31-12-2022

Preliminary Assessment of OC signal Transfer Quality on the Poznań-CERN Line in an Unmodified DWDM (Unidirectional) Network

Grant Agreement No.:	856726
Work Package	WP6
Task Item:	Task 1
Document Type:	White Paper
Dissemination Level:	PU (Public)
Lead Partner:	PSNC
Document ID:	GN4-3-22-19E15P
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The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 856726 (GN4-3).

Abstract
This white paper describes the assessment of the quality of optical frequency signal transfer in an unmodified (unidirectional) DWDM network with a range of more than 2000 km. It also covers a description of the necessary modifications to the Optical Carrier signal transfer system required to realise this type of transmission using a pair of optical fibres.

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Executive Summary

The development of optical clocks requires the use of new frequency transfer technologies because the technologies currently in use do not provide sufficient precision of the transmitted signals. To meet the requirements for such ultra-precision transmission, research teams are developing an optical carrier transmission. The most accurate method is the transmission of an optical carrier through dark fibres. However, it is not always possible to have access to dark fibres.

This document describes in-field tests of an optical carrier transmission in an unmodified (unidirectional) DWDM system. The tests were designed to determine the possibility of transmitting an optical carrier over a distance of 2000 km and to simulate planned development of the future connection on the Poznań - CERN line. The test link was established in the PIONIER network based on DWDM systems from ADVA Optical Networking. Tests have confirmed the possibility of optical carrier transmission at such distance and the long-term stability of about 1E-16.

1 Introduction

The rapid development of high-precision optical clocks has led to significant interest in the distribution of the signals generated by them, which is an unmodulated optical reference frequency, also known as an optical carrier (OC). The primary method of transfer of the OC signal is by bidirectional transmission in a single optical fibre. The use of a single fibre allows maximum symmetry of propagation delay fluctuations in opposite directions of transmission. As a consequence, these fluctuations can be effectively corrected and the impact on the quality of the transmitted signal can be minimised. However, in some cases, it may not be possible to obtain additional fibres for OC distribution or to modify existing telecommunications systems. In such cases, an alternate solution would be to transfer OCs using part of the optical spectrum in unmodified DWDM systems. This means, however, that signals in opposite directions will be transmitted in physically different optical fibres (although still in the same cable) and amplified in separate line amplifiers. The assumed perfect symmetry of propagation time fluctuations will be affected and the quality of the transmitted signal (stability and accuracy) will also be degraded. However, this signal quality can still be significantly higher than with other alternative methods for transfer of the reference frequency (e.g. satellite methods) [PREC]. Such a method of OC distribution is planned for the Poznań (PSNC) Geneva (CERN) link.

Estimation of the expected accuracy of the transmitted signal is crucial in order to determine the suitability of a given line for the designated objectives. Unfortunately, verification of the quality of the target link is difficult to carry out as it requires an alternative transmission system with a quality better than the expected accuracy of the target link. There is no alternative system guaranteeing adequate OC transfer quality on Poznań–CERN line, as initial experimental verification of the feasibility of transfer based on the national PIONIER network was carried out (using the same generation of DWDM equipment), which would simulate the future planned deployment. Measurements were arranged in the form of a geographical loop, which enabled the location of both ends of the line in one laboratory and direct comparison of input and output signals of the system (no additional/alternative transmission system is required).

In this document, Section 2 describes the objectives of the simulation. Section 3 presents the topology of the test system. Section 4 is a description of the required laser station modifications for the implementation of optical carrier (OC) signal distribution in unidirectional systems (unmodified DWDM). The last two sections describe the results and a summary of the tests performed.

2 Simulation Objectives

The connection for OC transfer between Poznań and Geneva is possible using the existing infrastructure of the PIONIER network - the current DWDM system. The same generation of equipment, from the same vendor, is also used for the national connections of the PIONIER network. Thus, it was possible to set up an alternative route in the form of a geographical loop using other sections of the network. The length of the fibre-optic line between Poznań and Geneva is quite long (2,700 km), so the mechanisms used to correct fluctuations of signal propagation time (having a direct impact on the quality of the transmitted reference signal - OC) also required verification. The construction of the OC transfer terminal equipment itself also required additional verification, due to the fact that transmission in opposite directions was split into two separate optical fibres.

3 Testbed Topology

Within the PIONIER network, it was possible to set up a test loop in an operational DWDM system of approximately 2,100 km. This route began and ended in Poznań and ran through Szczecin, Gdańsk, Suwałki and Warsaw (see Figure1).

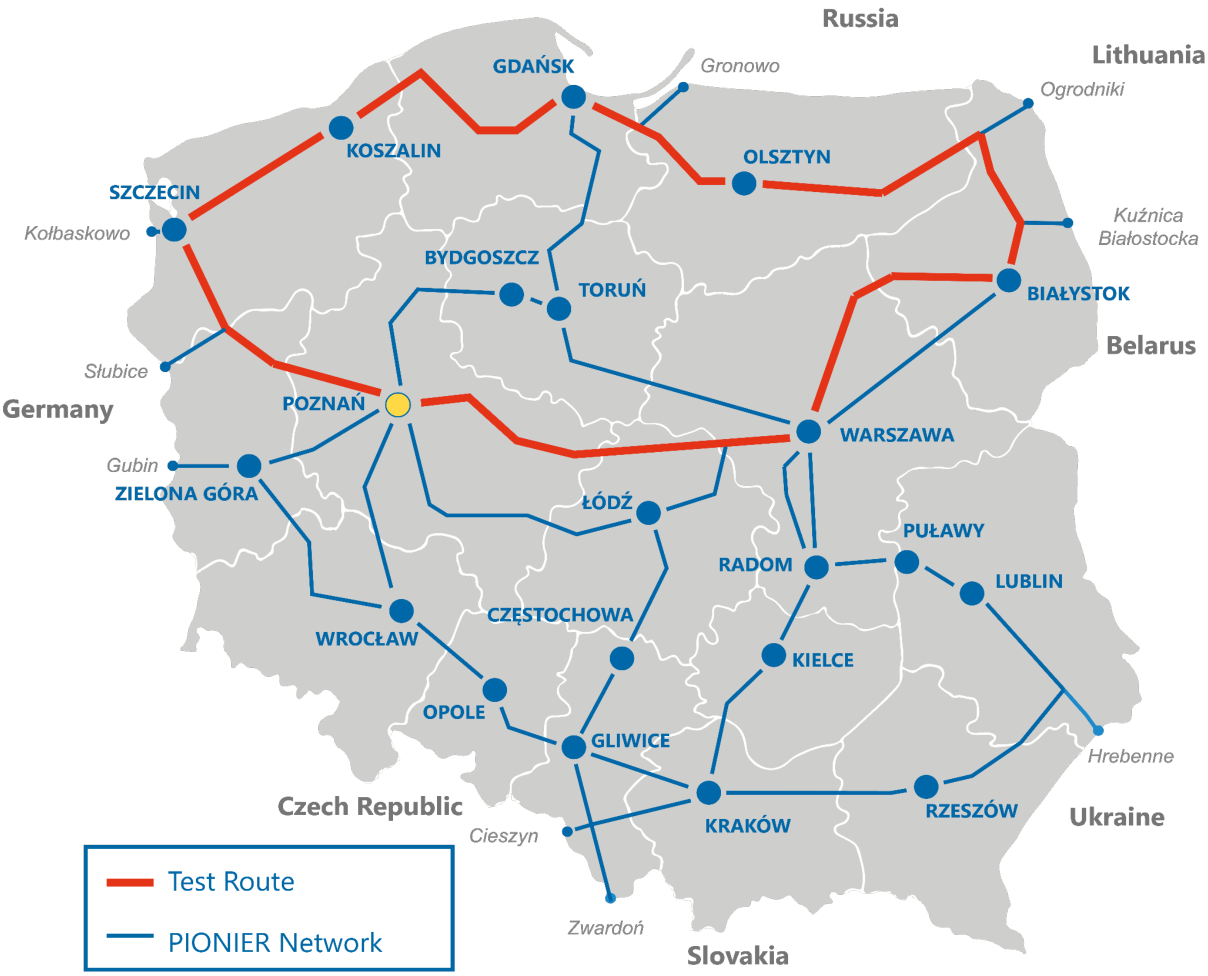
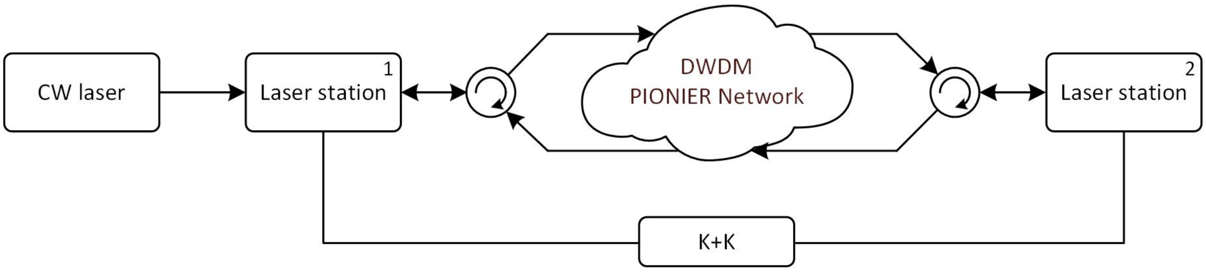


Figure 1: Route of the test network

ADVA optical devices dedicated to the transmission of coherent signals (the network did not have chromatic dispersion compensators) were used for the tests. Laser stations manufactured by PSNC and developed within the NLPQT project [NLPQT] were used to transmit, correct and receive the OC reference signal. The source of the OC reference signal was a Koheras ADJUSTIK laser and the evaluation of the quality (stability) of the transmitted signal was realised using a K+K phase comparator. A simplified block diagram of the experiment is shown in Figure 2.



4 Figure 2: Block diagram of the experiment Modification of Laser Stations for Unidirectional Transfer

The system dedicated to the bidirectional transfer of OC based on a single optical fibre has a Faraday mirror at the remote end that rotates the reflected signal by 90 degrees. This mirror ensures that the rotated signal approaching the sender (local laser station) will have the 'correct' polarisation, allowing it to be beaten with the transmitted (reference) signal (OC signals are strictly polarised). This beat note signal is necessary to determine the phase (propagation delay) changes of the OC signal in the optical fibre and to determine the necessary signal (frequency) correction (in the feedback loop). However, splitting transmission in two opposite directions between two physically different optical fibres means that the Faraday mirror at the remote end has lost its fundamental role. The mirror is unable to guarantee the correct polarisation of the returned signal due to the fact that the polarisation change in the two different fibres is not the same. As a result, maintaining the orthogonal polarisation of the signals (local and backward) is random. Such a system may work well for many days without any disturbance, but may also suffer for long periods of time from so-called cycleslips, that is, unexpected phase shifts of the signal (an example of cycleslips is shown in Figure 3).

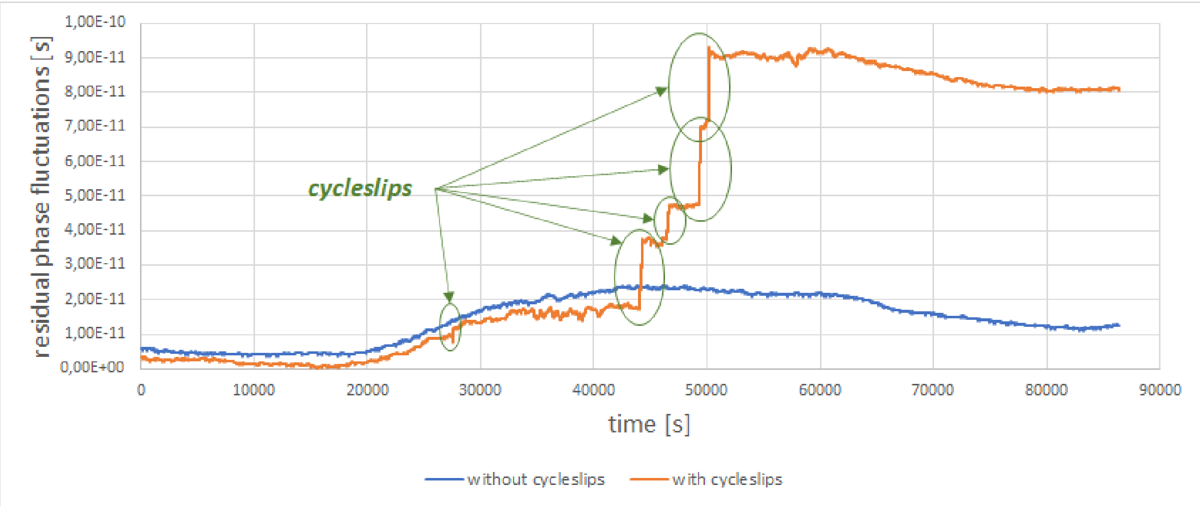


Figure 3: Example of cycleslips due to improper polarisation of the returned signal on the curve of residual (uncompensated) delay fluctuations

Therefore, it is necessary to implement an automatic polarisation control system operating for a single, reversed transmission direction (the place where the controller is plugged in is important). In our tests, two independent automatic polarisation control systems were deployed (see Figure 4), the second of them (located in the remote module) is responsible for maintaining the correct (fixed) polarisation of the output signal.

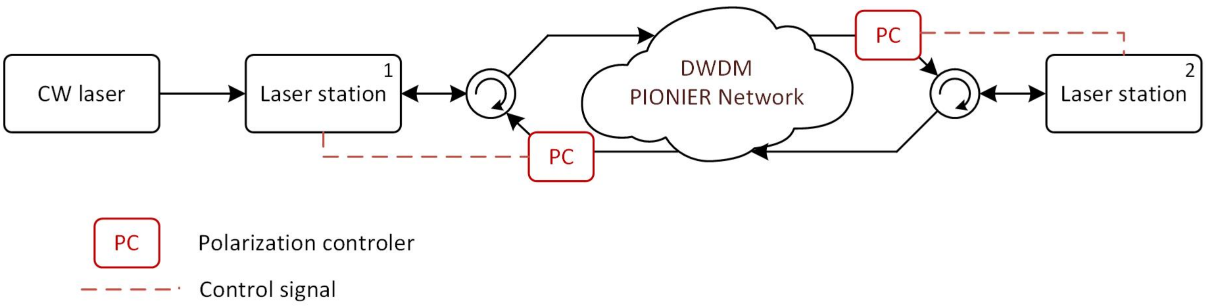


Figure 4: Placement of polarisation controllers in the OC unidirectional distribution system

In addition to the above-mentioned modifications in the OC signal distribution system for the unidirectional network, it is also necessary to adjust the settings of the individual feedback loops due to the total link length (line latency). The adjustment of these settings is specific to the hardware solution and unfortunately, there is no universal rule for solving this problem. In the described case, the hardware was constructed at PSNC so adjusting it to the needs of the link was significantly simplified.

5 Results

The performance of the solutions and modifications of transmitting devices (laser stations) described in Section 4 were verified in the operational PIONIER DWDM network (see Figure 1).

The tests focused on verifying the effectiveness of individual technical solutions discussed in more detail in Section 4. As a result, the stability of OC signal transfer in an unmodified DWDM network (unidirectional) was obtained around 1E-16 level for longer averaging times (more than one day). For short averaging times, this stability is almost 2E-14 (@1 sec). Detailed results are shown in Figure 5 in the form of the modified Allan deviation (MDEV).

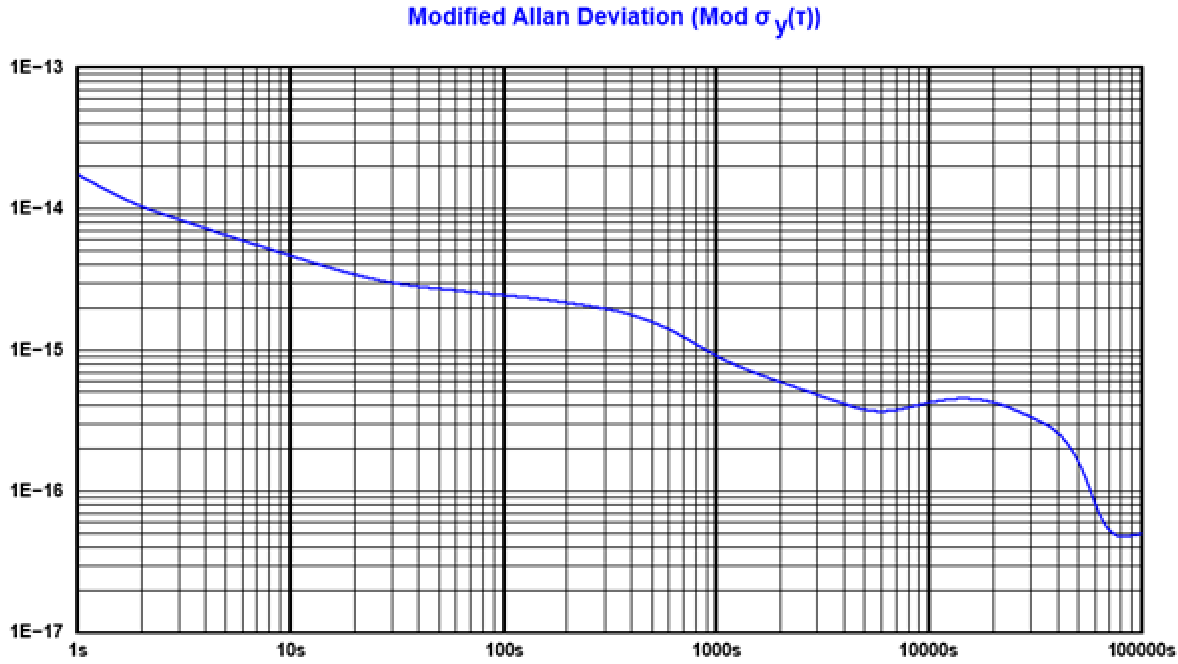


Figure 5: MDEV of OC signal transfer in unidirectional DWDM system (2100 km)

These results are consistent with previous experiments conducted at PSNC [STAB]. Short-time transfer stability is mainly limited by the number of nodes with DWDM devices and the efficiency of the air-conditioning systems (understood as the ability to accurately maintain a set temperature) located at these nodes. For long averaging periods (longer than one day), the influence of the asymmetric fluctuation of the signal propagation time in a pair of optical fibres dominates (influence of line cables). This influence is proportional to gradient of temperature changes and the total length of the fibre optic line.

As can be seen in the time plot shown in Figure 6, during the presented observation period, the phase difference of the transmitted and received signals shows a constant trend with a slope of -1E-16. In practice, this means that in addition to the component of fast (less than 24-hour) changes of the reference frequency at the output (well characterised by MDEV - see Figure 5), there is also a frequency offset not visible in the MDEV diagram and which, in the given case, is just ~1E-16. The source of this offset was identified in [STAB] and is caused by the asymmetric change in the delay of propagation in a pair of optical fibres in one cable. This differential delay change also affects the final frequency accuracy, and is therefore important for the accuracy of comparisons between two OC signals generated by the reference devices. The amount of reference frequency offset introduced depends on the fibre cable's temperature change over time (speed of temperature change) and the total length of the fibre line (the longer the fibre line the greater the change in differential time of propagation in the fibre pair) [STAB]. Unfortunately, accurate measurement of frequency offset values is not possible in practical implementations of OC signal distribution systems due to the fact that both ends of the line are not located in the same place. We estimate that the offset introduced by the transmission line on the target Poznań–CERN route may be approximately +/-2E-16. Moreover, appropriate algorithms and hardware solutions do not yet exist to reduce the transfer uncertainty associated with the mechanism described above that causes an offset in the transmitted reference frequency.

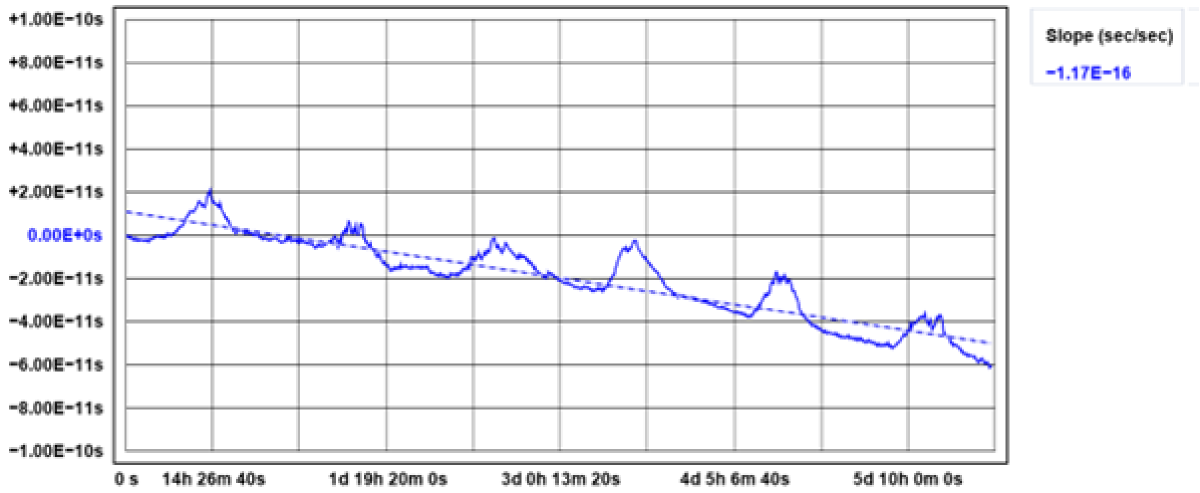


Figure 6: Residual (uncompensated) phase fluctuations of transmitted OC signal in unidirectional DWDM system (2100 km).

The effectiveness of automatic polarisation control systems was also positively verified. The number of cycleslips has been significantly reduced and they now occur sporadically (no more frequently than in systems based on dedicated, single optical fibres).

6 Conclusions

The tests carried out confirmed the possibility of optical carrier transfer in an unmodified DWDM (unidirectional) network. However, they also showed that the terminal equipment used must be suitably adapted by means of an additional polarisation controller. As shown in the unidirectional experiment, the transmission of an OC signal using a pair of fibres over such a long link (more than 2000 km) negatively affects the stability of the transmitted reference frequency. The long-term stability at 1E-16 is probably about two orders of magnitude worse than solutions using bidirectional transmission. The frequency offset caused by the differential delay variation of the fibre pair must also be taken into account in the link quality estimation. Despite the above limitations resulting from unidirectional transmission, the achieved transfer quality is still better than in solutions using satellite links (for a similar averaging range).

This experiment which simulated the planned deployment on the Poznań (Poland)–CERN (Switzerland) line was thus considered successful, and its implementation is expected to be performed soon for the benefit of the metrology community.

References

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[STAB]	K. Turza, P. Krehlik, Ł Śliwczyński - “Stability Limitations of Optical Frequency Transfer in Telecommunication DWDM Networks”, 2019, DOI: 10.1109/TUFFC.2019.2957176

Glossary

CERN	European Organisation for Nuclear Research
DWDM	Dense Wavelength-Division Multiplexing
MDEV	Modified Allan Deviation
OC	Optical Carrier
PSNC	Poznan Supercomputing and Networking Center