ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

RENOVATION OF THE TRIGGER DISTRIBUTION IN CERN'S OPEN ANALOGUE SIGNAL INFORMATION SYSTEM USING WHITE RABBIT

D. Lampridis*, T. Gingold, D. Michalik[1], T. Pereira da Silva,
A. Poscia, M. H. Serans, M. R. Shukla, CERN, Geneva, Switzerland
[1]also at Aalborg University, Aalborg, Denmark

Abstract

The Open Analogue Signal Information System (OASIS) acts as a distributed oscilloscope system that acquires signals from devices across the CERN accelerator complex and displays them in a convenient, graphical way. Today, the OASIS installation counts over 500 multiplexed digitisers, capable of digitising more than 5000 analogue signals and offers a selection of more than 250 triggers for the acquisitions. These triggers are mostly generated at a single central place and are then distributed by means of a dedicated coaxial cable per digitiser, using a "star" topology. An upgrade is currently under way to renovate this trigger distribution system and migrate it to a White Rabbit (WR) based solution. In this new system, triggers are distributed in the form of Ethernet messages over a WR network, allowing for better scalability, higher time-stamping precision, trigger latency compensation and improved robustness. This paper discusses the new OASIS trigger distribution architecture, including hardware, drivers, front-end, server and application-tier software. It then provides results from preliminary tests in laboratory installations.

INTRODUCTION

A common need among operators in the European Organisation for Nuclear Research (CERN) is to be able to observe, monitor and record the behaviour of equipment in the accelerator complex. Frequently, this behaviour is represented by analogue electrical signals which mirror physical phenomena, such as the current going through a magnet, the magnetic field, the horizontal and vertical position of the particle beam, and so on. Quite often, there is also the need to correlate these measurements, as for example in the case of transfer lines between accelerators where one might want to observe the currents going into the kicker magnets that are used to displace the beam, together with the beam position monitors detecting the beam passing to the next accelerator.

The Open Analogue Signal Information System (OASIS) [1–3] satisfies all of the above requirements by providing an oscilloscope-like user interface, which offers the possibility to select among more than 5000 available analogue signals, acquired from more than 500 multiplexed devices all across the CERN accelerator complex. This functionality implies the existence of a common trigger source, shared by all acquisition devices participating in a given measurement.

In fact, operators are interested in being able to trigger on different conditions, meaning that there is more than one trigger that needs to reach the acquisition devices. Today, OASIS counts over 250 such triggers which are mostly generated at a single central place, where they are also multiplexed. They are then distributed by means of a dedicated coaxial cable per digitiser, using a "star" topology.

This trigger distribution scheme has served OASIS well for many years, but it is beginning to show its limitations. Trigger multiplexers are located close to the central locations where the triggers are generated, while the connection between the multiplexers and the digitisers is done with long coaxial cables, especially since the digitisers are placed close to the analogue signal sources to preserve the integrity of the signals. Furthermore, there is no compensation for cable length differences, environmental conditions, etc. The fact that all triggers are generated at the same building creates a single point of failure. Last but not least, introducing new digitisers typically involves finding a free trigger multiplexer output and pulling the trigger cable from there to the digitiser, an expensive and not always feasible operation.

This paper presents a new trigger distribution architecture for OASIS based on White Rabbit Trigger Distribution (WRTD) [4, 5]. In this new system, triggers are distributed in the form of Ethernet messages over a White Rabbit (WR) [6,7] network, allowing for better scalability, higher time-stamping precision, trigger latency compensation and improved robustness.

BACKGROUND

OASIS

OASIS is built using a 3-tier architecture:

1. The front-end tier controls the hardware modules (digitisers, multiplexers, etc.) and provides a hardware independent interface to the upper layer. It uses the Front-End Software Architecture (FESA) [8, 9] framework to provide the interface to the server tier.

2. The server tier consists of an application server that manages the resources provided by the front-end layer and assigns them to the connections requested by the clients (the third tier). The server tier intends to maximise the number of concurrent acquisitions based on a sophisticated priority algorithm.

3. The application tier, provides the users with a graphical user interface that displays the signals and their settings, in a familiar oscilloscope-like way.

* dimitrios.lampridis@cern.ch

18th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2021, Shanghai, China JACoW Publishing
ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

Figure 1: Typical signal monitoring session in OASIS.

OASIS provides the virtual oscilloscope abstraction. A virtual scope is a software oscilloscope that takes its data from different hardware oscilloscopes and displays it as if it all came from the same module. Thanks to this scheme, users are able to observe several signals distributed around the accelerator complex, as if they were next to each other. Figure 1 shows a typical signal monitoring session in OASIS, with seven signals combined in one virtual scope, triggered by the same trigger.

In order to be able to combine signals coming from different digitisers in a common virtual scope, the hardware needs to be triggered by the same pulse. Figure 2a shows the current trigger generation and distribution scheme used in OASIS. The yellow part on the left represents the central timing system, where timing events are distributed from the master devices (MTT) to numerous timing receivers (CTR) spread across the accelerator complex. The timing receivers in turn are programmed to generate trigger pulses upon reception of a particular timing event, with optional delays and resynchronisation to external clock(s). Once the triggers are generated, they are driven into the inputs of trigger multiplexers (CTC, in green), which also provide the possibility to delay and resynchronise the signal to external clock(s), separately for each output. Finally, each output of a trigger multiplexer is connected to the external trigger input of a digitiser (DAQ, in purple).

WRTD

White Rabbit is a fully deterministic Ethernet-based network which provides sub-nanosecond accuracy. WR is based on the IEEE 1588 Precision Time Protocol (PTP) [10]. The improvements to PTP introduced by WR have been standardised as the High-Accuracy (HA) profile within the IEEE 1588 standard. WRTD provides a generic event distribution system on top of a standard WR network.

WRTD is a generalisation of a previous CERN development, the LHC Instability Trigger (LIST) [11, 12] distribution project. It is modelled after a group of so-called extended functions defined in the Local Area Network (LAN) eXtensions for Instrumentation (LXI) [13], namely the Clock Synchronisation [14], Event Messaging [15] and Timestamped Data [16] functions. The provided Application Programming Interface (API) mimics that of an Interchangeable Virtual Instruments (IVI) [17] driver, with a strong influence from the IVI-3.2 “Inherent Capabilities” [18] and IVI-3.15 “IviLxiSync” [19] specifications.

In WRTD, source nodes receive incoming pulses and distribute them to other nodes over WR in the form of network messages that carry the timestamp of the incoming pulse. The receiving (listening) nodes are programmed to take action (e.g. generate a pulse) upon reception of a particular message, potentially with some fixed delay added to the timestamp.

SYSTEM ARCHITECTURE

The proposed solution makes use of WRTD to distribute OASIS triggers over WR and deliver them to the various digitisers. In this system, when a source node receives an incoming trigger pulse, it precisely timestamps its rising edge and distributes it over the WR network to all other nodes, in the form of a timestamp, accompanied by the unique identifier of the source node itself. All nodes that receive the network message and are actively listening for this identifier will add a fixed delay to the received timestamp and configure themselves to generate an output pulse at that precise moment. As long as the fixed delay added is greater than the upper-bound latency of the network (a fundamental feature of WR itself), this precise moment will be in the future and all output pulses will be produced at the same time, thanks to the sub-nanosecond synchronisation provided by WR.

Even though the above scheme will have all digitisers triggering at the same time, that time will still be in the future with respect to the timestamp that was recorded by WRTD at the source node. The solution is to modify the acquisition parameters of the digitisers, in order to have them record enough additional pre-trigger samples to cover the fixed delay that was added to the trigger timestamp, provided of course that the hardware has a large enough memory buffer. This last limitation is only an issue for some old OASIS digitisers with fast sampling rates and small memory and a new project has been launched to design a new equivalent digitiser [20]. Once the acquisition is complete, the acquisition window is rolled back around the original timestamp and the extra post-trigger samples are discarded.

Figure 2b presents a high-level view of the implemented architecture; Compared to Fig. 2a, triggers are still generated by the central timing system (in yellow) and go through the trigger multiplexer (in green), but the outputs of the multiplexer are now timestamped by WRTD source nodes, featuring Time-to-Digital Converters (TDC), which then distribute the triggers as messages over the WR network. At the receiving end, WRTD listening nodes equipped with Fine Delay pulse generators (FD) receive the messages, add

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

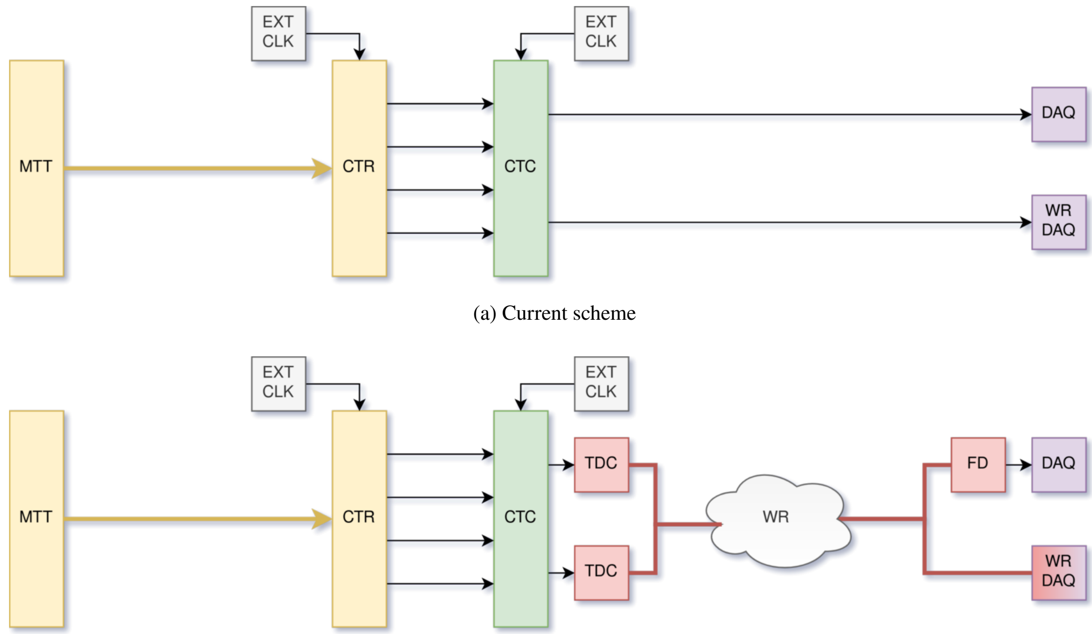


Figure 2: OASIS trigger distribution architectures.

the globally configured fixed delay and generate the output pulses that are then delivered to the external trigger input of the digitisers. In the special case of a WRTD-enabled digitiser, the FD is omitted since the digitiser is capable of triggering itself by retrieving the WRTD timestamp, taking into account the globally configured delay, and configuring itself to trigger internally at the specified time.

In the coming sections we discuss in more detail the developments performed at the various tiers of OASIS to implement this architecture.

Hardware

The OASIS WRTD network infrastructure is built using standard WR network switches [21] and optical fibres. For the purpose of this project, three new types of WRTD nodes were developed, all of them reusing the WR-enabled Versa Module Europa (VME) dual Field-Programmable Gate Array (FPGA) Mezzanine Card (FMC) carrier, also known as Simple VME FMC Carrier (SVEC) [22] and combining it with existing FMC modules. The most important development in this case was the creation of new FPGA designs (also known as gateware), to provide the necessary WRTD-related logic.

The first WRTD node is a SVEC with the two FMC slots populated with TDC mezzanine cards [23] ("TDC" block in Fig. 2b). Since each TDC mezzanine provides five input channels, the whole WRTD node offers 10 input channels, capable of timestamping incoming pulses and transmitting WRTD events on the WR network.

The second WRTD node is a SVEC with the two FMC slots populated with FD mezzanine cards [24] ("FD" block in Fig. 2b). Since each FD mezzanine provides four output channels, the whole WRTD node offers 8 output channels, capable of generating trigger pulses locally, at precise moments defined in WRTD events received from the WR network.

The third type of WRTD node is a SVEC with the two FMC slots populated with four-channel, 14-bit, 100 MHz ADC mezzanine cards [25] ("WR DAQ" block in Fig. 2b). This is an update to an existing piece of hardware, already used in OASIS, to add the possibility to trigger the ADC directly from WRTD events received from the WR network.

Front-End Tier

FECs related to accelerator controls at CERN run real-time software developed with the FESA framework. Device controls are implemented in FESA classes and instantiated on each FEC, one instance per controlled device. Such an instance is also called a FESA device.

For the renovation of the OASIS trigger distribution system, two new FESA classes were introduced, the WRTD Event Source and the WRTD Event Listener. Even though the design is made with OASIS triggering in mind, the aim was to make it generic enough to be reused in other applications as well in the future. This is why the two new FESA classes do not include "OASIS" in their names and the use of the word "Event" is preferred over that of "Trigger".

Additionally, two existing FESA classes, the OASIS Scope and OASIS Channel were extended.

Global Delay Configuration A global configuration delay value is stored in a configuration file and is made available to all WRTD Event Listener and OASIS Scope and Channel devices.

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

The purpose of this delay is to make sure that the trigger message is delivered to all WRTD Event Listener devices before the time to produce the trigger at the destination expires. As such, this value must always be superior to the worst-case trigger distribution latency (in the order of 100 µs), which is guaranteed by the upper-bound latency of the WR network itself.

WRTD Event Source The WRTD Event Source FESA class is used to model devices that receive pulses locally, timestamp them and generate messages (Events) over the WR network containing a unique identifier for this device and the timestamp of the pulse. Typically, such devices are individual channels of a TDC.

Each WRTD Event Source device represents one input channel. Thus, a five-channel TDC (which from the hardware point of view is a single device with five input channels) will be mapped to five separate WRTD Event Source devices.

More often than not, the inputs of the TDC will be connected to the outputs of a trigger multiplexer. The trigger multiplexer will be generating the trigger pulses, which will be then timestamped by channels of the TDC. In a few cases, a trigger signal might be directly connected to an input of the TDC, without a trigger multiplexer in between.

WRTD Event Listener The WRTD Event Listener FESA class is used to model devices that receive over the WR network the messages (Events) generated by WRTD Event Source devices and generate pulses locally at a specific moment with respect to the timestamp contained in the received message. Typically such devices are channels of an FD.

Each WRTD Event Listener device represents one output channel. Thus, a four-channel FD (which from the hardware point of view is a single device with four output channels) will be mapped to four separate WRTD Event Listener devices. In practice, the outputs of the FD will be connected to external trigger inputs of digitisers, in order to trigger the acquisition of the digitisers at the moment specified by WRTD.

Apart from FD generators, another type of device that is modelled by the WRTD Event Listener is a digitiser that is capable of triggering directly over WRTD. Such a digitiser will also provide a single WRTD Event Listener to model its capability to receive the WRTD message and produce the local trigger pulse internally.

OASIS Scope and Channel The OASIS representation of a digitiser is based on the combination of two FESA device classes, the OASIS Scope and Channel. The first one handles all aspects of triggering and "horizontal settings" (sampling rate, number of samples, etc.), while the second one handles the "vertical settings" (full-scale range, offset, etc.).

In the context of this project, these two FESA classes have been extended, to allow for the triggering over WR. In particular, the following modifications were performed:

1. A new configuration option was introduced to specify whether this scope is triggered over WR or not.
2. If a scope is triggered over WR, the global delay configuration is taken into account, affecting the number of pre-trigger acquired samples, in order to allow for the trigger latency introduced by the WRTD network.
3. Once such a scope is triggered, the global delay configuration value is subtracted from the trigger timestamp, in order to point to the moment in time when the original trigger was generated at the source, not when it was actually received by the digitiser.
4. Following that, the acquisition window is adjusted once again, in order to discard surplus samples and return the data around the original trigger moment.

It is worth noting that these calculations and adjustments of settings happen at the front-end tier level. The OASIS server and the applications are not aware of them. Thus, if a user selects a particular trigger and asks for 1000 samples with 50% pre-triggering, the front-end tier will silently perform the necessary adjustments and in the end it will simply return 500 samples before and 500 samples after the selected trigger.

Configuration Database

OASIS relies heavily on relations defined in the Controls Configuration Database (CCDB), to associate signals to signal multiplexers and digitiser channels, triggers to trigger multiplexers and digitisers, and so on.

In the context of OASIS WRTD, three new relations have been introduced and one existing relation has been reused:

COUNTER2WRTD: This new relation connects the output of a trigger multiplexer to a WRTD Event Source.

TRIGGER2WRTD: This new relation connects a trigger signal directly to a WRTD Event Source.

WRTD2SCOPE: This new relation connects a WRTD Event Listener to a digitiser.

TRIGGER2MUX: This existing relation connects a trigger signal to the input of a trigger multiplexer.

Server Tier

For the OASIS server to be able to route a specific trigger signal to a digitiser, it needs to identify a route and then to configure the devices on that route. The server discovers that information using the relations defined in CCDB.

WRTD Route Identification To find a possible route for the trigger signal, the server first needs to discover which WRTD Event Source devices the trigger signal is connected to.

The actual route identification requires the following steps:

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

1. Discover to which trigger multiplexer(s) and on which input the trigger signal is connected (via a TRIGGER2MUX relation).

2. Identify all WRTD Event Sources connected to the trigger multiplexer(s) found in (1), remember to which output of the multiplexer each WRTD Event Source is connected (via a COUNTER2WRTD relation).

3. Alternatively, detect whether the trigger signal is directly connected to a WRTD Event Source, without any trigger multiplexer in between (via a TRIGGER2WRTD relation).

Thanks to this initial discovery phase, a set of candidate WRTD Event Sources to use to distribute the trigger on the WR network is obtained. Among those candidates, the server then finds the first one that matches all of the following criteria:

1. The WRTD Event Source is running and reachable.

2. The WRTD Event Source is free (i.e. it is not already used to route a trigger).

Once a WRTD Event Source is identified, the server queries the declared CCDB relations to find out to which WRTD Event Listener the digitiser is connected to.

At this point all the equipment that will be used to route the trigger signal has been identified. This includes:

- The WRTD Event Source
- The trigger multiplexer and the input and output to use
- The WRTD Event Listener

WRTD Route Configuration After a route is identified, it is necessary to configure the different devices so that the trigger signal is correctly routed to the digitisers. The following operations are performed by the OASIS server:

1. Trigger multiplexer: close the route from the trigger signal to the selected WRTD Event Source

2. WRTD Event Source: enable the device

3. WRTD Event Listener: enable the device and set the WRTD event to be listened to

Following these operations, the trigger signal will be routed to the WRTD Event Source that will publish the trigger to the WRTD network. The WRTD Event Listener will listen to the event published by that source device and trigger the digitiser accordingly. Finally, when the user has finished observing the signal(s), the OASIS server needs to turn off the WRTD Event Source and Listener devices and release the route that was used in the trigger multiplexer.

Application Tier

Even though there are several applications that make use of OASIS, the most widely used one is the OASIS viewer (also shown in Fig. 1).

One of the core decisions taken during the planning phase of this project was to avoid any significant modifications and user interface redesigns of the OASIS viewer. Users of OASIS, CERN operators in particular, are accustomed to the current interface and the idea is to first renovate the trigger distribution system and then, slowly start introducing new features that would require an interface redesign, such as the possibility for a digitiser to trigger other digitisers, something that is not available with today's unidirectional trigger distribution system.

As such, the only modification that was done to the OASIS viewer was to add more information regarding the configured trigger path in the case of WRTD triggers (that is, the device names of the WRTD Event Source and Listener used).

TEST SETUP AND FIRST RESULTS

A standard CERN VME FEC with all the necessary hardware was deployed in the laboratory from the beginning of this project. This test setup was used extensively during development, also as a part of a Continuous Integration (CI) flow. Currently, this setup is running released and deployed versions of all components and it is being used for the final validation of the full system.

A high-level diagram of the test setup can be seen in Fig. 3. Two trigger pulses are generated by the timing system, separated by a 400 µs delay. Both triggers are fed into a trigger multiplexer. At the same time, the two trigger signals are also connected to analogue input channels of two scopes; the "normal" trigger goes to channel 1 of both scopes and the delayed trigger to channel 2.

Scope 2 is triggered directly by one of the outputs of the trigger multiplexer. Another output of the same trigger multiplexer is connected to a WRTD Event Source, and a WRTD Event Listener output is connected to the trigger input of Scope 1. Thanks to the trigger multiplexer, each scope can be triggered on either of the two signals, independently of each other. The WR network itself is made of two WR switches, separated by 10 km of rolled optical fibre. The global delay is configured at 400 µs.

Figure 4 shows the OASIS viewer application, with the four signals connected. The yellow traces are from Scope 1, while the magenta traces are from Scope 2. The OASIS viewer is configured with two virtual scopes; the top one displays the signals from channel 1 of both scopes, while the bottom one shows the channel 2 signals. Both of the scopes are set to trigger on the signal that is also connected to channel 1. The acquisition window is set to 500 µs (50 µs/div) and there is a horizontal delay of 200 µs applied. As it can be seen, there is no visible difference between the scope that is triggered by the pulse itself, and the scope that is triggered by the pulse passing first through the WRTD network, despite the latency of the network; the signals on both virtual

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

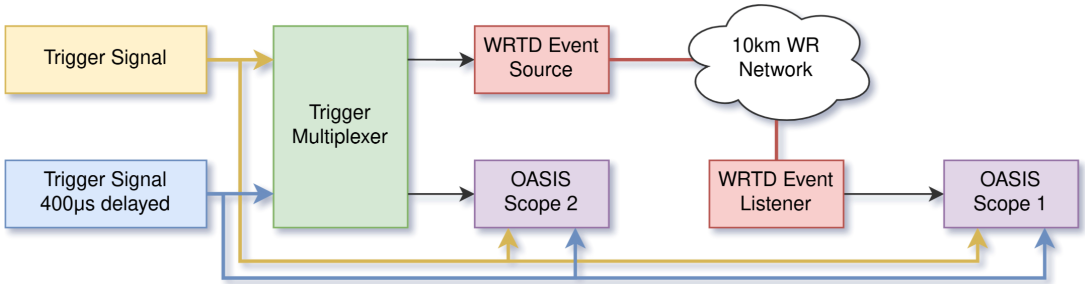


Figure 3: Laboratory test setup.

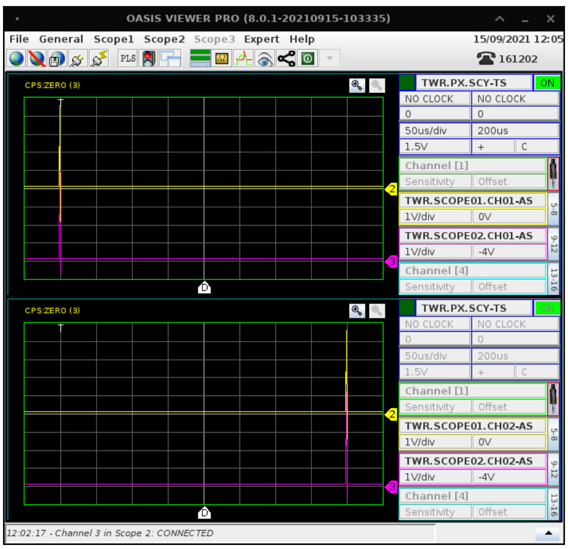


Figure 4: OASIS signal acquisition with WR triggers.

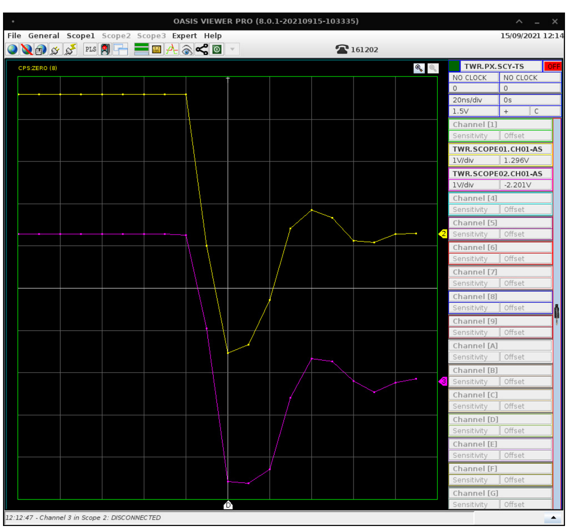


Figure 5: Zoom at trigger moment.

scopes are fully aligned, with the two sets of signals being 400 µs apart.

Figure 5 is a zoom in the moment of the trigger, using the two channel 1 signals from both scopes. The two digitisers are acquiring with a 100 MHz sampling rate (10 ns sampling period) and the OASIS viewer is set to display a 200 ns window. As a result, one can see the 20 individual samples from each scope (each sample represented by a dot) and how they are aligned to each other, despite the fact that the two scopes are triggered in two completely different ways.

CONCLUSIONS AND OUTLOOK

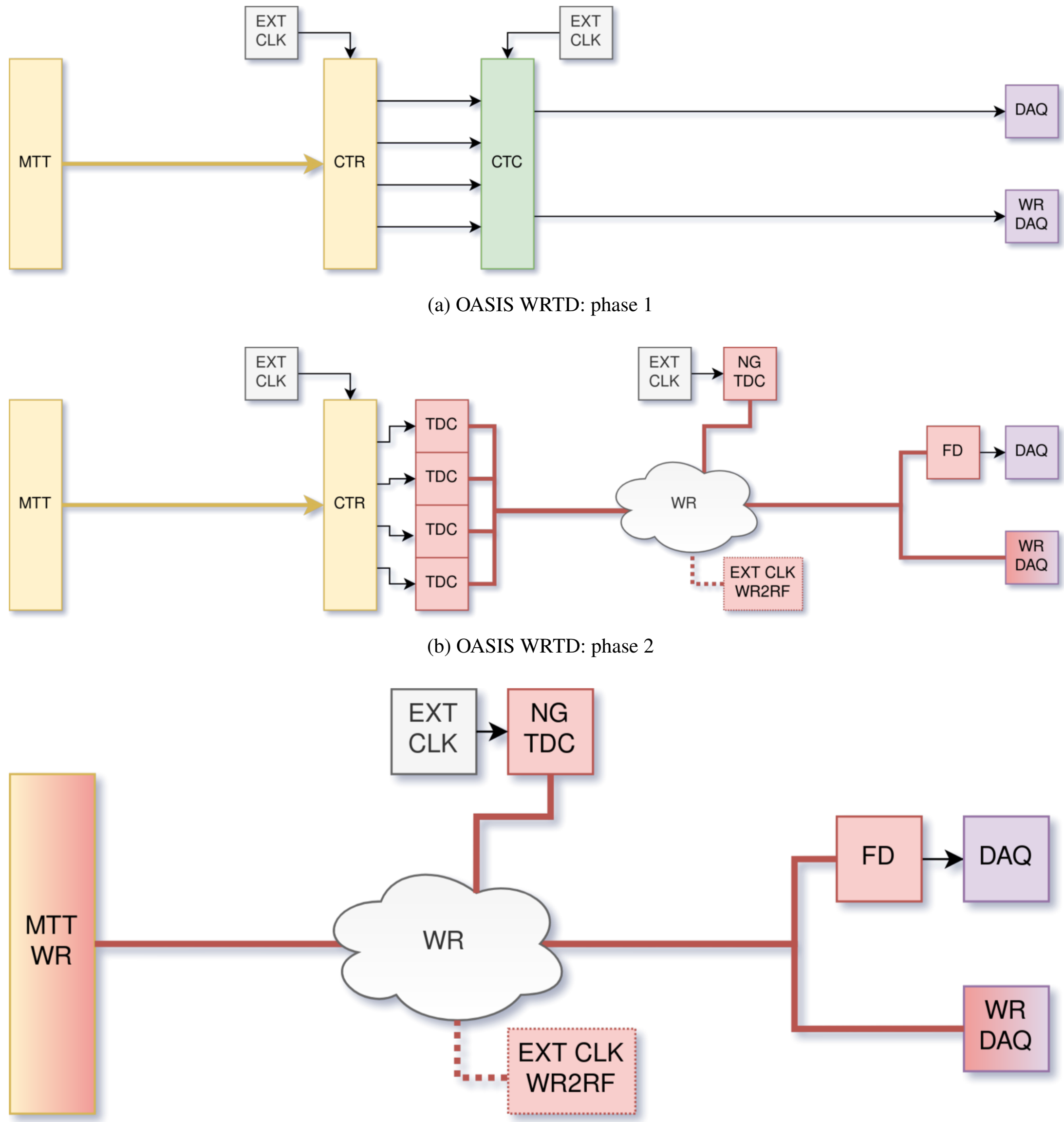
This paper has presented the new OASIS trigger distribution architecture based on WRTD. Currently, the development effort is almost complete, and the laboratory tests show that the full hardware and software stack is working and is well integrated inside the CERN accelerators' control system.

It is expected that the first operational OASIS triggers over WR will circulate before the end of 2021. Following that, a large campaign will take place to start replacing the complete trigger distribution installation.

There are also plans to further evolve the system, in three successive phases, with the work presented in this paper being part of the first phase. Figure 6 shows the proposed road-map, including a repetition of the block diagram from Fig. 2b to make the comparison between the three phases easier. In particular, the second phase involves the complete elimination of trigger multiplexers, in favour of direct timestamping of triggers by TDC channels. For this to happen however, new hardware developments are necessary, in order to provide a way to synchronise WRTD timestamps to external clocks, a feature provided today by the trigger multiplexer. This could happen for example with a new generation of TDC (NG-TDC in Fig. 6b), or with a module capable of receiving and reconstructing clock signals over a WR network (such as the WR2RF module [26] in Fig. 6b). In the third and last phase, that requires the complete central timing to be migrated to WR, there will be no more trigger pulses to digitise, and OASIS will be picking up timing events/messages from the WR network and using them for triggering its digitisers.

On another front, since WRTD itself is based on the existing IVI/LXI standards, it is foreseen to try to merge WRTD with these standards, in the same way that WR was merged and standardised within the IEEE1588 PTP standard. Such a development would allow instruments with an IVI driver and a WR interface to exchange events with each other. This

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01



(a) OASIS WRTD: phase 1

(b) OASIS WRTD: phase 2

(c) OASIS WRTD: phase 3

Figure 6: OASIS trigger distribution evolution road-map.

would also allow the industry to produce commercially available WRTD-enabled devices, which OASIS could then procure and use out of the box, with minimum integration effort.

REFERENCES

[1] S. Deghaye, D. Jacquet, I. Kozsar, and J. Serrano, "OASIS: a New System to Acquire and Display the Analog Signals for LHC", in *Proc. 9th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'03)*, Gyeongju, Korea, Oct. 2003, paper WP502, pp. 359–361.

[2] S. Deghaye, L. Bojtar, Y. Georgievskiy, and J. Serrano, "OASIS Status Report", in *Proc. 10th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'05)*, Geneva, Switzerland, Oct. 2005, paper TH3A.1-5O.

[3] L. Bojtar, C. Charrondiere, Y. A. Georgievskiy, F. C. Peters, I. S. Zharinov, and S. Deghaye, "OASIS Evolution", in *Proc. 11th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'07)*, Oak Ridge, TN, USA, Oct. 2007, paper WPPA04, pp. 322–324.

[4] D. Lampridis, T. Gingold, M. Malczak, F. Vaga, A. Wujek, and T. Włostowski, "The Distributed Oscilloscope: A Large-Scale Fully Synchronised Data Acquisition System Over White Rabbit", in *Proc. ICALEPCS'19*, New York, NY, USA, Oct. 2019, pp. 725–732. doi:10.18429/JACoW-ICALEPCS2019-TUBPR01

[5] *WRTD* project page, https://ohwr.org/project/wrtd/wikis/home

[6] *White Rabbit* project page, https://ohwr.org/project/white-rabbit/wikis/home

[7] J. Serrano *et al.*, "The White Rabbit Project", in *Proc. 12th Int. Conf. on Accelerator and Large Experimental Physics*

ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-THBR01

Control Systems (ICALEPCS'09), Kobe, Japan, Oct. 2009, paper TUC004, pp. 93–95.

[8] L. Fernandez *et al.*, "Front-End Software Architecture", in *Proc. 11th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'07)*, Oak Ridge, TN, USA, Oct. 2007, paper WOPA04, pp. 310–312.

[9] A. Schwinn *et al.*, "FESA3 – The New Front-End Software Framework at CERN and the FAIR Facility", in *Proc. 8th Int. Workshop on Personal Computers and Particle Accelerator Controls (PCaPAC'10)*, Saskatoon, Canada, Oct. 2010, paper WECOAA03, pp. 22–26.

[10] *IEEE 1588 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, Institute of Electrical and Electronics Engineers, 2008, ISBN 978-0-7381-5400-8.

[11] *LIST* project page, `https://ohwr.org/project/list/wikis/home`

[12] T. Wlostowski *et al.*, "Trigger and RF Distribution Using White Rabbit", in *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'15)*, Melbourne, Australia, 2015, paper WEC3O01, pp. 619–623.

[13] LXI Consortium, `http://www.lxistandard.org`

[14] *LXI Clock Synchronization Extended Function*, LXI Consortium, revision 1.0, 8 November 2016.

[15] *LXI Event Messaging Extended Function*, LXI Consortium, revision 1.0, 8 November 2016.

[16] *LXI Timestamped Data Extended Function*, LXI Consortium, revision 1.0, 8 November 2016.

[17] IVI Foundation, `http://www.ivifoundation.org`

[18] *IVI-3.2: Inherent Capabilities Specification*, IVI Foundation, revision 2.1, 9 March 2015.

[19] *IVI-3.15: IviLxiSync Specification*, IVI Foundation, revision 2.0, 9 October 2014.

[20] *Fmc-Adc-1G-8b-2cha* project page, `https://ohwr.org/project/fmc-adc-1g8b2cha/wikis/home`

[21] *White Rabbit Switch* project page, `https://ohwr.org/project/white-rabbit/wikis/Switch`

[22] *SVEC* project page, `https://ohwr.org/project/svec/wikis/home`

[23] *Fmc-Tdc-1ns-5cha* project page, `https://ohwr.org/project/fmc-tdc-1ns-5cha-gw/wikis/home`

[24] *Fmc-Del-1ns-4cha* project page, `https://ohwr.org/project/fmc-delay-1ns-8cha/wikis/home`

[25] *Fmc-Adc-100M-14b-4cha* project page, `https://ohwr.org/project/fmc-adc-100m14b4cha/wikis/home`

[26] *WR2RF-VME* project page, `https://ohwr.org/project/wr2rf-vme/wikis/home`