Photonic Services for Real-time Applications
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Innovation through participation

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- Authors participate on following projects:
  - GÉANT - GN3, www.geant.net
  - Large infrastructure CESNET, www.ces.net

Outline

- Motivation
- Overview of photonic services, advantages and disadvantages, general applications and possible implementation over fiber networks
- Examples
  - Accurate time transmission
  - Stable frequency transmission
- Q&A

Motivation

Applications **interacting with external processes** (i.e. running outside network) where timing of interaction limits quality or even the acceptability of results require real time network services.

- Remote access or control of unique instruments due to location and/or cost
  - examples: telescopes, medicinal instruments, stable/accurate clocks, ...
- Remote real-time data collection (e.g. early warning)
- Remote interactive collaboration

Photonic Service

- End-to-end connection between two or more places in network
- Described by photonic-path and allocated bandwidth
    - Photonic-path is a physical route that light travels from the one end point to the other or to multiple other end points respectively
    - Allocated bandwidth is a part of system spectrum that is reserved for user of Photonic service along the Photonic-path.
    - Minimal network impact on transmitted data
    - Path all-optical, no OEO except special cases.

Photonic service

- Advantages
  - Transparency to transmitted signals
  - Low and constant transmission latency (negligible jitter),
  - Future-proof design thanks to grid-less bandwidth allocation.
- Disadvantages
  - Limited service reach (no universal all-optical regeneration)
  - Potential waste of bandwidth.
  - All-optical nodes should be grid-less and direction-less.
  - Absence of global management in multi-domain scenario.
  - Possible problems with multi-vendor network interoperability.
    - *tests were already successful, e.g. concurrent 100GE and precise time transmission.*

Photonic services for real-time applications

General applications

- ***Interactive human collaboration***
  - Latency jitter limit: 10-50 ms (adaptive play-out delay buffer)
  - End-to-end latency: 100-200 ms
  - Penalty: mild (user disappointment).
- ***High definition video and Cave-to-cave***
  - Latency jitter limit: 20 ms (buffer dependent)
  - End-to-end latency: 150 ms
  - Penalty: mild (user disappointment).
- ***Remote instrument control***
  - Latency jitter limit: 20 ms
  - End-to-end latency: 100 ms
  - Penalty: depends on application (e.g. severe in case of tele-surgery)

General applications

- ***Comparison of atomic clocks***
  - Latency jitter limit: 50 ps (short time, typ. over 1000 s) and 1 ns (long time fluctuation, typ. over days)
  - End-to-end latency: should be minimized to the optical signal propagation delay
  - Penalty: mild (experiment failure) - principal (service impossible)

- ***Ultra-stable frequency transfer***
  - Latency jitter limit*: N/A
  - End-to-end latency: should be minimized to the optical signal propagation delay
  - Penalty: mild (experiment failure) - principal (service impossible)

*The term *jitter* is not appropriate here. The phenomenon is rather expressed as a stability that should correspond to the stability of primary frequency standard, e.g. 10^{-17} in ultimate case of optical clocks.

Possible implementation

- Dark fiber (unlit fiber)
  - + full spectrum available
  - + freedom in deployed equipment
  - + no interference with other transmissions
  - - very expensive esp. over long distances (deprecations/rental fees, maintenance….)
  - - difficult putting into service and troubleshooting

Possible implementation

- Dark channel – dedicated unlit bandwidth in fiber (e.g. traditional equipment bypassed)
  - + freedom in deployed equipment
  - + reduction in cost
  - - may exists interaction with other parallel transmissions
  - moderate cost of putting into service and troubleshooting

Possible implementation

- All-optical lambda – lambda passing through transmission system
  - + minimal cost
  - + simple troubleshooting and maintenance
  - - unidirectional channels (isolators in EDFAs, WSSs)
  - - noise and interaction with parallel transmission

Demonstrations

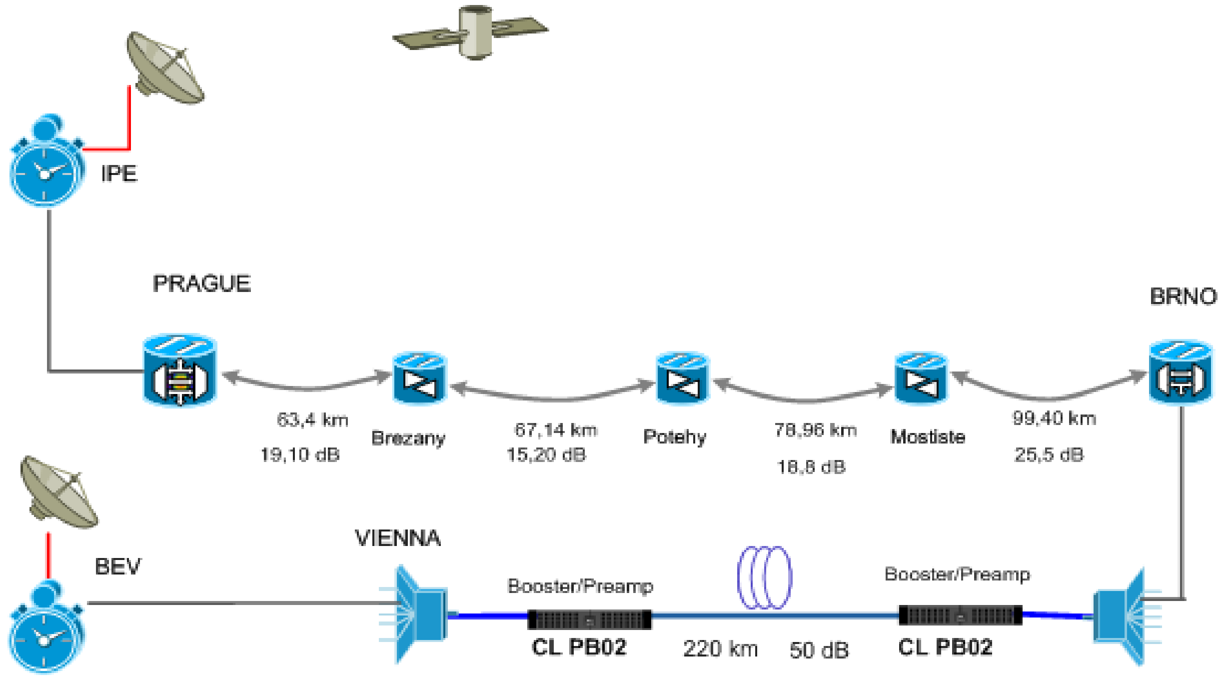
High definition video (e.g. 3D Full HD, 2K, 4K) broadcast

- Utilization of all-optical lambda
- Remote demonstration of a kidney surgery by robotic instrument (da Vinci robot) from the Masaryk Hospital in Ústí nad Labem, stereo 3D Full HD
  - About 2.5 Gbps stream
  - Specialized video processing device latency – up to 1ms
  - To Prague,CZ (130km/80mil by fibre), transmission latency <1ms
  - To Brno,CZ (550/340mil km by fibre), transmission latency < 3ms
  - To Tsukuba,JP, IP service, transmission latency about 150ms

Photonic services for real-time applications

Time transfer

- Comparison of time scales UTC(TP) and UTC(BEV), Caesium beam 5071A/001 atomic clocks, in operation since Aug 2011
  - Mixture of fibre types (G.652/655)
  - Mixture of transmission systems Cisco/Open DWDM Czechlight
  - Mixture of CD compensation types (DCF, FBG)
  - One way distance 550km/340miles (including 220km/137miles NIL) 137 dB



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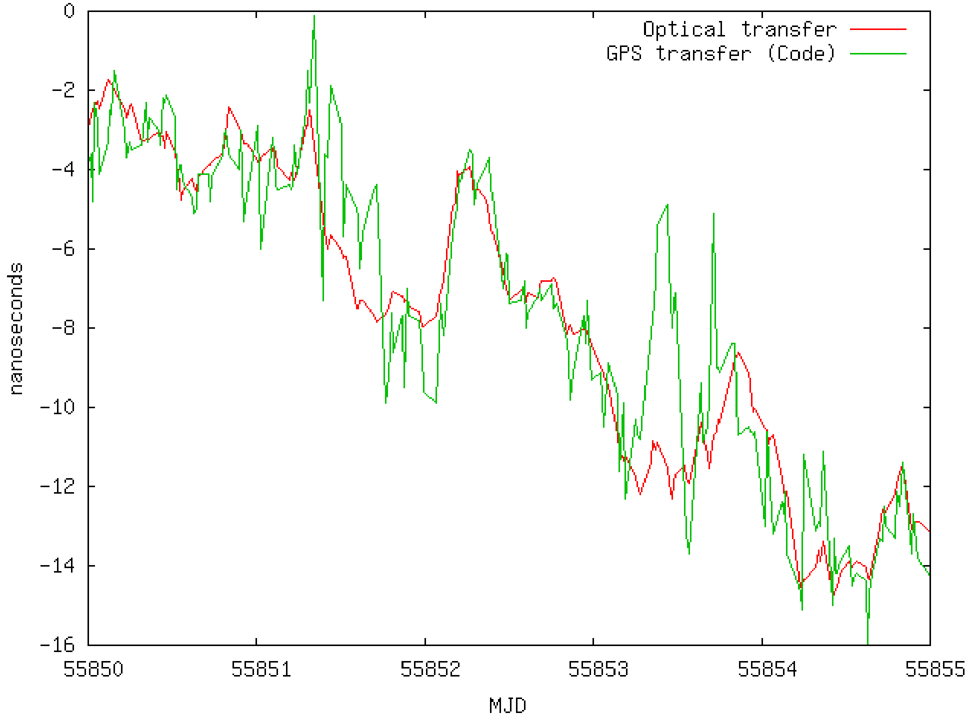
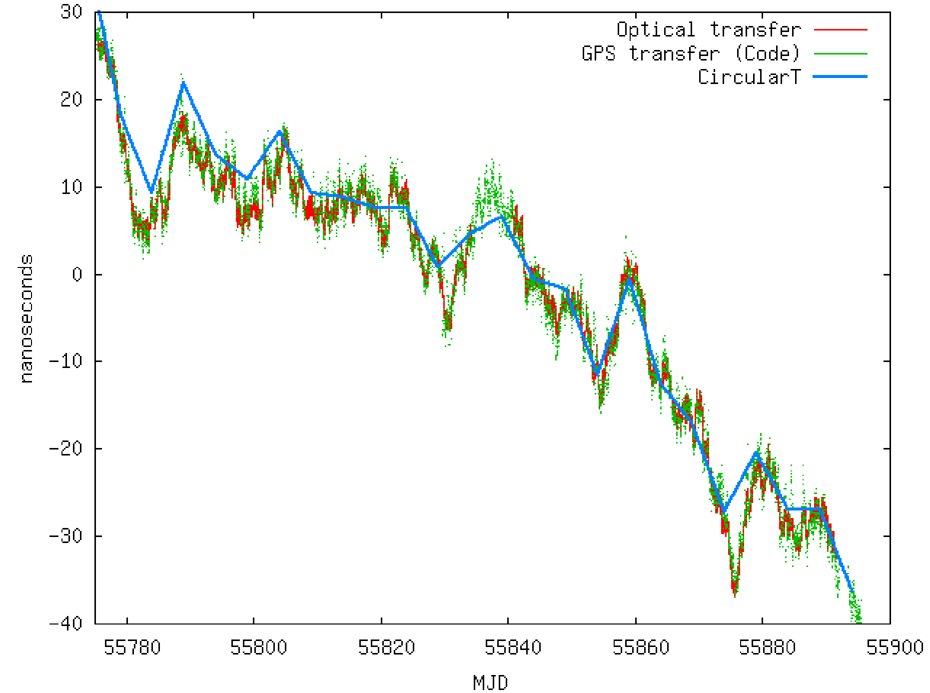
Time transfer





Red: optical transfer - linear regression over 780s

Green: GPS CV

Red: optical time transfer

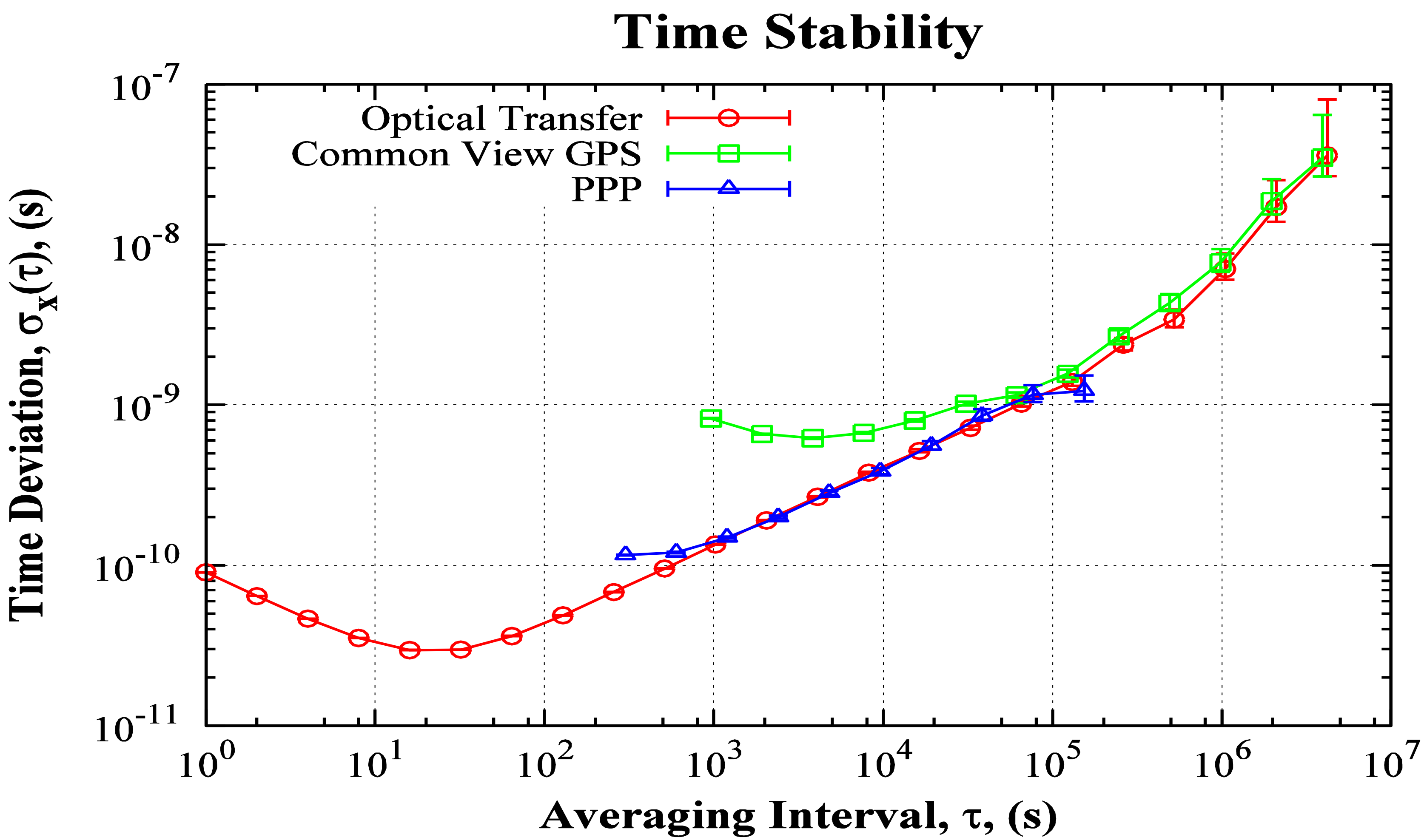
Green: GPS CV

Blue: Circular-T data

Significantly smaller short term noise

Photonic services for real-time applications

Time transfer



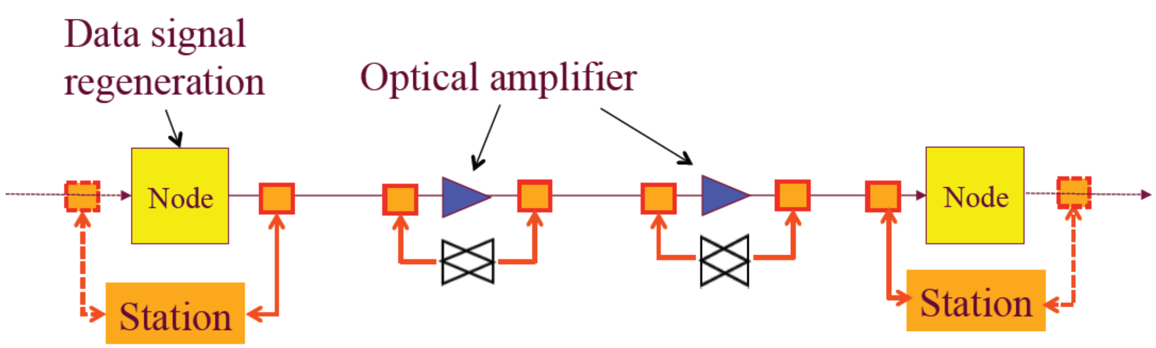
Smaller noise than both GPS methods

TDEV 30ps @ 20s averaging,

130 ps vs. 800 ps for 1000s averaging

Photonic services for real-time applications
Frequency transfer

- **Ultra-stable frequency transfers on live network RENATER**
- Utilization of dark channel
- Transmission of ultra-stable CW optical frequency itself (in band of 1550nm)
- Needs exactly same path in both directions for noise correction
- Telco unidirectional devices must be bypassed (e.g. EDFAs)



Source: G. Santarelli at al . ”Transmitting ultra-stable optical signals over public telecommunication networks”

Bypass : bidirectional amplifiers + OADM (+ AOM?)

Station : every 400 km -600km

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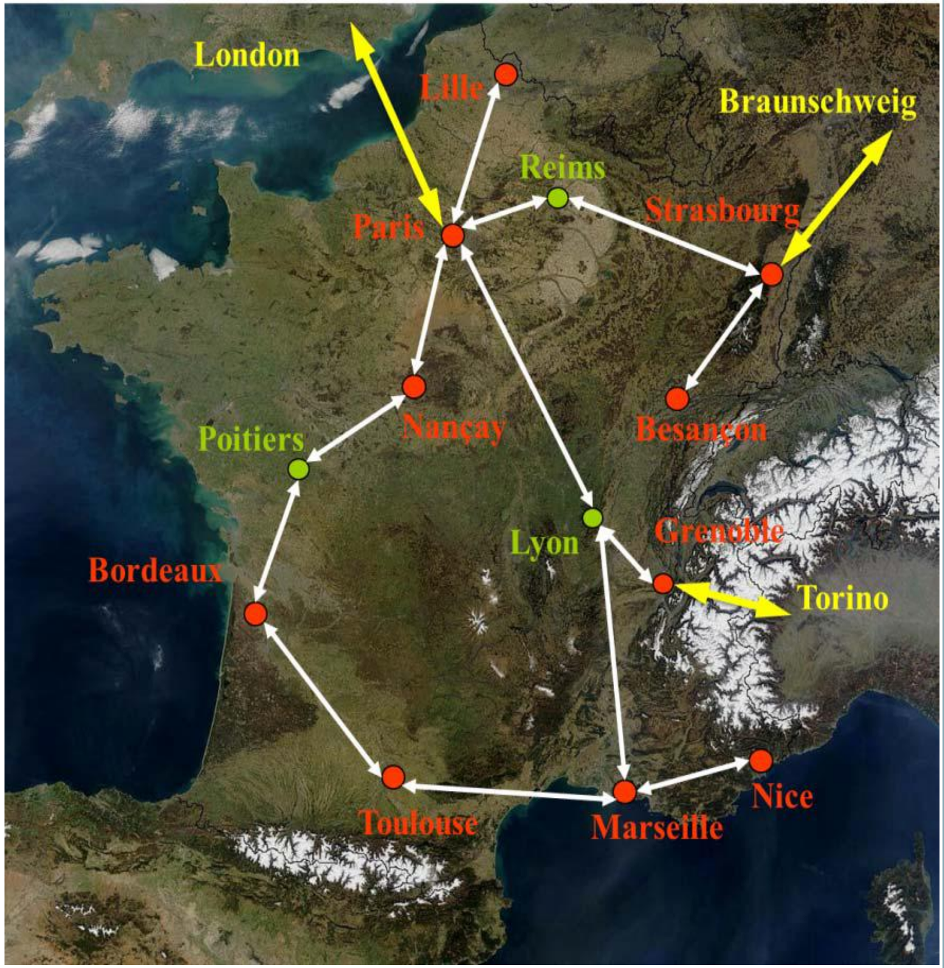
Frequency transfer

- **Ultra-stable frequency transfers: MPQ-PTB germany**
- Max-Planck-Institut für Quantenoptik (MPQ) in Garching and Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig,
- 2009 – dedicated fibre146km/90miles
- Dedicated fibre, 920km/572miles, 200 dB attenuation, bidirectional transmission and active stabilization
- 9x low noise bidirectional EDFA and Fibre Brillouin amplification with distributed gain
- Achieved stability 5×10^{-15} in a 1-second integration time, reaching 10^{-18} in less than 1000 seconds.

Ref: A. Predehl at al "A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place**", Science 2012**

Photonic services for real-time applications
Plans

- LPL-Nancy-LPL 1100km/684miles with one regenerator station
- LPL-Strasbourg-LPL1476km/713miles with three regenerator stations
- **RENATER: REFIMEVE+ Project:**
- RENATER, LNE-SYRTE and LPL laboratories applied for REFIMEVE for building of national infrastructure on RENATER fiber, able to disseminate ultra-stable frequency
- Planned start in 2012
- Interconnections on cross-border fibers would also be studied



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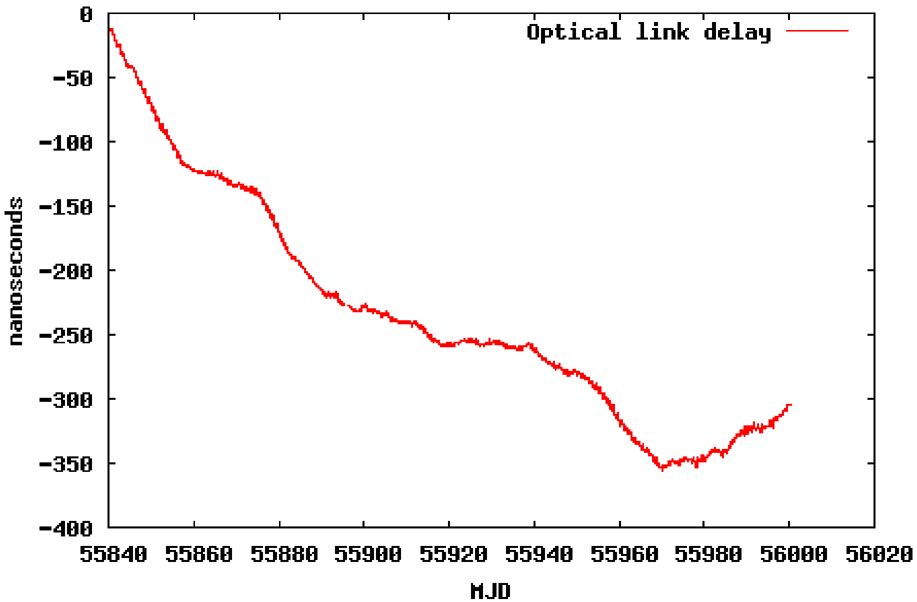
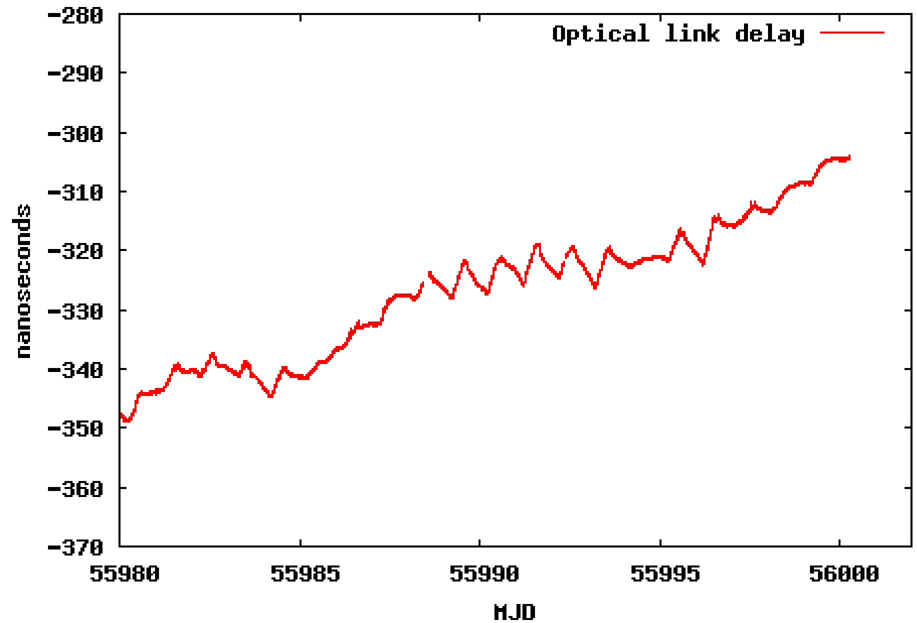
Thank you for attention!

Questions?

Photonic services for real-time applications
Time transfer





Propagation delay

Left: Seasonal October 7 2011 - March 14 2012 approximately 350ns, $1.3 \cdot 10^{-4}$ of avg. delay 2788 µs

Right: Daily changes 4-7ns

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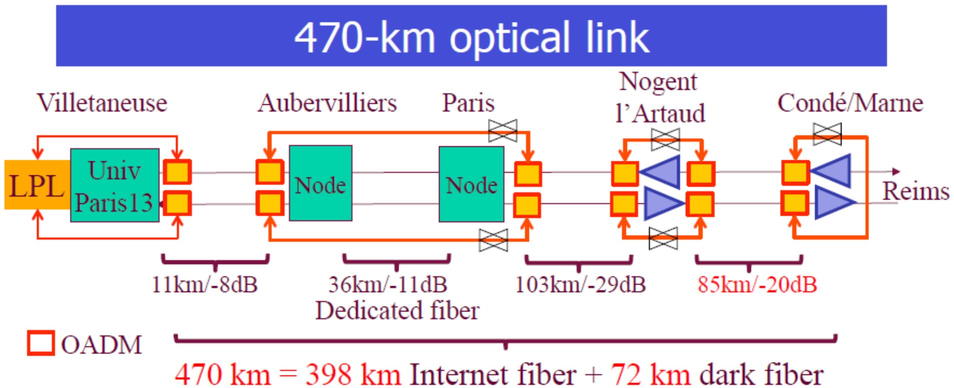
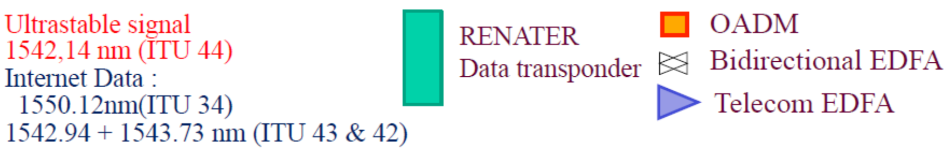
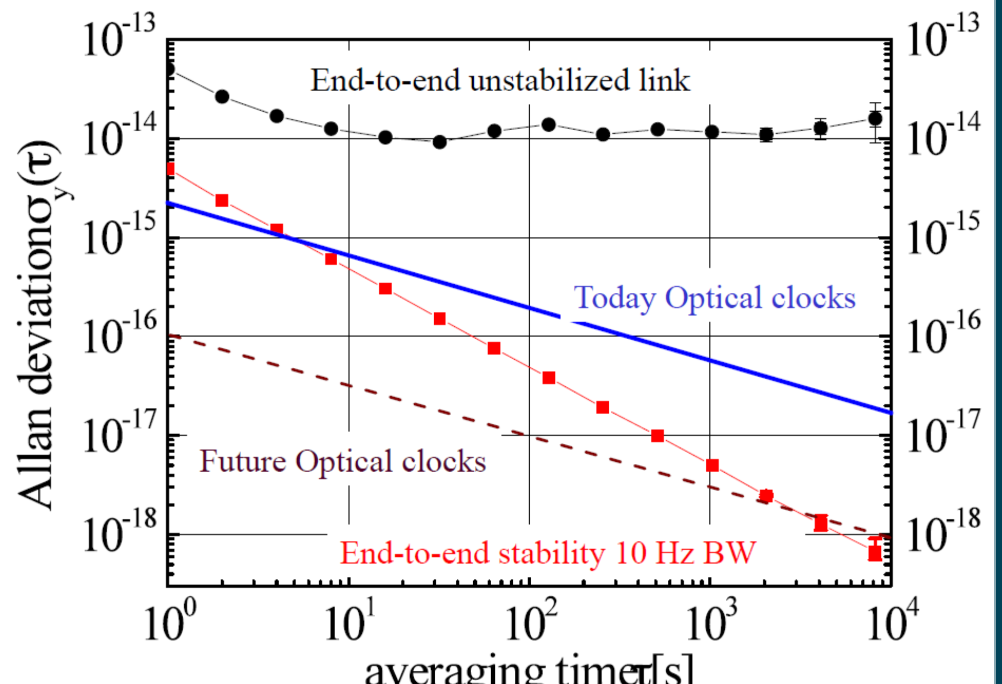
Frequency transfer

- **Ultra-stable frequency transfers on live network: RENATER**



- One-segment link – 12 OADM
- 136 dB attenuation compensated by 5 bidirectional EDFAs (+100 dB)





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Deviation 5x10e-15 at 1s averaging
8x10-19 at 10000s averaging