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Best Practices for Deploying White Rabbit Time Services in Long-Haul DWDM NREN Networks

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Abstract

This report presents the findings of the Long-Haul White Rabbit Incubator project, evaluating the deployment of a high-accuracy time service using White Rabbit technology over long-haul optical DWDM networks. Tests were performed in both the laboratory and the field. The results are presented and analysed, based on which a cost-benefit analysis is provided. The report concludes with best-practice recommendations designed to guide NRENs in selecting the most effective architecture for their synchronisation needs.

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Executive Summary

This white paper presents the findings of the Long-Haul White Rabbit (WR) Incubator project, run as part of the Technology task (Task 1) of the Network Development Work Package (WP6) of the GN5-2 project. The paper evaluates the technical feasibility and economic viability of distributing high-accuracy time services over existing National Research and Education Network (NREN) infrastructure. Noting that precise time & frequency (T&F) distribution is evolving into a critical service, driven by the demands of advanced scientific research and Global Navigation Satellite System (GNSS) redundancy, this white paper provides a strategic roadmap for integrating T&F services into legacy Dense Wavelength Division Multiplexing (DWDM) systems.

Key Findings and Results

- **Infrastructure coexistence**: Field trials running from July 2025 to November 2025 on the Prague–Vienna GÉANT route successfully demonstrated that 1.25 Gbps White Rabbit signals can coexist with 400G coherent data channels without any measurable impact on the Bit Error Rate (BER) of existing internet traffic.
- **Regeneration performance**: Laboratory tests compared three primary signal regeneration techniques—reamplification (1R), reamplification and reshaping (2R), and reamplification, reshaping and retiming (3R)—for links spanning several hundred kilometres:
    - **Bidirectional optical amplifiers (1R)** provided the best performance with lowest additive noise.
    - **Optical-electrical-optical (OEO) media converters (2R)** proved to be a cost-effective alternative for longer links, with performance nearly comparable to optical amplification.
    - **White Rabbit switches (3R)** added jitter in a cascade; they remain a valid solution for maintaining sub-nanosecond uncertainty across complex networks.
- **Performance stability**: The WR trial on the GÉANT network achieved a time-transfer stability of ±100 picoseconds (ps) over a 498 km field-installed fibre loop using five bidirectional amplifiers, significantly exceeding the standard 1-nanosecond (ns) requirement.

Strategic Recommendations

- **Deployment methodology**: For high-accuracy requirements, NRENs should prioritise single-fibre bidirectional transmission to eliminate the physical length asymmetries inherent in fibre pairs. This will also ensure ease of calibration after fibre repairs.
- **Optimal spectral efficiency**: It is recommended to deploy WR services at the edges of the C-band or within the L-band, utilising appropriate guard-bands (typically 100 GHz) to protect data integrity.
- **Choice of regeneration**: This will depend on the level of uncertainty that the NREN wishes to achieve. This white paper includes a cost calculator [1] to allow NRENs to carry out a cost-benefit analysis for their own needs.
- **Operational readiness**: Future deployments should include carrier-grade features, such as dual power supplies, remote management via optical supervisory channels (OSC), and rigorous calibration protocols to ensure long-term service reliability.

1 Introduction

As Research and Education Networks (RENs) evolve, the requirement for highly accurate time & frequency (T&F) distribution has moved from a niche metrology requirement to a critical infrastructure service. In this report, we analyse the challenges of using the White Rabbit (WR) solution [2] to meet the Research and Education (R&E) community's time distribution needs.

The national network infrastructure for research, academic and education communities in Europe is developed and managed by National Research and Education Networks (NRENs). Each NREN has its own national priorities, which can vary widely between European countries. For example, PCSS (Poland) and RENATER/REFIMEVE (France) have built high-precision frequency distribution networks in their countries to support National Metrology Institutes' (NMI) optical clock research, along with other scientific users. However, few other NRENs have the user demand and funds available to match the level of infrastructure achieved by PCSS and RENATER/REFIMEVE. A broad European effort is evolving to support this work – of particular note are the efforts by the FOREST consortium [3] to get frequency networks recognised as a Research Infrastructure (RI) under the European Strategy Forum on Research Infrastructures (ESFRI). The NREN and NMI community hopes that the success of FOREST will raise the opportunities for further funding in the coming years.

Since 2022, military jamming of the Global Navigation Satellite System (GNSS) has become a challenge for Europe. Growing awareness of this problem has recently increased pressure to find technical solutions to complement the European Galileo satellite network. A fibre-based time distribution system to fulfil this role, in alignment with the European Commission's (EC) objectives of sovereign digital infrastructures [4], is under consideration by the EC and EU member states. One of the leading candidates for distributing time over fibre is the White Rabbit technology, developed by CERN and the White Rabbit consortium [5].

In this white paper, we present the findings of the **Long-Haul White Rabbit Incubator project** and consider the technical and cost implications for NRENs of deploying WR in their networks. This report is written for European NRENs to help them decide on the best technical solution for deploying WR in their network.

Context

The Long-Haul White Rabbit Incubator project is built on the foundations established by GÉANT's GN4-3, GN5-1 and GN5-2 projects. GN4-3 introduced a focus on Optical Time & Frequency Networks (OTFN) through WP6 Task 1, Network Technology Evolution. This was developed in the following GÉANT project iterations, with WP6 running an incubator in the GN5-1 project that laid the foundations for the **Core Time and Frequency Network (C-TFN)**. GN5-2 saw WP6 run a second incubator, the results of which comprise this report. Concurrently, WP7 delivered the T&F pathfinder link in GN5-1, and is now working on the France–Poland frequency link in GN5-2.

Current Status

GÉANT, with the support of Horizon Europe, is currently developing the **Core Time and Frequency Network**. This initiative, guided by the **CLONETS-DS** [6] studies, aims to establish a pan-European infrastructure for T&F distribution. Following the recommendations of the GÉANT C-TFN Network Development Incubator report [7], GÉANT completed building the T&F pathfinder link in 2024, connecting Physikalisch-Technische Bundesanstalt (PTB), the German NMI, with the Polish frequency distribution network operated by PCSS. The GN5-2 work program has committed a significant investment of EUR 1.4M to allow GÉANT to build a dedicated fibre network for the C-TFN between France and Poland via the Netherlands in 2026–27.

The C-TFN will initially carry frequency services, but will be designed to allow the addition of time services in the future. This white paper serves as a guide for GÉANT, the NRENs and NMIs on their investment decision regarding adding White Rabbit time services to their existing networks.

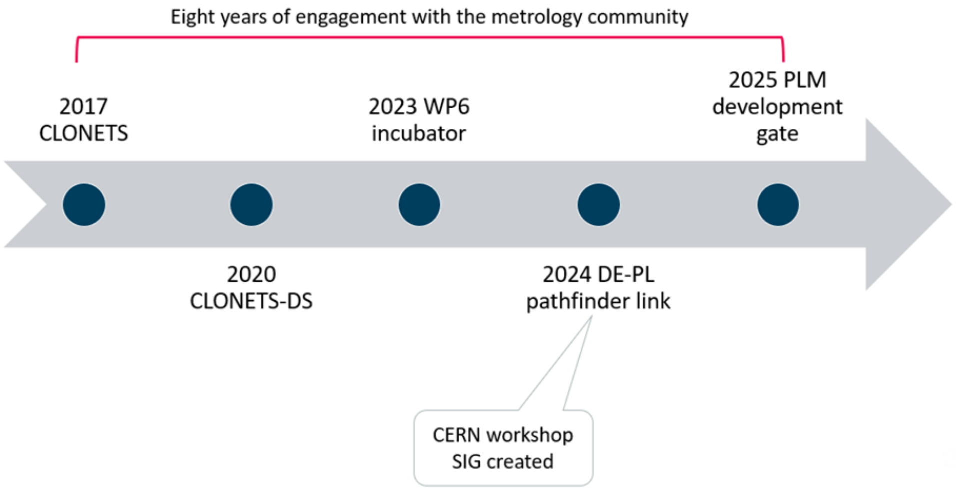


Figure 1.1: The C-TFN timeline: eight years of engagement between the NRENs and the metrology community

C-TFN Service Types

Overall, the C-TFN architecture is designed to support two distinct service tiers:

- **Frequency services**: Designed to interconnect optical atomic clocks at NMIs. These services utilise optical carriers and demand extreme stability, typically exceeding *1E-18* fractional uncertainty. In the GÉANT C-TFN network, this tier generally requires dedicated "dark" fibres.
- **Time services**: While time distribution can be transmitted over dedicated fibre frequency infrastructure (using technologies like White Rabbit or ELSTAB [8]), it is easier and more cost effective to add to existing DWDM systems compared to leasing new dark fibre. Overall, the time service tier has a lower stability target than the frequency service.

As noted, the current GÉANT C-TFN deployment is based around dedicated dark fibre for frequency transport (required for the *1E-18* stability needed by NMIs). This white paper, however, focuses specifically on testing whether high-quality time services can be successfully integrated into legacy long-haul DWDM systems.

The Case for Converged Infrastructure on Long-Haul DWDM Systems

Time services present fewer technical challenges than frequency services, which makes it possible to integrate time distribution into existing "legacy" DWDM systems. Shifting from a dedicated-fibre(s) model to a shared DWDM approach offers several strategic advantages:

- **Cost effectiveness**: Significant reductions in capital expenditure (CapEx) and operational expenditure (OpEx) by eliminating the need for new physical fibre leases and redundant infrastructure.
- **Operational simplicity**: A unified infrastructure allows network management teams to leverage existing monitoring, troubleshooting, and security frameworks.
- **Scalability**: Utilising the existing data footprint allows the time service to reach end-users of standard data services with minimal additional deployment friction.

The Long-Haul Challenge

White Rabbit has been successfully deployed over shared DWDM for short distances. However, deployment over long-haul distances (hundreds of kilometres) introduces significant technical hurdles. The primary challenge is the regeneration of the optical signal at amplifier sites, typically every 80–100 kilometres. In the case of unidirectional transmission (i.e., fibre carrying signals in one direction), the same regeneration techniques applied to data channels can be used, such as WR over alien wavelength. Such deployments already exist and have been previously studied under GN4-3 WP6's OTFN work [9][10]. However, the (unknown) difference in length of the two fibres in the pair (one per direction) degrades WR performance by causing asymmetry in transmission times. This asymmetry can be eliminated through **bidirectional** (BiDi) deployments: using a single fibre for both directions of transmission with different wavelengths in each direction.

While several techniques exist for WR transport over long distances, their relative performance and cost efficiency have remained unclear to the NREN engineers deploying these systems. This white paper addresses this gap in understanding by identifying and testing various regeneration techniques and providing the data necessary for NRENs to make informed deployment decisions.

Document Objectives and Structure

The objective of this report is to evaluate the technical feasibility and economic viability of distributing time services over long-haul DWDM networks using White Rabbit. The document is structured as follows:

Section	Content Description
Section 2	**Technology & use cases**: An overview of time service distribution via White Rabbit technology and the use cases for NRENs.
Section 3	**Technical solutions**: An overview of regeneration techniques for long-haul White Rabbit transmission and their practical considerations.
Section 4	**Experimental results**: Comparative lab testing of various solutions and the results of a 500 km field trial on the GÉANT route between Prague and Vienna.
Section 5	**Cost-benefit analysis**: A detailed economic evaluation of the different technical options.
Section 6 & Section 7	**Recommendations & conclusions**: Best practices for NRENs and GÉANT regarding long-haul WR deployment.
Appendix A	**EU landscape**: An overview of the current status of time service deployments across European NRENs and NMIs.

2 White Rabbit Technology

2.1 Technology Overview

White Rabbit [2] is a high-accuracy Ethernet-based synchronisation technology originally developed at CERN in 2008 to meet the extreme timing requirements—in the range of picoseconds—for the Large Hadron Collider (LHC) particle accelerators and future scientific infrastructures. It enables sub-nanosecond time synchronisation and frequency precision in the order of *1E-12* over distributed networks using standard fibre-optic links.

White Rabbit is based on and extends the IEEE 1588 Precision Time Protocol (PTP) [11] and ITU-T Synchronous Ethernet (SyncE) standard [12]:

- PTP provides protocol-level time synchronisation by exchanging timestamped messages between a grandmaster clock and slave clocks across a network.
- SyncE syntonizes (i.e., frequency-aligns) all nodes to the same physical layer clock reference over Ethernet Physical Layer 1, ensuring they operate at the same frequency as the grandmaster.
- WR adds enhancements including precise hardware timestamping, delay asymmetry compensation, and phase measurement techniques (e.g., Digital Dual Mixer Time Difference) to overcome asymmetries in fibre propagation and achieve sub-nanosecond performance.

WR is now included as the IEEE 1588 High Accuracy (HA) profile in the IEEE 1588-2019 standard, embedding many WR concepts into a standardised PTP profile.

2.1.1 Switch Types and Commercial Availability

White Rabbit offers two open hardware switch designs, while proprietary implementations extending these open designs are offered by commercial vendors:

- **Open-hardware White Rabbit Switch (WRS) v3.4**: A widely deployed version of the WR switch architecture, typically with 18 SFP 1GbE ports capable of sub-nanosecond time/frequency distribution over fibre. It is designed for use as a backbone element in WR networks to synchronise many nodes over 10s–100s of kilometres. A new v4.0 version of the switch is being developed with 10GbE ports for dual use as both 1Gbps and 10Gbps.
- **Open-hardware White Rabbit Switch Low Jitter (WRS-LJ)**: An enhanced variant with improved clocking hardware and firmware optimised for low jitter and low phase noise performance. Typical improvements include cleaner 1-pulse-per-second (PPS) outputs, better frequency stability (lower Allan deviation), and reduced clock noise at the outputs. These improvements are especially valuable in use cases where timing precision beyond basic sub-nanosecond accuracy is required (e.g., precision measurement, very long-baseline systems).
- **Proprietary implementations** extending towards carrier-grade deployments, e.g. with dual power, hot-swapable fans, multiple PTP profiles (ITU-T), failover capability, etc. Vendors of these commercially available switches include Safran (formerly Seven Solutions) and Creotech (see Appendix A). A list of vendors is also maintained on the official White Rabbit open-hardware wiki [13].

The key differences between the open-hardware WRS v3.4 and WRS-LJ versions are as follows:

- **Timing performance**: The WRS Low Jitter version is specifically designed to provide cleaner and more accurate 1-PPS and 10 MHz outputs, with reduced phase noise and jitter compared to the standard v3.4 switch.
- **Hardware improvements**: WRS-LJ includes a new voltage-controlled temperature-compensated crystal oscillator (VCTCXO) and an external phase-locked loop (PLL), often implemented via a daughterboard installed on top of the switch control board (SCB) in v3.3/v3.4 units.
- **Application focus**: While the standard v3.4 switch is suitable for general White Rabbit networking, the Low Jitter version, at a higher cost, is targeted at more demanding, high-precision time and frequency distribution applications.

2.2 Use Cases

WR technology is made available as both open hardware and open-source software. As an open-source technology, WR continues to evolve through global contributions, expanding its reach into diverse sectors. Recent deployments of the technology have taken place in multiple sectors:

- The energy sector providing precise synchronisation for Smart Grids [14]
- Financial for high-accuracy timestamping for financial transactions [15],
- Mobile network operators with new x-haul architectures and Time Division Duplex (TDD) implementations requiring time accuracy of 100ns or less [16]
- Scientific research for long-distance applications in radio astronomy requiring down to sub-nanosecond level time accuracy (e.g., EISCAT 3D international atmospheric and geospace research radar system requirements [17])
- Quantum metrology & NMIs
- A terrestrial time service to provide redundancy for GNSS (see Section 2.2.1)

A good source of information on WR developments and applications is the annual White Rabbit Workshop and Collaboration event [5] for stakeholders to ensure WR's sustainability and continuous development.

2.2.1 Resilience & Redundancy for GNSS

Europe's critical infrastructure—telecommunications, power grids, and financial markets—is dependent on precision time synchronisation. These infrastructures currently mostly derive their UTC time via Global Navigation Satellite Systems (GNSS) such as Galileo. However, the radio signals from Galileo satellites are received at low power due to their medium orbit altitude of 23,000 km, which makes Galileo signals susceptible to both natural interference and deliberate disruption.Vulnerability of Satellite-Based Time

Since 2022, geopolitical developments have exposed the following weaknesses in dependence on GNSS across Europe, prompting the search for terrestrial alternatives to maintain sovereignty and safety:

- **Jamming and spoofing**: Low-cost, illegal devices can easily overwhelm GNSS receivers with noise (jamming) or feed them false data (spoofing) to manipulate timestamps in financial transactions or desynchronise 5G cell towers.
- **Economic risks**: A large-scale GNSS failure was estimated in a UK Government report to cost the UK's economy alone over £1 billion per day due to disruptions in transport, emergency services, and automated trade [18], with similar impacts expected across other European countries.

- **Infrastructure sensitivity**: In smart grids, inconsistent timestamps can lead to grid instability or blackouts, while telecommunications networks require sub-microsecond accuracy to support 5G mobile networks.

Fibre as the Resilient Alternative

Building a resilient, fibre-based time distribution network provides a deterministic, secure, and high-performance backup that operates independently of the radio spectrum:

- **Inherent immunity**: Unlike radio-frequency signals, light travelling through optical fibre is immune to electromagnetic interference and atmospheric disturbances.
- **High performance**: Technologies such as WR enable sub-nanosecond accuracy over hundreds of kilometres, rivalling or exceeding GNSS precision while offering superior stability.
- **Strategic deployment**: By leveraging existing NREN fibre infrastructure, nations can distribute a traceable "ground truth" time signal directly to critical sites [19]. This terrestrial backbone ensures that even if satellite links are completely severed or compromised, critical infrastructure—from hospitals to financial hubs—can continue to operate without interruption.

The EU Radio Navigation Plan [20] and European Space Agency (ESA) have both identified increased resilience of GNSS as a requirement, and the EC's Joint Research Centre (JRC) has identified the NREN community as a key player able to deliver a robust terrestrial time service for critical societal services.

2.3 Accuracy and Stability of Time Transfer

White Rabbit is designed to provide time transfer with an accuracy of better than 1 ns. To put such a small interval into perspective: in 1 ns, a photon travels approximately 30 cm in a vacuum or roughly 20 cm in optical fibre. (For further context, the average time drift of a Caesium clock is also approximately 1 ns per day.)

The performance of time transfer between a WR Master and Slave can be measured directly in a laboratory environment using a time interval counter (TIC) connected to the 1-PPS outputs of both devices. In such setups, it is critical to use cables of identical length, as even a 20 cm difference introduces a delay of approximately 1 ns.

Beyond stability, absolute time-transfer accuracy remains a critical challenge. WR time transfer relies on the bidirectional exchange of data as defined by the PTP protocol. The WR hardware measures the round-trip time and either assumes a symmetrical delay in both directions—an assumption that does not hold at nanosecond resolutions in complex electro-optical setups—or requires precise knowledge of the real delay asymmetry. Consequently, the entire transmission chain must be rigorously calibrated to achieve these performance levels.

Network Synchronisation Technology	Typical Accuracy	Scope / Use Case	Comments
NTP (Network Time Protocol)	~1E-04 to 1E-3	General-purpose networks	Software-based; insufficient for high-precision applications.
PTP (IEEE 1588)	Sub- 1E-04 to multiple 1E-07	Industrial, telecom, media networks	An industry standard for precise synchronisation; requires hardware timestamping for best performance.
SyncE	Frequency only	Provides a stable frequency reference	Complements PTP; does not by itself synchronise absolute time.
White Rabbit (WR)	Sub- 1E-09 accuracy, sub-1E-10 stability	Ultra-precise timing, distributed systems	Combines PTP, SyncE and advanced delay asymmetry compensation and phase measurement techniques to achieve deterministic sub-nanosecond synchronisation.

Table 2.1: Overview of network synchronisation protocols

2.4 White Rabbit Calibration

White Rabbit utilises Synchronous Ethernet (SyncE) to align the frequency. Phase tracking is used to measure the precise phase shift through the path. This allows WR to account for the "propagation delay" of light through fibre optics. However, fibre and other components can introduce delay asymmetries – calibration is needed to account for these delays.

2.4.1 Calibration Approaches for Bidirectional Links

There are several approaches to calibration, as discussed in the following subsections.

2.4.1.1 Per-Component Calibration

Every possible source of asymmetry has to be calibrated independently: WR electronics, SFP transceivers, fibre, and other optical elements like amplifiers, filters, splitters, etc. The calibration results of WR electronics are provided by the manufacturer, including variances between different SFP ports on the switch. The use of an SFP transceiver can add asymmetry in the transmitting and receiving directions for each single SFP unit, even in the same series, so every single SFP unit has to be calibrated by measuring its asymmetry. Calibration of these can be done in the laboratory and does not depend on the place where the device will be operated.

As far as the optical part of the chain is concerned, the asymmetric delay in amplifiers, filters and other elements can also be measured in the laboratory. Calibration of the propagation speed in fibre (where the source of asymmetry is the dependence of the refractive index on the wavelength) is slightly more complicated, as it is difficult to measure directly, especially when the fibre is in use. Instead, an average value specific to the type of fibre is used. The WR system supports the inclusion of delay asymmetry values (WR port, SFP transceiver) and a so-called alpha (α)-coefficient, which represents dependence of the refractive index (and consequently the light speed) on wavelength. Formally, the α-coefficient is defined using the ratio of master and slave light speeds in fibre, which corresponds to their respective refractive indices:

$$\alpha \ = \ (v(\lambda_S)) \ / \ (v(\lambda_m)) \ - \ 1$$

The sum of all additional delay asymmetries can be included in the system as a time offset of the calculated one-way delay from master to slave.

- **Pros**: Parts of the time-transfer chain can be replaced (by new calibrated components); the resulting new calibration of the whole chain can be simply recalculated.
- **Cons**: Requires time-consuming calibration of each system component.

2.4.1.2 Whole-Setup Calibration

Typically, calibration is performed by comparing the system under calibration with another, more accurate time-transfer method. The issue is that the possible accuracy of WR (less than 1 ns) exceeds the performance of the majority of other time-transfer methods, e.g., 5–20 ns in GNSS-based systems. Therefore, while such calibration removes the systematic time offset of the WR setup under test, the calibrated WR setup provides a lower guaranteed uncertainty than it is able to, as it is limited by the uncertainty of the reference system.

The results of such calibration (e.g., the time offset between the WR setup under test and the reference system) can be included in the WR device config as a time offset of the calculated one-way delay from master to slave, as in the previous case.

- **Pros**: Simple and straightforward. Avoids the time-consuming calibration of all components in the transfer chain.
- **Cons**: Requires another time-transfer system as a reference. Calibration must be repeated after the replacement of any component (WR box, SFP, optical amplifier, etc) of the time-transfer chain.

2.4.1.3 Loop Topology

When an optical path is set up as a loop—i.e., both the master node and end-point slave node are in the same location (such as a laboratory or site room/rack)—the end-to-end path calibration is simple by directly measuring the time offset between master and slave using a time interval counter. Such a setup serves mainly for lab experiments, such as the evaluation of long-term stability. It can also be used to verify the correct “per-part” calibration of all components (except for the field-deployed fibre path) before deployment to final sites.

Loop topology is the methodology used in the field trial of this project to measure the performance of the deployed WR time service.

2.4.2 Calibration Approaches for Alien Wavelength Unidirectional Links

White Rabbit technology is fully functional over pairs of unidirectional fibres or channels (e.g., DWDM networks). Unfortunately, it cannot be guaranteed that both fibres in the pair are of equal length, and this uncertainty usually exceeds the uncertainties introduced by other sources of asymmetry. The whole setup can still be calibrated by comparing with another time-transfer method, but fibre maintenance (e.g., changes made by the network provider) usually invalidates such measurements. In the worst case, the WR service operator is not informed about changes made by the network provider and is not aware of the necessity of recalibrating the system. **It may also be impossible for NRENs to calibrate their setups without the involvement of external partners, NMIs or time service providers** (excluding those NRENs operating their own atomic clock and having the required level of expertise).

2.4.3 Understanding Calibration Results

In relation to WRS ports, the SFP calibration results, evaluated asymmetry, and α-coefficients relate to specific ports and are configured in each WR switch. If there is still some known residual time offset between master and slave, there are two possibilities for dealing with this:

- Store the value (residual time offset) in the slave switch as an additional offset of one-way delay.
- Consider the existing time offset and process it in the end-user device or application using the WR time information. This was the approach taken in our WR tests in this white paper: the setup was not calibrated; all data was normalised by **measuring the offset through the loop** (see Section 2.4.1.3 on loop topology), then removing the average offset, which was in the order of a few nanoseconds.

2.4.4 Testbed Calibration and Analysis Method

After applying the above analysis to the WR testbed, the following configuration was chosen for our setup:

- The setup topology was a loop with the WR master and slave in the same rack.
- No per-component calibration was performed except for the WR ports, which was done by the manufacturer.
- The offset between 1PPS outputs of the WR master and the slave was measured by a time interval counter.
- The mean of the measured offset in every test was then considered as our "calibration" result and subtracted from the measured data. The measured data, normalised by subtracting the mean offset (as in the point above), was then further evaluated and interpreted.

2.5 Survey on Status of White Rabbit Deployments

Several NRENs, NMIs, and mobile network operators have successfully deployed White Rabbit time distribution over existing commercial or research DWDM networks, sharing the fibre with telecom data. In 2025, we ran a survey with NRENs and NMIs on their White Rabbit time service deployments. A summary of the survey results is given in the following Table 2.2, with more detailed information is provided in Appendix A.

The survey focused on three key categories:

- Architecture and technical solution deployed
- WR network size
- Service users and accuracy provided

Org.	Architecture	WR optical channels	Bidirectional regeneration techniques	WR network size	Accuracy
CESNET	Shared with DWDM 100-400G coherent data channels Bidirectional (BiDi) WR preferred A few unidirectional setups on old routes (alien wavelengths)	L-band Ch.8 & Ch.9 (1570 nm band) bidirectional for new installation C-band Ch. 32–34 on old unidirectional, gradually being phased out	Bidirectional preferred with BiDi EDFA Czech Light amplifiers OEO tested but performance lower than BiDi amps, so not deployed	~ 1300 km total, up to 2500 km in 2026 Typically, 300 km between WRSs	GNSS (40 ns) or better
FUNET & VTT	Shared with DWDM Both bidirectional and alien wavelengths	L-band for bidirectional C-band edge for unidirectional	OEO	350 km (bidirectional) 800 km (unidirectional)	Research users: 1ns
SUNET & NetNod	Shared with DWDM Both bidirectional and alien wavelengths	L-band for bidirectional C-band edge for unidirectional	OEO	~ 1100 km	<10 ns Research users: 1ns
SWITCH	Shared with DWDM	L-band	OEO	~ 500 km	20 ns
RENATER & REFIMEVE	Shared with DWDM unidirectional WR Dedicated dark fibre high-stability frequency + time bidirectional	C-band edge	N/A (Alien wavelength service)	- Edge: ~1 km - Regional: ~10s km - National: 200-300 km Total planned WR links: 5000 km ~50 WR switches	Average 10 ns, with users ranging from 1ns to 100 ns
SURF	Shared with DWDM bidirectional	C-band edge	Short distances in NL mean no need for BiDi amps. WRSs are used for 3R regeneration.	11 locations in the national network	< 1 ns

Org.	Architecture	WR optical channels	Bidirectional regeneration techniques	WR network size	Accuracy
NPL	Dedicated T&F dark fibre	C-band	BiDi amplifiers used. OEO regeneration is under consideration but not used so far.	~ 360 km	<1 ns Experimental
INRiM	Dedicated T&F dark fibre Bidirectional	C-band	WR	~ 1,000 km of fibre Average distance between WRSs is 60 km (from 18 km to a maximum of 100 km)	Experimental

Table 2.2: Short summary of White Rabbit-based time services in NRENs and NMIs

3 Technical Solutions for White Rabbit over Optical Networks

3.1 Dedicated vs. Shared Fibres

Deploying White Rabbit technology requires a strategic decision of whether to use the existing optical infrastructure shared with data services, or new dedicated (separate) fibres.

The use of separate, so-called "dark" (unlit) fibres offers maximum flexibility and excludes any potential influence on the signal by other transfers. In this mode, the user has full control over the physical layer, which eliminates interference from other optical signals (data channels). Likewise, to achieve sub-nanosecond accuracy, it is advised to use the same wavelength in both directions on a single fibre, which is easier to implement on a dedicated fibre. This approach is widely used by metrology laboratories.

Dark fibre also has the advantage of being acquired with the lowest possible latency—i.e., fibre can be purchased that takes the shortest available path between endpoints (subject to fibre availability).

However, the main disadvantage of separate dedicated fibres is the high additional costs of leasing them or laying new optical cables, especially over long distances. Also, in-band management or remote internet access to in-line amplification (ILA) sites must be provided. This method is economical only if the user already owns cables with free fibres and has the necessary facilities for monitoring and servicing these optical routes.

From the perspective of operating costs, it is clearly preferable to deploy WR technology on fibres where other services are already operating. The main advantage of sharing fibres using technologies such as DWDM is a dramatic reduction in costs and greater utilisation of existing infrastructure. A suitably designed solution can take advantage of free wavelengths that would otherwise remain unused.

3.2 Bidirectional vs. Unidirectional Transmission

When deploying White Rabbit technology, the choice between using one or two fibres is a crucial decision that directly affects synchronisation accuracy and calibration complexity.

3.2.1 Two-Fibre Unidirectional

Although WR assumes a single-fibre setup, WR can also function using a pair of unidirectional fibres.

Advantages:

- The same wavelength can be used in both directions:
  - Reduces spectrum usage and simplifies spare part management (SFPs).
  - The same wavelength is used on both fibres, hence chromatic dispersion does not introduce a transmission delay asymmetry to compensate for.
- Possibility of using a free channel (lambda) in an existing DWDM system.
- Simpler components: Can use standard, duplex SFP modules; no need to bind DWDM transceivers into a single fibre.

Disadvantages:

- High length asymmetry: Even within one cable, two fibres can have slightly different lengths (e.g. due to twisting in the cable, splicing after fibre breaks, etc). A difference of only 20 cm in fibre length will cause a synchronisation error of about 1 ns, which can be critical for achieving sub-nanosecond time accuracy for WR services.
- Comprehensive calibration: Each line must be individually and very precisely measured and calibrated to compensate for length asymmetry. Calibration must be repeated after any cable (splice) repair. The majority of independent time-transfer methods used for calibration have uncertainty exceeding the nanosecond order, therefore even a well-calibrated two-fibre unidirectional WR setup cannot ensure sub-nanosecond accuracy.
- Full control of the fibre is required. When a third party maintains the fibre (e.g., when fibre is rented), the fibre length can be changed without notice, for example, during repairs made to fibre cuts.

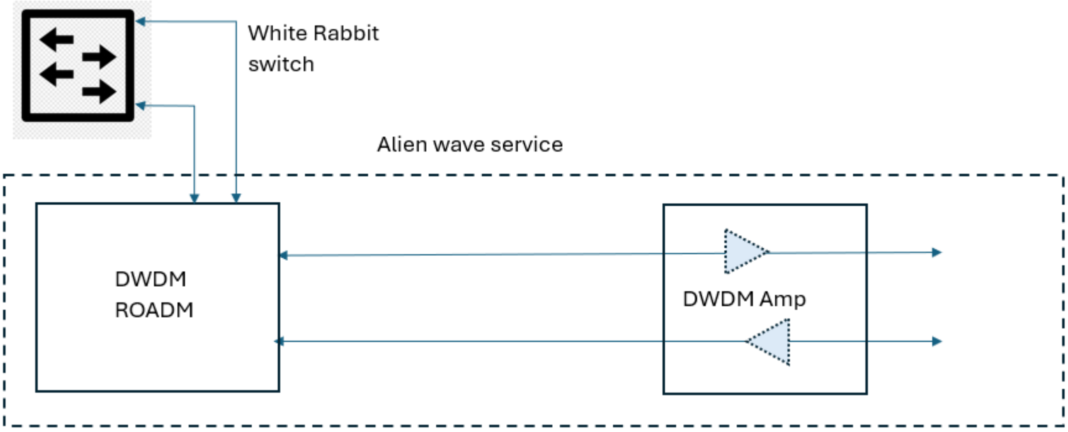


Figure 3.1: Example of a White Rabbit deployment with shared fibre on a DWDM system using two-fibre unidirectional transmission as an alien wavelength optical service

3.2.2 Single-Fibre Bidirectional

This is the standard method for WR transport on the optical layer. Originally, the WR developers at CERN preferred Wavelength Division Multiplexing (WDM) technology, where two different wavelengths (typically 1310/1490 nm) are used for the master→slave and slave→master directions within a single fibre.

When sharing fibre with data channels, DWDM technology is more suitable. It has been shown that two consecutive DWDM channels provide the best performance [21], where the wavelength stabilisation and small difference between wavelengths serve to limit the negative influence of chromatic dispersion.

Advantages:

- Elimination of physical fibre-length asymmetry: Since both signals travel through the same physical fibre, the path length is identical in both directions.
- Higher accuracy: Minimises errors caused by external influences in the optical fibre (i.e., mechanical, temperature, strain, etc.).
- Infrastructure savings: Requires only one fibre, which reduces the cost of renting paths for a dark-fibre solution.

Disadvantages:

- Delay asymmetry is introduced by chromatic dispersion, as different wavelengths propagate through the fibre at different speeds. This asymmetry needs to be compensated.
- Bidirectional amplifiers as well as external WDM filters may be needed where there are existing unidirectional telecoms amplifiers that need to be bypassed.

Given the current and future requirements for high accuracy of time signals and for long routes, we recommend using single-fibre (bidirectional) transmission. See the recommendations in Section 6 for further discussion.

3.3 Metro vs. Long-Haul

The reach of standard White Rabbit communication links is limited by optical fibre attenuation. For route lengths of 80–100 km, standard point-to-point connections can be used. For distances over 100 km, signal degradation occurs to such an extent that standard SFP transceivers are unable to maintain a stable connection. WR technology relies on accurate measurement of the round-trip propagation time of the signal. Over long routes, temperature changes affect the refractive index of the fibre, which affects the travel time of the wavelengths (and chromatic dispersion), thus introducing errors into the synchronisation. Even a change of 1°C along the fibre can shift the signal arrival time by picoseconds. At the same time, as the route length increases, phase noise (jitter) increases, which can affect the stability of the transmitted time synchronisation signals.

For longer distances, it is necessary to use one of the regeneration techniques for transmitting WR time signals. Figure 3.2 illustrates the three different regeneration techniques tested in the Long-Haul WR project. The advantages and disadvantages of each type are further explained in the following sections.

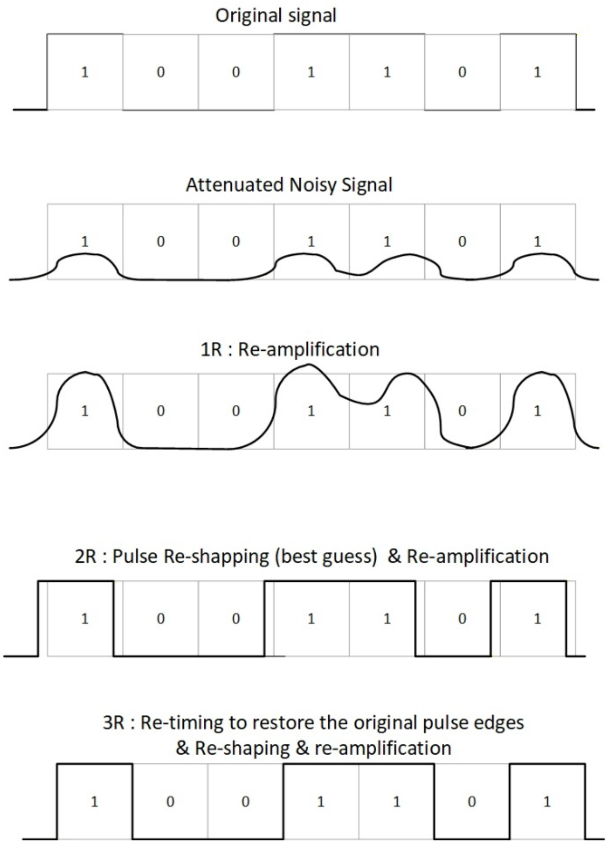


Figure 3.2: Examples of different regeneration levels (1R, 2R, and 3R) of an attenuated and noisy signal

3.4 Long-Haul Bidirectional Regeneration Techniques

3.4.1 WR Switch as a Regenerator

This is a type of 3R regeneration (Reamplification, Reshaping, Retiming), illustrated at the bottom of Figure 3.2. It is the simplest method, where the WR switch acts as a "regeneration node". The node receives the time, synchronises its internal clock and sends a new, clean signal further. Note that the WR switches are connected in a cascade, and each switch contributes its jitter and phase noise, hence the time error introduced by each switch will be accumulated. In some cases, it is possible to use a simplified WR switch for signal regeneration purposes.

For greater signal accuracy, it is advisable to use the WRS Low Jitter design (see Section 2.1.1). These are advanced WR switches with improved oscillators that minimise the phase noise added by regeneration.

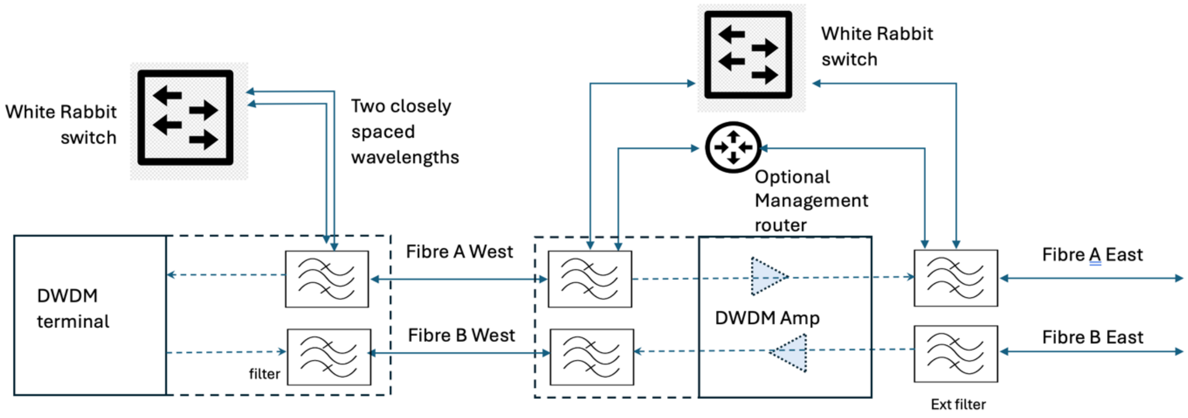


Figure 3.3: High-level design example of bidirectional WR signal regeneration by using WR switches

In this configuration, White Rabbit switches are used in a master-slave chain along the length of the DWDM line system. At each amplifier site, part of the optical spectrum is filtered out and sent to the WR switch. Both directions of transmission travel over a single fibre between WR switches on two closely spaced wavelengths.

3.4.2 OEO (Optical-Electrical-Optical) regeneration

2R-type regeneration (Reamplification, Reshaping) involves using common SFP-SFP media converters. 2R media converters only "clean" the electrical / optical signal and restore its steepness, but do not touch the clock signal (Retiming).

Advantages:

- Low latency (the signal passes almost instantly).
- Low price and low technical complexity of the device.

Disadvantages:

- Phase jitter accumulation: Since there is no retiming, all phase noise (jitter) collected on the optical fibre link and in the media converters is transmitted further, and accumulates with each subsequent 2R node.
- These simple regenerators often do not have matched signal-path lengths. They also lack advanced thermal management for the signal path on the PCB.
- The calibration of a field-deployed line using wavelength switching, as described by Dierikx et al. [22], might be complicated, as it must be performed for all segments optimally at once.
- Applying this type of regeneration on long chains built with lower-cost components might give lower reliability.

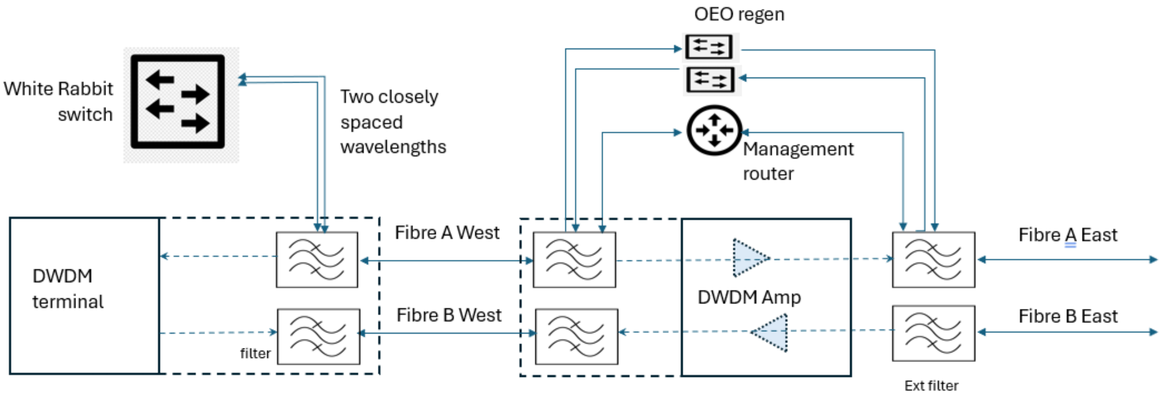


Figure 3.4: High-level design example of bidirectional WR signal regeneration using OEO media converters

In the above configuration, White Rabbit switches are used at the ends of the DWDM line in a master-slave configuration. At each amplifier site, part of the optical spectrum is filtered out and sent to an OEO regenerator. Two directions of transmission travel over a single fibre between WR switches on two closely spaced wavelengths.

3.4.3 Optical BiDi Amplifiers (EDFA)

This is a form of 1R (Reamplification) regeneration. Simple amplification of the optical signal (usually in the DWDM band) is used in both directions of transmission on a single optical fibre.

As 1R regeneration does not involve time recovery of the signal, the introduced delay is minimal. It keeps a strictly identical propagation path for both directions, a technique widely used in coherent reference transfers.

Advantages:

- An all-optical regeneration process avoids accumulated jitter from electronics, as is the case with the OEO and WR regeneration options discussed previously. Therefore, this approach offers minimal interference on the signal timing.
- Provides the possibility of amplifying multiple WR signals (multiple time domains) in a single unit.
- Does not contribute to fibre-length asymmetry, and thus does not require calibration.

Disadvantages:

- Additive EDFA optical signal noise limits the total length of the fibre route. There is a maximum number of amplifiers that can be connected in series before the signal needs to be regenerated in the electrical domain. This maximum number depends on the level of back reflection from the connectors and can vary from five to eight amplifiers.
- As bidirectional amplifiers are not a common off-the-shelf optical product, they are limited to the C-band and L-band and their overall market availability is restricted.

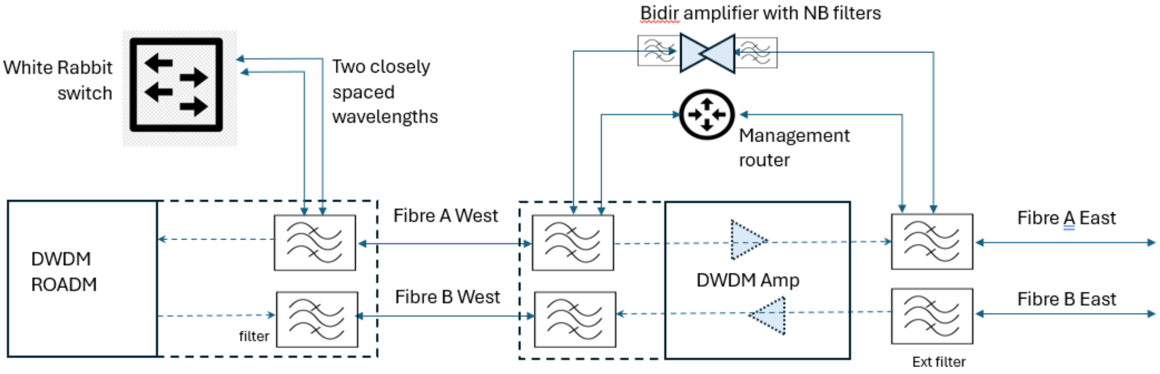


Figure 3.5: High-level design example of bidirectional WR signal regeneration using EDFA bidirectional amplifiers

In this configuration, White Rabbit switches are used at the ends of the DWDM line in a master-slave configuration. At each amplifier site, part of the optical spectrum is filtered out and sent to a bidirectional optical amplifier. Two directions of transmission travel over a single fibre between WR switches on two closely spaced wavelengths.

3.5 Effect of Regeneration on Time Accuracy

Each regeneration node brings specific properties to the time-transfer chain that must be accounted for:

- **Latency**: Each node adds a fixed delay, which White Rabbit can largely eliminate thanks to calibration. Where regeneration is applied, calibration is required for each individual span.
- **Additive jitter**: Even the highest-quality regenerator adds a few picoseconds (ps) of phase noise. When cascaded (e.g., over 5 nodes across 500 km), the total deviation can increase from 50 ps to between 200–500 ps. (See Section 5 for more detail.)
- **Temperature stability**: Maintaining the regenerator at a stable temperature is essential. The key is to compensate for temperature fluctuations in the locations where the regenerators are installed (such as outdoor cabinets).

3.6 Practical Aspects of Deployment in Optical Networks

Optical Consideration: Coexistence of Legacy OOK and Coherent Signals

The open-hardware White Rabbit switch v3 distributes precise time information over fibre links using the well-known 1G Ethernet (1GE) protocol, which is based on the simple on-off keying (OOK) modulation format. OOK encoding is the simplest modulation technique – 0s are transmitted as no light, and 1s are transmitted as light. OOK modulation is used for bit rates up to 10 Gbps without any problems, but for higher data rates, OOK becomes unsuitable because of undesirable effects, namely chromatic dispersion (CD).

These unwanted effects become so dominant as the data rate increases that new techniques were designed based on coherent high-speed optical transmission methods. These coherent systems use more complex modulation schemes by changing not only the amplitude, but also the phase of the optical signals. Commonly deployed examples include quadrature phase-shift keying (QPSK) for data rates up to 200 Gbps, and quadrature amplitude modulations (QAM) for higher rates up to 800 Gbps. This may pose a problem when OOK and QPSK/QAM signals are transmitted together in one fibre, due to other unwanted parasitic effects caused by OOK, such as cross-phase modulation (XPM). This is where OOK signals negatively affect the phase of coherent signals and thus increase the bit error rate (BER).

While academic literature does not provide much analysis on managing OOK and coherent signals in one fibre, CESNET and other NRENs have recently carried out lab experiments on the topic, publishing the results in workshops and conferences including SPIE [23][24][25] and CESNET CEF Workshops [26]. The findings are rather positive:

It is possible to transmit 1GE together with coherent signals, with some practical precautions – most importantly, implementing the spectral guard-bands of approximately 100 GHz (i.e., one channel in the standard ITU frequency spacing).

Furthermore, for a wider spectral gap, practical WR deployments could use the C-band (1530–1565 nm) for data and L-band (1560–1625 nm) for WR, as was done in this Incubator project.

Future Research: Coherent Optics for White Rabbit

As discussed, challenges remain with mixing gigabit Ethernet with coherent data in DWDM systems. Some DWDM equipment vendors continue to require optical spectrum guard-bands to prevent crosstalk. We believe that the lab testing and trials show that with the latest coherent modulation techniques, minimal use of guard-bands is required. To fully eliminate this requirement, further research is being conducted by Bell Labs in conjunction with RISE, the Swedish NMI, to develop coherent optics suitable for use with White Rabbit. While this research will aim to remove the guard-band constraint altogether, we believe that commercialisation of such a solution is still some years away.

Deploying Regeneration on Long-Haul Fibre

The deployment of regeneration systems on long-haul fibre comes with the following requirements:

- Infrastructure: Power and connectivity for active elements must be provided at regular intervals (ideally every 80 km). The most critical consideration is that attenuation must be kept below 22 dB or similar in bidirectionally amplified setups.
- Note that gain asymmetry can be expected on Raman amplified telecom spans.
- Monitoring: The use of surveillance systems at each point along the route in real time is vital.
- Redundancy: On long routes, it is important to consider backup routes, as the failure of one regenerator will disrupt synchronisation for the rest of the chain.

Components of a Bidirectional Solution

There are basically four components needed to build a bidirectional WR link:

1. WR switches
2. SFP transceivers
3. Passive (all-optical) components
4. ILA site equipment

For passive components, commonly used circulators or splitters have been shown to be less suitable for long-haul operation—rather, 3-port Optical Add-Drop Multiplexers (OADMs) are mostly used. Market availability of components was discussed in a GN4-3 white paper on the topic [9] – see Table 3.2 on page 12 of that paper.

In cases of limited commercial availability of certain components, such as some types of equipment (SFPs or filters) operating in L-band, joint coordinated procurement between NRENs might be useful to provide an incentive for manufacturers to produce larger volumes of components.

As discussed, modern coherent systems are tolerant to OOK signals, so bidirectional solutions do not require highly specialised filtering. DWDM filters are available with the standard ITU grid (be it 50, 100 or 200 GHz spacing); C/L bands filters are also available.

Erbium-Doped Fibre Amplifiers (EDFAs) are commonly available for the C-band (tens of vendors); fewer vendors support the L-band. The critical part of bidirectional EDFA deployments is the back-reflections, especially from optical connectors. All connectors must be angled physical contact (APC) – ideally FC/APC, which is preferred in laboratory environments for its stability, as opposed to the SC/APC, LC/APC and E2000/3000 connectors widely used in the optical networks. All connectors **must** be cleaned carefully and inspected by fibre microscopes as per standard procedure, and all splices must be of high quality.

Pluggable transceivers (SFP, SFP+ or others) are standard for the C-band. For the L-band, there is limited availability depending on chosen wavelengths – order lead times could be longer, perhaps up to 2 or 3 months, and with slightly higher pricing compared to C-band variants.

SFP transceivers acquired from smaller vendors should undergo rigorous qualification testing as they might not meet the requirements of specifications such as power consumption, and thus dissipated heat. This could lead to overheating, especially in simple regenerators with limited thermal management, and consequently cause issues with laser drift.

4 Incubator Test & Results

4.1 Test Methodology

To evaluate the WR technology in terms of time transfer accuracy and stability, we used the simple method of measuring the difference between 1PPS signals generated by WR boxes.

To be able to compare 1PPS events between the Master WRS and Slave WRS, we looped the connection, such that both ends of the line are always in the same location.

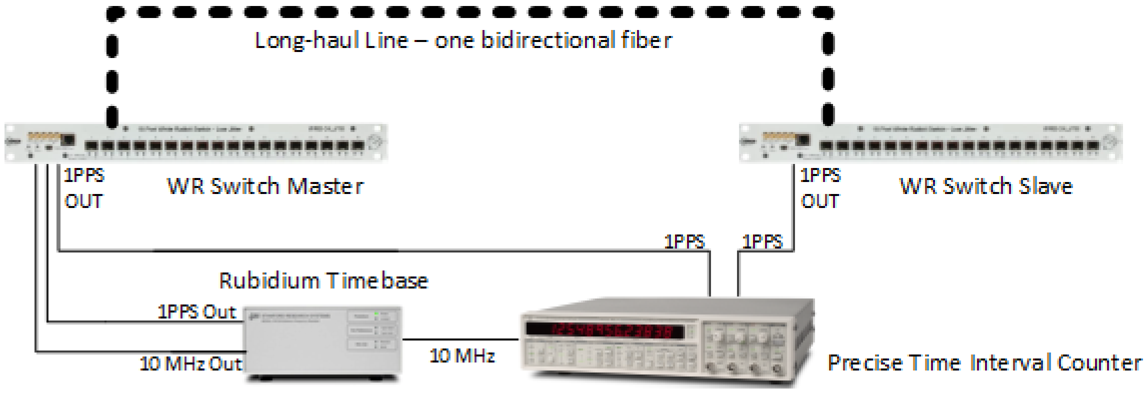


Figure 4.1: Example test setup for lab and field trial. Both the master and slave (boundary clock) WRSs are in the same location (lab/rack) and can be directly connected to the time interval counter to measure the performance of the WR time-transfer links

4.1.1.1 Utilised Devices and Tools

The following tools, utilities and devices were employed in our tests:

- **White Rabbit**: For our tests, we used common White Rabbit switches of the Open Hardware License (OHL) WRS v3.4 variety, manufactured by Safran (formerly produced by Seven Solutions).
- **Time interval counter**: For measurement of the time deviation Δt between 1PPS signals, we employed the SR620, a precise laboratory time-interval counter from Stanford Research Systems. Time interval measurements were taken every second, with the results collected by the laboratory PC (not shown in the preceding figure). Although the resolution of SR620 in single-shot time interval measurement is 1 ps, the uncertainty in terms of standard deviation is 20 ps.
- **Frequency source**: A Stanford Research Systems' Rubidium Frequency Standard PRS10 was used as the precise frequency and reference time signal source. The 10 MHz frequency output was used for the WR grandmaster input and provided the stable time base of the counter. The clock 1PPS signal output served as the WR grandmaster reference.

- **SFP transceivers**: To ensure the validity of comparisons between all tests and their results, we utilised identical 120 km DWDM SFP transceivers on L-Band Channel 8 and Channel 9, connected at opposite ends of a single fibre. Signals were combined into bidirectional mode using 100GHz DWDM filters.
- **Software**: All measured data was processed by the Stable32 program [27], commonly used to evaluate the accuracy and noise of time and frequency transfers.

4.1.1.2 Calibration

We deliberately chose not to calibrate the White Rabbit technology itself for the laboratory and field test. In real-world use, end-point calibration is necessary to achieve the required time-transfer accuracy and minimise uncertainty.

4.1.1.3 Performance Parameters

As previously described, the SR620 TIC measured the difference between 1PPS outputs of the grandmaster and slave WR switches, with results processed in Stable32. The following three statistics were calculated to best characterise performance in all tests. The resulting data is presented in a series of graphs with consistent scaling to allow for direct comparison between the various lab setups and field-trial results:

- **Time Deviation (TDEV)**: A statistic measuring time uncertainty (error) over specified averaging intervals (shown on the x-axis). Per WR specifications, the error should be below 1 ns. As TDEV relies on averaging, it can hide rare, isolated events when the target accuracy is not met.
- **MTIE (Maximum Time Interval Error)**: Tracks the maximum error between samples in a time interval. It is therefore a stringent measure of time-transfer performance that captures individual fluctuations in error.
- **Histogram**: A form of graph that shows the relative number of samples over a specified value interval. Histograms provide a very intuitive overview of time transfer performance, and can highlight any significant declination from the expected normal (Gaussian) distribution.
- **Allan Deviation (ADEV)** and **Modified Allan Deviation (MDEV)**: ADEV and MDEV are standard statistics commonly used for the evaluation of clock stability and noise identification. They record the fractional frequency stability as a function of the averaging time interval. As they have lower relevance to the evaluation of time transfer, they are omitted in this white paper.

The SR620 in time-interval-counter mode has an internal uncertainty with standard deviation (sigma) of 20 ps. This value should be kept in mind when interpreting the TDEV statistic, as it is limited by the counter noise.

4.2 Lab Tests – Setup

4.2.1 BiDi EDFA Amplification

As illustrated in the following Figure 4.2, our lab setup for this test used three bidirectional (BiDi) EDFA optical amplifiers for DWDM L-Band in the 1572 nm region with four 100 km fibre spools, emulating a 400 km fibre route for White Rabbit time transfer. For the actual transmission of WR signals, DWDM SFP transceivers were used on L-Band channels 8 & 9. DWDM bandpass filters (type 8skip0 for C-Band and 4skip0 for L-band) were also used to separate common DWDM data signals and allow precise frequency transmission.

At each end of the optical path, we also added bidirectional splitters to output 5% of the optical power to permit the connection of an optical spectrum analyser (OSA).

4.2.2 WRSs as Repeaters in Cascade

In the test using WRSs for signal regeneration, as illustrated in Figure 4.3, five WRS units were connected in series, of which three units served as signal repeaters on an optical path with a total length of 4x100 km. This is the simplest technique to implement long routes, which are broken into individual point-to-point connections of approximately 80–100 km between regeneration units.

This is an example of 3R (Re-amplification, Reshaping and Retiming) regeneration by using the same WR switches throughout the route as at the beginning (grandmaster) and end (slave/boundary clock) of the route. To combine the directions into one fibre, DWDM SFP 120 km L-Band transceivers and corresponding DWDM 100GHz filters for channels 8 & 9 were used for each section of the route. To maintain consistent conditions to allow comparisons of the results with other tests, the DWDM band filters—4skip0 for L-Band and 8skip0 for C-Band—remained connected along the route, along with the power splitters with a 5% tap.

4.2.3 OEO Media Converters as Repeaters in Cascade

To test OEO media converters as repeaters, as illustrated in Figure 4.4, the same connection was used as in the WRS cascade on a 4x100 km route. Three CTC Union 1GE SFP-SFP media converters (FRM200-1000DS) were used as signal repeaters.

This setup is an example of 2R (Re-amplification & Reshaping) regeneration. **It is very important to use only 2R in the case of OEO regeneration** – using a conventional 3R (Re-amplification, Reshaping and Retiming) media converter on such a route would cause significant degradation of the transmitted time signal because standard 3R media converters cannot accurately repeat WR signals.

As in the previous test, the same DWDM bandpass filters—4skip0 for L-Band and 8skip0 for C-Band—were used throughout the route. Similarly, the power splitters with a 5% tap were also installed. To combine the directions into one fibre, DWDM SFP 120 km L-Band transceivers and the corresponding DWDM 100GHz filters for channels 8 & 9 were used again for each section of the route.

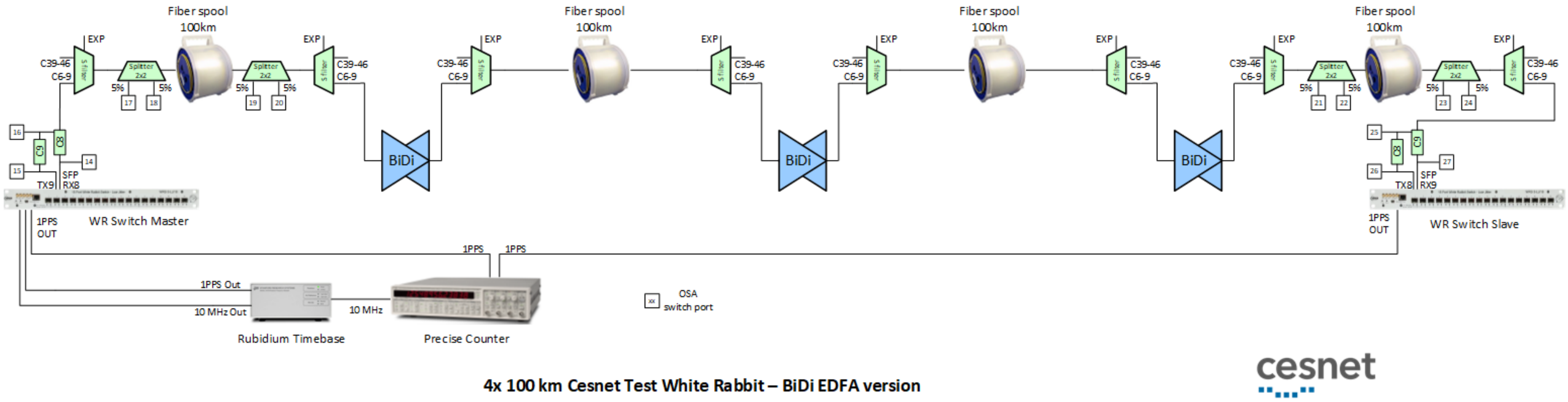


Figure 4.2: Lab test setup with regeneration of the WR signal through bidirectional EDFA amplifiers at every 100 km hop (400 km in total)

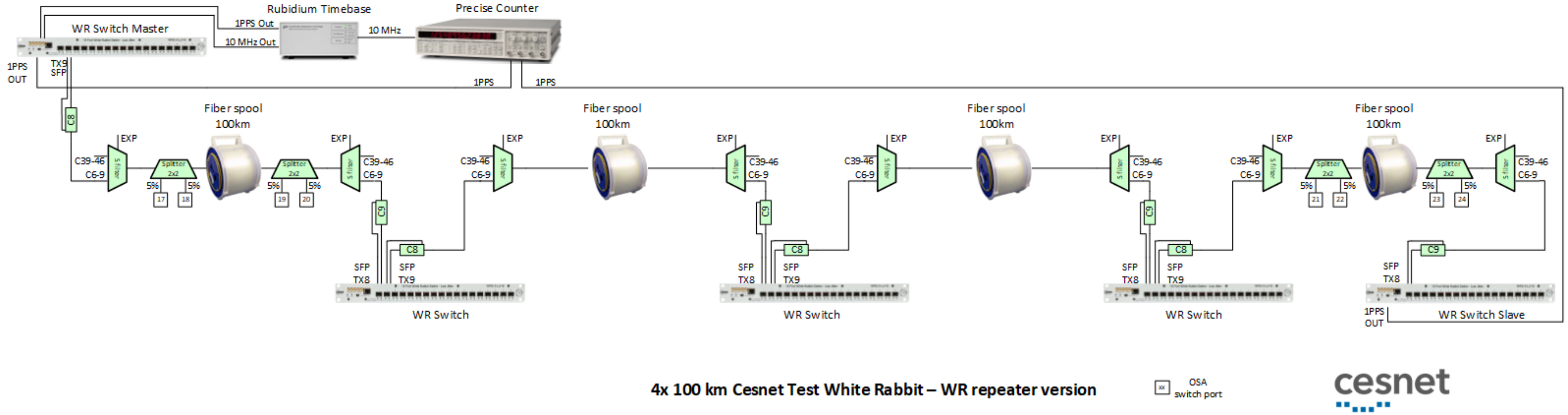


Figure 4.3: Lab test setup with regeneration of the WR signal through White Rabbit switches at every 100 km hop (400 km total)

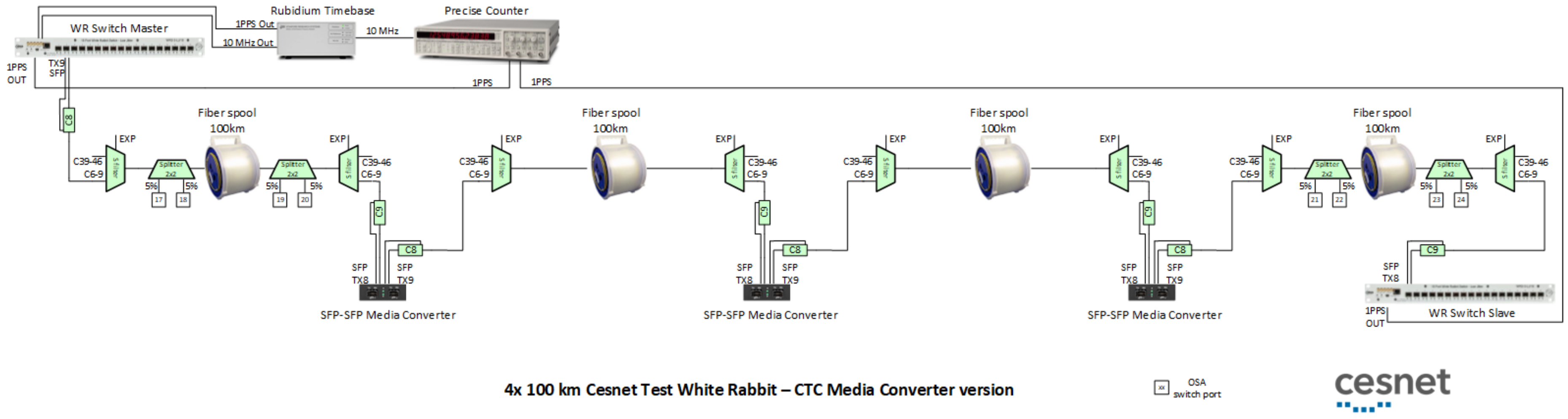


Figure 4.4: Lab test setup with regeneration of the WR signal through OEO media converters at every 100 km hop (400 km in total)

4.3 Lab Results: Comparison of Regeneration Techniques

4.3.1 Results Analysis

This section covers the laboratory-based time-offset results for each of the regeneration techniques tested. To recap:

- Three different types of regeneration techniques were tested in the laboratory environment at CESNET:
    - Optical BiDi amplifiers
    - Signal regenerators based on OEO (SFP-SFP regeneration)
    - Cascade of WR switches in boundary clock mode
- Each test used four 100 km fibre spools and three regenerator units.
- Tests were run for an extended period, from which a 4- to 5-day period was selected for the purpose of this analysis.

For evaluation of test results—i.e., the measured offset between Master WRS and Slave WRS—we use histograms and the TDEV and MTIE statistical metrics as described in Section 4.1.

Histograms are used to provide visualisations of the measured offset distribution. All of the following three histograms look like Gaussian (normal) distributions, but note that they have different standard deviation (sigma) – these values are given in Table 4.1.

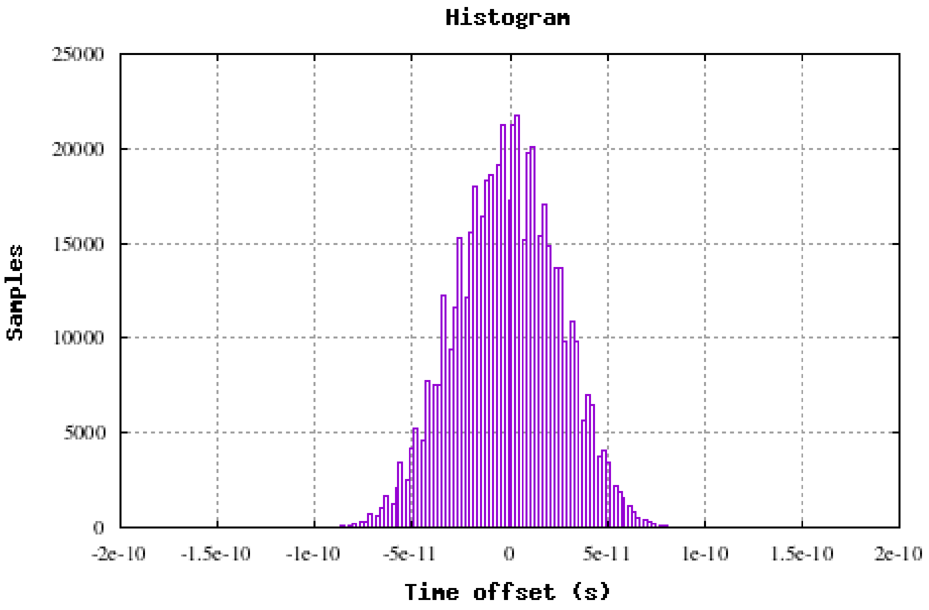


Figure 4.5: Histogram of bidirectional EDFA amplifier lab results

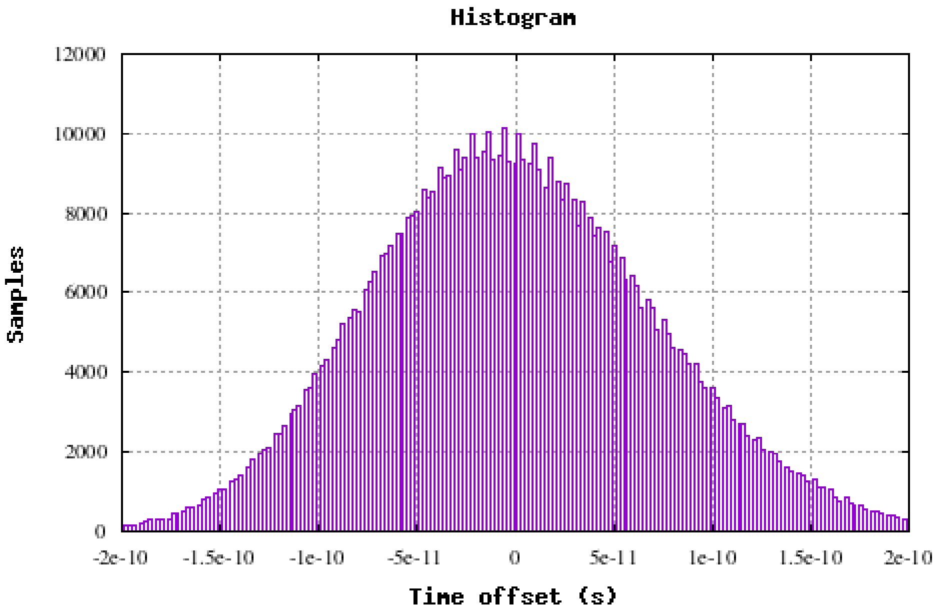


Figure 4.6: Histogram of White Rabbit switch regeneration lab results

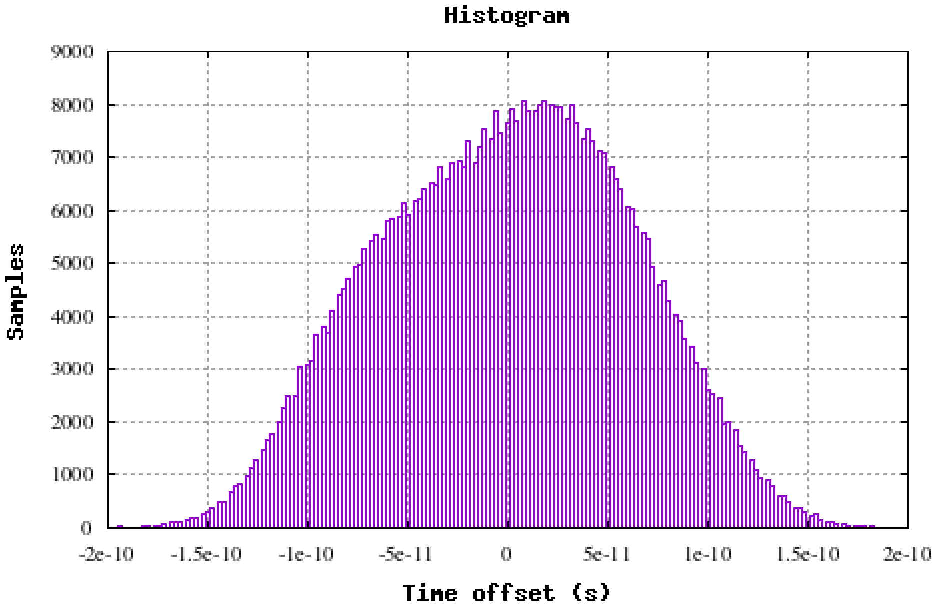


Figure 4.7: Histogram of OEO regeneration lab results

The results prove that any of the tested regeneration methods is fully valid for optical paths of hundreds of kilometres, and will provide performance that does not violate the required sub-nanosecond time-transfer stability (see the following MTIE graphs in Figure 4.9). Once the setup is calibrated—i.e., the measured offset is subtracted at the slave—the sub-nanoseconds accuracy can be met. However, note that none of these setups was calibrated for our tests; rather, we normalised the measured data.

The standard deviation and MTIE value for the 1-day period represent the maximal observed time offsets. In contrast, TDEV provides an estimate of the expected time offset fluctuation for specific averaging intervals. Of particular importance, as summarised in the following table, are the values for ~1,000 seconds, which typically represent a local minimum due to dominance of white phase noise; and the 10,000-second averaging interval, where one can observe the offset fluctuations due to daily environmental temperature fluctuations.

Technology	Std.Dev. - σ [ps]	MTIE (one day) [ps]	TDEV (10^3 s) [ps]	TDEV (10^4 s) [ps]
BiDi EDFA	48	200	3.3	3.3
OEO regenerator	104	400	4.3	3.2
WR cascade	61	600	5.2	8.3

Table 4.1: Summary of results for the three regeneration techniques tested

The TDEV graph compares the stability profiles of all three methods. It can be seen that the BiDi amplifiers offer the best performance, while the WR switch cascade adds more noise.

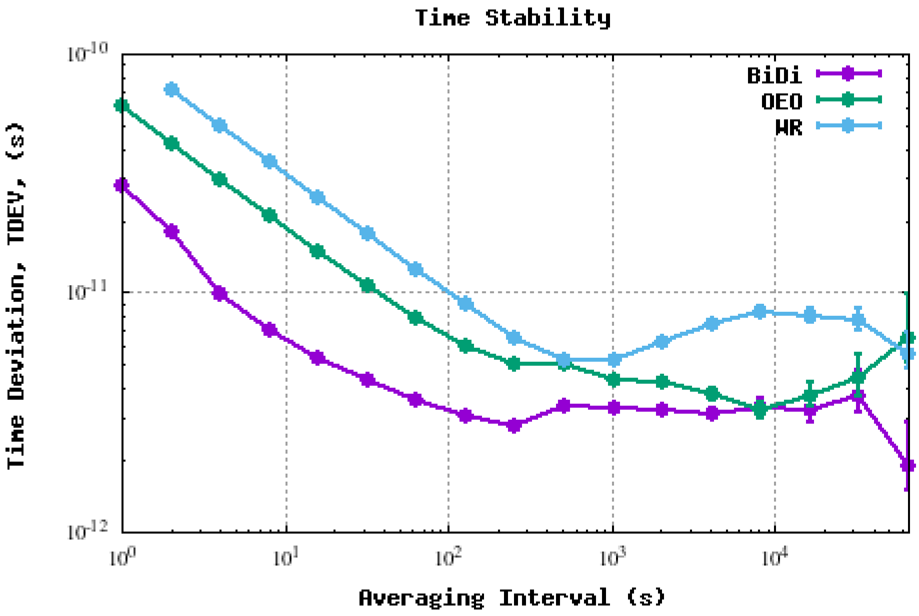


Figure 4.8: TDEV values of all three regeneration techniques

Similarly, the following graph gives a comparison of MTIE results for all three methods. Again, we see that BiDi amplifiers are the best method from the perspective of the lowest error.

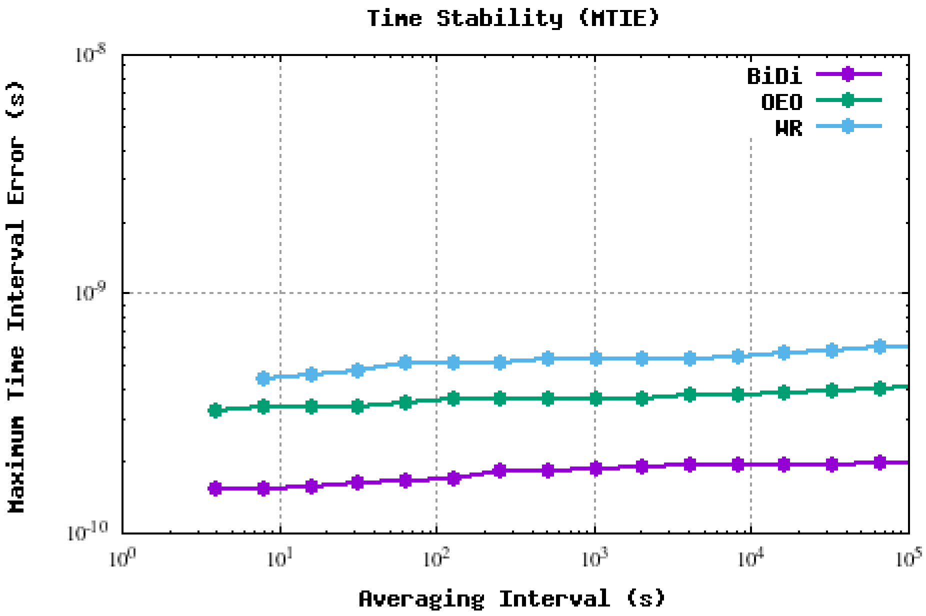


Figure 4.9: MTIE of all three regeneration techniques

Analysis

Three typical kinds of WR signal regeneration were compared. The results show that bidirectional optical amplification (1R) is the best method, while OEO regeneration (2R) is slightly worse. Splitting a long route into several segments connected by interleaved WR switches (3R) provides the worst performance, but still within the bounds of acceptability.

Thus, the tests proved that all three methods evaluated in the laboratory setup (400 km of fibre with three regenerations at 100 km intervals) are suitable for deployment in real systems with spans of several hundred kilometres.

Concerning the cascade of the WR switches, it can be concluded that four switches in a cascade (including the last one, the slave switch) maintains uncertainty on the sub-nanosecond order. This is a significant result, as a large, complex, real-world WR network would similarly have several regenerating WR switches on the route between the grandmaster and the slave switch, and our tests show that this produces acceptable results.

4.4 Field Trial with Bidi EDFA Regeneration

4.4.1 Field-Trial Setup

For a real-world field test of the implementation of White Rabbit technology on a DWDM system over a long path, the GÉANT Prague–Vienna route was chosen, as illustrated in Figure 4.10. The route is equipped with DWDM equipment from Infinera and currently runs a data flow of 2x 400Gbps with coherent frequencies in the C-Band. The route passes through several node points (Kouřim, Sachotin and Ivancice), where in-line DWDM amplifiers are located.

To test WR signal transmission over this route, we opted to amplify optical signals on a single fibre bidirectionally using BiDi EDFA, the best-performing technology from the preceding lab tests. For the BiDi EDFA, a device from CESNET's own development of the CzechLight series, the SDN series, was used. The SDN BiDi EDFA elements themselves were supplied by the Czech branch of CESNET's licensed partner, PEI-Genesis.

Both WR switches were collocated with time interval counters to measure the time instability. The fibre pair was used as a loop: one fibre for the Prague–Vienna direction and the other fibre to loop back in the Vienna–Prague direction:

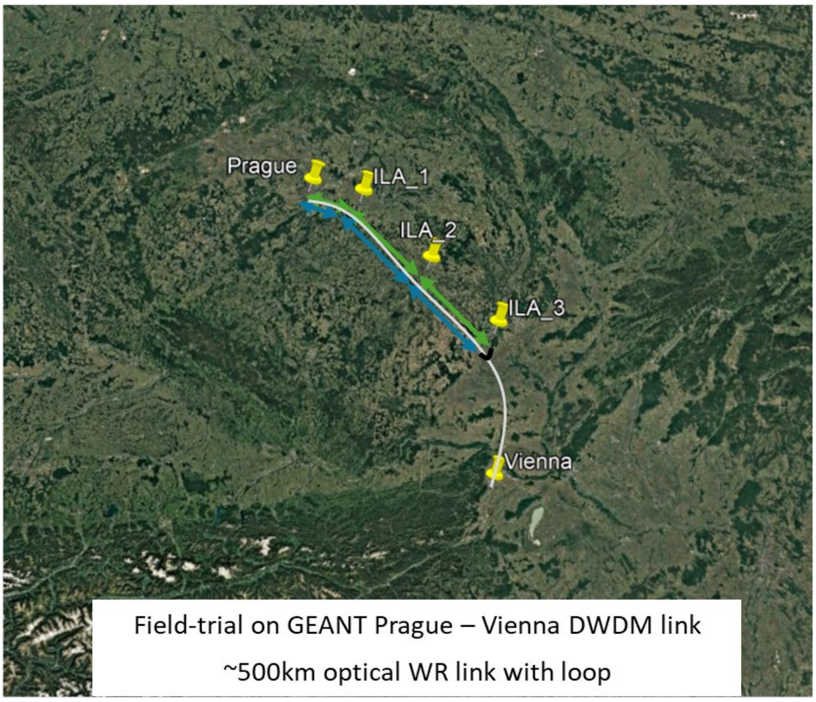


Figure 4.10: Map of the fibre layout loop for the field trial on GÉANT Prague–Vienna fibre pair (white). The green and blue arrows show the links between bidirectional amplifiers and fibre 1 (green) plus loopback fibre 2 (blue) in the DWDM fibre pair

As a starting point for the test, the DC Tower in Prague was chosen as it provided the necessary space in the CESNET rack to place both WR switches, a precise counter, a rubidium clock and a management switch. This also allowed the installation of a direct connection from the GÉANT rack to the Infinera equipment from the neighbouring hall.

The White Rabbit technology was installed using the already existing filters for L-Band DWDM, which are part of the installation of the Infinera DWDM element chassis.

To protect commercial confidentiality, the figure below shows only an indicative approximation of the spectrum used on the Infinera DWDM equipment. For this trial, we were able to use the free L-band from 1569.183 to 1609.624 nm. It should be noted that only C-band Raman pumps were installed—for this reason, the pump gain spectrum was approximately as indicated by the black curve in Figure 4.11.

The Infinera amplifier cards used were equipped with C-band Raman amplifiers in addition to standard EDFA amplifiers (including the Kouřim–Sachotin–Ivancice nodes). During the WR field test, coherent live internet data was transmitted only in the C-band; L-band Raman amplifiers were not present.

For the transmission of WR signals, the same DWDM channel 8 & 9 wavelengths (1570.42 nm and 1571.24 nm) were used as in the previous laboratory tests, along with the corresponding SFP DWDM 120 km transceivers. These L-Band channel 8 & 9 wavelengths are very close to the C-band and therefore were also partially amplified by C-band Raman amplifiers. This is due to the C-band Raman gain profile extending into the edge of the L-band, as shown in Figure 4.11.Figure 4.11: Indicative approximation of the Infinera DWDM spectrum used in the field trial

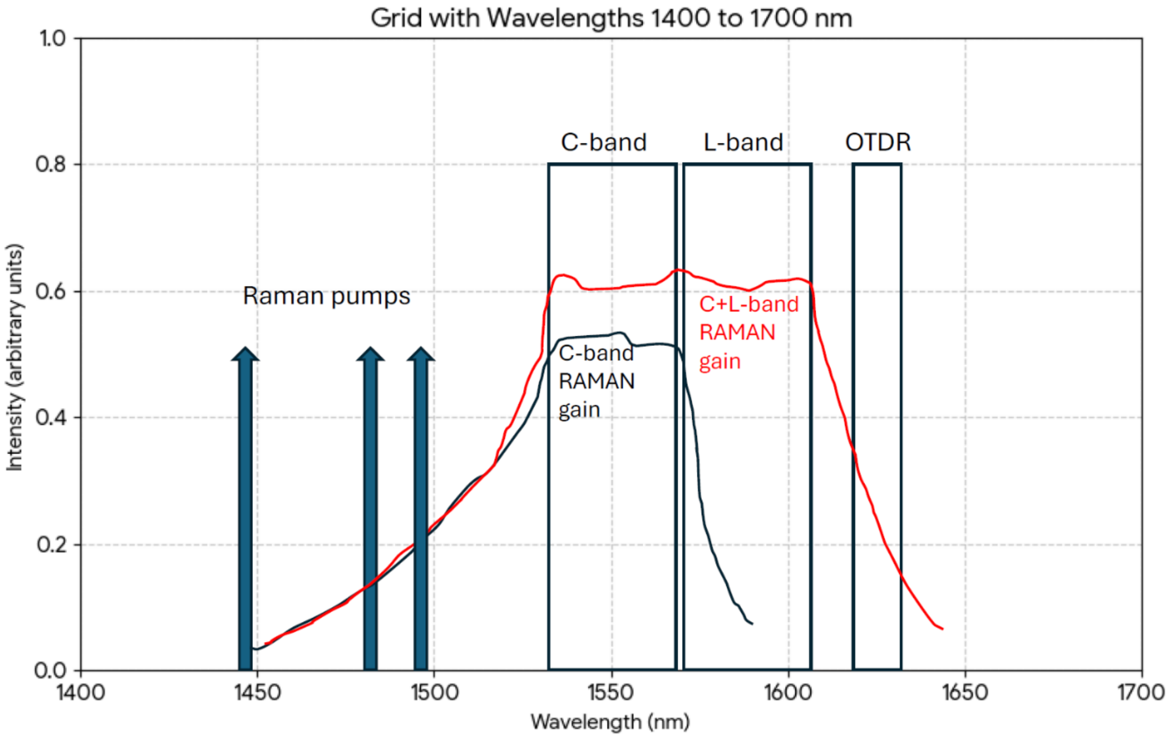


Figure 4.11: Indicative approximation of the Infinera DWDM spectrum used in the field trial

Alongside the benefits of amplification, the use of Raman amplifiers for the transmission of BiDi WR signals also has disadvantages. Bidirectional WR signals were found to be amplified unequally in both directions, introducing a slightly nonlinear optical-power gain into the path.

Correctly setting the power parameters of the BiDi EDFA amplifiers used for WR signals prevented this nonlinearity (within the level of a few dB) from causing problems—the transmission worked successfully. As there was no IP connectivity available at the intermediate DWDM amplification points on the optical path, we chose the Coarse Wavelength Division Multiplexing (CWDM) 1590 nm wavelength to provide an independent optical supervisory channel (OSC) for management. The WR and OSC channel signals were integrated via conventional DWDM L-band and CWDM filters. SFP CWDM 1590 120 km transceivers were additionally used.

The following Figure 4.12 shows the wiring diagram of the WR field test. Equipment was deployed in two steps, as indicated in the figure.

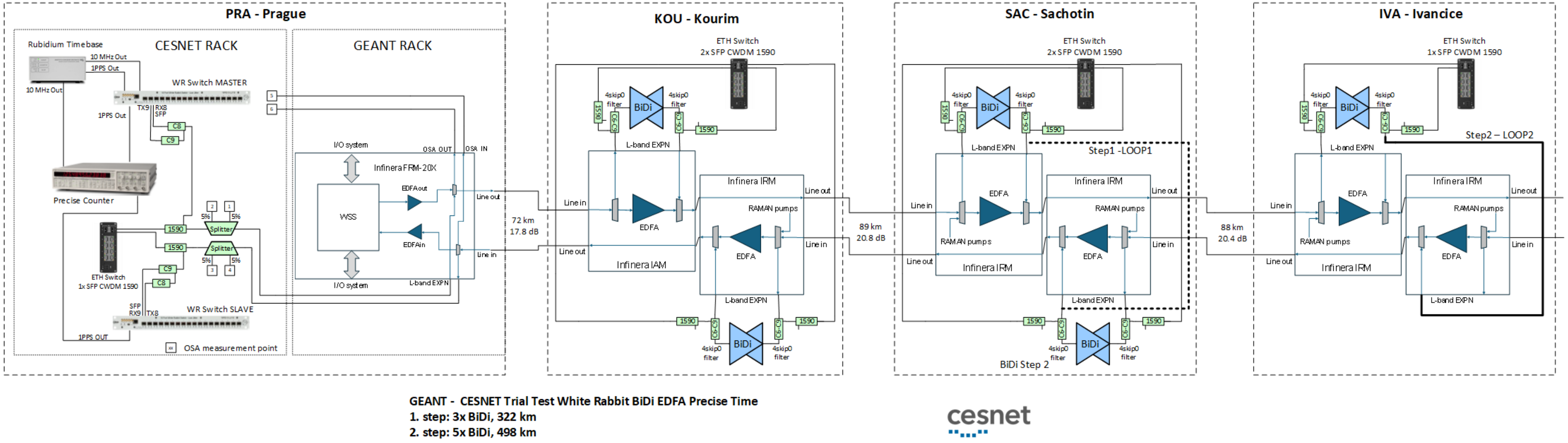


Figure 4.12: Field test setup deployed in two steps: Step 1 involved creating the loopback Loop1 in Sachotin with the WR time service link of 322 km (i.e., fibre 1 in the Prague–Sachotin direction, then looped on fibre 2 back to Prague); Step 2 was the setup of the loopback Loop2 in Ivancice, creating an end-to-end WR time service link of 498 km

The installation took place with full live internet traffic on coherent transmission in the C-band (2x 400Gbps). When we turned up the OOK signals of the WR and OSC channels, this had no effect on the data channels already in operation.

At the end node in DC Tower in Prague, illustrated in Figure 4.13, we used the free EXPN IN ports in the Infinera FRM-20X device to connect the WR master and OSC signals towards the route (WR signals are bidirectional). The EXPN OUT port was used for the incoming WR slave and OSC signals looping back on the route.

We also employed the OSA IN and OSA OUT ports in the CESNET rack to check for any possible effects on the transmitted coherent data signals on the C-band. In the first step, we installed the entire setup in DC Tower Prague and installed 2 BiDi EDFAs in the Kouřim location. In the Sachotin location, we installed only one BiDi EDFA and the end loop back to Prague. The entire route thus contained 3 BiDi EDFA amplifiers and was 322 km long.

As illustrated in the following figure, in Prague, in addition to DWDM Add/Drop filters that combined the directions of channels 8 & 9, there were also 1590 nm CWDM filters upstream to separate the OSC channel and connect the Ethernet switch for the OSC channel. Furthermore, in Prague we deployed the bidirectional 2x2 power splitters that tap 5% of the power from both directions to the OSA analyser.

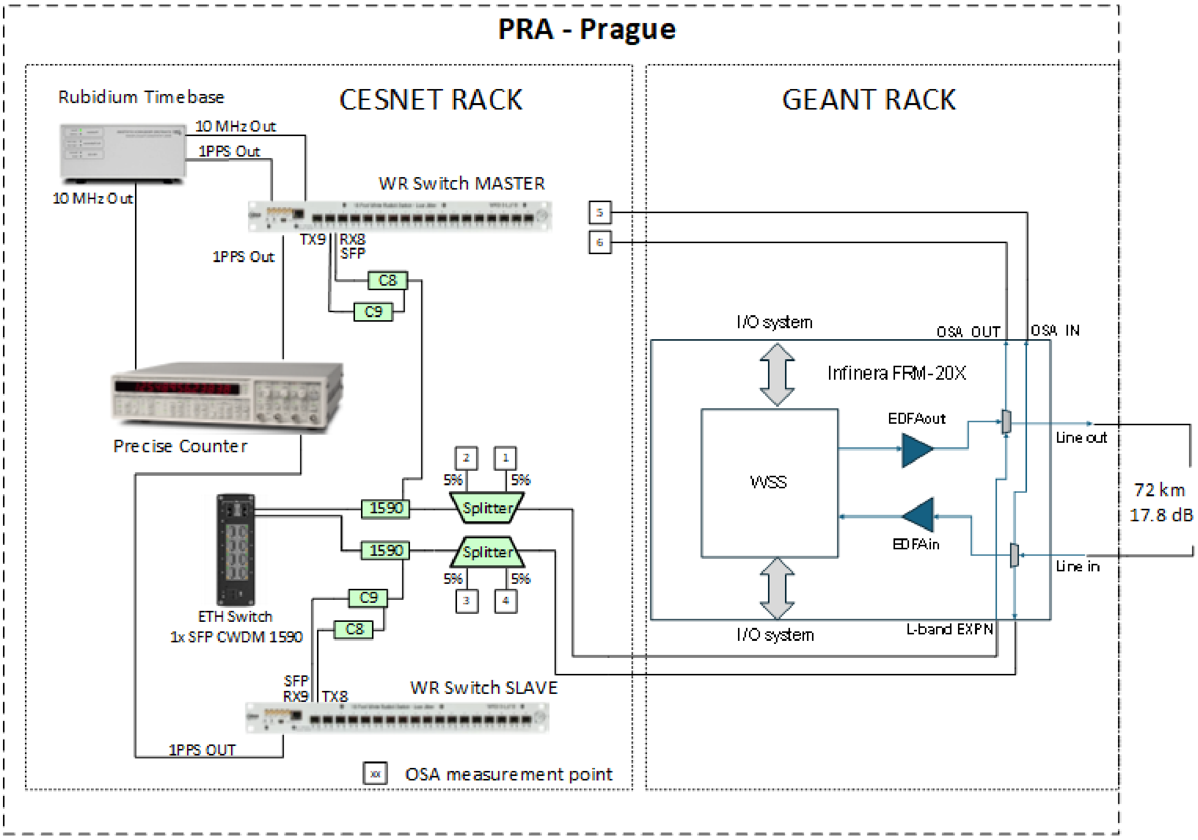


Figure 4.13: Wiring diagram of the setup in DC Tower, Prague

In the Kouřim amplification location illustrated in Figure 4.14, DWDM bandpass filters are connected to the free L-band EXPN OUT and EXPN IN ports of the Infinera line cards type IAM (facing towards Prague) and IRM (facing towards Sachotin).

DWDM bandpass filters of the 4skip0 type (covering channels 6–9 for a total of up to 4 DWDM channels) were used to filter any other noise from the route and help maintain a low overall noise level. CWDM 1590 nm filters with a connected Ethernet switch were used for the OSC management channel itself.

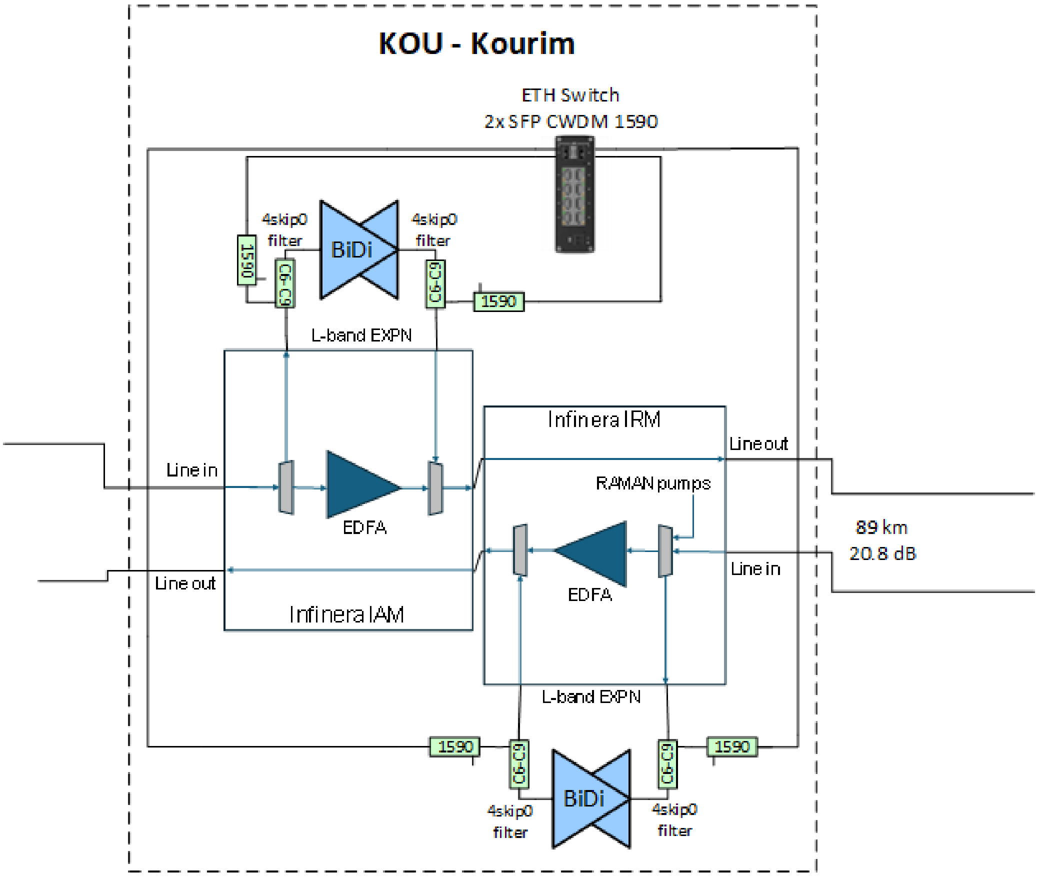


Figure 4.14: Wiring diagram of the setup in Kouřim

The Sachotin location was equipped similarly to the Kouřim location, except that in the first stage of the installation (Step1, loop 1) only one BiDi EDFA was used, and a loop was made to returns the WR signals back to Prague via the second fibre towards the WRS slave switch.

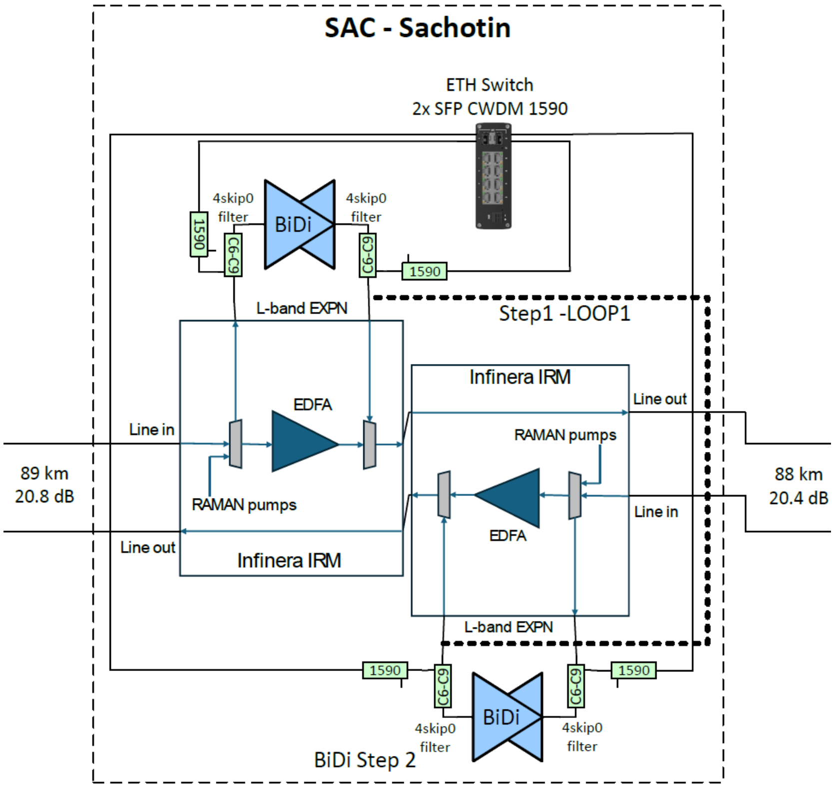


Figure 4.15: Wiring diagram of the setup in Sachotin

In the second stage of the installation (after confirming faultless operation of the connection and verifying the transmission parameters), the loop in Sachotin was removed. A second BiDi EDFA was connected, and the route was extended towards Ivancice.

In Ivancice, another BiDi EDFA was installed, and a loop was made to the second fibre back to Prague to the WR slave switch. The rest of the connection was similar to the previous locations; a full illustration is given in Figure 4.16. Again, DWDM 4skip0 bandpass filters and CWDM filters were used for the final Ethernet switch of the OSC management channel.

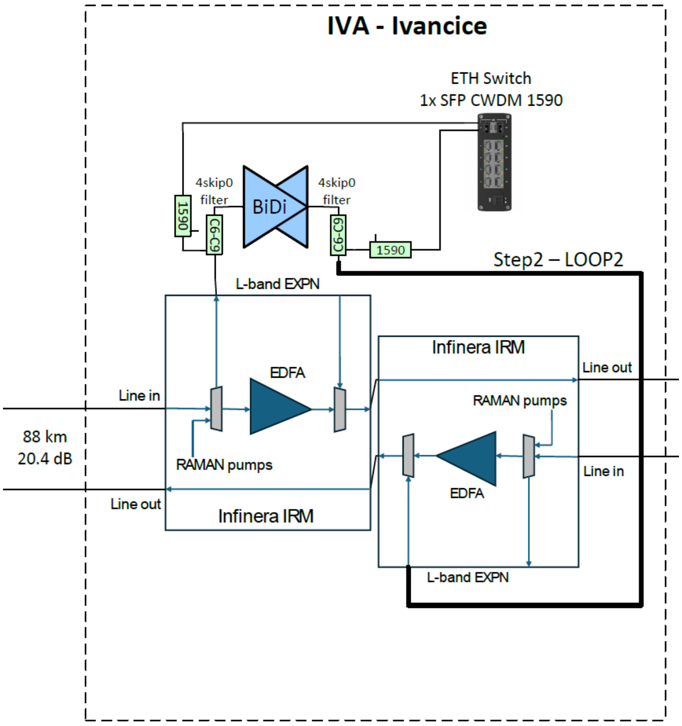


Figure 4.16: Wiring diagram in Ivancice

The Infinera IRM card contains, in addition to the standard DWDM C-band EDFA, a Raman amplifier for the given direction. The presence of Raman optical amplifiers on the route reduced the effective attenuation of the route even within the L-band. However, it also resulted in a degree of non-reciprocal attenuation, as the gain of the Raman amplifier was not identical in both directions of BiDi transmission over a single fibre. Raman amplifiers were present on the Kouřim–Sachotin and Sachotin–Ivancice sections of the route. Minor "virtual" fibre attenuation was compensated for during the actual installation by fine-tuning the BiDi EDFA settings and adding a passive simple attenuator before the amplifier.

The total length of the WR signal optical transmission, employing five EDFA BiDi amplifiers, reached 498 km.

4.4.2 Management and Monitoring of Field Test Values

In contrast with the lab measurement method described in Section 4.1, in the field trial the equipment was installed in amplifier sites along the route. This necessitated a remote monitoring solution for both the WR devices and the deployed optical amplifiers. For this, we used the CESNET monitoring system that is being developed for future WR production infrastructure.

In this system, the time interval counters measure the difference between 1PPS outputs of the WR grandmaster and slave. Its RS232 interface was connected through a converter to a Raspberry Pi running a custom Python script. This setup handled the automated logging of measured time interval data that were then stored in a time-series database (TSDB). This data can then be retrieved from the TSDB for further processing.

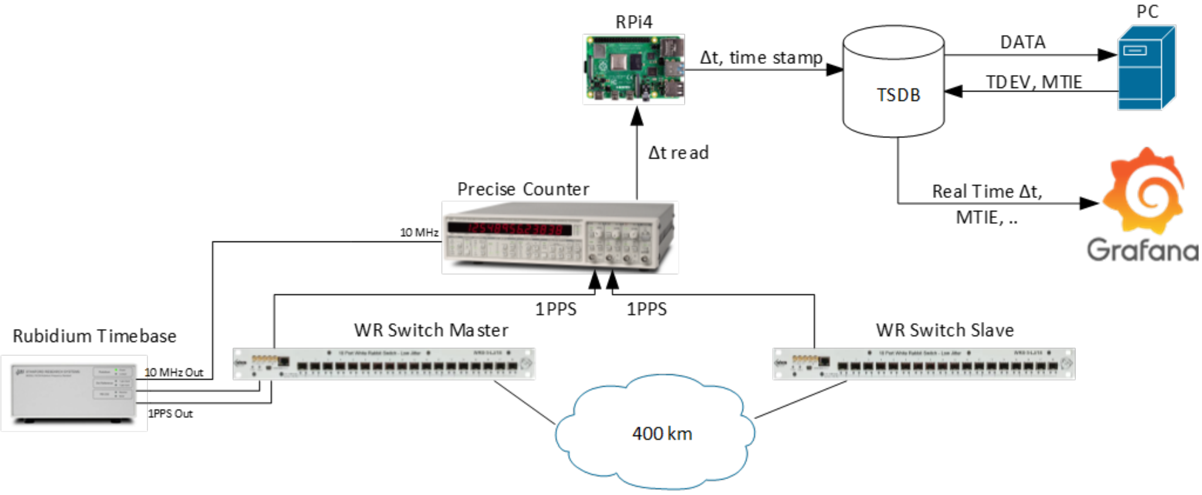


Figure 4.17: Field-trial management and monitoring high-level architecture

Data was also collected directly from WR devices using the Telegraf utility, which acted as an SNMP agent, issuing queries every 3 seconds. A combination of tools enabled seamless monitoring:

- SNMP interface metrics were gathered by the WR switches.
- The retrieved SNMP metrics were sent to a VictoriaMetrics time-series database for storage.
- Grafana was used to visualise and analyse the collected data in real time.

This multi-component setup provided robust and synchronised measurement of both physical timing signals and internal WR synchronisation metrics. As part of the field trial, the power levels at the ports of all BiDi EDFA amplifiers were read and logged, covering both transmission directions and on both optical ports (WEST, EAST).

Figure 4.18: Viewing field-trial values using a Grafana dashboard

4.5 Field-Trial Results

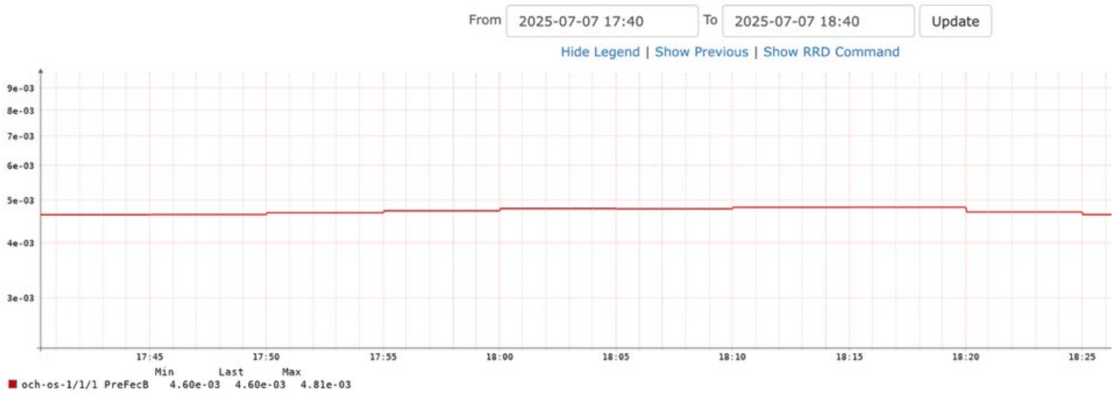
4.5.1 Coexistence of WR with Coherent Data Channels

In this test, we checked the impact of the 1GE on-off keying of the L-band White Rabbit service on the coherent data wavelengths. Two IP trunks were operational on the GÉANT fibre between Prague and Vienna. The internet service trunks operate at 400Gbps modulated using 16QAM and a baud rate of 69G. These two trunks operate on the following frequencies:

- Wavelength one: 196.025 THz – 196.125 THz
- Wavelength two: 195.925 THz – 196.25 THz

The L-band White Rabbit wavelengths were turned on at 18:15 on 7 July 2025. As can be seen from the pre-FEC BER plots, no meaningful changes in BER can be detected at turn-on.

The plot in Figure 4.19 shows the pre-FEC BER on the second wavelength at the Prague end of the link at pre-FEC BER in pra01-grv2. There is no measurable change in the pre-FEC BER at 18:15.



From 2025-07-07 17:40 To 2025-07-07 18:40

Figure 4.19: Pre-FEC BER on the second wavelength at the Prague end of the link

The plot in

From 2025-07-07 17:40 To 2025-07-07 18:40

Figure 4.20 shows the pre-FEC BER on the first wavelength at the Vienna end of the link at pre-FEC BER in vie01-grv1. There is no measurable change in the pre-FEC BER at 18:15.

Figure 4.20: Pre-FEC BER on the first wavelength at the Vienna end of the link

The plot in Figure 4.21 shows the pre-FEC BER on the second wavelength at the Vienna end of the link at pre-FEC BER in vie01-grv1. Again, there is no measurable change in the pre-FEC BER at 18:15.

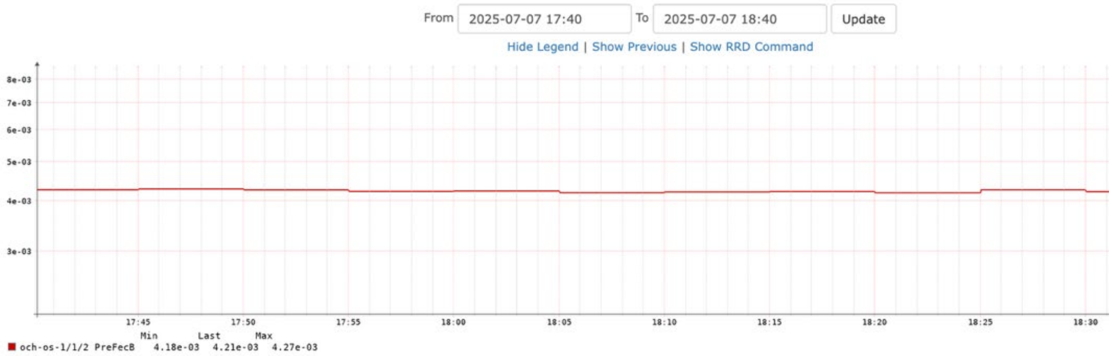


Figure 4.21: Pre-FEC BER on the second wavelength at the Vienna end of the link

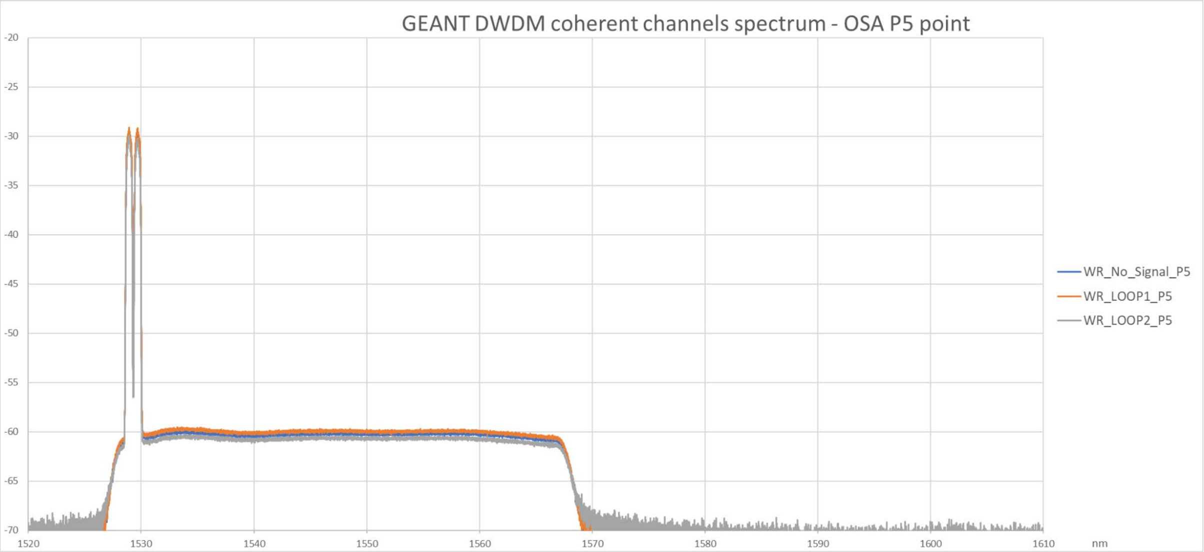


Figure 4.22: Measured DWDM C-band spectrum before and after White Rabbit installation

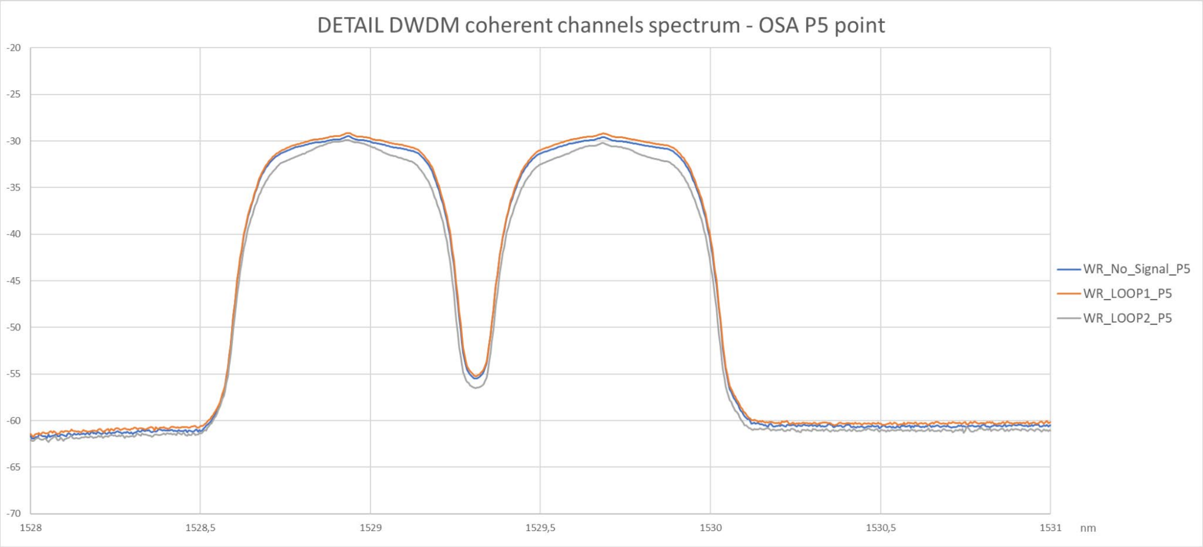


Figure 4.23: Detail of the 2x 400Gbps spectrum before and after White Rabbit installation

Analysis

From the results of the pre-FEC BER values recorded from the Infinera DWDM system and the measured spectral waveforms of the transmitted data channels, it can be seen that the installation of White Rabbit technology in the "live" GÉANT route did not affect this data traffic at all.

4.5.2 White Rabbit Performance Results

This section reviews the results of WR field trials using histogram graphs, as was done for the lab tests, and summarises key calculated parameters. All histograms appear to be close to normal (Gaussian) distribution, so it is appropriate to use the standard deviation (sigma) to characterise the data, as 68% of results are expected to lie within the interval (-σ, σ).

Step 1 – Loop 1 322 km results

The mean measured time offset was 2.73 ns (note: the setup was uncalibrated, therefore data was normalised) with a standard deviation (sigma) of 27.0 ps.

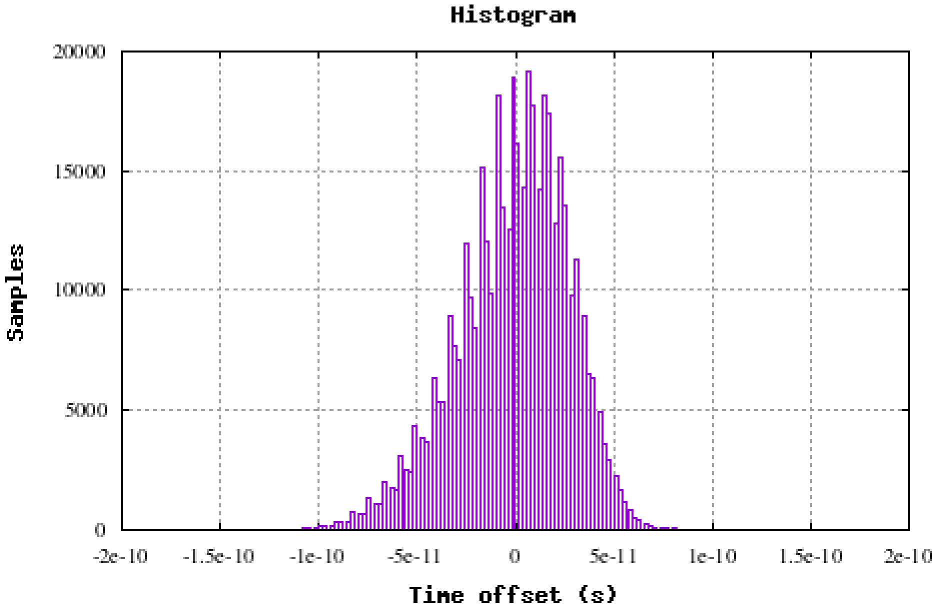


Figure 4.24: Histogram of loop 1 320 km field-trial results with bidirectional EDFA amplifiers

Step 2 – Loop 2 498 km results

The mean measured time offset was 1.6 ns (as above, the setup was uncalibrated, so data was normalised) with a standard deviation of (sigma) 33.7 ps.

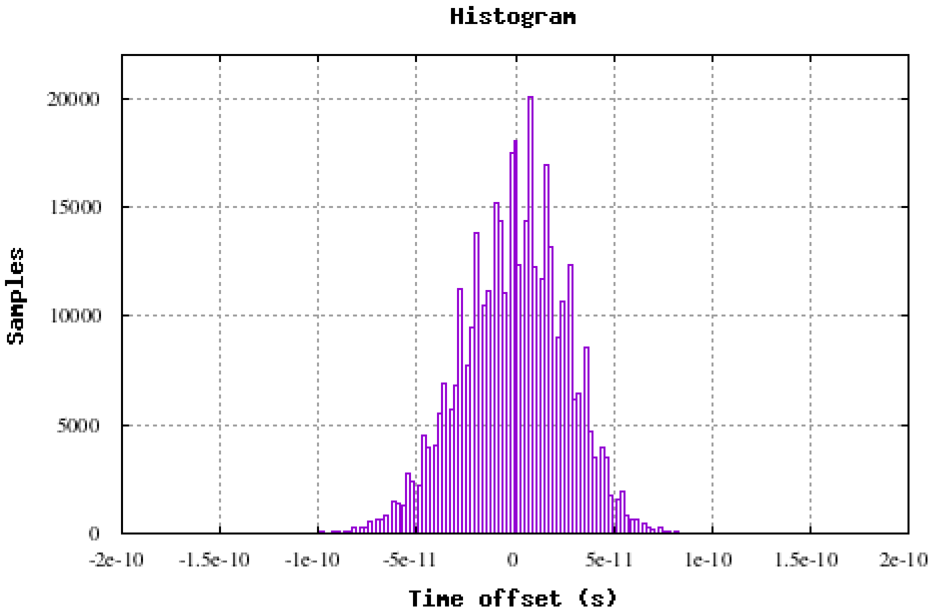


Figure 4.25: Histogram of loop 2 500 km field-trial results with bidirectional EDFA amplifiers

4.6 Field vs. Lab Results: Comparison and Analysis

In the field, the WR signal was amplified by BiDi EDFA technology, therefore its performance can be compared with the BiDi amplifier laboratory test case. As the results of both field setups (Step 1 and Step 2) are similar, we will refer to the longer loop of Step 2 here as the ‘field test’ results in the following graphs that compare the laboratory and field results. The results are summarised in the following Table 4.2.

Setup	Fiber length (km)	# of EDFA	Std. Dev. - σ (ps)	MTIE (one day) (ps)	TDEV (103 s) (ps)	TDEV (104S) (ps)
Laboratory	400	3	48	200	3.3	3.3
Field-trial (Loop 2)	498	5	34	240	8.0	6.0
Intermediate Step 1 – Loop 1	322	3	27	330	10.9	10.5

Table 4.2: Performance results with BiDi regeneration: laboratory versus field

The table contains two TDEV values for the two averaging intervals of 1,000 s and 10,000 s. The first reflects short-term behaviour, where white phase noise is the dominant type of noise, while the second displays environmental influences such as daily temperature cycles. Although the laboratory test of BiDi EDFA produced generally better results than the field trials, its standard deviation is worse. This can likely be explained by the resolution limits of the testing setup – the small fluctuation of measured offset between the WR master and slave is close to the floor of the SR620 counter's resolution, which has a sigma of 20ps in time interval mode.

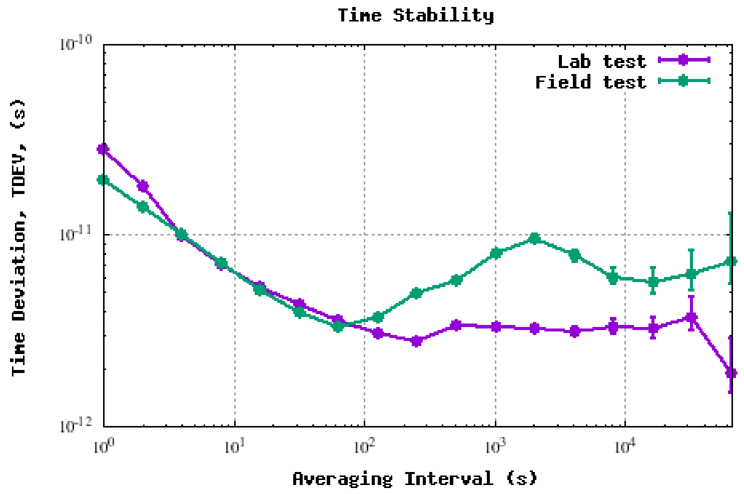


Figure 4.26: TDEV of 500 km (loop2) field-trial and lab regeneration (400 km) with bidirectional amplifiers

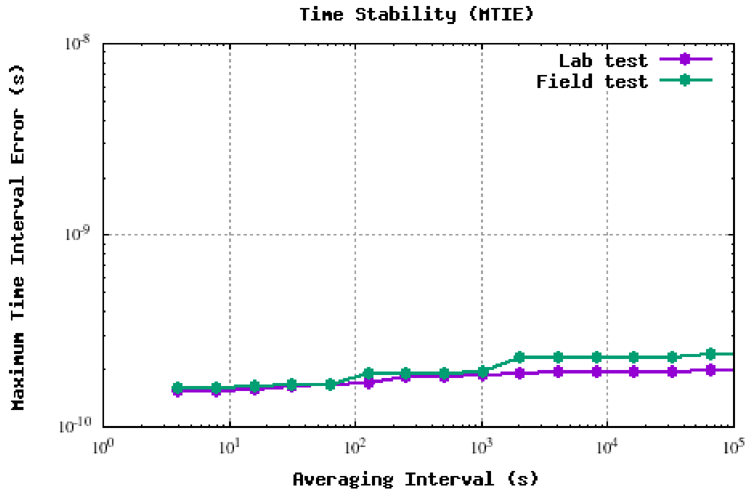


Figure 4.27: MTIE of 500 km (loop2) field-trial and lab regeneration with bidirectional amplifiers.

Conclusion: The differences between the lab test and the field trial are small and are within the measurement error. The exception to this is TDEV for 1,000 s to 10,000 s averaging interval. This can be explained by greater daily environmental temperature changes in the case of field-deployed devices (deployed August–October) compared to laboratory conditions.

Overall, the field-trial results corroborate the laboratory test. This is an encouraging observation, as it allows us to deduce that further laboratory tests in future can be expected to provide results applicable to the behaviour of real-world WR links over long distances.

Numerous experiments, including field trials conducted within the GÉANT WR Incubator activity, have demonstrated that time-transfer stability over several hundred kilometres of fibre using bidirectional optical amplifiers results in an instability significantly lower than the specified 1 ns. Specifically, we observed a WR time-transfer stability of ±100 ps over a 498 km fibre loop (118 dB total attenuation) utilising five bidirectional optical amplifiers during a measurement period lasting several weeks.

5 Cost-Benefit Analysis

For the WR incubator, GÉANT has developed a spreadsheet tool (available at [1]) that can be used by NRENs to calculate the cost of adding WR time links onto their existing DWDM transmission system. The results presented in this section make use of this spreadsheet.

We consider five scenarios for the purposes of costing a long-haul White Rabbit transmission system. The equipment needed for each scenario is summarised in the following table. In all scenarios, we assume that two White Rabbit time channels are needed to support easy calibration and validation of the time transfer. The cost of DWDM channels is not included in this calculation.

	Equipment	Scenario				
		Alien wave	**Bidi amp**	**OEO**	**WRS at amp**	**ELSTAB**
PoP site	Terminal Eth switch & optics	2	2	2	2	2
	Terminal WR Safran LG	2	2	2	2	0
	Terminal WR Safran CG	0	0	0	0	0
	Terminal ELSTAB	0	0	0	0	2
	Terminal T/F filter PTS	0	2	2	2	2
ILA site	ILA hut Ethernet switch and optics	0	1	1	1	1
	ILA hut filter	0	2	2	2	2
	ILA hut BiDi amplifier PTS single	0	0	0	0	2
	ILA hut BiDi amplifier CZL dual	0	2	0	0	0
	ILA hut OEO and optics single ch	0	0	2	0	0
	ILA WRS for regeneration	0	2	0	2	2

Table 5.1: List of equipment in each costing scenario

Alien Wave

In this solution, the WR signal is carried over a DWDM alien wavelength. Operation is unidirectional – i.e., each direction of transmission is on a separate fibre. From the point of view of the DWDM network operator, the WR service appears as an ordinary 1GBE service. Because of the NRZ modulation, a guard-band is needed to separate WR from coherently modulated wavelengths. The equipment needed for this solution is low, encompassing only the WRS and associated optics at each end of the link – no special bidirectional amplifiers or regens are needed. Two WR time channels are deployed for easy validation of the link operation. While this solution is simple, keep in mind that the accuracy is several orders of magnitude less than the bidirectional modes described next.

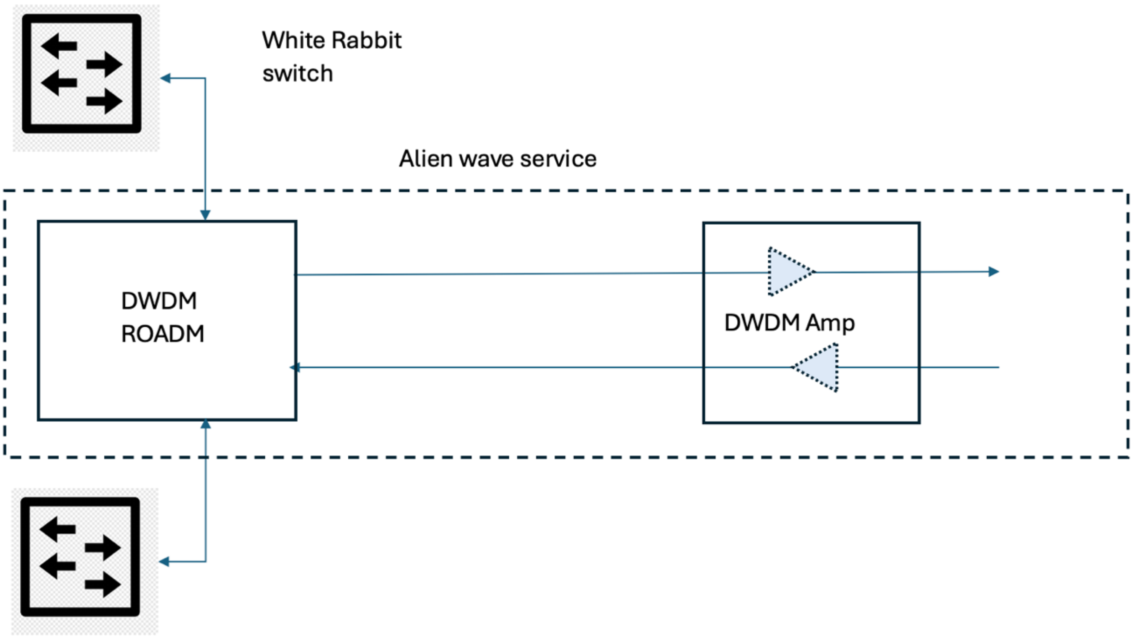


Figure 5.1: High-level diagram of White Rabbit time service over an alien wavelength optical service. WR signal regeneration is performed through the DWDM

BiDi C/L-Band Amplifier

In this configuration (see Figure 5.2: Scenario for C-TFN built with two White Rabbit links and regeneration through BiDi EDFA amplifiersFigure 5.2), the WR signal bypasses the telecoms amplifier and is sent to the bidirectional EDFA amplifier. This bidirectional amplifier is needed at every amplifier site. In addition, filters are needed to separate the bidirectional wavelengths from the unidirectional data wavelengths. Since this filter is required, it may be more cost effective to use L-band filters to solve the guard-band problem and keep the C-band free for internet traffic. This will reduce expenditure on spectrum in the cost calculations.

Some DWDM vendors include L-band filters suitable for WR channels in their equipment—e.g., Infinera/Nokia FlexILS offers L-band-capable amplifiers featuring bidirectional L-band ports on the amplifier cards.

Two WR time channels are deployed for easy validation of the link operation.

In the GÉANT network, the bidirectional amplifier does not include an integrated in-band management channel. For this reason, the cost of management switches is included.

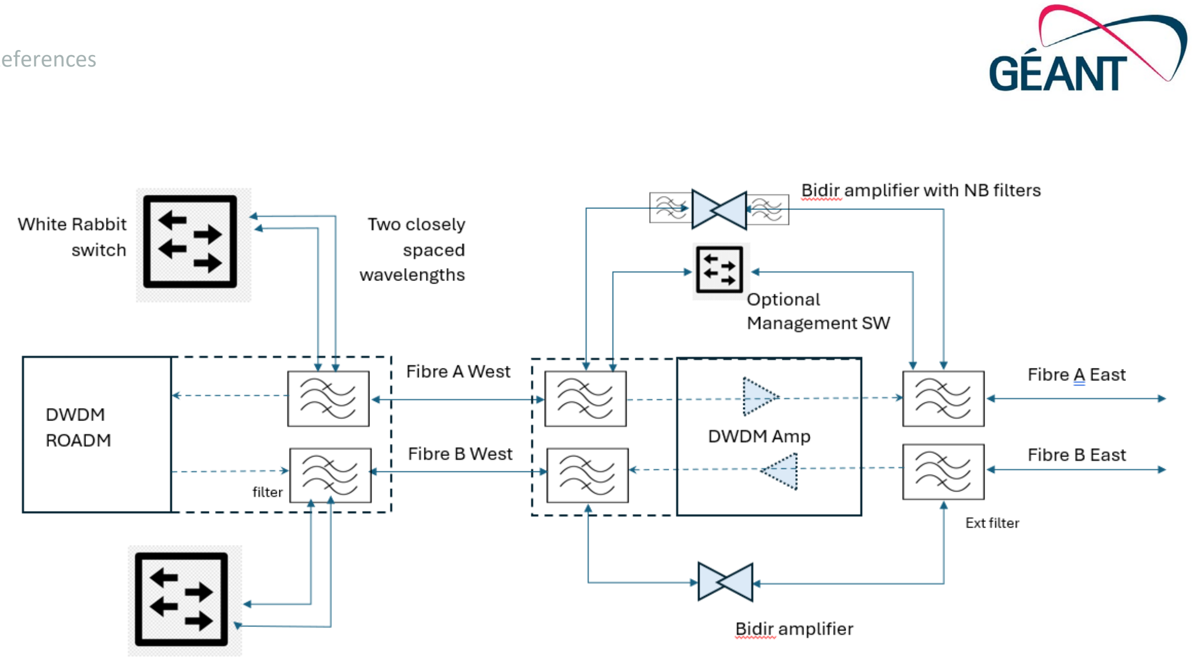


Figure 5.2: Scenario for C-TFN built with two White Rabbit links and regeneration through BiDi EDFA amplifiers

WRS at amplification sites C/L

It is possible to use a full White Rabbit Switch at each amplifier site. The WR signal bypasses the telecoms amplifier via a filter and is sent to a WRS acting as a 3R regenerator.

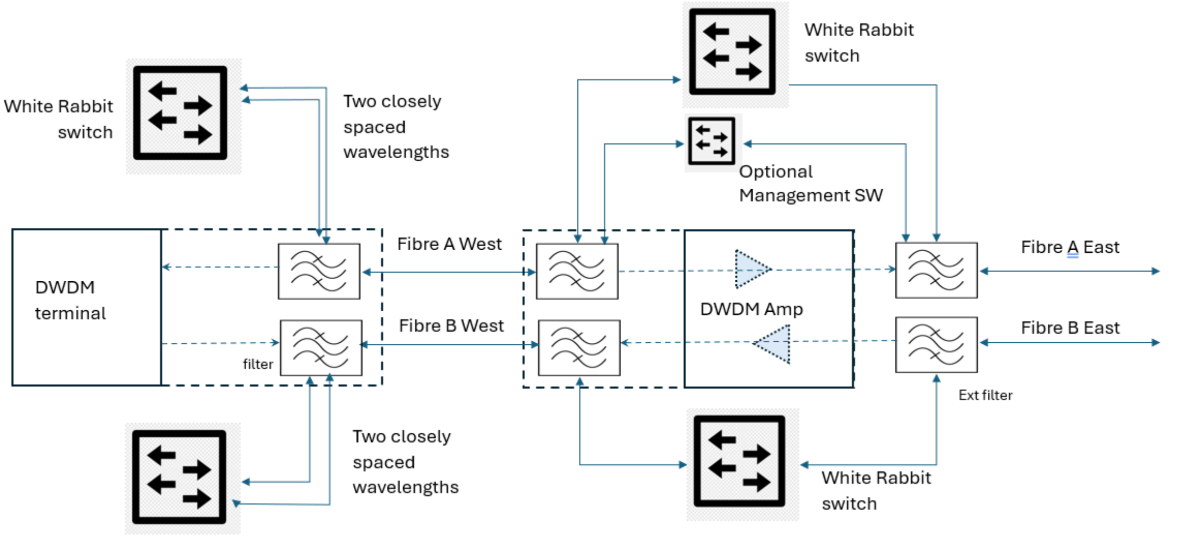


Figure 5.3: Scenario for C-TFN built with two White Rabbit links and regeneration through WR switches

OEO C/L band

In this setup, the WR signal bypasses the telecoms amplifier and is sent to an OEO 2R regenerator instead of a WR switch. Ethernet OEO regenerators can be purchased commercially at lower prices than a full WR switch. To manage this device, a separate Ethernet switch will need to be purchased to provide an in-band management channel. Again, two WR time channels are deployed for ease of validation of the link operation.

ELSTAB

In this solution, filters are used to allow the ELSTAB [8] signal to bypass the telecoms unidirectional amplifiers as illustrated in Figure 5.4. The ELSTAB solution gives the best quality performance of all the solutions proposed.

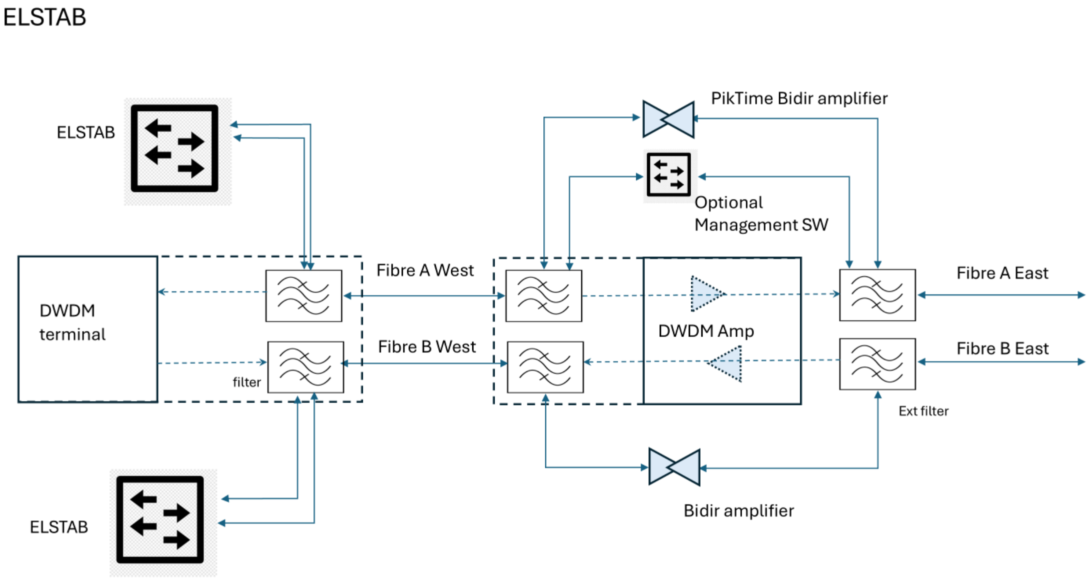


Figure 5.4: Scenario for C-TFN built with an ELSTAB system providing a time service

Comparison

The plot in Figure 5.5 outlines the costs of adding two services to a DWDM system. It shows how the cost changes depending on the number of ILAs present and the regeneration technique used. The cost of the spectrum is considered to be zero for all scenarios. The ELSTAB system uses Piktime System amplifiers, and the WR system uses the basic WR switches for grandmaster and slave nodes, employing the respective regeneration techniques at ILA sites as explained above.

The most expensive solution is ELSTAB, while the least expensive is the use of alien wavelengths.

When using White Rabbit, the use of bidirectional amplifiers is cost effective for links with up to five amplifier sites – note that beyond five sites, a WRS is used for 3R, hence the jump in cost at the sixth ILA site. The use of OEO regenerators becomes more cost effective for longer links. The use of a WRS at each amplifier site is both more expensive and less accurate than using OEO regenerators.

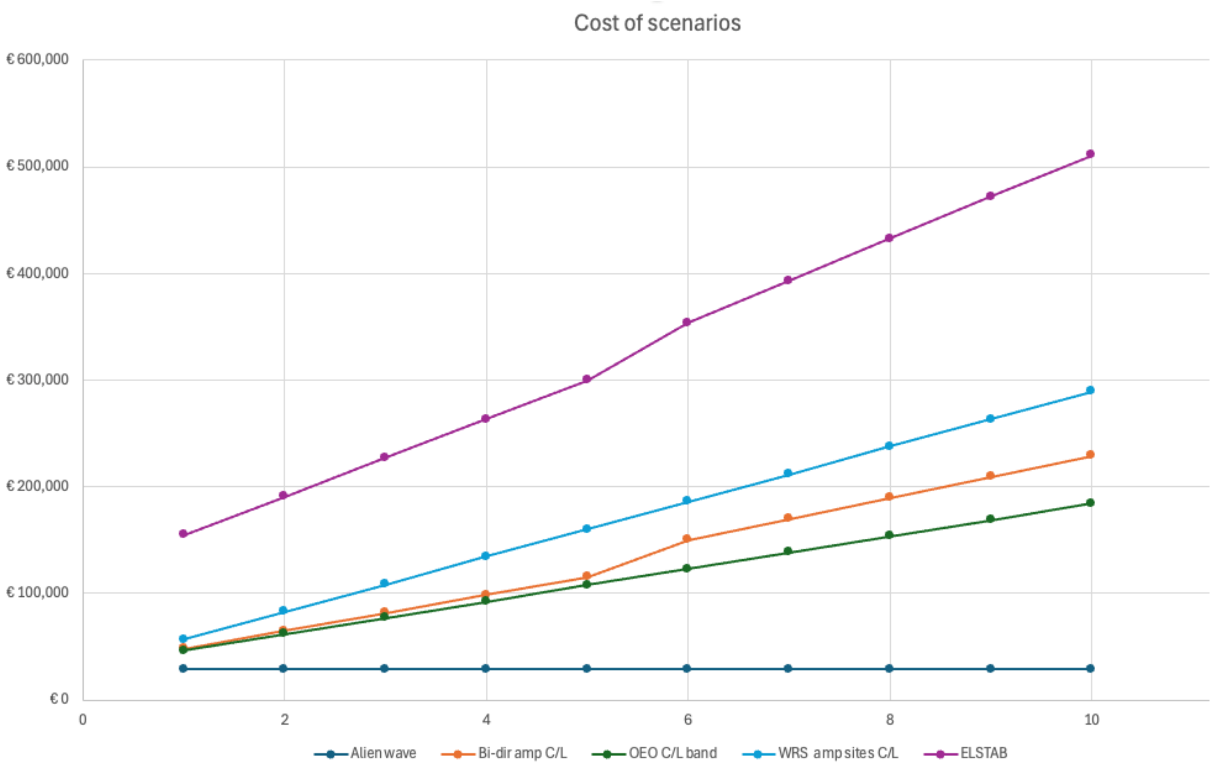


Figure 5.5: Example of costs when adding two WR time services in the GÉANT C-TFN with two White Rabbit links (utilising both fibres in the pair) in the DWDM system using different techniques. Graph illustrates total system cost (y-axis) as a function of number of ILA sites (x-axis)

6 Recommendations for NRENs

6.1 Optical Layer Considerations

The lab and field-trial results demonstrate that it is possible for WR to share a long-haul fibre with internet traffic without risking the integrity of the internet traffic. To ensure no degradation of the internet traffic, suitable guard-bands should be used.

6.1.1 L-Band vs. C-Band

NRENs often decide to deploy WR systems by sharing DWDM optical network with data channels. However, reserving some bandwidth for WR channels in the C-band introduces complications by reducing the spectrum available for data channels. One solution to be considered is utilising the fraction of the L-band that can be amplified by EDFA but is not usually used for data.

It is up to the network operator to determine whether WR signals are best allocated to the C-band or L-band. The choice will depend on several considerations:

- Is the WR deployment part of a new-build, or is it being retrofitted to a legacy system? In a new-build, filters can readily be added to allow access to the L-band, which will save spectrum on the C-band.
- Does the NREN's DWDM system come with built-in L-band filters? If so, L-band is a good choice.
- Is the NREN's DWDM system running out of available spectrum in the C-band? Lack of available spectrum on the C-band may necessitate the application of L-band filters.

Guard-bands need to be considered when evaluating which solution is best. Many NRENs choose to place their WR signal at one edge of the C-band. This halves the amount of spectrum allocated to the guard-bands compared to placing the WR signal in the middle of the C-band.

6.1.2 Regeneration Type

There are several ways to pass WR signals through an amplifier site, including BiDi amps, OEO regens and full WR switches. Based on our evaluation of both the cost and technical differences between these solutions, we draw the following conclusions:

- **Bidirectional amplifiers (1R)**: Testing demonstrates that this provides the best performance for users of time distribution services. However, there are some considerations to keep in mind:
    - The cost of this solution is higher for systems over longer routes.
    - 3R regeneration is needed after every 5–8 BiDi amplifiers.
    - Interaction with Raman pumps can cause asymmetric gain – this needs to be evaluated before embarking on designing a solution involving BiDi amps.
    - BiDi amps are subject to gain oscillations if reflections are present on the fibre. To mitigate this, the fibre length between amplifier sites should be kept below 80 km and the fibre attenuation should be less than 20 dB. Also, connectors on the fibre must be of the APC type to suppress reflections.

- **OEO regenerators (2R)**
    - These regenerators are readily available for a low cost.
    - Their performance is quite close to that achievable using bidirectional amps.
    - The advantage of OEO regenerators is that it allows the wavelength colour to change between regens. The disadvantage is that calibration becomes more complex.
    - Problems have been found with the cooling of OEO regens when operating with long-haul DWDM tuneable lasers.
    - Full carrier-grade OAM is not readily achievable with cheaper versions of these devices—this includes carrier-grade features such as dual power supplies, remote management, SNMP traps, etc. Careful consideration should be given to selecting an OEO regen that includes carrier-grade features.

- **WR switches (3R)**
    - It is possible to use WRSs in place of the OEO regens.
    - The performance is lower as the accuracy of the time signal degrades more quickly than in other regeneration types.
    - The cost will be higher.
    - It is important to pay attention to the clock stability in the WRS. A high-grade switch is particularly important in systems over long routes.
    - The cost of chaining WRSs is higher than the OEO solution.
    - Carrier-grade features should be included when purchasing these WRSs.
    - Vendors may not offer support with open-hardware WRS versions, along with limited hardware manufacturer warranties.

6.1.3 Cooling of DWDM Transceivers

During laboratory tests, we encountered a problem with insufficient cooling of SFP transceivers. DWDM optical transceivers use the temperature stabilisation feature of the DWDM DFB laser chip, thus consuming more energy during operation than conventional SFP transceivers. Therefore, they require enhanced cooling.

During our lab tests, when using CTC 2R SFP-SFP media converter cards in a simple chassis, the DWDM transceivers overheated after a few hours, thereby "retuning" to a different wavelength. Subsequently, the connection was interrupted.

For stable transmission of the DWDM signal, we had to use a different chassis variant with better heat dissipation and active cooling using fans. This resolved the issue and the WR signal transmission regained stability.

Therefore, when ordering transceivers, make sure to thoroughly consider the heat dissipation and cooling capabilities of the OEO regenerator chassis to be used.

6.2 Cost Considerations

In this section, we discuss some of the cost implications to be considered when choosing a technique for distributing time with WR.

6.2.1 Spectrum Costs

This report includes a cost calculator [1] that allows NRENs to calculate the cost of a wide variety of different technical solutions. The actual cost will vary widely between NRENs, particularly depending on the allocation of the cost of the DWDM spectrum used by the WR channel. The cost calculator allows users to enter any value for the cost of the WR channel and also to add the number of guard-bands reserved. Some NRENs will consider this spectrum to be zero cost, as the DWDM system build is already a 'sunk cost'. Other NRENs, for which spectrum is in short supply, may consider the use of the C-band spectrum to be a future cost if they will need to upgrade their fibre network. This will be particularly expensive if the WR channel is allocated in the centre of the C-band and two guard-band channels are needed on each side of the WR channel.

6.2.2 Regeneration Costs

A key factor to consider is the length of the transmission route to be built. Shorter paths will be better suited for bidirectional amplifiers. It is recommended to use the costing tool provided to understand the cost implications.

6.2.3 Optical Supervisory Channel (OSC) Costs

Normally, amplifier sites do not include local internet access. For this reason, an optical supervisory channel (OSC) should be built into the solution. If WRSs are deployed for regeneration, then it may be possible to use these for maintenance. Also, many DWDM amplifiers will have an Ethernet port by which the transmission equipment can be accessed via the OSC channel. If a BiDi amp or OEO generator is used, and there is no network connection on site, then the cost of an OSC channel should be included in the cost analysis (note: this is excluded from the cost calculator provided).

6.3 Operations, Administration, and Maintenance (OAM)

When designing a WR time distribution network, OAM is a critical consideration to ensure that the system can continue to be maintained and operated. The following features should be designed in:

- Dual power supplies for reliability.
- A CLI or API for monitoring and configuration.
- Support for alerting via SNMP traps.
- OSC channel for management – using the WR switch is an option.
- Local management Ethernet switch if needed.
- Monitoring of the fan speed.
- Temperature monitoring of the device and alarms in case of fan failure.

The WR consortium is discussing the addition of in-band management of the open-source WR switches using SNMP, but this feature is not defined yet.

It is necessary for any network provider building a White Rabbit time distribution network to develop a **support model** for the replacement of faulty hardware and application of software updates. GÉANT has a contract with an Integrator that will hold stores of spare equipment centrally in Europe, and when any equipment needs to be replaced, the Integrator will go to the site to replace the faulty equipment and return it to our supplier. Some NRENs will have their own staff on site who are able to do this work; others may seek to outsource this function.

6.4 Calibration

Calibration is an inevitable requirement in deployments of the WR system to support real-world time distribution with known uncertainty. See Section 2.4 for a discussion on calibration techniques for various network configurations. However, an in-depth discussion of calibration is out of scope of this document, focusing instead on WR coexistence with coherent high-speed data channels (400 GBE) and signal regeneration techniques.

6.5 Expected Performance

As our tests showed, the White Rabbit system, when deployed in an NREN's optical network sharing fibres with data channels (including coherent 400 GBE), can be operated without any observable degradation of data quality, maintaining sub-nanosecond time-transfer accuracy over a lengthy 500 km path.

7 Conclusions

The findings presented in this report confirm that White Rabbit is a viable technology for distributing high-precision time over long-haul DWDM networks. Through both controlled laboratory experiments and a 500 km field trial on the GÉANT Prague–Vienna route, we have demonstrated that sub-nanosecond time synchronisation is achievable while coexisting with high-speed coherent data traffic.

Our evaluation of various regeneration techniques provides a clear performance-to-cost trade-off for NRENs:

- **Best performance**: Bidirectional optical amplification (1R) stands out as the superior technical method, providing the highest stability (±100 ps) and the lowest additive jitter over long distances.
- **Economic**: While 1R amplification offers peak performance, OEO (2R) regeneration presents a highly cost-effective alternative for very long-haul links where extreme precision can be slightly traded for significant CapEx savings.
- **Interim solution**: As an interim solution that will allow rapid roll-out of WR links, NRENs may consider using alien waves. These will form a good first step that can be built on.
- **Infrastructure coexistence**: We have shown that WR signals can share the same fibre as 400G coherent channels without degrading the bit error rate of internet services, provided that a standard 100 GHz guard-band is maintained. NRENs are advised to consult with DWDM equipment providers to confirm that they will support this.

A decision must be made between bidirectional and unidirectional operation:

- For high-accuracy requirements, NRENs should prioritise single-fibre bidirectional transmission to eliminate physical length asymmetries inherent in fibre pairs. This will ensure higher precision and ease of calibration after fibre repairs.

To ensure a successful rollout of terrestrial time services, NRENs should adopt the following strategies:

- Use the cost tool accompanying this report to determine which regeneration technique best meets the cost/stability requirements.
- Where available, prioritise the L-band, otherwise use the edges of the C-band for WR signals to preserve valuable spectrum for data services and simplify filtering.
- Standardised calibration is recommended. As an NREN's time network expands, it is recommended to move from manual to automated calibration rigs to make the process scalable.
- To ensure high levels of resilience and OAM, it is recommended that deployments use carrier-grade hardware featuring dual power supplies and integrated SNMP monitoring to meet the availability requirements of critical infrastructure. A suitable support contract should be put in place with the NREN's equipment vendors as appropriate.

Appendix A Survey on Status of White Rabbit Deployments

Several NRENs, NMIs, and mobile network operators have successfully deployed White Rabbit time distribution over existing commercial or research Dense Wavelength Division Multiplexing (DWDM) networks, sharing the fibre with telecom data. In 2025, we ran a survey with NRENs and NMI on their White Rabbit time service deployments. Appendix A provides a summary of state-of-the-art deployments focusing on key categories of the technical solution (e.g., shared or dedicated fibres), type and size of network, whether regeneration is required (if yes, then what type is used), and the provided accuracy.

A.1 CESNET

Architecture

CESNET uses a shared fibre architecture (described in more detail in [28]) with a DWDM system and 100–400Gbps coherent data channels. CESNET uses Cisco, Ribbon (former ECI), and Czech Light as its system vendors & platform, with mixes of both C-band and C+L bands for data services. C+L-band filters are already in place in the majority of the network. To create a guard-band when WR operates in the C-band, the WR channels are set on the opposite part of spectrum from coherent data channels. CESNET prefers to transmit WR bidirectionally, however on some old routes, unidirectional (alien wavelength) transmission is deployed.

There are currently ~1,300 km of WR time links deployed in CESNET’s network, with a typical distance of 300 km between WRSs with bidirectional amplification (Czech Light BiDi EDFA). OEO regeneration has been tested in the lab, but since performance was found to be lower, it was chosen not to deploy them. At ILA sites, CESNET uses customised filters to add/drop the WR channels, namely the widely available DWDM 8skip0 or 4skip0 filters.

Channels 8 and 9 at 1570 nm (on the edge between the L-band and the C-band) are deployed in new installations, aiming to cover about 2,500 km of WR transfer lines, coinciding with the gradual phasing-out of channels 32–34 used in the old unidirectional C-band deployments. OOB management channels provided by the DWDM system are used to manage WRSs, bidirectional amplifiers, and other equipment at ILA sites.

Redundancy, i.e., failover between two master clocks, is currently a work in progress. The types of clock sources used in the CESNET network are caesium and active hydrogen masers, both owned and from partners. The WRS currently being used are Safran open-source switches as well as the proprietary enhanced product Z16, one of the few available commercial carrier-grade WR devices on the market. Only AC-powered WRSs are used.

Performance

Measuring the T&F performance is done using time interval counters: SR-620, Pendulum 91, and Pendulum 104s. Recently, CESNET installed the K+K FXE phase meter. The clock sources are atomic clocks (via the Czech NMI) when available on site; otherwise, a GNSS disciplined oscillator is used, with a rubidium clock as the last option. Using Stable32 software and CESNET’s own utilities for performance analysis. Calibration is currently performed manually; work is in progress to implement an automated calibration method.

OAM

Monitoring of the WRS network is achieved using ONTAP Hardware Watchdog (OHW) over SNMP. Monitoring of the Z16 WRS is done over API. CESNET is currently working to integrate this with the optical network management system, including alarms, and it is planned for the same CESNET NOC team to monitor both the transmission network and the WR network. The Czech Light BiDi amplifiers have their own management system.

Services

Time services are limited to public companies in accordance with CESNET's Acceptable Use Policy (AUP). The accuracy required by CESNET's customers is GNSS (40 ns), or better. The service is delivered to the end customers into their WRSs, coax cables limited.

A.2 NPL

Architecture

The UK's National Physical Laboratory (NPL) is deploying a White Rabbit time link of ~360 km between London–Birmingham through Jisc's dark fibre, with a maximum span of ~80 km. Bidirectional channels have been deployed using amplifiers from Keopsys.

Frequencies and filters for WRS: 8skip1s filters pass band channels 39-46 with 100GHz spacing, using C-band channels 45 and 46 (very close to ch44, used for frequency and to have it on the same BiDi amps). The Exail Regeneration Laser Station (RLS) is used for optical frequency transfer. The WR and Exail technologies have different power-level requirements, but over the distance that the system is operating, no problems have been observed.

To the best of our knowledge, while such an architecture has been planned (e.g., CLONETS), this is the first case of deployed frequency, ELSTAB, and WR in the same amplifier. Channel 44 is used for frequency on both fibres; ELSTAB on both fibres is on channels 40 & 41 for dissemination; channel 39, and channel 42 on the loop back from Birmingham, are used for monitoring; channel 43 is reserved for sensing. It is planned to deploy WR to the Paris Observatory, possibly using Safran open-hardware switches, although this is still in the early planning phase.

Performance

For measurement, verification, and monitoring T&F performance, NPL has deployed a loopback by sending a return signal on the second fibre in the pair. This fibre loop will be used for a WR time service as well as frequency. For frequency, NPL is using a KK counter & a PikTime time interval counter.

Calibration is performed manually. NPL has created its own golden calibrator (distinct from the CERN one), including all transceivers and α coefficients, and is further working on how to compensate for the Sagnac effect (this effort is still a work in progress).

NPL believes it can achieve 30 ps accuracy using ELSTAB, while WR is expected to be in the 100 ps range, although it is unknown as yet whether this is achievable. There is no redundancy or fibre diversity built into the system. The WR primary clock is UTC(NPL) via multiple hydrogen masers and one Cs fountain.

OAM

NPL uses a dedicated channel for management in the fibre itself (S-band CWDM) to monitor both amplifiers and WRSs. The management network is achieved with Ethernet switches in all amplifier sites. As of the time of writing, NPL has its own software monitoring the system (e.g., fibre, switches, etc), pinging every 15 minutes and sending an email alarm to sense a fibre break. However, monitoring of WR domain, e.g. alarms, is a work in progress. NPL uses an Orthogonal Frequency-Division Multiplexing (OFDM) system developed in-house to monitor the state of its fibre.

Services

NPL’s main use case is frequency; there are no currently defined use cases for time service through White Rabbit other than distributing UTC(NPL). The systems for frequency were already in place, so the White Rabbit time service could be added at minimal additional cost.

A.3 SUNET & NetNod

Architecture

SUNET has deployed both unidirectional and bidirectional White Rabbit setups multiplexed into the same fibres as the DWDM system on Adtran FSP3000R7 C-band. For unidirectional transmission, a filter is inserted between the line and the amplifier, which injects a light at a wavelength of 1610+-6,5 nm for White Rabbit and 1650 nm for optical time-domain reflectometer (OTDR) use. Specifications for the filter were drawn up together with FUNET and built by FS.com. As OTDR capability has been deployed on all routes except access fibres, the 1610 nm wavelength is free for timing distribution across the whole network. Tests have been run between Stockholm and Göteborg over a distance of ~698 km as a unidirectional alien wavelength, passing 9 ROADMs and 5 ILAs, with WR on 1Gbps C-band at 194.5 THz with 4 dB lower power than other channels. No performance impact has been observed on data channels.

For bidirectional deployment, White Rabbit has been deployed on ~440 km of fibre between Stockholm and Sundsvall using 1610/1611 nm and 1605/1615 nm wavelengths. The spans vary from 30 km up to 130 km. For regeneration of the bidirectional WR channels, SUNET used the following OEO media converters: CTC-Union FRM220-1000DS O/E/O plus chassis FRM220-CH02/SMT-AD and management controller FRM220-NMC-R3. However, WR switches are used in some sites to verify that the signal integrity is restored from the OEO regenerator spans. For add/drop on ILA sites, 1605/1615 nm filters are used (these are integrated with the OTDR filters). Placement of filters is as follows:

- **EDFA booster**: in front of booster
- **EDFA pre-amp only**: before pre-amp
- **EDFA/Raman**: between Raman and pre-amp

While the optical architecture described above is deployed by SUNET, note that for the WR time-service distribution deployments and related activities in Sweden, SUNET collaborates with both NetNod and RISE (the Swedish NMI). No redundancy or failover mechanism is implemented, as the WR time service is used only for comparison of time scales at the ends of the links: NetNod provides UTC, while the Swedish reference timescale UTC(SE) is realised by RISE.

Currently, eight caesium clocks are directly involved in the WR activities, but further caesium and hydrogen maser clocks are secondarily involved. NetNod maintains 12 timescales at 6 locations, calibrated and traceable to UTC(SE), while RISE, the NMI, has two locations in Sweden. SUNET/NetNod primarily use Safran open-HW switches, both standard and low jitter variants. At sites with only DC power, the WR switches v3.4 have been converted to -48 V DC by replacing the internal AC power supply.

Performance

For performance measurements, NetNod mainly uses Timetech’s MCTIC 10409, and a Microsemi 5071A as the clock source, with in-house software for analysis. From experience, NetNod has found that manual calibration of more than a few devices can be cumbersome, tedious and error prone—automated calibration mainly resolves this. Hence, NetNod has implemented an in-house automated calibration rig, with automated measurements and calculations using fibre relays and time interval counters, including the α coefficient. There is no in-situ calibration other than comparing the status with NMI calibration of equipment at route ends.

The 440 km bidirectional link has been stable within a nanosecond for over 4 years. Since the upgrade to WRS above v6.0.1 a few years ago, the link has always come back by itself with no manual intervention after events such as fibre outages, etc. The time error of the link is well within the margin of error for the calibration of the end equipment used by the NMI, thus no attempts have been made to further improve the performance.

The 690 km unidirectional link has shown stability of within +/- 5 ns, and a time error of about 80 ns (no outages yet, so no changes yet) over 3 months.

OAM

Management of the WR equipment makes use of the existing infrastructure for management of the ROADM/WDM equipment. For WRSs, SUNET uses the optical network management infrastructure (IP, routed, Ethernet interface), but does not integrate this with its DWDM OAM system. WRS alarms are received from time-measurement systems when available via log analysis and SNMP.

Services

Services are provided to public institutions, universities, and research centres. In terms of required accuracy and availability from customers, these are mainly experimental setups, with a few requiring nanosecond accuracy or better, e.g. [17]. SUNET foresees the potential of upcoming physical experiments requiring better than nanosecond accuracy and high availability. Typically, there is one time domain per link; currently, there are two time domains, with a move to four planned in the near future.

For security reasons, server administration at SUNET’s data centres requires traceability to UTC(SE). This will be provided with WR to the data centres and with PTP to the servers. GNSS/GPS will not provide the traceability required due to the risk of jamming and manipulation. A dedicated time-transfer service for the data centre eliminates the risk of manipulation of the timestamps on the IP layers. Unidirectional transfer gives more than enough accuracy for this application.

A.4 FUNET & VTT

Architecture

FUNET/CSC uses a similar optical architecture for WR time distribution as SUNET. Both unidirectional and bidirectional setups have been deployed via multiplexing into the same fibres as the DWDM system, which is Adtran FSP3000R7 C-band only. For bidirectional links, a 1610+-6,5 nm CWDM filter is built into the OTDR filter (a custom filter from FS.com, as described in the previous section). Typically, for alien wavelength deployment of unidirectional signals, 1Gbps WR wavelengths are set to 196.0 THz or 195.9 THz on the edge of the C-band with a 100–200 GHz guard-band for the data channels. In addition, side-band filters are also used for bidirectional WR links at 1605/1615 nm wavelengths.

FUNET (and SUNET) uses the following low-cost custom filter types:

- Customised C-band (1525-1570 nm), T&F (1610 +-6,5 nm) and OTDR (1630-1670 nm) filter:
  - 0,7 dB C-band loss (very important, similar to existing OTDR filter)
  - 1,0 dB T&F loss (very important on high-loss links)
  - 1,2 dB OTDR loss (less important)
  - Fully bidirectional (no calibration needed)
- Customised optical circulator for high-loss links (21+ dB), with 2 dB insertion loss
- Customised 1:2 optical splitter for low-to-medium loss links with 4 dB insertion loss

The unidirectional WR link is ~800 km in length, while the bidirectional link is ~350 km in length. The typical distance between WRSs in the bidirectional setup is between 130–300 km with the same OEO media converters as SUNET: 2R CTCU FRM220-1000DS with 1RU chassis with DC power supplies in between longer spans over 130 km. No bidirectional amplifiers are deployed.

There is no redundancy on current links. There is a planned fibre ring setup for EISCAT_3D with dual BiDi redundancy (both fibres in use) interconnected through the SUNET and Sikt networks. SUNET does not operate its own clocks but distributes the timescale from VTT (the Finish NMI) with clocks in two locations. EISCAT has its own rubidium clock—currently only one source, in Norway. EISCAT uses Safran open-HW switches with AC power supply only. In cases where the site only has DC power available, then OEO repeaters are deployed.

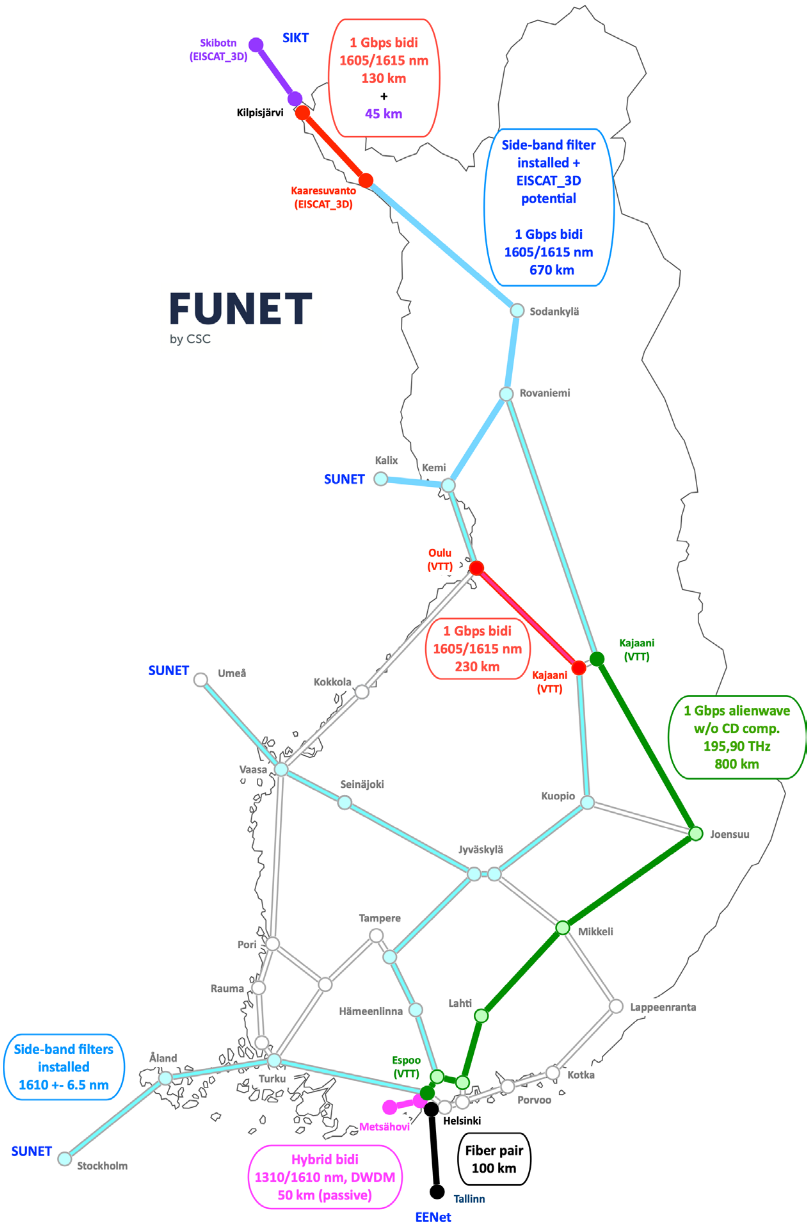


Figure A.1: FUNET T&F infrastructure in Finland as of 2025

Performance

FUNET does not measure or verify time-service performance; rather, the NMI both calibrates and measures it.

OAM

Currently, FUNET monitors devices using SNMP on some WR links with the same system as for its IP & optical network (Grafana, Telegraf and a few scripts). FUNET is planning to improve this in future by monitoring WR alarms and OEO repeaters. There is no NOC; in practice, the service is managed by the engineers operating the optical network.

Services

FUNET provides NTP to its general customers, while the WR time service has been deployed for research centre users. The required performance varies from case to case, with the most demanding being EISCAT, requiring above 1 ns accuracy.

In terms of pricing, currently FUNET’s WR time services are mapped to “10G managed wavelength” services.

A.5 REFIMEVE & RENATER

Architecture

The REFIMEVE time & frequency links are built using the RENATER optical network, which uses a mix of legacy equipment operating at 10Gbps, but mostly DWDM equipment, which covers over 95% of its network. The DWDM system is based on Coriant (Nokia) 7300 and OTN switching. T&F channels operate in the C-band only without any L-band filters in use.

For White Rabbit time distribution, REFIMEVE currently uses only unidirectional alien wavelengths provided by RENATER (i.e., each direction of transmission is on a separate fibre out of the pair). No guard-band is deployed, but REANTER use the edge of C-band: 196.0 THz frequency used for time distribution in the next-generation RENATER network, which keeps the lower frequencies available for long-distance transmission. As the WR time service is transported as an alien wavelength, the same signal regeneration is used as the DWDM data channels: this includes both EDFA and Raman in some links. For this reason, no bidirectional link regeneration technique is required.

In terms of the WR network size, it is divided into three tiers at different scales:

1. Regional, e.g. Paris, at circa 10km links.
2. Edge of ~1km to data centres, university networks, etc.
3. National links circa 200-300 km.

The network was first built in the Paris region and further developed with national links connecting to the Paris Observatory. As of February 2026, four ~200 km national links have been built and there are plans to extend this in the future up to 5,000 km of WR links in total. In this plan, the longest span between two WRSs would be ~600 km maximum, with a typical link length of 200–300 km.

REFIMEVE uses open-hardware White Rabbit switches from Safran chosen through an open tender; Safran was chosen as this vendor intends to follow the WR collaboration development in the future (main track firmware). Furthermore, REFIMEVE is a member of the WR collaboration.

In the case of frequency distribution, dedicated fibre is used, with channel 44 for frequency distribution with RLS. Single-source UTC(OP) is generated by the NMI located at the Paris Observatory. The primary WR clock is directly locked to UTC(OP); the primary WRS grandmaster source is operated from the observatory and then distributed through the WR network.

As of February 2026, there is no redundancy built into the WR network: it is currently a single tree (the network deploys a star topology from the observatory operating as master clock), but in the future REFIMEVE may deploy redundant links, i.e., a parallel WRS network, for each site.

Performance

The target accuracy for REFIMEVE links on the 1PPS feed out of the WRS is 10 ns (worst case on longest link) as this is good enough for most users, however there are services up to 100 ns and some links (research users) where sub-ns accuracy is required.

On regional links with unidirectional WR links, no loop is possible, hence measurements are performed using a reference clock deployed at the source end and also on the user side (not available all the time). The source can be a rubidium clock locked (disciplined) to GNSS or a local maser. To detect issues in the timescale/clock source being used, majority voting of three clock sources is needed to identify which device is faulty. Hence, on some sites requiring high availability, there are two local clock sources in addition to the WR time service. From the user perspective, they join the REFIMEVE network for the reference timescale. Performance verification requires measurements from both ends of the link, i.e., involving the end user with help from REFIMEVE experts.

Being part of the WR collaboration, REFIMEVE are using the CERN golden calibrator. In addition, a transportable calibration setup is being developed to investigate cases of discrepancy/issues on a site. This measurement can be fully automated, but the goal is to use the same setup (i.e., same counters, automation process, etc.), which is not always the case.

OAM

REFIMEVE (rather than RENATER) is responsible for monitoring the WR network. In the RENATER network, the WR service is treated as an alien wavelength, with the same NOC as operating the DWDM system.

REFIMEVE uses a separate management system for monitoring WR and frequency services. RENATER plans to get access to WR management information via SNMP to manage the optical layer. The target is to connect to the WRS and view the optical power injected in the fibre, and to be able to shut it down if there are issues in the optical layer.

REFIMEVE has a software tool (developed by Safran) connecting directly to the WRS. All supervision layer services, IP addresses, L3VPN, and BGP are provided by RENATER for REFIMEVE to access the WR switches.

Services

The users of the time services are mainly academic, such as physics labs. These users are typically the same for both frequency and time services. However, REFIMEVE also targets tech companies that need reference timescales for their R&D departments, and is licensed to provide both research and commercial services.

- 1PPS mostly between 10–100 ns, some sub-ns accuracy requirement.
- 10 MHz stability short-term: 10E-12 at 1s for the most demanding use cases, and 10E-10 for most customers with lower stability requirements.
- Availability level for academic users is best effort (95% a year).

A.6 SURF

Architecture

SURF launched its self-built time service in January 2026. SURF delivers the Dutch national timescale UTC(VSL) from VSL (the Dutch NMI) and has full control and ownership of the WR network. The WR network was deployed with the goal of offering services to universities, research centres and NMIs using WR signals. Currently, there are fifteen WRSs deployed using different types of DWDM SFPs with regeneration through WRSs. The WR time network shares fibre with a DWDM system from Ribbon, operating on C-band only.

The WR links are deployed bidirectionally using the edge of the C-band spectrum, with a guard-band of 100 GHz to the data channel frequencies. Currently, there are 4 WR C-band frequencies, i.e., two bidirectional WR links, at the edge with one additional channel (60) reserved and used for calibration.

SURF is part of the WR collaboration and uses Safran open-hardware WRS v3.4.-2.0.

Performance

Performance required throughout the network is at sub-ns time accuracy and picoseconds-level frequency. Calibration is complicated for achieving ns-level accuracy. For this purpose, SURF has a golden calibrator from CERN, included in the membership of the WR collaboration, including calibrated optics.

Everything is calibrated first in the lab, including filters, SFPs, ports, etc. For monitoring purposes, a loop is fed back to the grandmaster WRS to compare the returned WR signal.

OAM

SURF uses SNMP from WR integrated into Influx & Grafana dashboards for its performance and alarm-monitoring system.

Services

SURF delivers sub-ns time services and ps-level frequency services. Customers are universities, research centres and NMIs, with the development of optical clocks as a key use-case.

A.7 Switch

Architecture

White Rabbit operating at 1Gbs is deployed on the same fibres as Switch’s DWDM system. The DWDM system is based on the Ribbon Apollo platform operating at C-band only with data bitrates at 100–400Gbps, and with very few 10Gbps services left. The network is prepared for L-band, equipped with O+S+C+L band filters on most spans independent of DWDM vendor. DWDM and most other data services use two fibres, while both frequency and time services are deployed on bidirectional links: L84/L85 for WR (188.4 THz, 188.5 THz; 1590.41 nm, 1591.26 nm) and C07 190.7 THz for ultra-stable frequency distribution.

The total length of the WR network is ~500 km. The distance between WRSs varies greatly, from 5 km to 180 km, the latter with regeneration. Most links are 80–100 km between two WRSs or from WRS to OEO regenerator (2R CTC Union FRM220-1000DS without retiming; note this is the same as other NRENs discussed here). For add/drop on ILA sites, the OSCL filters mentioned above are used. For WR switches, after the OSCL filter, additional 2-channel L-band DWDM filters are deployed for bidirectional operation.

For redundancy, the network is built as a ring or mesh, using BMCA for master clock selection. In the future, redundant grandmaster clock sources are planned but not yet deployed. The clock source is active hydrogen maser providing the official national UTC timescale provided by the NMI.

The system uses Creotech WRS3-18 CERN open hardware. Up to now, all WR sites have AC power, but a DC-to-AC converter would be made available if needed. The WR switches currently being used only have a single power supply—an area that will be improved (dual supply) in the future.

OEO regeneration is about 40% of WRS, including filters and SFPs, which are identical for both solutions.

Performance

Measuring and validating T&F performance is performed by the NMI (METAS). For end-site validation, the NMI uses transportable caesium clocks and time interval counters (TICs). Devices are calibrated in the NMI lab with TICs. Measurements in the NMI lab are made using the direct clock source from UTC(CH); at the end site, the WR clock is used. A transportable caesium clock is compared to the UTC(CH) clock before and after field measurement. Clock comparison for performance measurement of the links is performed by the NMI as well.

The WRSs are calibrated semi-automatically with custom scripts. Calibration of the α coefficient of the line is performed using the second fibre of the pair as a loop on the same line with inverted frequencies, and a second WR switch at the measurement site, similar to the setup for the field trial of the Long-Haul WR incubator covered in this report. From experience, even using an estimate value for α based on a few measurements, provides surprisingly good results with total error well below 1ns.

Measurement results are available; see [29].

OAM

At ILA sites, the nodes are managed using the management network provided by DWDM equipment, fully IP routed. All equipment is owned and operated by the NREN using a single management network.

The WR network is not fully integrated into optical DWDM network management systems, as WR is not considered IP equipment, but it is integrated into the existing user management, config backup and statistics solution normally used for IP equipment. The NOC monitoring the DWDM network also monitors the WR network. Icinga2 (SNMP-based) is used for monitoring WRS alarms.

Services

Provided services:

- Ultra-stable frequency for research
- Precise time (PTP or WR/PTP HA or PPS/10 MHz) for all sectors (university/research as well as commercial)
- NTP/NTS for public

Commercial customers mostly focus on availability (independent of GNSS, an identical clock source in multiple locations); accuracy within ePRTC specifications of ~20ns is deemed sufficient. For many commercial customers, a plain Precision Time Protocol (PTP) service is more of interest than WR.

For time-service delivery, leased fibres to the end customer site are used, or a simple cross-connect within data centres, with optional White Rabbit CPE. Customer can also use their own WR device or PTP client. Only one WR time domain is implemented. The WR time service is also used locally as the time source for NTP/NTS services, which in turn is used as the time source for all Switch network equipment and servers.

A.8 INRiM & GARR

Architecture

The time and frequency service is deployed through a dedicated White Rabbit optical fibre infrastructure (i.e., not shared with data services) designed and developed by GARR and INRIM and autonomously operated by INRiM (the Italian NMI) over the Italian Quantum Backbone [30] to distribute the time and frequency signals of the Italian national timescale UTC(IT). This is an experimental network for research activities.

Currently, Alturna Networks' Solid Optics are used for the optical multiplexer, while White Rabbit switches from Seven Solutions and LEN (now Safran) are deployed (Safran Z16), along with ZEN and Creotech Instruments.

The DWDM multiplexer operates on C-band only, ITU channels 28-35; single filter on ITU CH44. C+L filters are not installed, so L-band operation would require additional components and system redesign.

A WRS is deployed in a bidirectional link on DWDM ITU channels 30 and 31. A guard-band of 100 GHz is deployed between WRS 1Gbps and the data channel frequencies for monitoring and control. A total of ~1,000 km WR links are deployed in the network, with an average distance of 60 km (minimum 18 km and maximum 100 km). At amplifier sites, WRSs are connected through optical multiplexers that separate the TX and RX signals and route them to the SFPs of the WR switches used as boundary clocks. Most of the devices are connected in series, with the intermediate ones configured as boundary clocks. Some devices, however, are used as branching nodes, distributing the signal in multiple directions to serve different users, thus forming a tree topology.

After approximately 700 km, the WRS could no longer lock to the signal received from the previous WRS. To restore synchronisation, a clean-up oscillator was introduced: it locks to the 10 MHz output of the upstream WRS, "cleans" the signal, and feeds it to an additional WRS configured as the grandmaster, which further disseminates the WR signal. The 1PPS outputs of both WRS units are measured using a TIC, and the resulting data is later compared offline with the signal received from the last device in the chain.

The time and frequency dissemination network is experimental, and no redundancy systems are in place.

Most of the stations are equipped with −48 V DC power supply. For the LEN mini-switches, INRiM has isolated DC/DC converters that convert −48 V DC to +5 V DC. For switches operating at 220 V AC, DC/AC inverters are deployed. The Safran WR switches (the proprietary version) can be powered either at −48 V DC or 230 V AC, depending on the power infrastructure available at the installation site. The WR switches from Seven Solutions and Creotech in the current inventory can only be powered by AC.

Performance

Performance is measured with respect to the Italian reference timescale UTC(IT) via GPS time. Equipment used for measurements includes a geodetic receiver, time interval counter, pivot clock (caesium or rubidium), and phase meter. The clock source used for this is the Italian timescale UTC(IT) from a hydrogen maser.

All devices are calibrated manually. The α value is measured using fibre coils in the laboratory, which, however, are not of the same type as the deployed fibre. In any case, it is estimated that for a single WR link, the contribution of asymmetry from chromatic dispersion cannot exceed 500 ps on the final measurement since the TX and RX frequencies are transmitted on contiguous 100 GHz DWDM channels.

Examples of link performances: 1E–11/tau for a 220 km link, and a target of 3E-11/tau for a link long 1,000 km.

OAM

It is operated as an experimental network over dark fibre, carrying WR traffic and running an internal-only network for device control. This management network is completely separated from the institutional GARR network. The alarm management system, working only on the experimental network, is under development (based on Zabbix).

Services

GARR and INRiM currently provide WR T&F services on an experimental basis to multiple users.

A.9 Mobile Network Operator Case

In 2025, a major European Mobile Network Operator (MNO) proposed a move away from GNSS as a source of time towards a mobile network-based solution to enhance application capabilities and generate new network value. GNSS has widespread adoption but faces significant challenges with indoor coverage and multipath errors. The rollout of 5G technology presents a viable alternative, offering precise positioning through cellular signals that can reach sub-10m accuracy in urban environments and sub-2m accuracy in indoor scenarios.

Market Drivers and Technology

Location data is a massive commercial driver; for instance, Google Maps serves over 1.8 billion monthly users, and a vast majority of the top 1,500 iOS apps request location access to improve functionality. To compete, MNOs are looking to 3GPP Release 16 methods, such as Multi-RTT, Angle of Departure (AoD), and Time Difference of Arrival (TDoA). By 2028, indoor 5G coverage is expected to exceed 50% in most markets, making cellular-based positioning commercially viable.

Implementation Challenges

The MNO identifies two dependencies:

- **Network infrastructure**: MNOs must invest in new components, specifically the Location Management Function (LMF) and GMLC. Currently, most vendors have these features developed for 2025–2026.
- **Device ecosystem**: Collaboration with chipset manufacturers is essential but currently limited. Support for advanced methods like Multi-RTT is still partial or non-existent in many current chipsets, and development may take several years.

The MNO proposes a three-pronged approach to drive adoption:

- **Hardware integration**: Encourage chipset manufacturers to integrate cellular-based positioning technology.
- **OEM adoption**: Urge app developers and OEMs to move from offline, database-backed location methods to real-time, online calculations using cellular signals for better accuracy.
- **Network deployment**: Prioritise the deployment of 5G NR location services and the Location Management Function (LMF) in dense urban and indoor areas.

In summary, the MNO surveyed would like to move away from GNSS-based time distribution for mobile devices, promoting the use of new 5G techniques as an alternative. It is argued this will reduce power consumption of mobile devices and increase resilience to attacks.

A.10 Other Deployments and Planning Phase

Other NRENs, e.g. Belnet and Sikt, are at the stage of new network designs to include White Rabbit as a possible time service distribution over their optical networks.

Sikt is planning with the Norwegian NMI, Justervesenet, the national telecommunications authority and other industry partners to deploy a proof-of-concept field trial. The design is based on using the bidirectional optical timing channel (OTC) provided by the Nokia OLS for White Rabbit time distribution in a bidirectional channel shared with the DWDM system, and possible use of the Nokia card for regeneration as well at ILA sites.

A Nordic White Rabbit time distribution network interconnecting the Nordic NMIs through the Nordic NRENs, and possibly further connecting mainland EU countries through SURF to VSL, is planned in 2026. In the first phase, the White Rabbit time service will be deployed through unidirectional alien wavelength links interconnecting the NRENs Sikt, FUNET, SUNET, NORDUnet, and DeiC as illustrated in Figure A.2. The use cases identified by NMIs are to compare UTC(NMI) reference timescales and maintain a coordinated UTC without relying on GNSS/GPS.

In the second phase, there is the possibility of creating bidirectional connections between the NRENs for a higher-accuracy WR time transfer.

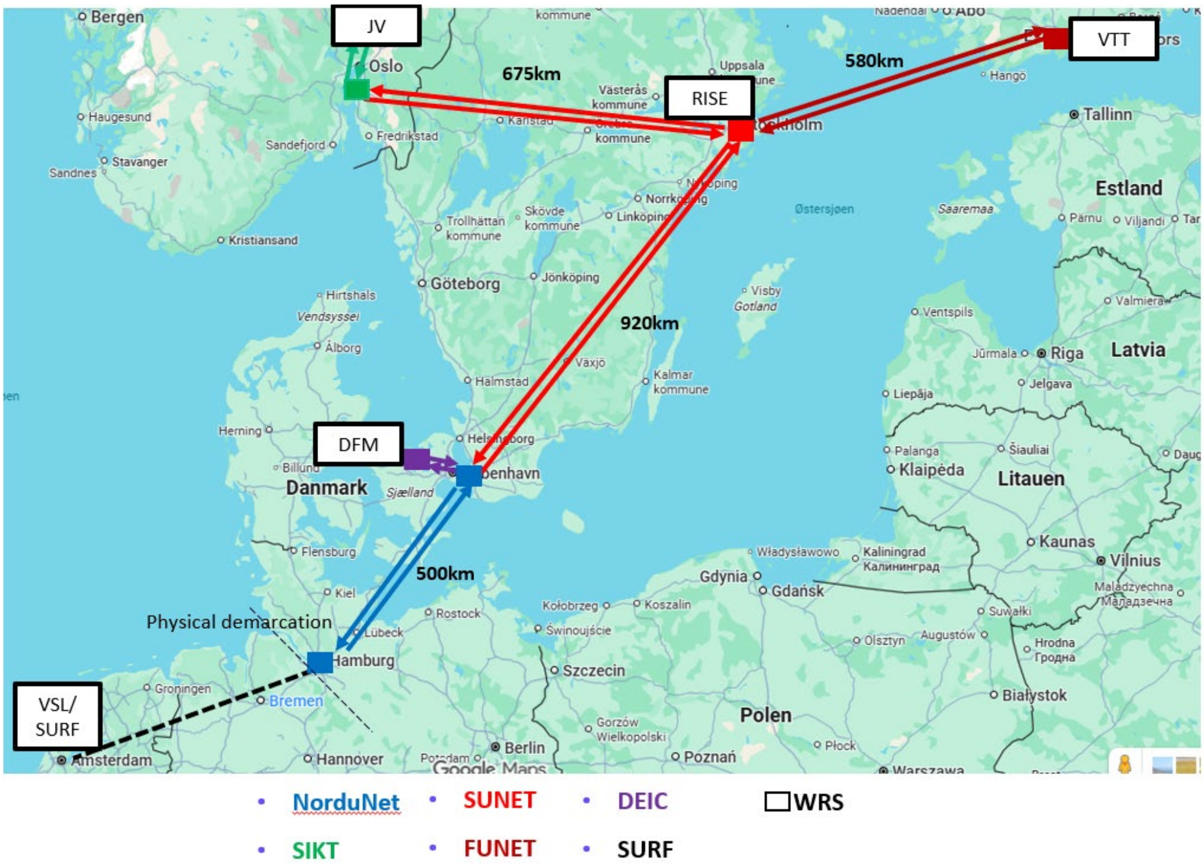


Figure A.2: NMI interconnectivity through Nordic NRENs (NORDUnet, SUNET, FUNET, Sikt, DeiC) White Rabbit time service, planned proof-of-concept 2026. The plan is to possibly extend the PoC towards mainland Europe through SURF to VSL

Glossary

A

ADEV	Allan Deviation
AoD	Angle of Departure
APC	Angled Physical Contact
AUP	Acceptable Use Policy

B

BER	Bit Error Rate
BiDi	Bidirectional

C

CapEx	Capital Expenditure
CD	Chromatic Dispersion
C-TFN	Core Time & Frequency Network
CWDM	Coarse Wavelength Division Multiplexing

D

DWDM	Dense Wavelength Division Multiplexing

E

EC	European Commission
EDFA	Erbium-Doped Fiber Amplifier
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures

G

GMLC	Gateway Mobile Location Centre
GNSS	Global Navigation Satellite System

H

HA	High Accuracy

I

ILA	In-Line Amplification

J

JRC	Joint Research Centre

L

LHC	Large Hadron Collider
LMF	Location Management Function

M

MDEV	Modified Allan Deviation
MNO	Mobile Network Operator
MTIE	Maximum Time Interval Error

N

NMI	National Metrology Institute
NOC	Network Operations Centre
NPL	National Physical Laboratory
NREN	National Research and Education Network
ns	nanosecond
NTP	Network Time Protocol

O

OADM	Optical Add-Drop Multiplexer
OAM	Operations Administration and Maintenance
OEO	Optical-Electrical-Optical
OFDM	Orthogonal Frequency-Division Multiplexing
OHL	Open Hardware License
OHW	ONTAP Hardware Watchdog
OOK	On-Off Keying
OpEx	Operational Expenditure
OSA	Optical Spectrum Analyser
OSC	Optical Supervisory Channel
OTC	Optical Timing Channel
OTDR	Optical Time-Domain Reflectometer
OTFN	Optical Time & Frequency Network

P

PLL	Phase-Locked Loop
PPS	Pulse Per Second
ps	picosecond
PTB	Physikalisch-Technische Bundesanstalt, the German NMI
PTP	Precision Time Protocol

Q

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying

R

1R	Reamplification
2R	Reamplification & Reshaping
3R	Reamplification, Reshaping & Retiming
R&E	Research and Education
REN	Research and Education Network
RI	Research Infrastructure

RLS	Regeneration Laser Station
ROADM	Reconfigurable Optical Add/Drop Multiplexer

S

SCB	Switch Control Board
SNMP	Simple Network Management Protocol
SyncE	Synchronous Ethernet

T

T&F	Time and Frequency
TDD	Time Division Duplex
TDEV	Time Deviation
TDoA	Time Difference of Arrival
TIC	Time Interval Counter
TSDB	Time-Series Database

V

VCTCXO	Voltage-Controlled Temperature-Compensated Crystal Oscillator

W

WDM	Wavelength Division Multiplexing
WP6	Work Package 6, Network Development
WR	White Rabbit
WRS	White Rabbit Switch
WRS-LJ	White Rabbit Switch Low Jitter

X

XPM	Cross-Phase Modulation

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