the time intervals is the relevant quantity for applications in industry and "synchronization" of arrays of instruments. Sagnac experiments, looking for differential delays between the two directions of propagations, is also another class of experiments where the accuracy in time, understood as a coordinate and not as an interval, is not a must, and where only the accuracy of the time interval(s) matter(s) [36]–[38].

Here, we introduce a novel phase demodulation technique, using compact, low cost, and wideband optical modems. The main achievement of this paper is to demonstrate a stable time interval transfer with sub-ps stability over 86 km of an urban fiber link, limited at short integration time by the time interval counter (TIC) single-shot resolution.

II. Experimental Setup

In this experiment, we investigate the phase modulation of an optical carrier by a single π-pulse, which is to say a phase step of π rad, and its optical demodulation. We, therefore, design an experiment to study the performances of the modulation/demodulation after guided propagation by using a single laser and a common-mode time signal.

We use a common-mode laser source without active stabilization in phase or frequency. The laser emits in the C-band (1560 nm, ITU-channel 21), its linewidth is about 3 kHz. The sketch of the experiment is represented in Fig. 1

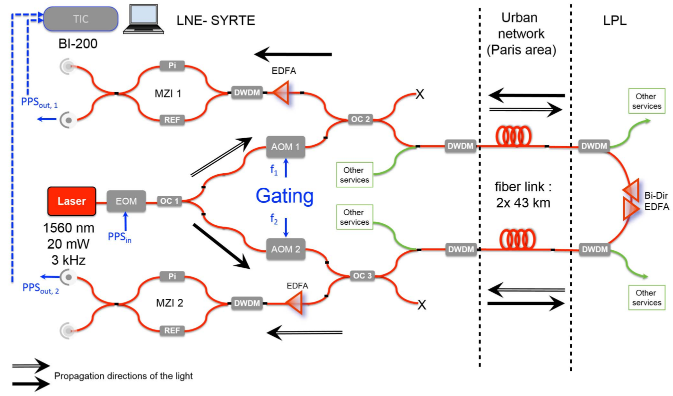

Fig. 1. Experimental setup. EOM: Electrooptic modulator. AOM: Acoustooptic modulator. MZI: Mach–Zehnder interferometer. OC: Optical coupler. PPS: 1 pulse per second. DWDM: Dense wavelength-division multiplexing filter, centered at 1560 nm.

The laser's light is modulated in phase by one fiber pigtailed electrooptical modulator (EOM). Its bandwidth is 14 GHz. The light is then equally split into two paths using the 50/50 optical coupler (OC1). The fiber link starts and ends at the same place. The two fibers are in the same cable. So, the whole link forms a Sagnac loop with the zero enclosed area. The π-pulse is generated from a one PPS signal out of a pulse distribution unit (TimeTech). The PPS signal is amplified and compressed using a pulse driver JDS Uniphase (JDSU), improving the rise time from about 500 to 150 ps. The signal is then sent to the EOM input. The pulse amplitude is chosen in such a way that a π-phase step is imprinted at the EOM output. The pulse is then encoded as a binary phase-shift keying (BPSK) to the optical carrier using the EOM.

The phase-modulated signals entered the fiber from the two ends in our laboratory, where two bidirectional 50/50 pigtailed OC2 and OC3 are set. Part of the signals propagate through 86 km of urban optical fiber and include one bidirectional erbium-doped fiber amplifier (EDFA), located approximately halfway. The propagation into the fiber is rigorously bidirectional. The signals at the other end of the fiber link are then extracted by the couplers OC2 and OC3 and then demodulated by two independent Mach–Zehnder interferometers (MZIs), one for each direction. The MZI has unbalanced paths and acts as delay line interferometers. The path difference corresponds to a phase shift of π. A continuous wave will produce a destructive interference at the end of the MZI. The PPS pulse will produce by contrast two constructive interferences after recombination by the MZI. A π-pulse will produce by contrast a constructive interference of duration $T = 1/\mathrm{FSR}$, where FSR is the free spectral range of the MZI. This setup is, therefore, a direct optical phase-to-amplitude demodulator. The MZIs used in this experiment are off-the-shelf components manufactured by Kylia [39]. Their FSR is 2.5 GHz, corresponding to a demodulated pulse length of 400 ps. This is the first time, to the best of our knowledge, that MZI is used for the demodulation of a sharp time signal.

The signal is amplified before demodulation with unidirectional EDFA with a gain of about 20 dB. Two dense wavelength-division-multiplexing (DWDM) filters at 1560 nm are used to reject the spontaneous emission of the EDFA.

The signals are detected by high-bandwidth photodiodes, Discovery DSC-40S. The bandwidth of the photodetection is 16 GHz. The electrical signals are then amplified with high-speed amplifiers. The time interval between the two signals, or with respect to a reference PPS signal, is measured with an ultralow noise two-channel TIC Carmel instrument BI-200 [40]. The time interval between the two signals is interpreted as the differential propagation delays for the two directions.

Only the independent sets of instruments (MZI, EDFA, TIC channel asymmetry, and electrical cables) and differential optical path between OC1-OC2 and OC1-OC3 introduce asymmetries.

Finally, to get rid of parasitic reflections arising from the link, filtering and recovery of the pulse of interest are achieved in the time domain using gated acousto-optic modulators (AOMs), AOM1 and AOM2 (see Fig. 1). The gating period is chosen to be long enough to be compared to the rise time of the AOM and as short as possible to have the better optical signal-to-noise ratio (the optical amplification has more gain in pulsed mode). This gating technique can be used arbitrarily for any fiber length. The MZIs are tuned with the help of temperature or with the help of a piezoelectric transducer. The FSR of the MZIs are not stabilized, but they are placed in a cartoon box with thermal and acoustic isolation rockwood. Other services, as coherent frequency transfer at 1542 nm, RF transfer, and data traffic on channels of the C-band, are carried simultaneously on the same fiber link using the DWDM techniques. No perturbation was observed between any of these signals.

III. Experimental Results

A. One Way

We first checked the one-way time transfer, i.e., free running, without propagation delay compensation. The reference signal is given by another output of the PPS distribution unit (Timetech). The rise time of the reference PPS is about 500 ps. The detected pulse has a typical amplitude of 35 mV, a midscale pulse width of 400 ps, and a rise time of 150 ps.

We observed a one-way delay of about 430 s, in good agreement with the expectation for 86 km of fiber link and in agreement with previous measurements. The time deviation (TDEV) starts at 10 ps and falls as $\sqrt{(\tau)}$ to 1 ps until 1000-s integration time, and then increases as the integration time τ and reaches 100 ps at $\tau = 20\,000$ s. This behavior at long integration time is similar to the one reported elsewhere with similar fiber lengths [30].

We observed a free-running peak-to-peak phase excursion of approximately 330 ps over a day–night cycle. This phase excursion is mainly due to thermal effects occurring in the optical fiber [41]. In accordance with the fiber length thermal sensitivity of 37 ps/km/K and given the length of the link, one found a temperature variation of the buried fiber of 1 K [42]. This order of magnitude is in agreement with the one-way delay measurement reported in [14] for a 540-km link.

In our case, the short-term stability is limited by the time jitter between the reference PPS and the PPS after the JDSU amplifier. Indeed, we measured the noise floor of the

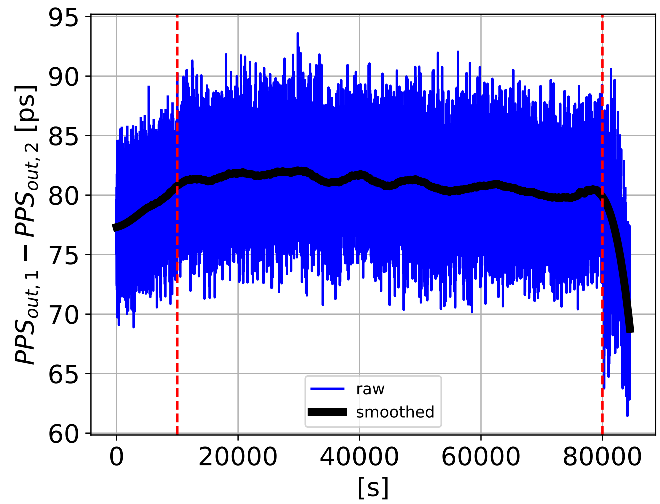

Fig. 2. Typical time trace of compensated two-way time transfer. An offset of 91.2 ns was removed. The mean value of 91 ns corresponds essentially to the length difference of Erbium-doped fibers used in the optical amplifiers of the detecting branches. The smoothed curve was obtained with a Savitzky–Golay filter.

PPS signals. The TDEV of two outputs of the Timetech distributor is 1.8 ps at $\tau = 1$ s. The TDEV of the same outputs after amplification by two independent JDSU drivers is 1.8 ps at $\tau = 1$ s, but the TDEV of one PPS out of the TimeTech and one PPS out of the JDSU shows 9-ps instability at $\tau = 1$ s. In all cases, the TDEV decreases as $\sqrt{\tau}$.

B. Two Way

We are now considering the time interval between the PPS out 1 and 2 in Fig. 1 This is a two-way signal, where the propagation delay is compensated in postprocessing [43].

For assessing the two-way performances, we count the time interval between the two output PPSs after an optical propagation. The reference PPS is not used anymore, and our two-way analysis is based on a common clock.

We obtained several acquisitions ranging from 1 h up to 2 days. A typical time trace of a two-way time transfer over 1 day is shown in Fig. 2. The mean value of 91 ns corresponds to the fiber length difference between the two EDFAs used at the detection stage for optical amplification.

For the first 10 000 data points, the smoothed curve of the measured phase difference exhibits a steady slope, which corresponds to the warm-up duration of the electronics inside of the TIC. Later on the counting process operates in steady mode, and we obtain a stable time trace. Finally, beyond 80 000 points, the time trace dropped down. This is due to the combined effect of unstabilized laser in frequency and unstabilized FSR of the MZIs. When the laser frequency and the MZI become out of tune, the signals fade out and the data become meaningless. In the following paragraphs, we present, therefore, a statistical analysis after excluding the warm-up and fade out region of the raw data as presented in Fig. 2.

The corresponding TDEV is shown in Fig. 3. We observe that the TDEV is 4.2 ps at $\tau = 1$ s. It decays with a rate of $\tau^{-1/2}$ until 100 s of integration time. This is the signature of white phase noise. At $\tau = 200$ s, we detect the signature of a periodic oscillation. We found that the typical

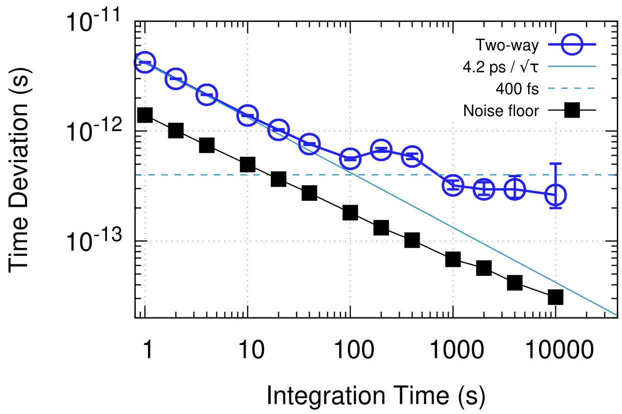

Fig. 3. Blue circles: TDEV obtained from the data plotted in Fig. 2. The sub-ps stability threshold is crossed for 20 s of integration time. Dashed line: level at 400 fs, which is crossed after 1000 s integration time. Solid line: model starting at 4.2 ps and averaging with $\sqrt(\tau)$, where τ is the integration time. Black squares: noise floor of the TIC.

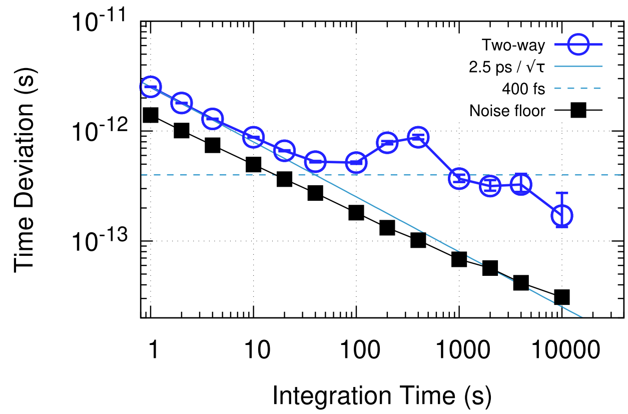

Fig. 4. Blue circles: TDEV of the best data set we acquired for two-way time transfer. The sub-ps stability threshold is crossed for 7.5 s of integration time. Dashed line: level at 400 fs, which is crossed after 1000 s integration time. Solid line: model starting at 2.5 ps and averaging with $\sqrt(\tau)$, where τ is the integration time. Black squares: noise floor of the TIC.

Fourier frequencies of the air conditioning system used in our laboratory match the characteristic period of the oscillation, according to theory [44].

The unbalanced optical paths among OC1, OC2, and OC3, as well as the fiber length difference of the two EDFAs, are sensitive to temperature fluctuations [41]. In our case, the mean delay difference measured with our method is 91 ns, which corresponds to a length imbalance of about 18 m. With a typical temperature amplitude of 1.6 K at about 560 s, and using a thermal sensitivity coefficient of 37 fs/K/m for the erbium-doped fiber, the corresponding propagation delay fluctuations is expected to value 1 ps. Yet, the TDEV remains sub-ps. Finally, after this first periodic perturbation is overcome, the TDEV is as low as 400 fs between 1000 and 10 000 s of integration time. The integration time was too short to determine whether we reach a plateau or if the TDEV can reach smaller values. Furthermore, a second periodic perturbation with a one-day period is expected to occur.

We also present our best case results, with a data set of 50 000 points, resulting in the TDEV plotted in Fig. 4. The TDEV is 2.5 ps at $\tau = 1$ s, then again decays with a rate of $\tau^{-1/2}$ until 10 s of integration time. We observe periodic oscillation with a signature of a 1000-s period due again to our air conditioning system, but the TDEV remains well below the ps level. Finally, after the periodic oscillation, the TDEV is at the level of 400 fs or below for $1000 < \tau < 10\,000$ s. The minimum TDEV reaches 160 fs at $\tau = 10\,000$ s but with significantly higher uncertainties. In this experiment, the short-term stability depends on the level of the signals and the optimization of the triggering levels of the TIC.

C. Two Way With a kPPS

In order to check this statement, we modified our setup by adding a fast comparator Analog Device ADCMP580. The input is a 1-kHz signal. The output signal is a kPPS signal, which substitutes the previous 1PPS signal before amplification. The output kPPS rise time is again about 150 ps. The TIC works then at a rate of 1 kHz. The optical modulation and demodulation stages are kept unchanged. The ability of changing the pulse rate that easily is an advantage of the two-way configuration and of the optical demodulation that we introduced in this paper.

When working at a higher signal rate, we expect to shift the limitation imposed by the single-shot resolution to lower integration times (higher Fourier frequency), which can lead in principal to a better TDEV for integration times from 1 s and longer. The results are presented in Fig. 5

At 1 ms of integration time, the TDEV is 3.9 ps, consistent with the single-shot noise resolution of the experiment. We observe a noise excess of unknown origin with a maximum at $\tau = 40$ ms. Finally, the TDEV floor of about 400 fs is reached already at $\tau = 1$ s, showing the advantage of this approach, and continues up to 200 s. To the best of our knowledge, the TDEV reported in Figs. 4 and 5 is among the best ones for a time transfer over a fiber link for an averaging time from 1 ms to 10 000 s [16], [30].

IV. Discussion

We have demonstrated here a time interval transfer with a time stability at the level of 3 ps. The behavior of the TDEV indicates that we are dominated by white phase noise until a seemingly white frequency floor at about 200–400 fs.

Better minimum TDEV than 200 fs was shown. For a short-term stability, the only comparable technique is [16]. Data in [14] and [15] are interpolated to 200 ps at 1 s of integration time. Thus compared to our previous experiment [14], we improved the short-term stability by a factor of 50 and reduced the cost of the demodulator by more than a factor of 20. We did not obverse any phase jumps as it was the case with our SATRE modems.

One can notice that such floor levels are met by several experiments using completely different technologies, signals, and processing methods [30], [45], [46].

The propagation delay fluctuations on the same free-running link are typically tens of femtoseconds at 1 s. It is only for longer integration time above hundreds of seconds at which the thermal noise of the fiber starts to dominate over the instrumental noise [47]. At this point, it is important to note that the TDEV floor would be the same either using unidirectional or bidirectional propagation, i.e., whether the

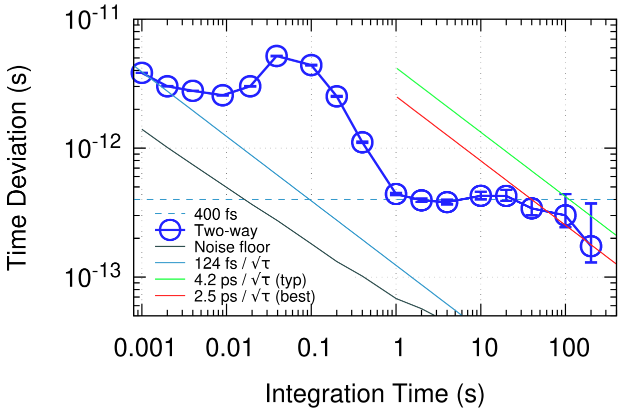

Fig. 5. TDEV of two-way time transfer using 1-kHz PPS signal. The sub-ps stability threshold is crossed for 300 ms of integration time. Dashed line: level at 400 fs, which is reached at 1 s integration time. Blue solid line: TDEV model starting at 3.9 ps and averaging with $\sqrt{(\tau)}$, where τ is the integration time. Red and green lines: models found in Figs. 3 and 4 plotted for comparison. Gray line: noise floor of the TIC as measured previously at 1 Hz, and translated in time to start at 1 ms.

round-trip is achieved on the same fiber or on two distinct fibers in the same bundle [48].

This means that for a time interval dissemination over fiber in a wide area network, largely "good enough" time services can be achieved by unidirectional propagation. On the very same fiber link of 86 km, we demonstrated recently in our group that the delay wandering can be kept to the level of 2 ps after 16 days of integration time, using a unidirectional propagation for rejecting the fiber noise [47]. So the main advantage of bidirectional propagation is the accuracy budget, as the one-way delay can be estimated accurately from the round-trip delay.

We presented here also an original method to look for the noise processes at work at higher Fourier frequencies and to improve the TDEV at 1 s. Our main motivation is the noise analysis at Fourier frequency higher than 1 Hz. The noise floor of our experiment is reached at 1 s of integration time. We believe that this method could be easily implemented in other experiments and especially in experiments such as White Rabbit, where the PPS rate is configurable from software. A common TIC used in laboratories such as the SR 620 can also be operated at 1 kHz for instance.

We show here the data for only a few tens of hours, essentially limited by the stability of the tuning of the MZI respective to the frequency of the laser. A longer data set could, in principle, be acquired with simple stabilization schemes and will be the objective for future work on this experiment. By contrast with coherent frequency transfer, we do not need an ultrastable laser to achieve these results. Indeed, the coherence length must not match any more the length of the link, but only the length mismatch of the MZI.

V. Conclusion

We have demonstrated a proof of concept experiment with sub-ps stability of the time intervals over 86 km of an urban fiber link, using optical phase modulation and phase-to-amplitude demodulation. We analyzed the stability of the time intervals. The obtained TDEV for the best case is as low as 160 fs for a data set of 50 000 s. The typical TDEV is below 400 fs for 1000 to 20 000 s of integration time. The corresponding modified Allan deviation is 3×10^{-17}. Hence, this paper opens the way to a comparison of atomic fountains, but also to a frequency transfer independent of the carrier frequency relying on an accurate time interval transfer. This paper has room for improvement, such as reducing the periodic oscillations, improving the sensitivity to temperature with reduced asymmetries, better pulse shaping, and better instrumentation. We hope to obtain much longer traces with an improved and consolidated experiment. The main challenge is to build now an uncertainty budget and make the calibration of the instruments.

Here, we also presented considerations for conducting unidirectional experiments, since the shown short-term TDEV is not limited by the fiber noise. A unidirectional scheme opens the opportunity to ps time (interval) transfer over widely deployed legacy WDM networks, at least on a regional scale.

Finally, given the sub-ps TDEVs obtained with a simple optical BPSK phase modulation of a *C*-band carrier and combined to an optical MZI demodulating scheme, this time transfer concept appears to us to be scalable to metropolitan networks in a cost-effective manner.

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Authors' contributions: F. Stefani and P.-E. Pottie designed the experiment. F. Stefani build the experiment and acquired the data. F. Frank processed the data. F. Frank and P.-E. Pottie wrote this paper. P. Tuckey and P.-E. Pottie managed the project and the contracts.

References

[1] C. Lisdat *et al.*, "A clock network for geodesy and fundamental science," *Nature Commun.*, vol. 7, Aug. 2016, Art. no. 12443. [Online]. Available: https://www.nature.com/articles/ncomms12443

[2] P. Delva *et al.*, "Test of special relativity using a fiber network of optical clocks," *Phys. Rev. Lett.*, vol. 118, no. 22, p. 221102, 2017. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.118.221102

[3] J. Guéna *et al.*, "First international comparison of fountain primary frequency standards via a long distance optical fiber link," *Metrologia*, vol. 54, no. 3, p. 348, 2017. [Online]. Available: http://stacks.iop.org/0026-1394/54/i=3/a=348

[4] N. Huntemann, C. Sanner, B. Lipphardt, C. Tamm, and E. Peik, "Single-ion atomic clock with 3×10^{-18} systematic uncertainty," *Phys. Rev. Lett.*, vol. 116, no. 6, p. 063001, 2016. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.116.063001

[5] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, "Cryogenic optical lattice clocks," *Nature Photon.*, vol. 9, no. 3, pp. 185–189, 2015. [Online]. Available: https://www.nature.com/articles/nphoton.2015.5

[6] K. Beloy *et al.*, "Atomic clock with 1×10^{-18} room-temperature blackbody stark uncertainty," *Phys. Rev. Lett.*, vol. 113, no. 26, p. 260801, 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.113.260801

[7] N. Nemitz *et al.*, "Frequency ratio of Yb and Sr clocks with 5×10^{-17} uncertainty at 150 seconds averaging time," *Nature Photon.*, vol. 10, no. 4, pp. 258–261, 2016. [Online]. Available: https://www.nature.com/articles/nphoton.2016.20

[8] S. Falke *et al.*, "A strontium lattice clock with 3×10^{-17} inaccuracy and its frequency," *New J. Phys.*, vol. 16, no. 7, p. 073023, 2014. [Online]. Available: http://stacks.iop.org/1367-2630/16/i=7/a=073023

[9] R. Le Targat *et al.*, "Experimental realization of an optical second with strontium lattice clocks," *Nature Commun.*, vol. 4, Oct. 2013, Art. no. 2109. [Online]. Available: https://www.nature.com/articles/ncomms3109

[10] C. Grebing *et al.*, "Realization of a timescale with an accurate optical lattice clock," *Optica*, vol. 3, no. 6, pp. 563–569, 2016. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=optica-3-6-563

[11] T. Ido, H. Hachisu, F. Nakagawa, and Y. Hanado, "Rapid evaluation of time scale using an optical clock," *J. Phys., Conf. Ser.*, vol. 723, no. 1, p. 012041, 2016. [Online]. Available: http://stacks.iop.org/1742-6596/723/i=1/a=012041

[12] F. Riehle, "Towards a redefinition of the second based on optical atomic clocks," *Comptes Rendus Phys.*, vol. 16, pp. 506–515, Jun. 2015. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1631070515000638

[13] J. Geršl, P. Delva, and P. Wolf, "Relativistic corrections for time and frequency transfer in optical fibres," *Metrologia*, vol. 52, no. 4, pp. 552–564, 2015. [Online]. Available: http://stacks.iop.org/0026-1394/52/i=4/a=552?key=crossref.1d01b9ee83ff7296e87e2c5e3f7cabf

[14] O. Lopez *et al.*, "Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network," *Appl. Phys. B, Lasers Opt.*, vol. 110, no. 1, pp. 3–6, 2013. [Online]. Available: https://link.springer.com/article/10.1007/s00340-012-5241-0

[15] M. Rost, D. Piester, W. Yang, T. Feldmann, T. Wübbena, and A. Bauch, "Time transfer through optical fibres over a distance of 73 km with an uncertainty below 100 ps," *Metrologia*, vol. 49, no. 6, p. 772, 2012. [Online]. Available: http://stacks.iop.org/0026-1394/49/i=6/a=772

[16] P. Krehlik, Ł. Śliwczyński, L. Buczek, J. Kołodziej, and M. Lipiński, "Ultrastable long-distance fibre-optic time transfer: active compensation over a wide range of delays," *Metrologia*, vol. 52, no. 1, p. 82, 2015. [Online]. Available: http://stacks.iop.org/0026-1394/52/i=1/a=82

[17] M. Lessing, H. S. Margolis, C. T. A. Brown, and G. Marra, "Frequency comb-based time transfer over a 159 km long installed fiber network," *Appl. Phys. Lett.*, vol. 110, no. 22, p. 221101, 2017. [Online]. Available: http://aip.scitation.org/doi/full/10.1063/1.4984144

[18] E. Samain *et al.*, "A sub-NS comparison between GPS common view and T2L2," in *Proc. Eur. Frequency Time Forum (EFTF)*, Jun. 2014, pp. 219–222.

[19] N. Chiodo, K. Djerroud, O. Acef, A. Clairon, and P. Wolf, "Lasers for coherent optical satellite links with large dynamics," *Appl. Opt.*, vol. 52, no. 30, pp. 7342–7351, 2013. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=ao-52-30-7342

[20] F. R. Giorgetta, W. C. Swann, L. C. Sinclair, E. Baumann, I. Coddington, and N. R. Newbury, "Optical two-way time and frequency transfer over free space," *Nature Photon.*, vol. 7, no. 6, pp. 434–438, 2013. [Online]. Available: https://www.nature.com/articles/nphoton.2013.69

[21] E. Samain, P. Vrancken, P. Guillemot, P. Fridelance, and P. Exertier, "Time transfer by laser link (T2L2): Characterization and calibration of the flight instrument," *Metrologia*, vol. 51, no. 5, p. 503, 2014. [Online]. Available: http://stacks.iop.org/0026-1394/51/i=5/a=503

[22] P. Exertier *et al.*, "Sub-NS time transfer consistency: A direct comparison between GPS CV and T2L2," *Metrologia*, vol. 53, no. 6, p. 1395, 2016. [Online]. Available: http://stacks.iop.org/0026-1394/53/i=6/a=1395

[23] E. Samain *et al.*, "Time Transfer by Laser Link (T2L2) in non common view between Europe and China," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, to be published.

[24] J.-D. Deschenes *et al.*, "Synchronization of distant optical clocks at the femtosecond level," *Phys. Rev. X*, vol. 6, no. 2, p. 021016, 2016. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevX.6.021016

[25] S. M. F. Raupach *et al.*, "Bi-directional optical amplifiers for long-distance fibre links," in *Proc. Joint Eur. Freq. Time Forum Int. Freq. Control Symp. (EFTF/IFC)*, Jul. 2013, pp. 883–884.

[26] O. Terra, G. Grosche, and H. Schnatz, "Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber," *Opt. Exp.*, vol. 18, no. 15, pp. 16102–16111, 2010. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=oe-18-15-16102

[27] O. Lopez *et al.*, "Cascaded multiplexed optical link on a telecommunication network for frequency dissemination," *Opt. Exp.*, vol. 18, no. 16, pp. 16849–16857, 2010. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=oe-18-16-16849

[28] C. Clivati, G. Bolognini, D. Calonico, S. Faralli, A. Mura, and F. Levi, "In-field Raman amplification on coherent optical fiber links for frequency metrology," *Opt. Exp.*, vol. 23, no. 8, pp. 10604–10615, 2015. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=oe-23-8-10604

[29] S. M. F. Raupach and G. Grosche, "Chirped frequency transfer: A tool for synchronization and time transfer," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 61, no. 6, pp. 920–929, Jun. 2014.

[30] P. Krehlik, Ł. Śliwczyński, L. Buczek, and M. Lipiński, "Fiber-optic joint time and frequency transfer with active stabilization of the propagation delay," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 10, pp. 2844–2851, Oct. 2012.

[31] O. Lopez *et al.*, "Frequency and time transfer for metrology and beyond using telecommunication network fibres," *Compt. Rendus Phys.*, vol. 16, no. 5, pp. 531–539, 2015. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01176012

[32] C. Clivati *et al.*, "A coherent fiber link for very long baseline interferometry," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 62, no. 11, pp. 1907–1912, Nov. 2015. [Online]. Available: http://ieeexplore.ieee.org/document/7321699/

[33] K. Przemyslaw *et al.*, "Remote atomic clock delivery to the VLBI station in Toruń," in *Proc. IEEE Eur. Freq. Time Forum (EFTF)*, Apr. 2016, pp. 1–3. [Online]. Available: http://ieeexplore.ieee.org/document/7477779/

[34] Y. He *et al.*, "Long-distance telecom-fiber transfer of a radio-frequency reference for radio astronomy," *Optica*, vol. 5, no. 2, pp. 138–146, 2018. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=optica-5-2-138

[35] S. Schediwy *et al.*, "Phase synchronization for the mid-frequency square kilometre array telescope," in *American Astronomical Society Meeting Abstracts #231* (American Astronomical Society Meeting Abstracts), vol. 231. Jan. 2018. [Online]. Available: http://adsabs.harvard.edu/abs/2018AAS...23121503S

[36] C. Clivati, D. Calonico, G. A. Costanzo, A. Mura, M. Pizzocaro, and F. Levi, "Large-area fiber-optic gyroscope on a multiplexed fiber network," *Opt. Lett.*, vol. 38, no. 7, pp. 1092–1094, 2013. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=ol-38-7-1092

[37] S. Schiller, "Feasibility of giant fiber-optic gyroscopes," *Phys. Rev. A, Gen. Phys.*, vol. 87, no. 3, p. 033823, 2013. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevA.87.033823

[38] C. E. Calosso *et al.*, "Frequency transfer via a two-way optical phase comparison on a multiplexed fiber network," *Opt. Lett.*, vol. 39, no. 5, pp. 1177–1180, 2014. [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=ol-39-5-1177

[39] *Kylia. MZI*. Accessed: Jan. 11, 2018. [Online]. Available: http://kylia.com/kylia/

[40] *BI200/BI201. Carmel Instrument*. Accessed: Jan. 11, 2018. [Online]. Available: http://www.carmelinst.com/Products/TIAs/BI201.aspx

[41] L. G. Cohen and J. W. Fleming, "Effect of temperature on transmission in lightguides," *Bell Syst. Tech. J.*, vol. 58, no. 4, pp. 945–951, Apr. 1979.

[42] R. L. Sydnor, M. Calhoun, J. Lopez, and W. Diener, "Stabilization of a fiber-optic link using a temperature controlled fiber segment," in *Proc. 28th Annu. Precise Time Time Interval Syst. Appl. Meeting*, 1996, pp. 163–168.

[43] D. W. Hanson, "Fundamentals of two-way time transfers by satellite," in *Proc. 43rd Annu. Symp. Freq. Control*, May/Jun. 1989, pp. 174–178.

[44] D. A. Howe, "Interpreting oscillatory frequency stability plots," in *Proc. IEEE Int. Freq. Control Symp. PDA Exhib.*, May 2002, pp. 725–732.

[45] N. Kaur, P. Tuckey, and P. E. Pottie, "Time transfer over a White Rabbit network," in *Proc. Eur. Freq. Time Forum (EFTF)*, Apr. 2016, pp. 1–4.

[46] M. Rizzi. *WRS Low Jitter Daughterboard*. Accessed: Jan. 11, 2018. [Online]. Available: https://www.ohwr.org/projects/wrs-low-jitter/wiki/experimental-results

[47] D. Xu, W.-K. Lee, F. Stefani, O. Lopez, A. Amy-Klein, and P.-E. Pottie, "Studying the fundamental limit of optical fiber links to the 10^{-21} level," *Opt. Exp.*, vol. 26, no. 8, pp. 9515–9527, 2018.

[48] A. Bercy, F. Stefani, O. Lopez, C. Chardonnet, P.-E. Pottie, and A. Amy-Klein, "Two-way optical frequency comparisons at 5×10^{-21} relative stability over 100-km telecommunication network fibers," *Phys. Rev. A, Gen. Phys.*, vol. 90, no. 6, p. 061802, 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevA.90.061802

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