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Effect of a timebase mismatch in two-way optical frequency transfer

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Abstract

Two-way frequency transfer on optical fibers is a powerful technique for the comparison of distant clocks over long and ultra-long hauls. In contrast to traditional Doppler noise cancellation, it is capable of sustaining higher link attenuation, mitigating the need of optical amplification and regeneration and thus reducing the setup complexity. We investigate the ultimate limitations of the two-way approach on a 300 km multiplexed fiber haul, considering fully independent setups and acquisition systems at the two link ends. We derive a theoretical model to predict the performance deterioration due to a bad synchronisation of the measurements, which is confirmed by experimental results. This study demonstrates that two-way optical frequency transfer is a reliable and performing technique, capable of sustaining remote clocks comparisons at the 10^{-19} resolution, and is relevant for the development of a fiber network of continental scale for frequency metrology in Europe.

Keywords: fiber frequency transfer, optical clocks comparisons, fiber links, phase noise measurements, optical phase post-processing

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, the transfer of optical frequencies via phase-stabilized telecom fibers has proved to be the most performing technique to compare distant frequency standards, allowing uncertainties below the mid 10^{-19} level [1–4] and enabling remote comparisons of optical clocks over thousands of kilometers at their intrinsic level of accuracy [5, 6].

The frequency dissemination over fiber relies on the so-called Doppler noise cancellation scheme, where an ultrastable laser at telecom wavelength is delivered to a remote laboratory and partly reflected back. The round-trip signal is compared to the original one in order to detect and compensate the additional phase noise due to environmental-induced fiber length variations. So far, the best performances in terms of noise cancellation have been obtained when the same

optical fiber is used in the two directions (hereafter we will refer to it as 'bidirectional fiber'), instead of using two parallel fibers as in standard telecommunications systems. One of the main issues when moving to long and ultra-long bidirectional fibers is the optical attenuation after a round-trip and several approaches have been proposed to deal with it. The simplest in terms of implementation is using a cascade of bidirectional erbium doped fiber amplifiers (EDFAs). However, the build-up of amplified spontaneous emission (ASE) deteriorates the optical signal-to-noise ratio (SNR) and causes saturation of the gain [7]. In most implementations the link attenuation cannot be completely compensated, resulting in sub-μW power on the round-trip laser signal and, as a consequence, weak beat-note amplitude. Moreover, chains of optical amplifiers have been reported to add significant amplitude instability. In contrast, fiber brillouin amplification (FBA) provides higher gain and a lower noise floor; however, the FBA gain bandwidth is <20 MHz, hence the amplifiers pumps have to be locked to the signal increasing the setup complexity [8]. Cascaded links where the optical carrier is regenerated at intermediate
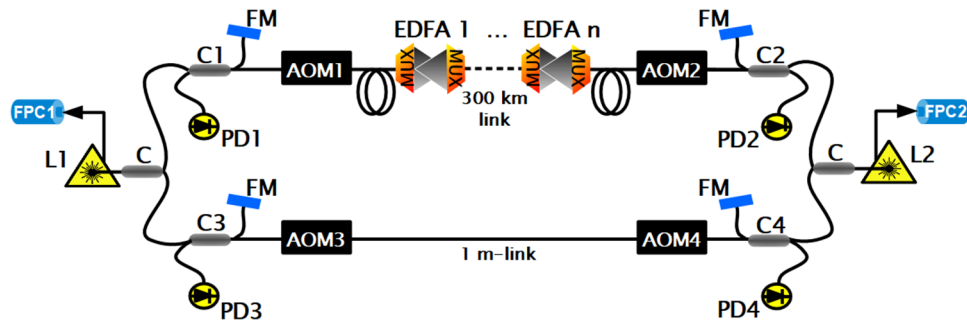
Figure 1. Experimental setup for frequency comparison. L, lasers; FPC, Fabry–Perot cavities; C, fiber couplers; FM, Faraday mirrors; PD, photodiode; AOM, acousto-optic modulators; EDFA, erbium-doped fiber amplifiers; MUX, dense wavelength division multiplexing filters.

shelters [9] and optical injections [10] may be valid alternatives. However, also in these cases, the setup complexity is increased.

An alternative solution to mitigate the effect of optical attenuation without increasing the link complexity is based on a two-way transmission [11]. It consists in sending two ultrastable laser signals along the same fiber in opposite directions. At each end, a beatnote between the local and the fiber-delivered signal is detected. By postprocessing the data, it is possible to reject the noise contribution of the link, which is partly common on the two counterpropagating signals, and to recover the optical sources' relative phase or frequency noise. Preliminary demonstrations of this technique were performed on short links with both ends in the same laboratory, using a single laser and sharing the acquisition apparatus [11, 12]. These experiments highlighted the potential of this technique and demonstrated the fundamental concepts. To overcome the issue of data exchange between remote laboratories and improve the link performances, a 'local' two-way scheme [13] and other post-processing techniques [14] have also been proposed. These schemes combine the two-way approach with the Doppler noise cancellation to avoid the need of an external synchronisation. However, they require the detection of a round-trip signal: this increases the setup complexity without taking advantage of the single-pass transmission, one of the most impacting operational features of the two-way technique.

Our purpose is to investigate the ultimate limit of the two-way frequency transfer in its most simple implementation on a realistic testbed. In particular, we used two completely independent experimental setups at the link ends, i.e. two transfer lasers and separate acquisition systems, to fully resemble a frequency comparison between remote laboratories. We show that in these conditions the data acquisition requires hardware-synchronization at the same level as the propagation time of light into the fiber, which is generally of the order of some milliseconds. In previous works [11], data interpolation had been proposed to process unsynchronised data and to compensate the effect of a timebase mismatch, however, we show that this approach is not effective, and would deteriorate the ultimate instability by orders of magnitude.

We performed a theoretical and experimental study. The tesbed was a pair of 150 km fibers, deployed between Torino and the French border and equipped with bidirectional EDFAs,

where the net single-trip loss amounts to 36 dB. We stress that on this link, considering the optical attenuation and the amplifiers shelters location, nor the active noise cancellation scheme, nor the 'local' two-way scheme could be implemented, unless a signal regeneration stage is introduced at the remote end. By contrast, the two-way transmission can be successfully employed. The experimental results demonstrate that the two-way technique and its performances are effective and robust, able to support long-haul remote clocks comparisons. Hence, we plan to implement it in the forthcoming 1700 km, dense-wavelength division multiplexed (DWDM) link between the Italian National Metrology Institute (INRIM) and the French homologue (LNE-SYRTE).

2. Experimental setup

Our experiment uses a couple of 150 km-long buried fibers, placed in the same cables between INRIM and the Laboratorie Souteraine de Modane (LSM) on the Italy–France border. The two fibers are joined together at LSM to obtain a 300 km loop with both ends at INRIM. This has been done for convenience, nevertheless two completely independent setups for signal detection and data acquisition have been realized. Our testbed is based on a looped configuration with both ends in the same laboratory and the signal travelling on two parallel fibers. The noise of the two fibers is partially correlated as the fibers are placed in the same cable: hence, the residual noise after processing is two orders of magnitude lower than for a real link where the two end points are spatially separated. However, this does not affect data acquisition and allows us to investigate the ultimate resolution of this technique. On both fibers, mixed dense- and coarse-wavelength division multiplexing transmission is implemented (14 km and 286 km respectively) where channel 44 of the ITU grid is dedicated to our experiment. The total loss of the fiber is 105 dB, as the metropolitan spans have significantly high losses and reflections at the connectors. Five EDFAs are used as intermediate amplification stages, reducing the uncompensated loss to 36 dB.

The experimental setup is shown in figure 1. We use two ultrastable lasers (L1, L2), locked to two high-finesse Fabry–Perot cavities. Both lasers are loosely phase-locked to an H-maser using a frequency comb, to ensure long-term frequency variations $y < 10^{-15}$. An ultimate frequency instability on the remote comparison of the order of $\dot{y}\delta$ had been

observed otherwise, being δ the link delay. In our case, with a drift of roughly 0.1 Hz s^{-1} and $\delta = 1.5$ ms, we observed a frequency offset at the level of $\sim 10^{-18}$.

The lasers are launched in the fiber in opposite directions. At both ends, couplers C1 and C2 are used to produce the beatnotes between local and remote lasers (bn1 and bn2 respectively). Two acousto optic modulators (AOM) shift the laser frequencies at each pass, to distinguish the signal from stray backreflections. We carefully isolated the couplers into two separate boxes to reduce noise on uncommon fiber branches. The beatnotes are detected with low-noise photodiodes and redundantly tracked with voltage-controlled oscillators, for cycle slips detection. To maximize the SNR, the polarization between local and remote laser is occasionally optimized using a manual polarization controller.

The phase variations of each beatnote can be written as:

$$\phi_{\text{bn1}}(t) = \phi_{L1}(t) - (\phi_{L2}(t) - \phi_{\text{link2}\rightarrow1}(t)) \qquad (1)$$

$$\phi_{\text{bn2}}(t) = \phi_{L2}(t) - (\phi_{L1}(t) - \phi_{\text{link1}\rightarrow2}(t)) \qquad (2)$$

where $\phi_{L1}(t)$ and $\phi_{L2}(t)$ represent the lasers contributions, while $\phi_{\text{link1}\rightarrow2}(t)$ and $\phi_{\text{link2}\rightarrow1}(t)$ are the contributions of the link in the two directions. By subtracting equations (1) and (2) (time dependence neglected for the sake of clarity):

$$\phi_{\text{bn1}} - \phi_{\text{bn2}} = 2(\phi_{L1} - \phi_{L2}) - \phi_{\text{link1}\rightarrow2} + \phi_{\text{link2}\rightarrow1} \qquad (3)$$

the correlated part of the fiber phase noise between forward and backward propagation cancels, limited by the propagation delay. Thus we can retrieve the uncorrelated phase noise together with the relative phase variations of the lasers.

In order to remove the lasers contribution and evaluate the residual noise of the system, we generate two additional beatnotes (bn3 and bn4) using a second pair of couplers (C3 and C4) linked by a short patchcord. Its noise contribution is cancelled out by performing the difference between bn3 and bn4, whose final expression is:

$$\phi_{\text{bn3}} - \phi_{\text{bn4}} = 2(\phi_{L1} - \phi_{L2}) \qquad (4)$$

which is used to cancel the laser noise:

$$\phi_{\text{link}} = (\phi_{\text{bn1}} - \phi_{\text{bn2}}) - (\phi_{\text{bn3}} - \phi_{\text{bn4}}) = -\phi_{\text{link1}\rightarrow2} + \phi_{\text{link2}\rightarrow1}. \qquad (5)$$

For the sake of clarity we remind that this is the residual noise contribution of the fiber link, whose power spectral density (PSD) has been evaluated as [11]:

$$S_{\phi,\text{diff}}(f) = \frac{1}{3}(2\pi\delta f)^2 S_{\phi,\text{fiber}}(f), \qquad (6)$$

in the limit of low frequencies, where $S_{\phi,\text{fiber}}(f)$ is the PSD of the one-way fiber noise and $\delta = \frac{n \cdot L}{c}$ is the link delay, with n the refractive index of the fiber and L its length. According to equation (3), when comparing two optical signals, this contribution is further divided by a factor of four.

In practice, we deal with sampled signals and shall assume that, if acquisitions are not synchronized, we cannot associate the same timestamps to the two data series and directly perform the subtraction. Hence, one of the two sampled series would need to be interpolated and recalculated on a common timebase. The sampled form of bn1 and bn2 can be written as

$\phi_{\text{bn1,k}} = \phi_{\text{bn1}}(t_0 + k\tau)$ and $\phi_{\text{bn2,k}} = \phi_{\text{bn2}}(t_0 + \Delta + k\tau)$ with $k \in \mathbb{N}$, where τ is the gate-time of the acquisition, t_0 is an arbitrary origin and Δ is the delay between the two acquisitions. The re-interpolated values of bn1 on the timebase of bn2 is:

$$\phi'_{\text{bn1,k}} = \frac{\Delta}{\tau}\phi_{\text{bn1,k+1}} + \left(1 - \frac{\Delta}{\tau}\right)\phi_{\text{bn1,k}} \qquad (7)$$

bn3 and bn4 are sampled on the same timebase as bn1 and bn2 respectively. Thus they are subtracted before performing the interpolation and they have been neglected here for simplicity. Equation (5) thus becomes:

$$\phi_{\text{link}}(t_0 + \Delta + k\tau) = \frac{\Delta}{\tau}\phi_{\text{bn1,k+1}} + \left(1 - \frac{\Delta}{\tau}\right)\phi_{\text{bn1,k}} - \phi_{\text{bn2,k}} \qquad (8)$$

and using the standard relations of Fourier calculus, we obtain the power spectral density of the residual link noise in a two-way scheme where timebase mismatch is considered:

$$S_{\phi,\text{interp}}(f) = \left|\frac{\Delta}{\tau}\left(\exp^{-\text{i}2\pi f\tau} - 1\right) - \left(\exp^{-\text{i}2\pi f\Delta} - 1\right)\right|^2 S_{\phi,\text{fiber}}(f), \qquad (9)$$

where $S(f)_{\phi,\text{fiber}}$ is the phase noise of the uncompensated fiber. It can be seen that the residual link noise depends both on the gate time of the data sampling τ and on the temporal mismatch of the acquisitions at the two fiber ends Δ, which is assumed to be constant. As expected, when Δ is of the same order of magnitude of the propagation delay $\delta = nL/c$, this contribution is comparable to the delay-limited noise expressed by equation (6) at Fourier frequencies $f \gtrsim \tau^{-1}$, while it is negligible at lower frequencies. On the contrary, when $\Delta > \delta$, this contribution becomes the dominant one and we stress that it cannot be neglected even if Δ is known precisely. A high sampling frequency, though sometimes unpractical, mitigates this effect. A solution to this problem is to trigger each counter with an external PPS of adequate performances, as available in most laboratories.

We note that we repeated the analysis with more sophisticated interpolation algorithms, specifically a sinc interpolation. However, the computational time increased by orders of magnitude without a significant improvement in the performances, as we obtained a maximum increase in stability of 20–30%. Therefore, we considered linear interpolation as the best trade-off between performances, computational time and easiness of modelling.

3. Experimental results

We show the results obtained on the 300 km test-bed, comparing measurements with and without external trigger. We acquired the beatnotes phase on two independent, dead-time-free phase/frequency counters, one for each side of the link. Figure 2 shows the phase noise PSD of each of the beatnotes between local and fiber-delivered light measured at opposite ends (red line) and of their difference evaluated from PPS-synchronized measurements (blue line). This noise is two orders of magnitude lower than expected from equation (6), since our test-bed is based on two parallel fibers. This is compatible with previous phase-noise measurements we
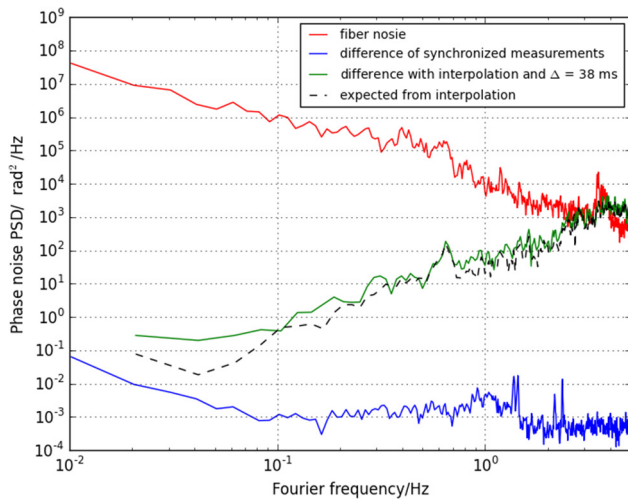
Figure 2. PSD of the fiber noise (red, uppermost), of the beatnotes difference with synchronised measurements (blue, lowermost) and with non-synchronised, interpolated measurements when $\Delta = 38$ ms (green); the black dashed line shows the expected noise contribution of interpolation.

Figure 3. Fractional frequency instablity, expressed in terms of Allan deviation, of the beatnote difference obtained without external PPS for different delay values (Δ) between the two counters.

Figure 4. Fractional frequency instablity, expressed in terms of Allan deviation, of the beatnote difference taken with the 300 km link triggering the counters with external PPS.

performed on each of the 150 km fibers, that showed correlation between the two. Indeed, the PSD of the phase-difference between the signals transmitted through the two fibers was 20 dB lower than the PSD of the signal transmitted through each of them in the Fourier frequency range between 0.1 Hz and 100 Hz. This does not affect the results reported here, which aim at determining the ultimate performances of a two-way scheme.

The green spectrum represents the beatnote difference between unsynchronized measurements, where the delay was determined by cross-correlation and data on one counter were interpolated to align the two timebases. Incidentally, we note that for unsynchronized measurements the cross-correlation is never as high as for synchronized measurements; this is a consequence of equation (7). A good agreement is observed with the expected noise as evaluated from equation (9) (black dashed line). The noise is several orders of magnitude higher than that of synchronized measurements, especially at high frequencies.

We stress that high frequency noise is responsible for an increase of the link instability even at long averaging times [15] when the Allan deviation is used as an estimator. This is due to the fact that the Allan deviation cannot improve faster than t_a^{-1}, where t_a is the measurement time, therefore the only way to mitigate this effect is to dramatically reduce the measurement bandwidth. As the high-frequency noise contribution increases, more selective filters are needed, which usually require additional computational effort. Therefore, a commonly used compromise, which we also exploit in this work, is to rely on a simple-averaging filter: this is obtained using phase/frequency counters in the so-called 'averaging' mode, or Λ-mode.

In figure 3 we show the Allan deviation calculated from phase samples obtained using a commercial counter in Λ-mode with a gate time of 100 ms; we considered multiple acquisitions where Δ assumed different values and we
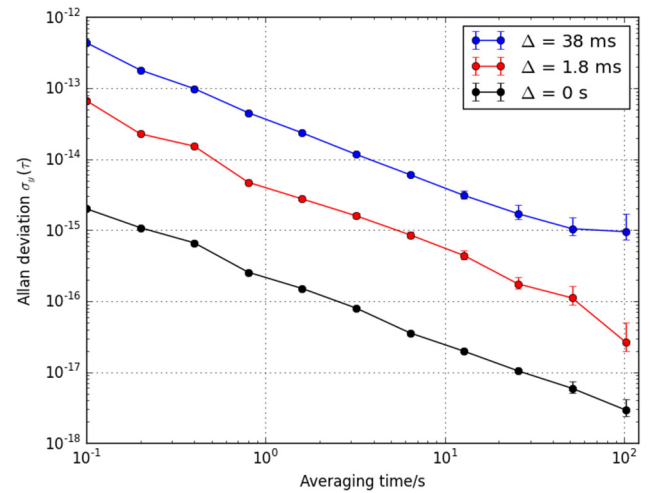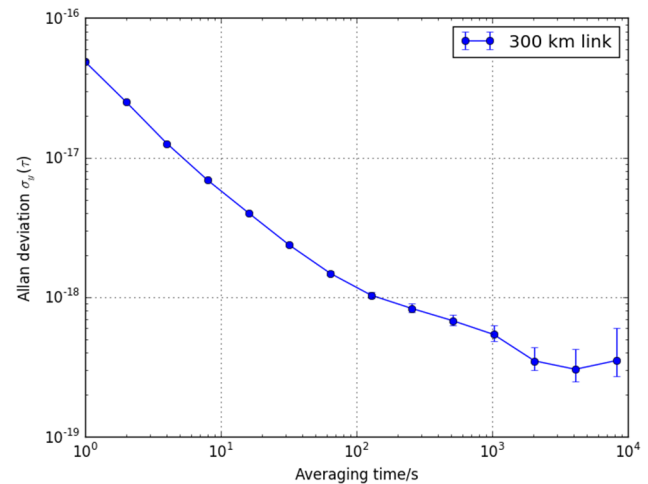
interpolated data following the approach detailed in section 2. The measurement noise depends on Δ as shown in equation (9) and we calculated it for the various acquisitions. We then calculated the Allan deviation corresponding to a noise of type $S_\phi(f) = h_2 f^2$:

$$\sigma_y^2(\tau) = \frac{h_2 f_H^3}{4\nu_0^2 \pi^2} \cdot t_a^{-2} \tag{10}$$

where f_H is the measurement bandwidth, ν_0 is the absolute frequency of the laser and t_a is the averaging time. Merging equations (9) and (10), it is straightforward to derive $\sigma_\Delta(t_a)/\sigma_0(t_a)$, in agreement with the results shown in figure 3.

Figure 4 shows the instability of the two-way frequency transfer over a 300 km link when the acquisition systems are hardware-synchronised to an external PPS. We removed two cycles-slips from the whole measurement, detected by redundant counting. A deviation from the t_a^{-1} slope is observed on the Allan deviation for $t_a > 100$ s, and this two-way implementation achieves an ultimate stability of

3×10^{-19} in 10^4 s. The interferometers noise floor accounts for an instability of $\sim 1 \times 10^{-19}$, which was measured by replacing the long link with a fixed attenuator. The 3×10^{-19} limit is attributed to polarization mode dispersion along the fiber link and is considered as the link ultimate uncertainty. No frequency shifts have been measured within this uncertainty.

4. Conclusions

We implemented an optical two-way transfer technique on a 300 km testbed using two completely independent setups for light transmission and data acquisition, which enabled us to investigate the ultimate technical limits of the technique. Under typical operating conditions, the link contribution to the instability can be rejected down to an ultimate level of 3×10^{-19}. We showed that similar results can only be obtained if the measurements are hardware-synchronized and that interpolation is not enough to recover the optimal performances. The limit of our setup is beyond the accuracy achieved by the best optical clocks, making it appropriate for metrological purposes.

As a last remark, we note that this approach for evaluating the effect of synchronization and interpolation can be adopted for modelling the signal processing in related problems, such as multi-clocks fiber-based remote comparisons. In fact, different pair-wise clocks comparisons where at least one of the clocks is common can be combined to retrieve comparisons between frequency standards which are not directly linked. This point is receiving much interest, motivated by the development of a fiber-based network between European NMIs. However, the amount of phase noise which affects the pair-wise measurements may not be negligible as compared to the intrinsic clocks noise at high Fourier frequencies, and its contribution must be considered carefully.

Acknowledgements

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