# White Rabbit
# Device Requirements
# And
# Validation Methods

*Version 1.0.0, 2025/12/17*

*REVISION HISTORY*

| Version | Author | Changes | Date |
|---|---|---|---|
| **0.1** | M.Lipinski, WRC/CERN | First draft | Jan-Jun 2025 |
| **0.2** | P.Jansweijer, M.Lipinski | Incorporated feedback by P.Jansweijer to pre-v0.1 version of this document: | 12 June 2025 |
| **0.2.3** | P.Jansweijer, M.Lipinski | ML: Incorporated/addressed/commented feedback by P.Jansweijer to v0.2, including outcome from follow-up discussions. Hand over to Peter for further updates on August 4, 2025 | 4 August 2025 |
| **0.2.4** | P.Jansweijer, M.Lipinski | PJ:Incorporated/addressed/commented feedback by M. Lipinski. | 11 August 2025 |
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| **0.2.6** | P.Jansweijer | PJ: Incorporate feedback from M. Lipinski and Guido Visser (Nikhef) | 11 September 2025 |
| **0.2.7** | M.Lipinski | Added missing references and text, updated WR Precision Classes | 15 September 2025 |
| **0.2.8** | M.Lipinski, P.Jansweijer | Incorporate feedback received from Paul Klop (SURF), Manfred Orsztynowicz(LMS), Adam Hassick (IOL), Dietrich Beck (GSI), Quentin Genoud (CERN), José López-Jiménez (Safran) | 15 December 2025 |
| **1.0.0** | M.Lipinski, P.Jansweijer | First release, public | 17 December 2025 |

# Table of Contents

# 1 Introduction

## 1.1 Purpose

This document is a comprehensive guide to validation of White Rabbit (WR) Devices. It describes technical requirements that need to be met by a device to be qualified as WR Device and be eligible for the White Rabbit Collaboration (WRC) logo[1]. The requirements concern interfaces, functional behaviour, standard compliance, configuration capabilities, calibration and performance, with different classes of performance distinguished.

In order to gain the status of a "qualified product", the device must implement WR Technology[2] which is open source. WR Technology itself may be embedded in a device with other proprietary parts. The WR requirements make sure WR Technology can be tested for qualification.

The requirements are supplemented with information about methods of validation and measurements. This includes description of measurement setups, test equipment and its validation methods, as well as sources of measurement uncertainty.

## 1.2 Scope

This document focuses on WR Technology verification. This does not include:

- EMC tests, CE marking
- Ethernet switching performance (RFC 2889 [1])
- Device testing over power-cycles
- Long-term testing
- MAC address generation
- Calibration of medium asymmetry (see 3.9.5).

The above is out of scope for this document.

## 1.3 Document structure

**Section one** provides basic introduction, explains WR Device types and their essential configuration; it also formally defines basic concepts and acronyms that are used throughout the document.

**Section two** of the document defines requirements to be met by WR Devices. Different types of requirements are listed in separate sections. The requirements depend on device type and configuration, and very often refer to external documents (e.g. standards) or further sections for details.

**Section three** describes test setups and provides details of how to perform validation, measurements and calibration of a WR Device to prove that it meets the requirements listed in section two.

**Section four** provides reference to documents that provide useful additional information but are not essential to verification of requirements (reference documents for requirements are provided in section two).

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[1] https://www.white-rabbit.tech/trademark
[2] https://www.white-rabbit.tech/wr-technology

**Annexes** provide supplementary information:

- **Annex A**: pointers to relevant sections in IEEE802.1Q
- **Annex B**: Information required to be provided in
  - WR Device Qualification report
  - WR Device data sheet
- **Annex C**: Test equipment - It details types and specification of test equipment needed, as well as methods to verify this test equipment.
- **Annex D**: Sources of error or type B uncertainties for time interval measurement devices

## 1.4 Basic concepts, definitions and configuration of WR Devices

### 1.4.1 WR Device types

A WR Device is based on the following networking standards: IEEE 802.1Q Bridges and Bridged Networks, IEEE 802.3 Ethernet and IEEE 1588 Precision Time Protocol (PTP). In line with these standards, two types of WR Devices are distinguished:

1) **WR Switch**
   a. An L2 Bridge according to IEEE 802.1Q. The device is capable of forwarding Ethernet traffic between multiple WR ports.
   b. A Boundary Clock (BC) according to IEEE 1588, it can act as Grandmaster (GM).
   c. A typical WR Switch has 18-24 WR ports and follows implementation in WR Switch repositories.[3]
2) **WR Node**
   a. An end-station according to IEEE 802.1Q. The device is capable of transmitting and receiving Ethernet traffic on its WR port(s).
   b. An Ordinary Clocks (OC) according to IEEE 1588, it can act as Grandmaster (GM). A typical WR Node is a device with a single WR port. It instantiates a WR PTP Core[4] in FPGA, usually along with some application-specific functionality such as Network Interface Card (NIC), Radio-frequency, trigger generation or timestamping.
   c. WR Nodes may have multiple ports. They are considered an assembly of logical WR Nodes if they do not implement a) and b) of the WR Switch functionality listed above.

[3] https://gitlab.com/ohwr/project/wr-switch-hw and : https://gitlab.com/ohwr/project/wr-switch-sw
[4] https://gitlab.com/ohwr/project/wr-cores/-/wikis/wrpc-core

### 1.4.2 WR Device configuration

This section describes the configuration of WR Devices that is relevant for this document.

#### 1.4.2.1 Timing modes

A WR Device can support one or more of the following timing modes:

- **Grandmaster (GM)** – A WR Switch or WR Node that synchronises to an external source of time and frequency to generate its Local WR/PTP Time. It is a source of WR Time (see 1.4.3.1) to other WR Devices in the WR Network. Highlights:
    a. Configuration: clockClass=6
    b. Operation: It never becomes slave to other WR Device and expects connection to an external source of frequency and Time of Day (ToD), e.g. 1PPS and 10 MHz input signals along with connectivity to a source of ToD, e.g. a NTP server.

2) **Free-running Master** – A WR Switch or WR Node that generates its Local WR/PTP Time without connection to an external source of time and frequency. It can be a source of WR Time (see 1.4.3.1) to other WR Devices in the WR Network, provided there is no **GM** in the network. Highlights:
    a. Configuration: clockClass=192
    b. Operation: It can become slave to other WR Devices and does not expect connection to external source of frequency and ToD. However, it will use NTP if available to set its Local WR/PTP Time.
3) **Boundary or Ordinary Clock (BC or OC)** – WR Switch or Node, respectively, that is expected to synchronise to another WR Device (GM, BC, OC). It can function as Free-running Master.

#### 1.4.2.2 Profiles, extensions and optional features

The IEEE 1588 standard [**RD.9**] defines operation of the PTP protocol that is highly parametrisable and extensible. The PTP's parameters are called attributes; these include for example clockClass, priority1, domainNumber, announceReceiptTimeout. The PTP standard includes optional features which add functionality to the protocol; these include for example unicast negotiation, configurable correction of timestamps, L1 Syntonization. To allow interoperability between devices implementing the PTP protocol, PTP Profiles are defined. A PTP Profile defines default and allowed values of attributes as well as required and allowed optional features and their attributes. Thanks to that, two devices implementing the same PTP Profile of the IEEE 1588 standard are meant to be interoperable.

Figure 1 compares at high level how White Rabbit was specified and in which documents before and after being standardised in IEEE 1588 as High Accuracy. The White Rabbit Specification [**RD.8**] defines **WR Extensions** of the PTP protocol, as well as the **WR Profile**. The **WR Profile** defines values of attributes and requires the **WR Extensions** to be implemented. **WR Extensions** are an integral part of the WR Specification and the **WR Profile**. IEEE 1588-2019 [**RD.9**] defines a number of WR-inspired **High Accuracy (HA) optional features** and the **High Accuracy Request-Response Default PTP Profile** (**HA Profile**, see, I.5 of [**RD.9**]). The **HA Profile** and the HA optional features are an integral part of the IEEE 1588-2019 standard. The HA optional features can be used independently from the **HA Profile** while the **HA Profile** requires these HA optional features to be implemented. While both profiles and sets of extensions allow the same performance and work with the same hardware, from the protocol point of view, the **WR Extensions** and HA optional features work differently and are not compatible. On the other hand, the values of common attributes specified by both profiles for the core PTP protocol are identical. Moreover, the **WR Profile** and the **HA Profile** are compatible with **Delay Request-Response Default PTP Profile** (see, I.3 of [**RD.9**]).

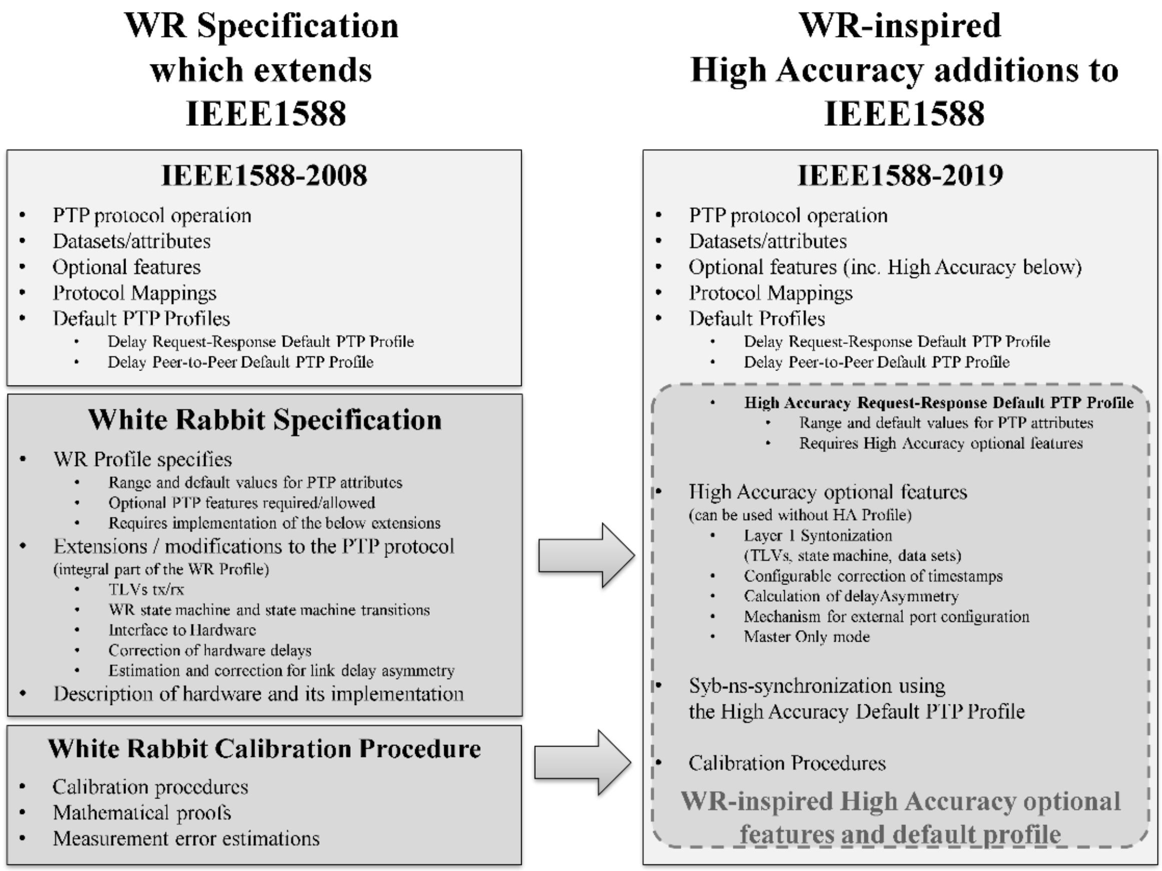


**Figure 1 - White Rabbit before and after standardisation in IEEEE1588-2019**

WR Devices typically support:

- WR and/or HA Profile with respective extensions and/or optional features, and
- Default PTP Profile.

Since the WR and HA Profiles have identical PTP attribute values/ranges and differ only in whether they use WR Extensions or HA optional features, the configuration of WR Devices provides configuration of a single WR/HA Profile and distinguishes the latter: WR or L1Sync. Where both WR Extensions and HA optional features are supported, auto-negotiation between the two is implemented (see [**RD.10**]).

### 1.4.3 Basic definitions

For the purpose of this document, the following terms are defined (based on [2] and [7]):

1.4.3.1 **WR Time** realised by a WR Device is the elapsed time since the PTP epoch measured using the second defined by International Atomic Time (TAI)[5]. It is represented by the output One Pulse Per Second (1PPS) signal and specified at the Time Marker (TM). Calibration of a WR Device and evaluation of its timing performance is accomplished by measuring time difference between the TM of a WR Reference device and the TM of the WR Device Under Test (DUT, see Figure 2).

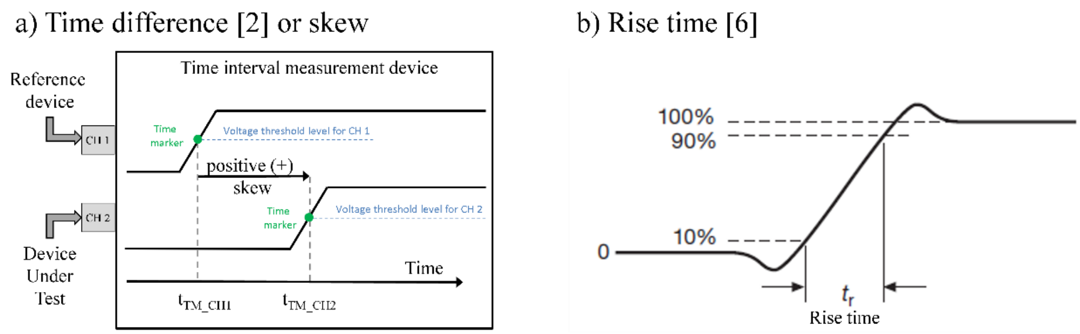


**Figure 2 - Illustration of rise time and skew between the reference (CH 1) and the device under test (CH 2)**

1.4.3.2 **Time Marker (TM)** of a (properly terminated) signal is defined as the time instance[6] when the rising edge of that electrical signal crosses a voltage threshold level at a well-defined reference plane.

1.4.3.3 **Rise time** is defined as the time required for the signal to go from 10% to 90% of its total transition [2][6]. See Figure 2b**.**

1.4.3.4 **Reference plane** [2] is chosen at the WR Device's output connector that generates the 1PPS signal (if applicable, according to the reference plane definition of that type of connector)**.**

1.4.3.5 **Voltage threshold level** for TM is equal to 50% of the steady-state, 50 Ohm terminated signal amplitude, i.e. 0.5 * ($V_{max\_steady} - V_{min\_steady}$).

**Note:** For verification purposes, it is recommended that the vendor of the WR Device specifies the expected voltage level of the 50% signal.

1.4.3.6 **Time difference** [2] or skew is defined between time instances[6] at which TM occurs at the reference planes. The time difference measured between the TMs of signals is defined as follows (see Figure 2a):
$skew_{CH1\_to\_CH2} = t_{TM\_CH2} - t_{TM\_CH1}$

**Note:** In practice, a *time interval measurement device* suffers channel to channel skew. Additionally, the coaxial measurement cables that transfer the signals to the *time interval measurement device* add skew. Definition of time reference planes is taken care of by calibration of the time interval measurement setup, including the measurement cables (see 3.2.3).

1.4.3.7 **Room temperature:** 23 degrees Celsius.

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[5] Definition aligned with "The timescale PTP" specified in 7.2.1 of [**RD.9**] (see 2.1).
[6] **Time instance** in this context is the exact time at which the TM occurs.

1.4.3.8 **Constant temperature:** temperature within ±1 ºC of the stated temperature, e.g. constant room temperature is 23±1 ºC, so in the inclusive range between 22.000 and 23.999 degrees Celsius.

1.4.3.9 **Uncertainty (of measurement):** A "*parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.*"[7] (see 2.2 of [7]). "*The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand. The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects*". (see 3.3 of [7]). Per [7], 2.3.2 and 2.3.3, uncertainty components are classified into two types depending on their method of evaluation:

- **Type A evaluation (of uncertainty):** method of evaluation of uncertainty by the statistical analysis of series of observations.
- **Type B evaluation (of uncertainty):** method of evaluation of uncertainty by means other than the statistical analysis of series of observations.

## 1.5 Acronyms

| Acronym | Definition |
|---|---|
| **1PPS** | One Pulse Per Second |
| **AXI** | Advanced eXtensible Interface |
| **DUT** | Device Under Test |
| **ENBW** | Equivalent Noise BandWidth |
| **FCS** | Frame Check Sequence |
| **HA** | High Accuracy |
| **PCIe** | Peripheral Component Interconnect Express |
| **RJ45** | Registered Jack – type 45 |
| **SFP** | Small Form-factor Pluggable |
| **SMA** | SubMiniature version A |
| **TM** | Time Marker |
| **UART** | Universal Asynchronous Receiver-Transmitter |
| **USB** | Universal Serial Bus |
| **WR** | White Rabbit |
| **WR Port** | Physical port of a White Rabbit device |
| **WRPC** | WR PTP Core |

[7] Text quoted from [7], where measureand is defined as a "well-defined physical quantity that can be characterized by an essentially unique value."

# 2 Requirements

## 2.1 Reference Documents (RD) for requirements

The following documents provide standards or specifications which are required to be fully or partially implemented by a WR Device, as detailed in subsequent sections.

| Ref. | Std. | Title | Version | Date |
|---|---|---|---|---|
| **RD.1** | IEEE Std 802.3 | IEEE Standard for Ethernet | | |
| **RD.2** | IEEE 802.1Q | IEEE Standard for Local and Metropolitan Area Networks-- Bridges and Bridged Networks | | |
| **RD.3** | MIL-STD-348 | Performance specification for radio frequency coaxial, triaxial, and twinaxial connectors and interfaces | | |
| **RD.4** | ITU-T G.703 | Physical/electrical characteristics of hierarchical digital interfaces | | |
| **RD.5** | RFC 5905 | Network Time Protocol Version 4 | | |
| **RD.6** | IRIG Standard 200-16 | Inter Range Instrumentation Group mod B | | Aug.2016 |
| **RD.7** | NMEA 0183 | National Marine Electronics Association: Serial Data Networking | | |
| **RD.8** | | White Rabbit Specification | 2.1 | 2026[8] |
| **RD.9a** | IEEE 1588-2008 | IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems | | 2008 |
| **RD.9b** | IEEE 1588-2019 | | | 2019 |
| **RD.10** | | Auto-negotiation between HA and WR | 1.0 | 2026[8] |
| **RD.11** | | White Rabbit Protocol Test Suite | | 2026[8] |
| **RD.12** | | High Accuracy Protocol Test Suite | | 2026[8] |
| **RD.13** | | Note on using WR Switch GM | | 2012[8] |
| **RD.14** | | WR Switch FRU content specification | 2.0 | 2026[8] |
| **RD.15** | | White Rabbit Calibration https://www.cern.ch/white-rabbit/documents | | 2026[8] |
| **RD.16** | | Jansweijer, P. P. M., and Peek, H. Z., "Measuring propagation delay over a 1.25 gbps bidirectional data link." https://www.cern.ch/white-rabbit/documents | | 2010 |
| **RD.17** | | Achieving deterministic phase in Xilinx GTX transceivers | | 2020[8] |
| **RD.18** | ANSI/TIA/EIA-644-A | Electrical Characteristics of Low Voltage Differential Signalling (LVDS) Interface Circuits | | 2021 |
| **RD.19** | | TI Application Report SLLA120, "Interfacing Between LVPECL, VML, CML, and LVDS Levels" https://www.ti.com/lit/an/slla120/slla120.pdf | | 2002 |
| **RD.20** | RFCs: 3411, 3412, 3413, 3416, 3417, 3418 | Simple Network Management Protocol (SNMP) | | 2002 |
| **RD.21** | IEEE 802.1AB | Station and Media Access Control Connectivity Discovery | | 2016 |
| **RD.22** | IEEE 802.1X | IEEE Standard for Local and metropolitan area networks-- Port-Based Network Access Control | | 2010 |
| **RD.23** | RFCs: 4510, 4511 | Lightweight Directory Access Protocol (LDAP) | | 2006 |
| **RD.24** | RFC 1541 | Dynamic Host Configuration Protocol (DHCP) | | 1997 |
| **RD.25** | RFCs: 4250-4254 | Secure Shell Protocol (SSH) | | 2006 |
| **RD.26** | RFC 791 | Internetwork Protocol Specification Version 4 (IPv4) | | 1981 |

[8] Reachable from https://www.white-rabbit.tech/tests/ (not necessarily at the time of publication of this document, gradually added throughout 2026).

## 2.2 Description of the requirements table columns

The requirement tables in the subsequent sections have the following columns:

1. **ID:** unique requirement identification.
2. **Level:**
   - O = obligatory, also expressed by using “shall” in text.
   - R = recommended, also expressed by using “should” in the text.
   - OW = obligatory with possibility of waiver, e.g. for *legacy* WR Devices or pluggable modules.
3. **Requirement:** textual description of the requirement to be fulfilled. It can include a requirement for the datasheet of the device to specify details regarding this requirement.
4. **Applicable to type:** the requirement is relevant for a specified WR Device type (see 1.4.1)
   - Switch = WR Switch,
   - Node = WR Node,
   - All = Any of the above.
5. **Applicable to config:** the requirement is relevant for the WR Devices which support a specified configuration (see 1.4.2) as stated in their datasheet:
   - GM = Grandmaster,
   - OC/BC = Ordinary or Boundary Clock,
   - All = Any of the above.
6. **Environmental:** applicable only to performance and calibration requirements, specifies any relevant consideration of environmental aspects, such as applicable temperature range.
7. **Func. type:** Functionality type
   - B = Basic: to be fulfilled by all WR Devices of applicable type and configuration,
   - E = Extended: to be fulfilled by WR Devices supporting optional functionality.
8. **Validation:** type of validation method for the requirement, more than one method can be applicable to a single requirement, for some requirements reference is provided to detailed description:
   - T = Test to measure the performance and/or functions,
   - I = Inspection of a physical element or SW code,
   - R = Review of datasheet or calibration information available for the *device*,
   - P = Perform calibration and/or validate the calibration results.
9. **Specification**: external document or section of this document which provides further details regarding this requirement.

The following types of requirements are specified in subsequent subsections:

- Interfaces requirements
- Functional requirements
- Standard compliance
- Configuration
- Calibration of ingress- and egress-latencies
- Performance

In the table, the term *device* (in italics) refers to the WR Device (a given model from a given vendor with a given firmware) subject to the stated requirements. The term DUT refers to the particular unit which is being tested. In general, the term *legacy WR Device*, refer to a WR Device designed before version 1.0.0 of this document was published, waivers for legacy WR Devices are granted on case-by-case bases.

## 2.3 Interface requirements

| ID | Level | Requirement | Applicable to | | Func. type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| | | | type | config | | | |
| **I.1** | O | Management Ethernet port connected to Operating System of the *device*<br>- Speed: 100Mbps or higher<br>- Allowed connectors: RJ45 or SFP cage | Switch | All | B | I+T<br>See 3.3 | Ethernet<br>[**RD.1**] |
| **I.2** | O | USB Type-A serial communication connection to the CPU (for management) of the *device*<br><br>**Datasheet:** specify baud rate and start-/stop-/parity-bits<br><br>**Note:** The *device* may have a different connection (e.g. DB-9, USB-C or RJ45 etc.) but an interface to a USB Type-A shall be supplied. | Switch | All | B | I+T<br>See 3.3 | |
| **I.3** | O | USB Type-A serial communication to the CPU in WRPC, one or both below:<br>- Physical UART<br>- Virtual UART over physical bus such as PCIe, AXI<br><br>**Datasheet:** specify baud rate and start-/stop-/parity-bits, and/or access registers if memory-mapped<br><br>**Note:** The *device* may have a different connection for the physical UART (e.g. DB-9, USB- C or RJ45 etc.) but an interface to a USB Type-A shall be supplied. | Node | All | B | I+T<br>See 3.3 | |
| **I.4** | O | Ethernet WR Port(s) - cage(s) for optical transceivers providing connectivity for WR/HA protocol using 1000BASE and/or10GBASE. | Both | All | B | I+T<br>See 3.4 | IEEE Std 802.3<br>[**RD.1**] |
| **I.5** | O | 1PPS and 10MHz output signal availability<br>- connector can be optionally mountable<br>- connector shall be mounted for DUT<br><br>**Note 1:** While the units of the *device* made available to the users can have no output 1PPS and/or 10MHz connectors, the device shall always allow (or support an interface to) such connectors to be mounted and/or accessed for the purpose of testing and qualification.<br><br>**Note 2:** It is allowed to multiplex 1PPS and/or 10MHz with other signals as long as the same FPGA bitstream is used.<br>**Note 3:** The 1PPS signal is expected to be generated when the WR Device is synchronised to the source of time/frequency in the network (e.g. GNSS, local oscillator of free-running Master). The 10MHz clock output is expected to be stable when 1PPS is generated. | Both | All | B | I | |

<table>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Func. type</th><th rowspan="2">Validation</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
<tr><td>I.6</td><td>OW</td><td>Aux output signal availability<br>- shall have the same specifications as for 1PPS (see I.9)<br>- connector can be optionally mountable<br>- connector shall be mounted for DUT<br>Note: While the units of the device made available to the users can have no output Aux connector, the device shall always allow (or support an interface to) such a connector to be mounted and/or accessed for the purpose of testing and qualification.<br>Waiver: not required</td><td>Both</td><td>All</td><td>B</td><td>I</td><td></td></tr>
<tr><td>I.7</td><td>O</td><td>1PPS and 10MHz input connector</td><td>Both</td><td>GM</td><td>B</td><td>I</td><td></td></tr>
<tr><td>I.8</td><td>OW</td><td>Output and input signals connector type: SMA female.<br>Waiver: allowed connectors: SMC, BNC, LEMO. The DUT may be supplied with a conversion cable to SMA. With respect to calibration, the device plus the conversion cable will be considered as one entity and calibration shall hold with respect the SMA reference plane.</td><td>Both</td><td>All</td><td>B</td><td>I</td><td>MIL-STD-348 [RD.3]</td></tr>
<tr><td>I.9</td><td>O</td><td>1PPS and Aux output signals characteristics (@ 50 Ohm load):<br>- DC coupled<br>- able to drive a 50 Ohm load<br>- 1PPS positive pulse width shall be between 100 ns and 500 ms.<br>- voltage: $V_{HIGH}$: 1.2 V to 5.5 V | $V_{LOW}$: -0.3 V to 0.3 V<br>- slew rate:
<table>
<tr><th>WR Accuracy Class (see 2.8, P.1)</th><th>Accuracy value [ps] (see 2.8, P.1)</th><th>Minimum slew rate at threshold level [V/ns][9] (see 1.4.3.5)</th></tr>
<tr><td>WR Class A (a.k.a. basic)</td><td>499 ps</td><td>0.5 V/ns</td></tr>
<tr><td>WR Class B</td><td>249 ps</td><td>1 V/ns</td></tr>
<tr><td>WR Class C</td><td>99 ps</td><td>2 V/ns</td></tr>
<tr><td>WR Class D</td><td>< 25 ps</td><td>10 V/ns</td></tr>
</table>
Note 1: Slow rise time increases time difference measurement uncertainty and effectively prevents evaluation of stringent WR Accuracy Class. Fast rise time requires measurement equipment with high input bandwidth.<br>Note 2: There are ongoing studies on accurate differential 1PPS signals. When introduced, they will be allowed in WR Devices.<br>Note 3: The measurement setup (cables and measurement device) will have influence on the measured time marker. The bandwidth of the cables and the input stage of a measurement device influence the measured rise time (see also Annex C.5.1).</td><td>Both</td><td>All</td><td>B</td><td>T</td><td>ITU-T G.703 Table 19-6 [RD.4]</td></tr>
</table>

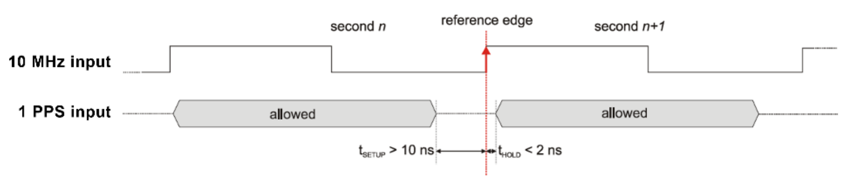
[9] The values are selected assuming 20mV trigger level uncertainty (from section 4.4 in [2]) and using the following formula to calculate the time error (TE) resulting from a given slew rate (SR): TE [ps] = 20mV / SR [V/ns]. The SR is selected such that TE is max 10% of the allowed accuracy, i.e. 8% (40ps) for Class A, 8% (20ps) for Class B, 10% (10ps) for Class C and 8% (2ps) for Class D.

| ID | Level | Requirement | Applicable to | | Func. type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| | | | type | config | | | |
| **I.10** | O | 10 MHz output signal characteristics, at least one of the following shall be available<br>**1. Single-ended:**<br>- Voltage amplitude 0.5 V to 2.5 V[10] (@ 50 Ohm termination)<br>- rise time: < 1ns from 10% to 90%<br>- DC or AC coupled<br>- square wave (50% duty cycle)<br>- able to drive a 50 Ohm load<br>**2. Differential (LVDS, LVPECL, CML)**<br>- Differential voltage amplitude 0.2 V to 1.0 V (@ 100 Ohm termination)<br>- rise time: < 1ns from 10% to 90%<br>- AC coupled<br>- square wave (50% duty cycle)<br>- able to drive a 100 Ohm load | Both | All | B | T | Single-ended : ITU-T G.703 Clause 20 [**RD.4**]<br><br>Differential: LVDS: TIA-644-A [**RD.18**], [**RD.19**] |
| **I.11** | O | Allowed 1PPS input signal characteristics:<br>- DC coupled<br>- Voltage amplitude 0.5 V to 5 V<br>- 50 Ohm termination; return loss < -10 dB (DC- 50 MHz)<br><br>**Datasheet:**<br>- State other types of signals acceptable on this connector (e.g. IRIG-B) | Both | GM | B | T | ITU-T G.703 19.1.1 [**RD.4**] |
| **I.12** | O | Allowed 10MHz input signal characteristics:<br>- AC coupled<br>- Voltage amplitude 0.5V to 5V<br>- Accept shape: square and sine<br>- 50 Ohm termination; return loss < -10 dB (DC- 50 MHz) | Both | GM | B | T | |

[10] Per the referenced ITU-T specification, the allowed peak-peak voltage value can be between 1V and 5V

## 2.4 Functional requirements

| ID | Level | Requirement | Applicable to | | Func. Type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| | | | type | config | | | |
| **F.1** | O | EEPROM content that follows the specification and with at minimum:<br>Hardware version, Manufacturer, Serial number | Switch | All | B | T | [**RD.14**] |
| **F.2** | O | Storage for persistent calibration data (e.g. EEPROM, FLASH) accessible from WRPC. | Node | All | B | T<br>See 3.5 | |
| **F.3** | O | Unique MAC address per each present Ethernet port<br>(management and WR ports). | Both | All | B | R<br>See 3.6 | |
| **F.4** | O | 1PPS signal present on output connector only when synchronisation established on Slave port, unless forced by configuration (see Configuration C.1) | All | BC/OC | B | T | |
| **F.5** | O | 1PPS signal present on output connector only when switch/node locked to external reference source, unless configured as free-running master. | All | GM | B | T | |
| **F.6** | O | 10 MHz signal always present (unless it is multiplexed, see I.5 note 2) on an output connector. | All | All | B | T | |
| **F.7** | O | The 10 MHz and PPS outputs shall have a fixed phase relation that can be arbitrary but is maintained over link re-starts and *device* power-up with known repeatability<br>**Datasheet:** state repeatability of skew between 1PPS and 10MHz output signals,<br>Repeatability: $r = \max(skew_{avg}[n]) - \min(skew_{avg}[n])$), see see in 3.8.2. | All | All | B | T<br>see<br>3.8.2 | |
| **F.8** | O | Signals present on 1PPS input connector and 10 MHz input connector used as reference source for WR time, unless configured otherwise<br>(e.g. 1PPS input configured to accept IRIG-B). | All | GM | B | T | |
| **F.9** | O | Support of NTP as source of ToD via management Ethernet port.<br>**Note:** Support of additional alternative sources of ToD is allowed<br>(e.g. NMAE, IRIG-B) | Switch | GM | B | T | RFC 5905 [**RD.5**], IRIG [**RD.6**], NMEA0183 [**RD.7**] |
| **F.10** | O | Support of one or more of the following sources of ToD: NTP, NMEA, IRIG-B, manual. | Node | GM | B | T | |
| **F.11** | O | VLAN support for PTP frames, including WR Extensions and HA optional features (at minimum over Transport of PTP over IEEE 802.3 transports) | Switch | All | B | T | |

| ID | Level | Requirement | Applicable to type | Applicable to config | Func. Type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| **F.12** | O | Management Ethernet interface implements: Static IPv4 configuration, DHCP, SSH server. | Switch | All | B | T | DHCP **[RD.24]**<br>SSH **[RD.25]**<br>IPv4 **[RD.26]** |
| **F.13** | O | Implementation/support of the following:<br>- "bitslide calibration" or "Low Phase Drift Calibration (LPDC)" mechanisms on WR Ports<br>- means to read the value associated with above (bitslide value or phase calibration starting point).<br>**Note:** bitslide or LPDC functionality itself will not be tested by an associated laboratory but only the fact that there is a means to readout their value. | All | All | B | T | Bitslide [**RD.16**], LPDC [**RD.17**] |
| **F.14** | R | Basic support for SNMP, LLDP, PNAC, LDAP<br><br>**Note:** A basic SNMP implementation supporting only “get” is sufficient (no “traps” or “sets”). | Switch | All | B | R | SNMP [**RD.20**]<br>LLDP [**RD.21**]<br>PNAC [**RD.22**]<br>LDAP [**RD.23**] |
| **F.15** | O | GM accepts 10MHz and 1PPS inputs with the relation as specified: the input 1PPS is **allowed** to occur:<br>- at earliest 2ns after the rising edge of 10 MHz input clock<br>- at latest 10ns before the rising edge of the 10 MHz input clock<br><br>**Note:** The “allowed” range in the figure above will not be tested by an associated laboratory. This specification simply ensures that a GM will lock to an external clock, based on the specification above. | All | GM | B | T | Note on GM [**RD.13**] |

## 2.5 Standard Compliance

| ID | Level | Requirement | Applicable to | | Func.Type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| | | | type | config | | | |
| **S.1** | O | Forwarding of Ethernet frames between WR Ports and related L2 Bridge functionalities:<br>- Filtering DB operation<br>- Static VLANs<br>- Learning<br>- Aging | Switch | All | B | T<br>See 3.7 | See **Annex A** |
| **S.2** | O | **All** of the following:<br>- PTP-HA: High Accuracy Delay Request-response Default PTP Profile of IEEE 1588-2019<br>- PTP-WR: White Rabbit profile/extension to IEEE 1588 | Switch | All | B | T<br>See 3.7 | WR Spec [**RD.8**], IEEE 1588 [**RD.9**] |
| **S.3** | O | Auto-negotiation mechanism between PTP-WR and PTP-HA | Switch | All | B | T<br>See 3.7 | Autoneg [**RD.10**] |
| **S.4** | R | Implement Delay Request-Response Default PTP Profile of IEEE 1588-2008 and/or of IEEE 1588-2019 | Switch | All | B | T<br>See 3.7 | IEEE 1588 [**RD.9**] |
| **S.5** | O | **One** of the following:<br>- PTP-HA: High Accuracy Delay Request-response Default PTP Profile of IEEE 1588-2019 (preferred)<br>- PTP-WR: White Rabbit profile/extension to IEEE 1588 | Node | All | B | T<br>See 3.7 | WR Specification [**RD.8**], IEEE 1588 [**RD.9**] |
| **S.6** | O | Transport of PTP over IEEE 802.3 transports | All | All | B | T<br>See 3.7 | IEEE 1588 [**RD.9**] |
| **S.7** | O | Transport of PTP over User Datagram Protocol over Internet Protocol Version 4 | Switch | All | B | T<br>See 3.7 | IEEE 1588 [**RD.9**] |
| **S.8** | R | Peer-to-peer delay mechanism operation with PTP-HA, PTP-WR, Default PTP Profiles | Switch | All | B | T<br>See 3.7 | IEEE 1588 [**RD.9**] |

## 2.6 Configuration

| ID | Level | Requirement | Applicable to | | Func. Type | Validation | Specification |
|---|---|---|---|---|---|---|---|
| | | | type | config | | | |
| **C.1** | O | Configuration to force 1PPS output regardless of device type and state | All | All | B | T | |
| **C.2** | OW | Mechanism to read and write the following IEEE 1588-2019 datasets<br>- 8.2.15.5.2 portDS.masterOnly<br>- 8.2.16 timestampCorrectionPortDS: ingressLatency, egressLatency<br>- 8.2.17 asymmetryCorrectionPortDS: scaledDelayCoefficient, constantAsymmetry<br>- 17.6.2 defaultDS.externalPortConfigurationEnabled<br>- 17.6.3 externalPortConfigurationPortDS.desiredState<br>- L.5 L1SyncBasicPortDS logL1SyncInterval, L1SyncReceiptTimeout<br><br>**Waiver:** Legacy WR Devices may have different names of parameters with equivalent functionality. | Switch | All | B | T | IEEE 1588 [**RD.9b**] |
| **C.3** | OW | Mechanism to access for read and write the following IEEE 1588-2019 datasets<br>- 8.2.16 timestampCorrectionPortDS: ingressLatency, egressLatency<br>- 8.2.17 asymmetryCorrectionPortDS: scaledDelayCoefficient<br><br>**Waiver:** Legacy WR Devices might have different names of parameters with equivalent functionality. | Node | All | B | T | IEEE 1588 [**RD.9b**] |
| **C.4** | O | Mechanism that allows residual correction of SFP calibration parameters | Switch | All | B | T | [**RD.15**] See 3.9.4 |

## 2.7 Calibration of ingress- and egress-latencies

| ID | Level | Requirement | Applicable to | | Environ-mental | Func. Type | Validation | Specification |
|---|---|---|---|---|---|---|---|---|
| | | | type | config | | | | |
| **Cal.1** | OW | WR Device shall be calibrated using a calibrator traceable to the WR Golden Calibrator at CERN[11].<br><br>**Waiver:** Calibration to a network-local calibrator is acceptable in justified cases, see 3.9.3.<br>**Datasheet:** State Details about the calibrator used and its traceability | All | All | Constant room temperature | B | R | See 3.9 |
| **Cal.2** | O | WR Device shall be always calibrated with SFPs compatible with wavelength 1490nm and 1310nm (1000BASE-BX10).<br><br>**Note 1:** Calibrating all devices with the same wavelength pair as a base ensures interoperability and eases the qualification process.<br>**Note 2:** Calibrating all devices with the same wavelength pair allows using reference SFP, see Cal.6. | All | All | Constant room temperature | B | R | See 3.9 |
| **Cal.3** | O | The calibration shall be performed for each WR Port of the WR Device using a reference SFP type. | All | All | Constant room temperature | B | P, R | |
| **Cal.4** | O | The calibration shall be performed for each particular<br>- Version of hardware, and<br>- Bistream generation (gateware)<br>Any change to the hardware or regeneration of bitstream invalidates the calibration, unless proven otherwise.<br>**Note:** Calibration is performed on a "representative" unit of a given type/version/vendor. It is expected that variations between individual units of the same type/version/vendor (part-to-part variation) are quantified by the manufacturer. Typically, the same calibration values are applied for each unit of the same type/version/vendor. If calibration uncertainty resulting from part-to-part variation is not acceptable for a given application, per-unit calibration is possible and is outside the scope of this document. | All | All | Constant room temperature | B | P, R | |

[11] In the future, this requirement might be replaced or complemented (alternative) with requirement for the calibrator to be calibrated using absolute calibration method, see 3.9.2.

| ID | Level | Requirement | Applicable to | | Environ-mental | Func. Type | Validation | Specification |
|---|---|---|---|---|---|---|---|---|
| | | | type | config | | | | |
| **Cal.5** | O | Each calibration shall consist of a minimum series of 10 measurements, see Figure 3. Before each measurement, the link and synchronisation between the calibrator and the DUT shall be re-established under software control (e.g. a system reset, system restart or link down/up). Each measurement shall provide the average over 2 minutes of time difference between the 1PPS outputs of the calibrator and DUT (i.e. 120 samples), see 3.8.1 and 3.9.3.<br>After the warm up period (see 3.2.2), the following temperatures shall be recorded during the measurements for the calibrator and the DUT:<br>a) ambient temperature<br>b) FPGA temperature (as reported by the *device*)<br>c) SFP temperature (if available and as reported by the SFP)<br>These temperatures shall be provided in the WR Device Qualification Report.<br><br>**Note 1:** Usually the FPGA die temperature can be monitored by instantiating an IP core, e.g. Xilinx SYSMON or XADC.<br>**Note 2:** The temperature does not need to be reported by the WR Core itself. It can be reported using another interface, provided it can be easily read and is well-documented.<br>**Note 3:** Temperature measurement recording can be slow, e.g. once every minute. | All | All | Constant room temperature | B | P (3.9) | WR Calib [**RD.15**] |
| **Cal.6** | R | The reference SFP used in **Cal.3** should be the same model as the reference SFP used by CERN[12]<br>**Note 1:** Using a known SFP, the above ensures a common notion of calibration when an associated laboratory performs calibration for ingress- and egress-latency correction.<br>**Note 2:** Residual correction for other SFP types that are calibrated, using WR Devices that apply ingress- and egress-latency correction based on the common known SFP, can be added to the existing database of SFPs. This database of SFP residual corrections will be supplied (for free). | All | All | Constant room temperature | B | R | |

[12] If the same SFP type (vendor/model/revision) is used, CERN's database of residual corrections for different types of SFPs can be re-used. Reference SFPs are available to WR Collaboration members.

| ID | Level | Requirement | Applicable to | | Environ-mental | Func. Type | Validat ion | Specificati on |
|---|---|---|---|---|---|---|---|---|
| | | | type | config | | | | |
| **Cal.7** | O | If desired to support more SFP types, calibration shall be performed for each SFP type. It can be performed for only a single WR Port. | All | All | Constant room temperature | E | R | |
| **Cal.8** | O | Ingress- and egress-latency values calibrated for the reference SFP shall be present in the per-port latency configuration.<br>Residual corrections of ingress- and egress-latency values for non-reference SFPs with respect to reference SFP shall be present in the per-SFP database (see 3.9.4). | Switch | All | Constant room temperature | B | R | 3.9.1<br>3.9.3 |
| **Cal.9** | O | Ingress- and egress-latency values calibrated for each SFP shall be present in the per-SFP latency configuration. | Node | All | Constant room temperature | B | R | 3.9.1<br>3.9.3 |

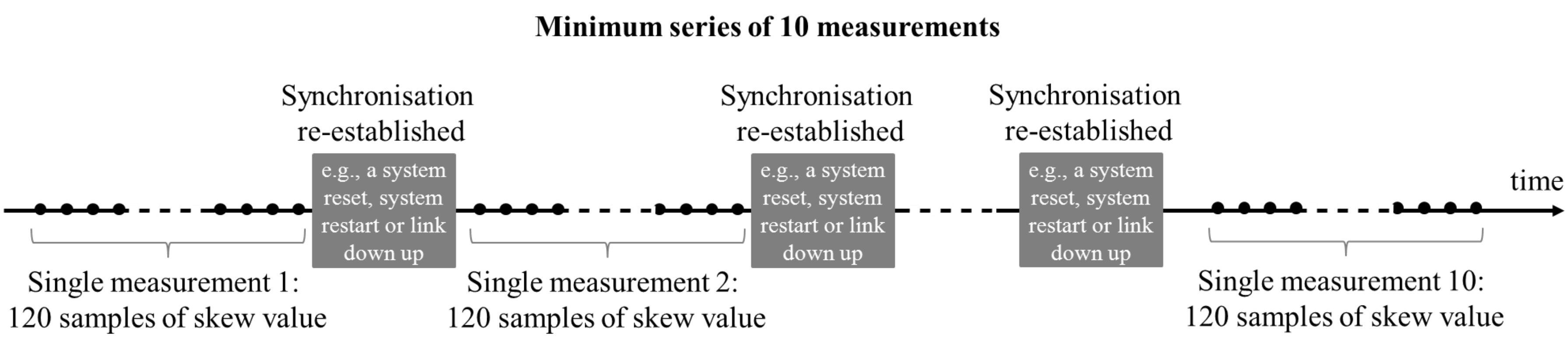



**Figure 3 - Minimum Series of 10 measurements**

## 2.8 Performance

<table>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Environ-mental</th><th rowspan="2">Func. Type</th><th rowspan="2">Validation</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
<tr><td>P.1</td><td>O</td><td>Accuracy: in the test setup where the DUT is synchronized to a GM as described in 3.1b) (CH2 is DUT output 1PPS), after calibration of 3.9.3, a series of 10 measurements is performed, see Figure 3. Before each measurement, the link and synchronisation between the GM and the DUT is re-established under software control (e.g. a system reset, system restart or link down/up). Each measurement provides the average over 2 minutes (i.e. 120 samples) of the time difference (skew, 1.4.3.6) between the 1PPS output of the GM and the DUT as described in 3.8.1, i.e. $skew_{avg}[n]$, where n is [1,10]. The results shall be as follows in the specified operating temperature range which shall include room temperature:<br>- Accuracy: a(temp) = $-0.5$ ns < average($skew_{avg}[n]$) < 0.5 ns<br>- Repeatability: r(temp) = max($skew_{avg}[n]$)-min($skew_{avg}[n]$) < 0.5 ns<br>Where temp is constant temperature as follows<br>- Room temperature (1.4.3.7)<br>- If operating temperature range is specified for synchronisation in the datasheet beyond room temperature:<br>  ○ Minimum temperature in the specified operating temp range<br>  ○ Maximum temperature in the specified operating temp range<br>Beyond meeting the above basic accuracy criteria, with respect to the absolute value of accuracy and the value of repeatability, the performance classes are defined as follows:
<table>
<tr><th>WR Accuracy Class</th><th>For all temp, abs(a(temp)) and r(temp) within range</th></tr>
<tr><td>WR Class A (a.k.a. basic)</td><td>250 – 499 ps</td></tr>
<tr><td>WR Class B</td><td>100 – 249 ps</td></tr>
<tr><td>WR Class C</td><td>25 – 99 ps</td></tr>
<tr><td>WR Class D</td><td>< 25 ps</td></tr>
</table>
Datasheet: specifies operating range for the device and/or specifically for synchronisation performance.<br><br>Note: If the time interval measurement device allows (i.e. it has more than two channels) then the validation of requirement F.7 can take place at the same time as requirement validation F.7 (see 2.4 and 3.8.2).</td><td>All</td><td>All</td><td>Constant temperature (1.4.3.8)</td><td>B</td><td>T 3.8.1</td><td></td></tr>
</table>

<table>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Environ-mental</th><th rowspan="2">Func. Type</th><th rowspan="2">Validat ion</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
<tr><td>P.2</td><td>O</td><td>

**Precision:** in the test setup where the DUT is synchronized to a GM as described in 3.1b) (CH2 is DUT output 1PPS), a series of 10 measurements is performed, see Figure 3. Before each measurement, the link and synchronisation between the GM and the DUT is re-established under software control (e.g. a system reset, system restart or link down/up). Each measurement provides the standard deviation (sdev) over 2 minutes (i.e. 120 samples) of the time difference (skew, 1.4.3.6) between the 1PPS output of the GM and the DUT as described in 3.8.1, i.e. $skew_{sdev}[n]$, where n is [1,10]. The results shall be as follows in the **specified operating temperature range** which shall include room temperature:

- Precision: p(**temp**) = max ($skew_{sdev}[n]$) < 50 ps

Where **temp** is constant temperature as follows

- Room temperature (1.4.3.7).
- If **operating temperature range** is specified for synchronisation in the datasheet beyond room temperature:
  - Minimum temperature in the specified operating temp range
  - Maximum temperature in the specified operating temp range

Beyond meeting the above basic accuracy criteria, with respect to the value of precision, the performance classes are defined as follows:

| WR Precision Class | For all temp, p(temp) within range |
|---|---|
| WR Class 1 (a.k.a. basic) | 25 – 49 ps |
| WR Class 2 | 12 – 24 ps |
| WR Class 3 | 6 – 11 ps |
| WR Class 4 | < 6 ps |

**Datasheet:** specifies operating range for the device and/or specifically for synchronisation performance.

</td><td>All</td><td>All</td><td>Constant temperature (1.4.3.8)</td><td>B</td><td>T<br>3.8.1</td><td></td></tr>
</table>

<table>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Environ-mental</th><th rowspan="2">Func. Type</th><th rowspan="2">Validation</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
<tr><td>P.3</td><td>O</td><td>
GM Phase noise: in the test setup where the DUT in GM Mode is synchronized to the time and frequency source as described in 3.1c), Phase Noise (PN) is measured between the 10 MHz output of the time and frequency source and the DUT as described in 3.8.3, i.e. SSB phase noise 10 MHz and RMS jitter over 1 Hz - 1 MHz. The results shall meet the criteria specified for PN “WR Class I (a.k.a. basic)”in the table below.<br>
Beyond meeting the basic PN criteria, with respect to the value of PN, the performance classes are specified in the Table below (see also Figure 4 for equivalent visual representation).
<table>
<tr><th>Offset from Carrier [Hz]</th><th>1</th><th>10</th><th>100</th><th>1k</th><th>10k</th><th>100k</th><th>1M</th><th>Maximum RMS jitter 1Hz-1MHz</th></tr>
<tr><td>WR PN Class</td><td colspan="7">Maximum SSB phase noise for the offset from carrier [dBc/Hz]</td><td>[ps]</td></tr>
<tr><td>WR Class I (a.k.a. basic)</td><td>-70</td><td>-70</td><td>-95</td><td>-120</td><td>-130</td><td>-130</td><td>-130</td><td>29.1</td></tr>
<tr><td>WR Class II (a.k.a. low-jitter)</td><td>-95</td><td>-95</td><td>-115</td><td>-130</td><td>-140</td><td>-140</td><td>-140</td><td>2.9</td></tr>
</table>
The above criteria shall be met when measured at constant temperature as follows:
<ul>
<li>for room temperature (1.4.3.7),</li>
<li>for the minimum and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.</li>
</ul>
</td><td>All</td><td>GM</td><td>Constant temperature (1.4.3.8)</td><td>B</td><td>T<br>3.8.3</td><td></td></tr>
</table>

<table>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Environ-mental</th><th rowspan="2">Func. Type</th><th rowspan="2">Validation</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
<tr><td>P.4</td><td>O</td><td>BC/OC Phase noise: in the test setup where the DUT is synchronized to a Class-II (i.e. low-jitter) WR Switch/Node in GM Mode as described in 3.1d), Phase Noise (PN) is measured between the 10 MHz output of the time and frequency source and the DUT as described in 3.8.3, i.e. SSB phase noise 10 MHz and RMS jitter over 1 Hz - 1 MHz. The results shall meet the criteria specified for PN “WR Class I (a.k.a. basic)” in the table below.<br>Beyond meeting the basic PN criteria, with respect to the value of PN, the performance classes are specified in the Table below (see also Figure 4 for equivalent visual representation).<br><br>
<table>
<tr><th>Offset from Carrier [Hz]</th><th>1</th><th>10</th><th>100</th><th>1k</th><th>10k</th><th>100k</th><th>1M</th><th>Maximum RMS jitter 1Hz-1MHz</th></tr>
<tr><th>WR PN class</th><th colspan="7">Maximum SSB phase noise for the offset from carrier [dBc/Hz]</th><th>[ps]</th></tr>
<tr><td>WR Class I (a.k.a. basic)</td><td>-70</td><td>-70</td><td>-95</td><td>-120</td><td>-130</td><td>-130</td><td>-130</td><td>29.1</td></tr>
<tr><td>WR Class II (a.k.a. low-jitter)</td><td>-90</td><td>-90</td><td>-107</td><td>-125</td><td>-135</td><td>-135</td><td>-130</td><td>5.3</td></tr>
</table>
The above criteria shall be met when measured at constant temperature as follows:<br>- for room temperature (1.4.3.7),<br>- for the minimum- and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.</td><td>All</td><td>BC/OC</td><td>Constant temperature (1.4.3.8)</td><td>B</td><td>T<br>3.8.3</td><td></td></tr>
</table>

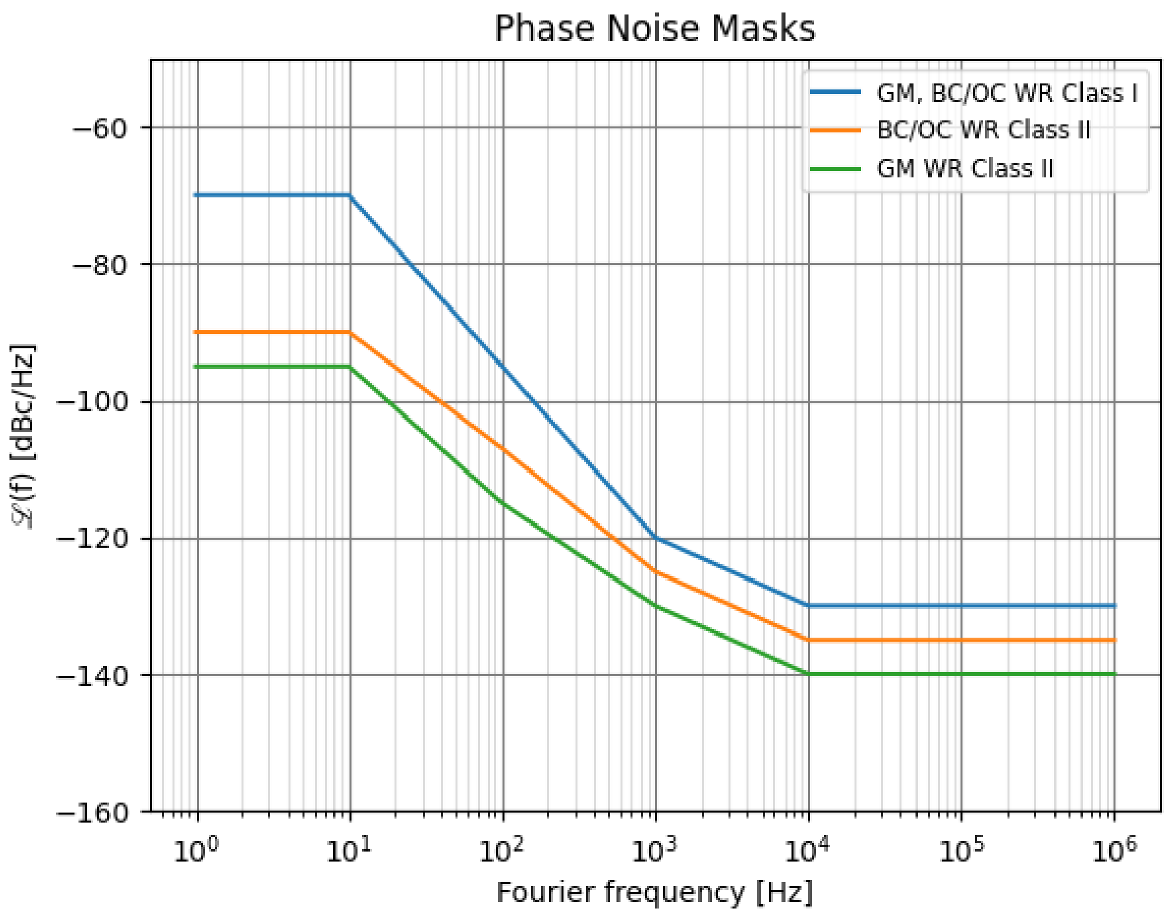



**Figure 4 - Phase Noise masks for P.3 and P.4**

<table>
<thead>
<tr><th rowspan="2">ID</th><th rowspan="2">Level</th><th rowspan="2">Requirement</th><th colspan="2">Applicable to</th><th rowspan="2">Environ-mental</th><th rowspan="2">Func. Type</th><th rowspan="2">Validation</th><th rowspan="2">Specification</th></tr>
<tr><th>type</th><th>config</th></tr>
</thead>
<tbody>
<tr>
<td>P.5</td>
<td>O</td>
<td>GM MDEV: in the test setup where the DUT in GM Mode is synchronized to the time and frequency source as described in 3.1c), Modified Allan Deviation (MDEV) is measured for 1000 s between the 10 MHz output of the time and frequency source and the DUT as described in 3.8.4, i.e. MDEV measured with equivalent noise bandwidth of 50 Hz. The results shall meet the criteria specified for MDEV “WR Class I (a.k.a. basic)” in the table below.<br>Beyond meeting the basic MDEV criteria, with respect to the values of MDEV, the performance classes are specified in the Table below (see also Figure 5 for equivalent visual representation).
<table>
<tr><th>Tau [s]</th><th>0.01</th><th>0.1</th><th>1</th><th>10</th><th>100</th></tr>
<tr><th>WR MDEV class</th><th colspan="5">Max MDEV(tau)</th></tr>
<tr><td>WR Class I (a.k.a. basic)</td><td>1E-9</td><td>1E-10</td><td>1E-11</td><td>1E-12</td><td>1E-13</td></tr>
<tr><td>WR Class II</td><td>3.16E-10</td><td>1E-11</td><td>1E-12</td><td>1E-13</td><td>1E-14</td></tr>
</table>
The above criteria shall be met when measured at constant temperature as follows:<br>- for room temperature (1.4.3.7),<br>- for the minimum and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.</td>
<td>All</td>
<td>GM</td>
<td>Constant temperature (1.4.3.8)</td>
<td>B</td>
<td>T<br>3.8.4</td>
<td></td>
</tr>
<tr>
<td>P.6</td>
<td>O</td>
<td>BC/OC MDEV: in the test setup where the DUT is synchronized to a Class-II (i.e. low-jitter) WR Switch/Node in GM Mode as described in 3.1d), Modified Allan Deviation (MDEV) is measured for 1000 s between the 10 MHz output of the time and frequency source and the DUT as described in 3.8.4, i.e. MDEV measured with equivalent noise bandwidth of 50 Hz. The results shall meet the criteria specified for MDEV “WR Class I (a.k.a. basic)” in the table below.<br>Beyond meeting the basic MDEV criteria, with respect to the values of MDEV, the performance classes are specified in the Table below (see also Figure 5 for equivalent visual representation).
<table>
<tr><th>Tau [s]</th><th>0.01</th><th>0.1</th><th>1</th><th>10</th><th>100</th></tr>
<tr><th>WR MDEV class</th><th colspan="5">Max MDEV(tau)</th></tr>
<tr><td>WR Class I (a.k.a. basic)</td><td>1E-9</td><td>1E-10</td><td>1E-11</td><td>1E-12</td><td>1E-13</td></tr>
<tr><td>WR Class II</td><td>5E-10</td><td>5E-11</td><td>5E-12</td><td>5E-13</td><td>5E-14</td></tr>
</table>
The above criteria shall be met when measured at constant temperature as follows:<br>- for room temperature (1.4.3.7),<br>- for the minimum and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.</td>
<td>All</td>
<td>BC/OC</td>
<td>Constant temperature (1.4.3.8)</td>
<td>B</td>
<td>T<br>3.8.4</td>
<td></td>
</tr>
</tbody>
</table>

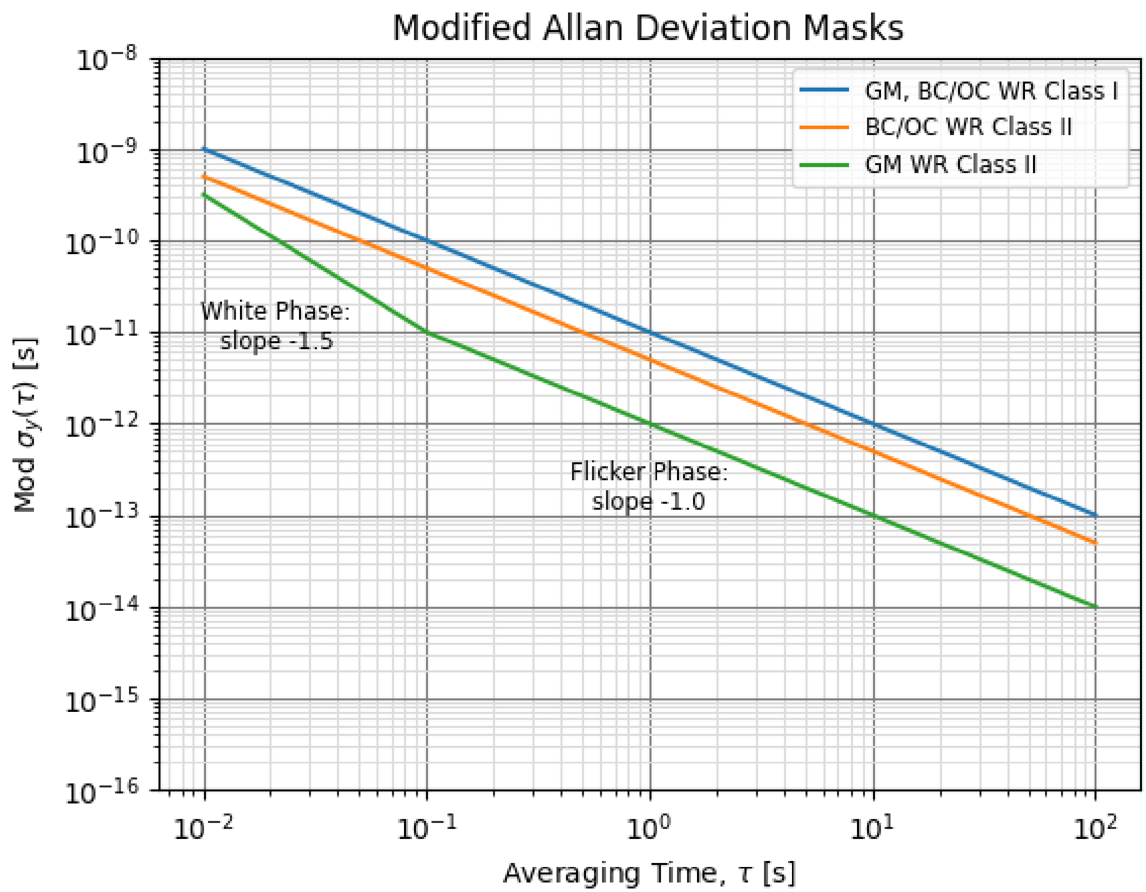



**Figure 5 - MDEV mask for P.5 and P.6**

# 3 Test setup

## 3.1 Test setup configurations

Basic test setup configurations which allow verification of requirements in 2 are illustrated in Figure 6 and listed below.

a) **Compliance tests** to validate requirements in 2.5
b) **Time transfer performance** and **calibration** to validate:

| CH2 (see Figure 6b) | Validation |
|---|---|
| DUT output 1PPS | P.1 & P.2 in 2.8, and perform calibration per 2.7 |
| DUT output 10 MHz | F.7 in 2.4 |

Table 1: Time interval measurement device CH2 connection

c) **Frequency transfer performance of DUT in GM mode** to validate P.3 & P.5 in 2.8
d) **Frequency transfer performance of DUT in BC/OC mode** to validate P.4 & P6 in 2.8

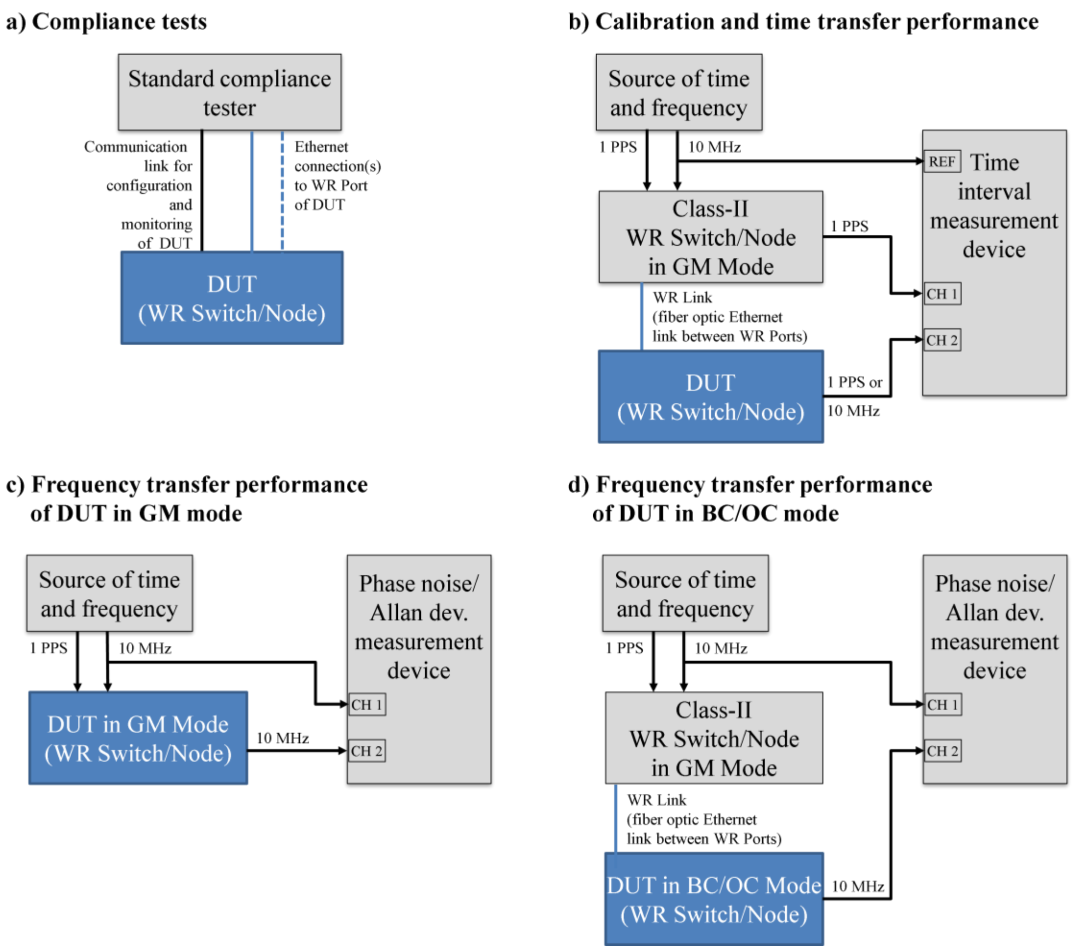



Figure 6 - Basic test setups

In Figure 6, a box with grey background represents the equipment required to perform the test, a box with blue background represents the Device Under Test (DUT). Black lines represent coaxial connections with arrows indicating direction of the signal (pointing to the device to which the signal is an input). The blue lines indicate bidirectional WR Link (fiber optic Ethernet link between two WR ports). Figure 6 does not show a management PC and its Ethernet connection to the DUT and other equipment that needs to be controlled.

The subsequent sections provide further description of the test setup preparation and how tests are performed. Annex C provides information about test equipment and test equipment validation.

The coaxial cables connecting the output of the DUT to the measurement devices shall be flexible phase stable measurement cables specified for a frequency range that is larger than the bandwidth needed for the measurement of the different WR Classes (see Annex C.8).

## 3.2 Test setup preparation

### 3.2.1 Calibration certificate

Measurement devices used for the measurements described in this chapter shall have a calibration certificate and their calibration validity period shall not have been expired.

### 3.2.2 Warm up

This step is relevant for test setups b, c and d in Figure 6, as well as in Figure 9, Figure 11 and Figure 13. Any measurement should be performed after all the devices in these setups have been stably working for at minimum:

- the warm-up time specified in their datasheet, or
- two hours, if no warm-up time specified.

### 3.2.3 Time interval measurement device calibration

A reference measurement using a setup as shown in Figure 7 is performed at constant room temperature (see 1.4.3.7). This reference measurement results in a calibration value $skew_{cal}$ for the channel skew of the combined set of input cables and the time interval measurement device such that the time reference plane shifts to the end of the input cables, i.e. the reference planes (1.4.3.4) of the DUT and the reference device.

Calibration is performed using an RF splitter. At the level of accuracies aimed for, it may not be expected that the splitter has equal delay from its common input to its outputs. Some asymmetry may be expected which will be addressed in the following calibration procedure of the time interval measurement device. Let the RF splitter have delays δ1 and δ2 from its input to its outputs 1 and 2, the coaxial measurement cables have delays δ3 and δ4 and the time interval measurement device have delays δ5 and δ6 between its input connectors and the internal timestamping unit where the timestamps are actually captured (see Figure 7).

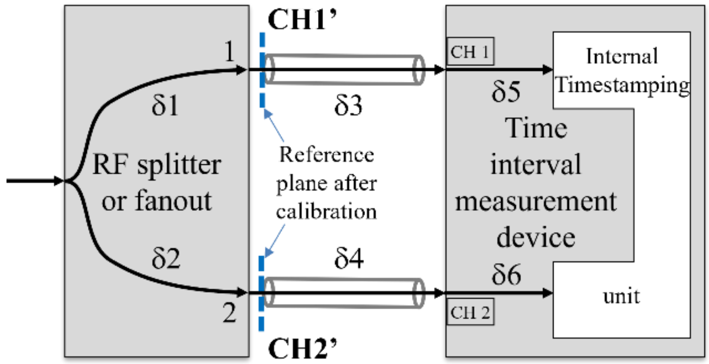



**Figure 7: Calibration of the time interval measurement device**

Multiple single-shot measurements can be averaged to lower the statistical uncertainty. A first skew measurement will result in:

$$skew1_{avg} = (\delta 2 + \delta 4 + \delta 6) - (\delta 1 + \delta 3 + \delta 5)$$

To take splitter asymmetry into account, the measurement is repeated by swapping the outputs 1 and 2 of the RF splitter which results in:

$$skew2_{avg} = (\delta 1 + \delta 4 + \delta 6) - (\delta 2 + \delta 3 + \delta 5)$$

The splitter asymmetry $A_S$ can be calculated by subtracting the measured skews:

$$skew1_{avg} - skew2_{avg} = 2(\delta 2 - \delta 1) = 2A_S$$

The $skew_{cal}$ at the time reference plane (i.e. at the end of the measurement cables: $CHA1'$ and $CHA2'$, see Figure 7) is

$$skew_{cal} = CH2' - CH1' = (\delta 4 + \delta 6) - (\delta 3 + \delta 5) = skew1_{avg} - A_S = skew2_{avg} + A_S$$

The Type A uncertainty of $skew_{cal}$ is the largest of sdev($skew1_{avg}$) or sdev($skew2_{avg}$).

The time interval measurement device reading must be compensated by subtracting calibration value $skew_{cal}$ from measured readings. From the definition in 1.4.3.6:

$$skew_{CH1\_to\_CH2\_corrected} = t_{TM_{CH1}} - t_{TM_{CH2}} - skew_{cal}$$

The Type A uncertainty of a single measurement "n" that consists of a number of "N" single measurements is:

$$Type\ A = \sqrt{sdev(skew_{cal})^2 + sdev(skew_{avg}[n])^2}$$

**Note:** This calibration does not mitigate errors outlined in Annex D.

## 3.3 Validation of Management Interfaces (req. I.1-3)

a) Physical management interfaces are validated by inspection (I) and testing (T). Virtual management interfaces can only be tested (T).
b) A management interface is considered operational if it returns a prompt and responds to any of the basic commands available in the *device*.

## 3.4 Validation of Ethernet WR Port (req. I.4)

a) Validation of the operation of WR Ports is a result of successful calibration of the port (see 3.9).

**Note:** WR Port calibration can only be successfully performed when WR Port is fully functional (i.e. if a WR Port does not function correctly, it is very unlikely to perform successful calibration).

## 3.5 Validation of storage for persistent calibration data on WR Node (req. F.2)

Different types of persistent storage are supported by WRPC (e.g. EEPROM, FLASH). The current format of the data stored is the SDB File System but it can change in the future. The tests below are meant to verify whether persistent storage is possible and correct, regardless of the memory type or file system type.

a) Use management interface (physical or virtual) to access the shell of WRPC.
b) Execute command to store calibration data and then read it back to verify:
    a. The command and its input data format are provided in the WR PTP Core User's manual [16].
    b. For WRPC-v5 release (see page 78 of User's Manual[13]) these commands are:
        *i.* Erase memory:
        *# sfp erase*
        *ii.* Write data:
        *# sfp add <PN> <deltaTx> <deltaRx> <alphaH> <alphaL>*
        *iii.* Read data:
        *# sfp show*
c) Read t24p value or manually trigger its calibration:
    a. The command and its input data format are provided in the WR PTP Core User's manual [16]
    b. For WRPC-v5 (see page 73 of User's Manual[13]) it is:
        *# calibration*

**Note**: If commands in b) and c) above return an error, it might indicate that the storage is not formatted with the SDB File System [17][18]. The formatting can be done by executing appropriate commands, see information in the WR PTP Core User's manual [16]. For WRPC-v5, typically this command would be:
*# sdb fs 0*

## 3.6 Validation of unique MAC address per each present Ethernet port (req. F.3)

a) Validation by request and review (R) of information from the manufacturer of how the MAC addresses are created.

---

[13] " White Rabbit PTP Core User's Manual" https://gitlab.com/ohwr/project/wr-cores/-/wikis/uploads/7cf8d2161b6e5fa86348455bbd022196/wrpc-user-manual-v5.0.pdf

## 3.7 Validation of networking standards compliance (req. S.1-8)

Figure 6a depicts a typical standard compliance validation setup for the DUT. The setup includes

a) **DUT**: WR Switch or WR Node
b) **Standard compliance tester:** a device that executes tests by
   a. Configuring and monitoring the DUT over the communication link
   b. Sending stimulus and observing Ethernet traffic on the Ethernet connection to the WR port(s) of the DUT
c) Ethernet connection(s) to WR Port(s) of DUT:
   a. When the DUT is a WR Switch, at least two of its WR ports are connected to the tester.
   b. When the DUT is a WR Node, its main WR Port is connected to the tester.
d) Communication link between the tester and DUT
   a. It is used to configure the DUT for the purpose of the tests
   b. It is used to monitor status of DUT for the purpose of the tests
   c. It can be for example
      i. SSH communication over management port of a WR Switch
      ii. Serial communication over the UART port of a WR Node

The validation of networking standard compliance does not verify networking or White Rabbit/High Accuracy timing performance of the DUT; however it does verify protocol operation and timeouts.

| Requirement(s) | Compliance with | Compliance tests specification |
|---|---|---|
| S.1 | L2 Bridge functionalities | Any 802.1Q test suite |
| S.2, S.5, S.6, S.8 | PTP-WR Profile/extension with<br>- Ethernet and IPv4 mappings<br>- Req-resp and peer-to-peer delay mechanisms | White Rabbit Protocol Test Suite [**RD.11**] |
| S.2, S.5, S.6, S.8 | PTP-HA Profile/extension with<br>- Ethernet and IPv4 mappings<br>- Req-resp and peer-to-peer delay mechanisms | High Accuracy Protocol Test Suite [**RD.12**] |
| S.4 | Default PTP Profile with<br>- Ethernet and IPv4 mappings<br>- Req-resp and peer-to-peer delay mechanisms | Any IEEE 1588-2019 test suite |
| S.7 | Transport of PTP over User Datagram Protocol over Internet Protocol Version 4 | Any IEEE 1588-2019 test suite |

**Table 2: Compliance tests specifications**

## 3.8 Measurement of time and frequency transfer performance

### 3.8.1 Time difference measurements

Measurement of time difference between WR Devices is essential for performing calibration (see 2.7 and 3.9) and time transfer performance measurement (P.1 and P.2 in 2.8) of WR Devices. This section highlights aspects that need to be considered when performing time difference measurement.

Per definitions in section 1.4.3, the **time difference** is evaluated between **Time Markers** of the 1PPS output signal of WR Devices. To obtain meaningful results that are repeatable, the uncertainty of such a measurement should be minimized and evaluated. Per [7], uncertainty components are classified into Type A and Type B depending on their method of evaluation, see 1.4.3.9.

In the context of acquiring time difference for the purpose of calibration (see 2.7 and 3.9) and time transfer performance evaluation (2.8), as illustrated in Figure 3:

- A single measurement "n" consists of many data samples collected over a stated period (e.g. 2 min) of continuous operation of the DUT. The data samples are used to produce statistical data:
    - Average: $skew_{avg}[n]$
    - Standard deviation: $skew_{sdev}[n]$
- A series of measurements consists of a number "N" of single measurements where operation of DUT is interrupted between the measurements (e.g. link down and up, or reboot). The statistical data form each measurement "n" is used to produce overall statistics for the series (where n is [1,10]):
    - Accuracy: $a = average(skew_{avg}[n])$
    - Repeatability: $r = max(skew_{avg}[n]) - min(skew_{avg}[n])$
    - Precision: $p = max\ (skew_{sdev}[n])$

The requirements related to calibration and time transfer performance state the (minimum) number of measurement repetitions (see Figure 3). With the resulting statistical data, the evaluation of uncertainty should be performed.

### 3.8.2 Validation of a fixed phase relation between 1PPS and 10MHz (req. F.7)

In the test setup where the DUT is synchronized to a GM as described in 3.1b) (CH2 is DUT output 10 MHz), a series of 10 measurements is performed at constant room temperature, see Figure 3. Before each measurement, the link and synchronisation between the GM and the DUT is re-established under software control (e.g. a system reset, system restart or link down/up). Each measurement provides the average over 2 minutes (i.e. 120 samples) of the time difference (skew, 1.4.3.6) between the 1PPS output of the GM and the 10MHz output of the DUT as described in 3.8.1, i.e. $skew_{avg}[n]$, where n is [1,10]. The repeatability, as defined in 3.8.1 (Repeatability: $r = max(skew_{avg}[n]) - min(skew_{avg}[n])$) shall be equal or smaller than the value stated in the datasheet.

**Note:** If the time interval measurement device allows (i.e. it has more than two channels) then the validation of requirement F.7 can take place at the same time as performance measurement P.1 (see 2.8).

**Note:** The Voltage threshold level will be likely different for PPS (typically DC) and 10MHz (typical AC) signals, in both cases, it should be set at 50% of the steady-state, per 1.4.3.5.

### 3.8.3 Phase noise measurements

Phase noise is measured with a qualified phase noise measurement device (see Annex C.6). ENBW should be set to 50 Hz. If applicable, the cross-correlation factor should be set to 10. Typically, spurs that are within 10 dB over the phase noise mask limits can be considered acceptable.

Figure 6c shows the phase noise measurement setup used for a DUT in GM Mode. The DUT is synchronized to the time and frequency source as described in 3.1c). Phase noise is measured between the 10 MHz output of the time and frequency source and the DUT, i.e. SSB phase noise 10 MHz and RMS jitter over 1 Hz – 1 MHz. The results shall at least meet the criteria for "GM, BC/OC WR Class I" in P.3 and Figure 4. The WR Device is eligible for higher classes if it meets the performance criteria set for them.

Figure 6d shows the phase noise measurement setup used for a DUT in BC/OC Mode. The DUT is synchronized to a Class-II (i.e. low-jitter) WR Switch/Node in GM Mode as described in 3.1d). Phase noise is measured between the 10 MHz output of the time and frequency source and the DUT, i.e. SSB phase noise 10 MHz and RMS jitter over 1 Hz – 1 MHz**.** The results shall at least meet the criteria for "GM, BC/OC WR Class I" in P.4 and Figure 4. The WR Device is eligible for higher classes if it meets the performance criteria set for them.

### 3.8.4 Modified Allan Deviation measurement

Modified Allan deviation is measured with a qualified Allan deviation measurement device (see Annex C.7).

Figure 6c shows MDEV measurement setup used for a DUT in GM Mode. The DUT is synchronized to the time and frequency source as described in 3.1c), Modified Allan Deviation (MDEV) is measured for 1000 s between the 10 MHz output of the time and frequency source and the DUT, i.e. MDEV measured with equivalent noise bandwidth of 50 Hz. The results shall at least meet the criteria for "GM, BC/OC WR Class I" in P.5 and Figure 5. The WR Device is eligible for higher classes if it meets the performance criteria set for them.

Figure 6d shows the MDEV measurement setup used for a DUT in BC/OC Mode. The DUT is synchronized to a Class-II (i.e. low-jitter) WR Switch/Node in GM Mode as described in 3.1d), Modified Allan Deviation (MDEV) is measured for 1000 s between the 10 MHz output of the time and frequency source and the DUT, i.e. MDEV measured with equivalent noise bandwidth of 50 Hz. The results shall at least meet the criteria for "GM, BC/OC WR Class I" in P.6 and Figure 5. The WR Device is eligible for higher classes if it meets the performance criteria set for them.

## 3.9 Calibration

### 3.9.1 Device and medium asymmetry

Calibration is meant to mitigate asymmetries. In WR networks, two types of asymmetries are mitigated with calibration:

1) Device asymmetry – this is the asymmetry resulting from different hardware delays between the timestamp point and the medium reference plane of the WR Device. This asymmetry is represented by **ingress- and egress-latency** (fixed delays) described in section 3 of [**RD.8]** and 7.3.4 of [**RD.9**]. The pair of ingress- and egress-latency values is calibrated for each port of a WR Device (for each hardware model and version, gateware bitstream) and SFP (type, revision). The values of **ingress- and egress-latency** has been so far calibrated using relative calibration [**RD.15**] while absolute calibration is intended to be introduced in the future [10][11].
2) Medium asymmetry – this is the asymmetry resulting from difference of medium delay when using different wavelengths for duplex communication over a single medium (fibre). This asymmetry is represented by the **medium relative delay coefficient** (alpha) parameter described in section 3 of [**RD.8**] and 7.4.3 of [**RD.9**]. It is calibrated for a given fibre type and pair of wavelengths used for transmission, e.g. wavelengths 1310 nm and 1490 nm used over fibre type G652. The value of medium relative delay coefficient has been so far mostly calibrated in the lab, yet in-situ calibration is possible and is being developed [11][12]. Calibration of medium asymmetry can be considered an absolute calibration.

Both types of asymmetry are considered for the purpose of calibration by the associated laboratory in order to validate compliance with WR requirements. However, the medium is not a part of the DUT therefor the medium relative delay coefficient will likely differ in the user environment.

### 3.9.2 Absolute and relative calibration

In the context of device asymmetry and calibration of ingress- and egress-latency, calibration can be either relative or absolute:

- **Absolute calibration:** The measurement of actual values of the latencies is referred to as an absolute calibration. In absolute calibration, the measurement of the latencies is not biased by the calibration device (calibrator) and thus it can be repeated with the same result using different calibrators, subject to their stated measurement uncertainty. Absolute calibration can be substituted for, or complemented by, relative calibration. Absolute calibration is described in [10][11].
- **Relative calibration:** In relative calibration, the measurement of the latencies is biased by the calibration device (calibrator). This bias, however, cancels out if WR Devices calibrated with the same calibrator are interconnected. The calibration is relative to a given calibrator, and all WR Devices must be calibrated using this calibrator (or its copy) to achieve enhanced accuracy of synchronization. Such a calibrator is called "Golden Calibrator". Relative calibration procedures are described in [**RD.15**] (this document has been translated into Annex N of [**RD.9b**]) and include the following procedures
    - Calibrator pre-calibration – used to create the (Golden) calibrator – section 4.3 of [**RD.15**]
    - WR Device calibration – used to obtain the values of latency for a WR Device – section 4.5 of [**RD.15**]
    - Recovering the calibrator – used to create copies of the (Golden) calibrator – section 6 of [**RD.15**]

The absolute and relative calibration types can be complementary, absolute calibration can be used to calibrate a calibrator that is later used to calibrate WR Device using relative calibration, mitigating the bias otherwise inherent to the relative calibration.

Calibration procedures can be used for network-level or global calibration. In the case of the network-level calibration, WR Devices are meant to achieve the required accuracy of synchronization within a single network operated by a single operator. In the case of the global calibration, WR Devices are meant to achieve required accuracy of synchronization when interchanged between different networks, systems and operators. Calibration can be achieved by:

1. An absolute calibration of all the WR Devices (suitable for network-level and global calibration);
2. A relative calibration of all the WR Devices using one or more calibrators which are, or are traceable to:
    a. An absolute-calibrated Golden Calibrator (suitable for network-level and global calibration),
    b. A network-specific golden calibrator, obtained using relative calibration (suitable only for network-level calibration),
    c. One single world-wide golden calibrator, obtained using relative calibration (suitable for network-level and global calibration).

While absolute calibration is currently still in research phase, relative calibration described in [**RD.15**] has been used for over 15 years and remains the official method for the time being. Therefore

- The Golden Calibrator or its copy shall be used for global calibration, when a WR Device under calibration is meant to be used in heterogeneous WR networks and achieve sub-ns accuracy when interconnected with WR Devices calibrated elsewhere and/or running official WR releases
- A local calibrator can be created from scratch for network-local calibration, when the WR Device under calibration is meant to be used in local networks in which all the WR Devices are calibrated to the same local calibrator.

### 3.9.3 Relative calibration of device asymmetry (ingress- and egress-latency)

The values of ingress- and egress-latency will vary per

a) WR Device hardware version
b) Gateware bitstream generation
c) Individual WR Port of the WR Device
d) SFP vendor/model/type/revision
e) Unit of WR Device and SFP (part-to-part variation)

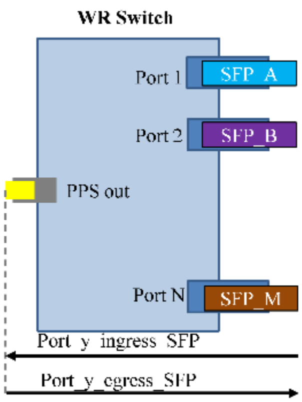
Depending on the tolerated uncertainties for the various WR Classes, part-to-part variation of WR Devices and SFPs can be considered negligible and can be ignored. However, for the most stringent requirements, calibration per unit must be considered.

### 3.9.4 Calibration for SFPs compatible with wavelengths 1490nm and 1310nm

In general, to achieve interoperability, WR Devices meant to be used in heterogeneous systems should have the base calibration performed using SFP compatible with 1490nm and 1310nm wavelengths. The calibration strategy is as follows:

1. A (golden) calibrator is available with (golden) SFP unit (see Annex C.4) compatible with 1490nm and 1310nm wavelengths.
2. Calibration base is selected which consists of
   a. A reference unit of a hardware version of a WR Device
   b. A reference port of the WR Device
   c. A reference unit of SFP for each vendor/type/revision that are compatible with the Golden SFP
   d. A base SFP unit with specific vendor/type/revision out of the reference SFP units (from c); currently, the base SFP unit is Blue Optics BO15C3149620D-WR[14]
3. For WR Nodes with a single port:
   a. This WR Port is calibrated with each SFP vendor/type/revision following the procedure "WR Device calibration" in section 4.5 of [**RD.15**]. The resulting values are ingress- and egress-latency for this particular WR Port, WR Device version/type, gateware version and SFP vendor/type/revision.
   b. The data is the input to the WR Node software.
4. For WR Switches with multiple WR Ports (see also Figure 8):
   a. Each WR Port of a WR Device is calibrated with the golden SFP unit (see Annex C.4) following the procedure "WR Device calibration" in section 4.5 of [**RD.15**]. The resulting values are ingress- and egress-latency for this particular WR Port, WR Device version/type, gateware version and SFP vendor/type/revision.
   b. One of the WR Ports of the WR Switch is calibrated using all SFP types/revisions available from different vendors, following the "WR Device calibration" in section 4.5 of [**RD.15**]. The resulting values of ingress- and egress-latencies for a particular SFP vendor/type/revision are subtracted from the values obtained using the base SFP unit. The resulting values are residual latency corrections for this particular SFP vendor/type/revision and can be applied to any WR Port and gateware version.
   c. The data from 4a) and 4b) above is used as follows:
      i. Values obtained in 4a) are stored in per-port ingress/egress latency database
      ii. Values obtained in 4b) are stored in per- SFP vendor/type/revision database
      iii. The final ingress- and egress-latency value used for a given WR Port is a sum of the per-port ingress/egress latency and its per-SFP residual correction.

[14] https://www.cbo-it.de/shop/white-rabbit-bo15c3149620d-wr-sfp-bidi-transceiver-1-gigabit-1000base-bx-u-single-mode-1310tx-1490rx-lc-simplex-20-kilometers




**Per-port Data Base**
obtained calibrating reference SFP, calibration for each HW/GW version

| Port number | Ingress/egress delays values |
|---|---|
| 1 | Port_1_ingress |
| | Port_1_egress |
| 2 | Port_2_ingress |
| | Port_2_egress |
| … | … |
| N | Port_N_ingress |
| | Port_N_egress |

**Per-SFP Data Base**
obtained calibrating one port with each SFP type valid for all HW/GW versions

| SFP Type | Ingress/egress correction |
|---|---|
| SFP_A (reference) | 0 |
| | 0 |
| SFP_B | SFP_B_ingress_corr |
| | SFP_B_egress_corr |
| … | … |
| SFP_M | SFP_M_ingress_corr |
| | SFP_M_egress_corr |

**Ingress/egress delays used in operation**

| Ingress/egress delays of a SFP type on Port N | Calculations when using | | |
|---|---|---|---|
| | SFP_A | SFP_B | SFP_M |
| Port_1_ingress_SFP | Port_1_ingress+0 | Port_1_ingress+SFP_B_ingress_corr | Port_1_ingress+SFP_M_ingress_corr |
| Port_1_egress_SFP | Port_1_egress +0 | Port_1_egress +SFP_B_egress_corr | Port_1_egress +SFP_M_egress_corr |
| Port_2_ingress_SFP | Port_2_ingress+0 | Port_2_ingress+SFP_B_ingress_corr | Port_2_ingress+SFP_M_ingress_corr |
| Port_2_egress_SFP | Port_2_egress +0 | Port_2_egress +SFP_B_egress_corr | Port_2_egress +SFP_M_egress_corr |
| … | … | … | … |
| Port_N_ingress_SFP | Port_3_ingress+0 | Port_3_ingress+SFP_B_ingress_corr | Port_3_ingress+SFP_M_ingress_corr |
| Port_N_egress_SFP | Port_3_egress +0 | Port_3_egress +SFP_B_egress_corr | Port_3_egress +SFP_M_egress_corr |

Figure 8: Per-port and Per-SFP databases and their effect on ingress/egress delay used in operation

### 3.9.5 Calibration of medium asymmetry (relative delay coefficient; outside the scope of this requirements document)

**The network medium is outside the scope of the WR Requirements** for a WR Device since the relative delay coefficient depends on the medium and not on the WR Device itself. However, for proper synchronization, the relative delay coefficient needs to be considered. If the medium is known, then the calibration can be performed:

- Ex-situ (in the lab), this has been so far the most widely used method, described in 4.3 of [**RD.15**] and N.4.5 of [**RD.9b**]
- In-situ (of already deployed fibres), this is becoming popular, and there are a number of ways it can be done, examples
  - Method described section 5 of [**RD.15**] – it is applicable to any type of SFPs
  - Method described in [11] and [12] – it is applicable when using DWDM
  - Methods described in [13] – applicable to any type of SFP

# 4 References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https://datatracker.ietf.org/doc/html/rfc2889

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https://iopscience.iop.org/article/10.1088/1681-7575/ab14bb

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[12] P. Jansweijer and H. Peek, "Insitu determination of the fiber delay coefficient in time-dissemination networks," 2019 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), Portland, OR, USA, 2019, pp. 1-6, doi: 10.1109/ISPCS.2019.8886632.
https://ieeexplore.ieee.org/document/8886632

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[14] *White Rabbit Requirements Reference Measurements*, Version 0.2.5, August 29, 2025.
(available for WR Collaboration Members on Request)

[15] White Rabbit Used And Validation Equipment
(available for WR Collaboration Members on Request)

[16] White Rabbit PTP Core (WRPC) wikis: https://gitlab.com/ohwr/project/wr-cores/-/wikis/wrpc-core

[17] Self-Describing Bus (SDB) Specification v1.1 – sdb specification available from
https://gitlab.com/ohwr/project/sdb/-/wikis/Documents/SDB-Specification-1.1

[18] SDB File System Manual – available from
https://gitlab.com/ohwr/project/sdb/-/wikis/Documents/SDB-File-System-Manual

# Annex A: Forwarding of Ethernet frames between WR Ports and related L2 Bridge functionalities (functional)

Implementation of the following is required in a WR Switch:

1) Creation and Deletion of a Static VLAN Registration
    a. 802.1Q 2005 Section - 12.7.5.1 ((Pg 101)
2) Creation (or not) of Dynamic Filtering Entry in the Filtering Database,
    a. 802.1Q 2005 Section - 8.6.1 (Pg. 47) and Section 8.8.3 (Pg. 56).
    b. 802.1Q 2005 Table 8-7 (Pg. 64), Section 8.6.2 (Pg. 48)
    c. 802.1Q 2005 Section - 8.6.2 (Pg. 48)
3) Update of the Dynamic Filtering Entry in the Filtering Database
    a. 802.1Q 2005 Section - 8.8.3 (Pg. 56)
4) Removal of Dynamic Filtering Entries from the Filtering Database, after Ageing time period
    a. 802.1Q 2005 Section - 8.8.3 (Pg. 56)
5) Forwarding of data frames on the out bound WR Port for which Static entry exists in the Filtering Database
    a. 802.1Q 2005 Section - 8.8.1.c, (Pg 54)
6) Forwarding of frames corresponding to the Static Forwarding entry for the VLAN, independent of the presence of any Dynamic entry specification.
    a. 802.1Q 2005 Section - 8.8.1 c.1 (Pg.53)
7) Forwarding of data frames for the VLAN Group on all the Ports which are set as Forwarding in the Port map of the Static Filtering Database Entry for the Group MAC address and VID.
    a. 802.1Q 2005 Section - 8.8.6 (Pg. 58)
8) Using PVID value associated with the port through which the frame was received as VID, when only Port-based classification is supported.
    a. 802.1Q 2005 Section - 6.7 (Pg. 26)
9) Using VID value carried in the received frame, when the frame contains Non-Null VID value.
    a. 802.1Q 2005 Section - 6.7.1.c (Pg. 27)
10) Not discarding of the frame received on the Port whose VLAN classification does not include that Port in its Member set, when Enable Ingress Filtering parameter for that port is not set (default).
    a. 802.1Q 2005 Section - 8.6.2 (Pg. 48)
11) Processing of the non VLAN-tagged frames when the Acceptable Frame Types parameter for the port through which the frame was received is set to the value Admit All frames.
    a. 802.1Q 2005 Section - 6.7 (Pg.26)
12) Discarding of the non VLAN-tagged frames when the Acceptable Frame Types parameter for the port through which the frame was received is set to the value Admit Only VLAN-tagged frames.
    a. 802.1Q 2005 Section - 6.7 (pg.26)
13) Not forwarding of data frames on an Untagged port, if the VID of the received frames do not match the PVID set on that port.
    a. 802.1Q 2005 Section - 7.5 (Pg. 37)
14) Discarding of frames received on the Port with VLAN ID as 0xFFF
    a. 802.1Q 2005 Table 9-2 (Pg. 76)
15) Re-calculation of the FCS when the transmitted frame is changed to tagged from untagged.
    a. 802.1Q 2005 Section - 8.6 (Pg. 47), Section 6.7.1 Note 1 (Pg. 27)
16) Not forwarding of the frame when for the frame's VID, as determined by the ingress rules, the port considered for transmission is not present in the Member set.
    a. 802.1Q 2005 Section - 8.6.2 (Pg. 48)

17) Discarding of the frames when the Member set for the frame's VID is empty.
    a. 802.1Q 2005 Section - 8.7.1 (Pg. 51)
18) Not forwarding of the received Untagged data frames on port with Acceptable frame type set to 'Admit only Tagged frames'
    a. 802.1Q 2005 Section - 10.3.a (Pg. 80)
19) When supporting only Independent VLAN Learning (IVL), for all VLANs, if an individual MAC Address is learned in one VLAN, that learned information is not used in forwarding decisions taken for that address relative to any other VLAN.
    a. Reference : 802.1Q 1998 Section - 3.5 (Pg. 7) 802.1Q 2003 Section - 3.9 (Pg. 7),
20) Forwarding of data frames as VLAN-tagged or as untagged frames depending on whether the sending port is a member of the tagged or un-tagged set.
    a. 802.1Q 2005 Section - 8.8.2.b.2 (Pg 55).

# Annex B: Information to be provided in documents related to WR Device

## B.1 WR Device Qualification Report

1. For all requirements in 2: Pass/Fail information
   a. If failed, information about failure reason
2. For 2.7 (calibration)
   a. Information about the calibrator used: manufacturer, model and serial number, traceability to Golden Calibrator (calibration chain, which Golden Calibrator, e.g. a direct copy of the CERN Golden Calibrator)
   b. Values of ingress- and egress-latency for each WR Port calibrated using the Golden SFP
   c. Residual corrections if other type of SFP used/calibrated
   d. Type A and B uncertainty of the measurement/calibration (see C.5)
   e. The following temperatures recorded during calibration for the calibrator and the DUT:
      i. Ambient temperature
      ii. All relevant temperatures (as reported by the WR Device)
      iii. SFP temperature (if available and as reported by the SFP)
3. For P.1 in 2.8
   a. Specified operating temperature range and tested temperatures
   b. For each temp, a(temp) and r(temp)
   c. WR Class
   d. Type A and B uncertainty of the measurement
4. For P.2 in 2.8
   a. Specified operating temperature range and tested temperatures
   b. For each temp, p(temp)
   c. WR Class
   d. Type A and B uncertainty of the measurement
5. For P.3 and P.4 in 2.8
   a. Specified operating temperature range and tested temperatures
   b. Measured SSB phase noise for frequency offsets: 1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz
   c. Measured RMS jitter 1 Hz – 1 MHz
   d. WR PN Class
   e. Phase noise plots for tested temperatures
6. For P.5 and P.6 in 2.8
   a. Specified operating temperature range and tested temperatures
   b. Measured MDEV for tau: 0.01 s, 0.1 s, 1 s, 10 s, 100 s
   c. WR MDEV Class
   d. MDEV plots for tested temperatures

## B.2 Information to be added to the datasheet of the WR Device

1. Manufacturer, Hardware version.
2. Type of WR Device (Switch or Node)
3. Supported configuration (see 1.4.2).
4. Supported extended functionality
5. Configuration for serial communication (UART), e.g. serial port baud rate and start-/stop-/parity-bits, access registers if memory-mapped.
6. Input/output connectors (e.g. SMC, BNC, SMA) and associated signals (e.g. 1PPS, 10MHz, programmable auxiliary), including other types of signals acceptable on 1PPS input (see I.10)
7. Reference planes used for calibration, e.g.
    a. SMA front panel connector according to [**RD.3**]
    b. SMA connector according to [**RD.3**] or a converter cable from another type of front panel connector
    c. SMC front panel connector according to [**RD.3**]
8. Characteristics of output signals, e.g. amplitude, slew rate.
9. The expected 50% signal voltage level of the 50 Ohm terminated 1PPS (1.4.3.5).
10. Operating temperature range for the device and/or specifically for synchronisation performance.
11. For calibration:
    a. Who performed the calibration
    b. Information about the calibrator used: manufacturer, model and serial number, traceability to Golden Calibrator (calibration chain, which Golden Calibrator, e.g. a direct copy of the CERN Golden Calibrator)
    c. Uncertainty of calibration (see C.5)
    d. Expected maximum part-to-part variation of accuracy after calibration (either measured or estimated)
12. The WR Class and corresponding performance results
    a. The results should state the following temperatures (temp):
        i. room temperature (1.4.3.7)
        ii. min/max operational temperature, if applicable
    b. The following WR Classes and performance results
        i. Accuracy: a(temp) and r(temp), see P.1 in 2.8
        ii. Precision: p(temp), see P.2 in 2.8
        iii. Phase noise for GM and/or BC/OC: phase noise plot for temp from 1 Hz to 1 MHz, see P.3 and P.4 in 2.8
        iv. MDEVGM and/or BC/OC: Modified Alan Deviation for temp from tau 0.01 s to 100 s, P.5 and P.6 in 2.8
13. Determinism (repeatability) of skew between 1PPS and 10 MHz, see 3.8.2

# Annex C: Test equipment[15]

## C.1: Standard compliance tester

### C.1.1 Description and required functionality/specifications/performance

This is a PC, a server or a dedicated Ethernet traffic generator and tester which can connect to WR Ports of the DUT and can run software implementing relevant compliance tests.

Requirements:

- Ethernet ports (SFP cages) that can be connected using fibre optic to WR Ports of the DUT (at relevant speed supported by the DUT, 1Gbps and/or 10Gbps)
    - One port if only WR Nodes are to be tested
    - Two or more ports if WR Switch are to be tested
- Software stack that implements relevant standard compliance tests listed in 2.5.

Not required:

- Support for WR/HA in hardware
- Support for synchronous Ethernet (SyncE)

### C.1.2 Validation method

It is recommended to execute relevant tests with a DUT that is known to be compliant, e.g. one of the off-the-shelf WR Switches in the hardware version that is compliant with the latest official firmware release and running such an official release, see [8]. The official WR Switch firmware releases are tested for compliance per 2.5.

[15] For examples of reference measurements and test equipment, see [14] and [15].

## C.2 Time and frequency source

### C.2.1 Description and required functionality/specifications/performance

It is a stable source of 10 MHz and 1PPS signals.

Requirements:

- Output signals meet the input specifications of the DUT, see I.11 and I.12.
- 10 MHz and 1PPS signals are coherent (fixed relationship).
  **Note:** The relation between 10 MHz and 1PPS is not required to meet specification of [**RD.13**]. This specification can be met by using cables with different delay.
- 10MHz output better than 2 ps RMS jitter over 1 Hz – 1 MHz
- Better than 1 ppb frequency stability
- Phase noise plot in datasheet

### C.2.2 Validation method

The noise floor of the time and frequency source should be at least 10 dB lower than the “GM WR Class II” phase noise mask (i.e. the definition for the highest WR Class) from 10 Hz up. The PLL bandwidth of WR Devices is typically tuned such that low frequency fluctuations of the time and frequency source are tracked which results in measuring the additive phase noise of the WR Device for 10 Hz and below.

A known stable low noise oscillator (e.g. as present in a phase noise analyzer in [14]) may be used as a reference oscillator to which the time and frequency source is compared.

## C.3 Reference WR Switch/Node (Golden Calibrator)

### C.3.1 Description and required functionality/specifications/performance

It is a validated WR Device to which the DUT is connected and to which the DUT is compared. To perform WR Calibration in 2.7, it shall be one of the following:

a) A local copy of CERN's Golden Calibrator and in future a calibrator obtained through absolute calibration, or
b) A network-specific calibrator (see 3.9.2, point 2b), e.g. provided by the owner of the DUT

To perform tests in 2.8 or 3.9.3, it shall be one of the following:

c) A calibrator from a) or b), or
d) A validated WR Device calibrated to the calibrator from a) or b) (i.e. a traceable derivative of the calibrator in a) or b).

The following functionality is required:

- Support of GM mode
- 1PPS and 10MHz outputs

Not required but highly recommended:

- Use of a WR Class-II Device (i.e. low jitter)

### C.3.2 Validation method

Ideally, it is a WR switch which runs an official release and is a copy of CERN's Golden Calibrator. During this process, the validity of this WR Device was tested.

## C.4 Golden SFPs used in the test setup

### C4.1 Description and required functionality/specifications/performance

A Small Form-factor Pluggable (SFP) optical module. Tests shall be performed with either the exact units which were used to calibrate or copy the Golden Calibrator, or units from the same batch.

Requirements:

- Compliant with 1000BASE-BX10
- Support for diagnostics (DOM) to allow temperature logging (see Cal.5 in 2.7)
- While calibration can be performed for multiple SFP types, it shall always be performed for a pair of 1G SFPs (1000BASE-BX10) that transmit/receive at 1490nm and 1310nm.

Highly recommended:

- Hardware revision numbers should reflect any changes in hardware that might influence SFP's latency.

### C.4.2 Validation method

The **Golden SFPs to-be-validated** are used in the process of copying CERN's Golden Calibrator (the Golden Calibrator is understood as a combination of WR Switch and SFPs). As such, they are validated with this copy of a Golden Calibrator.

1. The **Golden SFPs to-be-validated** are validated with CERN's Golden Calibrator, as follows:
    a. A **WR switch A** is calibrated using **already-validated Golden SFPs** to CERN's Golden Calibrator (or its validated copy). The skew between WR Switch A and the Golden Calibrator is zero within the uncertainty limits.
    b. The **Golden SFP-to-be-validated** is plugged into the **WR Switch A**
    c. While using each **Golden SFP-to-be-validated**, the skew between the **WR Switch A** and the CERN's Golden Calibrator (or its validated copy) is identical to that measured in item a) within the uncertainty limits

### C.4.3 Reference Golden SFP

Blue Optic: BO15C3149620D-WR[16] and BO15C4931620D-WR[17] - vendor guarantees to increment revision number on any changes.

[16] https://www.cbo-it.de/shop/white-rabbit-bo15c3149620d-wr-sfp-bidi-transceiver-1-gigabit-1000base-bx-u-single-mode-1310tx-1490rx-lc-simplex-20-kilometers
[17] https://www.cbo-it.de/shop/white-rabbit-bo15c4931620d-wr-sfp-bidi-transceiver-1-gigabit-1000base-bx-d-single-mode-1490tx-1310rx-lc-simplex-20-kilometers

## C.5 Time interval measurement device

### C.5.1 Description and required functionality/specifications/performance

This device measures time difference between time markers of the 1PPS output signal of the reference WR Device and the DUT.

Requirements:

- Functional:
    - Single-shot time resolution better than 20 ps.
    - Capable to lock or reference its time-base to an external 10 MHz reference
    - Two or more input channels set to 50 Ohm termination
    - Capable to measure time interval of max 0.5 s

      **Note:** Needed to cover maximum theoretical time difference between two 1PPS outputs.
- Performance:
    - The **Type A uncertainty** of the *time interval measurement device*, given the input signal characteristics specification (see I.9), is quantified as standard deviation from a series of repeated measurements. The size of the series should equal that of P.1 and P.2 (i.e. 120 samples).
    - The **Type B uncertainty** of the *time interval measurement device* is the systematic uncertainty related to the device's (see 3.8.1):
        - Chanel-to-channel calibration uncertainty
        - Trigger level uncertainty
        - Resolution limits, non-linearity and quantization error of measurement
        - Impedance mismatch and input filter or bandwidth characteristics of the device
        - Temperature dependence (over the accuracy range specified for "Constant temperature", see 1.4.3.8)
        - Phase stability of the measurement cables

The combined Type A and Type B uncertainty of the measurement should be at least 3 times smaller than the maximum allowed value for a certain WR Class. For 120 samples (see P.1 and P.2), the Type A statistical uncertainty is improved by a factor ~11. Therefore, the maximum single-shot measurement uncertainty must be less than ~11/3 = ~3.7 times the maximum allowed value for a certain WR Precision Class. If this value is taken as an indication for the maximum 10%-90% rise-time ($t_r$) then the minimum bandwidth (BW) of the measurement setup (cables and measurement device) can be calculated according to the equation below:

$$BW = \frac{0.35}{t_r}$$

Table 3 shows the relationship between WR Precision Class, *time interval measurement device* single-shot accuracy (necessary when a measurement is averaged over 120 samples) for the complete setup (i.e. *time interval measurement device* and measurement cables).

| WR Precision Class | Class maximum [ps] | Maximum single-shot measurement uncertainty [ps] |
|---|---|---|
| WR Class 1 | 49 | 180 |
| WR Class 2 | 24 | 88 |
| WR Class 3 | 11 | 40 |
| WR Class 4 | 6 | 22 |

Table 3: Relation between WR-Class and single-shot measurement uncertainty

### C.5.2 Validation method

Figure 9 illustrates the setup which can be used to validate and calibrate (see 3.2.3) the *time interval measurement setup*. It includes:

- Time and frequency source (see Annex C.2) to be used as time base reference.
- Device generating 1PPS output that has characteristics comparable with the 1PPS output of the DUT (amplitude, rise time, impedance and jitter):
    - Waveform generator (if capable of producing comparable pulses)
    - WR Device itself
- A wide bandwidth RF splitter or fanout which allows to provide a copy of the same signal to two channels of the *time interval measurement device*
    - If RF splitter is used, the influence on amplitude and impedance matching must be considered
    - If RF fanout is used, it is required to have less than 2 ps additive jitter and an output signal characteristics similar to the DUT (amplitude, rise time, impedance and jitter).

Note that splitting the signal will reduce its amplitude by √2 (i.e. * 0.707). Ideally, a waveform generator should be set to output 1.41 times the amplitude such that after the RF splitter, the signal is comparable with the DUT. If a WR Device is used as the generator, the amplitude and shape of the signal after RF splitter needs to be verified and voltage level of the TM adjusted.

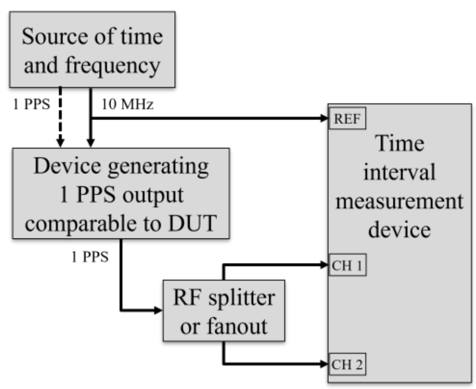


Figure 9 - Time interval measurement device validation

To validate the time interval measurement setup, Type A and Type B uncertainty are examined:

**Type A uncertainty** is the measured standard deviation of a set of 120 samples at *constant room temperature* (see 1.4.3.7).

**Type B uncertainty** is examined by performing multiple measurements of 120 samples while varying the environment (e.g. temperature, measurement cable manipulation etc.). It can be also evaluated from data provided in device's datasheet, if such data is available. The maximum spread between the mean values of these measurements is a measure for the sensitivity of the measurement with respect to the varied environmental property. For example, with respect to *constant room temperature* one would measure at 22 and 24 Celsius degrees to find the temperature dependance. Assuming a linear relation between measurement and temperature one may state that the temperature dependence (per 2 Celsius degrees) is the difference between the mean values found at these temperatures which is taken as Type B uncertainty for temperature dependance.

Total Type B uncertainty (Type $B_{tot}$) is the square root of the sum of the individual uncorrelated Type B uncertainties examined for different environmental conditions.

Finally, Type A and B uncertainty are not correlated so the total measurement uncertainty is calculated by:

$$Uncertainty = \sqrt{Type\ A^2 + Type\ B_{tot}{}^2}$$

This uncertainty must be at least 3 times less than the WR Precision Class maximum [ps] in order to be able to state that a WR Device complies to that specific WR Precision Class.

**Note:** The most challenging of the WR Classes is the WR Precision Class.

### C.5.3 Other sources of time interval measurement device error or Type B uncertainty:

Other sources of error or Type B uncertainty can be quantization error, non-linearity, trigger error, input impedance, bandwidth, etc. (see [2] and Annex D: Other sources of error or Type B uncertainty for time interval measurement devices). For the time being, these sources of error and uncertainty will not be addressed in this document but may need to be taken into account with increasing demand for accuracy and precision.

### C.5.4 Configuration

The following device and measurement configuration aspects must be considered:

- The trigger level at which the TM is measured must be set manually to the level defined in 1.4.3.5.
- Input impedance must be set to 50 Ohm.

## C.6 Phase measurement device

### C.6.1 Description and required functionality/specifications/performance

Phase measurement device capable of performing phase-noise measurements.

Requirements:

- Functional
    - Accept input signal: 10 MHz, sine or square
    - Must support the following in terms of measurement
        - Measurements in frequency offset range specified in P.3 - P.4
        - Measurements/calculation of Phase Noise (PN), root-mean-square (RMS) integrated phase noise jitter, measurement phase noise floor
    - Either have an internal reference oscillator or is capable to lock to an external 10 MHz source
- Performance
    - For a 10 MHz input signal, the residual phase noise floor (see also Figure 10) better than:

| Offset from Carrier [Hz] | 1 | 10 | 100 | 1k | 10k | 100k | 1M |
|---|---|---|---|---|---|---|---|
| | Maximum SSB phase noise for the offset from carrier [dBc/Hz] | | | | | | |
| Noise floor | -115 | -115 | -130 | -145 | -150 | -150 | -150 |

**Table 4: Maximum phase noise floor of the phase noise measurement device**

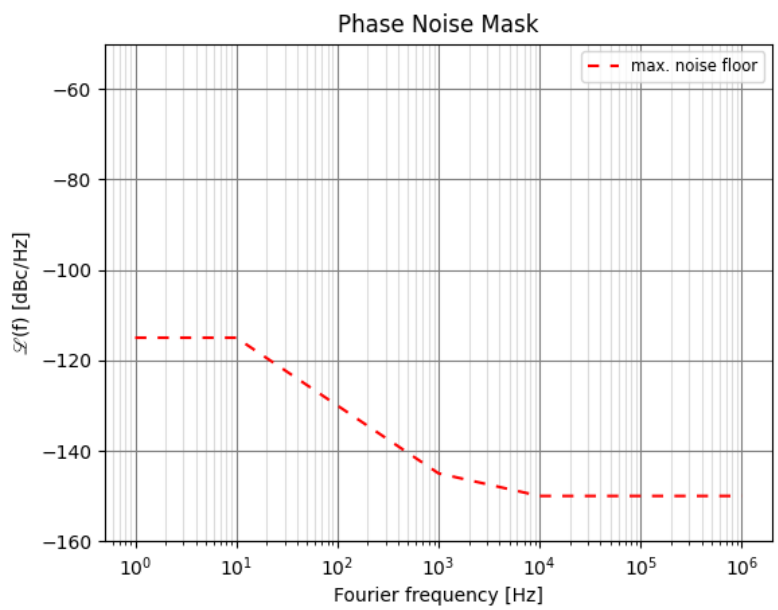


**Figure 10: Maximum phase noise floor of the phase noise measurement device**

### C.6.2 Validation method

Figure 11 illustrates a setup which can be used to validate the *phase measurement device*, either using an external- or internal reference oscillator.

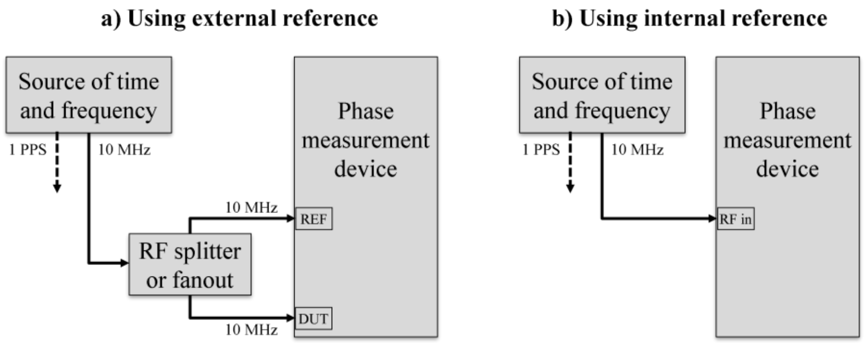


**Figure 11: Phase measurement device validation**

Figure 11 shows the test setup for a *phase measurement device*. It includes

- Time and frequency source, see Annex C.2
- In case the *phase measurement device* uses an external reference (Figure 11a) a RF splitter or fanout which allows providing a copy of the same signal to two channels of the device is needed. The phase noise introduced by this device must be lower than the residual phase noise floor required by the specifications of Annex C.6.1.

Using the setup in Figure 11, the *phase measurement device* must be capable to reach the SSB phase noise floor as specified in Annex C.6.1.

**Note:** The measured phase noise floor is a combination of the time and frequency source and the *phase measurement device*.

## C.7 Modified Allan Deviation measurement device

### C.7.1 Description and required functionality/specifications/performance

A measurement device capable of performing MDEV measurements.

Requirements:

- Functional
  - Accept input signal: 10MHz, sine or square
  - Must support the following in terms of measurement
    - Measurement Tau range specified in P.5 - P.6
    - Measurements/calculation of Modified Allan Deviation (MDEV)
  - Either have an internal reference oscillator or is capable to lock to an external 10 MHz source
- Performance
  - Allan Deviation typically less than $5*10^{-13}$ at 1 s (50 Hz ENBW)
  - For a 10MHz input signal, the Allan deviation measurement device must be able to reach Mod $\sigma_y(\tau)$ as low as shown in Table 5 (see also Figure 12):

| Tau [s] | 0.01 | 0.1 | 1 | 10 | 100 |
|---|---|---|---|---|---|
| | Maximum MDEV(tau) | | | | |
| floor | 5E-11 | 5E-12 | 5E-13 | 5E-14 | 5E-15 |

**Table 5: Maximum Mod $\sigma_y(\tau)$ of the Allan deviation measurement device**

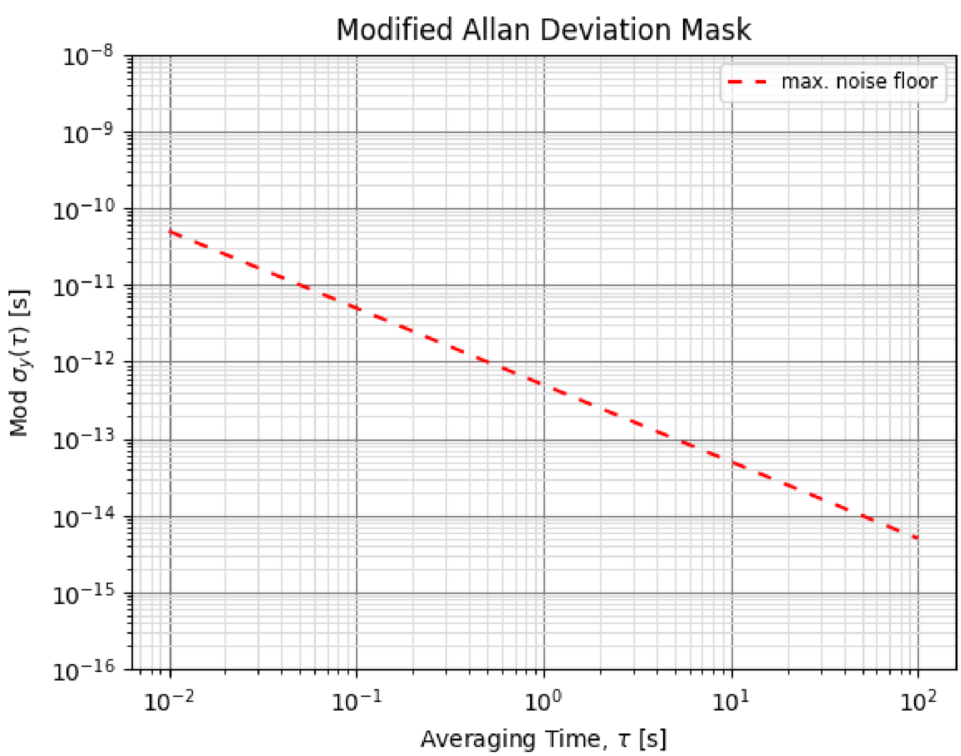


**Figure 12: Maximum Mod $\sigma_y(\tau)$ of the Allan deviation measurement device**

### C.7.2 Validation method

Figure 13 illustrates a setup which can be used to validate the *Allan deviation measurement device*, either using an external- or internal reference oscillator. It includes:

- Time and frequency source, see Annex C.2
- A RF splitter or fanout which allows providing a copy of the same signal to two channels of the *Allan deviation measurement device* (unless the device uses an internal reference). The phase noise introduced by this device must be low enough to reach the specifications stated in Annex C.7.1.

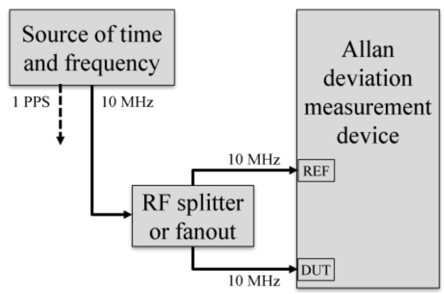


**Figure 13: Allan deviation measurement device validation**

Using the setup in Figure 13, the *Allan deviation measurement device* must be capable to reach Mod $\sigma_y(\tau)$ as low as specified in Annex C.7.1.

## C.8 Test bench coaxial measurement cables

### C.8.1 Description and required functionality/specifications/performance

The coaxial cables that are used in the measurement setups shown in Figure 6a to Figure 6d need to be flexible and ruggedized since they will endure many connecting- disconnecting cycles. Manipulation of the cables will affect signal phase which will have an influence on the measurement results. Special test bench measurement cables offer flexible, phase stable, low loss and high bandwidth, necessary for performing the measurements described in this WR Requirements document.

Test cables shall have at least 18 GHz bandwidth and phase stability vs. flexure better than 1 degree at 1 GHz.

## Annex D: Other sources of error or Type B uncertainty for time interval measurement devices

The components of Type B uncertainty can be reduced by carefully mitigating possible reasons for static errors listed below (based on [2][3][5]) and following procedures in 3.2 and Annex C.5.2.

a) **TIC quantization error:** can be estimated experimentally by measuring a constant delay with a jitter larger than the expected quantization error of the TICs. The uncertainty associated with the quantization in an ideal case can be estimated as δt/120.5 [2], where δt is the quantization error.

b) **TIC time-base error:** The TIC must be disciplined to an accurate external frequency reference which is common with that of the DUT. The external time-base relative accuracy should be at least $10^{-12}$ or better [2]. Under these conditions, when measuring a time interval smaller than 1s, the time base error is smaller than 1 ps and can be neglected.

c) **TIC non-linearity:** Measurements with TICs can be affected by a deterministic error that depends on the measured value, due to the nonlinear behaviour of the interpolator, also called the non-linearity error. Non linearity errors can be evaluated experimentally using an AOG (auxiliary offset generator) which produces a series of pulses, sent to the stop input of the TICs, with a known rate offset with respect to the time series going directly to the start input of the TICs.

d) **TIC trigger error:** Uncertainty proportional to the inverse of the 1PPS slew rate. For a fast-rising pulse with a slew-rate of 7 V per ns, the same uncertainty of 20 mV on the trigger level generates a timing uncertainty of approximately 3 ps.

e) **TIC impedance mismatch:** In case of deviation of the load impedance from its nominal value of 50 Ohm, the pulse amplitude is affected like in a voltage divider, so that the error induced by an impedance mismatch can be considered in the same way as a trigger error. For example, a real input impedance of (50 ± 5) Ohm, corresponds to a VSWR (voltage standing wave ratio) of 1.1. In such case an estimated timing error would be 7 ps for fast-rising pulses (slew rate of 7 V per ns).

f) **TIC input filter:** It limits the input bandwidth of the TIC, effectively adding a dispersive element in the measurement system that introduces a delay dependent on the shape of the 1PPS signal. It may also reduce the slope of the signal to the TIC internal comparator, thus increasing the impact of trigger level uncertainty. A rough measurement of the input bandwidth can be carried out by using stable, fast-rising (< 500 ps) 1PPS signals and plotting the measured delay as a function of the trigger level.

g) **Cable delays:** A bias in the measured time difference depends on the characteristics of the pulse and of the cables [2][3]. In an example in [2], for 10 m long, RG58 coaxial cable, a nominal delay of 50 ns corresponding to a pulse with virtually infinite slew rate (100 ps). To this nominal value, the following delay should be added (see Figure 14): 53 ps for pulses with a rise time of 350 ps, 280 ps for pulses with a rise time of 3.5 ns. The plots show the additional cable delay to be considered for rise times larger than 100 ps and RG58 C/U cable type. It is recommended to use short, high bandwidth, flexible, phase stable measurement cables (see Annex C.8.1).

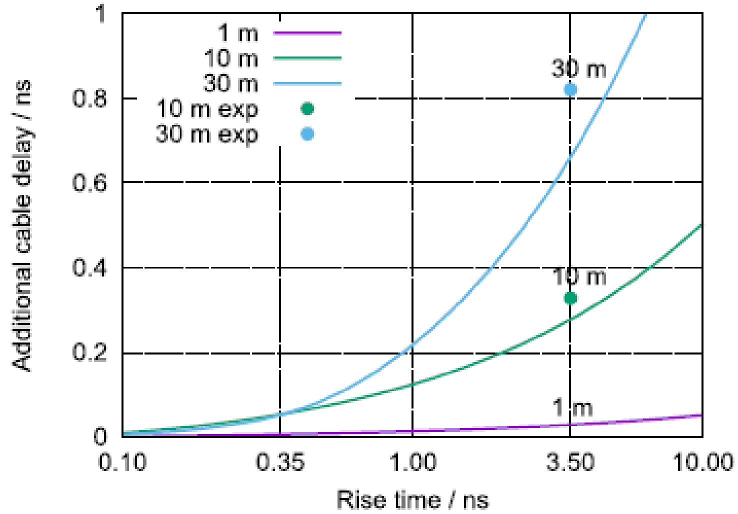


**Figure 14 - Additional cable delay versus rise time for different lengths of RG58 coaxial cable - simulated (solid line) and experimental (dot) – figure from [2]**

h) **Connectors:** with respect to the reference plane at the output connector of the device that generates the 1PPS signal of the time scale, the exact position of the reference plane within the connector can be critical, since 1 mm of coaxial transmission line introduces a delay of about 5 ps [2]. Avoid BNC connectors; they are notorious for mis-match and for delay variations and step changes. The connectors, in increasing order of quality are BNC, TNC, SMA, and precision N [4].

i) **Temperature:** uncertainty of time difference measurement due to temperature effects can be related to
  - Temperature-dependency of wavelengths and SFP delays
  - Temperature-dependency of internal delays (PCB, FPGA) of DUT or measurement device
  - Temperature-dependency of delays through fibres and coaxial cables

    For example, for typical SFPs using 1310/1490nm wavelengths, temperature variation of Fiber optic results in uncertainty of ~1 ps / C degree / km [9].
  - WR Device results in uncertainty of ~0.25 ps / C degree / km

    These effects can contribute to uncertainty of measuring the medium relative delay coefficient (alpha, see 3.9.1), calibrating ingress/egress latencies and performing accuracy performance evaluation.
  - Performing the accuracy performance measurement at a temperate different than that of calibration will result in constant error contributing to the **Type B uncertainty**
  - Performing any measurement at varying temperature will result in higher standard deviation of the measurement (low precision) contributing to **Type A uncertainty**. Depending on the temperature profile it can also contribute to **Type B uncertainty** (imagine the measurement runs 1/3 of time at room temperature during day and 2/3 at lowered temperature during night, the entire measurement would be biased).

Apart from ambient temperature, device temperature due to its operation must be taken into account. This includes
  - Warm-up of the device. Any measurement must be performed after proper warm-up of the DUT and the test equipment, see 3.2.2
  - The device should be calibrated at the intended load or operational temperature. Imagine the DUT is a WR Node in a form of PCIe card that is typically used inside a server. In such case, the ambient room temperature applies to the server with the PCIe WR Node card, not a stand-alone node.