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Engineering Rules for Bi-Directional Photonic Transport for a White-Rabbit Time and Frequency Transfer Service on Existing In-Service Infrastructure.

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Abstract

This document describes engineering and implementation rules for the bi-directional transport of White Rabbit Giga Bit Ethernet DWDM waves in a practical DWDM photonic transport network, commonly found in networks of NRENs and carriers. Solutions are provided for different implementations of the Optical Supervisory Channel and Line-Fibre

Interface Modules. We found that non-linear distortion in SOAs in combination with dispersion limits the transport distances to a conservative 800km.

I. COPYRIGHT NOTICE

II. DELIVERY SLIP

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III. DOCUMENT LOG

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IV. APPLICATON AREA

This document is a formal deliverable for the GA of the project, applicable to all members of the ASTERICS project, beneficiaries and third parties, as well as its collaborating projects.

V. TERMINOLOGY

A list of specific abbreviation related to this report can be found at the end of the document (pag. 44)

A complete project glossary is provided at the following page:
http://www.asterics2020.eu/glossary/

VI. PROJECT SUMMARY

ASTERICS (Astronomy ESFRI & Research Infrastructure Cluster) aims to address the cross-cutting synergies and common challenges shared by the various Astronomy ESFRI facilities (SKA, CTA, KM3Net & E-ELT). It brings together for the first time, the astronomy, astrophysics and particle astrophysics communities, in addition to other related research infrastructures. The major objectives of ASTERICS are to support and accelerate the implementation of the ESFRI telescopes, to enhance their performance beyond the current state-of-the-art, and to see them interoperate as an integrated, multi-wavelength and multi-messenger facility. An important focal point is the management, processing and scientific exploitation of the huge datasets the ESFRI facilities will generate. ASTERICS will seek solutions to these problems outside of the traditional channels by directly engaging and collaborating with industry and specialised SMEs. The various ESFRI pathfinders and precursors will present the perfect proving ground for new methodologies and prototype systems. In addition, ASTERICS will enable astronomers from across the member states to have broad access to the reduced data products of the ESFRI telescopes via a seamless interface to the Virtual Observatory framework. This will massively increase the scientific impact of the telescopes, and greatly encourage use (and re-use) of the data in new and novel ways, typically not foreseen in the original proposals. By demonstrating cross-facility synchronicity, and by harmonising various policy aspects, ASTERICS will realise a distributed and interoperable approach that ushers in a new multi-messenger era for astronomy. Through an active dissemination programme, including direct engagement with all relevant stakeholders, and via the development of citizen scientist mass participation experiments, ASTERICS has the ambition to be a flagship for the scientific, industrial and societal impact ESFRI projects can deliver.

VII. EXECUTIVE SUMMARY

This document provides a view on how SURFnet envisions the implementation and roll out of a Time and Frequency Transfer (TFT) transport service as described above. Considerations are given and preferred choices are motivated for the particular case of SURFnet. Where possible alternatives that may apply to networks of different NRENs are touched upon. This would allow other NRENs to copy the concept with little changes.

This document will focus on technical aspects required for engineering the links such that they can be used by the White-Rabbit [5] system.

This deliverable touches on the practical implementation of a Time and Frequency Transfer (TFT) transport service based on the White Rabbit concept. Because bi-directional transmission is not common in the telecommunications carrier community and at the same time it is desirable to have this TFT transport service implemented in a compatible fashion, several options have been outlined how this implementation can take place.

Analysis has been performed on the expected impact of different single mode fibre types and how this relates to dispersion compensation schemes and the resulting time transfer uncertainty.

A simulation tool has been developed for the purpose of simulating the impact of long cascaded Semiconductor Optical Amplifier (SOA) amplified spans with per span filtering. In order to make this a validated exercise the tooling is based on a tool set, which contains validated models used before to investigate the non-linear behaviour of SOAs. This has resulted in a quick and fast working tool which predicts around 800km of reach using a Giga Bit Ethernet (GbE) signals. The tool shows how transmission impairments accumulate and

confirm that the interaction of SOA induced non-linear distortion with chromatic dispersion, present in optical fibre, determines this 800km maximum reach (conservative estimate).

With 800km reach delivery of the TFT service between any two points in SURFnet's national network is possible.

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1 Introduction

1.1 Motivation and Scope

This document is written from the perspective of an NREN, such as SURFnet, who intends to offer a Time and Frequency Transfer (TFT) transport service to its customers and end-users (e.g. scientists). More and more frequently, scientists rely on accurate timing to perform high-quality research. This document aims to provide a view on the different aspects that come into play once such a transport service is to be created and delivered to a diverse set of customers, who are already connected to SURFnet's infrastructure. The requirements for a TFT service at the level of accuracy needed for the ASTERICS project (sub-nanosecond accuracy) differ significantly from the requirements for regular Internet data transport (microsecond accuracy). Key aspects to observe are bi-directional signal propagation and the transmission impairment, delays, and jitter, which impact the fidelity of the optical signal and can eventually have a negative impact on the performance of the TFT service. For this reason, implementation of a TFT service in an existing network infrastructure, designed for legacy Internet and Internet-alike services is far from trivial, Deliverable 5.1 of Work Package (WP) 5 has been devoted entirely to this task.

Because a time and frequency service is quite a niche service, it is not appropriate to include such a service as a generic service for all customers and users, but deliver this service to selected customers who are expected to contribute in terms of financial resources or in kind. For this reason, SURFnet can leverage its fibre infrastructure by allowing optical waves to propagate in the vicinity of the production waves in the C-band. In the past few years SURFnet has already explored the concept and considered it feasible.

The research aims of WP 5 of ASTERICS forms an illustrative example of a scientific use case requiring a fibre-optic TFT service. The engineering rules reported in this document are directly applicable to WP 5 of ASTERICS, and together they form deliverable 5.1.

1.2 Objective

This document provides a view on how SURFnet envisions the implementation and roll out of a Time and Frequency Transfer (TFT) transport service as described above. Considerations are given and preferred choices are motivated for the particular case of SURFnet. Where possible alternatives that may apply to networks of different NRENs are touched upon. This would allow other NRENs to copy the concept with little changes.

This document will focus on technical aspects required for engineering the links such that they can be used by the White-Rabbit (WR) [5] system. SURFnet considers the WR platform a suitable candidate because it originated from the research community and is based on Ethernet, a well-known protocol to SURFnet. The documented and free to use WR concept has resulted in commercial spin-offs offering mature hardware platforms.

1.3 Structure

Chapter 2 will provide a brief description of the fibre infrastructure and transport system used by SURFnet. The description will be as generic as possible for other operators to relate to when considering a similar roll-out of a TFT service.

This document is not about the service parameters of the TFT service, but on the optical performance of the signals carrying the TFT service. Chapter 3 will describe the requirements the TFT service imposes on the photonic bi-directional transport of the waves. The equipment is currently under design; hence generic specifications will be used. At a later stage these specifications can be adjusted and the link engineering rules adapted. Adjustments and changes to the engineering rules are considered minor as the transmission technologies are mature.

Chapter 4 will describe the engineering rules. Chapter 4 will detail on the way link design is optimized and explains the impact and placement of functional components such as amplifiers, dispersion compensation modules, optical-electrical-optical regenerators (time and frequency unaware) and service termination equipment used for service delivery and regeneration on a service level (time and frequency aware).

In Chapter 5 some additional requirements will be listed that may not be present in the first release of the service and equipment. These requirements can be considered recommendations for equipment and software features in the future. A summary and outlook is given at the last section of this chapter.

2 Fibre and Transport Infrastructure.

2.1 Fibre Infrastructure

SURFnet operates two networks: one network is the national production network and the other network is composed of three Cross-Border Fibres (CBFs) running from Amsterdam to Hamburg, London, and Geneva.

SURFnet's fibre infrastructure is based on long-leased dark fibre. The fibre adheres to the G.652 [2] standard for Standard Single Mode Fibre (SSMF) also known as Non Dispersion-Shifted Fibre (NDSF) and the G.655 [4] standard for Non-Zero Dispersion Shifted Fibre (NZDSF). Because the dark-fibre is of all ages both .A, .B, .C, and .D types of both standards can be expected. Only on the Amsterdam Geneva CBF, so-called Zero-Dispersion Shifted (ZDSF) has been deployed, according to G.653.B

Fibres terminate in optical distribution frames (ODFs) situated in a rack of the operator, close to the transmission equipment or in a Meet-Me-Room (MMR). In the first case approximately 0.5dB of extra losses must be accounted for. In the latter case excess loss can amount to 1.5dB depending the complexity of patching between MMR and ODF in the operator's rack.

In the remainder of this document the following assumptions are made:

- Loss of the optical fibre amounts to 0.25dB/km.
- Chromatic Dispersion profile is according to the applicable standard of the fibre span. Subsection 0 discusses the chromatic dispersion and dispersion slope compensation.
- Polarization Mode Dispersion (PMD) is 0.5ps/km$^{0.5}$
- Fibre non-linearity is assumed absent. This is only valid when fibre launch power is low and the spectral distance of the White-Rabbit GbE channels to the production channels in the C-band is relatively large. This distance amounts to approximately 20nm. Walk-off between different waves and the reduced non-linear interaction results in Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM) to manifest themselves as lower order impairments compared to Chromatic Dispersion, and Amplified Spontaneous Emission introduced by the loss-compensating optical amplifiers.
- Average ODF loss: 1dB.

2.1.1 Chromatic Dispersion and Dispersion Slope Compensation

Managing dispersion in an optical link is required to guarantee the signal's optical fidelity at the receiving end. Avoiding inter symbol interference (ISI) and dispersion penalties is normal practice. In general the services build on top of the transport layer do not depend on the amount of chromatic dispersion as long as the dispersion does not cause the underlying transport service to introduce transport errors. In the case of the TFT service dispersion is an issue as it causes asymmetry between the two counter propagating waves. Although both waves could be assigned the same wavelength, this would lead to a very rapid reduction of optical signal fidelity caused by scattering and reflection on for example connectors and splices. Hence two different wavelengths must be used. Chromatic dispersion causes one wavelength to traverse the same medium in a different time compared to the other counter propagating wave. The difference divided by two contributes to the error introduced in the replicated time.

Chromatic dispersion is deterministic in nature, but it may randomly vary from fibre to fibre due to small differences in production parameters such as glass composition and geometric variables. As a result, the G.652 and G.655 standards specify a chromatic dispersion interval for an optical fibre. Table 2-1 shows chromatic dispersion parameters of G.655 and G.652 fibre types. The seventh column shows the expected uncertainty when transferring time, assuming the average delay is compensated for by configuring this on the White Rabbit Equipment. From this table several observations can be made. G.655 fibre has changed over time in terms of dispersion profiles. The reason for this is that the old fibre (A, B, and C) types were made in times with consensus that optical links must have as little dispersion as possible. Later it was found that dispersion is important in mitigating or avoiding non-linear deterioration of optical signals. Hence type D and E have higher dispersion values and much more control exists over the production environment. The latter reflects in a lower uncertainty for the time transfer application. Still, the uncertainty is large and mainly caused by the variations in rare-earth concentration in the optical fibre to synthesize the desired dispersion profile and guaranteeing low loss and optical confinement. G.652 is the most conventional fibre and requires little synthesis of the dispersion profile, hence there is much more accuracy and agreement between fibres produced by different manufacturers. The most significant variation can be found in the zero-dispersion wavelength. For this reason, G.652 introduced the lowest dispersion uncertainty, which is more than a factor of 20 better than dispersion synthesized fibres.

Type of Fibre	Min. Dispersion @1511nm [ps/nm/km]	Max. Dispersion @1511nm [ps/nm/km]	Average Dispersion @1511nm [ps/nm/km]	Min. Delay difference @ 50GHz [ps/km]	Max. Delay difference @ 50GHz [ps/km]	Worst case uncertainty per 100km [ps]	Comment
G.655.D	-0.233	4.939	2.353	-0.089	1.882	98.6	
G.655.E	3.711	7.295	5.503	1.414	2.779	68.3	
G.655.A,B,C	-3.655	3.881	0.113	-1.393	1.479	144	no standard, data used from vendor
G.652	14.70	14.93	14.81	5.601	5.643	2.1	

Table 2-1: Overview of dispersion parameters for G.655 (non-zero dispersion shifted fibre) and G.652 (non dispersion-shifted fibre or standard single-mode fibre)

Table 2-2 shows two examples of the potential impact of dispersion-slope compensating modules (DSCM) inserted in the link. In this example a 100km module was used to compensate 100km of G.655.D and G.652 fibre. DSCM fibre is fibre with high doping in order to create negative dispersion and a negative dispersion slope in order to compensate dispersion across a wide range of optical wavelength. Using DSCM relaxes the dispersion penalty encountered by the receiver and for this reason it is used as soon as the total dispersion in a link increases to a level close to the receiver dispersion tolerance. From the 7th column of Table 2-2 it can also be observed that introduction of dispersion slope compensation has a worsening effect on the time uncertainty when using G.652 fibres, where dispersion is the highest, while it could have a positive effect when using G.655.D fibres, where dispersion is the lowest and compensation might not be required for waves with low-speed modulation of up to 1GbE (as is the case for White Rabbit (WR) transmission).

Type of Fibre	Min. Dispersion @1511nm [ps/nm/km]	Max. Dispersion @1511nm [ps/nm/km]	Average Dispersion @1511nm [ps/nm/km]	Min. Delay difference @ 50GHz [ps/km]	Max. Delay difference @ 50GHz [ps/km]	Worst case uncertainty per 100km [ps]	Comment
G.655.D	-1.60	-0.724	1.16	-0.610	-0.276	14.9 to 141	
G.652	-14.82	-13.92	-14.36	-5.64	-5.30	3.7 to 14.0	Derived from a 100km DSCM module

Table 2-2: Effect of dispersion-slope compensating modules on the time transfer uncertainty

The overall conclusion is that dispersion slope compensation is not trivial and that in the case DSCM modules are part of the actual span, and not part of the nodes, it should be left in place for G.655 fibre and moved from the span into the node for G.652 fibres.

2.2 Transport Infrastructure of Main C-band Transport Services

This section describes the current photonic system implemented in SURFnet's network. Photonic systems of different make can in most cases be mapped to the architectures outlined in this section. Such systems operate in the C-band and support 88 or more wavelength channels, spaced 50GHz apart. Differences exist in the way supervisory channels are implemented and optimization of the channels is implemented (algorithm and performance).

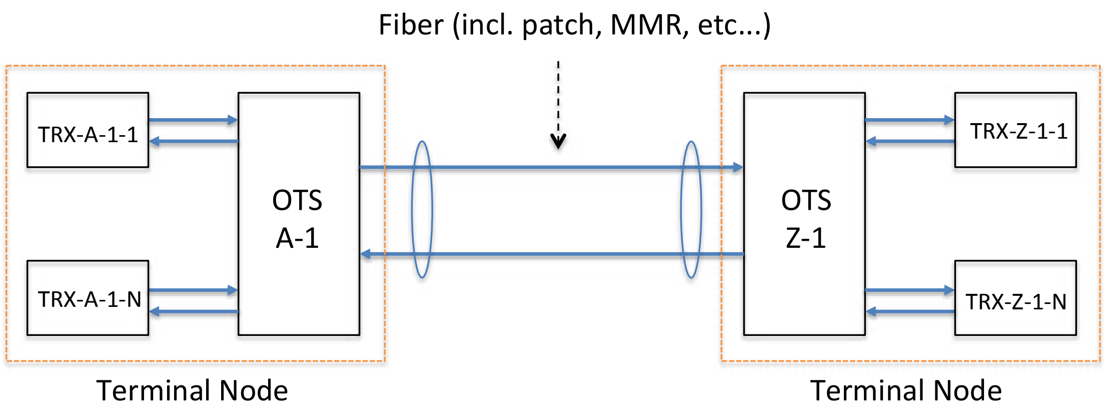

Figure 2-1. Simple Point-to-Point link

Figure 2-1 shows an optical span, which is part of a basic point-to-point link. Such a link is composed of an optical transport section (OTS) at both the A and Z end. OTS-A-1 is connected to OTS-Z-1 by means of an optical fibre infrastructure. To this end each OTS contains a line-fibre interface module (LIM), which interfaces to this infrastructure. The line fibre relies not only on optical fibre, but may include the optical transmission fibre (line fibre), patch cables, and if applicable Meet-Me-Room (MMR) connectivity. To OTS-A-1 and OTS-Z-1 transceivers (TRX-A-1-1, TRX-A-1-N, TRX-Z-1-1, and TRX-Z-1-N) are connected. The transceivers connect to add and drop facilities that are part of the OTS. The OTS is responsible for connecting TRX-A-1-1 to TRX-Z-1-1 and TRX-A-1-N to TRX-Z-1-N such that point-to-point communication between each pair of transponders becomes possible.

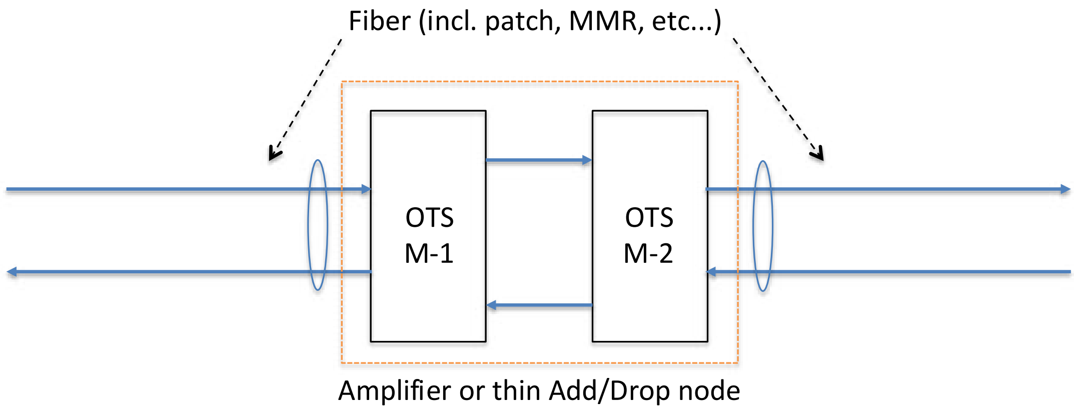

Figure 2-2. Amplifier connected by to line fibres. A similar configuration can also be used as a simple add and drop configuration (Transceivers are not drawn).

Figure 2-2 shows an in-line optical amplifier or simple add and drop node. Two OTSs terminate the line fibre and are interconnected to maintain an optical path. Depending on the desired functionality and fibre parameters a certain amplifier configuration has become part of OTS-M-1 and OTS-M-2.

A third special node is called a reconfigurable add and drop node, also referred to as a ROADM (Figure 2-3). In the ideal case (when routing between any arbitrary set of two line fibres is required) each OTS is connected to the other OTSs that are part of the node.

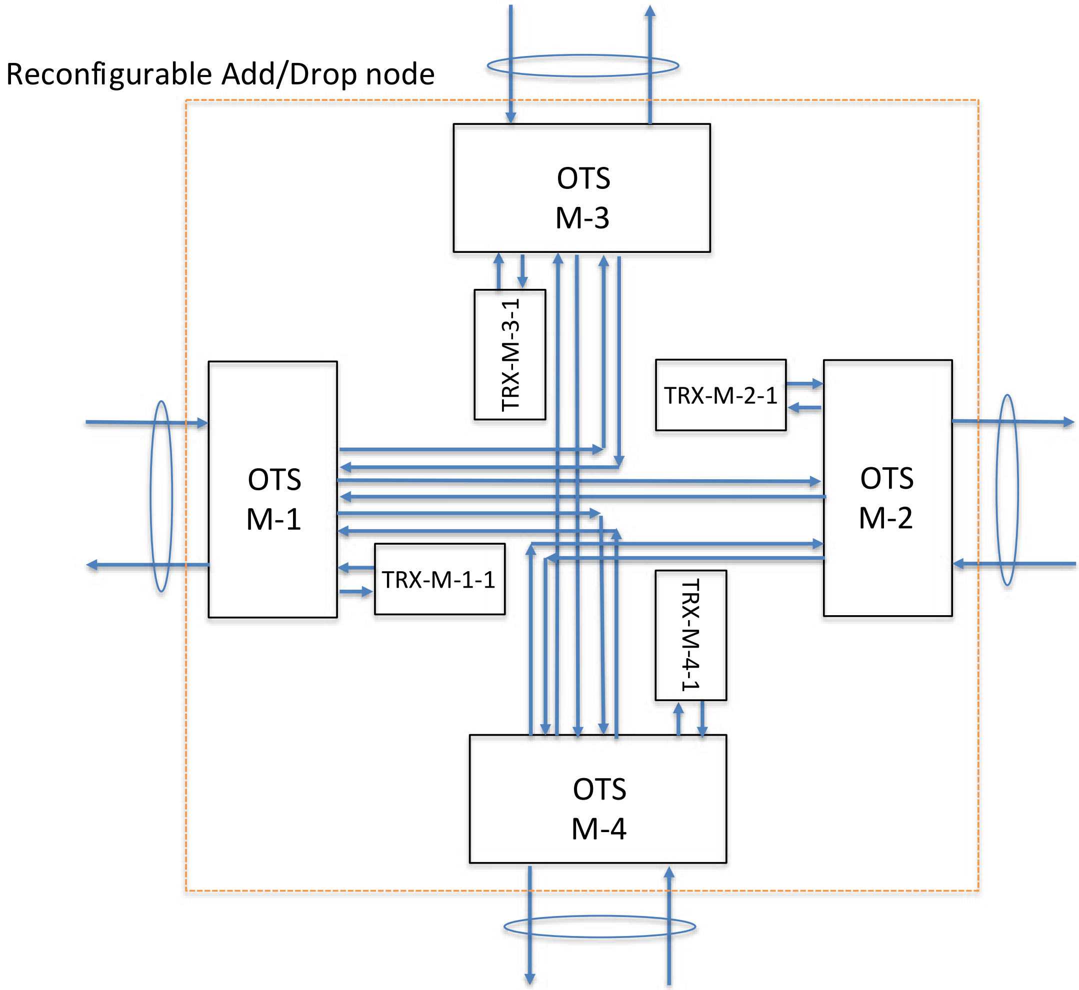

Figure 2-3. Reconfigurable add and drop node. In this picture each OTS has been equipped with a transceiver. This node allows waves to be routed between line fibres and therefore functions as an optical cross connect.

In this case the composition of the OTS-M is different compared to the OTSs of Figure 2-1 and Figure 2-2 as these optical termination systems must be equipped with wavelength selective switching technology to allow for photonic routing between line fibres.

In the remainder of this section it is important to understand the basic elements of an OTS that play a role when rolling out a time and frequency transfer service conform.

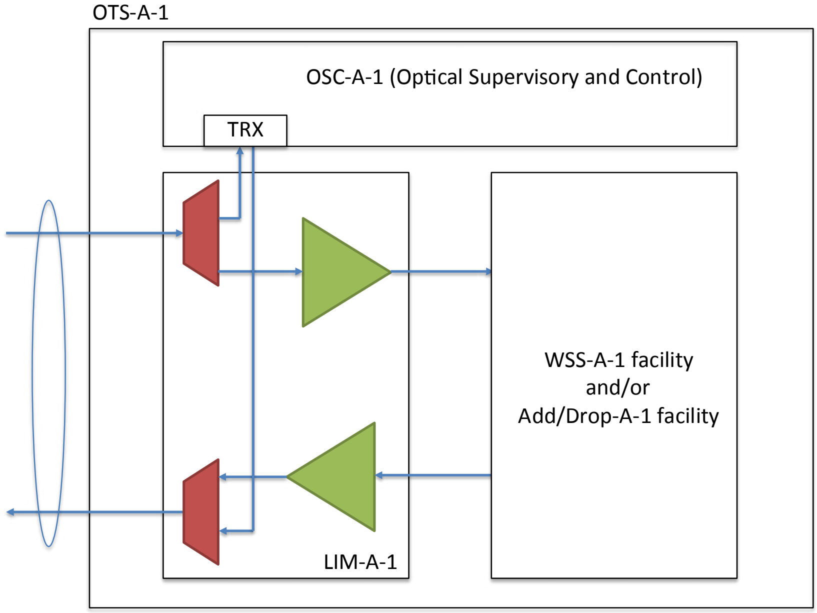

Figure 2-4. Schematic of an OTS. In this picture the Line Interface Module (LIM) is composed of two EDFAs, a pre-amplifier and a booster. Each OTS has a unit used for Optical Supervision and Control.

The network of SURFnet uses Dispersion Slope Compensating Modules to counter the transmission impairment caused by a wavelength dependent propagation of 10Gbps Non-Return-to-Zero modulated Amplitude Shift Keyed (NRZ-ASK) carriers, which causes the optical signal to suffer from ISI.

DSCM modules can be placed in front of the OTS or as a part of the OTS. In the first case, the DSCM module can be regarded as part of the fibre infrastructure and both the C-band production waves as well as the TFT bi-directional waves undergo dispersion compensation. In the latter case, the DSCM only acts on the C-band signal and not on the TFT bi-directional signals as these signals are routed around the OTSs. This is explained in the next Section 0

2.3 Adding and dropping of White Rabbit signals

This subsection touches on architectures for adding/dropping two bi-directional waves onto each fibre of the fibre pair of a span. The architectures take into account the different possibilities that may be used by the vendor of the photonic system to implement the line interface modules and interfacing to the Optical Supervisory Channel (OSC). For each case a short discussion is given on the implications with respect to interoperability

2.3.1 Case 1, fully separated OSC and LIM

Figure 2-5 shows an implementation where the vendor has chosen to implement the OSC as a physical different module than the LIM. This means the OSC channel needs to be exchanged between the OSC and the LIM. This is done by means of a patch cord. In such a case the White Rabbit (WR) terminal including all optics to extract the WR waves can be placed between the OSC and the LIM. Because the WR signals are in the same Course Wavelength Division Multiplexing (CWDM) band as the OSC channel (usually one uses CWDM multiplexers for this purpose because the OSC channel is not as wavelength accurate as a Dense Wavelength Division Multiplexing (DWDM) signal) the OSC channel must be converted to a wave of which the wavelength is much better defined such that it can be added and dropped together with the WR signals in a DWDM multiplexing structure. To this end the OSC channel is regenerated as a DWDM wavelength for the TX direction only. This automatically implies that on the remote end of the span the OSC will receive a DWDM TX signal instead of a CWDM signal. Generally speaking, this will not be an issue as CWDM receivers and DWDM receivers show the same optical bandwidth and these signals are not amplified (ASE-signal and ASE-ASE beat noise). The advantage of this system is that the OSC always measures the correct received OSC power. A disadvantage is that the OSC transmit power is determined by the transmitter of the DWDM regenerator and is not measured. This may lead to problems when the controller of the photonic transport system calculates the span loss of a section and uses this information in its algorithms or for sending alarms. A failure of the OSC laser results in a loss of signal at the receiver of the regenerator and this can be detected to switch off the regenerating transmitter as well. A failure of the regenerating laser may not be detected by the OSC, however it must be noted that there are also a number of scenarios where the OSC laser may be defected and this not being noticed by the near end OSC controller.

The biggest advantage of this architecture is the possibility to insert the White-Rabbit Add/Drop Facility without breaking the optical path of the DWDM payload carrying waves. When installing the WR equipment only the OSC will fail and these alarms can be ignored. A properly designed state of the art photonic light system will continue to function, although certain functions and features may not work properly (such as optimization and add/dropping of payload carrying waves). As the introduction of the WR equipment takes only a few minutes, limited inconvenience is to be expected and therefore no ticketing is required.

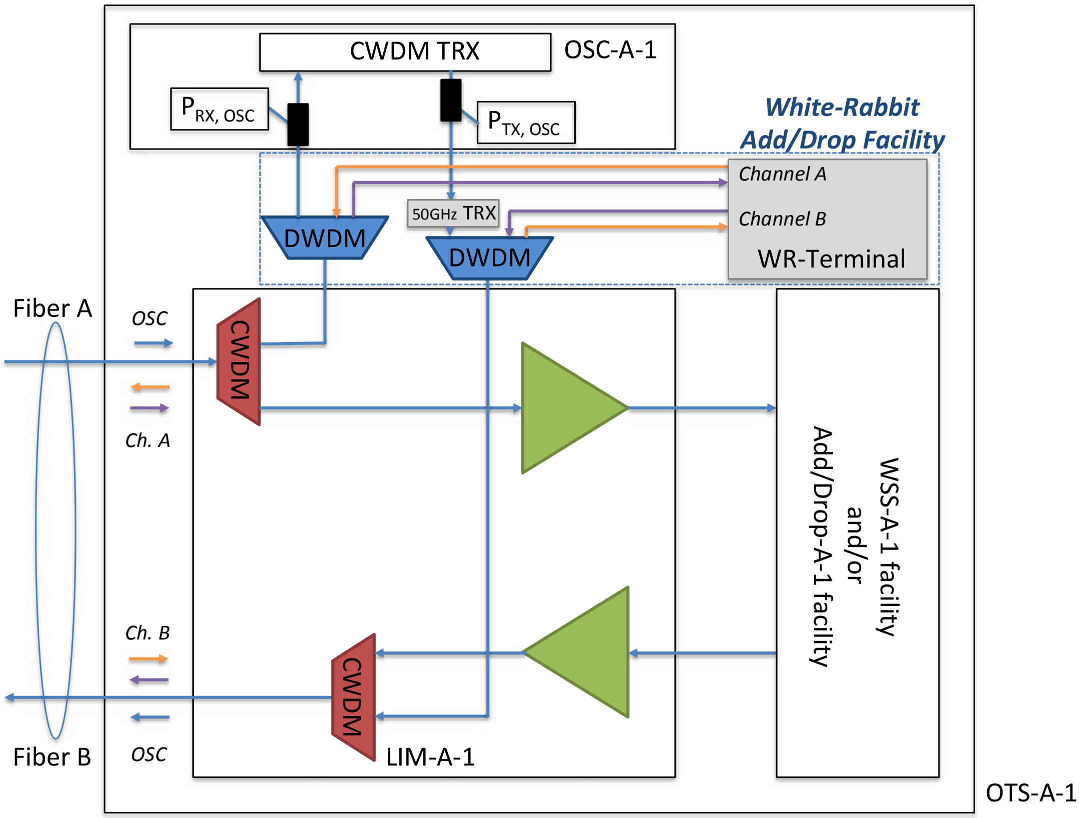

Figure 2-5. Example of an OTS where the optical supervisory channel (OSC) is not terminated on the LIM but on a different OSC module, providing access to WR channels that can be placed in the same CWDM band, which also accommodates the OSC channel. In this example the power measurements of the OSC channel (TX and RX) has been implemented on the OSC unit.

2.3.2 Case 2, partially separated OSC and LIM

In this case the Optical Supervisory Channel (OSC) is terminated on a separate OSC module, however the photonic light system still relies on LIM module for measuring received and/or transmitted power. There are systems where only the OSC RX power is measured because the TX power is controlled to a fixed value by the OSC transmitter module. An example of a partially separated OSC and LIM is depicted in Figure 2-6. In this concept, there is a problem concerning the received OSC power in the LIM unit. $P_{RX,OSC}$ also contains the ingress WR signal of Channel A. Hence it may happen that the far end OSC laser fails and that this is not detected in $P_{RX,OSC}$ because of the still present WR signal. Moreover, if the photonic system's control algorithms rely on a properly measured received OSC power, unpredicted behaviour and associated instabilities may occur. It may be required to instruct the Network Operations Centre (NOC) to also take OSC signal degrade alarms seriously as these alarms must now be interpreted as a possible OSC fail (The RX port on the OSC TRX will issue a loss of signal in case the OSC fails). Span loss cannot be verified against OSC channel reported power levels.

Also in this case the added value of this solution is that introduction and repairs of the WR equipment can be made without interrupting the optical path and therefore the paid services.

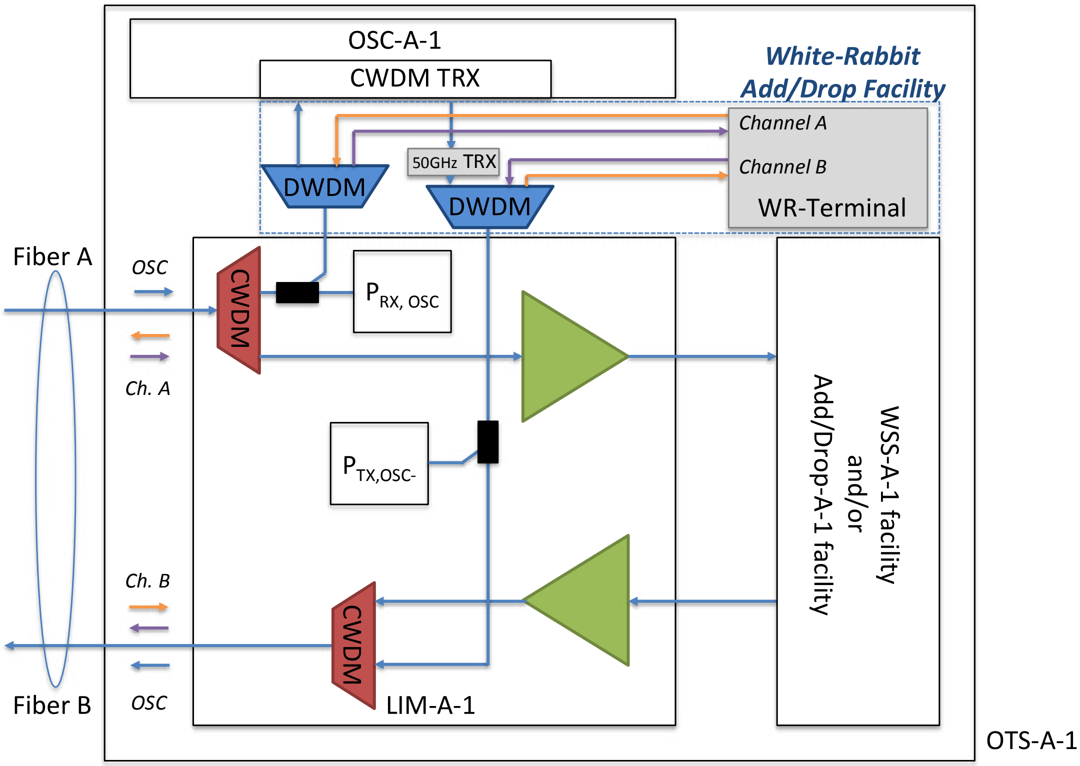

Figure 2-6. Example of an OTS where the optical supervisory channel is not terminated on the LIM but on a different OSC module, providing access to WR channels that can be placed in the same CWDM band, which also accommodates the OSC channel. In this example the power measurements of the OSC channel (TX and RX) has been implemented on the LIM.

2.3.3 Case 3, fully integrated OSC and LIM onto a single unit

Figure 2-7 depicts the case where the OSC channel is terminated at an integrated OSC function on the LIM unit. In this case there is no possibility to access the OSC channel optically other than by accessing the line fibres A and B. This means that the optical path of the paid services is interrupted. In this case adding and dropping the WR signals can only be accomplished by inserting an optical multiplexer in fibre A and B. It is recommended to place the WR waves in a different part of the spectrum such that the OSC channel is not affected.

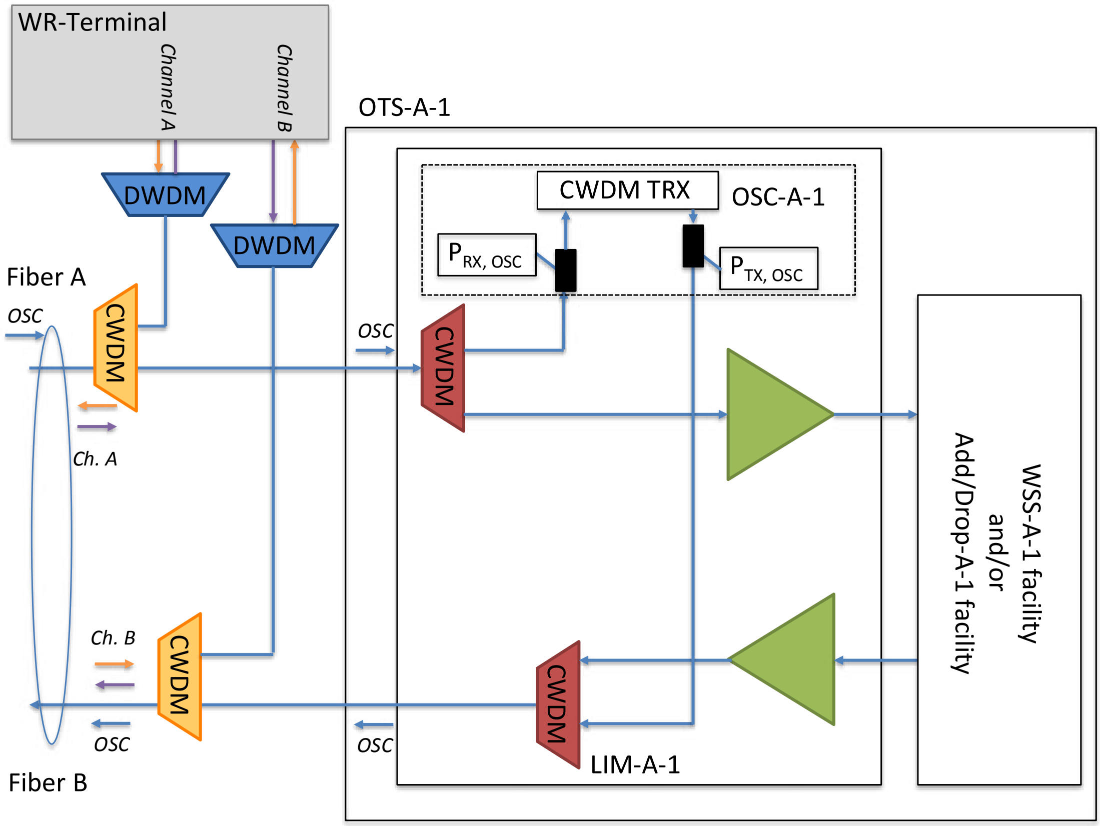

Figure 2-7. Example of an OTS where the optical supervisory channel is terminated on the LIM prohibiting access to WR channels that must now be added and dropped in a CWDM band of their own. In this example it is no longer relevant where OSC TX and RX power are measured.

The disadvantage of this method is that the span loss, as experienced by the paid services, becomes higher by an amount equal to twice (near- and far-end) the pass-through insertion loss (IL) of the CWDM module.

This configuration is however the most universal configuration and can always be designed around any existing photonic system.

3 TFT Service and Transport Requirements.

3.1 TFT-Service

The TFT service is to be implemented using the White-Rabbit Precision-Time-Protocol (PTP). This protocol runs over Gigabit Ethernet (GbE) and exchanges timing information with both and A and Z node. In order for his service to run reliably two conditions must be met from a transport point of view:

1. The GbE signals must be received with sufficient performance in order for the WR protocol to consider the link error-free.
    a. This means that between transmitter and receiver the total encountered dispersion (in either direction) must be less than what can be tolerated by the transceivers.
    b. Receive power levels at the receiver must be sufficient to guarantee proper receiver operation. Too low receive power implies the thermal noise of the receiver will cause errors. Too much power and the receiver is overloaded or even damaged.
    c. Fibre launch powers must be moderate in order not to induce fibre non-linearity manifesting themselves via SPM, XPM and FWM.
    d. In case optical amplification is used the total amount of noise accumulates and causes the high optical signal to noise ratio at the output of the laser to deteriorate along each span of the link. At the receiver the impact is similar to a low power input signal when the Optical Signal to Noise Ratio (OSNR) has degraded below a certain threshold.
    e. In case optical amplification is implemented using Semiconductor Optical Amplifiers (SOA), optical signals may distort because of the saturating properties of SOAs. Saturation is caused when an NRZ-ASK signal changes from “0” to “1”. During the amplification of a “0” (“0” is mapped to zero or very little optical power, a “1” is mapped to a high level of optical power) the amplifier does not need to convert its excited electrons to its non-excited state as no photons are present in the active layer to be amplified. When the amplifier needs to amplify the beginning of a “1” gain is maximal (amplifier is fully inverted) but during amplification of the “1” bit, carriers are consumed and the optical gain drops to eventually a constant level that matches the output power level of the amplifier, called the Saturation Output Power (P_{sat}) that matches the input power, gain and output power in accordance to the life time of inverted electrons (typically, 200ps for SOAs). The net effect in the case of the 800ps long bit time of a GbE symbol, is that the first 200ps of a “1” symbol experience a high gain and therefore a high output power, while the last 200ps of the symbol and possibly trailing “1” symbols experience a significant lower gain and output power. This distortion results in the effect that every time the signal is amplified the power distribution along the bit-

time is shifted such that the signal becomes sensitive to distortion of the leading edge (non-linear!) as power keeps on increasing. In the case of multiple consecutive “1” symbols the first “1” will be received correctly while the trailing “1” will have the least energy and will be more sensitive to noise and will be more frequently the cause of an error (“1” interpreted as a “0”).

2. The GbE signal transmitted from A to Z must experience the same delay as the signal transmitted from Z to A.
    a. As long as both signals are in the same fibre, the path delay difference between both counter-propagating waves is nominally zero (fast fibre length variations may still cause small, transient delay differences). In the case of amplifiers or termination on a transceiver, both signals are processed independently and are therefore guided into individual fibres and will experience different delays. Calibration of this difference and accounting for the accumulated effect allows the WR system to be calibrated and become insensitive to this delay in replicating time.
    b. Bi-directional transport signals can use the same wavelength in either direction, however this results in added noise because of scattering (Raleigh) and power fading when multiple reflections on connectors cause periodic constructive and destructive interference. For this reason, different wavelengths are used for each of the propagation directions. This however causes a different effect, as propagation delay is dependent on wavelength (Chromatic Dispersion). The difference in wavelength causes a delay difference between waves propagating from A to Z and from Z to A. Although this effect is deterministic (it can be compensated for a full 100%, when measuring the dispersion), determining the dispersion is a complex measurement and invasive to the services. Alternatively, the standards allow the estimation of the average encountered dispersion (given the length of the fibre and the wavelength and type of the fibre) and the uncertainty in dispersion based on the total minimum and maximum allowed dispersion. This value multiplied by the transmission distance and spectral distance between both counter-propagating waves provides a first estimate of the expected time inaccuracy. If this uncertainty is acceptable no further measures are required. Alternatively, if dispersion compensation is required for the GbE signals to be received with sufficient fidelity, this would automatically improve the end-to-end dispersion induced uncertainty.

3.2 TFT transport-equipment

3.2.1 Convention and definition of waves and directions.

In the case of uni-directional transmission each amplifier has an input and output port. Field engineers and trouble-shooting engineers are accustomed to this concept and during first trials with bi-directional amplifiers; this has caused some issues, as port identification now becomes wavelength dependent. To this end a convention must be introduced that binds a wavelength to an input port. By naming a port "input port" the wavelength λ_1 is assigned as the wave entering the port. By convention λ_2 is the wavelength that exits the port. This convention implies that a TFT service is delivered in the direction of input ports to output ports, from master clock to slave clock. From the operator's point of view the direction of the TFT-service is not relevant as both underlying GbE carrier services must be up and running. In case of issues in the TFT-service domain (for example synchronization is not working properly), actual trouble shooting will start once the master and slave nodes have been identified by either consulting the Inventory Management System (IMS), the configuration on the equipment, or the customer using the service. In the latter case not only SURFnet has access to the WR equipment, but also the customer or user. The latter case is the preferred model for SURFnet because it enables the end-user to set up and configure the TFT service as they see fit and allows SURFnet to focus solely on the transport of the GbE waves and providing, publishing, or configuring the delay correction to account for the delay asymmetry between both wavelengths.

3.2.2 Generation and multiplexing of WR signals.

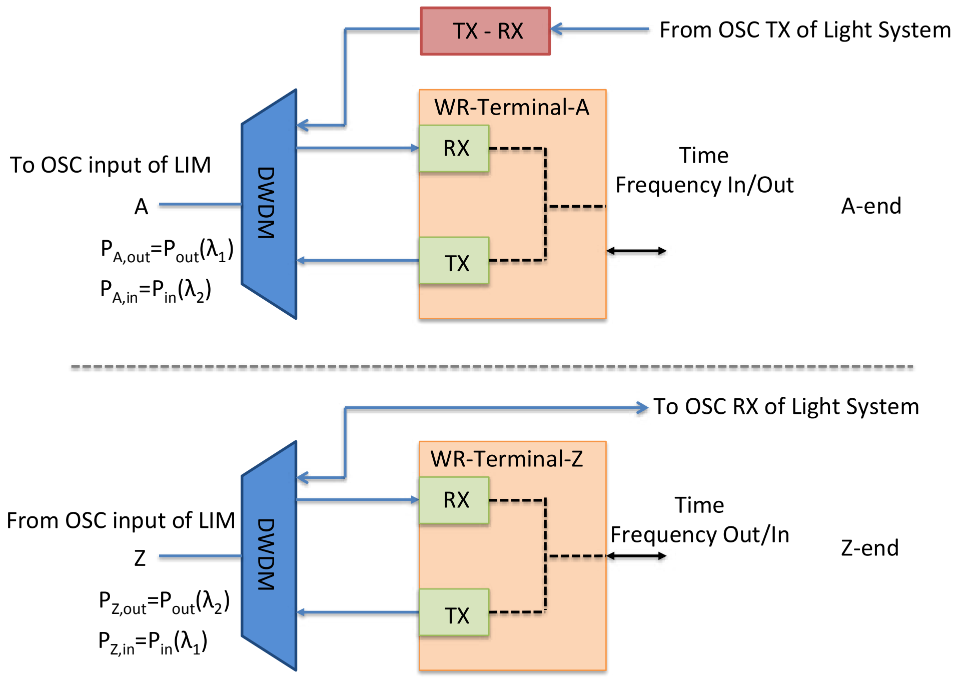

Figure 3-1. Generation and Termination of WR-signals on A-end and Z-end.

Figure 3-1 shows the terminal configurations at the A-end and Z-end of the service. In addition to the outlined convention in Subsection 3.2.1 the transmitted wavelength of the OSC co-propagates with wavelength λ_1. This implies that on the other fibre of the fibre pair the TFT service is always in the opposite directions such that also in this direction the OSC transmitted wavelength co-propagates with wavelength λ_2. This does not mean that when both fibres are used, the actual transfer of time and frequency is always in the same direction. It is up to TFT service definition to select one of the four possibilities that are possible without violating the convention in Subsection 3.2.1 and this subsection:

a. Fibre 1: A to Z and Fibre 2: A to Z
b. Fibre 1: Z to A and Fibre 2: A to Z
c. Fibre 1: A to Z and Fibre 2: Z to A
d. Fibre 1: Z to A and Fibre 2: Z to A

In conclusion a separation exists between the TFT application or TFT service and TFT transport or TFT transport-service. This separation is essential as it allows the operator to implement processes such as installation, maintenance, repair, etc. using same design and engineering rules and with as little training as possible of the field-engineers and NOC personnel. The complexity of establishing the accuracy and uncertainty of the service can be left to the users of the service. The most important exchange of information between the operator and the users is the asymmetry introduced by the equipment. This can be retrieved from the IMS using serial number references of the installed equipment or the use of an advanced mechanism such as a Link Layer Discovery Protocol (LLDP) to make the TFT service layer topology and infrastructure aware. Information on the inaccuracy and uncertainties introduced by the fibre is to be delivered by requesting the proper fibre parameters from the IMS system using adjacency information configured on the terminal equipment. This latter information can never be learned using LLDP as it involves the physical connection and selection of the fibre 1 or fibre 2 of the fibre pair.

3.2.3 Point to Point transport – Amplification of WR signals

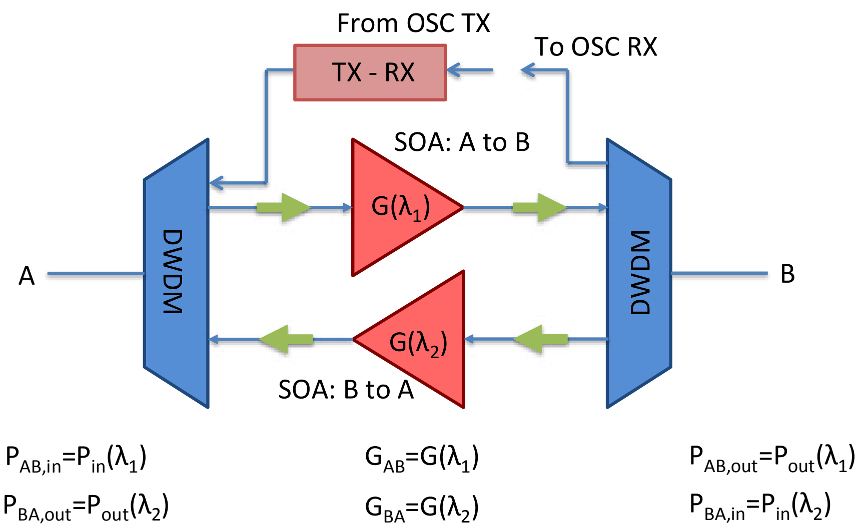

Figure 3-2. Bi-directional amplification

Where possible optical amplification, such as outlined in Figure 3-2. Bi-directional amplification will be used to regenerate the optical signal after transmission in a span of optical fibre. Optical amplification is cheap and does not degrade performance of the service as much as Optical Electrical Optical (OEO) regeneration (section 4.2.2) or regeneration on the service level. Moreover in the future it is expected that such functionality can be integrated on photonic integrated circuits with ease using bulk SOAs and ring-resonance based filters.

Optical power budget of span with single amplifier			
Component	Input Power [dBm]	Loss [dB]	Output Power [dBm]
Amplifier (fiber-to-fiber)	-25.3	-28.25	2.95
splice	2.95	0.05	2.9
isolator	2.9	0.8	2.1
splice	2.1	0.05	2.05
DWDM filter	2.05	0.6	1.45
splice	1.45	0.05	1.4
DWDM filter	1.4	0.6	0.8
connector	0.8	0.4	0.4
CWDM filter	0.4	0.6	-0.2
connector	-0.2	0.4	-0.6
ODF	-0.6	0.4	-1
Fiber	-1	20	-21
ODF	-21	0.4	-21.4
connector	-21.4	0.4	-21.8
CWDM filter	-21.8	0.6	-22.4
connector	-22.4	0.4	-22.8
DWDM filter	-22.8	0.6	-23.4
splice	-23.4	0.05	-23.45
isolator	-23.45	0.8	-24.25
splice	-24.25	0.05	-24.3
PDL	-24.3	1	-25.3

Table 3-1. Optical power budget of an amplified span conform Figure 3-2.

Table 3-1 shows an example of the power budget of a single span with optical amplification. This example accounts for all losses expected in the link and the amplifier internals. The fibre loss is assumed 20dB, sufficient for spans of 80km. The amplifier must possess a gain of approximately 28dB and a polarization dependent gain of less than 1dB. All values are end-of-life. In case more losses exist because waves are routed through a MMR, a total gain of 30dB might be required. The Output power of the SOA has been limited to approximately 3dBm in order to reduce non-linear saturation of the amplifier. Amplifiers with internal mechanisms such as gain clamping can be used to improve on saturation performance.

3.2.4 Point to Point transport – Dispersion compensation of WR signals

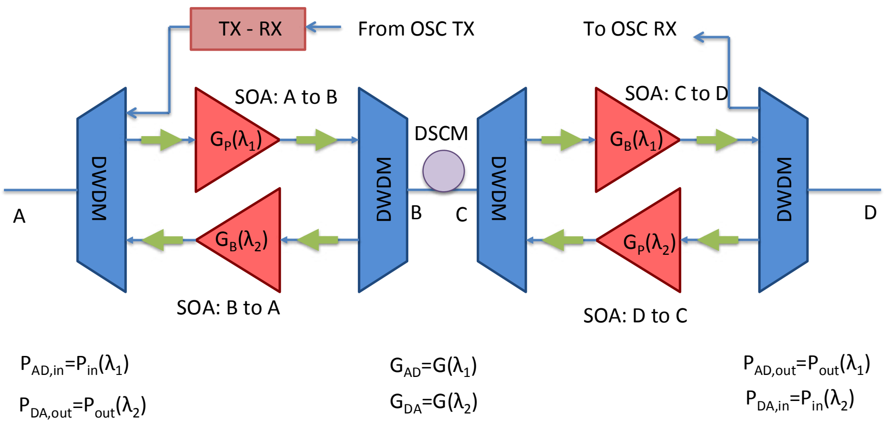

Figure 3-3. Bi-directional two-section amplifier with dispersion compensation.

In case transport has resulted in the optical signal to have experienced more dispersion than the receiver has been designed to resist, the use of a dispersion slope compensation module (DSCM) can be the solution to reduce the dispersion to an appropriate level. Moreover, DSCM can also be used to pre-compensate the GbE ASK-NRZ signal such that energy is “smeared”-out across multiple bits to allow the saturable SOAs to experience an optical signal that resembles more a continuous wave signal and therefore introduces less distortion. Figure 3-3 shows how a DSCM module can be integrated as part of a bi-directional amplifier. Because of the loss of the DSCM module a dual stage amplifier is required. The optical power levels incident to the DSCM module must also be lower as DSCM fibre is known for its non-linearity. Table 3-2 shows the power budget of a 20dB span (80km of 0.25dB/km of optical fibre) with a dual stage amplifier including the loss of a DSCM module suitable for compensation of up to 100km of standard single mode fibre in the 1500nm window.

Optical power budget of span with dual amplifier with DSCM			
Component	Input Power [dBm]	Loss [dB]	Output Power [dBm]
Pre-amplifier (fiber-to-fiber)	-22.3	-21	-1.3
splice	-1.3	0.05	-1.35
isolator	-1.35	0.8	-2.15
splice	-2.15	0.05	-2.2
DWDM filter	-2.2	0.6	-2.8
splice	-2.8	0.05	-2.85
DWDM filter	-2.85	0.6	-3.45
splice	-3.45	0.05	-3.5
DCF (DSCM)	-3.5	10	-13.5
splice	-13.5	0.05	-13.55
DWDM filter	-13.55	0.6	-14.15
splice	-14.15	0.05	-14.2
isolator	-14.2	0.8	-15
splice	-15	0.05	-15.05
Post-amplifier (fiber-to-fiber)	-15.05	-21	5.95
splice	5.95	0.05	5.9
isolator	5.9	0.8	5.1
splice	5.1	0.05	5.05
DWDM filter	5.05	0.6	4.45
splice	4.45	0.05	4.4
DWDM filter	4.4	0.6	3.8
connector	3.8	0.4	3.4
CWDM filter	3.4	0.6	2.8
connector	2.8	0.4	2.4
ODF	2.4	0.4	2
Fiber	2	20	-18
ODF	-18	0.4	-18.4
connector	-18.4	0.4	-18.8
CWDM filter	-18.8	0.6	-19.4
connector	-19.4	0.4	-19.8
DWDM filter	-19.8	0.6	-20.4
splice	-20.4	0.05	-20.45
isolator	-20.45	0.8	-21.25
splice	-21.25	0.05	-21.3
PDL	-21.3	1	-22.3

Table 3-2. Optical power budget of a dual-amplified span with dispersion slope compensating fibre conform Figure 3-3.

From Table 3-2 it becomes clear that the two amplifiers must not be the same. Because of the launch power restrictions of the DSCM the pre-amplifier requires a lower gain and saturation output power while the post-amplifier must act more like a booster amplifier. Only when the fibre launch power is increased to +2dBm both amplifiers provide the same gain of 21dB for a 20dB fibre span loss.

3.2.5 Point to Point transport – Regeneration of WR signals

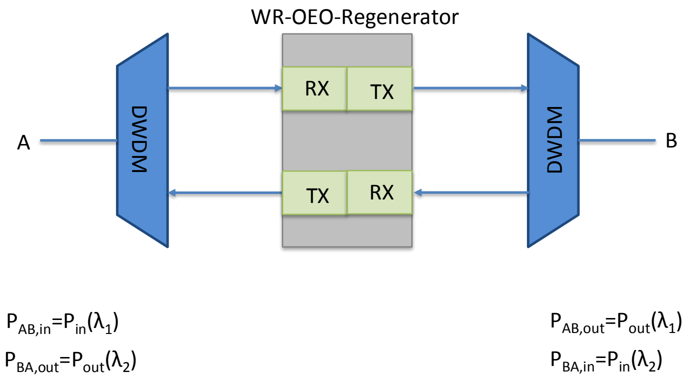

Figure 3-4: Bi-directional Optical-Electrical-Optical regeneration (connections to the OSC TX and RX are not drawn).

Figure 3-4 displays a configuration where the electrical output of the optical receiver and the electrical input of the optical transmitter are connected such that the electrical receive signal drives the transmitter. Industry standards make the electrical receive signal conform to known interfaces, such as common mode logic or emitter coupled logic. If required timing can be added, however this must not lead to unwanted phase variations caused by Phase Locked Loop (PLL) clock slips.

Optical-Electrical-Optical regeneration is considered required when the optical signal is degraded to such an extent, that an extra amplifier makes reception no longer possible. This can be caused by either OSNR deterioration or distortion by SOAs or fibre non-linearity (in case span loss cause a too high fibre launch power).

A second reason to implement OEO regeneration is the need to change the wavelength of the GbE signal. Cases where this may occur are cases where more than one GbE signal is present in the OSC band and the active one is already in use. Alternatively interfacing to other domains where a different wavelength scheme is in place.

In case the electrically received signal is terminated on a GbE physical media dependent sub-layer (Ethernet-Phy) and the Ethernet consolidation layer, the TFT service can be recovered and from the service layer a new GbE signal can be initiated as further discussed in Subsection 0.

3.2.6 Service termination and multiplication

Figure 3-5 shows a node where the service is fully recovered and replicated, in order to be transported across a new photonic network. Although this can be considered a new clock domain or timing domain, it is not always needed to actually patch through the recovered frequency and timing signals, but instead remain in the Ethernet domain.

This node is also required to allow TFT services to grow organically. Project internal discussions have led to the insight that such functionality contributes approximately 100ps to the time uncertainty. WR equipment developers are committed to reduce this uncertainty to a level on the order of tens of picoseconds. From an architectural point of view such a function would have to be placed at a central location.

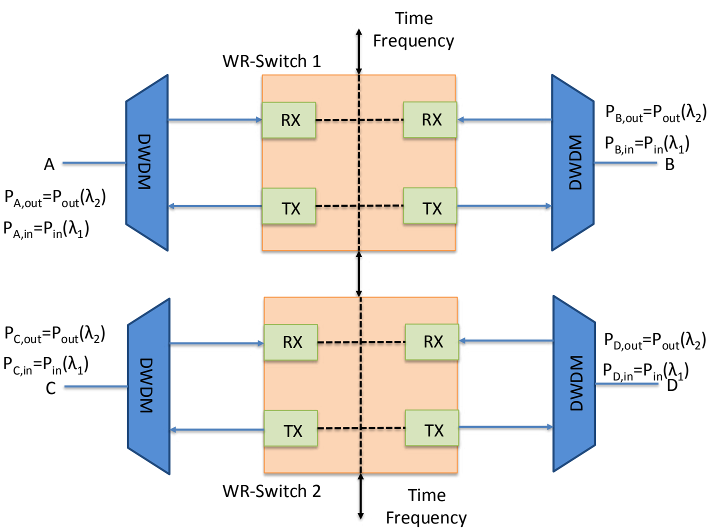

Figure 3-5. Termination of optical signals for delivery of the TFT service or for distribution of the TFT service amongst different customers.

The aim of this architecture is to allow TFT services to organically grow depending on the required usage.

4 Link and Network Engineering

This chapter will focus on engineering rules that can be applied such that the TFT transport-service allows the TFT service to grow organically in SURFnet's network.

In Section 2.1 the optical fibre infrastructure was discussed. The optical transmission fibre will not be considered a component, which is subject to selection depending on the technology, which is for example the case for laser diodes and photodiodes.

In the case operators use commercially available equipment, specifications apply to the external connectors on the chassis or blades and not on internal components. Because not all specifications are known at the time of writing of this document, it was decided to use key-numbers for the most important components making up an end-to-end link.

4.1 Optical Component Specifications

4.1.1 DWDM Transceiver

The GbE DWDM transceiver cannot be constructed using conventional GbE-grade components. GbE is not a technology used in the C-band or close to the C-band. At present DWDM grade lasers are produced predominantly for the 10G transport market. These pluggable modules are available in either SFP+ or XFP form factor. In the case of the GbE TFT transport service these types of lasers will be used to generate two waves between 1511nm and the C-band, 50GHz or 100GHz apart. Compatibility with GbE is achieved by packaging these lasers in SFP form factor pluggable modules. As there is no standardized grid commercially adopted in this range (The C-band 100G grid with commercially available wavelength starts at approximately 1519.48nm and ends at approximately 1577.03nm), tuneability will not be a requirement as such tuneable lasers will not be generally available. In the remainder of this section it is assumed that the light source will be an Integrated Laser Mach-Zehnder modulator or Integrated Laser Electro-Absorption modulator source driven at GbE speeds instead of uncooled direct modulation.

The photodiode used will be an Avalanche Photo Diode (APD) as this is the most commonly used detector for 10G pluggable modules. The APD is connected to a trans-impedance amplifier and a limiting amplifier. The electrical part will be GbE where retiming will be done on the host board (Ethernet MAC chip).

Transmitter Parameter [unit] (EOL)	Value
Average Optical Power [dBm]	2
Extinction Ratio []	> 10
Frequency Stability [GHz]	+/- 2.5GHz
Line Width [nm]	< 0.2

Table 4-1. Transmitter Parameters Required for Link Engineering

Receiver Parameter [unit] (EOL)	Value
Receiver Sensitivity, unamplified [dBm]	-32
Dispersion Tolerance [ps/nm]	>2400
OSNR [dB/0.1nm] @ 0 ps/nm	13
OSNR [dB/0.1nm] @ 2400 ps/nm	16
Receiver Overload [dB]	-7
Electrical BW [GHz]	1
Optical BW [GHz]	25

Table 4-2. Receiver Parameters Required for Link Engineer

Table 4-1 and Table 4-2 display the important parameters used to perform link engineering using a simulation tool based on the SOA model in [1] and [2].

4.1.2 SOA

SOA-module Parameter [unit] (fibre-to-fibre EOL)	Value
Peak Gain (800um SOA) [dB]	30
Peak Wavelength [nm]	1511
Optical BW [nm]	40
Carrier Lifetime [ps]	200
Polarization Dependent Gain (dB)	1.0
Noise Figure (dB)	9.0
Saturation Output Power (1dB) [dBm]	10

Table 4-3. SOA parameters used for simulation and link engineering (single-SOA amplifier)

Pre SOA-module Parameter [unit] (fibre-to-fibre EOL)	Value
Peak Gain (800um SOA) [dB]	24
Peak Wavelength [nm]	1511
Optical BW [nm]	40
Carrier Lifetime [ps]	200
Polarization Dependent Gain (dB)	1.0
Noise Figure (dB)	8.5
Saturation Output Power (1dB) [dBm]	13

Table 4-4. Pre-Amplifier SOA parameters used for simulation and link engineering (dual-SOA amplifier)

Post SOA-module Parameter [unit] (fibre-to-fibre EOL)	Value
Peak Gain (800um SOA) [dB]	18
Peak Wavelength [nm]	1511
Optical BW [nm]	40

Post SOA-module Parameter [unit] (fibre-to-fibre EOL)	Value
Carrier Lifetime [ps]	200
Polarization Dependent Gain (dB)	1.0
Noise Figure (dB)	8.0
Saturation Output Power (1dB) [dBm]	15

Table 4-5. Post-Amplifier SOA parameters used for simulation and link engineering (dual-SOA amplifier)

4.1.3 Filters

The DWDM optical filters are assumed Gaussian shaped with a spectral width of 25GHz. CWDM filters are assumed to be flat for the optical signals +/- 6.5nm around the centre frequency as defined in the CWDM ITU-standard. The optical signals are all DWDM and therefore considered narrow in the CWDM defined spectrum. DWDM signals filtered by a CWDM filter are assumed to be on the flattop part of the CWDM filter profile.

4.2 Network Engineering

Link engineering can only be done successfully if the architecture and placement of nodes are known. For example if Service Replication takes place at distances less than 200km. It does not make sense to create engineering rules for links up to 1000km or more when these distances will never be reached.

4.2.1 Service Replication Node

Service replication nodes as outlined in Figure 3-5 can be placed at nodes with a nodal degree of three and higher. In the meshed core network of SURFnet this means at all locations that are part of the core network, and are capable of routing waves. From the core locations it is possible to reach approximately 90% of all customers directly, i.e. without needing a second service replication node.

4.2.2 OEO regeneration node

Optical Electrical Optical regeneration will be considered in case the OSNR has decreased below a certain level or in case optical dispersion compensation cannot be deployed as it increases time uncertainty. Because OEO regeneration does not involve re-timing, is symmetrical for both waves, and can be calibrated for delay differences between each direction, it is a suitable candidate to be also deployed instead of dispersion compensation. Small differences in delay will remain and are caused by signal-level dependent amplification and decision-making electronics.

In case of dispersion compensation, the decision is purely economical and depends on the difference in cost between an Optical Amplification node with Dispersion Compensation and an OEO regeneration node.

4.2.3 Optical Amplification node

Optical amplification nodes contribute only to the uncertainty by means of the following three mechanisms:

1. Errors in the calibration of the differential delay between both counter-propagating waves. This error can be made relatively small and is under control of the operator.
2. Delay differences in propagation delay of the semiconductor material. This delay is caused by phase changes caused by saturation of the semiconductor material. These phase changes are limited to a few cycles of the optical carrier. Hence they are in the femto-second range.
3. Saturation effects caused by gain saturation of the medium. This can lead to dispersion of energy between bits and consequently can cause time uncertainty, as receivers will experience more jitter on the input.

4.2.4 Optical Amplification with Dispersion Compensation

The same reasoning as outlined in Subsection 4.2.3 applies to the impact of dispersion-slope compensation fibre as discussed in Subsection 0. This type of node will only be used in case chromatic dispersion becomes an issue and in case Optical Dispersion Compensation is more economical compared to OEO regeneration.

4.3 Link Engineering

In this section two types of link engineering are discussed. In Subsection, 4.1.2, 4.2.3 and 4.2.4 the SOA, and amplifier nodes have been discussed. The use of SOAs allows the TFT service to rely on a well-known link in terms of the amount of unknown residual asymmetry in delay. This is mainly due to the fact that the propagation delay in the SOA does not change significantly with the amount of gain saturation. Also SOAs are temperature controlled and for this reason the propagation delay is also very stable.

One issue when chaining SOAs is the fact that power fluctuation may occur as not all fibre spans have the same loss. When designing links with fibre amplifiers the gain of the fibre amplifier can be adjusted by modifying the pump power. When modifying the pump power, the gain of the amplifier is changed and also the saturation output power. Because of the large life time of the excited atoms of the gain medium, distortions of the optical signal are independent of the saturation output power, moreover, if the output power is not high enough, more pump power is applied, until the required output power is observed at the output.

SOAs cannot be controlled in a similar fashion as can be done with EDFAs (Erbium Doped Fibre Amplifiers). When SOAs need to produce less gain, reducing the pump power not only impacts the optical gain, but also the saturation output power. The small carrier life time constant (200ps, typically) leads in case of a high input power (the reason why less gain is required) in combination with the lower saturation output power to non-linear distortions or amplitude modulated signals with bit times greater than tens of ps. GbE signals are such signals and their quality will degrade rapidly if saturation output powers are not several dBs higher compared to the output power. This is the reason it is not possible to increase launch powers in SOA-amplified links to improve performance.

The only possible way of reducing gain, is to decrease the length of the amplifier while maintaining or even increasing the electrical current (i.e. increase the pump power density). This mode of operation is referred to as Model A.

Alternatively one could attenuate a signal with high input power to a level where the output power does not significantly saturate the SOA and launched fibre power is adequate. This mode is referred to as model B.

4.3.1 Model A: Flexible Gain

In this model each amplifier has different specifications. Similar, as outlined in the case of the two-stage amplifier with dispersion-slope compensating fibre, Figure 4-1 shows a link where each amplifier requires a different gain and therefore a different length. In case there are three different amplifiers (low, medium and high gain), 18 possible combinations exist when also taking into account that the amplifiers are direction dependent because of the bi-directional propagation of the two waves of different wavelength.

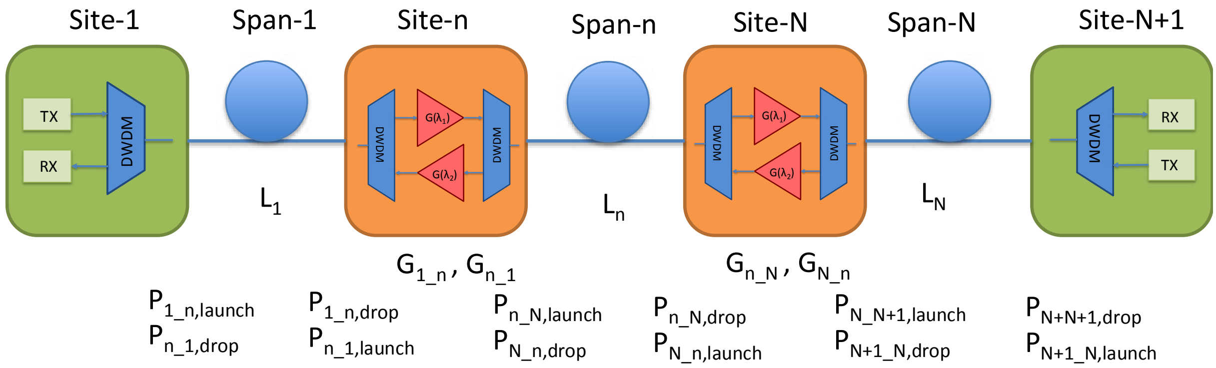

Figure 4-1: Link for TFT using amplifiers with gain and saturation output powers adjusted to the length and attenuation of each span.

4.3.2 Model B: Fixed Gain

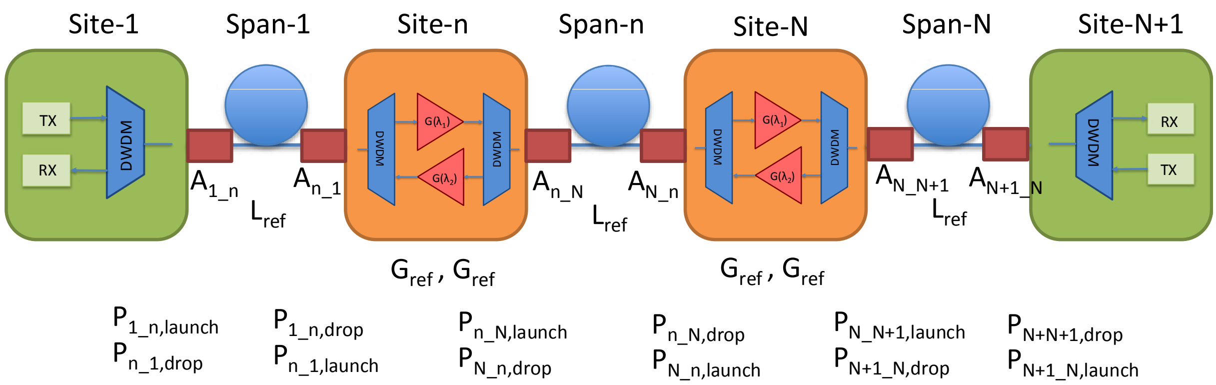

Figure 4-2: Link for TFT using amplifiers, all with the same gain and saturation output powers. Attenuators are added to each span in order to adjust the link attenuation to the gain of the amplifier.

Figure 4-2 outlines the case where only one type of amplifier is required. In this case attenuators are added to the spans to avoid the SOAs to become saturated. The dimensioning of the attenuators is in this design relatively easy. Each pad will have a value equal to the excess gain of the amplifier compared to the span loss, divided by two. The bi-directional nature of the link justifies this symmetrical placement of the attenuators.

Model B can perform satisfactory on links where span loss is already distributed. For SURFnet this would entail to use Model B on its cross-border fibres.

In its national production network SURFnet could consider to start with Model B and once service take-up has reached a threshold, introduce amplifiers with a high and a low gain (Model A) to improve optical performance.

4.4 Link Simulation

For the purpose of verifying link design a simulation tool has been developed capable of simulating SOA-amplified links as presented in this document.

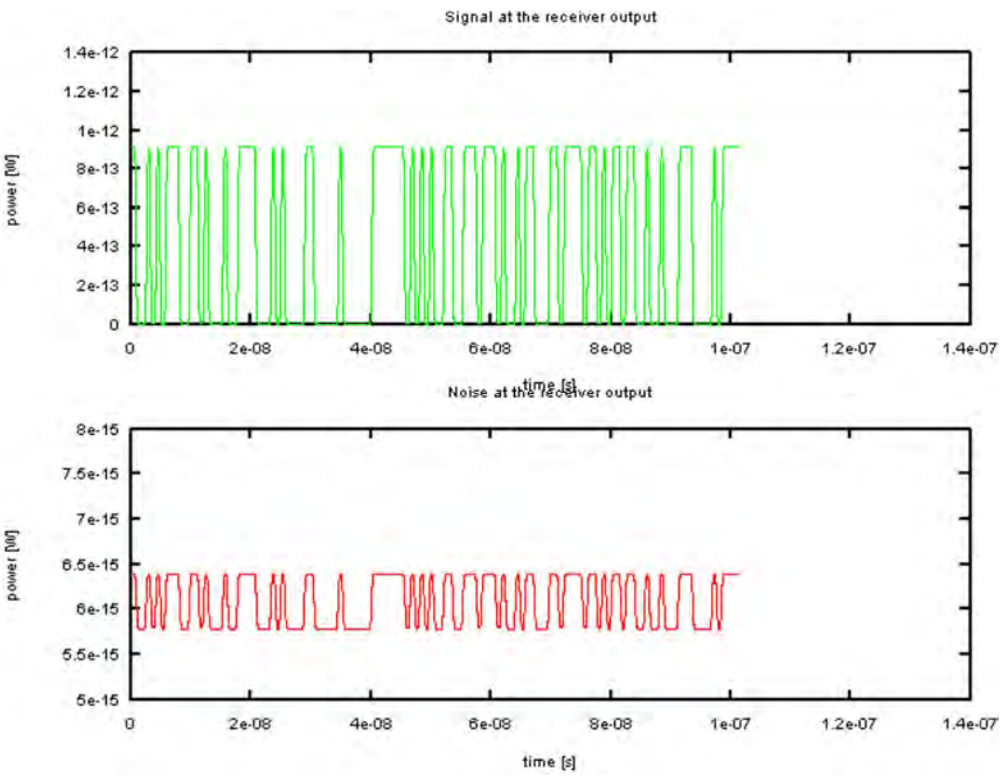

Figure 4-3: 2^7-1 PRBS ASK-NRZ GbE signal. The GbE signal has a Bit Error Rate (BER) of $8.8*10^{-10}$ at an optical input power of -31dBm. This is the reference transceiver.

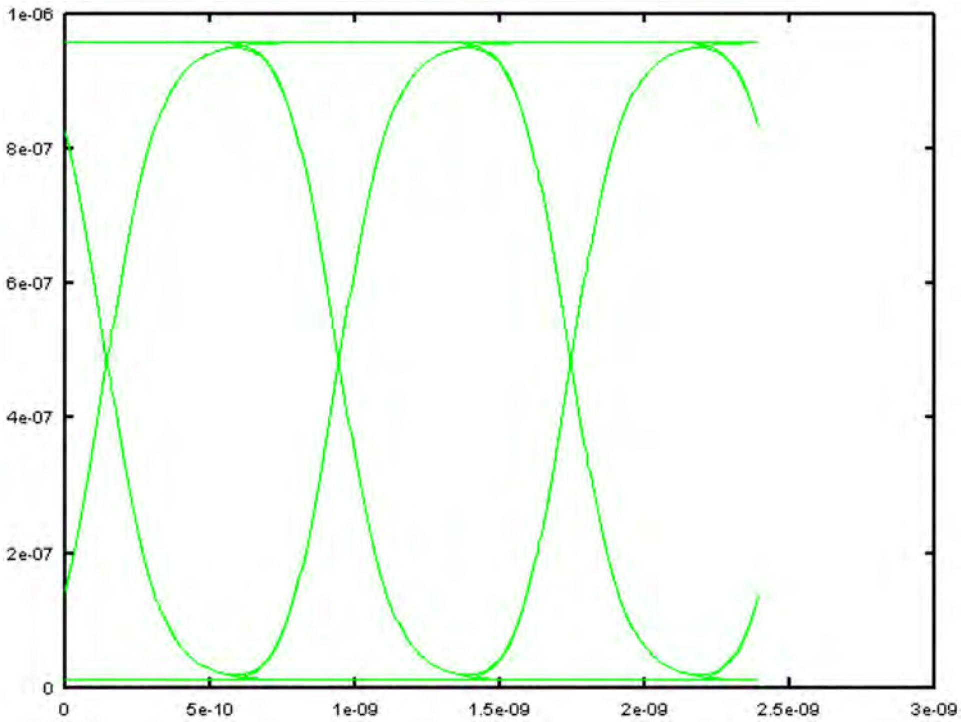

Figure 4-4: Eye diagram of the back-to-back received GbE signal. Both “1” and “0” bit levels overlap as is expected in the absence of dispersion and non-linear SOA-based amplification.

Figure 4-3 and Figure 4-4 show the received electrical signal and electrical noise power and the eye diagram of a back-to-back setup. The received power was attenuated to -31dBm for a Bit Error Rate (BER) of $8.8*10^{-10}$. These figures clearly show the symmetry and almost perfect shape of an optical ASK-NRZ signal.

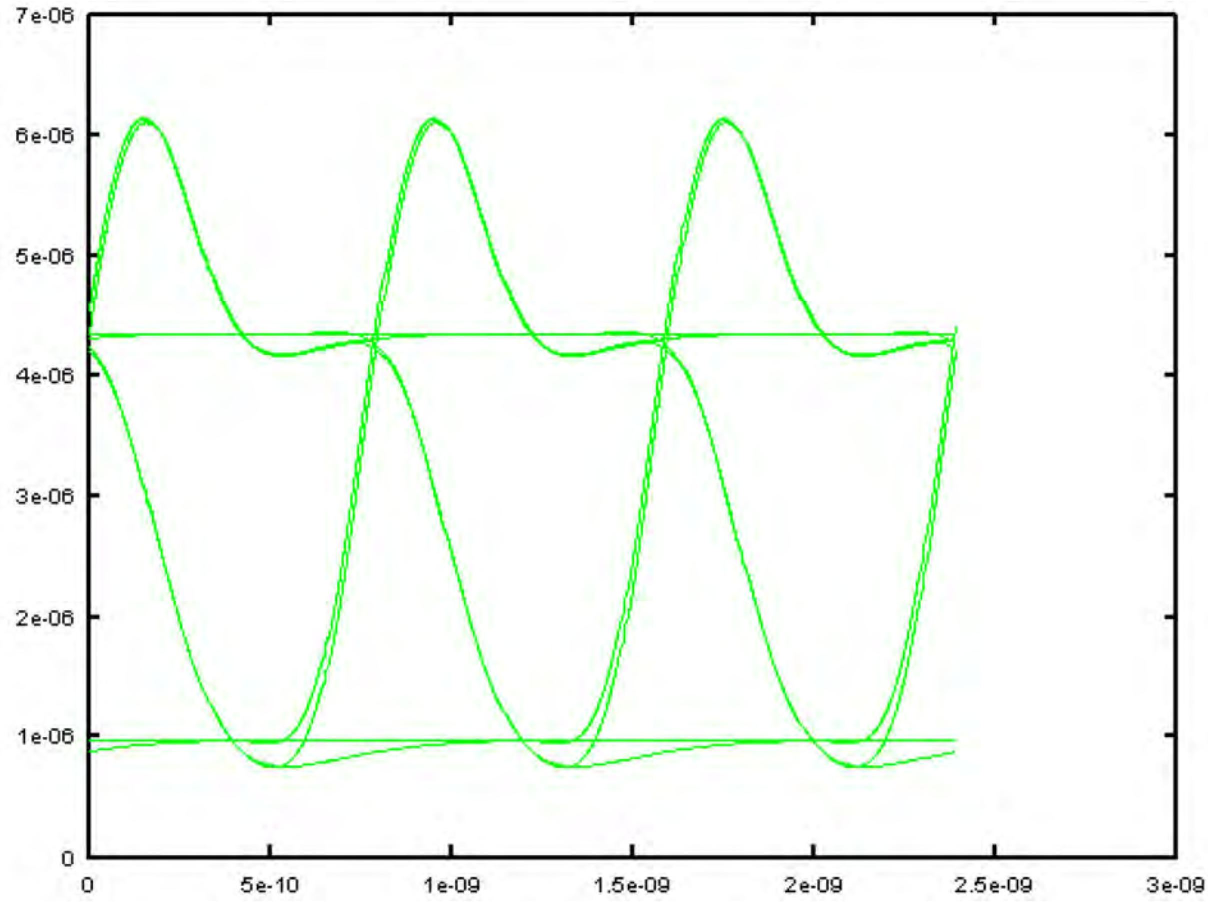

Figure 4-5: Eye diagram of the received GbE signal after 800km (10 sections of 80km of 4 ps/nm/km NZ-DSF) Fibre launch power was set at -3dBm. The over-shoot in this eye diagram is caused by the saturation of the SOAs. The SOAs gain was set to 28.25dB (on-chip) with a noise figure of 9dB (on-chip). The 3dB gain-compression saturation output power was set to 10dB (on-chip). Chip to fibre couple losses equal to 3dB. The received BER amounted to 5.4*10^{-45} at a received power of -23dBm.

Figure 4-5 and Figure 4-6 show two received optical eye-diagrams of 800km link composed of 10 sections of 80km of NZ-DSF. The saturation output power of the SOAs was set to 10dBm and 13dBm respectively. These pictures show that the SOAs already saturate on the noise they generate by themselves. This is expected behaviour for SOAs with gains close to the 30dB. The fact that in the TFT transport solution filters are required avoids the spectral shift of the gain profile. If filtering was not implemented the spectral shift and increase saturation would not allow for 800km transmission.

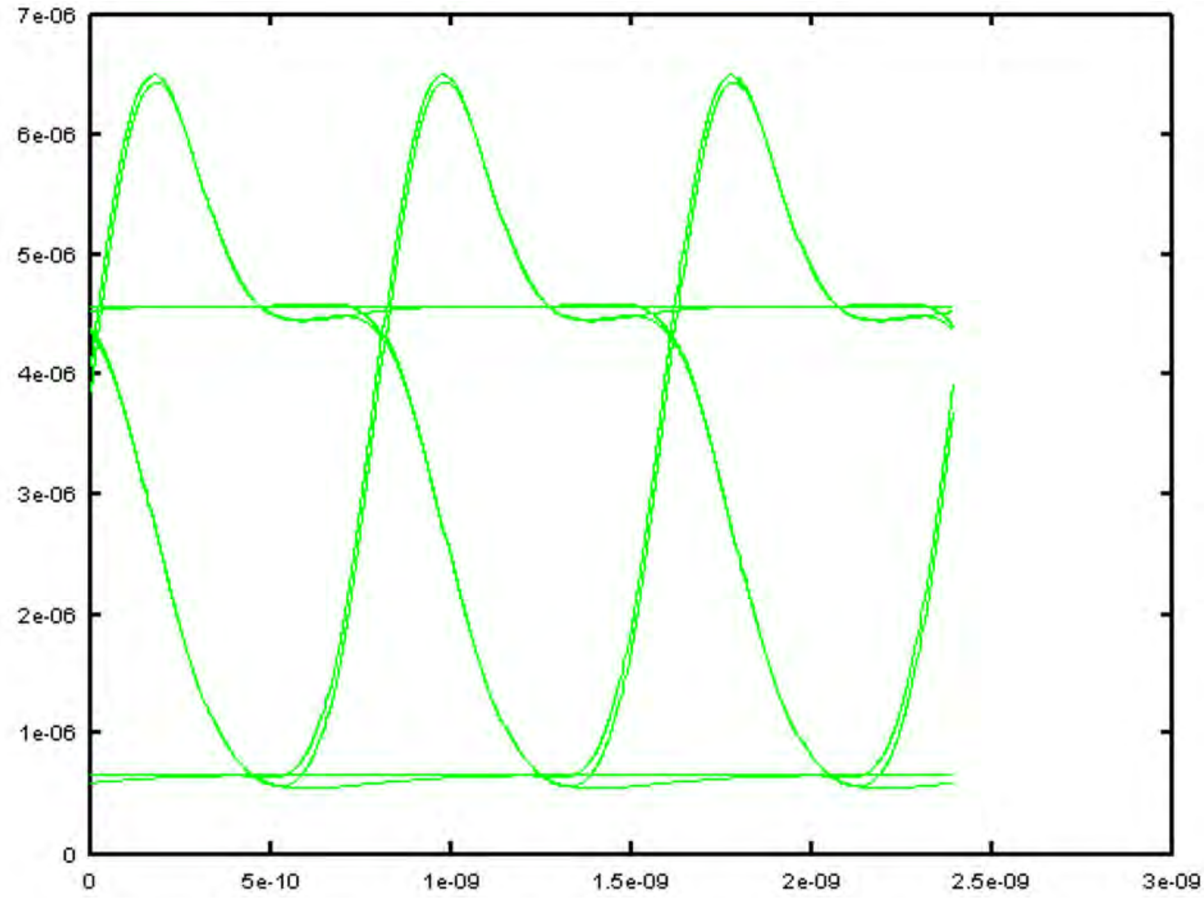

Figure 4-6: Eye-diagram under the same conditions as simulated in Figure 4-5, but with a saturation output power of 13dBm instead of 10dBm (on-chip). The BER improved to $5.7*10^{-126}$.

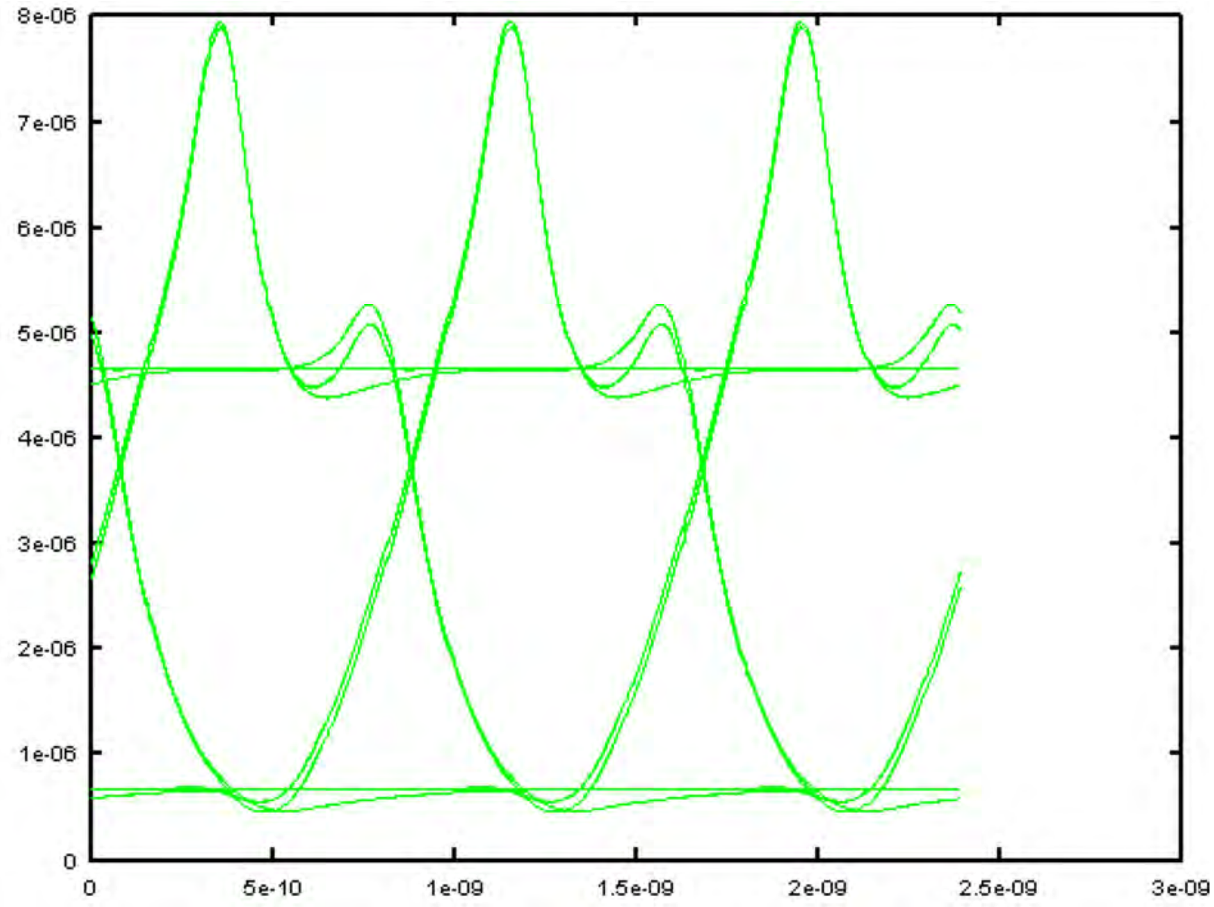

Figure 4-7: Eye diagram under the same conditions as simulated in Figure 4-6 (with a saturation output power of 13dBm, on-chip) In this case the fibre was set to SSMF (non-dispersion shifted). The BER improved to $8.9*10^{-133}$. This is mainly caused by the dispersive effects on the non-linear gain saturation distortion. This causes the power fluctuations to manifest themselves more favourable for selected bits.

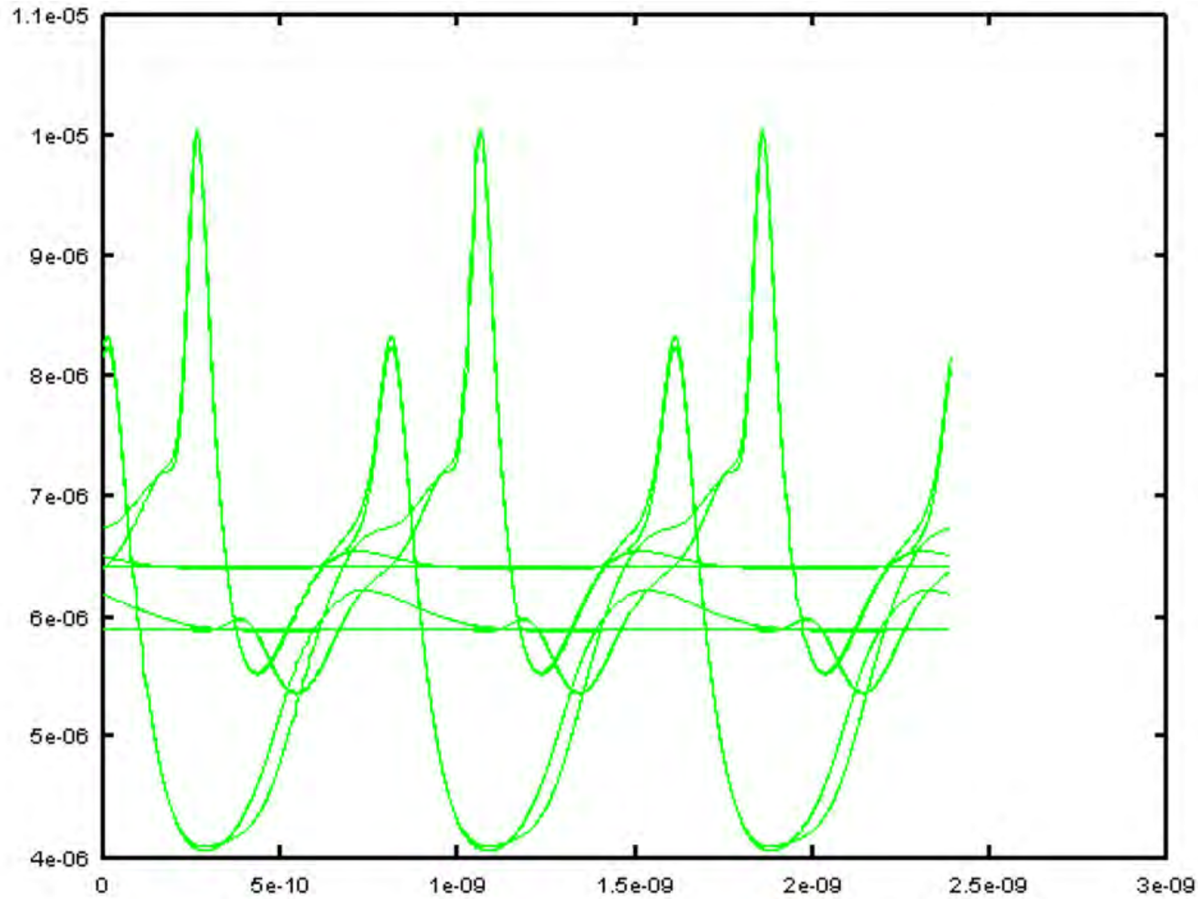

Figure 4-8: Eye-diagram of the received optical signal after 1600km of 4 ps/nm/km of NZDSF. The signal has degraded such that the BER is equal to 0.03.

Figure 4-8 shows a link of 1600km of NZDSF. Chromatic dispersion is not the major contributor of this poor performance. The extensive amplification by the SOAs has resulted in this distorted signal. Not only has the eye closed dramatically, but also a large amount of jitter is visible in the “0” to “1” and “1” to “0” crossings. In this example, the jitter has accumulated to more than half the bit time, i.e. > 400ps. Even a very high-end PLL, which is part of the GbE media dependent sub-layer, would not be able to recover a clock signal, which could be used for high-precision clock generation by the WR service platform (assuming the BER would be sufficient in the first place).

5 Additional Requirements and Summary Conclusions

5.1 Additional Requirements

So far this document has only focussed on the transport plane of the GbE signals required for the TFT service. Although this is a significant part of what needs to be accomplished, other aspects must not be forgotten. Not discussed in this document, but very relevant for successful deployment are requirements on additional topics. As these requirements deviate significantly from operator to operator (Physics do not, hence the focus on the transport) this section will provide a short list of topics (not exhaustive), which must be addressed in terms of requirements:

- Calibration of the link where each element contributes in the delay asymmetry of each of the two waves.
- Training of personnel, incl. the Network Operation Centre
- Performance monitoring
- Alarm monitoring and follow up
- Release management
- Escalation
- Service Level Specifications
- Service Level Agreements
- Sparing and repair
- Planning
- Configuration management
- Change planning
- Interfacing with the Campus
- Testing
- Problem management
- Disaster recovery procedures

Most of the implementations will be compatible with existing procedures. This will vary significantly from NREN to NREN. Moreover, not all implementations must be completed before service roll-out can commence, as long as there is awareness and a procedure in place which governs implementation.

5.2 Summary Conclusions

This document contains basic engineering rules required for the transport of GbE signals for a time and frequency transfer service. It is shown how such a service can co-exist with existing photonic transport systems.

Insight is provided in the impact of fibre types and dispersion slope compensation fibre modules on the uncertainty. Because often operators cannot choose freely for a type of optical fibre, it is important to understand the implications so that changes to the deployment of for example dispersion slope compensation modules can be made.

Network engineering rules have been outlined and a tool has been created based on existing software, which allows simulation of the link when different components become available or can provide insight into the impact of new amplifiers and transceivers.

The tooling can be used to assist in the selection of a particular link model and can help in working around cases where exceptions must be implemented.

5.3 Future Work

The next steps are to implement a basic service and perform validation based on the actual parameters. The fact that 800km can be achieved relatively easy, while 1600km is not possible indicates that a first implementation around a few hundred kilometres would be ideal to understand a practical system better, while not running into problems in case certain parameters of, for example a SOA module, deviate from targeted specifications.

In the future work it is important to take into account the fact that at present SURFnet is required to retender its photonic transport network, according to European and National law. This may have impact as the configuration of the line fibre interface modules may change. In addition, SURFnet is also reviewing its fibre infrastructure. This may result in changes in terms of length of fibre spans and type of fibre. The tooling and design guidelines in this document have been drafted such that they can meet reasonable changes and therefore these two risks have been taken sufficiently into consideration.

Abbreviations

APD	Avalanche Photo Diode
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
BER	Bit Error Rate
CBF	Cross Border Fibre
CWDM	Course Wavelength Division Multiplexing
DSCM	Dispersion Slope Compensating Module
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fibre Amplifier
EOL	End of Life
FWM	Four Wave Mixing
GbE	Giga Bit Ethernet
IL	Insertion Loss
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LIM	Line Fibre Interface Module
LLDP	Link Layer Discovery Protocol
MMR	Meet Me Room
NDSF	Non Dispersion Shifted Fibre
NOC	Network Operations Centre
NREN	National Research and Education Network operator

NRZ	Non Return to Zero
NZDSF	Non-Zero Dispersion Shifted Fibre
ODF	Optical Distribution Frame
OEO	Optical Electrical Optical
OSC	Optical Supervisory Channel
OSNR	Optical Signal to Noise Ratio
OTS	Optical Transport Section
PLL	Phase Locked Loop
PMD	Polarization Mode Dispersion
PRBS	Pseudo Random Bit Sequence
PTP	Precision Time Protocol
ROADM	Reconfigurable Optical Add and Drop Multiplexer
RX	Receiver
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
SSMF	Standard Single Mode Fibre
TFT	Time and Frequency Transfer
TRX	Transceiver
TX	Transmitter
WR	White Rabbit
WSS	Wavelength Selective Switch
XPM	Cross Phase Modulation

References

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[3] ITU-T G.652 standard

[4] ITU-T G.655 standard

[5] http://www.ohwr.org/projects/white-rabbit/documents