Long-haul White Rabbit Time Distribution:

Challenges and solutions for white rabbit time distribution over long-haul DWDM systems

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GEANT InfoShare
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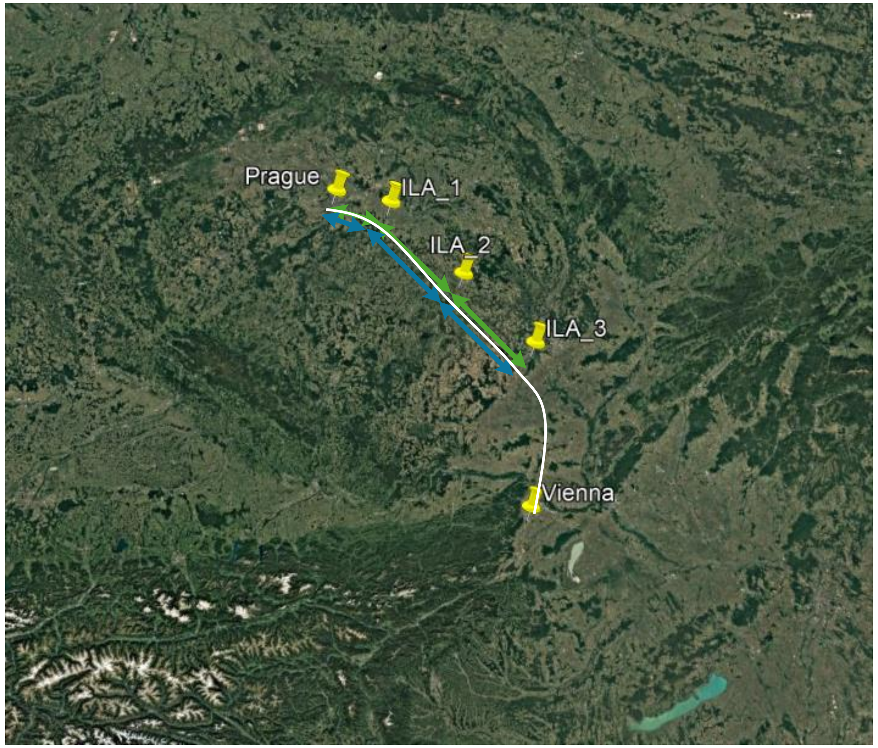
GN5-2 WP6 NETDEV Incubator Project
(April 2025 to Feb. 2026)

- Partners: GEANT, SIKT, CESNET, SUNET, FUNET, GARR
- Goal:
  - learn from existing deployments of WR over long-haul DWDM systems and carry out lab and field tests focusing on bidirectional WR transmission
- Requirement
  - coexistence of white rabbit 1G & 10G legacy OOK modulation and coherent signals: no impact on data traffic!
- Objectives:
  1. Survey on status of current WR deployments in NRENs & NMIs
  2. Evaluate performance in lab and field of the different bidirectional regeneration techniques
  3. Cost-benefit analysis
  4. Recommendations: best practices on how NRENs can get the best out of WR time service in their networks

Main deliverable: Whitepaper
"*Best Practices for Deploying White Rabbit Time Services in Long-Haul DWDM NREN Networks* "



Field-trial on GEANT Prague – Vienna link

~500km optical link with loop

Disclaimer: the project does not consider or evaluate calibration techniques.
All tests are run without pre-calibrated system and relative performance is compared.

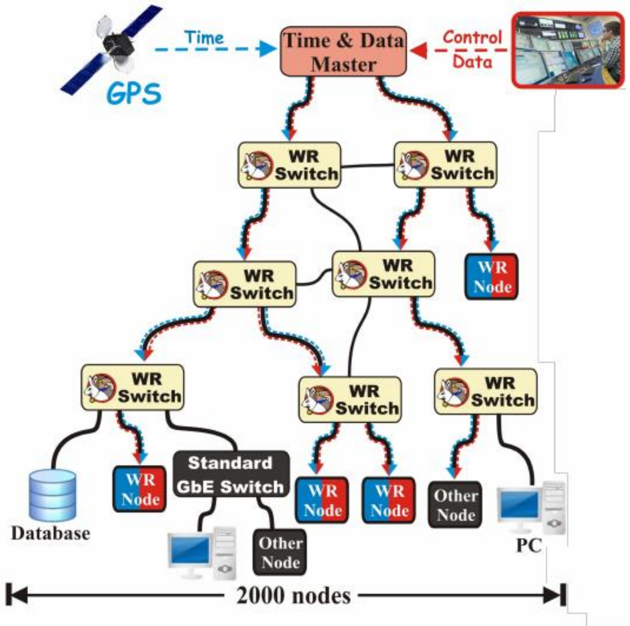
Content

Whitepaper structure and agenda of this infoshare

- Part 1 (this presentation)
  - Challenges & solutions for WR bidirectional transmission over DWDM
  - EU Landscape: status of WR time service deployments across European NRENs and NMIs
- Part 2 (Jaromir Sima)
  - Laboratory tests
  - Field-trial
  - Results analysis
- Part 3 (Guy Roberts)
  - Cost-benefit analysis
  - Recommendations of WR time-service deployments

White Rabbit Protocol for Sub-Nanosecond Time Accuracy
IEEE1588-2019 High Accuracy Profile

- First developed at CERN in 2008, meant for Big Physics facilities, e.g. CERN, GSI, NIKHEF
- Enhancements to Precision Time Protocol (PTP IEEE1588-2008):
  - Clock syntonization over the physical layer using Synchronous Ethernet (SyncE).
  - Enhancement of timestamps precision through phase measurement.
  - Evaluation and compensation of hardware and transmission link asymmetries
- Open Source and commercially available
- Initial specs for links < 10km and scalable to 2000 nodes. Being deployed for long-haul link in the ranges hundreds of km. Maintaining sub-ns accuracy for ~ 14 to 20 WR nodes in a chain.



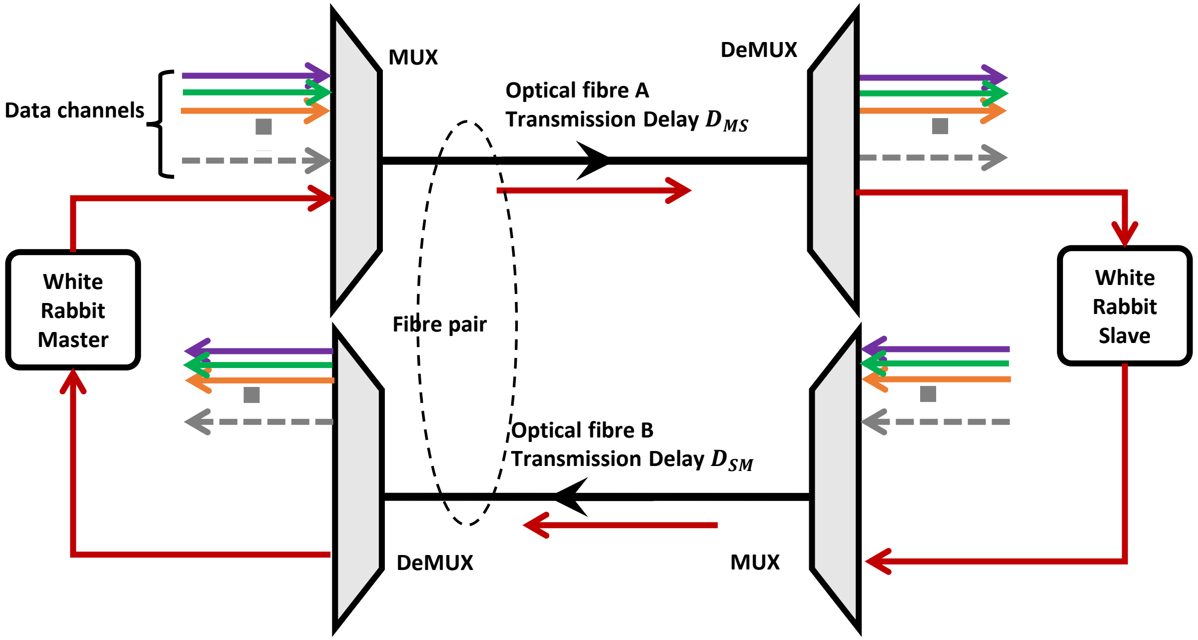
Source: J. Serrano, GEANT Time and Frequency Workshop

More info on White Rabbit Collaboration
15th White Rabbit Workshop (27-28 May 2026)

White Rabbit over Fibres Shared with DWDM
Two-fibre transmission

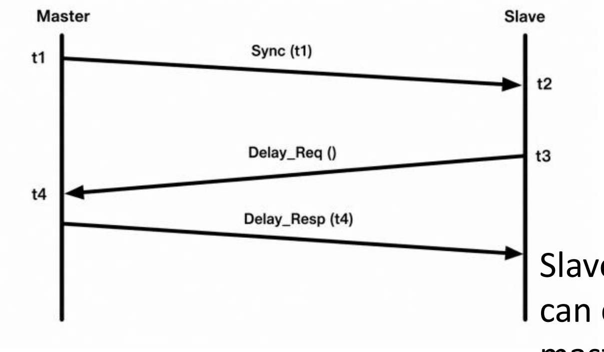
- Unidirectional Transmission: WR as an alien wavelength service
- Key advantages come from being compatible with existing DWDM
  - Use a free wavelength channel in your existing DWDM system (guardband required)
  - The same wavelength is used in both directions
    - simplifies spare part management
  - Use standard components
    - e.g. duplex SFP modules, no need to bind DWDM transceivers into single fibre
  - No need for "new" regeneration systems, same amplification as for data channels
- Disadvantage: asymmetry introduced by different lengths of the fibres in the fibre pair

Optical Dense Wavelength Division Multiplexing (DWDM)



Asymmetry Introduced by «Legacy» DWDM Optical Networks
Two-fibre transmission

- PTP message exchange assumes symmetry of transmission path delays
- Simplified PTP message exchange

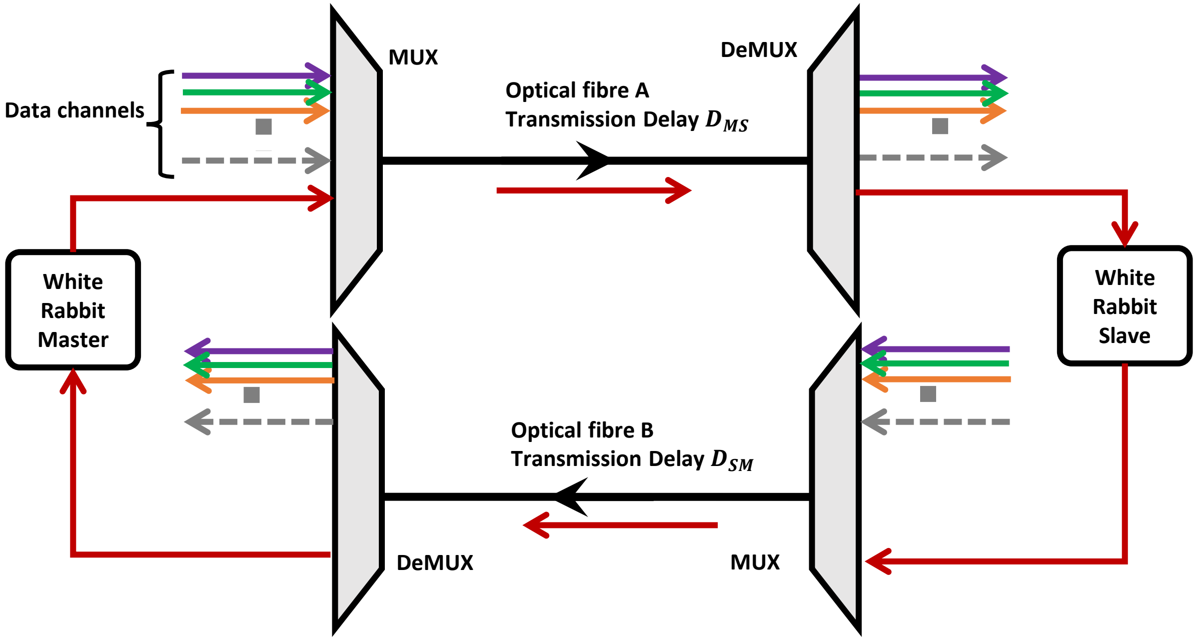


Slave knows t1, t2, t3, t4 can calculate offset from master

PTP calculation of offset:
- Delay Master-> Slave : D_{MS} = t2-t1
- Delay Slave -> Master : D_{SM} = t4-t3
- Mean path delay = RTT/2= $\frac{(t4-t3)+(t2-t1)}{2}$
- Offset from master = (t2-t1) – mean path delay

Improvement of by including path asymmetry
- Asymmetry= $(D_{MS}$ - $D_{SM})$
- Offset = Calculated offset - Asymmetry/2

Optical Dense Wavelength Division Multiplexing (DWDM)



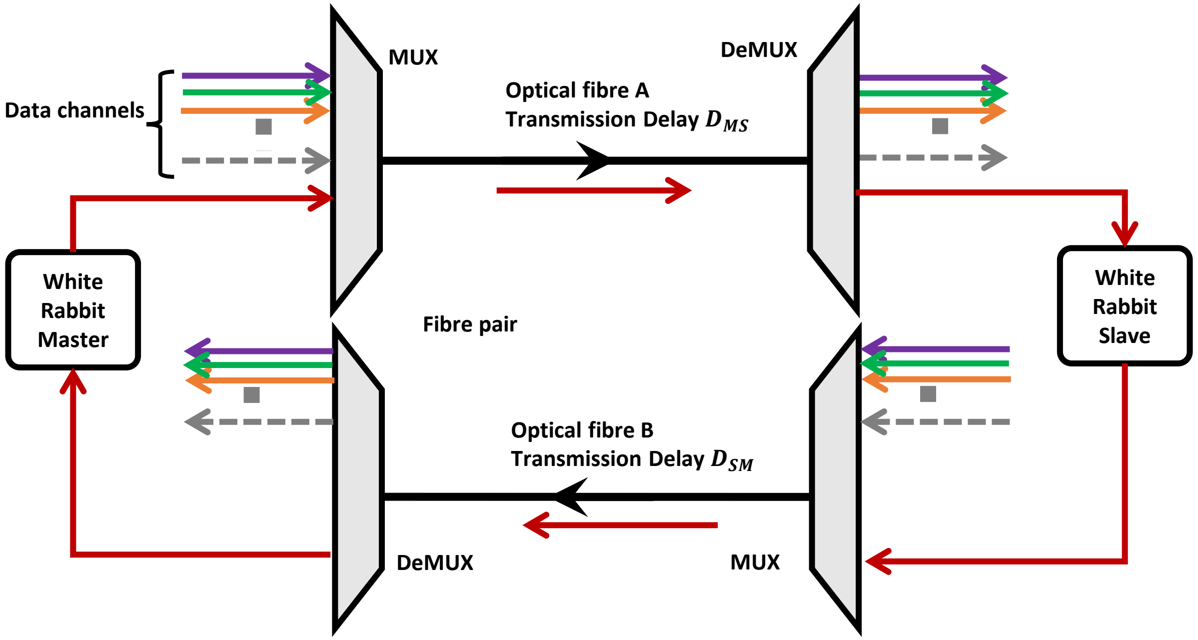
Asymmetry Introduced by «Legacy» DWDM Optical Networks (cont'd)

Two-fibre transmission

- Rule of thumb: speed of light in optical fibre 2/3 of speed of light in vacuum
  - ~5 ns/m -> 1ns ~ 20cm
- Fibres have different lengths even in the same cable from few to tens of meters.
  - $D_{MS} \neq D_{SM}$
  - The "unknown" asymmetry introduces "unknown" time error

    offset = calculated offset – asymmetry/2
- Calibration is difficult as every "fix" of a fibre break will introduce unknown Δ(A,B) fibre length
  - E.g. after a fibre break lengths might change, unknown as maintenance from 3rd parties

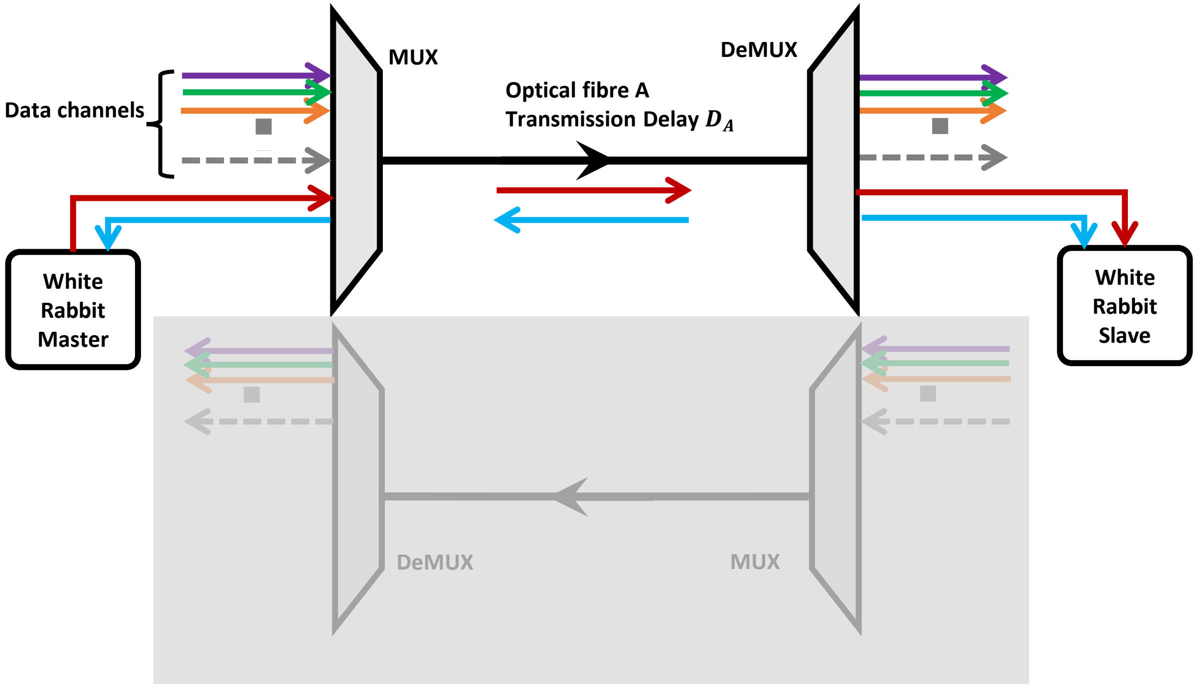
Optical Dense Wavelength Division Multiplexing (DWDM)



Solutions Using Single Fibre – Bidirectional Transmission

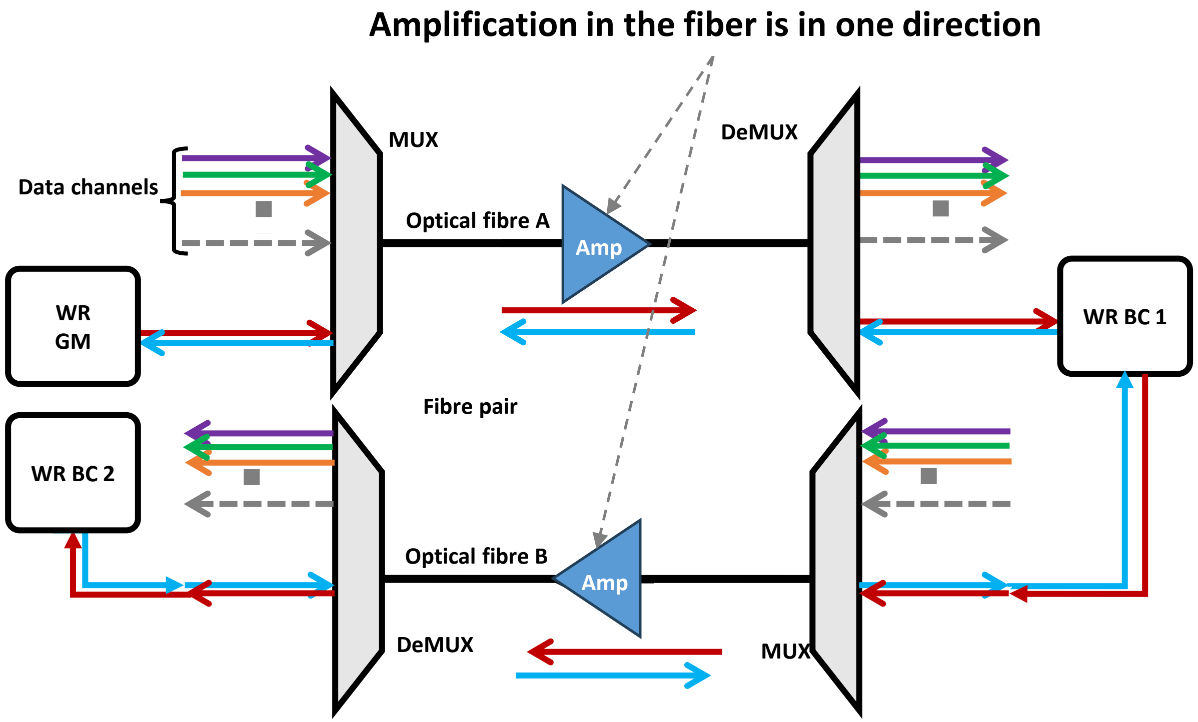
- Single fibre with different wavelengths per direction (bidirectional):
  - the standard CERN method for WR transport on WDM (1310nm & 1490nm)
  - remove the “unknown” fibre lengths asymmetry component
  - asymmetry is still introduced because of chromatic dispersion: different wavelengths travel at different speeds in the fibre medium
    - Typically, around 17ps / (nm * km)
    - Use continuous DWDM wavelength channels with 0.8 nm (100 GHz) channels spacing ~ 13.6 ps/km
    - Compensated with calibration

Optical Dense Wavelength Division Multiplexing (DWDM)



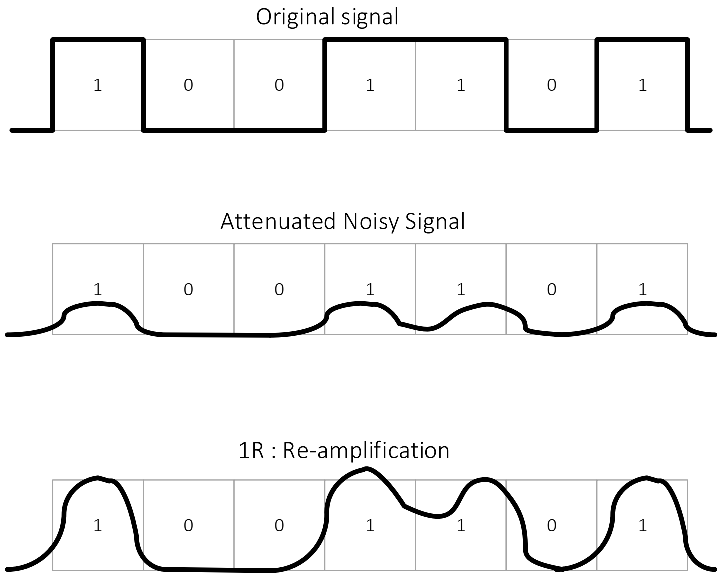
Challenge in Long-Haul Transmission - Bidirectional Signal Regeneration

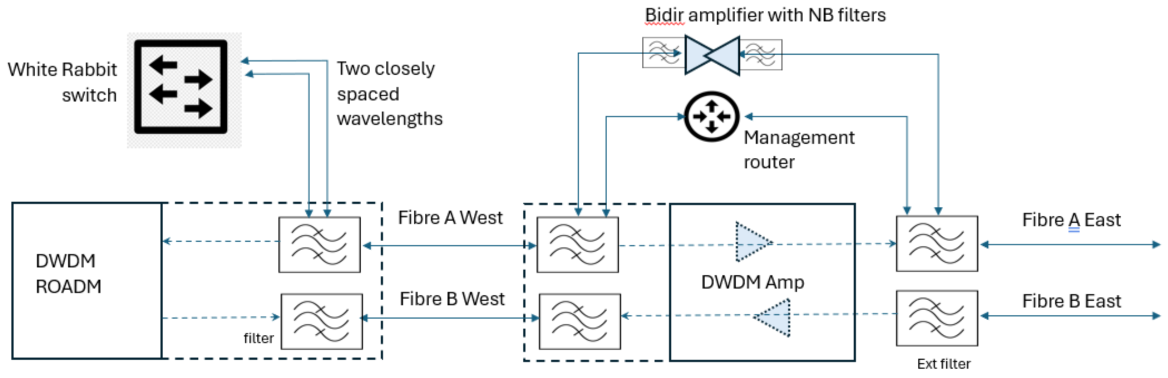
- In optical network the signal fades (~0.2dB/km) needs to be regenerated, e.g. every ~ 80 to 100km
  - E.g. at In-line Amplification (ILA) sites
- Regeneration together with the Telecom DWDM channels is not possible!
  - Amplification is unidirectional on the fiber.
  - Cannot be used for the bidirectional WR channels
- Bidirectional solution allows the possibility to loopback the WR time service and measure the performance



1R — Bidirectional Amplifiers

- Advantages
  - An all-optical regeneration avoids accumulated latency and jitter from electronics (as is the case with 2R and 3R)
  - Possibility of amplifying multiple WR signals in a single unit
  - No need for calibration as it does not add fibre length asymmetry
- Disadvantages
  - Cost & availability: not a common-off-the-shelf optical product
  - Additive optical signal noise limits the total length of the fibre
  - Interaction with Raman pumps can cause asymmetric gain — must be evaluated up front
  - Gain oscillation if reflections are present

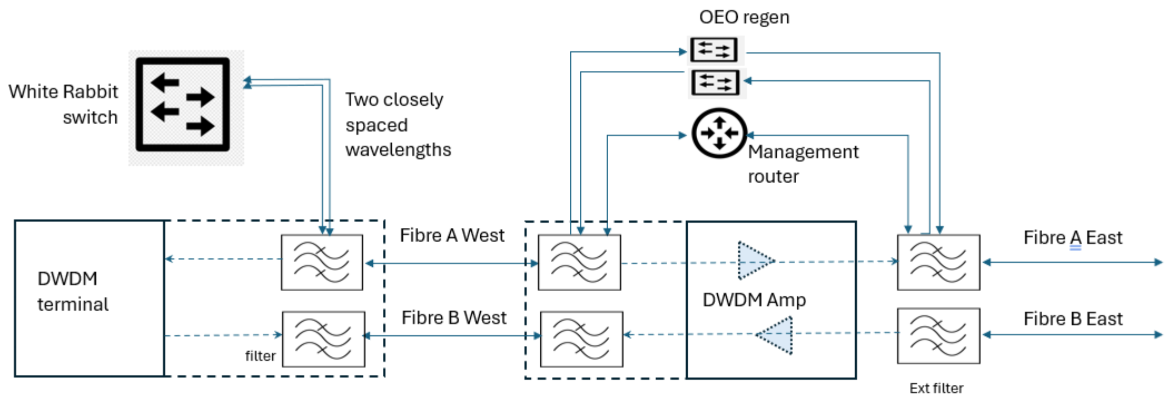


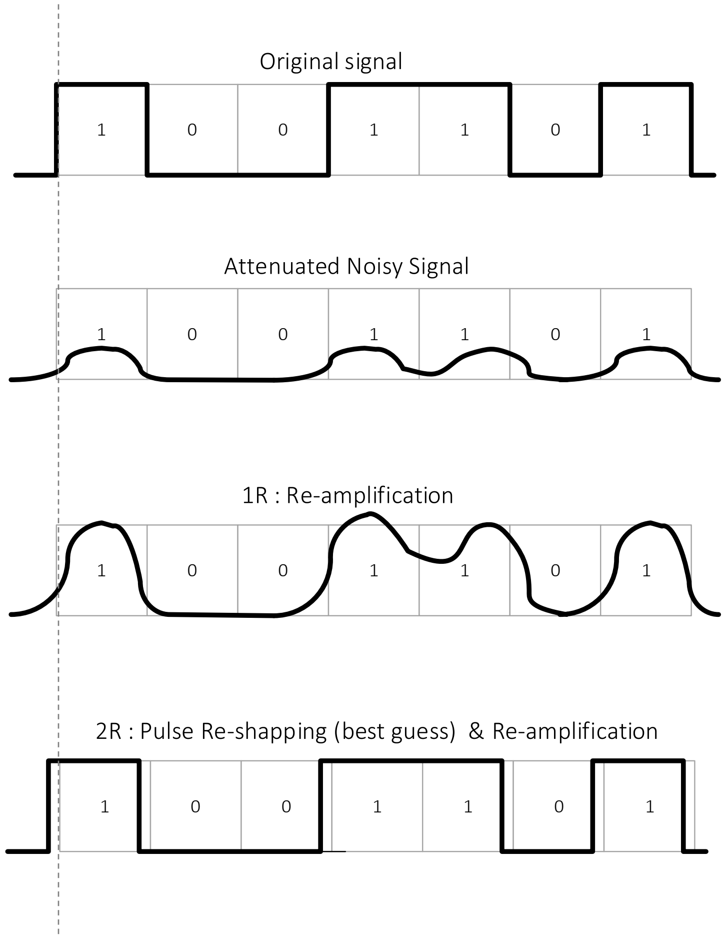


2R - OEO (Optical-Electrical-Optical) Regeneration

Re-Amplification and Re-shaping (restore steepness) through media converters e.g. back-to-back SFPs

- Advantages
    - low cost & low technical complexity of the device
- Disadvantages
    - Accumulation of phase noise of fibre and all OEO devices in the chain (there is no re-timing)
    - calibration of field deployed line might be complicated, as it must be performed for all segments optimally at once.
    - carrier-grade requirements might not be met, e.g. OAM, cooling, etc.

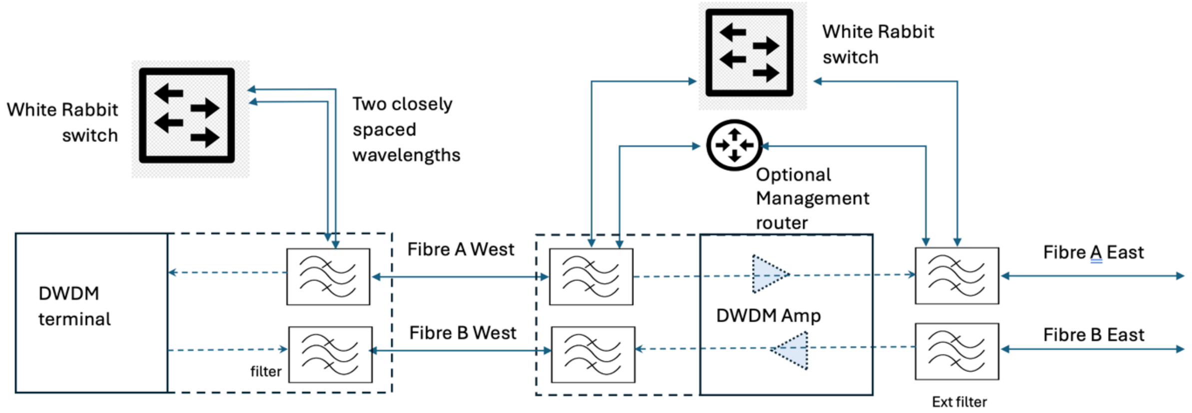


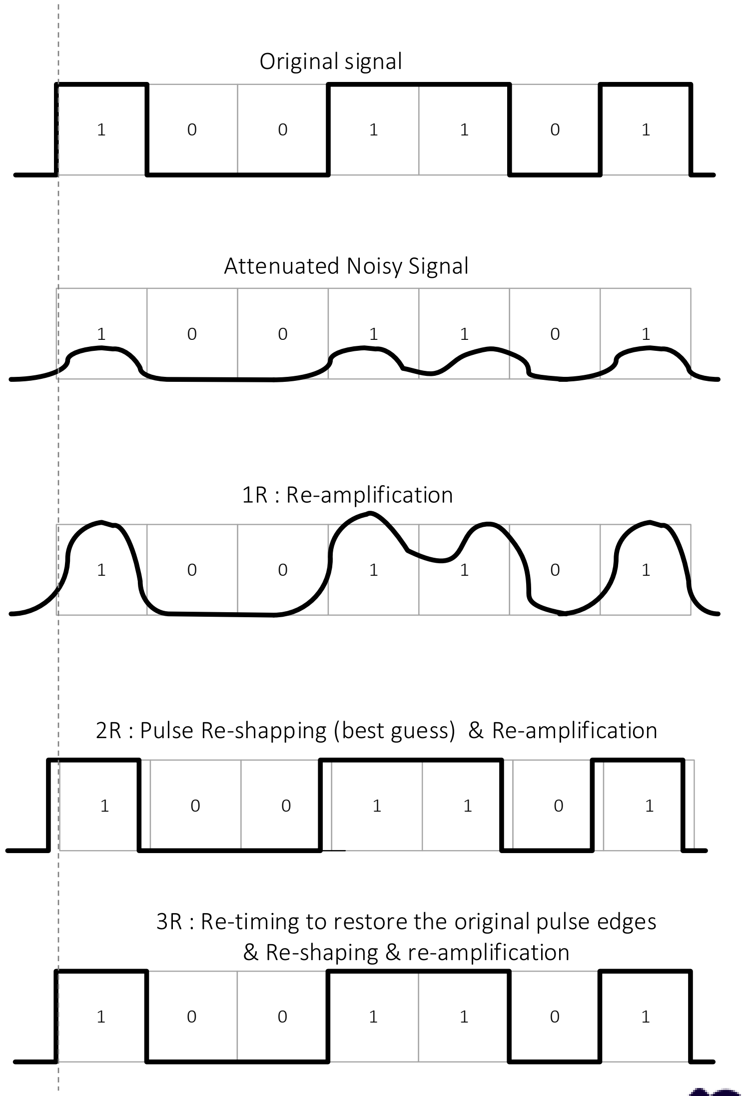


3R — White Rabbit Switches

Re-amplification and Re-shaping and Re-timing

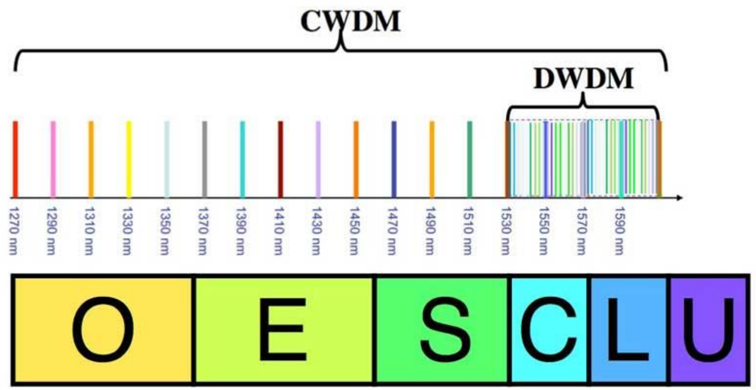
- Advantages
  - Simplest method where a WR switch acts as regeneration node
  - No need for new type of devices in the network, easier spare parts management
- Disadvantages
  - Each switch contributes its jitter and phase noise, hence the time error introduce by each switch will be accumulated in the chain
  - High cost if only being used for regeneration





Status of white rabbit time service deployments

- Interviews and offline questionnaire Q3.2025 to Q1.2026
- Deployments: SURF, RENATER & REFIMEVE, CESNET, SUNET & NETNOD/RISE, FUNET & VTT, SWITCH, NPL, INRIM
- Planning or evaluation phase: BelNet, Sikt & JV, NORDUnet, Asiera
- Architecture
  - Shared fibres with DWDM – preferred
  - Dedicated dark fibres used for high stability frequency re-used for WR time service as well
  - Unidirectional vs. Bidirectional: both deployments are equally present
- Optical channels used for white rabbit
  - Edge of C-band with minimum 100GHz reserved guardband
  - L-band (as widely used as C-band links)



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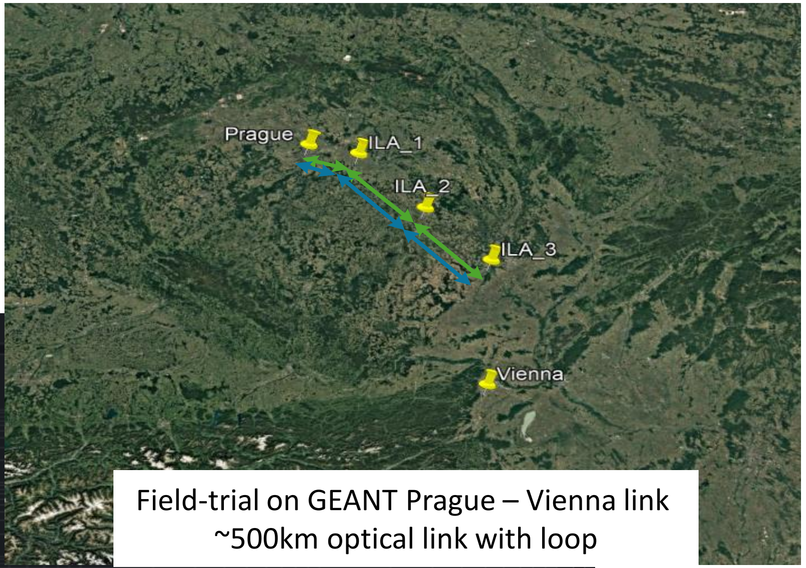
Status of white rabbit time service deployments (cont'd)

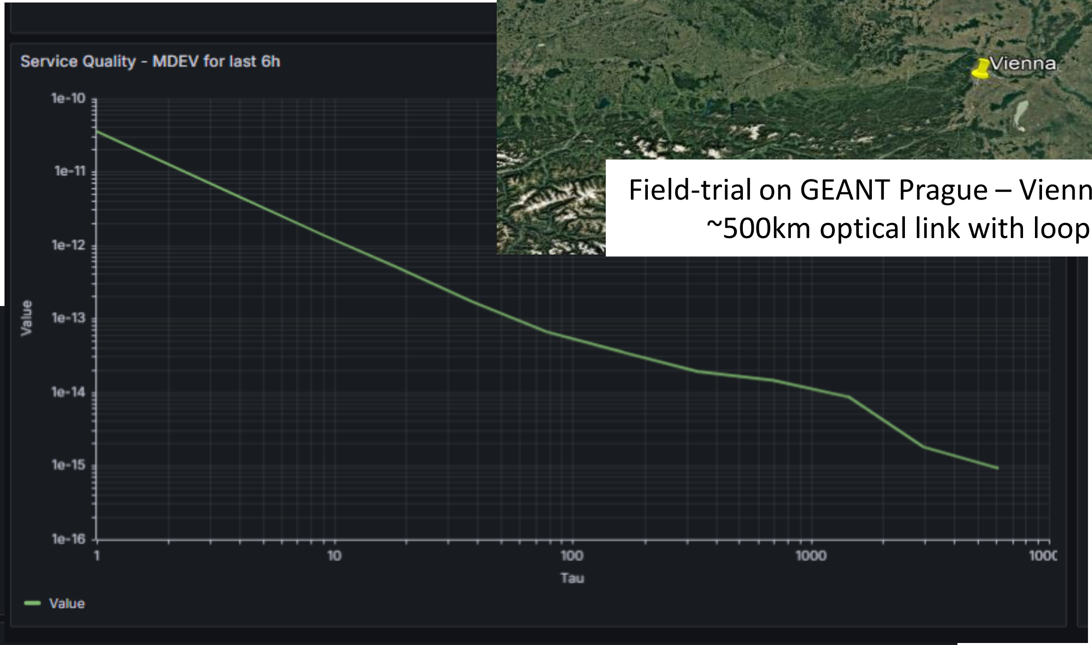
- Regeneration techniques for bidirectional WR service
  - White rabbit switch – most common for regeneration
  - OEO regenerators – deployed in the Nordics with long-haul WR links
  - Bidirectional amplifiers – CESNET Czech Light BiDi amp
- Network(s) size of WR deployments
  - Varying lengths in-between WR time service nodes. Representative example
    - Edge ~1 km
    - Regional 10s km
    - National 200-300 km
  - From tens of WR nodes to large networks planned to 100 nodes
  - Unidirectional WR link up to 800km (FUNET)
- Accuracy range: from sub-nanosecond for research users to GNSS (40ns) or better
  - Average 10ns
  - Sub-ns for research users

Next: Lab Tests and Field-Trial Results

- Trial to demonstrate the high precision WR time distribution over the L-band in GEANT network



Field-trial on GEANT Prague – Vienna link
~500km optical link with loop



With integration period of 10,000 s can achieve accuracy of one part in 1e15