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Time and frequency transfer over optical networks

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Abstract:

This paper aims to summarize and express network requirements of time and frequency transfer over optical networks performed in National Research and Education networks of France and Czech Republic. Time transfer experiment in Czech Republic converts microwave output frequency of cesium atomic clocks into train of optical pulses that carries accurate time over all-optical network with two network domains. Frequency transfer experiment references optical comb etalon to frequency of atomic clock. An optical frequency of optical comb is then sent throughout optical network in a single bidirectional channel. The paper highlights advantages and challenges of both transfer approaches.

Keywords: Time Transfer, Frequency Transfer, Optical Networks, Special Applications, Backbone Networks

1. Introduction

Today we really live in an electronic world surrounded by electric devices of all kinds. They communicate with us as well as with each other to enhance and support our life. Communication or even their very function would not be possible without timing information. Moreover in some cases the more accurate the timing information is the better is device performance. Therefore time etalons has been established and became time standards.

The time standard is usually provided by cesium atomic clocks that are placed all over country. The time information between atomic clocks is compared and averaged to determine the Coordinated Universal Time (UTC) that is then distributed throughout the country. The preferred method of comparison of atomic clock time standards was by radio signal using satellites that required complex instruments. Advances in optical networking have opened a new comparison option by using light pulses that are timed accurately every second with a resolution in the order of tens of nanoseconds 1. Or more precise method of ultra-stable frequency transfer can be used that utilize one bidirectional channel and advanced synchronization mechanism to lock onto frequency source 1. The transfer of time or ultra-stable frequency between two distant points is required by experts working in the fields of time and frequency metrology, astrophysics, particle accelerators and fundamental physics. One straightforward and beneficial approach is to utilize NRENs that already connect many research institutes and universities 34. Here a successful transfer of both time and ultra-stable frequency has been already demonstrated over a network with live traffic 5.

2. Time Transfer

A time transfer system that converts microwave frequency from an atomic clock to an optical pulse train has been developed in CESNET within the Czech-Austrian experimental project. This system implements a two-way transfer method that relies on a symmetrical transport delay in both directions. In such a system two adapters are connected by a bidirectional optical link over optical fiber pair. These adapters are based on a Field Programmable Gate Array (FPGA) Virtex-5 chip and use Small Form-factor Pluggable (SFP) transceivers for electro-optical conversion of time information. Figure 1 shows a working sample of a developed adapter.

Figure 1: Working sample of a two-way transfer adapter

Produced optical pulse train is sent directly into DWDM optical backbone network. As time transfer method is very sensitive to end-to-end latency jitter, the pulse train preferably must not leave optical domain and evade all Opto-Electro-Optical (OEO) regeneration sites. Electric processing in regeneration sites usually adds variable delay to the pulse train unless an OEO regeneration site designed for time transfer is used.

In the pilot experiment the all-optical path was created through the operational DWDM network of CESNET. The part of network uses Cisco DWDM system and the other part OpenDWDM system of CzechLight. The CzechLight DWDM link was operating in a so-called “hut-skipping” or Nothing-In-Line (NIL) regime overcoming distance of 220km. The overall setup is shown in Figure 2.

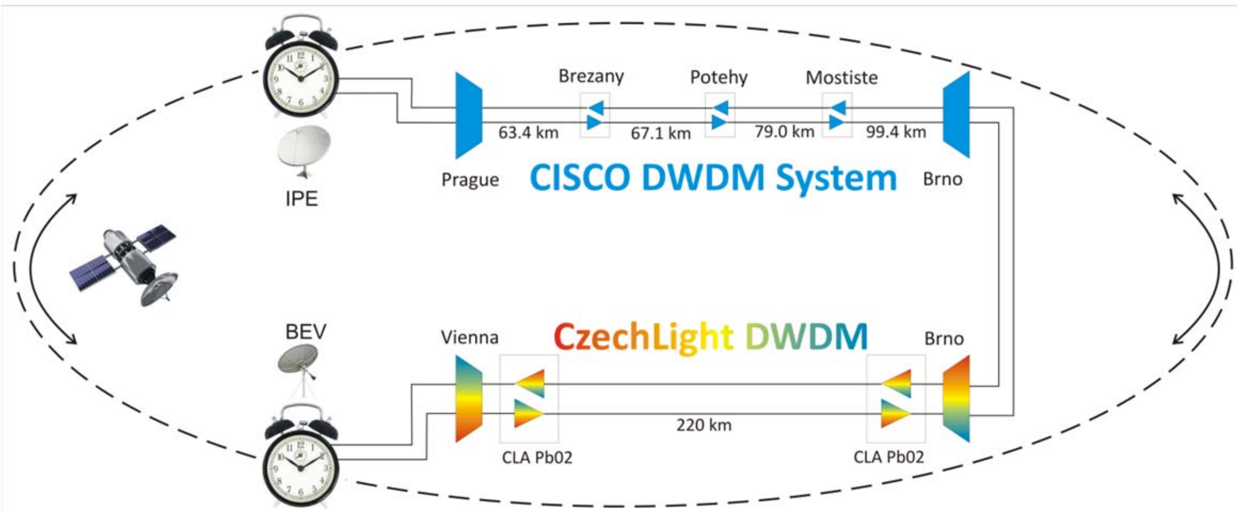

Figure 2: IPE - BEV all-optical path

We offer this time comparison of atomic clocks over our optical network as a Photonic Service, because underlying network is able to establish all optical channels on demand. The Photonic Service between Czech and Austrian national time and frequency laboratories in Prague and Vienna was brought into operation in August 2011. All-optical, a Photonic path, between the Institute of Photonics and Electronics (IPE) in Prague, and the Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna has a total length of 550 km and consists of several segments. The longer part of link, connects Points of Presence (PoPs) in Prague and Brno. This part utilizes a dedicated optical channel of 100 GHz in the Cisco DWDM system of CESNET2 production network. The part of link between Brno and Vienna University uses the same DWDM channel across borders but in OpenDWDM system of CzechLight. Both national laboratories covered the last mile to the NRENs point of presence using rented dark fiber lines. The optical pulse train is amplified by 7 EDFAs (Erbium Doped Fiber Amplifier) and uses the same dedicated optical channel at 1551.72 nm wavelength (i.e. C-band, ITU channel #32) in both directions. A description of particular segments is summarized in **Error! Reference source not found.**.

Segment	Length [km]	Attenuation [dB]	Technology
IPE – CESNET PoP	16	7.0	dark fiber
CESNET PoP – Brno University	309	78.6	Cisco ONS (DWDM channel)
Brno University – Vienna University	220	50.0	CzechLight (DWDM channel)
Vienna University – BEV	5	1.5	dark fiber

Table I: Photonic Path Segments

The optical method of time transfer has been compared with the Common View GPS standard method and recently also with more accurate Precise Point Positioning (PPP) method 55. A very good correlation between optical time transfer and GPS based methods was observed. The difference between optical time transfer and PPP method is up to 200 ps with observed daily periodicity. Measurement data of the time stability are shown in Figure 3. The red line represents optical measurement data, the green line stands for Common View GPS method, and the blue line shows the stability computed according to PPP method.

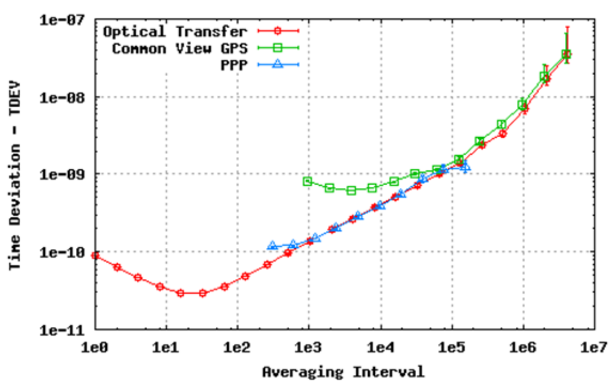

Figure 3: Time stability measured using an optical link (red), via GPS (green) and computed by PPP method (blue)

It is important to note that the Photonic Service of time transfer is now running over the same fibers as IP traffic and on an adjacent channel with no measurable impact on IP traffic. The slight advantage in optical time transfer method accuracy is multiplied by simple network requirements as both commercial and OpenDWDM optical networks can be used without modifications.

2. Frequency Transfer

Since 2010, the LNE-SYRTE (Laboratoire national de métrologie et d'essais – Système de Références Temps-Espace) and the LPL (Laboratoire de Physique des Lasers) laboratories have been working with the French NREN RENATER, to realize ultra-stable frequency transfers on the RENATER-5 live network by using a dedicated ITU-T DWDM wavelength. In 2012, they applied successfully for funds to launch a project called in French REFIMEVE+ (Metrological Fiber Network with European Vocation). The purpose of this project is to build a national infrastructure on RENATER fiber, capable of disseminating ultra-stable frequency signals to scientific laboratories that need to work with high-accuracy instruments. European interconnections by cross-border fibers will also be studied within this project.

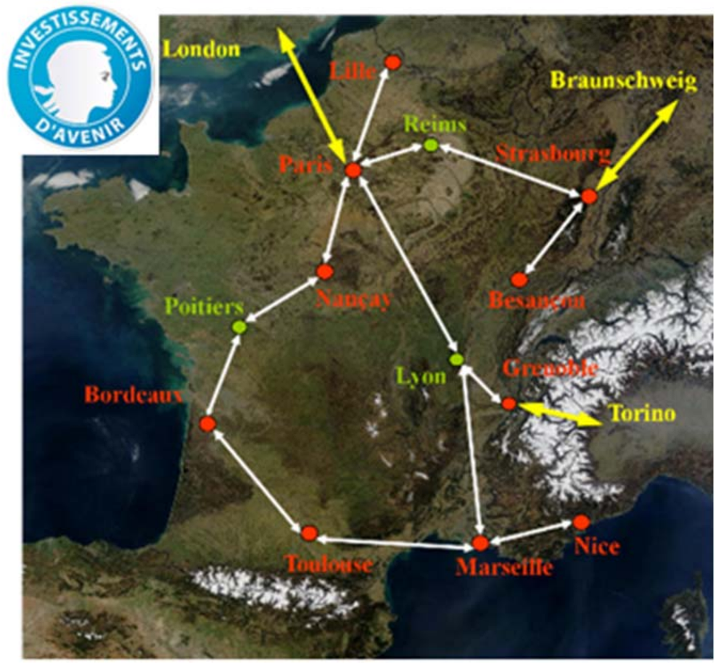

Figure 4: REFIMEVE+ project infrastructure

Unlike legacy DWDM systems where modulated data is carried (e.g. with NRZ, DQPSK…), data carried in REFIMEVE+ is a frequency, or said in another way, an ultra-stable wavelength chosen on the light spectrum. This frequency is sent by a thin, constant and low-powered laser beam emitted from the Paris Observatory to the laboratories.

To ensure the spectral stability of the frequency at destination, a control loop is built by sending the frequency back to the Observatory. A signal correction is then performed by comparing the source and the frequency having done a round trip. Hence the main particularity of this photonic service is its bidirectionality, which is incompliant with legacy DWDM systems that require isolators most of the time.

To deal with this issue, dedicated Optical Add-Drop Multiplexers (OADMs) were inserted in each fiber segment between the RENATER optical devices already in production.

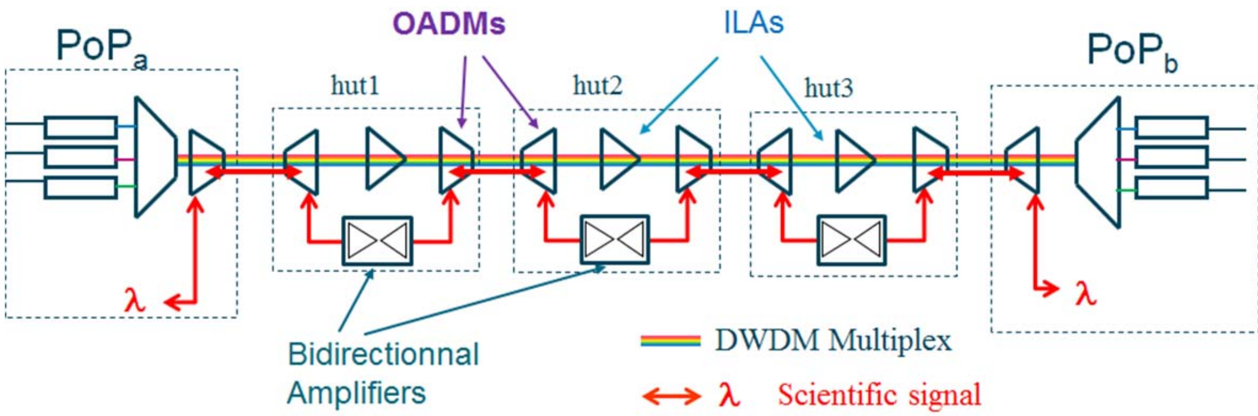

Figure 5: REFIMEVE+ circuit deployment in RENATER

A review of optical budgets on each impacted link was made in RENATER to guarantee the continuity of existing DWDM circuits while inserting new equipment and therefore adding losses to links. From this design review, it was possible to derive the power adjustments necessary on the transceivers and amplifiers during the deployment. Finally and as expected, a loss average of 2 dB was observed between the RENATER equipment on each span. During link re-engineering a further check was made to ensure that the link capacity (maximum amount of DWDM channels supported by the network design) would not be affected by the OADM insertions. Moreover, a theoretical study verified that no impact on the optical supervision channel should have been expected. This channel, which uses a 1510 nm wavelength, cannot be re-amplified by the EDFA classically used by telecommunication networks and therefore an additional loss on optical budgets could have been harmful to its transmission.

Consideration was also given to the selection of DWDM channel used to transmit the project signal. As the RENATER-5 architecture had been conceived for DWDM transmission on C band (1565 nm to 1530 nm), a wavelength from this spectrum part was reserved to minimize disturbance to production traffic. Channel availability was studied on each backbone link, to avoid, as far as possible, selecting a wavelength that required the modification of too many existing DWDM circuits. Moreover, the viability of interconnection with neighbouring NRENs was ensured by selecting the same #44 DWDM channel.

The use of an existing DWDM backbone to deploy an ultra-stable frequency circuit involves therefore some technical constraints, but this solution still remains interesting compared to a deployment on dedicated fibers because it enables SYRTE and LPL to benefit from RENATER's mesh and connectivity, while avoiding the costs due to fiber location and the time spent on fiber procurement.

In 2011, a frequency signal was transmitted on 540 km from Paris to Reims using 468 km of RENATER fiber and bypassing two in-line amplification sites. In the Reims point of presence, the ultra-stable signal coming from one of the fibers was looped back to the other fiber to the

LPL. The circuit is shown in Figure 6 below. In this way, both link end points were located in LPL, making it easier to evaluate the transmission and stability performance of the optical link. Stability and accuracy of the transmitted clock signal was 10-19 during a day. This result is beyond requirements and demonstrates the feasibility of the architecture deployed to achieve a long-haul circuit. Moreover, no perturbation between RENATER traffic and REFIMEVE+ frequency was noticed as so far on the DWDM backbone.

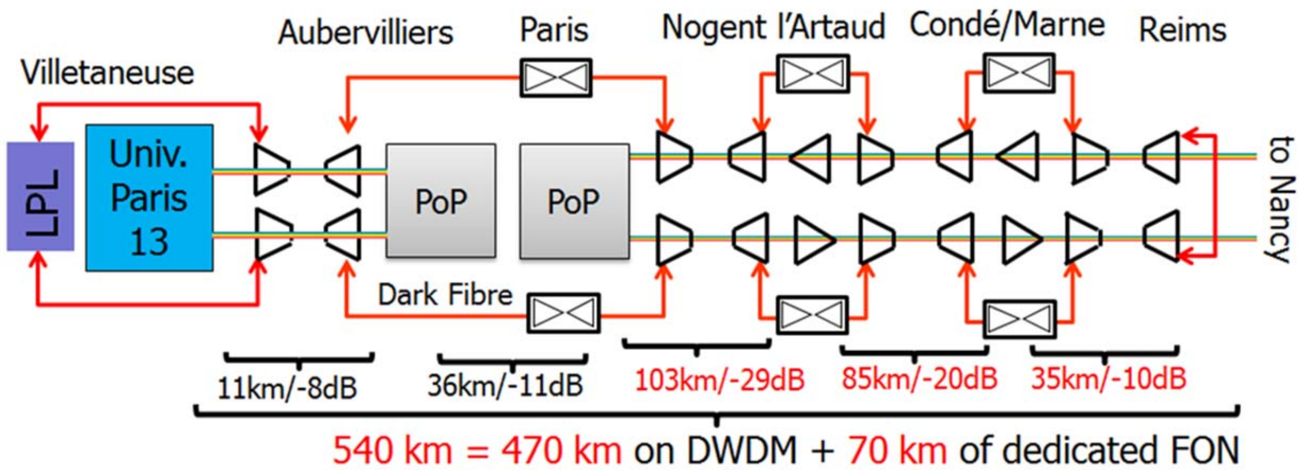

Figure 6: Circuit deployed in RENATER in 2011

A new extension is already deployed to Nancy (1100 km) and bidirectional amplifiers will be installed on the link in 2013. The next step is to complete the deployment of the REFIMEVE+ national infrastructure to ensure the capacity of the project partners to develop a scalable solution. A middle term goal (end of 2013) is to reach the German border to interconnect to an ultra-stable signal coming from German laboratories.

A new technique of ultra-stable optical link was demonstrated, which should make it possible to interconnect European metrology laboratories and to compare a very large number of optical clocks. The best frequency references developed in these metrology laboratories then become available to any laboratory, opening the way to a wide range of applications in the field of high-accuracy measurement: antenna networking in astrophysics, fundamental constants measurements, satellite link tests, fundamental physics tests, geodesic applications, etc.

4. Conclusions

The paper discusses transfer of two basic physical quantities, time and frequency. It provides details on optical network implementation of both methods of transfer. Time transfer over optical networks is another method to compare standard atomic clock trading part of its accuracy for simplicity of network implementation. Still the performance of this method is slightly superior to standard microwave methods. Implementation and performance is shown over multi-domain optical DWDM network. The frequency transport over optical network is a suitable method of optical atomic clock comparison with sufficient accuracy and resolution. This method requires bidirectional channel and amplification throughout optical backbone network, but can share fiber infrastructure together with standard IP traffic. The importance of this method for future metrology and frequency distribution was recognized by European Union and supported in project REFIMEVE+.

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