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White Paper: Management and Monitoring of Time and Frequency Services

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Abstract

This white paper describes how various European National Research and Education Networks manage and monitor production time and frequency (T&F) services implemented over optical fibres. It covers T&F transfer techniques, management areas, consistent monitoring of T&F equipment, and optical considerations for the successful operation of T&F services.

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Executive Summary

This white paper summarises the experience of individual National Research and Education Networks (NRENs) involved in Work Package 6 Network Technologies and Services Development, Task 1 Network Technology Evolution of the GN4-3 project in managing and monitoring time and frequency (T&F) services over optical fibres. Undoubtedly, the implementation of these types of services requires extensive collaboration between NRENs and the institutions generating such signals (for example, national metrology institutes). Close coordination of activities and effective communication are essential to guarantee the high availability of this type of service and the continuity of coexisting data transfer services. The document describes how T&F services can be managed successfully by NRENs and how T&F systems can be run effectively and with the necessary monitoring and alerting.

The white paper first provides an overview of the three main time and frequency transfer techniques: optical carrier (both stabilised transfer and two-way comparison), electronically stabilised time and frequency distribution system (ELSTAB) and White Rabbit (WR).

The three separate but interacting management areas for bi-directional T&F services transmitted over a shared fibre are A) metrology signal sources (usually ultra-precise clocks located in metrology laboratories); B) the metrology signal transfer and regeneration system; C) the telecommunication data transmission system (DWDM). Closely correlated management of the individual system components, effective communication and a single point able to see and monitor all three environments – namely, the NREN Network Operations Centre (NOC) – are essential.

It is also essential, when introducing T&F services into the network, to comply and fit in with existing NOC procedures and rules, to ensure the network's integrity and continuity of existing services. The paper describes how two NRENs have achieved this, outlining their monitoring architecture, the protocols and key parameters used to monitor the metrological equipment, and the methods and tools used to display the metrics.

Typical optical considerations and risks relating to the implementation of T&F services include bandwidth reservation and traffic isolation in a DWDM system; amplifier lasing; cross-modulation; cohabitation of Raman amplifier with bi-directional signals in the network; and T&F equipment shutdown procedure. The paper describes how these have been addressed by individual NRENs.

The increasing demand for high-quality T&F signals presents an opportunity for NRENs to both meet end-user needs and contribute to the development of new standards and technical solutions. Their experience to date demonstrates that T&F services can be successfully and safely implemented in networks primarily established for data transfer, with comprehensive management and monitoring ensuring the integrity of both T&F and data transfer services.

1 Introduction

During recent years, time and frequency (T&F) dissemination devices and networks have advanced significantly, from simple optical links for testing T&F signals to whole optical T&F dissemination networks with hundreds of specialised devices. Devices from the experimental phase have entered the production phase.

T&F networks are no different from data networks from the point of view of a network operator, as their main goal is to provide services to end users. National Research and Education Networks (NRENs) aim to deploy T&F and data services in the most cost-efficient way, sharing infrastructure where possible. Similar to data networks, T&F dissemination networks need appropriate standards for management and monitoring that will be compatible with existing solutions in data networks.

This document outlines the main challenges in managing time and frequency transfer infrastructures. Particular emphasis has been placed on the solutions that multiplex data and metrology signals in a single transmission system, as this is considered to be the most demanding aspect.

Section 2 of this document describes the main T&F transfer techniques and characteristics. The choice of the appropriate system depends mainly on the end-user requirements relating to the format of the transmitted signal and the required accuracy. Section 3 describes the different management areas of T&F transfer systems. The whole process of metrological signals distribution (from the source to the end user) is described, and this description can help to organise the management structure of such a service. Section 4 describes the interfaces and protocols for communicating with devices that transmit the metrology signals. Section 5 describes typical optical issues relating to the implementation of T&F services.

This document can be used both as a support for institutions that want to implement T&F transfer services in their network and as an inspiration for NRENs that already have such services but are looking for new solutions to manage them.

The work is supported by the GN4-3 project in Work Package 6, Network Technologies and Services Development, Task 1 Network Technology Evolution.

2 Main T&F Transfer Techniques

This section provides a general description of the three main time and frequency transfer techniques: optical carrier, electronically stabilised time and frequency distribution system (ELSTAB) and White Rabbit (WR).

2.1 Optical Carrier

Optical carrier transfer is a high-end technology that aims to distribute state-of-the-art ultra-stable frequency over long distances. This technology is of interest to multiple different scientific areas, and in particular metrology, and is being used for international comparison of optical clocks and to provide the highest-level reference for T&F metrology applications.

There are two well-known setups of optical carrier transfer that have been comprehensively investigated [CLONETS_D1.5]:

- Stabilised transfer, to distribute an ultra-stable frequency reference to an end user.
- Two-way comparison, where two laboratories are comparing their references and both are therefore T&F providers and end users simultaneously.

Each of these is described below.

2.1.1 Stabilised Transfer

The stabilised transfer of an ultra-stable optical carrier is based on the active compensation technique, which relies on correcting the introduced noise and fluctuations while the T&F signal is propagating in the fibre. An appropriate correction is added into the emitted signal in either the optical or electrical domain. The correction is based on a feedback loop, which drives a phase error between the signal from the reference and the round-trip signal (i.e. the signal reflected from the remote terminal) to zero (see Figure 2.1).

The correction is usually applied at the local terminal by controlling an acousto-optical frequency shifter (often also called an acousto-optical modulator (AOM)). The uncertainty introduced on the optical carrier by this transfer technique is below 10^{-19} after 10^{4} s of integration time, when implemented on a single bi-directional fibre more than a thousand kilometres long.

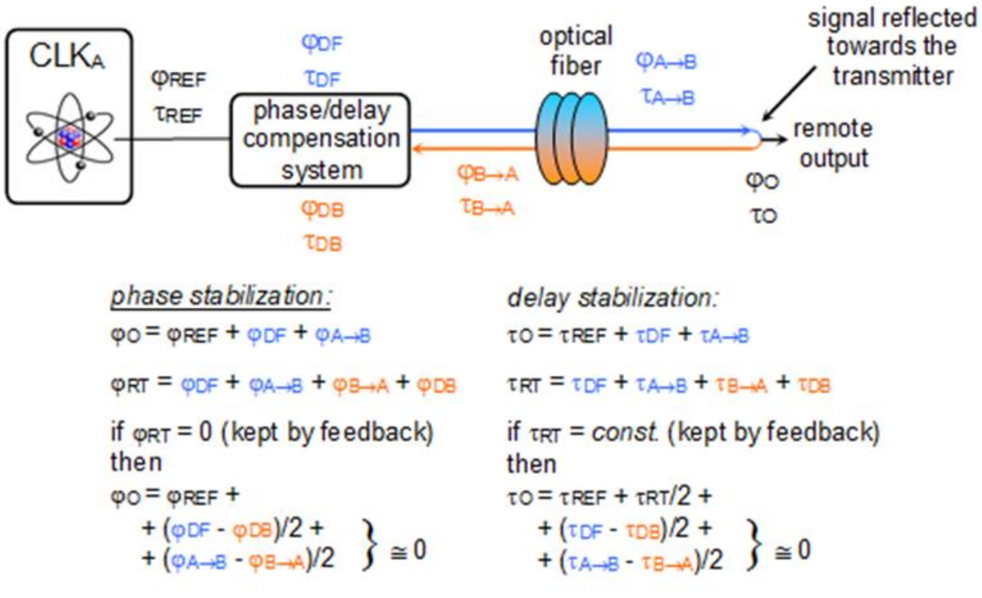

Figure 2.1: Dissemination of reference signals in a phase/delay stabilised link [RIE_2017]

2.1.2 Two-Way Comparison

In the two-way comparison technique, two ultra-stable optical carriers with approximately the same wavelength are injected into opposite ends of the fibre link. Post-processing the frequency data acquired at the two ends of the fibre subtracts the noise contribution of the fibre link. This technique has uniquely been employed for metrological comparisons of optical clocks. It has been demonstrated that it is possible to achieve an uncertainty to the optical carrier below 10^{-20} after 10^4 s of integration time, if a single bi-directional fibre is used.

Two-way comparison (see Figure 2.2) is a replica of the two-way satellite time and frequency transfer (TWSTFT) technique, applied to an optical fibre. This technique is applicable only when both locations are equipped with their own clocks.

The reciprocity of the fibre allows the subtraction of the unknown propagation delay of the fibre through a post-processing of the data collected at the ends of the link, first exchanging it between the involved locations using some other communication channel. This is why the two-way comparison is an off-line service, not working in real time.

Institutions that are most interested in clock comparisons are T&F laboratories providing UTC signals and research teams involved in the development of optical clocks. When used with a dark fibre or a dark channel approach operating bi-directionally, this technique can be used to assess a time difference between two distant clocks; when operated uni-directionally, a two-way comparison can be used to assess the relative stability only.

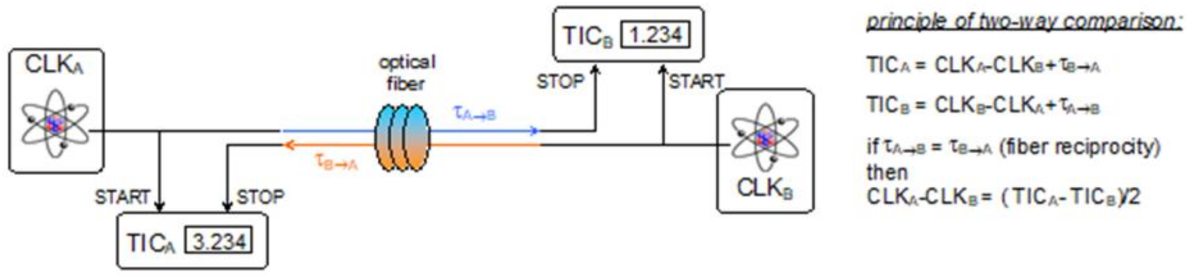

Figure 2.2: Clock comparison using the transmission in a reciprocal fibre [RIE_2017]

It must be well understood that optical carrier transfer is looking to achieve state-of-the-art performance. This type of T&F transfer, therefore, requires the end user (mainly research institutes or national metrology institutes) to have expertise in operating ultra-stable frequency applications, as frequency combs (the equipment locked to the transferred reference) are to be operated by the end user themselves.

2.2 Electronically Stabilised Time and Frequency Distribution System (ELSTAB)

The electronically stabilised time and frequency distribution system (ELSTAB) has been developed at AGH University of Science and Technology in Poland [ELSTAB]. It is a fibre-optic system comprising active stabilisation of the propagation delay, bi-directional fibre-optic amplifiers and a procedure enabling the calibration of a two-way time transfer. Lab demonstrations over 480 km have shown a time deviation below one picosecond (10^{-12} s). A stabilised propagation of the time signal in the link is realised by marking the occurrence of the 1 PPS time signal through the introduction of specific phase modulation on a 10/100 MHz square-wave signal. At the far-end transceiver, a de-embedder is used to extract the 1 PPS pulses.

This system, which is still being developed, is widely implemented in the NREN network in Poland. In addition, the system is also used by telecommunication operators in Germany and other research centres around the world.

Although the system has been designed to distribute time (1 PPS) and radio frequency (RF) signals (5/10/100 MHz) in a network based on dedicated optical fibre, it is also possible to transfer them in Dense Wavelength-Division Multiplexing (DWDM) telecommunication networks [TUR_2018].

From the management and monitoring point of view, this system provides the operator with a set of the necessary information to assess the correctness of its operation. Apart from basic information about the optical signal levels at individual system points (both amplifiers and transmitting and receiving stations), it is also possible to monitor the presence of input reference signals (T&F) and the correctness of their transmission through the ELSTAB system. It should be mentioned that the system in its basic version independently maintains a constant and unchanging delay between the input and output of the system and no additional operator action is required in this respect. The system operates largely autonomously and does not require advanced knowledge specific to T&F signal transfer systems. The only element that is not controlled in an ELSTAB system is the quality of the input signal. The ELSTAB system “transparently” transfers the signal from the input to the output. This means that from a T&F transfer service management point of view using ELSTAB, the operator has full knowledge of the entire system, except for the previously mentioned reference signal quality. Therefore, it is necessary to develop a method of communication between the laboratory generating the source signal and the ELSTAB operator, in order to obtain full knowledge of the system state at one point in the network.

In addition to the aforementioned issues, the ELSTAB system requires an initial calibration before initial operation and after any major failure that changes the optical length of the optical fibre link. This procedure is not complicated and is described in detail in the ELSTAB device manual; however, it requires the use of a time interval counter (TIC), which is not standard equipment for telecommunication network operators. Laboratories maintaining T&F reference signal sources potentially have all the prerequisites (appropriate knowledge and TIC) to perform this calibration correctly. Additionally, such calibration is performed at the starting point of the system, i.e. at the laboratories generating the reference signal.

2.3 White Rabbit

White Rabbit (WR) is a time and frequency transfer technology developed in CERN that provides sub-nanosecond accuracy and picosecond precision of synchronisation for large distributed systems. Its main features include:

- Single fibre bi-directional communication.
- Utilisation of Synchronous Ethernet (SyncE).
- Connecting thousands of nodes.
- Distances of up to hundreds of kilometres between nodes.
- Small Form Factor Pluggable (SFP) transceivers.
- Fully open hardware, firmware and software.
- Multi-vendor commercially produced hardware (e.g. WR switches are manufactured by four companies).

White Rabbit nodes provide their basic functionality in the form of an IP core called WR PTP Core. Several WR node implementations exist; however, the most common and versatile is the White Rabbit switch (WRS) [WR_SWITCH].

For short distances (up to 10 km) of dedicated single-mode fibre, cheap SFP can be used, utilising wavelengths of 1,490 nm and 1,310 nm. Long-reach SFPs are required for longer distances (unamplified single span of 120 km to 160 km or amplified transmission system up to 1,000+ km). It is also possible to operate WR in bi-directional DWDM systems and corresponding SFPs. WR has so far been using SFP (i.e. 1 GbE devices), but recently Miguel Jiménez-López et al. [JIM_2020] proposed an architecture that allows 10 GbE compliant synchronisation using SFP+ transceivers.

In a WR network, WR switches are connected over standard optical fibre. A WR grandmaster switch requires a 10 MHz frequency and 1 PPM signal. The master can be connected to multiple WR slave switches, which can act as a master for other slaves, creating a hierarchical structure; end-point equipment can also be WR time nodes such as a WR-LEN [WR_LEN] or WR-SPEC [WR_SPEC] device. The best stability performance can be achieved with a WR switch [DMI_2019].

The *White Rabbit Good Practice Guide* presents in detail many practical WR issues [DMI_2019].

2.3.1 White Rabbit Standardisation

The White Rabbit technology is an extension of the *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems* [IEEE_1588-2008]. It was later generalised and integrated into the standard IEEE 1588-2019, under the name “High Accuracy”, in the third default PTP Profile in Annex I [WR_in_1588].

3 Management Areas for Bi-Directional T&F Services Transmitted over a Shared Fibre

The concept of reference signal transfer has been described in detail in many articles. An overview of the leading solutions and methods is given in [CLONETS_D1.5]. The key requirement for this type of transfer is bi-directional transmission in a single fibre (this is the precondition for correct compensation of transmission path delay variations). This requirement is contrary to the practice in existing long-distance DWDM telecommunication systems, which realise bi-directional transmission using uni-directional transmission of signals in a pair of optical fibres. In practice, this requires demultiplexing of metrological signals at the input of each uni-directional telecommunication amplifier, their bi-directional amplification by a dedicated amplifier, and their re-multiplexing with the data signal (at the output in the optical fibre line). Figure 3.1 presents a general overview of the topology of a time and frequency link with data sharing.

The provision of T&F signal transfer services involves the need to monitor three separate but interacting environments:

A) Metrology signal sources (usually ultra-precise clocks located in metrology laboratories).
B) The metrology signal transfer and regeneration system.
C) The telecommunication data transmission system (DWDM).

Since the individual parts of the system may interact with each other (e.g. disabling Raman amplification in the DWDM system will reduce amplification in the metrology data transfer system, or significant amplification of metrology signals may lead to interference of data signals), it is necessary to place great emphasis on effective and correlated management of the individual system components. In addition, providing a high level of service requires end users to be able to both report system failures and receive information about the current state of the system in one place. For day-to-day operations, having a single view of the information would be an asset.

To provide the highest quality of T&F services in optical networks, therefore, there is a need for close cooperation between each of the three environments (A, B, C), but also a single point with the ability to monitor all three of them. It is obvious that national metrology institutes (NMIs) do not have the capacity and experience to monitor the entire T&F transmission system. This role should be performed by NRENs and especially Network Operations Centres (NOCs), which have been monitoring DWDM systems for years and have the relevant experience. However, they need strong support from NMIs to develop and implement systems that allow monitoring of primarily environment A. Moreover, effective methods need to be developed to respond to potential interruptions to the T&F service.

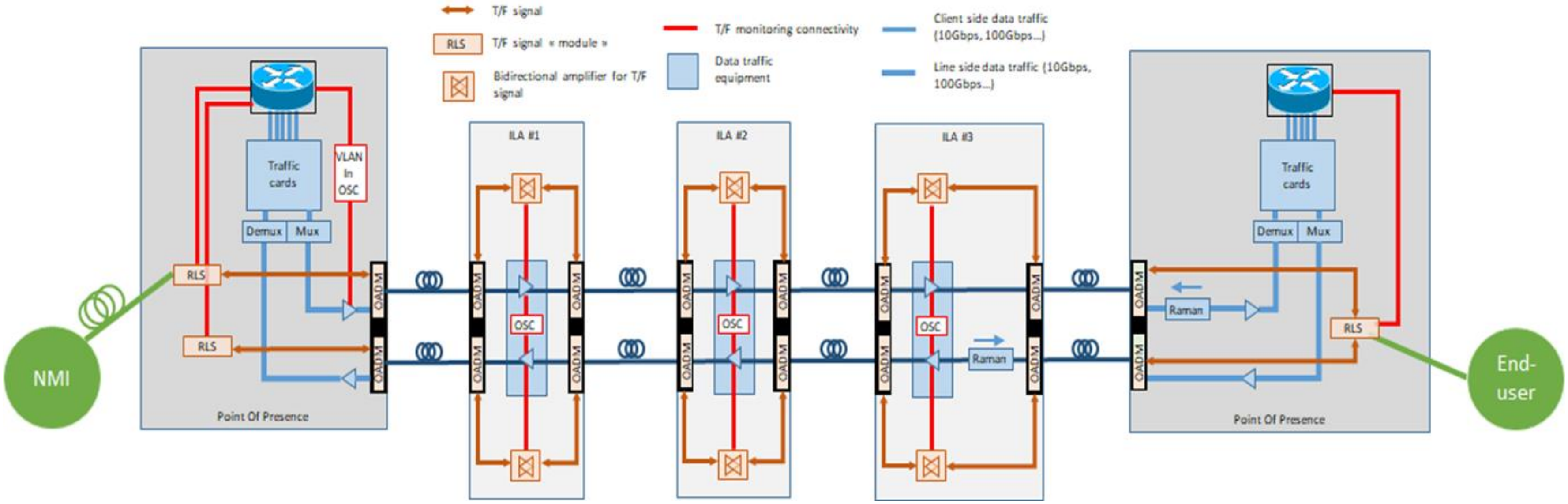

Figure 3.1: Topology view of a T&F link

The most commonly used management protocol in network devices is Simple Network Management Protocol (SNMP). It seems that its implementation in all environments, A, B, and C, would facilitate management and monitoring of the whole T&F system. All devices in the C environment support SNMP and are ready for management and monitoring by NOCs, but most of the devices in the A and B environments do not support SNMP at all. Additional work is required to at least implement the SNMP standard in these devices.

In France, environment A is monitored by the NMI (Observatoire de Paris), while environments B and C are monitored jointly by iXblue [iXblue] (previously called Muquans, the company that build the French Repeater Laser Station (RLS)) and RENATER (see Figure 3.2).

In Poland, PSNC is responsible for environments B and C, leaving A to the NMI and the T&F laboratory (see Figure 3.3).

In the Czech Republic, CESNET is responsible for B and C. The partner CITAF [CITAF], which operates time and frequency sources, is responsible for A (see Figure 3.4).

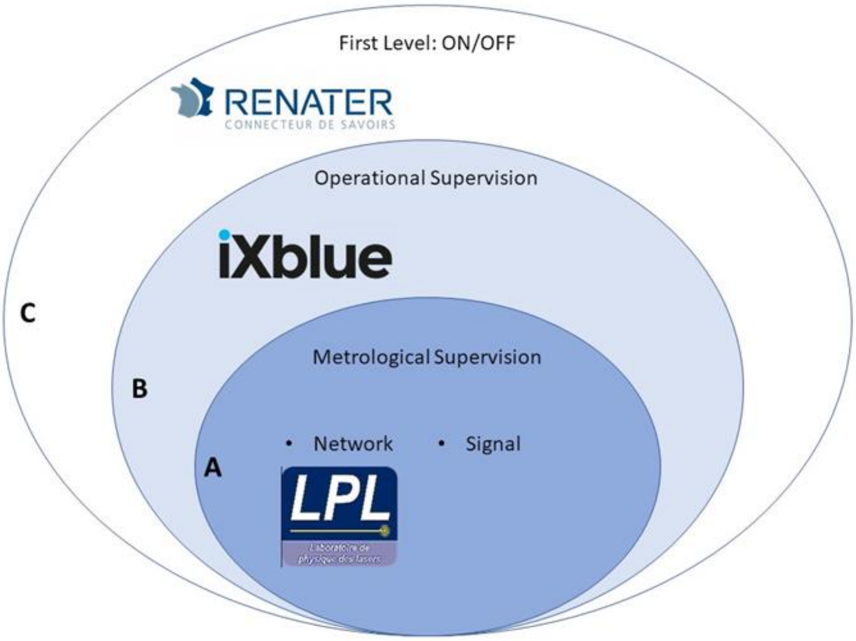

Figure 3.2: Levels of responsibility in the French metrological network

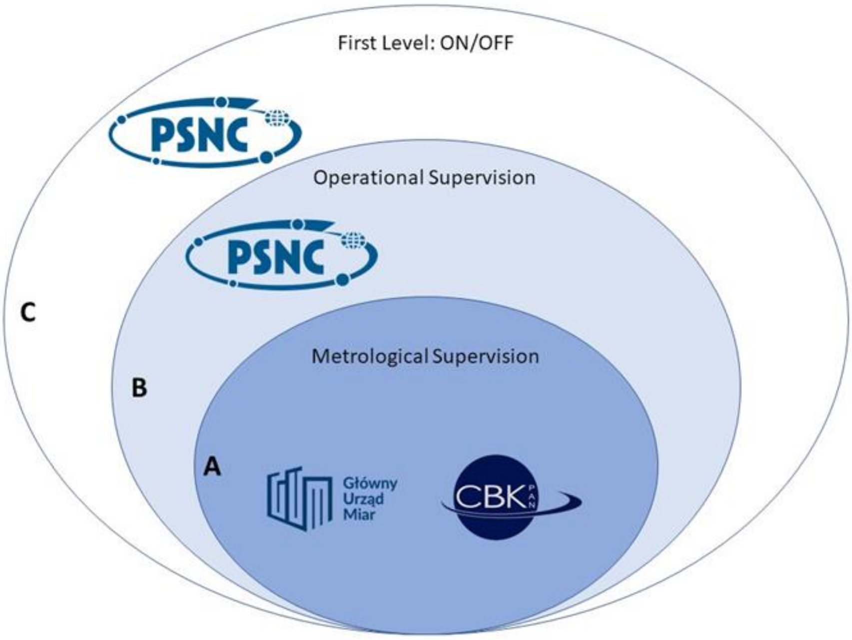

Figure 3.3: Levels of responsibility in the Polish metrological network

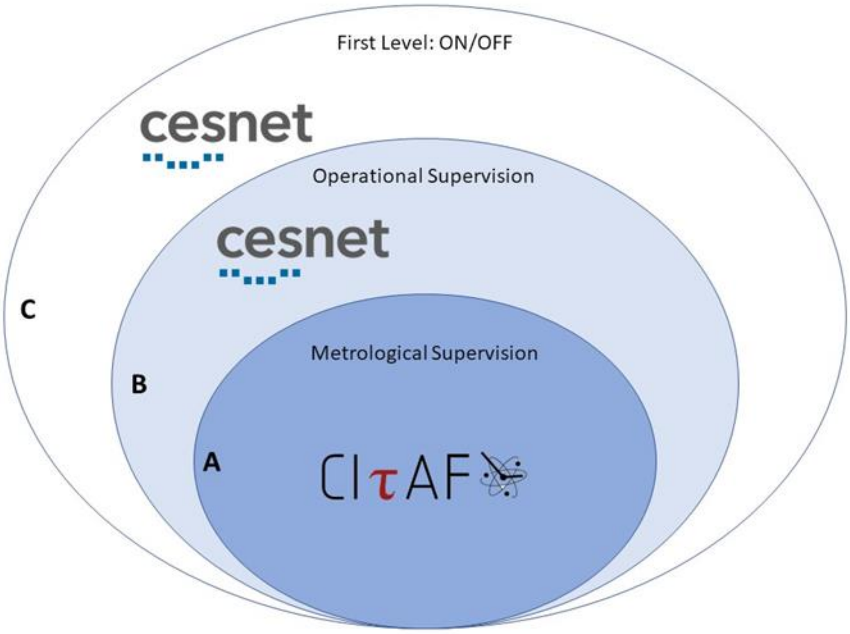

Figure 3.4: Levels of responsibility in the Czech metrological network

4 Setting Up Consistent Monitoring of T&F Equipment

With a community of millions of daily end users, NRENs' top priority is the continuity of their services. Every NREN relies therefore on a Network Operations Centre (NOC), whose role includes monitoring the network and the services it delivers 24/7.

Adding any new element into the network must comply with day-to-day procedures and other rules to ensure the network's integrity, even if there is only the slightest probability this element can disrupt the rest of the network.

This section explains how to bring IP connectivity into inline amplifier sites and describes how management and monitoring of metrological equipment is done in NRENs, in particular RENATER and CESNET. In addition it explains how communication is achieved with White Rabbit devices.

4.1 RENATER's Monitoring Architecture

4.1.1 Bringing IP Connectivity into Inline Amplifier Sites

A typical T&F optical carrier transfer link (with shared fibre) is based on the following equipment (see Figure 4.1):

- A transmitter (in the examples below a Repeater Laser Station (RLS)) for the system that is locked (directly or indirectly) to an optical frequency reference or a time and RF reference (optical atomic clocks or atomic clocks).
- Amplifiers, to compensate for the losses of the fibre-induced attenuation. Solutions are mostly based on Erbium-Doped Fibre Amplifiers (EDFA) and Brillouin amplifiers.
- Optical Add/Drop Multiplexers (OADMs), which are (mainly) passive components that are implemented in setups where T&F signals are co-propagating with data traffic (i.e., in DWDM networks). OADMs are used to insert and extract metrological signals that need to propagate bi-directionally in the same fibre (while standard telco communications rely on a pair of fibres, one used in forward direction (west to east) and the other in backward direction (east to west)). This extraction must be done wherever mono-directional equipment has been installed or it will prevent the bi-directional propagation.

Because the metrological signal is extracted from other signals (see Figure 3.1), bi-directional amplifiers cannot be monitored through the standard Optical Supervisory Channel (OSC) and it was necessary to provide an alternative to supervise and monitor metrological equipment within the ILAs (see Figure 4.1 and Figure 4.2).

A solution was to bring IP connectivity through ports that are usually only used while equipment is being deployed. These ports are provided so that field teams can use them to get connectivity and communicate with the rest of their team in the adjacent sites when working in black spots (tunnels, far from phone masts, etc.). It only requires an extra Ethernet cable to be deployed between the metrological amplifier and the standard telco amplifier.

For example, in the Infinera (ex-Coriant) hiT 7300 equipment (amplifier), a small portion of the OSC or GCC0 bandwidth is accessible through two Ethernet port “User Ports” (USER 1 and USER 2) and two distant ports from two distant amplifiers can be virtually connected through a “User Channel”.

One can therefore take advantage of those ports and configure a point-to-point Ethernet connection starting from a router located in the Point of Presence at the edge of the line (see Figure 3.1).

One port of this router is configured to be in the metrological L3VPN and connected to the first hiT 7300 amplifier User Port to carry supervision/monitoring traffic which is added in the OSC and extracted in the next hut in one of the two User Ports. One can then use the second User Port of the hiT 7300 to generate traffic to the next hut, bringing IP connectivity into every site.

Figure 4.1: Housing of bi-directional amplifiers in ILAs

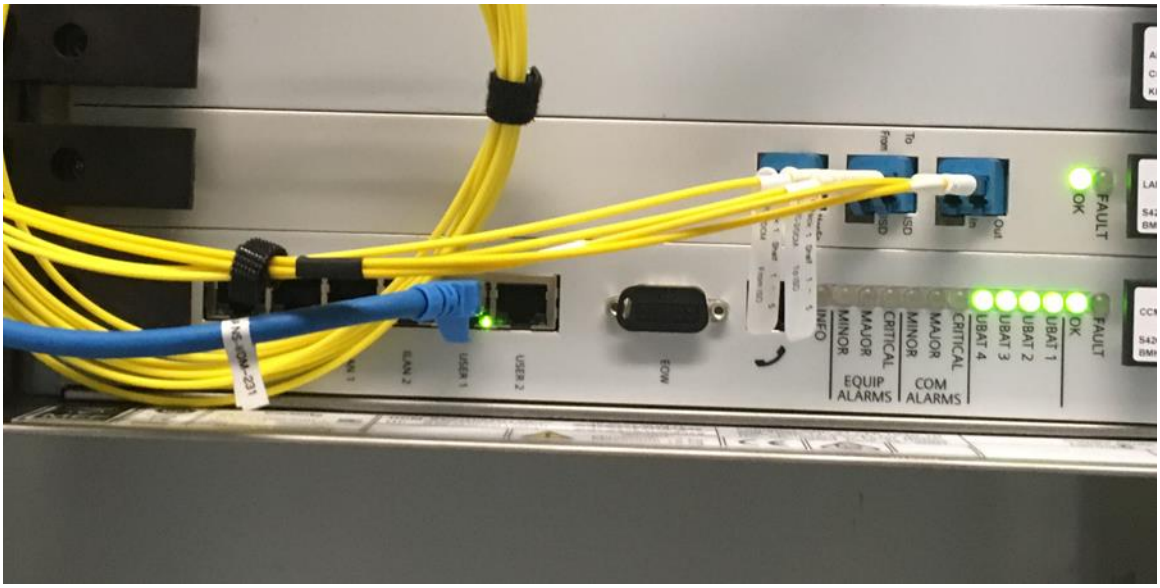

Figure 4.2: Bringing connectivity into huts to monitor metrology amplifiers through USER 1 User Port 1 (blue Ethernet cable in the picture)

When possible, the different T&F elements are directly connected to routers and configured to be in the dedicated metrological L3VPN (see Figure 4.3).

Figure 4.3: Repeater Laser Station connected directly to the routers (blue Ethernet cable) in an extremity site

4.1.2 Metrological Equipment Monitoring

The text and tables below summarise the protocols used to monitor metrological equipment and key parameters (performance, state, alarms, etc.) that need to be added to NOC supervision tools.

Table 4.1 lists the types of ports that are available in different T&F elements implemented in the French metrological network, where channel 44 (194.4 THz) of the ITU-T grid is saved for T&F service distribution.

Port Type	Repeater Laser Station	Bi-Directional Amplifiers	OADM (passive equipment)
10/100/1000 Base-T port	10/100/1000 Base-T port	10/100-Base-T port	X
Optical port	NO	NO	X

Table 4.1: Monitoring ports available in the French metrological network

So far, there are two ways to monitor and supervise T&F equipment (see Table 4.2). The use of the SNMP protocol is currently recommended as it can easily be automated.

Protocol	Repeater Laser Station	Bi-Directional Amplifiers	OADM (passive equipment)
SSH	YES	YES	X
SNMP v2/v3	SNMPv3	YES (SNMPv2)	X

Table 4.2: Protocols available in the French metrological network

RLS and bi-directional amplifiers deployed in the French metrological network are designed, built and maintained by two companies: Lumibird [Lumibird] and iXblue [iXblue]. RENATER required some parameters to be accessible with Read and Write privileges in order to be integrated into their network monitoring system.

The most useful parameters are listed in Table 4.3 (RLS) and Table 4.4 (bi-directional amplifiers).

Type	Description
A – Identification	1 – Type of RLS (74 or 76)
	2 – Product ID
	3 – Version
B – General parameters	1 – Temperature of the equipment (°C)
	2 – State of the diode (0: Off; 1: On)

Table 4.3: Monitored parameters of a Repeater Laser Station (RLS)

- A-1. As there are two types of RLS, one should be able to clearly identify which one is installed to prevent any mismatch in the network in case of substitution.
- Parameters A-2, A-3 and B-1 are typical in any supervision system.

- B-2 will be the key parameter to indicate whether a T&F signal is injected in the fibre or not. This will be very important while troubleshooting an incident in the network.

Type	Description
A – Identification	1 – Serial number
	2 – Customer serial number
	3 – Firmware
B – General parameters	1 – Pump state (0: Off; 1: On)
	2 – Preamp diode current setpoint (value in mA)
	3 – Temperature of the rack (°C)

Table 4.4: Monitored parameters of bi-directional amplifiers

- A-1, A-2, A-3 and B3 are typical parameters that can be added in any supervision system.
- B-1 gives an indication of whether the EDFA pumps are on or off.
  => It cannot be known for sure whether a real T&F signal is injected in the channel.
- B-2 gives an indication of the pump power in mA. It was decided to look for pump power in mA instead of gain in dB in Refimeve+ infrastructure [Refimeve+].
- B-1 (bi-directional amplifiers) and B-2 (bi-directional amplifiers and RLS) are the key parameters that indicate whether there is some power in the metrological channel.

Other elements listed above provide useful information to identify the equipment (serial number, type) and raise necessary alarms, e.g. if the temperature is rising (as for any other active equipment) or ping loss.

If necessary, the NOC can connect (SSH command or send set request) to the RLS and bi-directional amplifiers and shut them down (thanks to parameters B-1 and B-2 Write privilege), thus reverting the link to the situation of having data traffic only, without any “non-standard” signal. Once it is done, NOC can troubleshoot incidents as for any standard telecom case.

4.2 CESNET’s Monitoring Architecture

The Czech T&F transmission infrastructure CITAF is typically formed via dark fibre or dark spectrum in the case of sharing telecom fibre. Such a dark channel is formed by OADMs. To retain the advantage of proportional propagation, optical losses should be compensated via bi-directional amplification.

Monitoring of bi-directionally lit dark spectrum is realised via monitoring of optical powers reported by CzechLight bi-di EDFAs [CzechLight] deployed on that channel. This monitoring allows fast reaction to any change of physical conditions, e.g. higher attenuation, a sudden increase of reflections, etc.

Such a bi-directionally lit channel is able to carry multiple T&F services [VOJ_2017]; these services need to be monitored independently. Monitoring of precise time and RF reference transfers realised by White Rabbit devices is described below in Section 4.3. Transmission of coherent optical frequency monitoring is done via RF beat observation; this is described in Section 5.2.2, where it is also used for unwanted lasing detection and avoidance.

4.2.1 Monitoring of Inline Amplifiers

Inline bi-di amplifiers are deployed on lines shared with data in the majority of cases. Amplifiers are under the full control of CESNET. There are several ways to control and monitor CzechLight inline bi-di amplifiers. Available protocols include CLI control utilities over SSH (used mainly for verification and experiments), web UI (for ad hoc intervention), email (for alert notifications), SNMP (in read-only mode for long-term monitoring of critical parameters), and the RSYSLOG service (for preserving logs in case of sudden problems on diskless device).

With regard to the long-term perspective, crucial metrics are stored in the time series database (TSDB) VictoriaMetrics [VictoriaMetrics]. The data are provided by both pull and push techniques, mostly pulled from amplifiers over SNMP. Some metrics (e.g. number of firewall rules) are not available via SNMP and are therefore collected periodically by Ansible playbooks (scripts) and transformed to a suitable format and pushed into the TSDB.

Monitored metrics are: internal temperature of the box, pump current, optical input/output power, PSU voltage, CMOS battery status, list of firewall rules, ping status, SNMP service status, hardware and software configuration.

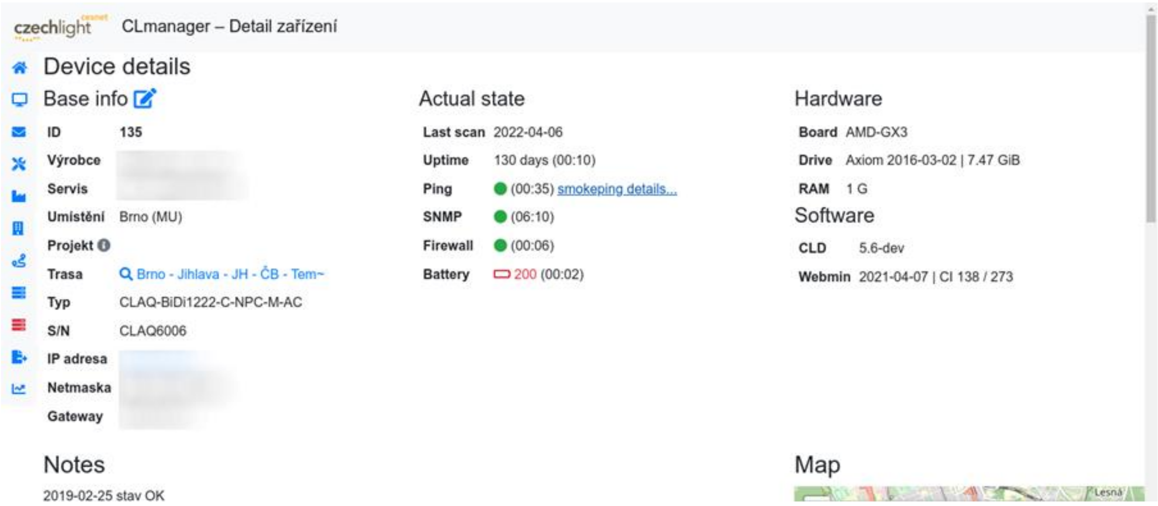

Figure 4.4: CESNETS's internal application CLmanager for reporting and monitoring of CzechLight boxes (amplifiers, ROADMs, VMUXs)

Relevant information is shown for a selected device, including that required for service works, hardware position on map, etc.

Some metrics are shown statically in the internal application CLmanager (see Figure 4.4) rather than in the TSDB. For the long-term metrics, the Grafana dashboards are configured to provide clear and understandable graphs/plots, which are very useful for tracing the operational events (e.g. sudden loss of input power in case of fibre cut). Examples of such a dashboard are shown in Figure 4.5, Figure 4.6 and Figure 4.7.

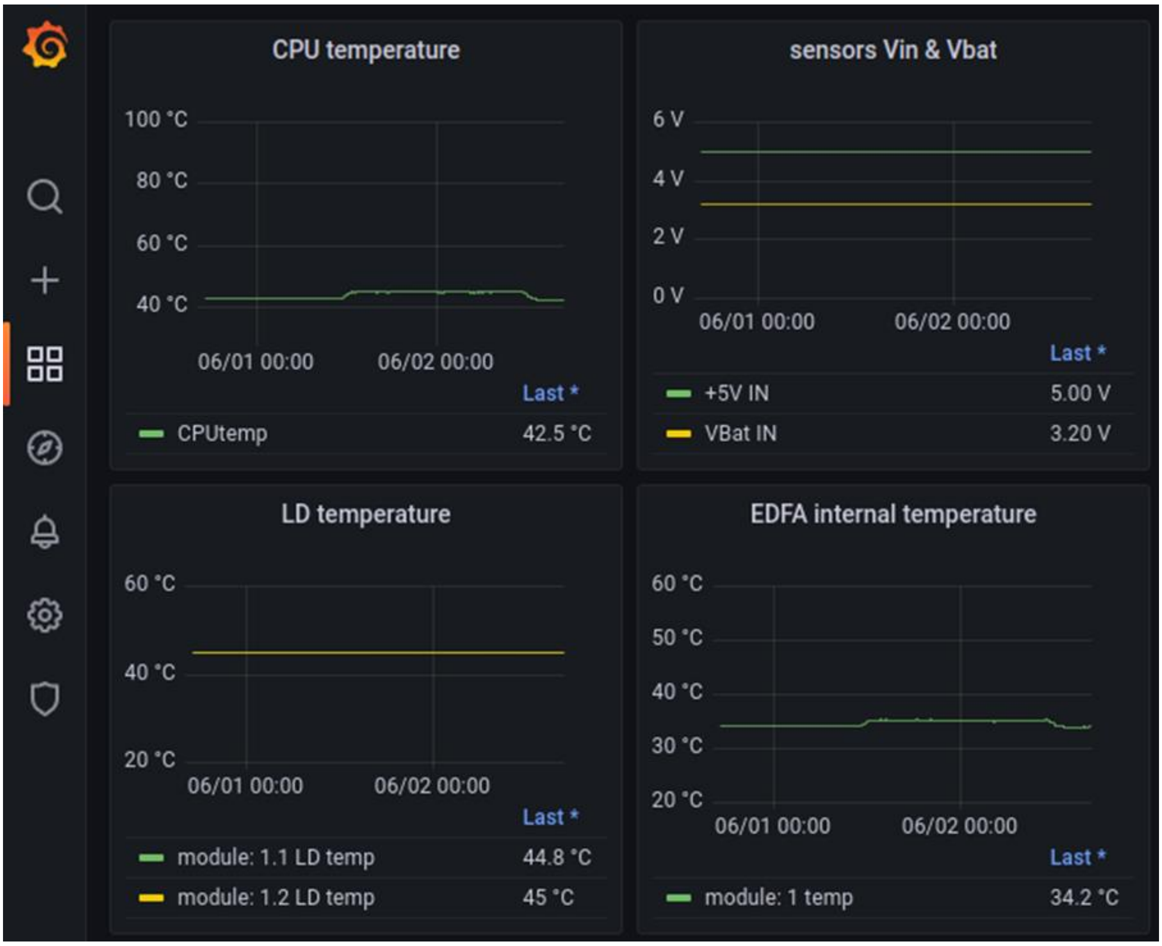

Figure 4.5: Grafana dashboard graphical display showing significant parameters during the evaluation interval, e.g. PSU, battery voltages and different temperatures

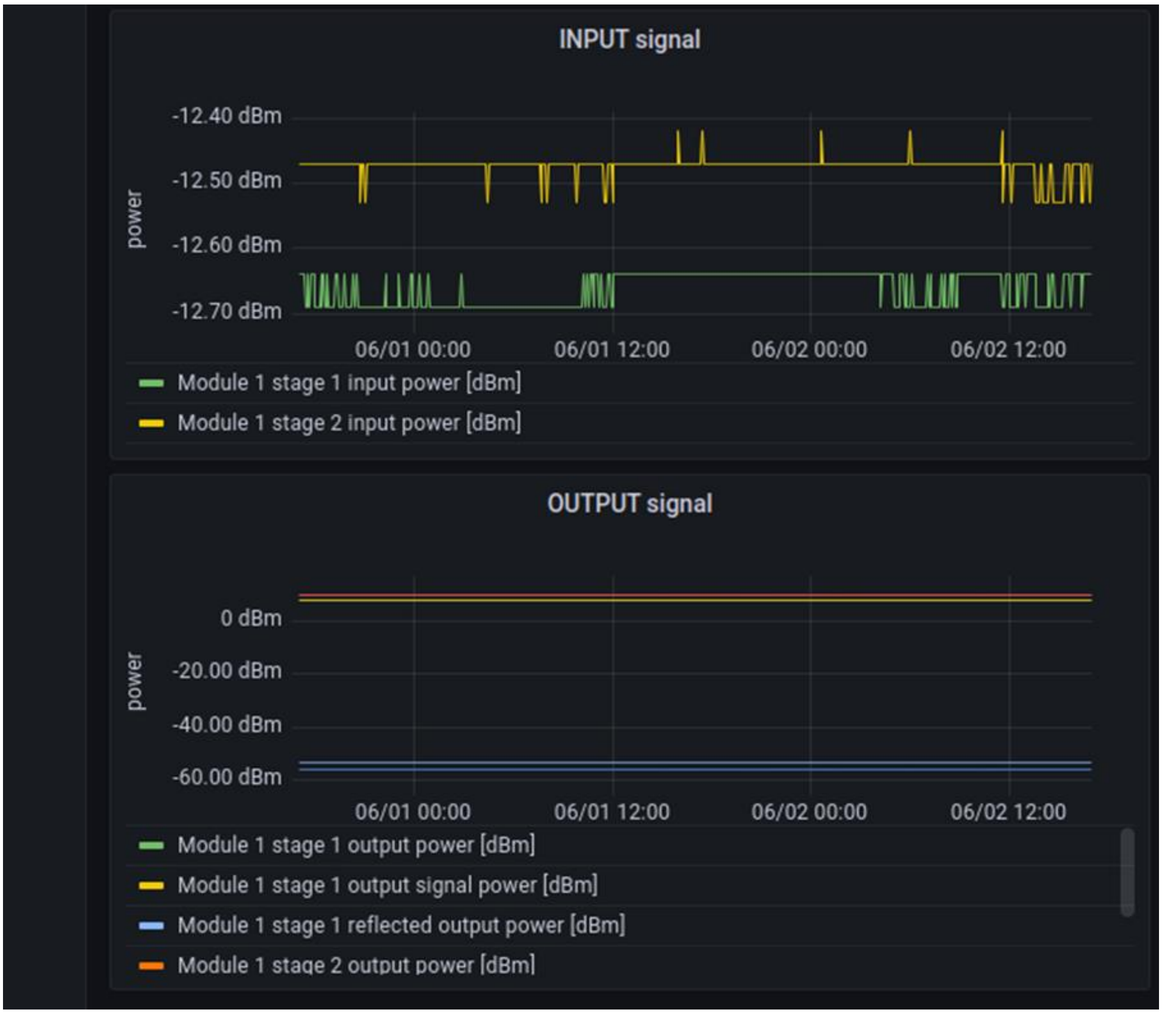

Figure 4.6: Grafana dashboard graphical representation of power of input/output signal during the evaluation interval,

Figure 4.7: Grafana dashboard combined view of significant parameters

4.2.2 Inline Amplifiers Control

The common operational service on CzechLight bi-di amplifiers could be managed via SSH or a web graphical user interface (GUI) that provides full control of the amplifier for the administrator. SSH access is used in the case of software-driven experiments (e.g. link balancing) and for semi-automated maintenance tasks such as deployment of new software versions, firmware reconfiguration and so on.

An example of the web GUI is presented in Figure 4.8, which shows the control interface of an EDFA allowing selection of the amplifier control mode (APC, AGC and ACC). The current values of input power, gain and output power are shown on a well-arranged schema of the bi-di C-band amplifier.

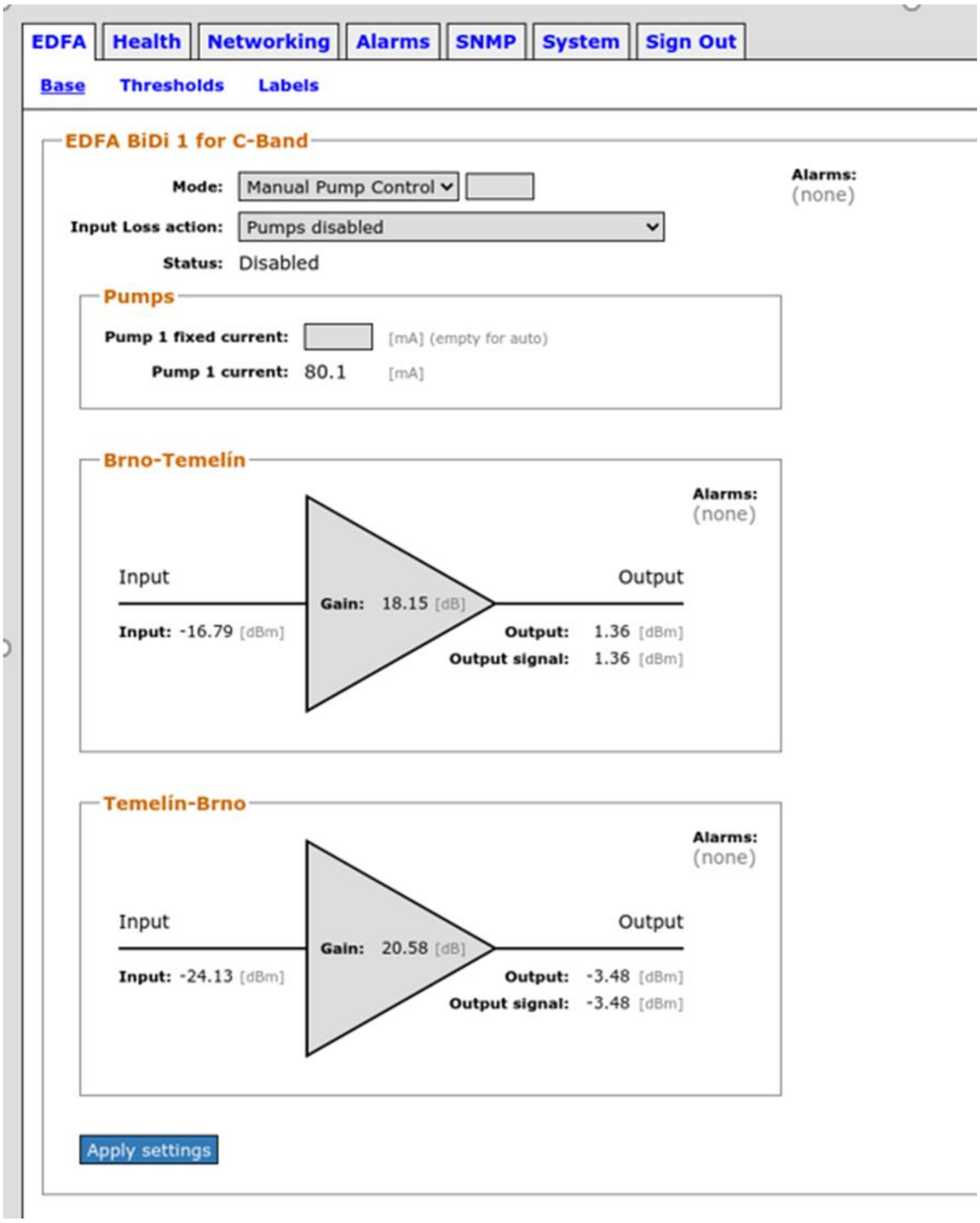

Figure 4.8: CzechLight amplifier's web GUI allowing authorised users full control, including pump current changes

4.3 White Rabbit

The White Rabbit (WR) system is currently deployed in many NRENs (e.g. ACOnet, CESNET, GARR, Funet, SANET, SURF). To achieve stability by design, bi-directional optical links are required. Dedicated bi-di amplifiers are often used, for which management and monitoring are in general the same as for other T&F systems.

There are several manufacturers of WR boxes. The most common White Rabbit device is the switch (WRS) [WR_SWITCH]. The commercial clones of the original open hardware vary in monitoring and control methods. The most common variant (see WR switch open hardware project [WR_SWITCH_OHP]) includes the following configuration and monitoring options:

- Serial access using USB socket (e.g. using Minicom in Linux or PuTTY in Windows).
  - Command line of the ARMv5 GNU Linux.
  - Suitable for basic configuration including setting up Ethernet ports.
  - Several command line tools are available.
- SSH access, equal to USB.
  - The same functionality as serial USB socket.
  - Insecure old Dropbear implementation (2017) [Dropbear].
- Web management interface – GUI.
  - Provides a summary overview of interfaces status.
  - Monitoring/configuration utility.
- SNMP.
  - Management Information Base (MIB) file.
  - Suitable for monitoring by NOC at operator level.

Figure 4.9 shows the WR switch GUI. The insecure SSH implementation with vulnerabilities is a serious issue that has not yet been solved. Operation of the WR switch in an open network is therefore not recommended.

In contrast to WRS, WR-LEN is the competitive White Rabbit alternative capable of supporting daisy-chain configurations [WR_LEN]. It is equipped with only two SFP interfaces and therefore is used mainly as a terminal device of the time distribution tree. WR-LEN also supports SSH access. However, practical implementations prefer to use serial port access over out-of-band connectivity.

Figure 4.9: White Rabbit GUI

5 Optical Layer Considerations for the Operation of T&F Services

Section 3 distinguished three separate but interacting areas of monitoring. This section focuses on considerations in the optical layer relating to the implementation and operation of T&F services. Fibre sharing for both bi-directional T&F transfer systems and uni-directional data transfer introduces specific risks that need to be understood. The aspects discussed are:

- Bandwidth reservation and traffic isolation in a DWDM system.
- Amplifier lasing.
- Avoidance of unwanted lasing.
- Cross-modulation.
- Cohabitation of Raman amplifier with bi-directional signals in the network.
- T&F equipment shutdown procedure.

5.1 Bandwidth Reservation and Traffic Isolation in a DWDM System

5.1.1 Single-Channel OADMs

As depicted in Figure 3.1, OADMs are implemented after telco uni-directional amplifiers. They are used to multiplex metrological T&F signals with other data traffic. Table 5.1 below highlights the main (optical) characteristics of OADMs that are specifically designed to protect (through high isolation) and lower the degradation for data traffic (<0.7 extra dB for all but channel 44 and <1 dB for channel 44). OADM manufacturers can even guarantee better performance if necessary but this is more expensive as it requires testing and selecting only the best products.

Characteristic	Value
Bi-directional	YES
Add channel (= T&F signal) insertion loss (dB)	<1 dB
Drop channel insertion loss (dB)	<1 dB
Pass through insertion loss (dB) (client to line side)	<0.7 dB
Passband bandwidth (nm)	±0.11 nm

Characteristic	Value
Isolation	25 dB
Return loss	45 dB
Polarisation-dependent loss (PDL)	<0.2 dB
Polarisation mode dispersion (PMD)	<0.2 ps
Add/drop connector type (channel #44)	FC/APC
Line/client connector type	LC/PC
Supported optical power (mW)	300 mW

Table 5.1: Usual characteristics of single-channel OADM (channel #44 in this case)

Figure 5.1 shows an example of two OADMs:

Figure 5.1: Two OADMs with their simplex connectors

There are 3 ports in each OADM:

- Network port: “line” side with multiplexed signals.
- Express port: “client” side, all signals except channel 44 (to which classic data equipment is connected)
- Channel 44 port: channel 44 extraction/insertion port (to which T&F metrological equipment will be connected).

There are 2 OADMs per rack, which means one rack for each direction (because of the two fibres), and consequently 2 racks in each ILA (for the two directions).

Note that the individual ports on the OADM module are alternately named Network or Common, Express or Reflect, Channel XX or Pass.

5.1.2 OADMs Covering Multiple Channels or Bands

Parallel transmission of more T&F services or simply coherent optical frequency together with precise time transfer can be achieved using broader channels and wavelength multiplexing within such channels. Typically, the channel is formed by using OADM, covering 4 or 8 consecutive DWDM channels. Such OADMs are typically named 4 skip 0 or 8 skip 0, with characteristics shown in Table 5.2 below. In critical segments with high attenuation, specific methods are used to limit attenuation as much as possible: OADMs are sorted and only pieces with IL below 0.6 dB are accepted. Instead of 1RU units OADMS in the form of so-called cable dongles are used, leveraging additional patch cabling. To minimise reflections, angled polished (APC) is used. Also, traditional 3 mm diameter ferrules are provided because of better cleanability.

Characteristic	Value
Dimensions (width, depth, height) (inch, mm, RU)	Cable dongle to minimise connectors or standard 19”, 1 RU (see photos below)
Pass channels	CH(n)~CH(n+3)
Add/drop bandwidth (= T&F signals) insertion loss (dB)	<0.8 dB
Pass through insertion loss (dB) (client to line side)	<0.6 dB
Passband bandwidth (nm)	CH(n+3)-0.11~CH(n)+0.11 nm
Isolation	20 dB
PDL	<0.1 dB
PMD	<0.1 ps
Add/drop connector type	SC or FC/APC
Line/client connector type	SC/APC
Supported optical power (mW)	500 mW (higher possible, but require special connectors)

Table 5.2: Usual characteristics of multi-channel OADM (e.g. channels 46–43)

CESNET is also working on migration of T&F services from the middle of the C band (channels 44, 46) into the 1570 nm band in order to limit C-band spectrum fragmentation, and also to allow larger guardbands between the T&F channel and high-speed coherent data channels. In order to support this, dual-band OADMs are deployed, covering legacy C-band channels and also target channels in the 1570 nm band, as shown in Figure 5.2. By careful selection, the insertion loss from the line port to the client (named NCS in Figure 5.2) is kept below 1 dB.

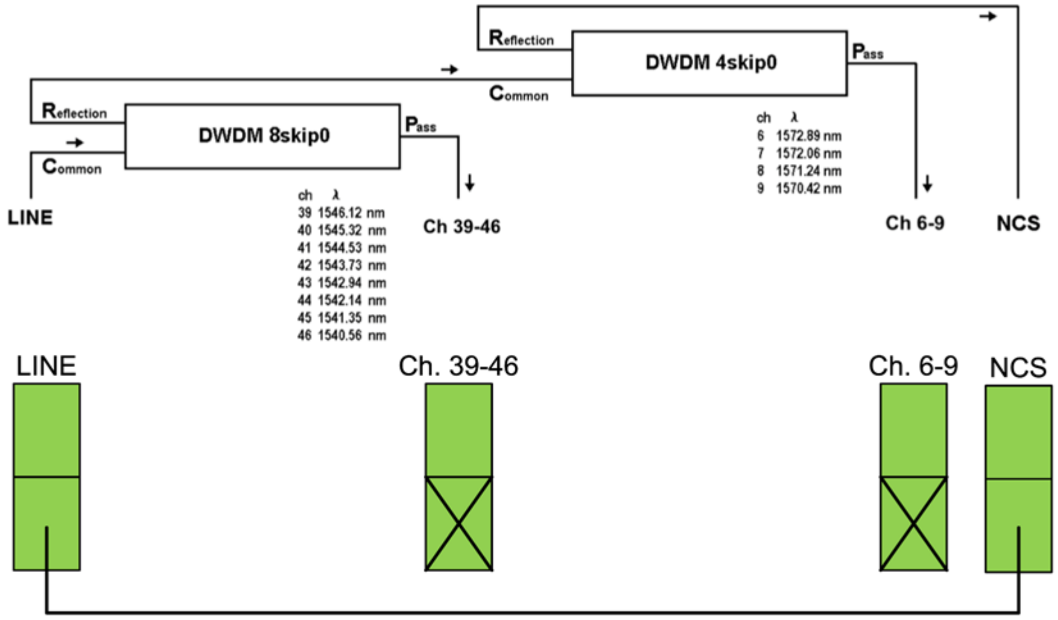

Figure 5.2: OADM filter for multi-band C band (ch. 39–46) and L band (ch. 6–9)

The project that is working towards interconnection of Ca+ ion optical clocks between the cities of Brno and Olomouc in Czechia also requires interconnection at 1458 nm. Tri-band OADMs have already been deployed and are shown in Figure 5.3 and Figure 5.4. This 1458 nm bi-directional channel features compensation of insertion losses by bi-directional amplifiers based on semiconductor optical amplifiers [VOJ_2018].

Figure 5.3: Physical view of OADM filter for multi-band S (1451 nm), C band (ch. 43–46) and L band (ch. 7)

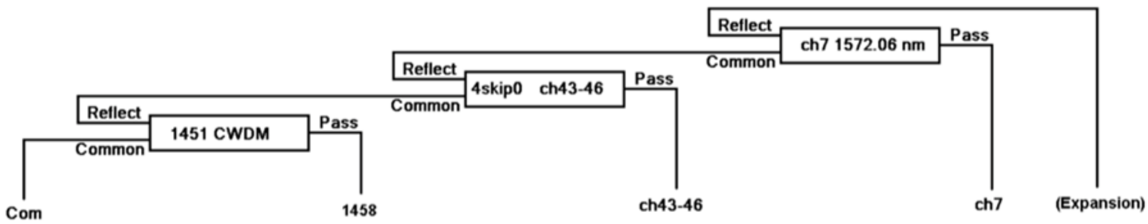

Figure 5.4: OADM filter for multi-band S (1451 nm), C band (ch. 43–46) and L band (ch. 7)

5.2 Amplifier Lasing Issue

An “amplifier lasing” issue may occur in the Erbium-Doped Fibre Amplifiers (EDFAs) when deployed in metrological networks. This issue as well as possible measures to mitigate or prevent unwanted lasing are described below.

5.2.1 Issue Description

Erbium-Doped Fibre Amplifiers (EDFAs) are by far the most important fibre amplifier technology used in the context of long-range optical fibre communications and have been widely deployed since the early ’90s. They can efficiently amplify light in the 1.5-µm wavelength region, where silica-based telecom fibres have their minimum loss.

These amplifiers can achieve gains of more than 27 dB for long fibre distances and a higher DWDM channel count, but their design includes isolators to prevent any backscattering signals from being amplified. This fits perfectly with the way data is sent uni-directionally in the fibre, but prevents the propagation of bi-directional signals.

Metrological networks rely instead on their own bi-directional amplifiers, which have to be deployed extremely carefully. The situation can easily arise where two reflections occur at both sides of the bi-directional amplifiers and, if the reflectance is high (due to bad splicings, dirty connectors, fibre bendings, etc.), a laser cavity can be created (see Figure 5.5 and Figure 5.6) that will generate lasing oscillations under certain conditions.

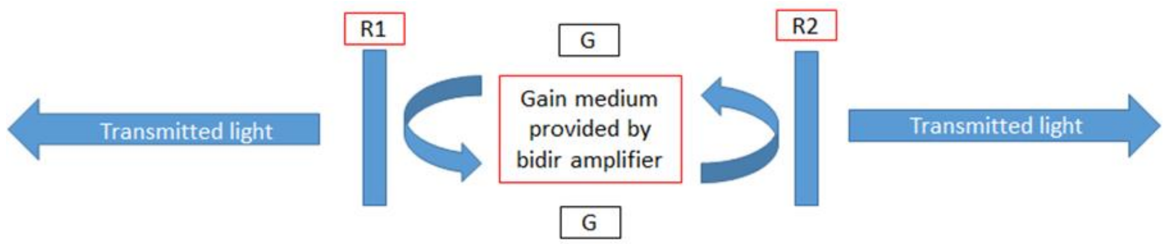

Figure 5.5: A typical LASER cavity with a gain medium and two mirrors with partial reflectance

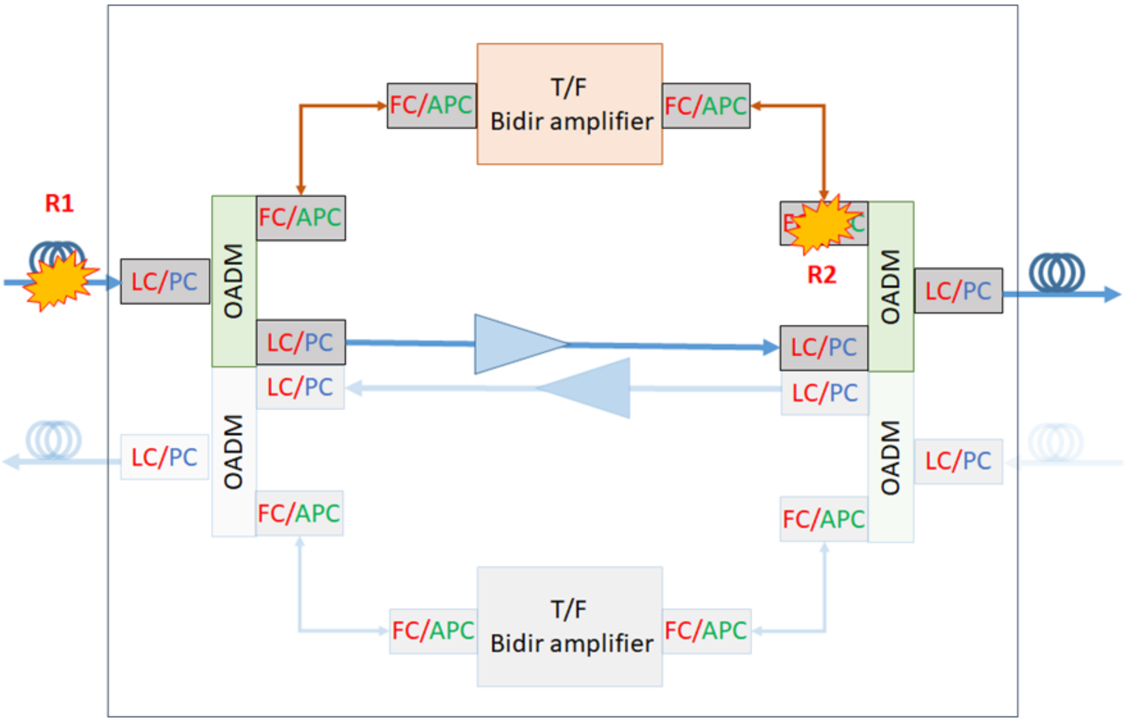

Figure 5.6: Example of a realistic scenario of lasing oscillations in an ILA

In the Figure 5.6 example, lasing oscillations occur due to composite Rayleigh backscattering from fibre together with:

- R1 that has a high reflectance event due to bad splicing.
- R2 that has high reflectance due to a dirty connector.
- Top T&F bi-directional amplifier as a gain medium (G).

To be in a situation where laser oscillations occur, one has to verify the condition that the gain obtained by amplification exceeds the internal and mirror losses. Simplified, the oscillation condition (expressed on a linear scale) can be written as:

$$G^2 > 1/R1R2$$

Such a scenario was reproduced in the iXblue ~~our~~ laboratory. Figure 5.7 and Figure 5.8 present the output power of the top-right LC/PC connector (after the R2 reflection) with the purple line being the power threshold of the lasing oscillations.

- Figure 5.7: if the gain (yellow curve) is low and remains below the purple line, nothing happens.
- Figure 5.8: if the gain is above the purple line (gain higher than losses), oscillations occur.

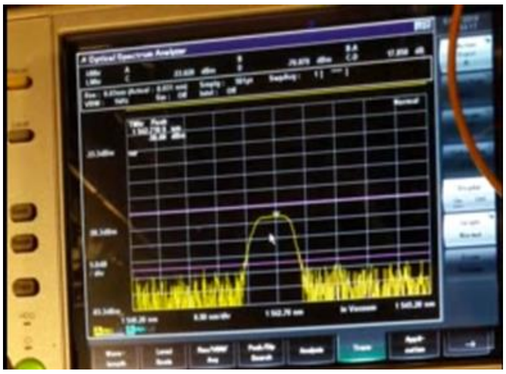

Figure 5.7: Gain lower than losses (*image captured from a video*)

Figure 5.8: Gain higher than losses – oscillations occur (*image captured from a video*)

When gradually increasing the gain of the bi-directional amplifier, interference will first be visible in the transmitted T&F signal. Distortion of the data channels (even without guard band) requires a significant excess of gain above the threshold $G^2R1R2=1$.

The side effect of optical feedback is that the metrological amplifiers' gain has to remain much lower than telco amplifiers with an average gain of around 12 to 15 dB, to avoid the self-lasing oscillations.

To reduce the risk of this feedback, reflections can be limited. It is therefore recommended either to splice junctions or to use angled (APC) connectors throughout the fibre link.

The conclusion is that oscillations in the metrological channel that are significant enough to impact the data traffic should not occur in normal operational conditions.

5.2.2 Preventing Unwanted Lasing

Unwanted lasing as shown in Figure 5.8 can be detected using bi-directional EDFAs with Optical Spectrum Analyser (OSA). These analysers can be built in, as proposed in [HAV 2018]. However, methods based on Optical Channel Monitor (OCM) and/or OSA detect the lasing only when it occurs permanently and is intensive. In recent years, an approach has been investigated by CESNET and the Optoelectronics Research Centre, University of Southampton (ORC), based on monitoring of low frequency noise, which seems to be applicable to detection of even pre-lasing states.

For Coherent Optical Frequency (COF) transfer, it is crucial to obtain a clear beat note between the transferred signal back, reflected at the remote end, and the local oscillator. The resulting beat note is used primarily for cancelling Doppler noise [CIZ_2022]. [SLA_2022] shows how to heuristically detect lasing from beat note spectral analysis and how to optimise gains of bi-directional amplifiers to achieve the best beat note and long EDFA pump life. The setup for beat note evaluation (added to the setup used for Doppler noise cancellation) is shown in Figure 5.9 and Figure 5.10.

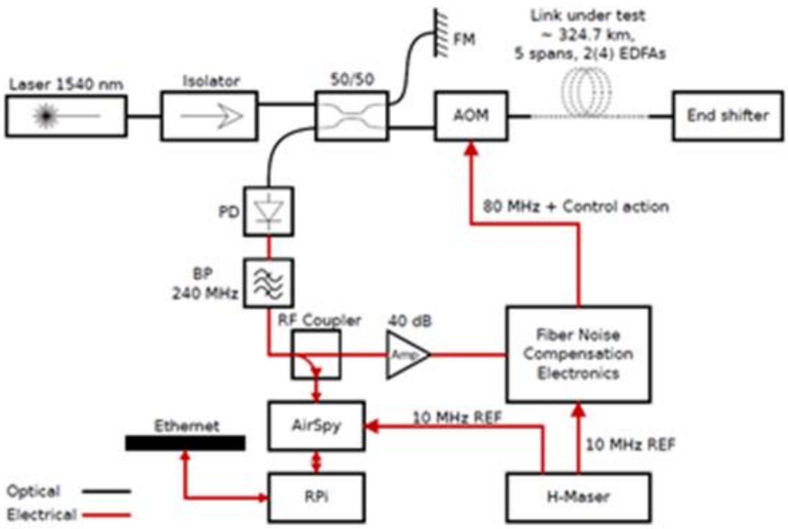

Figure 5.9: Hardware schematics of beat quality monitoring setup via RF tap and SDR on COF lines

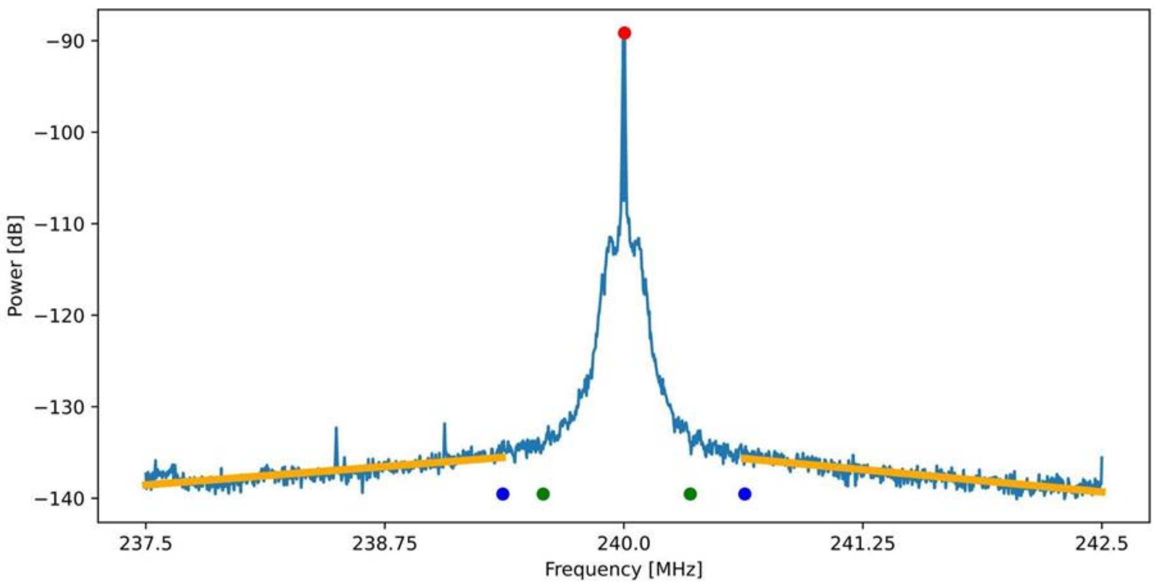

Figure 5.10: A beat note recorded after a 324 km round trip in an experimental testbed

The red circle in Figure 5.10 is the top of the beat note, while the green circles represent the peak's width and the blue circles are the tolerance from which the intervals (orange line segment) for noise analysis start.

5.3 Cross-Modulation

All widely used transmissions of precise time and radio frequency deploy amplitude modulation of the optical signal. In the case of a shared fibre, this unfortunately has a negative influence on parallel coherent data transmission. In CESNET, for services that need to be established immediately, precise time is transferred as "alien lambda" in a regular DWDM system (uni-directional transmission). Typically, wavelengths corresponding to channels 31–34 are used. Good practice shows that placing a White Rabbit signal (which corresponds to 1.25 GbE amplitude modulated signal) next to coherent channels can cause serious degradation of coherent channel performance and it is reasonable to allow at least 200 GHz guard bands relative to coherent 100+ Gbps transmissions to limit pre-FEC BER increase which happens with a low guard band. In Figure 5.11 below, taken from the live system, coherent channels are located in the left part of the spectrum, and WR non-coherent channels are located in the right part of the spectrum.

Figure 5.11: Spectral plot from Cisco NCS system showing parallel transmission of coherent 400G lambdas and WR signals within the DWDM

Within the scope of various experiments conducted in the operational PIONIER network in PSNC (Polish NREN), no negative influence on the data channels of the transfer of amplitude modulated T&F signals (ELSTAB system) as OC signals was observed. An example is the experiment realised in a 1500 km loop in the PIONIER network and presented in the article [TUR 2020]. During the conducted experiments, the operational interference of 100G channels was observed. In the presented case, metrological signals were transmitted as "alien lambda" in a separated spectrum (around channel 44) in an unmodified structure of the DWDM system (uni-directional transmission).

Within the TiFOON project [TiFOON], experiments were also conducted with hybrid system transfer (OC and ELSTAB signals placed in a single DWDM channel – ch. 44) using bi-directional transfer in a DWDM system (a metrological signal gated in each node and amplified by dedicated bi-directional amplifiers). The tests were conducted in a dedicated DWDM infrastructure but using real fibre optic cables. The test line consisted of two sections of 65 km and 110 km and also included Raman amplifiers. In parallel to the metrology signals, 200G and 100G data channels were transmitted (as in Figure 5.12).

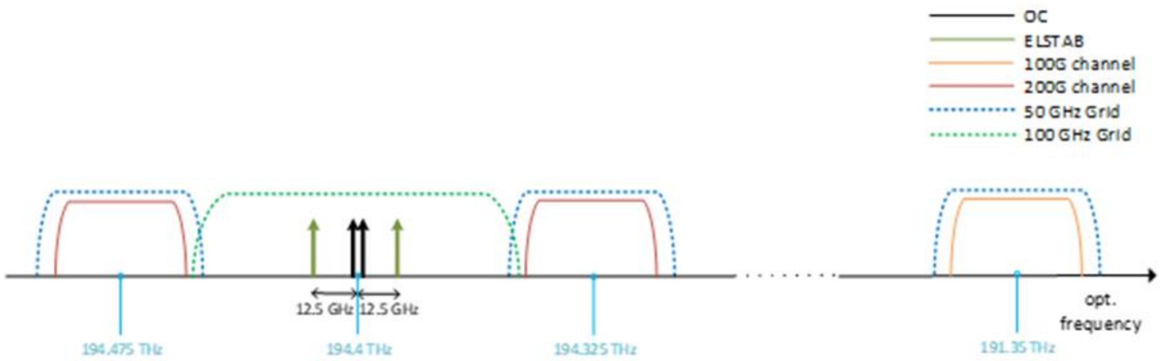

Figure 5.12: Placement of tested metrological signals and data in the optical spectrum

Despite the fact that the metrology and data channels were adjacent to each other (no guard band), no cross-interference of the transmitted signals was observed. Of course, this applies to a "normal" situation where the power levels of the metrological signals are not too high and there is no amplifier lasing phenomenon as described in Section 5.2. Undoubtedly, the selection of appropriate power levels must be made by a qualified network engineer taking into account the specific configuration of a given DWDM system operation.

5.4 Cohabitation of Raman Amplifier with Bi-Directional Signals in the Network

One of the main concerns regarding bi-directional signals cohabitating with data networks is when high-powered T&F signals (at the output of bi-directional amplifiers, around 3 dBm) are amplified with Raman pumps, which are usually installed to cope with very long distances.

Most telecommunication systems use fibres in a uni-directional way, i.e. the data signals propagate in only one direction in the fibre, to prevent interactions between two signals propagating in opposite directions. Raman pumps are usually implemented in a counter propagation setup, meaning at the end of a span with low-power incoming signals that are to be amplified thanks to Raman gain.

For cohabitation with bi-directional signals, a co- or counter propagation setup is not applicable, as the metrological signals are propagating bi-directionally in the fibre (see Figure 3.1).

In many solutions the transmitted T&F signal has a very small spectral width, and in many cases it is an advantage. However, these ultra narrowband signals are prone to Stimulated Brillouin Scattering (SBS).

If such a narrowband signal is co-propagating together with a Raman pump signal, it is therefore "more likely" to induce a backscattered signal SBS shifted by about 11 GHz from the spectrum of the main signal. The high level of SBS (caused by the very high power level of the T&F signals co-propagating with the Raman pump) leads to significant Rayleigh scattering – this time co-propagating with the

Raman signal and amplified by it again. This signal in turn generates a second order of SBS (shifted once again by 11 GHz) etc. (see Figure 5.13).

The result is an optical pseudo-comb whose distortions extend mainly towards longer wavelengths of light (towards the L band).

In this case the data signals (of neighbouring channels) can also be affected, so special attention should be paid to the level of the T&F signal co-propagating with the Raman signal.

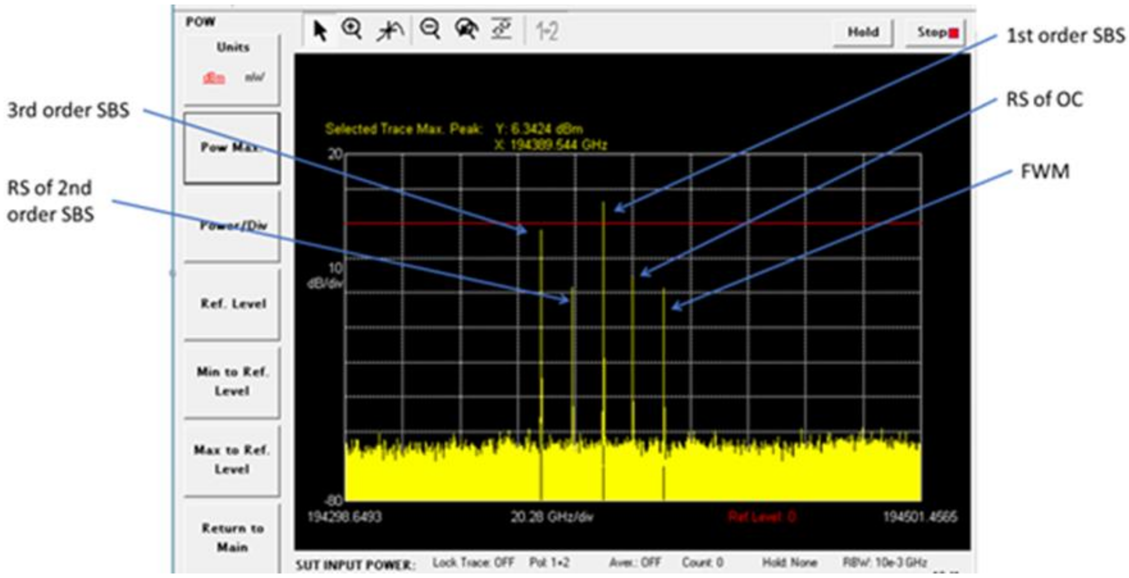

Figure 5.13: The effect of an optical comb caused by too high level of optical carrier (OC) signal co-propagated with a Raman pump signal. RS – Rayleigh Scattering, SBS – Stimulated Brillouin Scattering, FWM – Finite Wave Mixing.

The generation of undesired combs has been investigated in depth in the CLONETS public Deliverable D1.3, *Best Practice Guide "Alien Wavelength Services"* [CLONETS_D1.3].

[RAD_22] presents a clear comparison between generation of Brillouin products by high power at the output of bi-directional amplifiers and generation of additional spectral components via Four Wave Mixing (FWM), where thresholds are lowered due to Raman pumping, as can be seen in Figure 5.14 and Figure 5.15. In the laboratory, the increased sensitivity of Non Zero Dispersion Shifted Fibres (NZDSF) fibres (according to ITU-T G.655 [ITU-T_G.655]) to these effects has been shown.

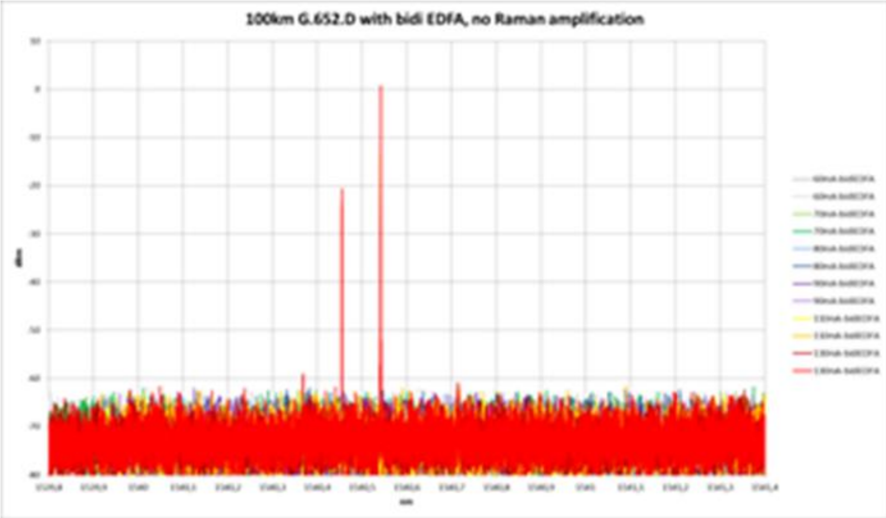

Figure 5.14: Two sidebands formed via SBS when EDFA output is over a certain threshold of roughly 7 dBm for standard single-mode fibre (SMF)

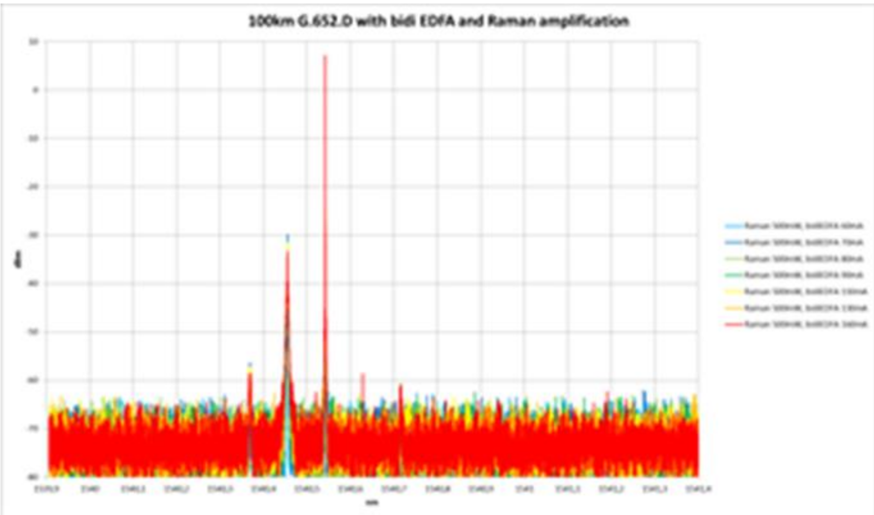

Figure 5.15: With active Raman amplification, other spectral products are formed via FWM

The Raman amplifiers are used in telecommunication as distributed amplifiers, as they amplify the signal in “the line” of the fibre. Therefore, they interact with both data signals and T&F signals. Consequently, from a management point of view, it is difficult to separate the T&F and telecommunication data operator functions in such a network. However, if such a separation of functions occurs, an effective exchange of information on the applied adjustments to the settings of both systems is strongly recommended.

5.5 T&F Equipment Shutdown Procedure

As stated in Section 4, the top priority of every NREN is the continuity of the service. Thus telecommunication networks are built with a high level of resilience to be able to cope with multiple incidents in the network, and very short guaranteed recovery times are contracted with fibre operators, which can go down to 4 hours for patching issues, for instance.

The procedures used by a NOC play a key role in troubleshooting, to help identify the root cause of incidents as fast as possible.

The RENATER teams have therefore discussed with the engineers in their NOC (which is currently outsourced to Computacenter) how the metrological signal is propagating in the network, its spectral power/frequency, the different pieces of T&F equipment and how this “non-standard signal” should be integrated into the existing procedures (see Figure 5.16).

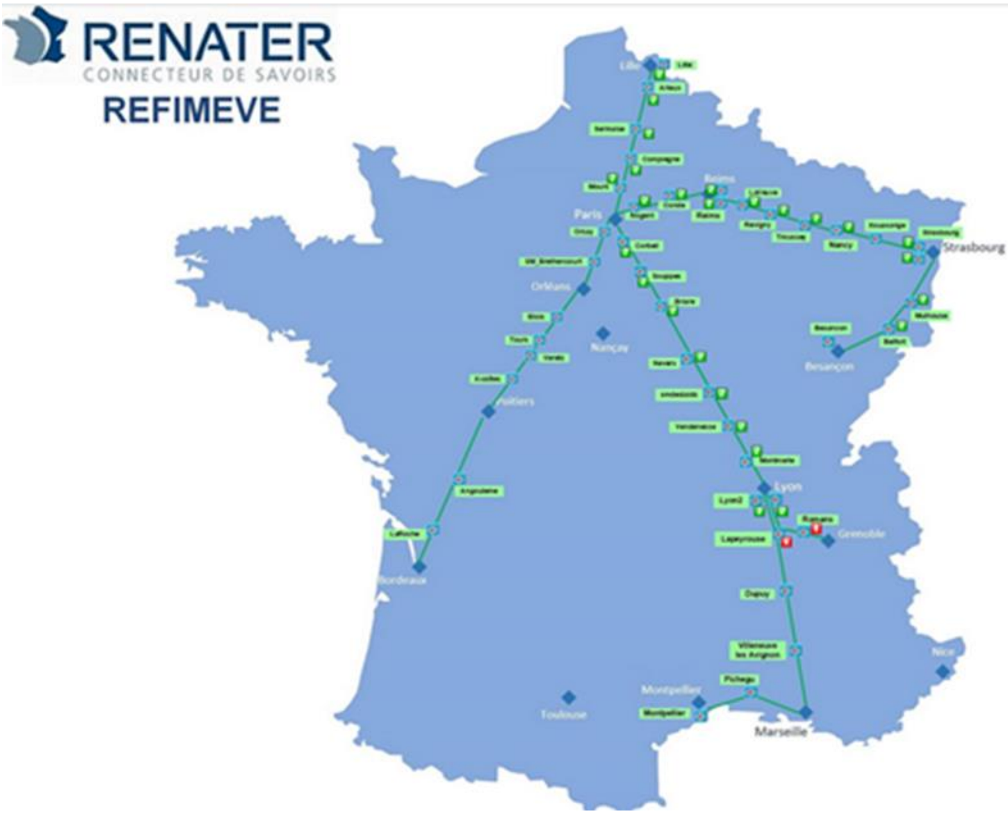

Figure 5.16: The RENATER NOC has a dedicated weather map for the French metrological network

The NOC engineers can easily monitor all optical equipment through SNMP v2 or v3 (see Figure 5.17) to highlight the main parameters described in Section 4.1.2.

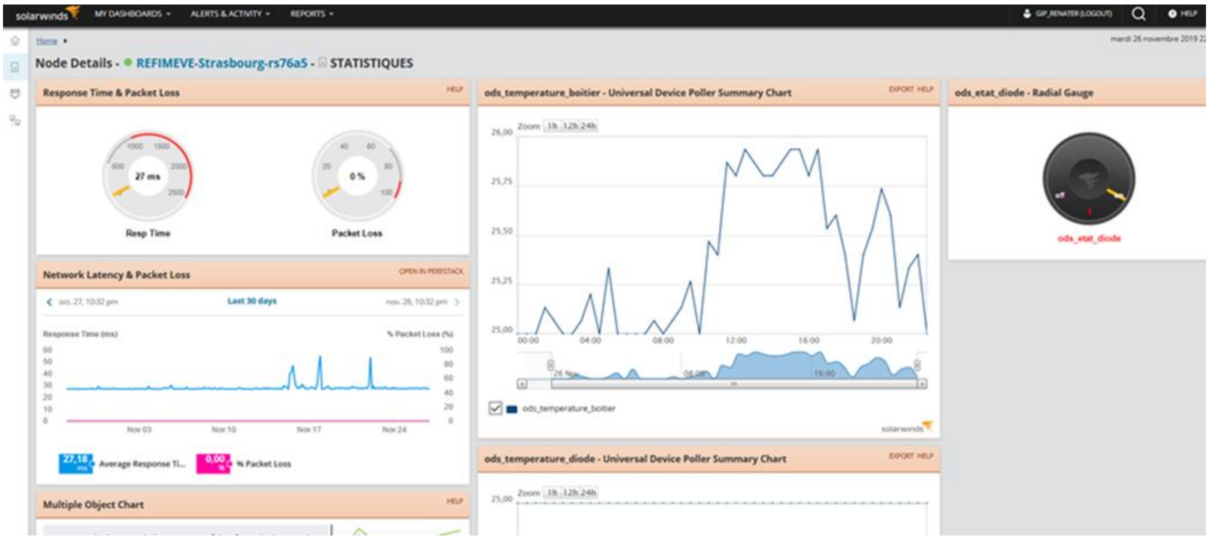

Figure 5.17: RLS monitoring by the RENATER NOC in Strasbourg (laser diode state at the top right)

The shutdown procedure followed by the NOC when T&F signals are cohabiting with data traffic is shown in Figure 5.18.

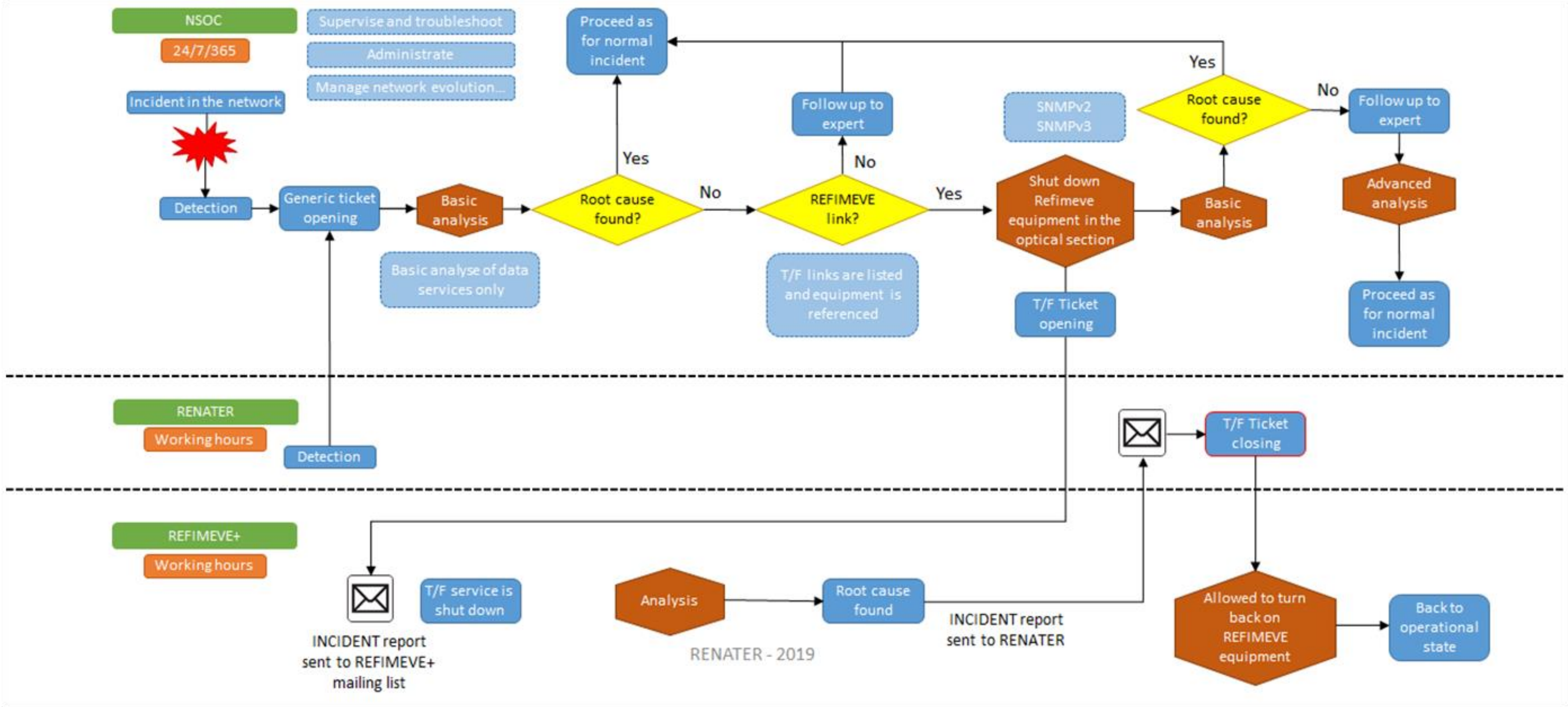

Figure 5.18: The NOC shutdown procedure when T&F signals are cohabiting with data traffic

It should be noted that this procedure has only been used once in the past 4 years (the NOC had to shut down 3 amplifiers and 1 RLS for 5 working days) but it is very important that the procedure exists as it guarantees that any NOC is easily able to get used to dealing with the T&F “unknown” equipment in a standard telco network and to quickly revert to a situation where all T&F equipment is shut down, meaning telco standard procedures can be executed.

In France, the NOC is able to shut down all active metrological equipment if necessary and it was decided that only the core Refimeve+ team will be responsible for setting up and turning on metrological equipment.

In practice, unlike data transmission devices, some T&F devices such as the WR-LEN adapter that produce metrology signals do not support remote shutdown of the optical output. This issue can be handled by installing an external shutter on the output port, or by shutting off the pumps of the bi-directional amplifier that is closest to the WR switch or adapter, as unpumped EDFA amplifiers exhibit large attenuation as shown in Figure 5.19.

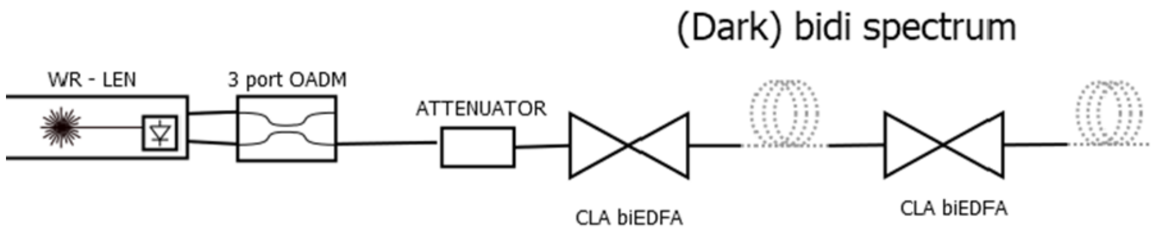

Figure 5.19: WR shutdown on bi-directional channel via the nearest attached bi-directional EDFA

6 Conclusions

Transmitting time and frequency services in networks focusing primarily on data transfer requires strong collaboration with the institutions generating reference T&F signals (most often these are national metrology institutes). Bi-directional signal transmission in a single fibre is often a significant technical challenge that raises concerns about the quality of transmitted data signals. This makes commercial telecommunication operators reluctant to implement services of this type, even though more and more scientists and individual sectors of the economy require high-quality T&F signals. This is undoubtedly a space for NRENs to both meet customer expectations and develop new standards and technical solutions that guarantee the high robustness of transmitted signals.

Despite the considerable reluctance of operators and doubts relating to the implementation of T&F transfer services in telecommunication networks, there is growing evidence from deployments to date that safe implementation of T&F services is possible. Among the important aspects that should be considered when deciding to implement such a service are:

- Guaranteeing effective cooperation and information exchange procedures between the NOC of the network operator and the institution generating T&F signals.
- Selection of an appropriate T&F transfer solution suited to the current and future needs of users and to the possibilities of implementation in a given optical network.
- Maximum reduction of the number of connectors with flat polishing (being the source of significant reflections) in those network fragments where the signal is transmitted bi-directionally.
- Taking special care when implementing bi-directional EDFA amplifiers. This is even more important on lines equipped with Raman amplifiers.

From the examples described in this paper, it also seems that NRENs are able to guarantee comprehensive management and monitoring of T&F distribution systems and support for end users. Continuously developed systems of this type ensure the monitoring of a growing set of parameters enabling identification of the location and cause of any malfunctions.

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Glossary

ACC	Automatic Current Control
AGC	Automatic Gain Control
AOM	Acousto-Optical Modulator
APC	Angled Physical Contact (fibre connectors)
APC	Automatic Power Control (amplifier control mode)
BER	Bit Error Rate
Bi-Di	Bi-Directional
CERN	European Organisation for Nuclear Research
CITAF	Czech Infrastructure for Time and Frequency
CLI	Command-Line Interface
CLONETS	CLOck NETwork Services project – Strategy and innovation for clock services over optical-fibre networks
CMOS	Complementary Metal Oxide Semiconductor
COF	Coherent Optical Frequency
DWDM	Dense Wavelength-Division Multiplexing
EDFA	Erbium-Doped Fibre Amplifier
EFTF	European Frequency and Time Forum
ELSTAB	Electronically Stabilised Time and Frequency Distribution System
FEC	Forward Error Correction
FWM	Four Wave Mixing
GbE	Gigabit Ethernet
GCC	General Communication Channel
GNU	GNU's Not Unix – free operating system software
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IL	Insertion Loss
ILA	Inline Amplifier
IP	Internet Protocol
ITU-T	International Telecommunication Union Telecommunication Standardisation Sector
L*n*	Layer *n*
MIB	Management Information Base
NCS	Network Convergence System
NMI	National Metrology Institute
NOC	Network Operations Centre
NREN	National Research and Education Network
NZDSF	Non Zero Dispersion Shifted Fibres
OADM	Optical Add/Drop Multiplexer
OC	Optical Carrier

OCM	Optical Channel Monitor
ORC	Optoelectronics Research Centre
OSA	Optical Spectrum Analyser
OSC	Optical Supervisory Channel
PDL	Polarisation-Dependent Loss
PMD	Polarisation Mode Dispersion
PoP	Point of Presence
PPM	Parts Per Million
PPS	Pulse Per Second
PSU	Power Supply Unit
PTP	Precision Time Protocol
Refimeve+	Réseau Fibré Métrologique à Vocation Européenne
RF	Radio Frequency
RLS	Repeater Laser Station
RS	Rayleigh Scattering
RSYSLOG	Rocket-fast SYStem for LOG processing
RU	Rack Unit
SBS	Stimulated Brillouin Scattering
SDR	Software-Defined Radio
SFP	Small Form Factor Pluggable
SFP+	Enhanced Small Form Factor Pluggable
SMF	Single-Mode Fibre
SNMP	Simple Network Management Protocol
SPEC	Simple PCIe FMC carrier
SSH	Secure Shell
SyncE	Synchronous Ethernet
T&F	Time and Frequency
TIC	Time Interval Counter
TiFOON	Time and Frequency over Optical Networks
TSDB	Time Series Database
TWSTFT	Two-Way Satellite Time and Frequency Transfer
Tx	Transmitter
UI	User Interface
USB	Universal Serial Bus
UTC	Coordinated Universal Time
VLAN	Virtual Local Area Network
VMUX	Virtual Multiplexer
VPN	Virtual Private Network
WP	Work Package
WP6	GN4-3 Work Package 6 Network Technologies and Services Development
WP6 T1	WP6 Task 1 Network Technology Evolution
WR	White Rabbit
WR-LEN	Competitive alternative to the White Rabbit Switch (WRS)
WR-SPEC	Kit, composed of two nodes, that operates as input time-stamping or programmable output pulse generator
WRS	White Rabbit Switch