Stability Limitations of Optical Frequency Transfer in Telecommunication DWDM Networks

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***Abstract*— This article investigates the fundamental limitations of optical frequency transfer stability related to cost-effective implementation of signal transmission in duplex, unidirectional optical paths offered by a standard dense wavelength division multiplexing (DWDM) network. We pointed out the effect of a significant mismatch of phase fluctuations observed in pairs of fibers even when located in a common cable. We also measured the thermal sensitivities of individual DWDM optical modules in the context of the effectiveness of the signal stabilization system. Finally, we present the real implementation of the coherent optical carrier transfer in the operational DWDM network, showing the overall impact of all individual effects. We demonstrated that it is possible to obtain the long-term stability (one day averaging) within the range from 2×10^{-16} to 4×10^{-16} and typical frequency offset at the level of few times 10^{-16} in a 1500-km-long line by using the soil-deployed cables.**

***Index Terms*— Alien wavelength, dense wavelength division multiplexing (DWDM) network, optical fiber, optical frequency transfer.**

I. Introduction

THE current, significant progress in the development of atomic clocks causes a strong motivation to develop effective systems for comparing and distributing these sources of ultraprecise frequency signals. However, further significant improvements in satellite techniques [1], [2] for frequency comparisons seem to be not possible due to fundamental limitations. The solution to these problems was found in the frequency transfer using optical fibers, which allowed the comparison of clocks with unprecedented accuracy. The demand for frequency transfer in optical networks is found in both international [3]–[5] and regional networks [6]–[8]. The implementation of fiber-optic frequency distribution techniques has also allowed the use of these signals in scientific fields not directly related to metrology, such as astronomy [9]–[12], spectroscopy [13]–[15], or geodesy and fundamental science [16]. Unfortunately, an approach based on dedicated fiber [17]–[21], and offering the highest accuracy and stability require large financial investments related to the lease of fiber infrastructure and deployment of dedicated optical amplifiers. Hence, a great interest is observed in sharing the same infrastructure for data transmission and frequency transfer in the same dense wavelength division multiplexing (DWDM) system. One of the alternatives is the bidirectional transfer in the DWDM network [22], but it requires physical modification of the existing DWDM nodes and still needs dedicated optical amplifiers for frequency transfer.

Another available solution is the duplex unidirectional transfer in DWDM [23]–[27], which does not require modification of the existing telecommunication infrastructure or installation of additional hardware (apart from the transmitting and receiving stations of the frequency distribution system). Therefore, such an approach is the cheapest and simplest solution for the transfer of ultra-stable frequency signals. This is at the cost of decreased stability, which problem is thoroughly analyzed in this article.

II. Frequency Transfer in Unidirectional Telecommunication Networks

The easiest way to transfer optical frequency in DWDM networks is to inject an unmodulated light of known and stable frequency into a dedicated optical channel, through existing Add/Drop points—optical multiplexers. These elements of the network combine many optical signals, with a strictly defined optical spectrum width (channel). Typically, duplex transmission (in both directions) is carried out on physically separated optical fibers and DWDM components (amplifiers, optical filters, dispersion compensation modules, reconfigurable optical add-drop multiplexer (ROADM), and the likes). The entire spectrum of the optical band (all transmitted channels) is amplified through common optical amplifiers.

In the context of the optical frequency transfer, it is important that in the DWDM network, transmitted signals will suffer from unequal delay changes in the forward and backward

Manuscript received September 10, 2019; accepted November 27, 2019. Date of publication December 2, 2019; date of current version April 24, 2020. This work was supported in part by the TiFOON 18SIB06 Project through the EMPIR Programme co-financed by the Participating States and through the European Union's Horizon 2020 Research and Innovation Program. *(Corresponding author: Krzysztof Turza.)*

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Digital Object Identifier 10.1109/TUFFC.2019.2957176

directions, whereas only symmetrical (correlated) fluctuations can be effectively compensated. Any asymmetrical changes (herein referred to as differential delay fluctuations) would inevitably degrade both stability and absolute accuracy of the transferred reference frequency to some extent.

It should also be noted that different generations of DWDM systems may slightly differ, one from the other. In this work, we focused on the latest generation of DWDM systems designed to convey 100 Gb/s coherent signals. The most important difference in comparison to previous generation is the total absence of in-line chromatic dispersion compensators whose impact on frequency transfer has been extensively described in [28].

Despite all the problems mentioned above and also those raised in our previous articles [28], [29], the use of the telecom DWDM network for frequency transfer is one of the cheapest and sometimes the only available method of transferring these types of signals. For this reason, the analysis of all components of such networks, affecting the stability of transfer seems to be crucial for determining the available limits and correct identification of the sources of impairments. Our further analysis focuses on the main sources of the transmitted frequency degradation: the first one related to the influence of optical lines (cables) and the second one to various DWDM components.

III. Impact of the Transfer in Two Parallel Optical Fibers on the Stability of Transmitted Frequency

The most important factor influencing the change of delay in optical fibers is related to changes in their temperature [30], [31], although, for short observation times, acoustic disturbances (fiber vibrations) [32]–[34] are also important. Unidirectional frequency transfer in a DWDM network uses two adjacent (neighboring) fibers in the same optical cable. The crucial question we are going to address in this section is to what extent can the delay fluctuations in such a pair of fibers be assumed to be symmetric—as mentioned before, any differential delay fluctuations limit the frequency transfer performance [25], [35].

In our previous experiment [29] with stabilized frequency transfer in the DWDM network, we observed some long-term differential delay fluctuations, which seem to be related to fiber temperature, and thus, suggesting some level of asymmetry in two parallel fibers when used in the stabilized frequency transfer link. Therefore, we decided to arrange a set of experiments to isolate this phenomenon in the manner not blurred by the presence of network equipment.

We made three experiments: two in soil-deployed and one in aerial fiber cables available within the Polish National and Research Network (PIONIER) resources. The test setup exploited is shown in Fig. 1(a).

In the first experiment, a pair of fibers in 50-km-long soil-deployed cable started at the Poznan network node was tested. The intensity-modulated signal was delivered to the far end localization using the additional fiber of the same cable, then amplified and sent back through a passive optical

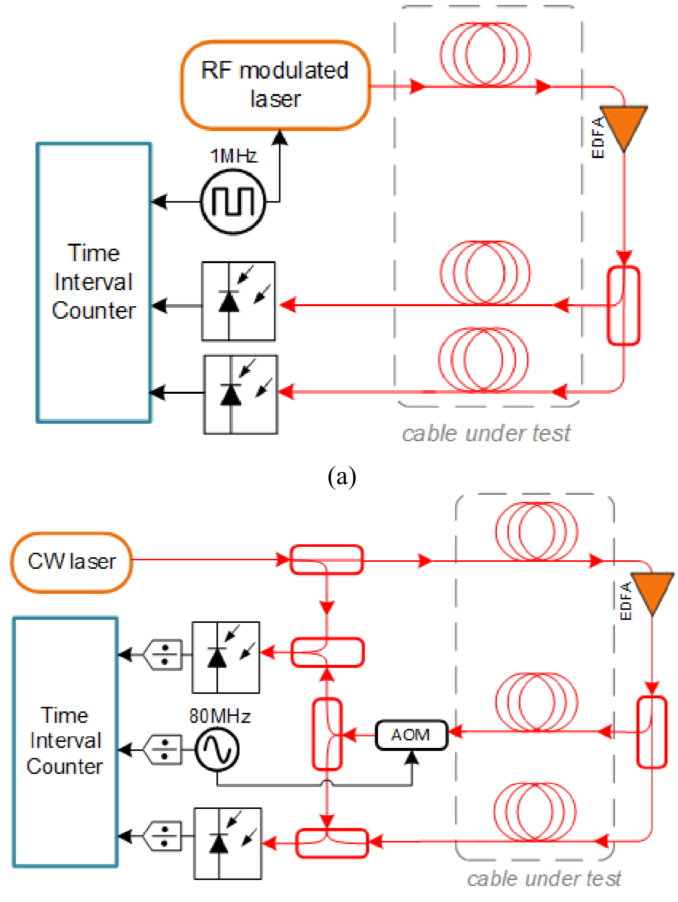

Fig. 1. Block diagram of the measurement system built to investigate the differential fluctuation of the fibers' delays. (a) The first campaign of measurements with the intensity-modulated signal. (b) Next measurements with unmodulated coherent OC. AOM stands for the acousto-optic modulator.

splitter simultaneously via the pair of fibers under test. The phase fluctuations of the received signals were registered by the MTC108 multichannel time interval counter [36]. We registered both: differential delay changes between the two "backward" fibers, and the total delay changes in the loop ("forward" plus one of "backward" fibers).

In Fig. 2(a), we present the results of almost 40 days of observations. (Herein, and in all following similar measurements, we give the total delay changes for one fiber, i.e., the round-trip results, divided by two.) One can notice the clear correspondence between the total delay changes (caused by the cable temperature changes) and the differential delay between the two fibers. Thus, it may be conjectured that the thermal sensitivities of these two particular fibers are not exactly equal—differential delay fluctuations are approximately 1.2% of the total ones (in magnitude).

As we could not find any satisfying explanation for this observation, we repeated the experiment with different cables. The second one was carried out on a 110-km line (started at Warsaw network node), using an aerial cable. The results are presented in Fig. 2(b). As the aerial fiber is exposed to drastically higher temperature fluctuations, the resulting total

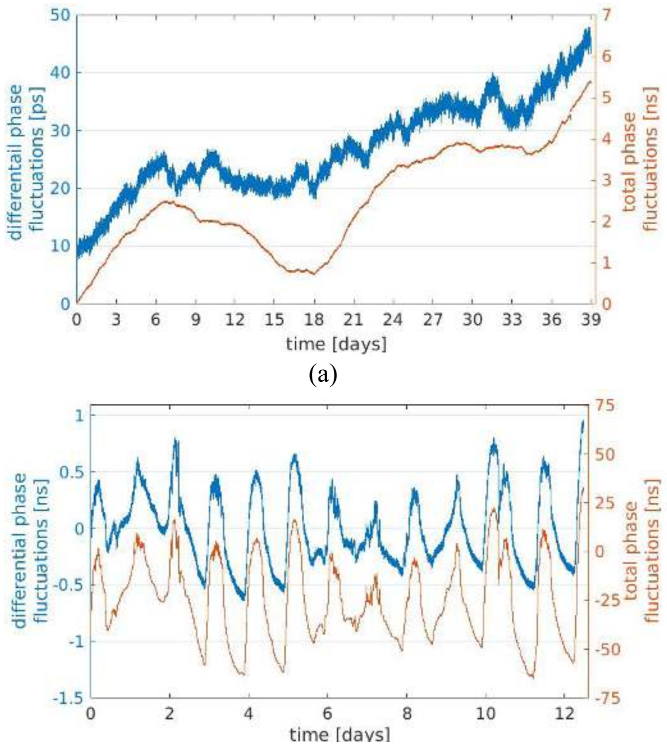

Fig. 2. Total and differential phase fluctuations (orange and blue curves, respectively) between two fibers. (a) 50-km-long soil-deployed cable. (b) 110-km-long aerial cable. Note different vertical axis scaling for total and differential delays. Measurements performed in the setup from Fig. 1(a); short-term noise visible in the differential delay is mainly due to time interval counter noise floor.

TABLE I

SUMMARY OF FIBERS' DIFFERENTIAL DELAY FLUCTUATIONS

Cable type	Line length	Fibers no.	Fiber type	Optical asymmetry	Differential delay*
soil-deployed	50 km	23/24	G.652	--	1.2%
aerial	110 km	29/30	G.652	1 ns	1.6%
soil-deployed	70 km	3/4	G.655	4,9 ns	3%
soil-deployed	70 km	22/23	G.652	5,7 ns	0.5%
soil-deployed	70 km	23/24	G.652	3,0 ns	0.3%
soil-deployed	70 km	25/26	G.652	0,5 ns	0.2%

* The differential delay fluctuations normalized to the total delay

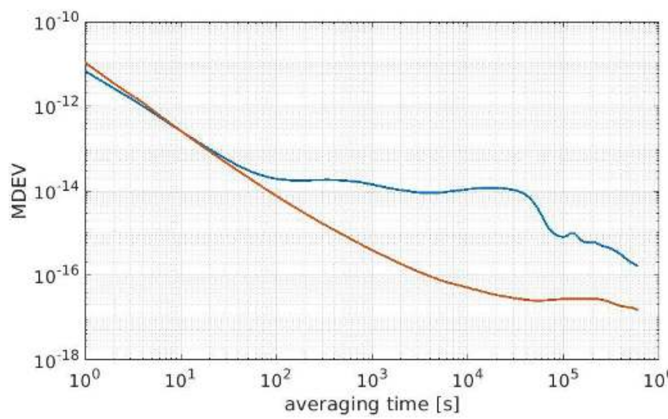

Fig. 3. MDEV of the differential delay fluctuations in 110-km-long aerial (blue) and 70-km-long soil-deployed cable (orange). Measurements performed in the setup from Fig. 1(a); for short averaging, the stability is limited by the noise of the time interval counter. Before MDEV calculations, we divided the differential delay fluctuations by factor of two, as half of these fluctuations are present at the output of a stabilized system.

delay fluctuations are also much higher (approximately 50-ns peak-peak) and display a well-visible diurnal period. In spite of this, the differential delay fluctuations are about 1.6% of the total fluctuations, which is the same order of magnitude as the previously investigated case.

The same experiment was repeated in another 70-km long, soil-deployed cable started at Poznan network node. In this cable, we have access to seven fibers, five standard ones (G.652), and two dispersion-shifted (G.655). In all cases, we observed the clear correspondence between the differential and total delay fluctuations; however, the magnitude of the differential delay varies from pair to pair, even for the same fiber type and cabling. The results of those experiments are summarized in Table I. In this table, we added the optical length mismatch of the fibers in each pair, to illustrate that it was extremely small (in the range of 10^{-5}) and so cannot be the reason of the differential delay fluctuations on the scale observed. In all cases, both fibers of particular pair were located in the same inner tube of multitube cable, which is a common practice in DWDM installations. Typically, the tube of 2.4-mm inner diameter, which guarantees very similar thermal conditions for all fibers.

As the differential delay fluctuations cannot be compensated in any closed-loop phase stabilization system, they cause the limit of achievable frequency transfer stability. We used the obtained results to calculate such a limit in the form of a modified Allan deviation (MDEV). Fig. 3 shows MDEV plots for 110-km-long aerial cable and 70-km-long soil-deployed one. For the aerial cable, the stability is limited to approximately 1×10^{-14} for averaging up to half-a-day and decays to approximately 1×10^{-15} for one-day observation time. For soil-deployed cable, the MDEV plot crosses the 1×10^{-16} level for 1 h averaging, and displays no bumps or plateau.

We also calculated the one-day averaged frequency offset for consecutive 24-h periods. The maximum observed value for aerial cable was 3×10^{-15}, and the mean was about 2×10^{-17}. For soil-deployed cable, they were 2×10^{-17} and 1×10^{-17}, respectively.

For long-term averaging, the stability is limited by external factors (like temperature fluctuations); but for short-term averaging, however, the presented measurements occurred to be limited by the noise of the time interval counter. Thus, in the next step, we decided to repeat some measurements with the improved measurement setup using an unmodulated coherent optical carrier (OC) [see Fig. 1(b)]. In this setup, the beat note at the upper photodiode reflects the optical phase fluctuations of round-trip OC transmission, and the beat note at lower photodiode reflects differential phase fluctuations within

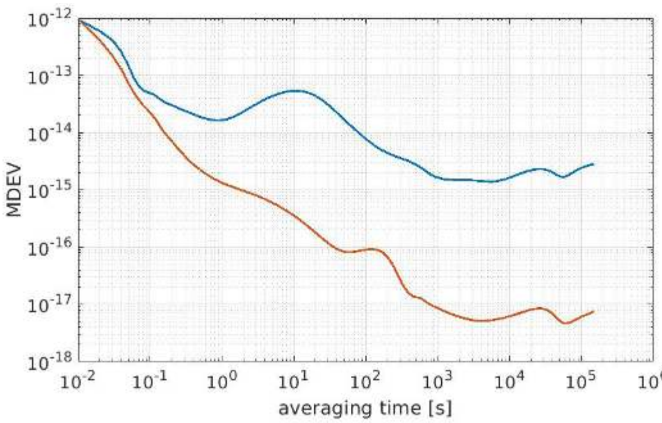

Fig. 4. MDEV of the total (blue) and differential (orange) delay fluctuations in 70-km soil-deployed cable, measured with the unmodulated coherent OC. The bump in the orange curve at 100 s is caused by the influence of air conditioning in the laboratory on the interferometer of the measurement system.

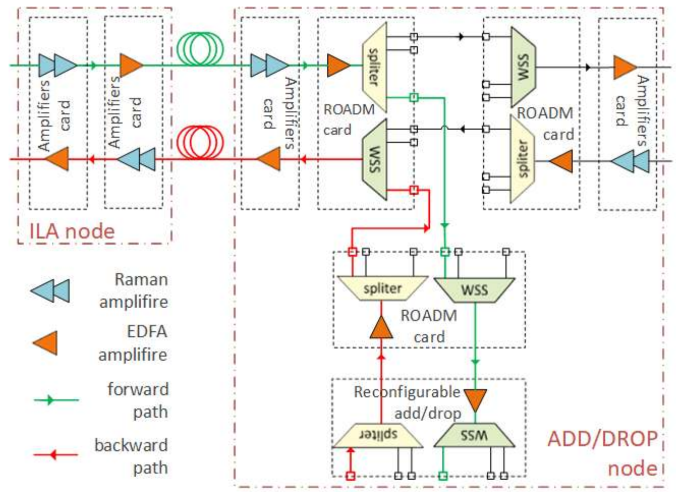

Fig. 5. A simplified example of a DWDM system arrangement.

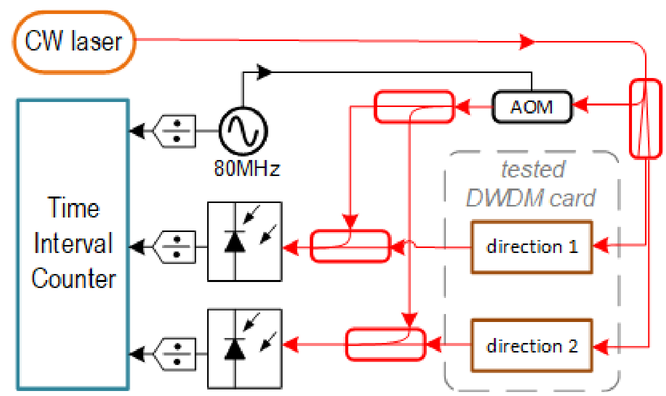

Fig. 6. Block diagram of the measurement system to investigate the differential delay fluctuation in the two directions of the single DWDM card.

the pair of fibers under test. Thanks to the optical phase to electrical phase conversion, the delay fluctuations registered by the time interval counter were magnified by the factor of approximately 2×10^6; thus, these new results were not limited by the counter.

The results are presented in Fig. 4. The stability calculated from differential delay fluctuations is at the level of 1×10^{-15} for 1 s averaging, and goes below 1×10^{-17} for 1000 s. For averaging longer than 10 s, the ratio between MDEV calculated from total and differential fluctuations is close to 200, which once again illustrates the limitation of possible phase stabilization.

The total delay fluctuations plot (see Fig. 4) also shows a bump at 10 s. It is related to the indoor part of the fiber-optic cable, more specifically the part running through the server room. This part of the cable was exposed to large and relatively fast changes in temperature, associated with a very strong supply of air conditioning of this room.

The authors cannot provide any solid explanation for the relatively large asymmetry between the delay fluctuations observed for neighbor fibers in the same optical cables. However, all the measurements carried out (and repeated) for more than two years confirm this observation. In the authors' opinion, this effect is an unavoidable limitation for the effectiveness of phase stabilization in optical frequency transfer in DWDM networks, when two parallel fibers are used to form a loopback for phase stabilization.

IV. Influence of DWDM Components on Frequency Transfer Stability

DWDM network is a complex structure built from various system modules (optical splitters and filters, erbium-doped fiber amplifiers (EDFA) and Raman amplifiers, wavelength selective switches (WSS), etc.). Each individual module is constructed in the form of a card which is placed in dedicated chassis (enclosures).

All cards are connected by dedicated fiber-optic cabling. Individual cards usually have two directions of optical signal flow (for the forward and backward signals). Example in Fig. 5 shows a fragment of a DWDM network consisting of two nodes. From the point of view of frequency transfer, it is important to note that the individual cards have a different structure in the forward and backward direction (signals have to pass through different types of modules), which can be expected to result in an asymmetrical change of delays in both directions. To determine the impact of the entire DWDM system on this type of transmission, we carried out laboratory tests of thermal sensitivity of delay for a few popular cards. We focused on the examination of the overall card forward and backward directions and differences between them. The block diagram of the measurement setup used is presented in Fig. 6.

Our first observation was that all directions of the cards, which do not contain an EDFA, have relatively small temperature sensitivity at the level of about 0.2–0.5 ps/K, whereas all cards, including EDFA, display much higher values. It should be noted that EDFAs are used not only in cards dedicated to optical signal amplification but are often also part of other cards, such as ROADM optical switches (reconfigurable optical add-drop multiplexer) or tunable optical filters terminating

TABLE II
TEMPERATURE SENSITIVITY OF DWDM CARDS

Card type	Direction*	Measured delay	Temp. sensitivity	Asymmetry of temp. sensitivity
EDFA	direction 1 (amplifier)	250 [ns]	1.9 [ps/K]	1.7 [ps/K]
	direction 2 (splitter)	-	0.2 [ps/K]	
RAMAN /EDFA	direction 1 (RAMAN)	46 [ns]	0.3 [ps/K]	1.4 [ps/K]
	direction 2 (EDFA)	220 [ns]	1.7 [ps/K]	
ROADM	direction 1 (EDFA+splitter)	304 [ns]	2,2 [ps/K]	1.7 [ps/K]
	direction 2 (WSS)	78 [ns]	0.5 [ps/K]	
Reconfigurable filter	direction 1 (EDFA + WSS)	269 [ns]	2.3 [ps/K]	1.8 [ps/K]
	direction 2 (splitter)	65 [ns]	0.5 [ps/k]	

* Optical modules used in specific direction within a card are listed in brackets.

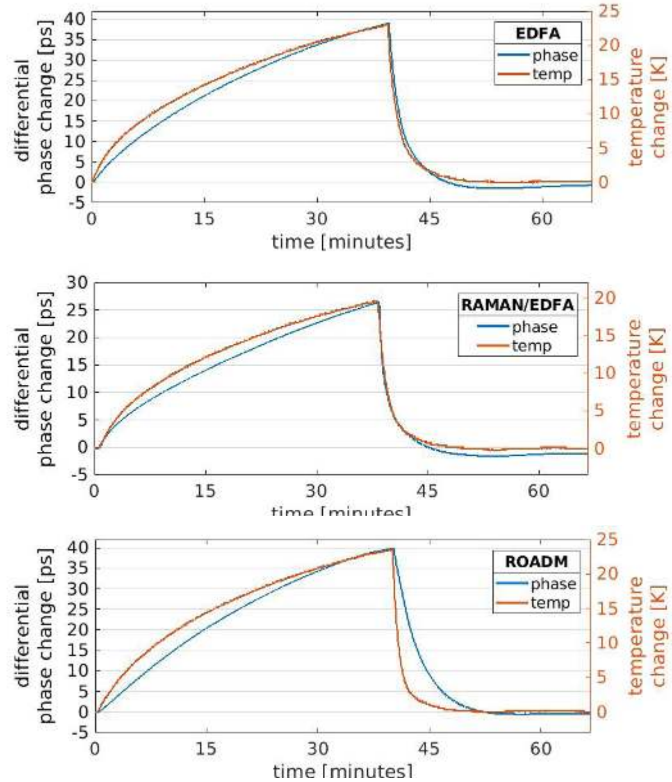

Fig. 7. Measured temperature impact on differential phase change in opposite directions in a single DWDM card. Different types of cards present different thermal inertia, and thus, the speed of reaction to temperature changes.

selected optical wavelengths in a given node. In the case of modules with EDFA amplifiers, the thermal sensitivity was within the range from 1.7 to 2.3 ps/K. It follows that providing similar temperature variations on cards with EDFA modules working in opposite directions (by placing them close together) can significantly reduce the impact of temperature changes on the stability of frequency transfer.

Table II summarizes the results of our measurements. As one can notice, the thermal sensitivity is basically proportional to the absolute delay of the module, which is its optical length. This confirms the reason for the high thermal sensitivity of EDFA modules, and its construction requires the use of (erbium-doped) fiber with a length of tens of meters. A few examples of measured differential temperature sensitivity between opposite directions in the single card is presented in Fig. 7.

Although, in practice, individual EDFA amplifiers may differ by several percentages in the length of the fiber used, the above analysis of the thermal sensitivity of particular cards shows that placement of EDFAs (working in opposite directions) close to one another is crucial for minimizing the differential impact of temperature, and thus, for improving the stability of frequency transfer.

Due to the functions of individual DWDM network nodes, they can be divided into two types: Add/Drop (enabling the insertion and termination of an individual transmission) and in-line amplifier (ILA)— responsible for optical amplification. In addition to the function, these nodes also differ in the degree of complexity of the structure and the number of elements (see Fig. 5). ILA nodes are usually small compact solutions containing several cards inside one shelf. The influence of such nodes on the instability of frequency transfer is caused mainly by the nonidentical optical length of the used EDFA amplifiers (in opposite directions) and the differential temperature changes between both modules. Due to the compact structure of these nodes, the temperature distribution inside the chassis is usually well correlated.

In contrast to ILA nodes, Add/Drop nodes are usually multishelf solutions. Often, in size, they exceed the capacity of a single telecommunications cabinet, and thus, individual shelves may differ significantly in absolute temperature and in the dynamics of temperature changes.

All the above-mentioned thermal effects affect the overall stability of the frequency transfer. Anyway, particular numbers depend on the operation of air conditioning systems at each node, the spatial locations of the equipment cards, and the arrangement of cold air distribution. Fortunately, all the modules have individual temperature sensors, which in conjunction with measured (or estimated) temperature sensitivities, allow the predicting the impact of the devices installed in a particular network node.

V. EXPERIMENTAL OPTICAL FREQUENCY TRANSFER IN DWDM NETWORK

For verification of the above analysis, we performed the experiment with the optical frequency transfer in the operational PIONIER DWDM network (see Fig. 8). It was implemented over a 1500-km-long route, forming a geographical loop with both ends (local and remote) accessible at AGH University in Kraków. The optical frequency signal was transmitted as an "alien wavelength" service using International Telecommunication Union (ITU) channel 44 (1542.12 nm).

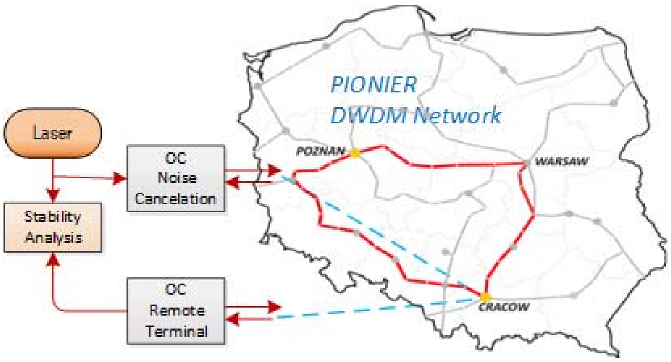

Fig. 8. Diagram of the experimental frequency transfer in operational PIONIER network using unmodulated coherent OC.

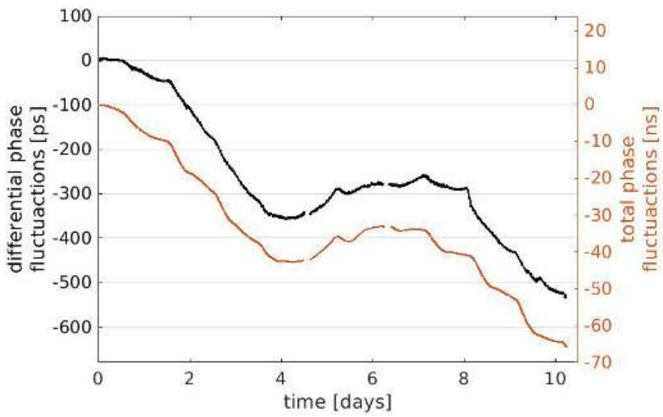

Fig. 9. Phase fluctuations of total delay (orange) and differential (uncompensated) delay of unmodulated coherent OC transfer in unidirectional DWDM. Note different vertical axis scaling for total and differential delays.

We arranged a standard closed-loop noise cancellation scheme [25], but contrary to a common solution exploiting bidirectional transmission in a single dedicated fiber, we used the standard telecom network infrastructure, with separated (parallel) fibers in a soil-deployed cable and network device used for forward and backward directions. Along the optical path, there were 11 ILA-type network nodes and five Add/Drop nodes. The source of the optical frequency signal was a narrow linewidth fiber laser (Koheras Adjustic by NKT Photonics) externally locked to a high-finesse ultra low expansion (ULE) cavity. For stability analysis, we registered the phase fluctuations of the beat note generated by combining the source laser with the remote optical signal. Additionally, in a different optical channel, we sent an intensity-modulated optical signal from the local to the remote end, without delay compensation, for simultaneous monitoring of the overall delay fluctuations of the optical path.

Similar to the previous experiments, we observed evident correspondence between the total delay fluctuations and residual ones in the stabilized frequency transfer (see Fig. 9). In a ten days period, the total delay change was approximately 65 ns, when, at the same time, the residual phase drift in stabilized frequency transfer (caused by differential delay changes) reached 260 ps. Taking into account that in the stabilized system only half of the forward-backward asymmetry is visible

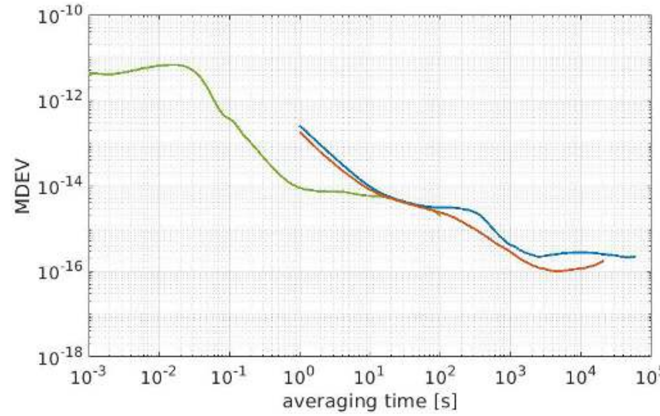

Fig. 10. Stability of unidirectional transfer in a DWDM network. The green curve shows the influence of acoustic noise. The blue curve shows the stability of the frequency transfer in the case of suboptimal (asymmetric) cooling within a single ILA node, while the orange curve shows the stability of the transfer after optimizing the airflow within this node.

[37], the differential delay change was 0.8% of the total delay, which is consistent with the previous results observed in shorter spans (see Section III).

Fig. 10 illustrates the stability of frequency transfer in the form of MDEV plots. In the case of measurements with 1 kHz sampling, a strong bump related to acoustic noise (10–50 ms) can be observed. At 1 s averaging time, the stability reaches the level of 10^{-14} and does not decrease substantially for longer averaging, which suggests a substantial amount of phase fluctuations with periods of some hundreds of seconds, typical for the impact of air conditioning systems in vulnerable locations, in our case, the network nodes. Especially in the first long-term measurement (curve marked blue in Fig. 10), the evident bump about 200 s is visible. We tried to identify the source of this bump by analyzing the relation between the phase fluctuations and temperature data recorded at each network device in the time domain. We discovered an evident correlation between phase trace and differential temperature changes between two EDFAs' amplifiers (DWDM cards) working in opposite directions in one particular node. To verify this, we turned off the air conditioning in the suspected node for forty minutes and then switched it on again. As a result, the evident impact on frequency transfer stability was observed (see Fig. 11). The reason for such a significant influence of this particular node was not related to extraordinary behavior of its air conditioning, but to the fact that the locations of cards containing EDFA modules working in opposite directions, were substantially different; one was exposed directly to the air blow from a cooling fan, whereas the second one was screened. We tried to improve the airflow around this equipment, and in this way, the bump was significantly reduced (see the curve marked in orange in Fig. 10).

The long-term stability (one day averaging) obtained in measurements repeated several times was within the range from 2×10^{-16} to 4×10^{-16}. We also calculated the frequency offset for one day averaging. The worst observed value was 1.2×10^{-15}, typically a few times 10^{-16}.

The results obtained in this real 1500-km-long link may be compared with stability derived from differential delay

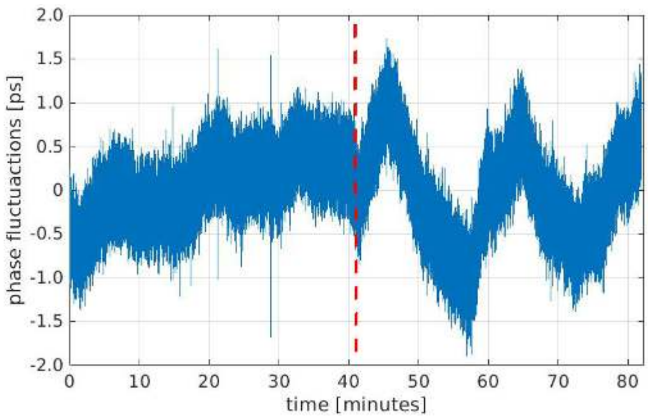

Fig. 11. Influence of non-optimal cold air distribution in one of the ILA nodes on the frequency transfer stability. Up to 40 min of the test, the air conditioner was powered OFF, then back ON.

measurements in 70-km-long pair of fibers (curve orange in Fig. 4). Both short-term stability (1 s averaging) and long-term one (averaging longer than 10^4 s) stability in the long link is approximately an order of magnitude worse, which is generally consistent with the fact that our long link is more than 21 times longer than the cable tested before. However, for medium averaging (10–1000 s), the stability degradation is significantly more pronounced, which should be attributed to the impact of DWDM devices exposed to rapid temperature gradients in the network nodes.

VI. Conclusion

It has been demonstrated that the fibers in the common cable show asymmetry of delay changes correlated with the general temperature changes of the fiber-optic cable. The ratio of these changes differs for different fiber pairs even in the same cable. They can reach values of up to a small percentage of the overall changes. This effect results in a fundamental limitation for the effectiveness of phase stabilization in optical frequency transfer based on two fibers. Aerial fiber-optic lines are exposed to large daily temperature changes, which makes them definitely less suitable for frequency transfer in a DWDM network.

The stability of frequency transfer using DWDM networks is also directly related to the symmetrical change of delay in the forward and backward directions within individual nodes of the network (devices). An important parameter is the thermal sensitivity of individual optical modules, which in turn is related to their optical length. The deliberate placement of individual cards can minimize the negative impact of DWDM nodes on the stability of frequency transfer. Among the optical modules, the placement of EDFA modules is crucial because they are the most sensitive to temperature changes. These changes are mainly medium-term (from a few to several tens of minutes) and are directly related to the cycle of air conditioning operation.

Experimental transfer of optical frequency carrier in 1500-km DWDM line shows that with the use of soil-deployed cables, it is possible to obtain the long-term stability (one day averaging) within the range from 2×10^{-16} to 4×10^{-16} and typical frequency offset at the level typically few times 10^{-16}.

The demonstrated long-term stability floor is comparable to that obtained in the most sophisticated satellite frequency transfer techniques [38], [39], the fiber-optic approach, however, allows obtaining results a hundred times faster. On the other hand, it may be concluded that the cost-effectiveness of using standard DWDM infrastructure is sacrificed by significant stability degradation when compared with a bidirectional transfer in a single fiber.

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