



**TIMEFUNC
White Rabbit
Good Practice Guide**

02 May 2019

VSL

Thijsseweg 11
2629 JA Delft
Postbus 654
2600 AR Delft
Nederland

T +31 15 269 15 00

F +31 15 261 29 71

E info@vsl.nl

I www.vsl.nl

This work has been carried out by: VSL
On request of: EMPIR MSU



This work is published under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license

Document control

Document Title	WR Good Practice Guide
Document Code	15SIP04_TIMEFUNC_D3

Author	Erik Dierikx	
Author	Yan Xie	
Reviewer		

Version	Date	Description
1.0	2 May 2019	The first version of this document.

Table of contents

Document control	3
Table of contents	4
List of Abbreviations	5
1 Introduction	6
1.1 TIMEFUNC	6
1.2 White Rabbit Terminology	6
2 WR link and network design	7
2.1 General	7
2.2 Hardware	7
2.2.1 WR hardware	7
2.2.2 SFPs	7
2.2.3 Fibres and connectors	8
2.2.4 Wavelength multiplexers/demultiplexers	9
2.2.5 Bi-directional optical amplifiers	9
2.3 Budgetary considerations	9
3 Optical delay calibration	11
3.1 Introduction	11
3.2 Measurement method	11
3.3 Performing the calibration	13
3.4 Traceability	14
3.5 Uncertainty calculation	14
4 WR Switch and Time Node calibration	16
4.1 Introduction	16
4.2 The calibration problem	16
4.3 Equipment requirements	17
4.4 Reference WR Calibrator calibration	18
4.5 Derived WR Device calibration	20
4.6 Uncertainty evaluation	21
5 Fibre delay asymmetry calibration	23
5.1 Introduction	23
5.2 Fibre delay asymmetry calibration method	23
5.3 Detailed calibration procedure	24
5.4 Uncertainty analysis	29
5.5 Fibre asymmetry calibration of a multi-section link	30
6 Link management	32
6.1 Introduction	32
6.2 Connection strategy	32
6.3 Communication protocols and Software tools	33
6.4 Instrument settings	33
6.5 Parameters to monitor	33
References	35

List of Abbreviations

BC	Boundary Clock
CWDM	Coarse Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
HTTP	Hypertext Transfer Protocol
NTP	Network Time Protocol
PPS	Pulse Per Second
PTP	Precision Time Protocol
SFP	Small Form-factor Pluggable optical transceiver module
SNMP	Simple Network Management Protocol
SSH	Secure SHell protocol
UTP	Unshielded Twisted Pair
WR	White Rabbit
WDM	Wavelength Division Multiplexing filter

1 Introduction

1.1 TIMEFUNC

The first version of this document was developed within the framework of the EMPIR project 15SIP04 TIMEFUNC, with funding from the European Metrology Programme for Innovation and Research (EMPIR) co-financed by the Participating States and in part by the European Union's Horizon 2020 Research and Innovation Programme. Further financial support has been received from the Dutch Ministry of Economic Affairs and Climate

The TIMEFUNC project stands for "Time Synchronisation IMPact Enabling FUture Network Communication". This project is intended to stimulate the take up of the White Rabbit (WR) Precision Time Protocol (PTP) for accurate time and frequency transfer via optical fibre networks for industrial and commercial application. This 'WR Good Practice Guide' should support new and existing user of the WR technology in building WR networks for transferring time and frequency signals that are traceable to SI units with metrological accuracy. Therefore, this guide emphasizes calibration techniques for all relevant components in the WR network. The document is written from a user's perspective rather than from a WR developer's perspective.

The authors are aware that this document is not complete and reflects only the current insights of the authors. Others are invited to further complement this document, and if necessary, modify the contents with new insights.

1.2 White Rabbit Terminology

White Rabbit (WR) is a time and frequency transfer technique suitable for optical fibre networks. A lot of information about WR can be found on the White Rabbit project website in the Open Hardware Repository, <https://www.ohwr.org/projects/white-rabbit/wiki> [1].

In a WR link, time and frequency are transferred from a **master** device to a **slave** device.

A **WR grand master** is a WR master device which receives accurate time and frequency from an external clock by means of 10 MHz and 1 PPS signals.

A **WR boundary clock** (BC) is a device which is both master and slave at the same time. On a slave port, the BC receives time from a master, and on a master port, the BC provides time to one or more other slave devices.

2 WR link and network design

2.1 General

The design of WR links can vary from a single link between a WR master and a WR slave to an entire network of one or more WR masters to many WR slaves. Although for continuity of service, deployment of redundant links is to be recommended in situations where high reliability is required, this document will not go into these kinds of details. At the time of writing this document, features for support of redundant links are being developed and implemented in the WR firmware.

This document focuses on 2 specific use cases:

- 1) efficient dissemination of time and frequency from a single WR master to multiple WR slaves within a building. The fibre lengths in this case are typically less than 100 m.
- 2) time and frequency transfer over long distance optical fibre links from one WR master to one WR slave.

2.2 Hardware

2.2.1 WR hardware

WR hardware is available in a few different flavours from several providers.

- WR switch
- WR switch with low-jitter daughter board.
- WR SPEC
- WR time node / WR LEN
- ...

Use case 1:

For point to multi point dissemination, the WR master or grandmaster is typically a WR switch. Depending on the number of end-points, one or more layers of intermediated WR switches may be required.

For the end-points, typically WR time nodes, WR LENs or WR SPECs are used.

Use case 2:

For setting up a long distance WR link, the WR hardware typically consists of two WR switches. The main reason for this is that for the fibre asymmetry calibration on the WR master at least three ports are required and at the WR slave two ports are required. Another reason is that, currently, the stability performance of the WR switch is slightly better than the WR SPEC, WR time node and WR LEN devices.

2.2.2 SFPs

SFPs (small form-factor pluggable transceivers) are the interfaces between the electrical and optical domain of the signals used for the time and frequency transfer. SFPs are standard telecom and network devices, available from many suppliers and in a variety of wavelengths and transmit rates.

Looking at [1], it is stated that White Rabbit should follow the 1000BASE-BX10 standard and use 1310/1490 pairs with a single LC connector. More specifically, the Switch ports transmitting downstream (to endpoints) should use 1490 nm on the transmitter and 1310 nm on the receiver.

Use case 1

In a network of limited physical dimensions, using the wavelengths 1490 nm and 1310 nm is a reasonable choice. SFPs for these wavelengths are well available for a reasonable price. The difference between the wavelengths is

significant, but on a short fibre link, the effect of chromatic dispersion will remain small and will not significantly affect the time transfer (even without calibration of the fibre delay asymmetry).

Use case 2

On long distance WR links, effects of chromatic dispersion will be significant. To keep this effect as small as possible, besides the calibration of the fibre delay asymmetry, the wavelengths can be selected as close together as possible. Standard telecom networks typically use either coarse wavelength division multiplexing (CWDM) or dense wavelength division multiplexing (DWDM). For CWDM, the minimum spacing between two separate wavelengths is 20 nm, and for DWDM, this is 0.8 nm. WR will work with both CWDM and DWDM wavelength spacing, however, since the wavelength of lasers in DWDM SFPs is better stabilized than for CWDM SFPs, the best performance will be obtained with DWDM wavelengths, especially when the two wavelengths are selected close to each other.

Furthermore, for long distance WR links, the optical power budget should be taken into account. The optical power budget is the ratio of the optical output power from the laser transmitter with respect to the minimum required optical receive power of the photo diode receiver. The optical power budget should be larger than the total attenuation of the fibre link. Nowadays, SFPs are available with a power budget of up to 40 dB. This is typically enough to cover a fibre distance of about 120 km without the need for optical amplifiers.

Some examples of SFPs for long distance links are:

Stable Technology Co., Ltd. 1.25G CWDM 120 km, 1490nm

Stable Technology Co., Ltd. 1.25G CWDM 120 km, 1470nm

FLEXOPTIX 1.25G DDM SFP 1490nm 160 km S.1612.41.LD

FLEXOPTIX 1.25G DDM SFP 1470nm 160 km S.1612.41.KD

SOLID-OPTICS SFP-DWDM31-37dB+, 1.25G, 150 km, TX Wavelength: 1552.52

SOLID-OPTICS SFP-DWDM33-37dB+, 1.25G, 150 km, TX Wavelength: 1550.92

SFPs can have either a single, combined in- and output port, so-called bi-directional (bidi) SFP, or can have separate transmit and receive ports. In the latter case, a wavelength multiplexer and a demultiplexer are required for combining the forward and reverse signal into the same fibre. The multiplexers introduce additional asymmetry and thus uncertainty in the time transfer. SFPs with high output power, for covering long distances, are typically non-bidi SFPs. For distances up to 10 km, bidi SFPs are easily available.

Note: Standard Copper SFP modules give a bad WR timing performance

However, for connecting PC network cards to a switch or applications where the high timing resolution of WR is not needed, Gigabit Ethernet copper SFP's may be used. Data transfer will work as expected, but the timing part of White Rabbit will be severely impacted. The copper SFPs to be used should follow the 1000BASE-T standard and the same module type can be used on both sides (switch and PC or other end node).

2.2.3 Fibres and connectors

Fibres and fibre patches are available with a wide variety of connectors. For time transfer, it is recommended to use angle-polished, physical contact connectors (APC) connectors. The angle-polished connector causes less reflection of light into the fibre. The reflections cause so-called multi-path effects and can make the time transfer noisier.

Most SFPs don't have APC connectors; they have LC/UPC connectors.

It is strongly recommended to use single mode fibres. Fibres following the G652 recommendations [5] should work well. This fibre is optimised for 1310nm, which compensates for the dispersion wavelength of the worst of the two wavelengths used. For any wavelengths in the range between 1470 nm and 1550 nm, proper operation of long distance WR links has been demonstrated as well. The attenuation of G652 fibre for this range of wavelengths is typically around 0.2 dB/km.

In long links, effects from polarisation mode dispersion and chromatic dispersion increase and may affect the communication between WR devices. Polarisation mode dispersion may cause fading of the signal and therefore may cause a loss of lock of the WR slave. Chromatic dispersion, besides fibre delay asymmetry, may cause some additional jitter in the time transfer. Especially in very long links with one or more amplifiers, the dispersion may cause so much distortion of the signal that regular packet transfer is no longer possible. In this case, the lock of WR slave will be lost. As a remedy to this problem, one of the amplifiers can be replaced with a WR switch in boundary clock mode. This WR boundary clock will effectively regenerate the timing signal. The authors of this document have not performed any experiments to estimate or evaluate effects of dispersion on WR time transfer.

Although single mode fibres are recommended for building WR links, multimode fibres can also work well on connections of up to some tens of meters. The performance may become noisier, because the path delay is not as well defined.

2.2.4 Wavelength multiplexers/demultiplexers

In small scale networks, the use of wavelength (de)multiplexers (WDM) can often be avoided by using bi-directional SFPs. However, in cases where WR-link needs to be combined with other data traffic over the same fibre, WDMs would still be required for merging and unmerging the wavelengths.

On long distance WR links, the use of WDMs is often unavoidable. Bi-di SFPs with a high power budget required for covering distances up to 100 km or more don't exist. So, for these applications two-port SFPs are used with separate transmit and receive ports. The transmit and receive wavelengths need to be merged/unmerged at each end of the link.

WDM are commercially available from several vendors. Most commercial products apply regular CWDM or DWDM multiplexing schemes. When purchasing WDMs, make sure that the WDM wavelengths match with the selected SFP wavelengths.

2.2.5 Bi-directional optical amplifiers

For building WR links of more than 100 km or for building WR links on fibres with high losses, it might be required to amplify the signal somewhere on the way. Several types of optical amplifiers are available. However, not all are suitable for this specific application. Since WR uses bi-directional transfer in a single fibre, the amplifier should also be bi-directional. To avoid lasing effects from amplified back reflected signals, the amplifier should be selective in the wavelength range it amplifies. This makes the popular erbium doped fibre amplifier (EDFA) less attractive for this purpose. A better solution is a quasi bi-directional amplifier based on a design described in [6] and [7], using semiconductor optical amplifiers combined with WDMs for the wavelength selection (Figure 1). This type of amplifier is nowadays also commercially available.

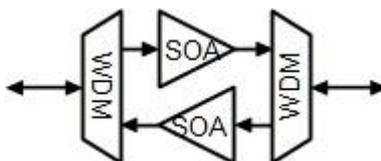


Figure 1. Schematic diagram of an SOA-based quasi bi-directional optical amplifier.

2.3 Budgetary considerations

Compared to other available techniques for optical fibre time and frequency transfer, WR has a very favourable performance to cost ratio. The basic equipment for setting up a WR link (the master and slave device) is significantly less expensive than equipment required for other techniques with performance at about the same level of accuracy.

Use case 1

In a small-scale network, the following recommendations apply:

- Using optical fibre infrastructure that is already available can save costs of installing new fibres.
- Even if the existing infrastructure is built from multimode fibres, as long as the distances are short, WR can still work over these fibres.
- In networks with many end-nodes, choosing the most efficient network topology will keep the number of WR boundary clocks to a minimum and thus reduce costs of hardware.
- Using standard CWDM telecom wavelengths offers a large selection of available SFPs that are relatively cheap.

Use case 2

- For building long distance WR links, the high part of the costs is the lease of optical fibres. It is therefore recommended to negotiate well with owners, providers and brokers for optical fibres. Currently, providers of optical fibre are still hard to convince that WR time and frequency transfer will not interfere with other services on the same fibre but on different wavelengths. Therefore, the provider will probably offer an expensive dark fibre, while just two wavelengths is enough for WR. Examples of WR and other data traffic over the same fibre already exist. So, this can be used in new negotiations.

In the negotiations, be aware that contracts for longer duration may be significantly cheaper than short term contracts.

- Another important contribution to the cost is the number of amplifiers on the link. It is therefore recommended to minimize all attenuations and furthermore select a fibre route with convenient hosting location for the amplifiers.

- An alternative to the use of an amplifier is using a WR boundary clock at an intermediate location. The boundary clock will introduce additional uncertainty (both statistical and systematic) in the time and frequency transfer, but the boundary clock is less expensive than an amplifier. In very long links with multiple amplifiers, replacing an amplifier with a WR boundary clock may help to increase the stability of optical power levels along the link, as the signal is effectively regenerated by the boundary clock SFP.

- In the design of the link there is a trade-off between performance and cost when it comes to the selection of wavelengths. Using DWDM wavelengths that are close together will improve the accuracy, because the effect of chromatic dispersion is smaller, but DWDM SFPs and WDMs are significantly more expensive than CWDM equipment.

3 Optical delay calibration

3.1 Introduction

This procedure is meant to determine the time delay and or time delay asymmetry of components to be used in a White Rabbit optical fibre time transfer link. This procedure applies to: fibre patch cables, wavelength division multiplexers, optical amplifiers, optical attenuators.

3.2 Measurement method

The method is suitable for measuring time delays of optical components of up to 1 ms. The resolution of the measurement is 1 ps.

The estimated uncertainty of this calibration procedure is dependent on the quality of the reference frequency signal used in the calibration setup and has a minimum of approximately 20 ps.

A schematic diagram of the measurement set-up is shown in Figure 2 and the list of required equipment is given in Table 1.

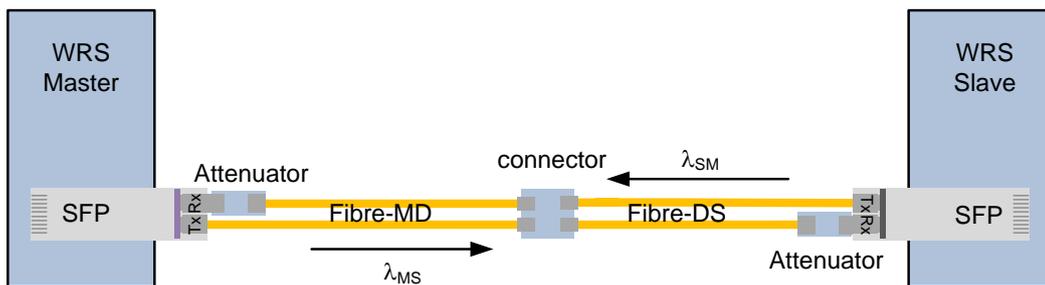


Figure 2. Calibration set-up for time delay of optical components for optical fibre time transfer links

Table 1. List of equipment

Equipment	ID	Description
WR master device	WRS-Master	The devices can be either WR switches, WR SPEC-boards, WR Time node or other formats of WR equipment. So far, the best results have been obtained with a pair of WR switches.
WR slave device	WRS-Slave	
SFP for master	SFP-Master	Currently, WR equipment requires SFP with 1 Gb/s data transfer rate. The SFP in the WR master device shall transmit at wavelength λ_{MS} and the SFP in the WR Slave device shall transmit at wavelength λ_{SM} . These wavelengths λ_{MS} and λ_{SM} shall be the same as the wavelength used in the application of the device under calibration. Non-bi-directional SFPs shall be used for this purpose. The transmit power of the SFPs is not very critical in this set-up, however, if the power is too high for receiver on the opposite end of the setup, attenuators should be applied at the receive port of the SFPs for protection of the photo diode. Typically, SFPs are equipped with LC connectors.
SFP for slave	SFP-Slave	

2x duplex fibre patch cord	Fibre-MD Fibre-DS	2 Duplex single mode fibres, with LC/UPC connectors on one end, and on the other end, connectors that match the device to be calibrated. The length of the fibre patch cords is not very critical; approximately 1 m to 2 m is recommended.
Fibre connector	Fibre connector	Optical fibre through adapter. The type of connector on this adapter shall match the connector type of the device to be calibrated.
Optional: Attenuator 2x	Attenuator	2 optical attenuators of nominally the same value. The value depends on the output power of the SFP transmitters and the maximum allowed input power of the SFP receivers.
Optional: Mechanically tuneable attenuator	(not shown)	For the calibration of an optical amplifier, inserting a mechanically tuneable attenuator in addition to the fixed attenuator is required to compensate for the gain of the amplifier.
Optical power meter	(not shown)	Optical power meter to measure the output power and input power of the SFPs.
Optional: Reference clock	(not shown)	10 MHz and 1PPS reference signals from a reference oscillator or timescale realisation to be provided to the WRS-master for operation in grandmaster mode.
Optional: Reference frequency counter	(not shown)	In case the WRS-master is operated in free-running master mode, a calibrated frequency counter shall be used to measure the frequency offset of the master oscillator.
Computer	(not shown)	A computer connected to the management port of the WRS-slave for collecting the measurement data.

The method of measurement is based on the measurement of a round-trip-time (rtt) of the WR signals from the WRS-master to the WRS-slave and back to the WRS-master. The measurement is first performed with the setup as shown in Figure 2 to determine the delay of the calibration setup itself. In the second step, the fibre connector is replaced by the device under test (DUT) as shown in Figure 3 and Figure 4. The delay of the DUT is found from the difference in round-trip-time between the second and the first measurement.

For collecting data from the WR device, it is recommended to follow the instructions in the user's manual [2], [3]. For example, when using a WR switch in combination with a Windows computer, PuTTY software can be used, either via the Ethernet management port of the WR switch or via the USB serial port of the WR switch.

For subsequent data processing, your favourite data processing tools can be used.

The customer should specify explicitly at which wavelength the calibration shall be performed, and whether the device is intended for CWDM or DWDM networks.

In case of the calibration of the delay of an amplifier, the nominal optical input power and nominal gain shall be specified.

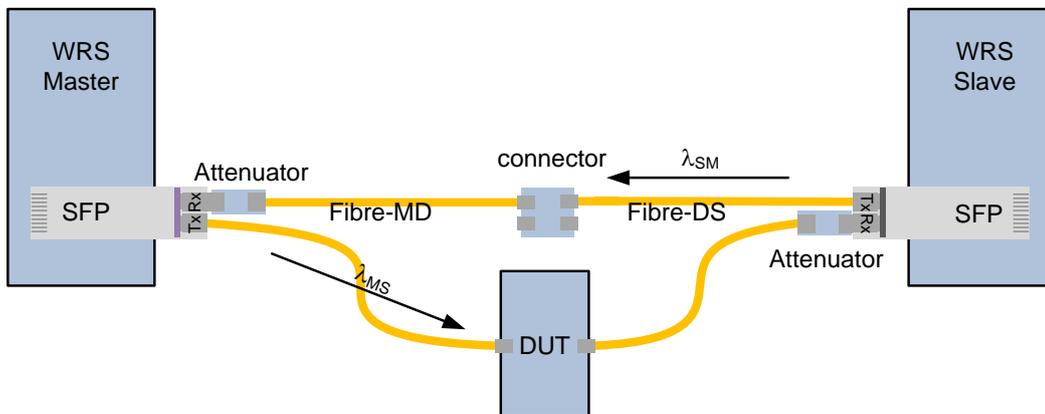


Figure 3. Set-up for DUT delay calibration at λ_{MS}

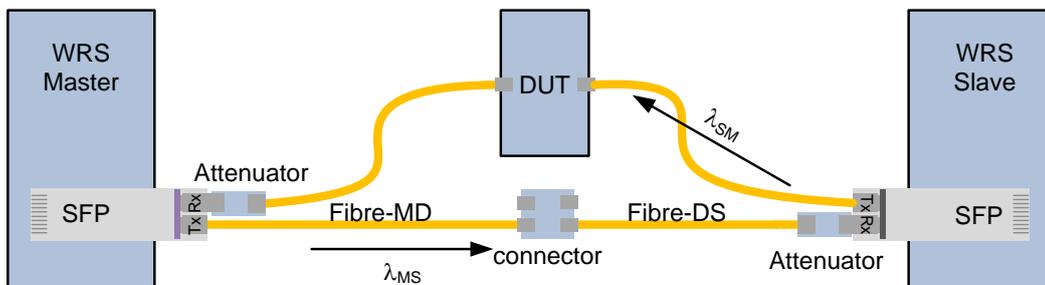


Figure 4. Set-up for DUT delay calibration at λ_{SM}

3.3 Performing the calibration

- in case of a WR grandmaster, verify that the master is locked
- in case of free running master, measure the frequency offset of the WR master oscillator with a calibrated frequency counter.
- Select appropriate SFPs with the required CWDM or DWDM wavelengths
- Insert the SFPs in the WR devices and measure the optical output power.
- Select appropriate attenuators. Check the minimum and maximum input power of the selected SFPs. Select the attenuators such that the receiver power is below the maximum input power and well above the minimum input power of the SFP receiver. Insert the attenuators into the receive ports of the SFPs.

For the delay calibration of an optical amplifier, insert a mechanically tuneable attenuator in the path in which the amplifier will be inserted and set the attenuator to minimum loss.

- Connect the SFP transmitters to the fibre patch cords as in Figure 2. For calibration of an optical amplifier, include the tuneable attenuator.
- Measure the optical power at the fibre output and verify that the power level minus the attenuator loss is within the input range of the SFP receiver.

Connect the fibres to the receivers of the SFPs via the attenuators.

- Verify that the WR protocol starts by monitoring the data from the WR-slave. The servo status shall indicate TRACK_PHASE.

Monitoring of a WR switch can be done by connecting a PC to the WR switch via SSH and then run:

```

wr_mon
Use 'q' to stop wr_mon.

```

- Start the data collection. It's recommended collecting at least 300 s of data, divided in 5 sets of 60 s. After each set of 60 s, disconnect and reconnect the fibre to restart the WR PTP protocol.

On a Windows PC, use PuTTY to connect the PC to the WR switch via SSH and use the logging setting to store the data in file.

On a Linux PC, an SSH session can be directly from a command line terminal:

```
ssh root@<x.x.x.x>
```

The data collection is started by issuing the command:

```
wr_mon -ei
```

The data collection is stopped by pressing the ESC-key.

- Use your favourite data processing tools to extract the corrected round-trip-time (cr_{tt}) from the logged files. The computed average value is d_{offset} and $s(d_{offset})$ is the standard deviation in the measurements.

- Insert the DUT in the fibre path. Depending on the required wavelength, use the configuration as shown either in Figure 3 or in Figure 4.

Note on the delay calibration of optical amplifiers: The delay of the receiver in an SFP is power dependent. Therefore, it is important to attenuate the optical power coming from the amplifier to the same level as in the offset measurement. The attenuation can be done by means of a mechanically tuneable attenuator.

- Restart the data collection and collect again at least 300 s of data, divided in 5 sets of 60 s.

- Extract the cr_{tt} again from the logged files. The computed average value is d_{meas} and $s(d_{meas})$ is the standard deviation in the measurements.

- The optical time delay of the DUT is: $d_{DUT} = d_{meas} - d_{offset}$

3.4 Traceability

The delay measurement described in this procedure is based on the difference between two cr_{tt} measurements. The cr_{tt} measurement is based on the frequency of the internal oscillator of the WR switch. This oscillator can be locked to an external oscillator.

Traceability of the time delay measure to the SI second is obtained from a calibrated reference timescale in case the WR master switch receives an input 1PPS and 10 MHz signal, and is configured in grandmaster mode. Alternatively, when the WR master is operating in free-run mode, the traceability can be obtained by measuring the 10 MHz output from the WR switch with a calibrated frequency counter.

3.5 Uncertainty calculation

The optical time delay of the DUT is:

$$d_{DUT} = d_{meas} - d_{offset} \quad (1)$$

The delay measurement d can be written as $d = n / f$

f = frequency of the internal oscillator which is nominal 62.5 MHz; $1 / f = 16$ ns.

n = the number of periods of the internal oscillator fit into the measured interval. With the digital dual mixer time difference (DDMTD) phase detector, the resolution of n is approximately $1 / (2^{14})$, which corresponds to a time delay of about 1 ps.

The uncertainty in the delay measurement, $u(d)$, has one absolute component $u(d_{abs})$ related to the resolution of n and one relative component related to the uncertainty in the frequency of the internal oscillator $u(d_{rel})$.

$u(d_{abs})$: The resolution of the phase detector of the DDMTD is $(1 / 2^{14}) \cdot (1 / f) = 1$ ps. Each delay measurement includes two DDMTD readings. Therefore, the combined uncertainty $u(d_{abs})$ is estimated to be 2 ps.

$u(d_{rel})$: The delay measure is derived from the frequency of the internal oscillator, running at 62.5 MHz. This oscillator can be either free running or locked to an external reference source (grandmaster mode). The relative uncertainty of the internal oscillator frequency depends on its lock status:

- free running: $u(f) = u(d_{rel}) = 1 \times 10^{-7}$ Hz/Hz
- free running, but calibrated by frequency counter: $u(f) = u(d_{rel}) = 1 \times 10^{-9}$ Hz/Hz
- lock to external reference (grandmaster mode): $u(f) = u(d_{rel}) = 1 \times 10^{-11}$ Hz/Hz

Quantity	Value		std. unc.		distribution	sensitivity		unc. contribution	
d_{meas_rel}	920	ns	1.00E-07	s/s	normal	920	ns	0.000	ns
d_{meas_abs}	920	ns	0.002	ns	normal	1		0.002	ns
d_{offset_rel}	900	ns	1.00E-07	s/s	normal	900	ns	0.000	ns
d_{offset_abs}	900	ns	0.002	ns	normal	1		0.002	ns
$std(d_{DUT})$			2.00E-02	ns	normal	1		0.020	ns
d_{DUT}	20	ns			tot. unc.	$k=1$		0.020	ns
					Exp. Unc.	$k=2$		0.040	ns

Notes for delay calibration of optical amplifiers.

The delay of the receiver in an SFP is power dependent. Therefore, it is important to attenuate the optical power coming from the amplifier to the same level as in the offset measurement. The attenuation can be done by means of a mechanically tuneable attenuator. The attenuation principle is based on a small air gap in an optical fibre. The width of the gap is variable. This attenuator is continuously adjustable and the influence of the attenuation setting on its delay is very small. For example, extending the gap from 0 mm to 1 mm has an effect on the delay d_{att} of:

$$d_{att} = l_{gap} / c = 1 \times 10^{-3} \text{ m} / 3 \times 10^8 \text{ m/s} = 3 \times 10^{-12} \text{ s.}$$

The estimate actual displacement is less than 1 mm, so the contribution of d_{att} is less than 3 ps.

4 WR Switch and Time Node calibration

4.1 Introduction

This section discusses the delay calibration of WR equipment. This is mainly information taken from the dedicated WR calibration sections [8] of the www.ohwr.org website and the calibration method should be the same as the one described in the WR calibration document [9]. This document will only discuss the relative calibration procedure for WR equipment; the absolute calibration procedure so far is not included.

With **WR equipment** or **WR Device** is meant: any device that supports WR synchronization over an optical link. This can be e.g. the WR Switch, the SPEC board, or any custom hardware made for a specific application. A WR Device can run as WR master or/and WR slave.

For the relative calibration, a **WR Calibrator pair** is defined as: any pair of WR master and slave devices selected from the available set that is used as a reference to calibrate the rest of the WR devices used in a synchronization system.

4.2 The calibration problem

In section 3, it was already explained that the WR protocol uses round-trip time measurements for establishing two-way time transfer. In this section, further details of this round-trip time measurement are explained for understanding the specific need for calibrations to achieve accurate time transfer.

A WR link established between two devices is characterized with hardware delays and fibre propagation delays as presented in Figure 5. The fibre propagation delay of a short patch fibre can be determined with the method explained in section 3, so therefore one-way fibre delays δ_{MS} and δ_{SM} are here considered to be known. In this section about the calibration of WR device internal delays, it is assumed that the fibre used for connecting the WR slave to the master is short; e.g. 1 or 2 m. The fibre delays are constant for the duration of the calibration and the effect of fibre delay asymmetry is small enough to be neglected or is known and can be corrected for. (The detailed procedure to determine the fibre asymmetry parameter α for long fibre links will be discussed in section 5.)

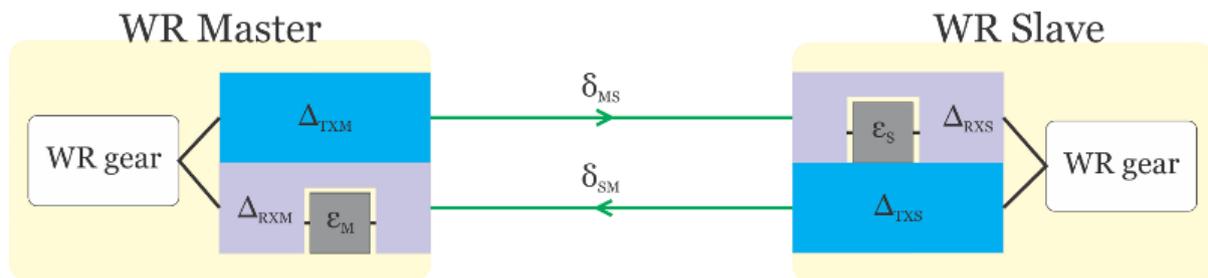


Figure 5. WR link delay model

Each WR Master and WR Slave has some constant transmit and receive delays:

Δ_{TXM} : transmit delay of WR Master:

Δ_{RXM} : receive delay of WR Master

Δ_{TXS} : transmit delay of WR Slave

Δ_{RXS} : receive delay of WR Slave

They are the summed delays of SFP transceivers, PCB traces and electronic components as well as the delays inside the FPGA chip. Additional receive delay is also caused on both sides by aligning the recovered clock signal to the inter-symbol boundaries of the data stream. This is called the bit-slice value and is marked in Figure 5 as:

ϵ_M - bit-slice of master receive path

ϵ_S - bit-slice of slave receive path

Based on these parameters the round-trip delay (Δ_{MM}) is defined as the sum of all delay contributions described above:

$$\Delta_{MM} = \Delta_{TXM} + \Delta_{RXS} + \varepsilon_S + \Delta_{TXS} + \Delta_{RXM} + \varepsilon_M + \delta_{MS} + \delta_{SM} \quad (2)$$

However, since the bit-slide values can be easily obtained from the WR software, the calibration procedure described in this document uses a modified round-trip delay, without ε_M and ε_S :

$$\Delta'_{MM} = \Delta_{MM} - \varepsilon_M - \varepsilon_S = \Delta_{TXM} + \Delta_{RXS} + \Delta_{TXS} + \Delta_{RXM} + \delta_{MS} + \delta_{SM} \quad (3)$$

In the synchronization process, the PTP daemon tries to calculate the current offset between the slave and master clock. For that, it needs a precise estimation of the one-way link delay which, using the described link model, is the sum of four contributions:

$$\Delta_{MS} = \Delta_{TXM} + \delta_{MS} + \Delta_{RXS} + \varepsilon_S \quad (4)$$

The calibration procedure described in this document is required because the values of the hardware transmit and receive delays (Δ_{TXM} , Δ_{RXM} , Δ_{TXS} , Δ_{RXS}) are still unknown. This prevents from estimating Δ_{MS} as half of the round-trip Δ_{MM} , and therefore prevents from automatic alignment of the 1PPS output of the slave to the 1PPS output of the master.

4.3 Equipment requirements

The calibration procedure described in this document makes no assumption on what kind of WR devices will be used as the reference WR Calibrator pair. However, there are a few general requirements listed below:

- the two WR devices to be selected as the reference WR Calibrator pair shall be two exactly the same WR devices, having the same PCB design, the same bitstream downloaded into the FPGA and using complementary SFP transceivers (the same producer, and matching Tx/Rx WDM wavelengths);
- all WR Devices (i.e. the Calibrator and devices under calibration) shall be capable of producing 1PPS output signals from their local clock and providing it through an on-board connector or test point;
- two coaxial cables of the same delay or different but known delays shall be used for connecting the 1PPS outputs of the WR devices to the time interval counter or oscilloscope, so that a correction can be made for all 1PPS difference measurements described in the document;
- a time interval counter, oscilloscope or any other device that is able to measure time intervals of less than 1 ns for measuring 1PPS time differences.

Initial state

Initially, none of the transmit / receive delays or asymmetry of WR devices are known. Therefore, the values of appropriate parameters should be set to 0 in the configuration file of all nodes and switches which will be calibrated. In the WR PTP Core (for WR SPEC) this can be done by modifying the SFP database and setting Δ_{TX} , Δ_{RX} and α values to 0 for all supported transceivers.

For the WR switch, please, modify the `/wr/etc/dot-config` file on the switch as shown in the example below.

Firmware v5.0 / Hardware v3.4 / v3.3 (7Solutions and Creotech)

```
#
# Port Timing Configuration
#
CONFIG_PORT01_PARAMS="name=wri1,proto=raw,tx=0,rx=0,role=slave,fiber=0"
CONFIG_PORT02_PARAMS="name=wri2,proto=raw,tx=0,rx=0,role=master,fiber=0"
#
# SFP and Media Timing Configuration
#
CONFIG_SFP00_PARAMS="vn=Axcen Photonics,pn=AXGE-1254-0531,tx=0,rx=0,wl_txx=1310+1490"
CONFIG_SFP01_PARAMS="vn=Axcen Photonics,pn=AXGE-3454-0531,tx=0,rx=0,wl_txx=1490+1310"
CONFIG_FIBER00_PARAMS="alpha_1310_1490=0"
```

4.4 Reference WR Calibrator calibration

Having the parameters of fibre δ_f measured, a WR Calibrator pair has to be selected among the set of available WR devices. The only constraint for the selection is having two instances of the same device for the calibration procedure described here. They must have the same PCB layout and the same FPGA bitstream.

To determine the transmit and receive delays (Δ_{TX} , Δ_{RX}) of the WR Calibrator, one of the connections shown in Figure 6 has to be established. Set-up A is used for bi-directional SFPs and set-up B is used for non-bi-directional SFPs as would be used for establishing a long WR link. (Note that in set-up B two identical attenuators are included at the Rx ports in case the transmit power from the lasers is too high for a direct connection.)

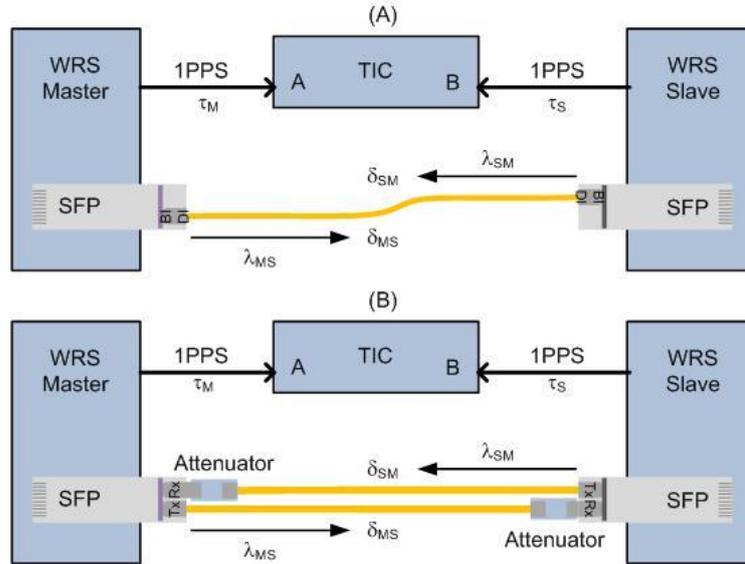


Figure 6. Set-ups for measuring reference WR Calibrator delays. Set-up A uses a single fibre for bi-directional SFPs and set-up B uses a duplex fibre for non-bi-directional SFPs.

1. Since both master and slave are exactly the same devices (the same FPGA bitstreams, PCB layout, complementary SFPs from the same producer) the sum of their TX and RX latencies is assumed to be equal:

$$\Delta_{TXM} + \Delta_{RXM} = \Delta_{TXS} + \Delta_{RXS} \quad (5)$$

This means that the total transmit + receive delay caused by each of those devices can be determined by simply dividing the round trip delay without the RX bitslides values and the fibre round-trip delay by a factor of 2:

$$\Delta_{TXM} + \Delta_{RXM} = \Delta_{TXS} + \Delta_{RXS} = (\Delta'_{MM} - \delta_{MS} - \delta_{SM}) / 2 \quad (6)$$

Starting from the initial state with all Δ_{TX} and Δ_{RX} values set to zero, Δ'_{MM} can be read from the WR device as *crtt*.

2. Naturally, the reference WR Calibrator has some internal asymmetry, which means that $\Delta_{TX} \neq \Delta_{RX}$. There are two ways to determine the exact values of Δ_{TX} and Δ_{RX} .

- It can be done either by establishing a WR link with a WR Device having a well-known internal asymmetry which is not available since all other devices will be calibrated with respect to the reference WR Calibrator;
- or, it can be done by taking apart the Calibrator and measuring the delays of PCB traces, electronic components, SFP transceivers - that is possible, not trivial at all, and raises many other problems like measuring the delay between the SFP electrical input and its optical output and measuring the delay inside the FPGA chip.

Therefore, at this point an assumption is made that the WR Calibrator has no asymmetry:

$$\Delta_{TX} = \Delta_{RX} \quad (7)$$

This means that as a first estimate, the parameters describing the transmit and receive delays of both WR Calibrator devices are set in the configuration to:

$$\Delta_{TX_est} = \Delta_{RX_est} = \frac{crtt - \delta_{MS} - \delta_{SM}}{4} \quad (8)$$

3. Configure WR Calibrator devices with the estimated Δ_{TX_est} and Δ_{RX_est} values. This is done, either by modifying the /wr/etc/dot-config file for WR switches or by modifying the SFP database for the WR PTP Core.

After inserting these parameters in the configuration, the difference between the 1PPS signal from the master and the 1PPS signal from the slave can be measured with an oscilloscope or a time interval counter (TIC). The difference, after correcting for the 1PPS cable delays is expected to be within 1 ns.

4. For fine-tuning of the parameters, with the set-up from Figure 6, collect the TIC measurements from 5 series of measurements of about 5 minutes (300 samples) and before each series restart the PTP daemon. Compute the averages of all TIC values.

Note: *In this step of the calibration, it is crucial to take into account the trigger level of the TIC and the internal offset of the TIC. The trigger level selected during the calibration shall be used for all further use of the calibrated devices. For our experience, well-reproducible results can be obtained at a trigger level of 0.5 V.*

The internal offset of the TIC (or oscilloscope) shall either be calibrated and corrected for, or shall be eliminated from the measurement by exchanging the 1PPS signals at the input of the counter.

$$TIC_{MS} = \frac{(TIC_{MS} + TIC_{offset}) - (TIC_{SM} + TIC_{offset})}{2}$$

The new parameter values can now be determined from:

$$\begin{aligned} \Delta_{TXM} &= \Delta_{TXM_est} + \frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S)) \\ \Delta_{RXM} &= \Delta_{RXM_est} - \frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S)) \\ \Delta_{TXS} &= \Delta_{TXS_est} - \frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S)) \\ \Delta_{RXS} &= \Delta_{RXS_est} + \frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S)) \end{aligned} \quad (9)$$

where TIC_{MS} is the average TIC reading with the 1PPS signal from the master connected to channel A and the 1PPS signal from the slave connected to input channel B,

and where τ_M and τ_S are the 1PPS coaxial cable delays from respectively the master and the slave.

Proof:

If T_M and T_S are the timescales from the 1PPS outputs of the WR master and WR slave respectively, the relation between these two is described by:

$$T_S = T_M - \Delta_{TXM} - \delta_{MS} - \Delta_{RXS} + \frac{1}{2}crtt + \Delta_{TXM_est} + \Delta_{RXS_est}$$

Taking into account the 1PPS cable delays:

$$(T_S - \tau_S) = (T_M - \tau_M) - \Delta_{TXM} - \delta_{MS} - \Delta_{RXS} + \frac{1}{2}crtt + \Delta_{TXM_est} + \Delta_{RXS_est} + (\tau_M - \tau_S)$$

So, the measured time difference from a TIC or oscilloscope is:

$$TIC_{MS} = (T_M - \tau_M) - (T_S - \tau_S) = +\Delta_{TXM} + \delta_{MS} + \Delta_{RXS} - \frac{1}{2}crtt - \Delta_{TXM_est} - \Delta_{RXS_est} - (\tau_M - \tau_S)$$

where $\delta_{MS} = \frac{1}{2}crtt$, because the asymmetry on the short fibre is negligible.

Thus:

$$TIC_{MS} = +\Delta_{TXM} + \Delta_{RXS} - \Delta_{TXM_est} - \Delta_{RXS_est} - (\tau_M - \tau_S)$$

or after rearranging:

$$TIC_{MS} + (\tau_M - \tau_S) = (\Delta_{TXM} - \Delta_{TXM_est}) + (\Delta_{RXS} - \Delta_{RXS_est})$$

Assuming $(\Delta_{TXM} - \Delta_{TXM_est}) = (\Delta_{RXS} - \Delta_{RXS_est})$:

$$(\Delta_{TXM} - \Delta_{TXM_est}) = (\Delta_{RXS} - \Delta_{RXS_est}) = \frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S))$$

and

$$(\Delta_{TXS} - \Delta_{TXS_est}) = (\Delta_{RXM} - \Delta_{RXM_est}) = -\frac{1}{2}(TIC_{MS} + (\tau_M - \tau_S))$$

5. Configure the WR Calibrator devices with the new Δ_{TX} and Δ_{RX} values.

After inserting these new parameters, the TIC reading (taking into account the offset) should be typically within ± 50 ps. This is currently the best accuracy that can be achieved for the relative calibration of a reference WR calibrator pair.

Note: *It is possible to create a reference WR Calibrator pair with devices that are not identical. However, in this case the sum of Δ_{TX} and Δ_{RX} of the devices are most probably unequal. Therefore, the values of Δ_{TX} and Δ_{RX} and the sum of these values found in the calibration procedure may be very different from the real values. Nevertheless, if all master devices in the system are calibrated against the reference WR Calibrator slave, and all slave devices are calibrated against the reference WR Calibrator master, the synchronization of all devices in the network will be consistent.*

4.5 Derived WR Device calibration

Having the WR Calibrator selected among the available WR devices, and the fibre cable used in the previous steps (with known propagation delay δ_{MS} and δ_{SM} and asymmetry small enough to be neglected), the calibration of all other devices that will be included in the WR Network can be started.

The set-up remains the same as in Figure 6, but either the WR master or the WR slave calibrator is replaced with another device with unknown Δ_{TX} and Δ_{RX} parameters.

1. Connect the Calibrator to an unknown WR device under test (DUT) using the fibre with the known delay measured earlier. Remember to use an appropriate SFP transceiver on each side depending on whether your DUT is supposed to run as a WR master or a WR slave. If the flexibility is required of selecting master/slave mode later through device configuration, the calibration procedure described below should be performed twice - with the SFP that will be used in master mode, and the SFP that will be used in slave mode.

Set the initial values of Δ_{TX} , Δ_{RX} and α of the DUT to zero.

2. Run the monitoring software on the slave node and record the corrected round-trip time $crtt$ and the fixed delays of both master and slave (Δ_{TXM} , Δ_{RXM} , Δ_{TXS} , Δ_{RXS}). The reported transmit delay Δ_{TX} for the DUT is the value from its initial state, which is zero. The value reported for the receive delay Δ_{RX} is its initial value plus the current RX bitslide value ε . Considering that the initial value of Δ_{RX} of the DUT was set to zero, the reported value is just ε .

3. Calculate the average (coarse) transmit and receive delays for the DUT device:

- for a slave DUT:

$$\begin{aligned}\Delta_{TXS} + \Delta_{RXS} &= crtt - (\delta_{MS} + \delta_{SM}) & (10) \\ \Delta_{TXS_{est}} = \Delta_{RXS_{est}} &= \frac{1}{2} crtt - \frac{1}{2} (\delta_{MS} + \delta_{SM})\end{aligned}$$

- for a master DUT:

$$\begin{aligned}\Delta_{TXM} + \Delta_{RXM} &= crtt - (\delta_{MS} + \delta_{SM}) & (11) \\ \Delta_{TXM_{est}} = \Delta_{RXM_{est}} &= \frac{1}{2} crtt - \frac{1}{2} (\delta_{MS} + \delta_{SM})\end{aligned}$$

4. Write the Δ_{TX} and Δ_{RX} delays to the configuration of the DUT and restart the PTP daemon so that it synchronizes again using the new values.

5. At this point the WR DUT knows the coarse values of the transmit and receive delays. The difference between the 1-PPS signals generated by the calibrator and the DUT can be measured with the TIC or oscilloscope and is probably still a few nanoseconds. That is because the transmit and receive delays are not equal (as the coarse values above). This asymmetry can be measured and used to correct the coarse values of Δ_{TX} and Δ_{RX} .

6. Measure the difference between the master and slave 1PPS output signals with a TIC or oscilloscope. For evaluation of the stability, it is recommended to perform at least 5 series of measurements of 300 s. Before each series, restart the PTP daemon. The corrected values for Δ_{TX} and Δ_{RX} are then given by:

- if the DUT is a WR slave:

$$\begin{aligned}\Delta_{TXS} &= \Delta_{TXS_{est}} - (TIC_{MS} + (\tau_M - \tau_S)) & (12) \\ \Delta_{RXS} &= \Delta_{RXS_{est}} + (TIC_{MS} + (\tau_M - \tau_S))\end{aligned}$$

- if the DUT is a WR master:

$$\begin{aligned}\Delta_{TXM} &= \Delta_{TXM_{est}} + (TIC_{MS} + (\tau_M - \tau_S)) & (13) \\ \Delta_{RXM} &= \Delta_{RXM_{est}} - (TIC_{MS} + (\tau_M - \tau_S))\end{aligned}$$

7. After putting the new delay values in the configuration of the WR Device, the PTP daemon can be restarted and this time the device will synchronize to the Calibrator with an offset below 50 ps.

8. This procedure has to be performed for all other WR Devices (WR Masters and WR Slaves) to be connected in the same network. When calibrating a WR Switch, this calibration procedure has to be performed for all relevant WR ports of the device.

4.6 Uncertainty evaluation

The uncertainty of the WR device calibration is evaluated from the difference of the 1PPS output signals from the master and slave device after setting the appropriate values of Δ_{TX} and Δ_{RX} in both devices.

Systematic uncertainties in the 1PPS output differences can be minimized by doing one or two additional iterations of steps 6 and 7 in the previous section.

If the fibre link between the master and slave device is short (1 m or 2 m) the effect from the fibre delay asymmetry is small enough to be neglected.

Thus, the uncertainty in the calibration values Δ_{TX} and Δ_{RX} is mainly determined by the uncertainty from the TIC or oscilloscope and the difference of the 1PPS cable delays ($\tau_M - \tau_S$).

A typically example of an uncertainty budget for a measurement with a time interval counter is given in Table 2.

The uncertainty in the TIC is divided in two contributions:

There is an uncertainty in TICMS caused by the internal frequency offset in the TIC. This contribution is estimated to be very small: < 0.005 ns with a rectangular distribution.

The uncertainty for uncompensated offset in the TIC reading. This contribution is estimated to be less than 0.050 ns with a rectangular contribution.

Then there is an uncertainty from the 1PPS cable delay difference ($\tau_M - \tau_S$). This uncertainty is estimated to be less than 0.010 ns, with a rectangular distribution.

And finally, there is a contribution from the fluctuations in the measurements. This contribution includes both the noise in the WR time transfer and the noise from the TIC. A typical value for the standard deviation $\sigma(TIC_{MS})$ is 0.020 ns.

Table 2. Example uncertainty budget for WR device calibration

Quantity	value	std unc	sensitivity	contribution
TIC_{MS}	0.030 ns	0.003 ns	1.000	0.003 ns
TIC_{offset}	0.000 ns	0.029 ns	1.000	0.029 ns
$(\tau_M - \tau_S)$	0.000 ns	0.006 ns	1.000	0.006 ns
$\sigma(TIC_{MS})$	0.000 ns	0.020 ns	1.000	0.020 ns
$\Delta TX - \Delta TX_{est}$ $\Delta RX - \Delta RX_{est}$	0.030 ns		Tot. unc. (k = 1)	0.036 ns
			Exp. unc. (k = 2)	0.072 ns

In this case, the estimated uncertainty (95 % probability) is about 0.08 ns.

5 Fibre delay asymmetry calibration

5.1 Introduction

This chapter describes the calibration procedure for the fibre delay asymmetry coefficient for long distance WR links in which the WR master and slave are in different locations.

A WR link is a two-way time transfer link which consists a pair of WR devices, optical fibres and, if necessary, multiplexers/demultiplexers and optical amplifiers. One of the WR devices is a WR master and the other is a WR slave. To avoid significant delay differences between the forward and reverse path of the two-way time transfer, WR links are preferably implemented on a single fibre, using one wavelength for sending information from master to slave λ_{MS} and another wavelength λ_{SM} for sending information from slave to master. The wavelengths are selected different from each other to avoid false measurements of the rtt from back-reflected signals.

In order to transfer accurate time packets and recover the original WR master timestamps at the WR slave side, the one-way propagation latency in the link is estimated from a round-trip time (rtt) measurement and then compensated at the slave side by adjusting the phase. Besides the internal delays of the WR devices and the delays of multiplexers and demultiplexers, the fibre delay asymmetry needs to be taken into account to accurately determine the master-to-slave signal propagation delay.

Delay asymmetry in an optical fibre is mainly by caused chromatic dispersion; this is the effect that the velocity of light in the fibre depends on wavelength of the light. For long distance WR links in which the fibre delay asymmetry becomes significant, it is recommended to keep the spacing between λ_{MS} and λ_{SM} as small as possible.

5.2 Fibre delay asymmetry calibration method

The method for performing a fibre delay asymmetry calibration is based on performing two delay measurements in which the forward wavelength λ_{MS} and reverse wavelengths λ_{SM} are interchanged (Figure 7).

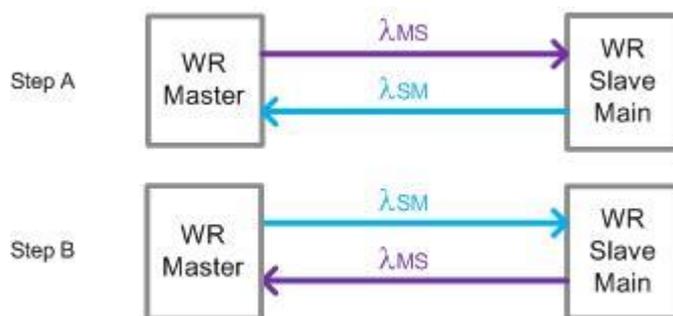


Figure 7. Schematic diagram of the fibre delay asymmetry calibration

To evaluate the time transfer difference between step A and step B, a direct measurement of the 1PPS output from the slave with respect to the 1PPS output from the master with a time interval count (TIC) is not possible because of the long distance in between. Therefore, besides the main WR link that is being calibrated, a reference WR link is created for providing a replica of the WR master 1PPS at the slave side (Figure 8). This replica 1PPS of the master, WR Slave REF, can have a constant offset with respect to the original WR master 1PPS, but as long as the offset is stable during the measurements, it will not affect the asymmetry calibration result.



Figure 8. Calibration principle with WR reference link as replica of the WR Master 1PPS

The WR protocol will automatically correct the 1PPS output signal of the WR slave to compensate for the path delay from the master to slave. The applied correction is half of the measured round-trip-time from master to slave and back to master (including corrections for internal instrument delays). This means that if the fibre delay from master to slave δ_{MS} for wavelength λ_{MS} equals the fibre delay from slave to master δ_{SM} for wavelength λ_{SM} , the 1PPS output from the WR slave would be perfectly aligned with the 1PPS output from the WR master. However, if δ_{MS} is larger than δ_{SM} , the applied delay correction from the WR protocol is less than the actual δ_{MS} and therefore, the output 1PPS of the WR Slave is still a bit delayed with respect to the 1PPS output from the WR master. And, vice versa, if δ_{MS} is smaller than δ_{SM} , the applied delay correction from the WR protocol is more than the actual δ_{MS} and therefore, the output 1PPS of the WR Slave is a bit ahead of the 1PPS output from the WR master.

The fibre delay asymmetry parameter, α , is available in the WR protocol to compensate for the delay difference and is defined by (14):

$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}} \quad (14)$$

The α parameter can be determined from the difference of the two TIC measurements in step 1 and step 2 of Figure 8 and the corrected round-trip-time measurements.

5.3 Detailed calibration procedure

The diagrams in Figure 9 and Figure 10 show more detailed set-ups of Figure 8 for an example of a fibre delay asymmetry calibration. Here below, the steps are described for performing the calibration.

Step 1: Calibration preparation

Select the WR switch ports that will be used in step A and step B in the calibration. In our example, on both the master and the slave switch, port #01 is selected for step A of the measurement and port #02 is selected for step B of the measurement. The ports used for the reference link don't have to be calibrated.

Calibrate the selected WR switch port delays Δ_{TXMA} , Δ_{RXMA} , Δ_{TXSA} , Δ_{RXSA} and Δ_{TXMB} , Δ_{RXMB} , Δ_{TXSB} , Δ_{RXSB} used in the main link, using the procedure described in section 4. Note that all the WR Switch delays are calibrated with fixed 1 PPS output coaxial cables. An example of calibration results from ports of a pair of WR switches is given in Table 3.

Table 3. Example of calibration results from a WR master-slave pair for ports #01 and #02

Step	WRS	mode	port	SFP		λ (nm)	Δ (ps)	U(Δ) (ps)
A	WRS-18P sn. 014	Master	#01	1.25G SFP 1490nm sn. F78E77W	TX	1490	Δ_{TXMA} 226120	50
					RX	1470	Δ_{RXMA} 227227	50
A	WRS-18P sn. 066	Slave	#01	1.25G SFP 1470nm sn F78JUYX	TX	1470	Δ_{TXSA} 224940	50
					RX	1490	Δ_{RXSA} 224063	50
B	WRS-18P sn. 014	Master	#02	1.25G SFP 1470nm sn F78IEMV	TX	1470	Δ_{TXMB} 224603	50
					RX	1490	Δ_{RXMB} 227891	50
B	WRS-18P sn. 066	Slave	#02	1.25G SFP 1490nm sn. F78PQYX	TX	1490	Δ_{TXSB} 224788	50
					RX	1470	Δ_{RXSB} 225959	50

Besides the WR master, the WR slave and the fibre, a long distance WR link usually also includes wavelength (de-)multiplexers (WDM). Calibrate the delays of WDMs for both λ_{MS} and λ_{SM} using the procedure described in section 3. The sum of the delays of all WDMs yields $\Delta_{WDM-\lambda_{MS}}$ and $\Delta_{WDM-\lambda_{SM}}$ respectively. An example of calibration results from a set of WDMs is given in Table 4.

Table 4. Example calibration results from a set of WDMs

WDM		λ (nm)	$\Delta_{WDM-\lambda_{MS}}$ (ps)	U(Δ) (ps)	λ (nm)	$\Delta_{WDM-\lambda_{SM}}$ (ps)	U(Δ) (ps)
sn. 53	mux	1490	138623.9	35	1470	129397.4	35
sn. 52	demux	1490	147840.4	35	1470	157133.5	35
Sum		1490	286464	50	1470	286531	50

When the equipment has been calibrated, it can be installed and connected to the fibre.

Step 2: Calibration system Initialization

Set the WR switch delay calibration results in the configuration of the master and slave WR switches and set the fibre asymmetry coefficient 'alpha' in both Master and Slave to zero.

This configuration is to be set in the *dot-config* file of WR switches. This procedure is explained in detail in reference [2].

In the step A as described in Figure 9, port #01 of the master should be configured with Δ_{TXMA} and Δ_{RXMA} according to Table 3, and also the SFP information should be inserted. Besides, the fibre asymmetry coefficient is set to zero. Port #01 of the master should be set as follows:

```
CONFIG_PORT01_PARAMS="name=wri1,proto=raw,tx=226120,rx=227227,role=master,fiber=0"
CONFIG_SFP00_PARAMS="vn=FLEXOPTIX,pn=S.1612.41.LD,tx=0,rx=0,wl_rxx=1470+1490" #1490nm
CONFIG_FIBER00_PARAMS="alpha_1470_1490=0"
```

And similarly, port #01 of the slave should be set as:

```
CONFIG_PORT01_PARAMS="name=wri1,proto=raw,tx=224940,rx=224053,role=slave,fiber=0"
CONFIG_SFP00_PARAMS="vn=FLEXOPTIX,pn=S.1612.41.KD,tx=0,rx=0,wl_rxx=1470+1490" #1470nm
CONFIG_FIBER00_PARAMS="alpha_1470_1490=0"
```

In a similar way, Master port #02 and Slave port #02 which are used in Set-up B are set:

```
CONFIG_PORT02_PARAMS="name=wri2,proto=raw,tx=224603,rx=227891,role=master,fiber=0"
CONFIG_SFP00_PARAMS="vn=FLEXOPTIX,pn=S.1612.41.KD,tx=0,rx=0,wl_rrx=1470+1490"#1470nm
CONFIG_FIBER00_PARAMS="alpha_1470_1490=0"
```

```
CONFIG_PORT02_PARAMS="name=wri2,proto=raw,tx=224788,rx=225959,role=slave,fiber=0"
CONFIG_SFP00_PARAMS="vn=FLEXOPTIX,pn=S.1612.41.LD,tx=0,rx=0,wl_rrx=1470+1490"#1490nm
CONFIG_FIBER00_PARAMS="alpha_1470_1490=0"
```

Step 3: Building the set-up for step A and performing data acquisition

The set-up for step A of the measurement is built as shown in Figure 9. The 3 elements of the set-up are: the main WR link, the reference WR link, and the TIC.

When the two WR links have been properly connected, restart the WR master, the WR slave and WR reference slave, and wait until the slave ports of the WR slave and WR Ref are locked to the master's ports.

For the TIC measurements, the 1 PPS output from the WR Ref is connected to channel B of the TIC, and the 1 PPS output from the WR Slave is connected to channel A of the TIC. The trigger levels of both TIC channels are set to 0.5 V. The data acquisition is started when both the main link and the reference link are in the TRACK_PHASE status. It is recommended to collect at least 350 samples of $crtt$ data from the WR slave and, at the same time, at least 350 samples of $TIC_{SR,A}$ data from the TIC.

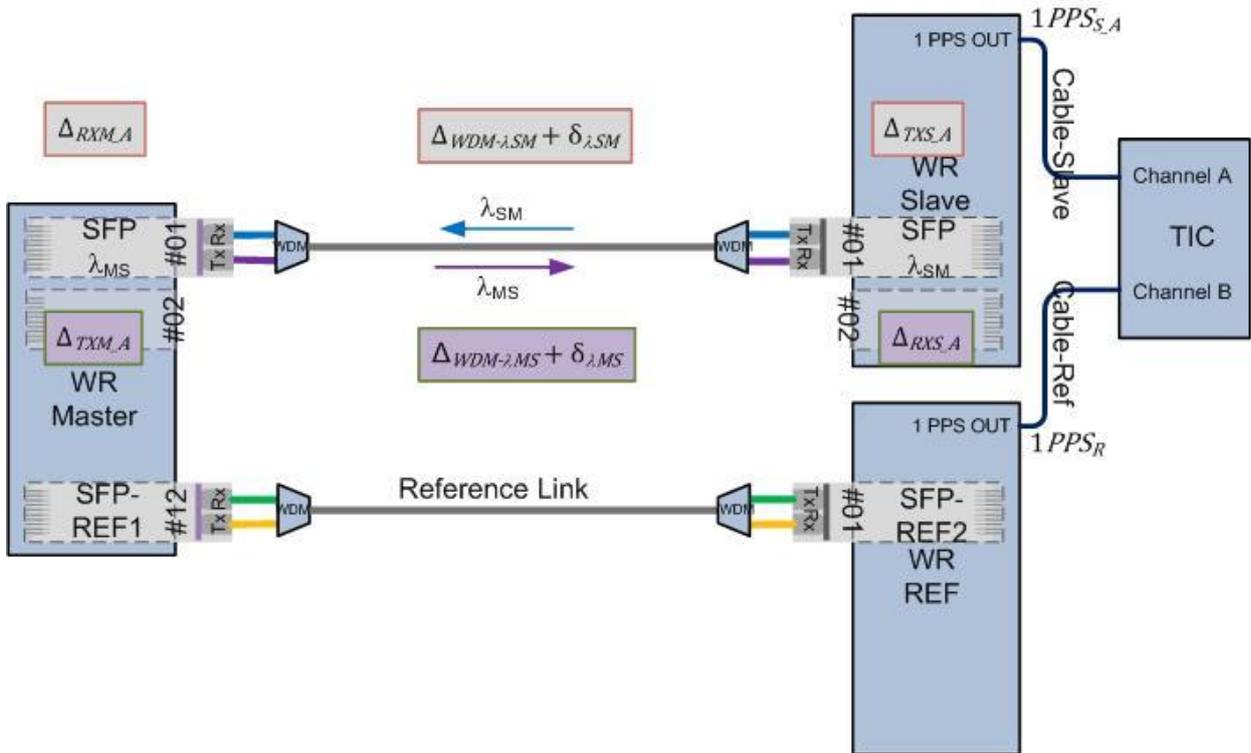


Figure 9. Step A: Set-up with master-to-slave link at the wavelength of λ_{MS} and slave-to-master link at the wavelength of λ_{SM} .

Step 4: Building set-up B and performing data acquisition

Disconnect the fibre from the WR main link of step A and now connect the fibre to the appropriate SFPs in the ports for step B (see Figure 10). The WR reference link remains unchanged, and the connections of the 1 PPS output signals to the TIC also remain unchanged.

After the main link is properly connected, reboot the WR Slave and wait until it is in the track-phase status again. Note that WRS Master and WRS Ref, preferably, shouldn't be rebooted in order to avoid any phase changes in the 1 PPS output signal of the WR Ref.

When both the main link and the reference link are in the TRACK_PHASE status again, we can start collecting $crtt$ and TIC_{SR_B} data. Again, it is recommended to collect at least 350 samples of $crtt$ data from WRS Slave, and, at the same time, collect at least 350 samples of TIC_{SR_B} data from the TIC.

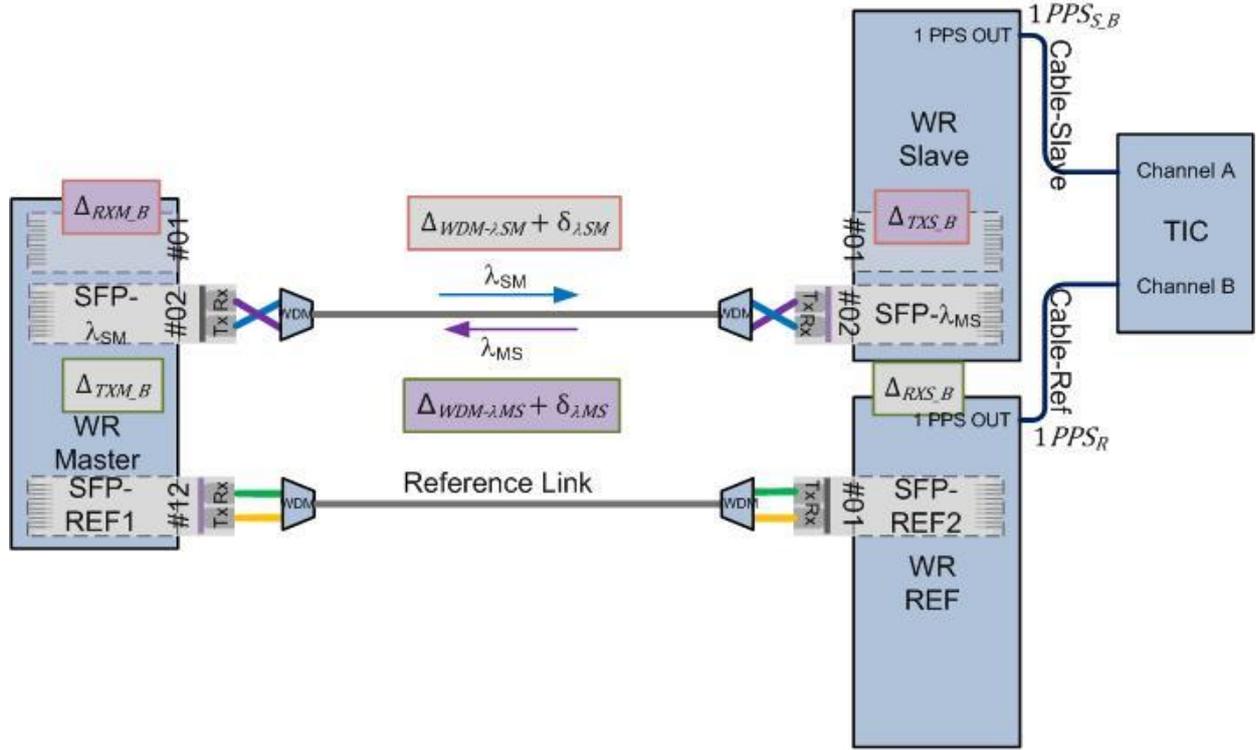


Figure 10. Step B: Set-up with master-to-slave link at the wavelength of λ_{SM} and slave-to-master link at the wavelength of λ_{MS} .

Step 5: Fibre asymmetry calibration

For the collected TIC data, the first 50 samples are discarded. The average is taken of the next 300 samples and stored as TIC_{SR_A} and TIC_{SR_B} .

$crtt$ data is collected in both step A and step B and should have quite the same value in both steps. Therefore, $crtt$ data is processed by discarding the first 50 samples in each step, and then taking the average of the two sets of remaining 300 samples (600 samples in total).

From this data, the fibre asymmetry coefficient α is calculated as explained below.

To improve the reliability of the calibrated α value, Step 3 and Step 4 should be repeated typically 4 more times, and the average value of the 5 measurements is the final fibre asymmetry calibration result.

In step A as shown in Figure 9, the master-to-slave latency Δ_{MS_A} in the main link is given by:

$$\Delta_{MS_A} = \Delta_{TXM_A} + \Delta_{RXS_A} + \Delta_{WDM-\lambda_{MS}} + \delta_{MS} \quad (15)$$

And the slave-to-master latency is given by:

$$\Delta_{SM_A} = \Delta_{TXS_A} + \Delta_{RXM_A} + \Delta_{WDM-\lambda_{SM}} + \delta_{SM} \quad (16)$$

Note that in these equations, $\Delta_{WDM-\lambda_{MS}}$ and $\Delta_{WDM-\lambda_{SM}}$ are the sums of internal delays of all the WDMs in the link for the respective wavelength.

Similarly, in step B, with the wavelengths from the master-to-slave link and the slave-to-master link interchanged, the delays of the main link are:

$$\Delta_{MS_B} = \Delta_{TXM_B} + \Delta_{RXS_B} + \Delta_{WDM-\lambda_{SM}} + \delta_{SM} \quad (17)$$

$$\Delta_{SM_B} = \Delta_{TXS_B} + \Delta_{RXM_B} + \Delta_{WDM-\lambda_{MS}} + \delta_{MS} \quad (18)$$

Note that in step B, another pair of SFP is used and different ports on the master and slave switch are used. Therefore, Δ_{TXM_A} , Δ_{RXM_A} , Δ_{TXS_A} and Δ_{RXS_A} are not the same as Δ_{TXM_B} , Δ_{RXM_B} , Δ_{TXS_B} and Δ_{RXS_B} .

With the WR device delays calibrated and configured in devices, the corrected round-trip time $crtt$ in both step A and step B is the round-trip time of both WDMs and fibres, and can be written as:

$$crtt = \Delta_{WDM-\lambda_{MS}} + \delta_{MS} + \Delta_{WDM-\lambda_{SM}} + \delta_{SM} \quad (19)$$

When the WR slave is properly locked to the master, it will synchronise its clock phase to the master's clock with an estimated correction for the one-way path delay of the WR messages from the master to the slave. This estimate correction is given by:

$$\Delta_{estiMS} = \frac{1}{2} crtt + \Delta_{TXM} + \Delta_{RXS} \quad (20)$$

When the WR internal delays have been properly set and the fibre asymmetry coefficient α and WDM delays are set to zero, the phase difference between the 1 PPS output from Master and Slave reflects the difference between the actual one-way delay and the estimated one-way delay.

For step A:

$$\begin{aligned} TIC_{SM_A} &= 1PPS_{S_A} - 1PPS_M \\ &= -\Delta_{MS_A} + \Delta_{estiMS_A} \\ &= \frac{1}{2}(\delta_{SM} - \delta_{MS}) + \frac{1}{2}(\Delta_{WDM-\lambda_{SM}} - \Delta_{WDM-\lambda_{MS}}) \end{aligned} \quad (21)$$

where TIC_{SM_A} is a hypothetical measurement of a time interval counter between the 1 PPS output for the slave $phase_{S_A}$ and the 1PPS output from the master, $phase_M$ in step A.

Similarly, for step B:

$$\begin{aligned} TIC_{SM_B} &= 1PPS_{S_B} - 1PPS_M \\ &= -\Delta_{MS_B} + \Delta_{estiMS_B} \\ &= \frac{1}{2}(\delta_{MS} - \delta_{SM}) + \frac{1}{2}(\Delta_{WDM-\lambda_{MS}} - \Delta_{WDM-\lambda_{SM}}) \end{aligned} \quad (22)$$

The hypothetical measurements TIC_{SM_A} and TIC_{SM_B} cannot be performed directly because of the distance between the master and slave. However, the reference WR link, the 1PPS output of the WR slave REF in Figure 9 and Figure 10 provides a replica of the WR master 1PPS output at the slave side with a constant phase offset C. Therefore:

$$\begin{aligned} TIC_{SR_A} &= 1PPS_{S_A} - 1PPS_R = TIC_{SM_A} + C \\ TIC_{SR_B} &= 1PPS_{S_B} - 1PPS_R = TIC_{SM_B} + C \end{aligned} \quad (23)$$

From these two equations the hypothetical time interval measurement $TIC_{S_A S_B}$ is defined as:

$$TIC_{S_A S_B} = TIC_{SR_A} - TIC_{SR_B} = TIC_{SM_A} - TIC_{SM_B} \quad (24)$$

Combining equation (24) with (21) and (22) yields:

$$TIC_{S_A S_B} = (\delta_{SM} - \delta_{MS}) + (\Delta_{WDM-\lambda_{SM}} - \Delta_{WDM-\lambda_{MS}}) \quad (25)$$

Finally, the one-way fibre latencies $\delta_{\lambda_{MS}}$ and $\delta_{\lambda_{SM}}$ can be calculated from equation (19) and (25):

$$\delta_{MS} = \frac{1}{2}(crtt - TIC_{S_A S_B}) - \Delta_{WDM-\lambda_{MS}} \quad (26)$$

$$\delta_{SM} = \frac{1}{2}(crtt + TIC_{S_A S_B}) - \Delta_{WDM-\lambda_{SM}} \quad (27)$$

The fibre asymmetry coefficient α is then determined as:

$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}} = \frac{-[TIC_{S_A S_B} + \Delta_{WDM-\lambda_{MS}} - \Delta_{WDM-\lambda_{SM}}]}{\frac{1}{2}(crtt + TIC_{S_A S_B}) - \Delta_{WDM-\lambda_{SM}}} \quad (28)$$

Using the values from the previous example, the fibre asymmetry coefficient calibration result is shown in Table 5.

Table 5. Fibre asymmetry coefficient calibration result

Calibration Paramters (units: ps)					Calibration Results
$TIC_{S_{R_A}}$	$TIC_{S_{R_B}}$	$crtt$	$\Delta_{WDM-\lambda_{MS}}$	$\Delta_{WDM-\lambda_{SM}}$	α
-252	24369	979331809	286464	286531	5.045e-5

Step 6: WRS timing configuration

Reconnect the main WR link as in step A and set the calibrated α value in the configuration of the WRS Slave. For the example shown in Figure 9, write α value into port #01 of slave and add the WDM delays to the slave port delays in *dot-config* file as follows:

```
CONFIG_PORT01_PARAMS="name=wri1,proto=raw,tx=511471,rx=510517,role=slave,fiber=1"
CONFIG_SFP00_PARAMS="vn=FLEXOPTIX,pn=S.1612.41.KD,tx=0,rx=0,wl_rrx=1470+1490"#1470nm
CONFIG_FIBER01_PARAMS="alpha_1470_1490=5.045E-5"
```

As a result, the fibre asymmetry in the long-distance fibre link as well as the main WR link in set-up A are fully calibrated.

5.4 Uncertainty analysis

Based on equation (14), the uncertainty of the chromatic dispersion coefficient α can be estimated.

The contributions are:

$TIC_{S_A S_B}$: The average difference of the TIC measurements from step A and from step B. In this difference, there will be a small random contribution from the noise in the reference WR link. However, the systematic offsets from the TIC will be eliminated in the difference of the two measurements. The estimated uncertainty is 70 ps ($k = 2$). The sensitivity coefficient is approximately $2/crtt$

$\Delta_{WDM-\lambda_{MS}}$: The sum of delays of wavelength λ_{MS} from all wavelength multiplexers in the link.

$\Delta_{WDM-\lambda_{SM}}$: The sum of delays of wavelength λ_{SM} from all wavelength multiplexers in the link.

The values of these delays are calibrated before the installation of the equipment. The estimated uncertainty is 50 ps ($k = 2$). The sensitivity coefficient is approximately $2/crtt$

$crtt$: The signal round-trip delay time as determined by the WR protocol and corrected for the calibrated internal delay of the WR master and slave devices. The estimated uncertainty is 1 ns ($k = 2$). The sensitivity coefficient is: approximately $2[TIC_{S_A S_B} + \Delta_{WDM-\lambda_{MS}} - \Delta_{WDM-\lambda_{SM}}]$

σ : The standard deviation in the α measurement. This uncertainty depends on the situation. A typical value found in a calibration experiment was 5×10^{-8} .

A practical example of an α calibration on a link of approximately 100 km with CWDM wavelengths 1470 nm and 1490 nm is given in Table 6.

Table 6. Uncertainty budget for the fibre asymmetry coefficient calibration

Quantity	Value		Std.Unc.		Sens. coeff.	Contribution
$TIC_{S_A S_B}$	-24621	ps	35	ps	2.04E-09	7.15E-08
$\Delta_{WDM-\lambda MS}$	286464	ps	25	ps	-2.04E-09	5.11E-08
$\Delta_{WDM-\lambda SM}$	286531	ps	25	ps	2.04E-09	5.11E-08
$crtt$	979331809	ps	500	ps	5.12E-14	2.56E-11
σ	-		5.0E-08		1	5.0E-08
α	5.045E-5				$u(\alpha) k = 1$	1.25E-07
					$U(\alpha) k = 2$	2.5E-07

So, the total expanded uncertainty (95 % probability) is 0.25×10^{-6} . It should be noted that this is a short term uncertainty evaluated only during the calibration process. α may change due to changes in the fibre properties, or due to changes in the wavelengths from the SFPs.

Changes of fibre properties can only be evaluated by long term experiments.

The stability of the wavelengths from CWDM SFP is estimated to be within 2 nm.

Considering ITU-T specifications for single mode fibre of type G652, the dispersion coefficient D around 1480 nm is specified as: $8.625 + 0.052(\lambda - 1460) \leq D(\lambda) \leq 12.472 + 0.068(\lambda - 1460)$ ps/(nm km). This means that, in theory, the $TIC_{S_A S_B}$ measurement can vary within ± 0.5 ns, and the corresponding uncertainty $U(\alpha) = 1.32 \times 10^{-6}$.

5.5 Fibre asymmetry calibration of a multi-section link

In some cases, a WR link may be built over multiple sections of optical fibre with optical amplifiers in between. In such cases, the fibre asymmetry of the total link can be determined from the calibration of the individual sections of the fibre. Figure 11 shows an approach for calibrating the asymmetry of the individual sections of the fibre link in consecutive steps.

The calibration can be performed during the installation of the amplifiers along the link. For this process, it is easiest to work with two teams: one team at each end of the section to be calibrated. The calibration starts from the master side of the link. In this way, there is always an accurate time and frequency reference signal available for the calibration. For the calibration steps, it is useful to have two portable calibration units.

The first unit consists of a WR switch configured as boundary clock and an additional set of WDMs.

The second unit consists of two WR switches in slave mode and a WDM. This WDM and one of the WR slave switches will be the instruments that in the end will remain at the slave side of the total link. The second WR slave is used for creating the WR reference link as described previously in section 5.2.

For the fibre asymmetry calibration, two ports on the boundary clock switch need to be calibrated with respect to 2 ports on the WR slave switch of the main link. Also, the delays of the multiplexers WDM-CAL-A and WDM-SL-B need to be calibrated before the fibre asymmetry calibration.

The calibration process will yield values of δ_{MS} , δ_{SM} and α for each section of the link.

The effective fibre delay asymmetry coefficient can be found from equation (14), in which δ_{MS} is the sum of the values δ_{MS} from all individual sections and δ_{SM} is also the sum of the values δ_{SM} from all individual sections of the WR link.

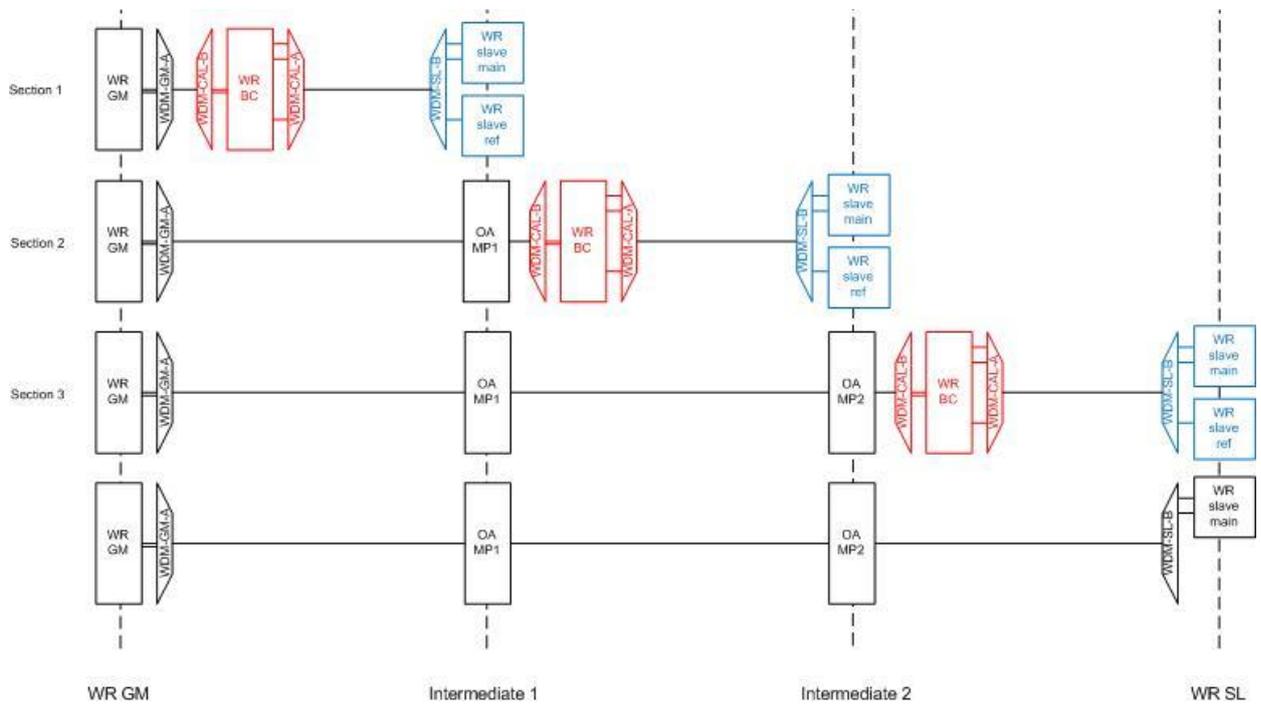


Figure 11. Scheme for a calibration of a multi-section optical fibre link with optical amplifiers in between

6 Link management

6.1 Introduction

This document provides information on how the remote management of WR equipment in link between VSL and Tallgrass was set up.

This document discusses: connection strategies, communication protocols, software tools, instrument settings and relevant parameters to monitor during routine operation of a WR time transfer link. Additional information can be found in [1].

6.2 Connection strategy

For the management of the WR equipment, on each WR switch, a static IP address was set to the management port of the switch.

With each WR switch, an Ethernet switch is installed which has at least one SFP port and typically multiple RJ45 sockets.

The management port of the WR switch is connected with an unshielded twisted pair (UTP) cable to an RJ45 socket of the Ethernet switch. The SFP port on the Ethernet switch is equipped with an SFP that connects to one of the SFP ports on the WR switch. Typically, SFP port 18 on the WR switches is selected for the data connection.

On the WR master side (VSL), a computer (PC) is connected via the Ethernet switch directly to the management port of the WR master.

From the Ethernet switch on the master side, via the optical fibre path and the Ethernet switch on the slave side (Tallgrass) the management port of the WR slave switch is reached.

Considering that the WR devices are designed to operate at 1 Gbit/s bit rate, it is best that the data communication fibre links also operate at a bit rate of 1 Gbit/s.

A schematic diagram of the link management connections is shown in Figure 12.

This configuration of WR equipment management is called in-band management, because the management data for the WR equipment is transported over the same wavelengths as the WR time transfer.

Note: In general, from a security point of view, in-band management is not recommended practice; it is better to separate the WR time and frequency transfer from the management data of the equipment. One method of doing this, is by using one pair of wavelengths on the optical fibre link for the management of equipment and another pair of wavelengths on the same fibre for the WR time transfer. Combining and separating the wavelengths is done by wavelength division (de-)multiplexers (WDM).

In this project, in-band management was chosen, because only two wavelengths were made available on the fibre link between TDCG and Nikhef. Access to four wavelengths would be more expensive.

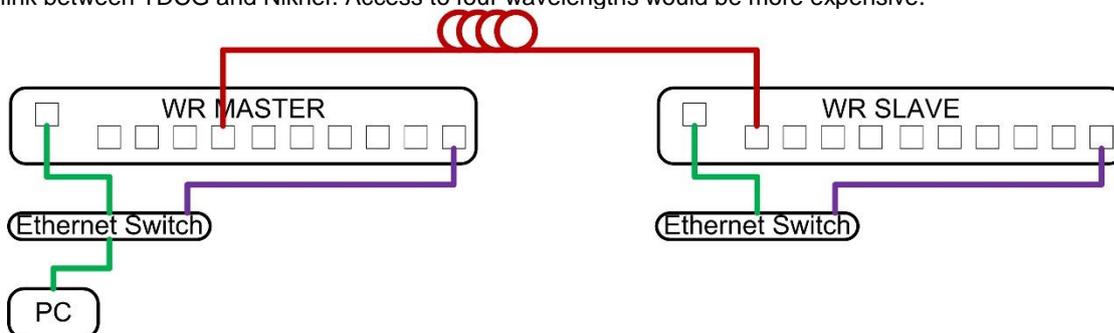


Figure 12. Schematic diagram of the WR link management connections. (Red is an optical fibre connection for WR and data; violet is an optical fibre connection for data; green is a UTP cable for data.)

6.3 Communication protocols and Software tools

The most common tools for remote management of WR equipment are the Secure SHell (SSH) protocol and Simple Network Management Protocol (SNMP).

SSH provides the most direct and in-depth management of the WR equipment. It allows both reading parameters from the device as well as writing relevant calibration parameters into the device.

SNMP is a common protocol for reading status information from network devices and for sending alerts from the devices to the user.

Alternatively, WR switches have a built-in Hypertext Transfer Protocol (HTTP) server, which allows limited read and write access to parameters in the device.

In the WR set-up of this project, WR switches from two suppliers were used: 7Solutions and OPNT. From the experiments, it was found that the SSH and SNMP communication are very much the same for the equipment from both suppliers. However, for the HTTP, it was found that in the OPNT version some of the functionality of the webpage was lost.

Using HTTP has the advantage that nearly any web browser can be used to communicate with the WRS. However, for automated tasks, this is not the most convenient choice. Therefore, SSH and SNMP are commonly the most popular protocols to be used.

In Linux operating systems, the SSH protocol is already embedded in the system and can be started from a 'Terminal' window. In Microsoft Windows operating systems, SSH is not supported by default. However, the 'PuTTY' software is a convenient tool for starting SSH sessions.

The SNMP is not supported by default in both Linux and Windows, however, the tool net-snmp is available for both operating systems. The net-snmp tool is a good starting point for developing applications in common programming languages for communicating with the WRS.

For automatically retrieving status and operating parameters from the WRS, there is an important difference in the update rate of information between SSH and SNMP. SSH provides new updated information every second, whereas information retrieved by SNMP is updated only with an interval of 5 s.

6.4 Instrument settings

As discussed in the previous section, communication with the WRS via a local area network (LAN) can be done by either HTTP, SSH or SNMP. These protocols can also be used for changing instrument settings.

Using HTTP by means of web browser is the easiest way. However, in both the WRS from 7Solutions and from OPNT, only a limited number of settings can be accessed through the web interface.

SNMP can be a good alternative in case the user has dedicated software for accessing the instrument settings.

SSH provides the best access to the WRS instrument settings, because it allows direct access to the file in which the settings are stored: `/wr/etc/dot-config`

Although this may be very useful, care must be taken that the configuration is not corrupted during the file access.

For changing settings related to the Ethernet management port, it is recommended to use the USB serial connection.

6.5 Parameters to monitor

During normal operation, relevant parameters can be monitored from a WR switch by SSH (or the USB serial connection), using the command:

```
wr_mon -ie
```

The output from this command is in the format:

```
TIME sec:1520934962 nsec:185375 SERVO lock:1 sv:1 ss:'TRACK_PHASE' mu:1018624  
dms:511787 dtxm:227005 drxm:227005 dtxs:226896 drxs:231846 asym:-4950 crtt:105872  
cko:-3 setp:15792 ucnt:152
```

Using SNMP, similar information can be retrieved by polling the following parameters:

SNMP Object Identifier	Object Type
'1.3.6.1.4.1.96.100.7.5.1.6.1'	'wrsPtpServoState'
'1.3.6.1.4.1.96.100.7.5.1.13.1'	'wrsPtpRTT'
'1.3.6.1.4.1.96.100.7.5.1.16.1'	'wrsPtpDeltaTxM'
'1.3.6.1.4.1.96.100.7.5.1.17.1'	'wrsPtpDeltaRxM'
'1.3.6.1.4.1.96.100.7.5.1.18.1'	'wrsPtpDeltaTxS'
'1.3.6.1.4.1.96.100.7.5.1.19.1'	'wrsPtpDeltaRxS'
'1.3.6.1.4.1.96.100.7.1.1.1.0'	'wrsDateTAI'

'1.3.6.1.4.1.96.100.6.1.1.0'	'wrsMainSystemStatus'
'1.3.6.1.4.1.96.100.6.1.2.0'	'wrsOSStatus'
'1.3.6.1.4.1.96.100.6.1.3.0'	'wrsTimingStatus'
'1.3.6.1.4.1.96.100.6.1.4.0'	'wrsNetworkingStatus'
'1.3.6.1.4.1.96.100.7.3.2.1.0'	'wrsSpillMode'
'1.3.6.1.4.1.96.100.6.2.2.2.0'	'wrsSoftPLLStatus'

References

- [1] Open Hardware Repository, White Rabbit, <https://www.ohwr.org/projects/white-rabbit/wiki>
- [2] A. Rubini, A. Wujek, B. Rat and etc. White Rabbit Switch: User's Manual. Information about configuring the White Rabbit switch, for final users (wr_switich-sw-v5.0.1). August 2017.
- [3] B. RAT, J. Diaz (Seven Solutions), M. Jimenez (UGR), "WR SPEC Starting Kit", 15 may. 2014 - v2.0
- [4] R. Smets, "Engineering Rules for Bi-Directional Photonic Transport White-Rabbit Time and Frequency Transfer Service on Existing In-Service Infrastructure", ASTERICS GA DELIVERABLE: D5.1, www.asterics2020.eu, May 2016.
- [5] "Recommendation ITU-T G.652, SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS, Transmission media and optical systems characteristics – Optical fibre cables Characteristics of a single-mode optical fibre and cable", ITU-T, Nov. 2016.
- [6] Amemiya *et al.*, Proc. IEEE IFCS, pp. 914-918 (2005)
- [7] Sotiropoulos *et al.*, Opt. Express **21**, 32643-32654 (2013)
- [8] <https://www.ohwr.org/projects/wr-calibration>
<https://www.ohwr.org/projects/white-rabbit/wiki/Calibration>
- [9] G. Daniluk, "White Rabbit calibration procedure, version 1.1", CERN BE-CO-HT, 9 November 2015, <https://www.ohwr.org/documents/213>.
- [10] Master of Science thesis, Grzegorz Daniluk, "White Rabbit PTP Core, the sub-nanosecond time synchronization over Ethernet"