

Improving Accuracy of Optical Frequency Transfer Over Non-Modified DWDM Optical Networks

Przemysław Krehlik , Krzysztof Turza , Łukasz Śliwczyński , and Kamila Lewandowska

Abstract—Dedicated fiber links become the most precise and desirable means of transferring optical frequency at distances up to a few thousand kilometers. However, the need of installing special equipment along the link, and usually renting fibers exclusively for this use, cause that this preferable solution is cumbersome and expensive, and so accessible in severely limited range. In this paper we propose a method which improves the frequency transfer quality when only a standard (i.e., not modified for this purpose) DWDM optical telecommunication network is available. The proposed solution is based on the correlation identified between the residual phase noise present in a DWDM-based optical frequency transfer and the in-loop phase correcting signal, which can be easily registered and used for improving the transfer accuracy by means of data post-processing. As we demonstrated, using the proposed method the frequency comparison uncertainty can be reduced to below 1×10^{-16} for links up to 1500 km long.

Index Terms—DWDM networks, link asymmetry, optical clock comparisons, optical frequency transfer.

I. INTRODUCTION

THE main factors limiting stability and accuracy of the optical frequency transferred via an optical fiber are acoustic noise picked up along the fiber and temperature changes which affect both the physical length and the refractive index of the fiber. In the context of clock comparisons the influence of the acoustic noise is less significant, as it can be efficiently reduced by averaging of registered phase/frequency data. More severe is impact of temperature, which is generally not periodic and contains long-lasting trends which cannot be reduced by averaging.

A well-established solution for overcoming this limitation is based on bidirectional signals exchange in a single fiber.

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In this situation the phase noise (called alternatively as phase fluctuation) picked-up in the forward and backward directions is nearly perfectly matched one to the other, and therefore the impact of this noise can be efficiently canceled out in a feedback scheme [1], [2], [3]. Applying optical amplifiers, as bidirectional erbium-based amplifiers [4], Raman amplifiers [5] or Brillouin amplifiers [6], and repeater laser stations [7], [8] allows to extend the distance of frequency transfer to more than 1000 km [9], [10], [11]. The residual instability of the frequency transfer, even for long links, drops below 1×10^{-19} for moderate observation time (some thousands of seconds) [10], [12], [13]. The bidirectional scheme of frequency transfer is however very demanding in terms of installation effort, equipment, and mostly the need of access to dedicated fiber, which must be devoted by network operators for bidirectional signal flow. Therefore, after many years of efforts, there is still a limited number of permanent long-distance links (networks) carrying bidirectional frequency transfer [10], [14], [15], [16], [17], [18]. Many laboratories related to optical clock development, and other users needing ultra-accurate optical frequency reference still have no alternative for GNSS-based frequency transfer, which could offer the uncertainty at the level of 10^{-16} only after very long averaging, and requires using proprietary algorithms for resolving phase ambiguity [19], [20], [21], [22].

In this situation adopting dense wavelength division multiplexing (DWDM) telecommunication networks to the needs of the optical frequency transfer seems to be an attractive solution. One option, giving practically the same stability and accuracy of frequency transfer as in dedicated fibers, relies on isolating a piece of optical spectrum in the fibers carrying the regular data transmission, and arranging the bidirectional frequency transfer “in parallel” to unidirectional data transmission [14], [23]. As this method implies hardware modifications of the infrastructure (installing additional add-drop filters and bidirectional amplifiers), the DWDM network operators are extremely rarely open for adopting this scheme.

A different solution, generally accepted by the network operators, relies on a so-called “alien lambda” service, i.e., renting a piece of spectrum in standard, unmodified DWDM infrastructure. In this situation, however, the bidirectional signals flow in a single fiber is not further possible, and is substituted with two parallel, but physically different, unidirectional optical paths for “forward” and “backward” propagating signals - see Fig. 1. Phase noise cancellation is still possible, but is less effective because the matching between the forward and backward direction noise is not as strict as in a single fiber. The work presented in this

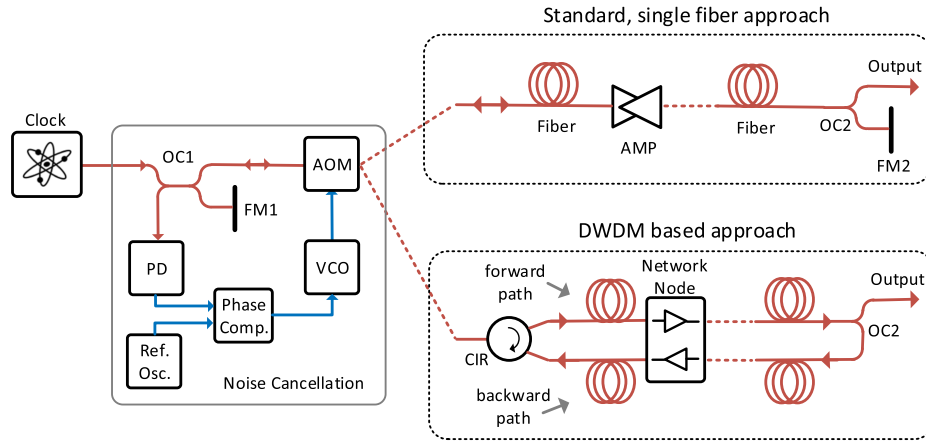


Fig. 1. Actively stabilized frequency transfer in a single fiber and in a DWDM network. OC stands for optical circulator, AOM - acousto-optic modulator, PD - photodiode, FM - Faraday mirror, VCO - voltage controlled oscillator.

paper is oriented on minimizing the impact of this compromise approach on accuracy of the frequency transfer.

From the practical point of view using standard DWDM telecommunication network instead of dedicated links is very attractive. The costs are dramatically reduced because the frequency transfer occupies only one channel (usually a 50 GHz or 100 GHz spectrum slot) in the fiber pair carrying normal data traffic. Optical amplification is carried out in network nodes without the need for additional equipment, and management and maintenance are covered by a telecom network operator without extra effort. Moreover, optical paths in nowadays DWDM networks are remotely (re)configurable, and may be established (and paid for) only for needed time periods.

II. PROPAGATION ASYMMETRY IN DWDM NETWORK

The commonly used method for phase/frequency noise cancellation in fiber-based frequency transfer is to stabilize the round-trip optical phase in a closed-loop arrangement, with an acousto-optic modulator (AOM) used for introducing phase corrections for signal passing in both directions. It may be shown that in case of a full symmetry of the forward and backward phase noise, this also leads to cancellation of the remote-side noise, which is our goal. In the DWDM-based approach, some asymmetry originates from the separate forward and backward optical paths in the optical amplifiers and routing devices located in the network nodes, and not fully identical phase fluctuations observed for fibers used in the forward and backward directions between the nodes, despite the fact that these fiber pairs are located in the same cable and are exposed to the same environmental conditions [2], [3], [24]. This asymmetry may be expressed as differential phase fluctuation, being the difference between the forward and backward fluctuation. It may be noticed that when the round-trip fluctuation (i.e., sum of the forward and backward ones) is compensated with the AOM (see Fig. 1), a half of the differential fluctuation is still present at the output (see (4) below), forming the limit of frequency transfer stability.

In the network nodes the differential phase noise is mainly caused by air conditioning, working usually in an on-off mode,

with the air blowing in some particular places and individual equipment fans being started and stopped occasionally. This leads to non-equal, time-varying temperature patterns within the network devices installed along the forward and backward paths. The temperature patterns in the nodes are generally periodic and not mutually correlated [25], so the resulting phase/frequency fluctuations are limited and can be efficiently reduced by averaging [26].

Regarding the pair of fibers located in the same outdoor cable, the long-term differential phase fluctuations were observed in all examined node-to-node cable sections and also long routes going through many nodes [26]. The effect is visible in both soil-buried and aerial suspended cables. The fundamental empirical observation, underlying the method proposed in this paper, is that the differential phase fluctuation is well correlated with the round-trip fluctuation. The intensity of the differential fluctuation related to the round-trip fluctuation as we experimentally observed is usually 0.1% to 1.5% [26]. The physical background behind the differential phase fluctuation is not clear, and up to the authors' knowledge is not sufficiently explained till now. Our laboratory-scale experiments show that it vanishes after removing the primary coatings (i.e., the acrylic coating deposited directly on the fiber cladding) from both fibers. This observation suggests that the primary coating (which is not precisely controlled in terms of its thickness, chemical composition and hardening process) generates a temperature dependent stress upon the fiber, which apparently is not identical for fibers from different production runs. Relating this observation to long-haul fiber installations, it may be noticed that different tubes and fibers are color-marked in cables, and fibers in consecutive cable pieces are spliced methodically, i.e., the fibers forming long spans are spliced preserving the color code used by the manufacturer to mark individual fibers inside the cable. This reduces the randomization of segments, and may explain why differential fluctuations are clearly visible even for very long links.

An important matter in our discussion is the similarity of temperature fluctuations affecting different parts of a long fiber link. In case of soil-buried cables its temperature changes slowly,

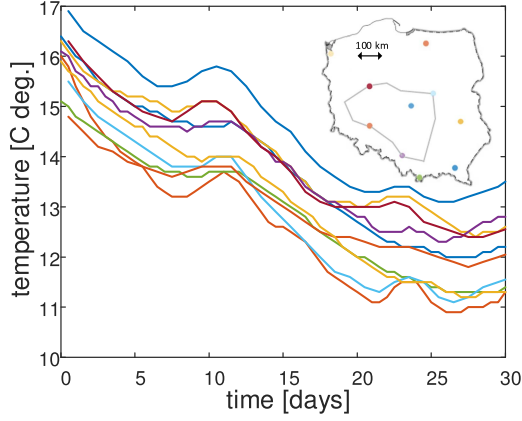


Fig. 2. Soil temperature registered 1 m below the surface in October 2024. In the inset locations of the weather stations are marked. Among others, the data from Tatra mountains region (Zakopane) and close to Baltic sea (Szczecin) are included. The gray outline represents the fiber route.

with many days lasting trends, and very low diurnal oscillations. Therefore, it is affected mainly by long-term (lasting for many days) weather trends, which are usually quite similar even for extensive area - see Fig. 2. For numerical description of temperature fluctuation similarities we calculated the correlation coefficient between the mean value of all registered temperatures, and data from particular weather stations. The correlation was surprisingly high - in the range from 0.988 (Szczecin vs. mean) to 0.998 (Wroclaw vs. mean). The fact that temperature conditions are similar along the entire link causes that differential fluctuation, accumulated along the segments displaying not necessarily similar characteristics in terms of asymmetry, is still well correlated with the round-trip fluctuation - see Fig. 6 and also [24], [26], [27], [28].

The observations described above may be summarized in a simple model relating the phase fluctuations for forward and backward fibers $[x_{NF}(t)$ and $x_{NB}(t)]$. The above mentioned asymmetry may be represented by the equation:

$$x_{NB}(t) = (1 + m)x_{NF}(t), \quad (1)$$

where m is a small mismatch parameter, specific for each particular pair of fibers. Here and further we describe phase in time units, i.e., $x(t) = \varphi(t)/(2\pi\nu_0)$, where $\varphi(t)$ is phase in radians, and ν_0 is the nominal optical frequency [29]. Consequently,

$$x_{NF}(t) - x_{NB}(t) = -\frac{m}{2+m}[x_{NF}(t) + x_{NB}(t)], \quad (2)$$

which reflects the observed correlation between the differential and round-trip phase fluctuations. The mismatch parameter m in the above equation is the value accumulated (averaged) along the link, and we do not assume that the local asymmetry (local m) is necessarily constant along the entire route. It should be stressed however that the usefulness (accuracy) of the relation (2), with m averaged along the link, rely on the assumption that temperature fluctuations affecting the consecutive pieces of the link are well correlated.

III. PROPOSED IMPROVEMENT OF FREQUENCY TRANSFER ACCURACY

Let us consider a clock comparison scheme as depicted in Fig. 3. The optical frequency of the Clock A is transmitted via a stabilized link arranged with two parallel optical paths in a DWDM network. The phase evolution of Clock A referred to a nominal frequency is represented by x_{CLOCK_A} , so corresponding time derivative is the fractional frequency offset. (The linear phase slope resulting from the frequency offset introduced naturally by the phase noise cancellation setup is omitted as being unimportant in further considerations.) Clock B, characterized by its own frequency offset is represented by corresponding x_{CLOCK_B} evolution. The optical signal produced by Clock A is transferred to the remote side of the link. By beating the remote copy of Clock A with Clock B at photodiode PD2, the mutual phase evolution (frequency difference) of the two clocks can be obtained, which is however corrupted by an error x_{ERR} , resulting from imperfect cancellation of the link noise. Please note that all phase evolutions are analyzed and registered in the time domain, which however will not be written *explicite* in the further considerations.

As the noise cancellation loop stabilizes the round-trip phase, i.e.,:

$$x_{AOM} + x_{NF} + x_{NB} + x_{AOM} = 0, \quad (3)$$

the remote phase error may be calculated as:

$$x_{ERR} = (x_{NF} - x_{NB})/2. \quad (4)$$

Consequently, the raw result of clocks comparison, i.e., x_{COMP} registered at the remote end of the link (see Fig. 3) is affected by x_{ERR} :

$$x_{COMP} = x_{CLOCK_A} - x_{CLOCK_B} + x_{ERR} = x_{AB} + x_{ERR} \quad (5)$$

Although the true x_{ERR} cannot be directly measured, it can be estimated basing on (2) and (3), and the evolution of x_{AOM} measured at the local side of the link:

$$x_{ERR_EST} = -\frac{m}{2+m}x_{AOM}. \quad (6)$$

Therefore one may correct the measured x_{COMP} by subtracting the estimated error:

$$x_{COMP_COR} = x_{COMP} - x_{ERR_EST} = x_{COMP} + \frac{m}{2+m}x_{AOM}. \quad (7)$$

Consequently, the estimate of the fractional frequency difference between clocks, y_{AB} , may be calculated as:

$$y_{AB_EST} = \Delta x_{COMP_COR} / \Delta t \\ = \left(\Delta x_{COMP} + \frac{m}{2+m} \Delta x_{AOM} \right) / \Delta t, \quad (8)$$

where Δt is the time interval, over which the changes Δx_{COMP} and Δx_{AOM} are taken. The time evolution of x_{COMP} and x_{AOM} can be directly registered with standard phase/frequency recorder, but still the challenge is to find the correct value of the mismatch parameter m .

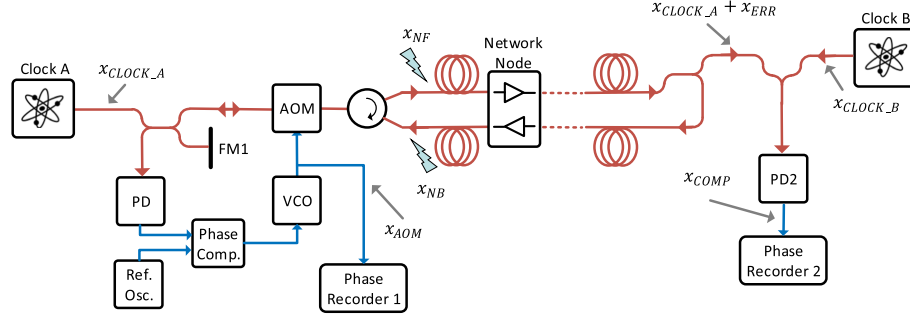


Fig. 3. Scheme of clock comparisons with additional phase recorder at the AOM electrical port.

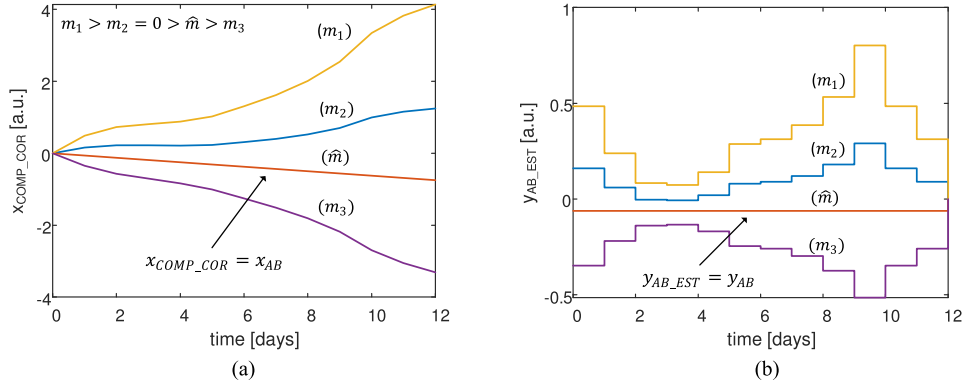


Fig. 4. Illustration of searching for proper value of the mismatch parameter m . Plot (a) shows corrected mutual phase evolution, and (b) the resulting fractional frequency difference calculated on a daily basis.

Our idea how to determine the value of m is based on the observation, that a “true” fractional frequency difference of the clocks produces a linear trend in x_{COMP} , whereas the phase error x_{ERR} generally adds to x_{COMP} both linear and nonlinear components. Therefore the nonlinear component, when observed in the x_{COMP} evolution, is a “watermark” of the mismatch of the forward and backward fibers, and would vanish in the corrected phase data x_{COMP_COR} for properly chosen m , as illustrated in Fig. 4(a) by the red line. This means that the estimation of fractional frequency difference y_{AB_EST} , calculated day-by-day, becomes constant and equal to the true frequency offset of the clocks, as shown in Fig. 4(b). It should be stressed that whereas only the nonlinear component of phase error x_{ERR} is useful for determining the mismatch parameter m , properly chosen m placed in (7) allows to correct both linear and nonlinear components of the phase error introduced by the forward/backward mismatch.

As our model described by (1) and (2) is only an approximation of a real situation, in practice the spreading of day-by-day calculated values of y_{AB_EST} does not vanish completely for any value of m . In this situation the best possible estimate of m (marked by $\hat{m}$) can be found by minimization of the standard deviation of $y_{AB_EST}^{i,m}$ series, i.e.,

$$\sigma_{y_{AB}}(\hat{m}) = \min(\sigma_{y_{AB}}(m)), \quad (9)$$

where $\sigma_{y_{AB}}(m)$ is calculated as follows:

$$\sigma_{y_{AB}}(m) = \sqrt{\frac{1}{I-1} \sum_{i=1}^I \left(y_{AB_EST}^{i,m} - \overline{y_{AB_EST}^{i,m}} \right)^2}. \quad (10)$$

In the above equation i is the index of consecutive days of the measurement period, and I is the length of this period.

IV. EXPERIMENTAL RESULTS

For practical evaluation of the method we arranged a 1500 kilometer link within the Polish scientific network PIO-NIER. The link was configured as a geographical loop with both ends accessible in the same location (Poznan Supercomputing and Networking Center). Measurements of the phase fluctuations were conducted continuously for 51 days in September and October 2024. Instead engaging a full optical clock arrangement, we used a laser source locked to an ultra-stable cavity (which may be regarded as a clock flywheel). The setup allowed direct measurement of phase fluctuations x_{NF} , x_{NB} , and (with a separate recorder channel) its difference $(x_{NF} - x_{NB})$ - see Fig. 5. The redundant $(x_{NF} - x_{NB})$ measurement was used for data validation, especially detection of potential cycle slips. The AOM was used for defining the nominal frequency of the beat note (40 MHz) at all photodiodes. We also added a polarization controllers (PC) to avoid vanishing of the beat notes caused by uncontrolled polarization wandering. The beat-note

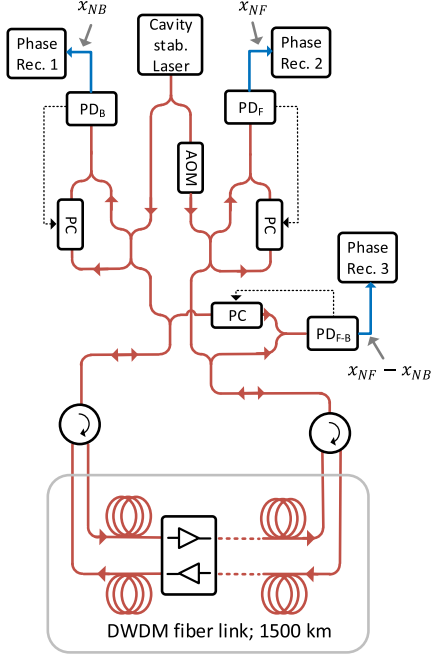


Fig. 5. Measurement setup used for long-term registration of the phase fluctuations in the DWDM link.

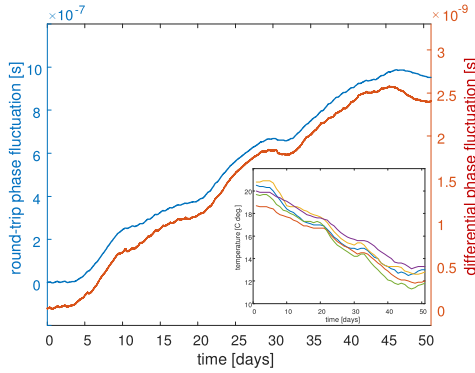


Fig. 6. Long-term round-trip and differential phase fluctuations. In the inset the soil temperature registered by five weather stations along the link route. Note different vertical scales for round-trip and differential fluctuations.

frequencies were registered with 1 s resolution, in the Λ -mode. The results are shown in Fig. 6, where one may notice the expected correlation between the round-trip ($x_{NF} + x_{NB}$) and differential ($x_{NF} - x_{NB}$) fluctuations (and, for reference, the soil temperature registered at a depth of 1 m by a few weather stations along the link).

As our goal was to use the measured fiber-related data in the numerical experiment demonstrating the possible accuracy of clock comparisons, we introduced a realistic model of clocks taking into account their white frequency noise (corresponding to Allan Deviation ADEV of 1×10^{-15} @ 1 s), flicker frequency noise (limiting the long-term ADEV at the level of 1×10^{-18}), and mutual fractional frequency offset equal to -2×10^{-16} . This means that in following experiments we used Δx_{COMP_COR}

in the form:

$$x_{COMP_COR} = x_{AB} + x_{NA} + x_{NB} + x_{ERR} - x_{ERR_EST}, \quad (11)$$

where x_{AB} is linear phase trend reflecting the assumed relative frequency difference of the clocks (-2×10^{-16}), x_{NA} and x_{NB} are randomly generated phase noises of the modeled clocks. The time evolution of x_{ERR} and x_{ERR_EST} , was calculated from forward and backward phase fluctuations x_{NF} and x_{NB} , registered in the long-term fiber link measurement, i.e., from the same data as the round-trip and differential fluctuations shown in Fig. 6. Equations (3), (4) and (6) were used. Dedicated Matlab procedures was used in the experiments presented below.

For a preliminary demonstration of practical usefulness of the proposed method we took the data from the first week of the measurement, and we calculated x_{COMP_COR} in the way describe above, for varying m . We decimated the phase data to one point per day to calculate $y_{AB_EST}^{i,m}$ (an estimate of the fractional frequency difference) at daily basis. Then the spreading (standard deviation) of $y_{AB_EST}^{i,m}$ was calculated in the way defined in (10), for various values of parameter m . Fig. 7(a) shows the dependence of this spreading on taken value of m . An evident minimum is visible, with $\hat{m} = 4.9 \times 10^{-3}$. It may be noticed that when this value of m is used for correcting the clock comparisons results, the evolution of x_{COMP_COR} becomes close to linear, which was expected - see Fig. 7(b). The result of the procedure is the mean value of $y_{AB_EST}^{i,\hat{m}}$, calculated over the full (one-week) taken period. In this case the obtained value of fractional frequency difference between the clocks is -1.51×10^{-16} , which means that the estimation error is 0.49×10^{-16} (as offset of -2×10^{-16} was intentionally introduced in the calculations).

In the next step we investigated the impact of the length of data record (taken between 3 and 30 days) on the clocks comparison uncertainty. As we have 51 days of data in total, we slide the window of given length along the available period with one-day resolution, to obtain a maximum number of possible traces of each length. For better randomization of the sets of data for each chosen period we generated numerically individual (different) realization of the clocks noises. For relatively long measurement periods (as 10 days and longer), we observed satisfactory results, but for short periods, as 3–4 days, the results were poor in many cases, giving the error of the clocks offset estimation up to a few times 10^{-15} , which is in fact worse than the results calculated from the raw data. We identified two kinds of situations leading to such unsatisfactory results. The first one is a lack of substantial nonlinear component in the evolution of x_{AOM} , which implies that also x_{ERR} evolves linearly, and the mismatch cannot be distinguished from the clocks offset. The second group of traces giving unsatisfactory results were characterized by a poor correlation between the measured x_{COMP} [see (5)] and x_{ERR_EST} defined by (6), which means that accuracy of our model in these cases was presumably affected by significantly ununiform weather conditions along the link, or by abnormal temperature changes in particular network node(s), or some human activity affecting the cable or network devices. Therefore

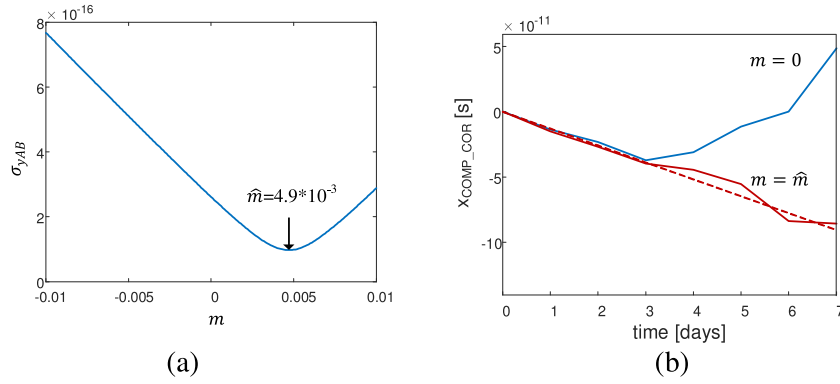


Fig. 7. Correction of seven-day long clock comparisons. Plot (a) shows how $\hat{m}$ was obtained from the dependence of σ_{yAB} on m . Plot (b) shows mutual phase evolution calculated from raw data ($m = 0$) and obtained after correction ($m = \hat{m}$).

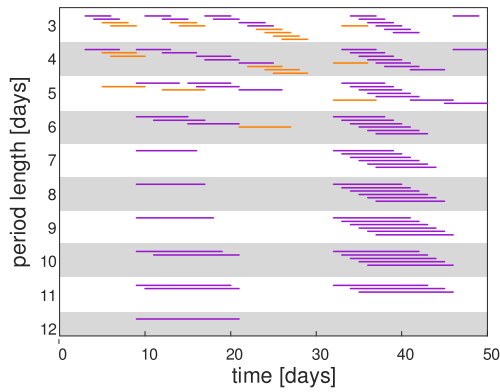


Fig. 8. Excluded data sets of different length located along the experiment duration axis. Orange and purple lines represent data sets which violate condition (12), and (13), respectively.

we added two conditions which qualify the data sets as offering a properly conditioned estimate of the mismatch parameter m . First condition has a form:

$$\frac{\sqrt{\frac{1}{I-1} \sum_{i=1}^I (\Delta^i x_{AOM} - \overline{\Delta^i x_{AOM}})^2}}{\frac{1}{I} \sum_{i=1}^I |\Delta^i x_{AOM}|} > th_1 \quad (12)$$

where $\Delta^i x_{AOM}$ stands for change of x_{AOM} over the day indexed by i , and th_1 is the threshold value. The left side of the inequality may be interpreted as a normalized deviation from linear evolution of x_{AOM} .

The second condition is:

$$|\rho(\Delta^i x_{COMP}, \Delta^i x_{AOM})| > th_2 \quad (13)$$

where ρ stands for the correlation coefficient, $\Delta^i x_{COMP}$ stands for change of x_{COMP} over the day indexed by i , and th_2 is the threshold value.

We experimentally determined that $th_1 = 0.2$ and $th_2 = 0.8$ are values allowing to exclude most of badly conditioned data sets, simultaneously not excluding too much of the sets. The locations and lengths of the excluded data sets along the entire experiment duration is presented in Fig. 8. Applying the proposed conditions eliminates 50% of the shortest, three-day

measurement periods, but only 16% of seven-day periods, and none of the two-week or longer ones. As one can notice, the condition (12), eliminating periods with linear evolution of x_{AOM} , is active only for short period lengths, when condition (13), related to poor correlation between x_{AOM} and x_{COMP} , acts also for longer periods. We have not observed long sub-periods in our data in which the conditions defined by (12) or (13) would persistently not be fulfilled. The practical recommendation is that one should plan a period of at least 10–15 days for scheduling the clock comparison campaign.

The results of the procedure described above is illustrated in Fig. 9. For periods of given length (picked-up from the 51-day-long record), we calculated the clock comparisons errors, marking the obtained values by blue circles. Fig. 9(a) shows the errors obtained when the fractional frequency difference of the clocks was calculated directly from the registered x_{COMP} data, and Fig. 9(b) shows the errors when the offset of the clocks was calculated using the proposed procedure. It may be noticed that mean value of errors calculated from the raw data (for all period lengths) is close to -3.4×10^{-16} , i.e., the obtained results of clock comparisons are significantly biased. This is related to the fact that we performed the measurements in September and October, when the soil temperature was mainly decreasing, and therefore the error caused by the forward/backward fibers mismatch was prevailing of the same sign. For data processed with the proposed method [see Fig. 9(b)], the mean error is at the level of 1.4×10^{-17} to 2.9×10^{-17} (for 10 days and longer periods), i.e., is more than an order of magnitude reduced. The root-mean-square (rms) error, which may be regarded as an estimation of the comparison uncertainty, is approximately 3.5×10^{-16} when the raw data were used, and is at the level of 4.4×10^{-17} to 8.7×10^{-17} (for 10 days and longer periods) in case of processed data, which indicates approximately 4–8 times improvement. It is also worth to notice that in case of using processed data the rms error can be reduced by conducting longer measurement, in contrary to the raw data based results, when longer measurement periods did not reduce the rms error noticeably.

The results described above were obtained with relatively low frequency flicker noise assumed in the model of the clocks. To check its influence we increased the flicker noise in a way that

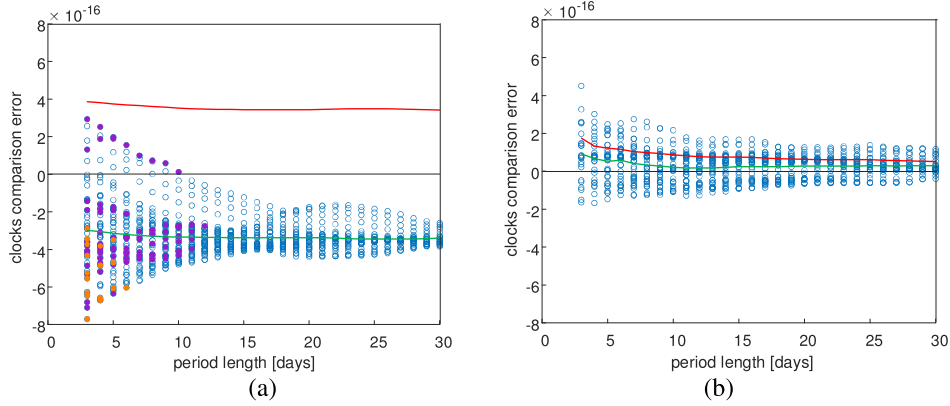


Fig. 9. Clock comparisons errors for periods of given length, calculated without correction (a) and with the proposed correction (b). Green and red lines show mean and rms errors respectively, for each period length. The errors were calculated in respect to the intentionally introduced clocks offset, being 2×10^{-16} . In plot (a) orange and purple filled circles represent data sets excluded by conditions (12) and (13), respectively.

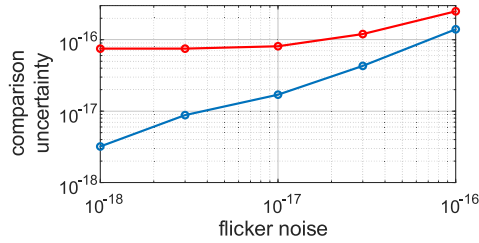


Fig. 10. Uncertainty of clock comparisons versus clocks flicker noise. Red curve represents the total uncertainty (with the impact of fiber noises reduced with the proposed method), and the blue one shows the isolated impact of the clocks noise only.

the long-term stability floor was changed from 1×10^{-18} to 1×10^{-16} (with the white frequency component unmodified). The clocks offset was determined then for all possible periods of the measured fiber phase fluctuations, using our method for mismatch correction - i.e., we calculated the results in the same way as presented in Fig. 9(b), but for higher flicker noise attributed to the clocks. Additionally, for reference, we run the same procedures with the correction method switched off, and with fibers phase fluctuations zeroed. This way we isolated the impact of the modelled clocks noises from all others factors. Fig. 10 shows the rms comparison error obtained from all two-week-long periods. Increase of the flicker noise from 1×10^{-18} to 3×10^{-17} had minor impact on the uncertainty of the entire procedure, but for higher flicker noise the results were significantly affected. It should be noted that this deterioration of the results has two reasons: first of all the high flicker noise values fundamentally limits comparison uncertainty (see the blue line in Fig. 10), but it also make our procedure less effective. The general observation may be formulated that our method is not excessively sensitive to the clocks flicker noise, and the long-term stability of the clocks (limited by the flicker noise) should not be worse than approximately 1/3 of the expected uncertainty of the proposed method.

The discussion presented so far was oriented on a “clock comparison campaign”, understood as a single event planned for

some relatively short duration, with the clocks frequency offset being an outcome. On the other hand, however, such a period may be additionally treated as a calibration of the fiber link, which in this case means determining the mismatch parameter m of this particular link. The mismatch obtained this way may then be used in future, as long as the link is not re-routed, i.e., it uses still the same fiber pair. This future use would not necessarily be comparing the high-end clocks, but for instance continuous disciplining the lower-grade clock at the remote end. To evaluate this option we took $m = 4.9 \times 10^{-3}$ determined from the first week of the long-term measurement of the fibers phase fluctuations (see Fig. 7(a) and related description in the text), and used this value to calculate an estimate of the fiber-induced phase error x_{ERR_EST} , accordingly to (6). Then we subtracted this estimate from the true phase error x_{ERR} defined by (4), which leads to the residual phase error, being the manifestation of the imperfectness of the proposed model and procedures. Fig. 11(a) shows the phase error before the correction, and the residual error after the correction, which starts after the first week, which was necessary to estimate the m . Fig. 11(b) presents the corresponding instability (modified Allan deviation MDEV), which after the proposed correction is 6.1×10^{-17} for one day averaging, and 1.7×10^{-17} for ten days averaging. The fractional frequency error calculated for one-day periods from the phase errors is presented in Fig. 11(c). The rms frequency error before correction was 3.8×10^{-16} , and was reduced to 9×10^{-17} after applying the correction.

We can compare the MDEV presented in Fig. 11(b) to the stability reported in previous works using the scheme with two parallel fibers, but with much shorter testbeds (38, 43 and 100 km), described in [3], [24], [30], respectively. For short averaging our 1500 km-long link reveals much higher instability (approximately two orders of magnitude for 1 s averaging, and one order of magnitude for 100 s averaging). This should be attributed not only to the much longer outdoor optical cable, but also to the impact of the optical amplifiers and routing devices located in the DWDM network nodes [26], not present in the experiments described in [3], [24], [30]. For one day averaging, however, our corrected stability is only 3.5 times

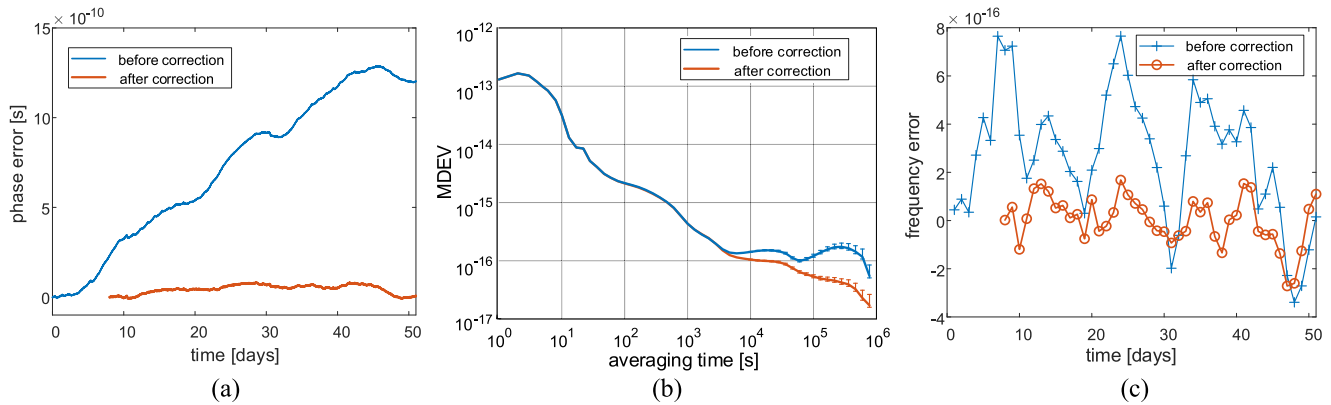


Fig. 11. Phase error (a), MDEV (b) and frequency error calculated at daily bases (c); all calculated before and after correction.

worse comparing to obtained for 35 times shorter path in [24]. This should be partially explained by applying of the proposed correction, and partially by some degree of randomization of the mismatch between the two fibers in consecutive sections constituting the long link.

V. CONCLUSION AND OUTLOOK

We presented the method for reducing the instability and uncertainty of the optical frequency transfer based on the widely accessible, non-modified DWDM optical telecommunication network. The method is based on the observation that differential phase fluctuation, which cannot be directly compensated by any phase stabilizing setup, is correlated to the round-trip phase fluctuation, which is being compensated. Therefore it may be easily registered by the phase/frequency recorder connected to the VCO which provide the phase correction to the AOM located at the local side of the frequency transfer system, and this additional data may be used for correcting the raw results of the clocks comparison. In our nearly two-months long experiment running over a 1500 km-long DWDM link we demonstrated approximately 5 times improvement of the comparison uncertainty (to the level significantly below 1×10^{-16}), and notable improvement of instability (MDEV close to 1×10^{-16} after three-hour averaging and mid- 10^{-17} for averaging longer than one day). As in the experiment we used a very long link, covering a large part of Poland, the noticeably better results might be expected for real (not so distant) locations at national level, at least in the European area.

Comparing the proposed method with the most sophisticated GNSS-based solutions [19], [20], [21], [22] in terms of (in)stability, it may be noticed that the realistic noise floor seems to be a few times 10^{-17} for both cases, but the level of 1×10^{-16} is reached much faster in case of our DWDM-based solution (a few hours versus a few days).

In terms of possible scenarios for using the proposed method, the obvious one is to use it for optical clocks comparison in the cases where a bidirectional, single-fiber link is either unavailable, or is out of the financial reach. But the other option is that using a transportable, highly-stable (but not necessarily calibrated in the sense of its absolute frequency) clock only for a

limited period (a few weeks), the mismatch parameter of particular link can be determined, and used further for calibration, monitoring or disciplining slightly lower-grade (commercial) optical clocks, or (with help of a frequency comb) a hydrogen maser or other microwave clock. Other possible application is referencing of the atomic/molecular spectroscopy and other measurements and experiments requiring high stability and accuracy of optical frequency.

It is worth to mention that in the reported experiment we used the link based on soil-buried optical cables, which is typical case in Poland. Concerning aerial cables, we also observed the correlation between differential and round-trip phase fluctuations, but because of a very limited access to such cables we were not able to perform similar experiments till now.

Last but not least, the proposed idea may be extended for (nearly) on-line correction of the frequency transfer (distribution) in DWDM links. If the mismatch parameter of particular link is initially determined (as described above), the constantly measured round-trip phase fluctuation may be used to correct continuously the phase error at the remote end of the link. This is the idea under current investigation and will be reported soon.

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