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THE INCLUSION OF WHITE RABBIT INTO THE GLOBAL INDUSTRY STANDARD IEEE 1588

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Abstract

White Rabbit (WR) is the first CERN-born technology that has been incorporated into a global industry standard governed by the Institute of Electrical and Electronics Engineers (IEEE), the IEEE 1588 Precision Time Protocol (PTP). This showcase of technology transfer has been beneficial to both the standard and to WR technology. For the standard, it has allowed the PTP synchronisation performance to be increased by several orders of magnitude, opening new markets and opportunities for PTP implementers. While for WR technology, the review during its standardisation and its adoption by industry makes it future-proof and drives down prices of the WR hardware that is widely used in scientific installations. This article provides an insight into the 7-year-long WR standardisation process, describing its motivation, benefits, costs and the final result. After a short introduction to WR, it describes the process of reviewing, generalising and translating it into an IEEE standard. Finally, it retrospectively evaluates this process in terms of efforts and benefits to conclude that basing new technologies on standards and extending them bears short-term costs that bring long-term benefits.

INTRODUCTION

White Rabbit

White Rabbit (WR, [1]) is an open-source [2] technology developed to provide the Large Hadron Collider (LHC) accelerator chain with deterministic data transfer, synchronisation with sub-nanosecond accuracy and a precision of a few picoseconds. First used in 2012, the technology has since then expanded its applications [3] outside the field of particle physics and is now deployed in numerous scientific infrastructures worldwide. Moreover, it has shown its innovative potential by being commercialised and introduced into different industries, including telecommunications, financial markets, smart grids, the space industry and quantum computing. On 16 June 2020, the WR synchronisation method was recognised by being included in the worldwide industry IEEE 1588 standard called Precision Time Protocol (PTP, [4]), governed by the Institute of Electrical and Electronics Engineers (IEEE, [5]), the world's largest technical professional organisation dedicated to advancing technology.

WR's wide-spread use in scientific installations and its adoption into industry can be attributed to 3 factors:

1. The open-source and commercial nature.
2. The collaborative and welcoming community.
3. Basing it on standards, extending them if needed.

This article focuses on the third factor to the success of WR.

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Standards and Standard-Defining Organisations

A technical standard is usually a formal document that establishes uniform engineering or technical criteria for externally visible operational aspects of a technology. While independently developed products (e.g. devices, software) that follow the same standard are meant to inter-operate, innovation is made possible in the internal implementation of these standard-based solutions.

Technical standards are prepared by groups that gather expert representatives of industry and academia specialised in a given domain. These groups are referred to as standard-defining organisations (SDOs) and can be organised as international organisations, unions, associations or consortia. Examples of SDOs relevant to this article:

1. International Telecommunication Union (ITU): a specialised agency of the United Nations responsible for information and communication technologies.
2. Institute of Electrical and Electronics Engineers (IEEE): a professional association for electronic engineering and electrical engineering (and associated disciplines).

Our everyday life is heavily dependent on standards prepared by IEEE and ITU. The ITU standards govern the operation of mobile networks. Commonly used means of communication, such as Ethernet, Local Area Networks and WiFi are all defined in IEEE standards.

IEEE1588 Standard

The IEEE 1588 standard defines the Precision Time Protocol (PTP) that provides precise synchronisation of clocks in packet-based networked systems. The standard is commonly used to synchronise devices (e.g. sensors, actuators) in factories, power plants, distributed measurement systems as well as in finance, audio-video and telecommunication. First published in 2002, it was updated in 2008 and 2019.

The operation of PTP is divided into two main actions: establishment of a synchronisation hierarchy in the network and synchronisation of network devices following the established hierarchy. The IEEE 1588 standard is actually a "generic framework" that defines the above-mentioned mechanisms, as well as numerous options and parameters to enhance and fine tune its operation. The configuration of this "generic framework" is called a "PTP Profile". The framework cannot be used without a profile, thus the IEEE 1588 standard includes generic-purpose profiles, called Default PTP Profiles. Many industries define PTP Profiles adjusted to their particular requirements [6]. For example ITU-T defines PTP Telecom Profiles (e.g. G.8265.1) and the IEEE defines PTP Profiles for Power (C37.238) as well as Audio/Video, Automation and Automotive (802.1AS).

Notably, the IEEE 1588 standard purposely does not define requirements with respect to synchronisation perfor-

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mance or hardware. These requirements can be defined in the PTP Profiles. As such, synchronisation performance of PTP devices depends on their implementation and the PTP Profile used. Typically PTP devices provide synchronisation at the microsecond level.

WR AND ITS MOTIVATION FOR USING AND EXTENDING STANDARDS

The WR project was launched to renovate CERN's General Machine Timing (GMT), a system that orchestrates and synchronises operation of all the CERN accelerators. The GMT was created over two decades ago as a custom-made system based on the RS-422 standard. As such, it requires costly in-house support and tailor-made spare parts, resulting in maintenance challenges.

Apart from the technical requirements [7], the goal of the WR project was to create a technology with decades-long support from industry to minimise the cost of spare parts and maintenance. Achieving this goal was based on 3 pillars which are complementary: (1) open-source and commercial nature of WR, (2) collaborative and welcoming WR community, and (3) choice of well-established standards as the basis of WR. The public availability of design sources allows enhancement and reuse, as well as commercialisation by multiple companies. The more applications and users, the more attractive commercialisation is for companies while preventing vendor lock-in. The more companies sell WR devices, the more competitive is the price of WR gear, encouraging new users. Both companies and users favour investing in standard-based solutions for a number of reasons, such as stability and maturity, availability of existing products and tools, and interoperability of products from different vendors.

As even standard technologies become obsolete (e.g. RS-422) the choice of the base standard(s) is important. WR is based on the family of well-established IEEE 802 networking standards (IEEE 802.1Q and IEEE 802.3) and IEEE 1588, with good provisions for evolution and long-term support.

While the chosen base standards provided the functionalities (data transfer, synchronisation) required from WR, CERN's requirements exceeded their performance capabilities. At that time it was decided that any enhancements to improve the performance should be made compatible with the base standards for the following reasons:

1. Off-the-shelf standard gear can be used to minimise costs where high performance is not needed.
2. Off-the-shelf standard existing tools can be used.
3. The improvements are more likely to be implemented by companies.
4. The improvements can evolve with the standard allowing long-term support.
5. The improvements might make it into the base standard.

The above reasoning shaped the way in which the WR synchronisation method was specified, i.e. a WR extension to the IEEE 1588 standard.

WR EXTENSION TO IEEE 1588

CERN's requirement for the WR technology specified synchronisation at the sub-nanosecond level, which was well beyond the performance achievable by IEEE 1588 devices at the time of WR's conception. Within the WR project, the standard's shortcomings were identified and solutions proposed to overcome them:

1. Clock syntonisation over the physical layer.
2. Enhancement of timestamps through phase detection.
3. Automatic evaluation and calibration of asymmetries.

While initially, it was considered to specify the above PTP enhancements as an independent protocol around the operation of the Default PTP Profile, the flexibility of PTP's "generic framework" allowed to use its built-in extensions mechanisms to accommodate the proposed solutions. And thus, the WR synchronisation method is described in the *White Rabbit Specification - draft for comments* [8] as an extension of the IEEE 1588-2008 standard in the form of a White Rabbit PTP Profile (WR PTP Profile). After substantial efforts and consultations with the author of IEEE 1588, this profile was defined such that it is compatible with the Default PTP Profile and it looks as any other PTP Profile. The WR PTP Profile specified in [8] includes:

1. Theoretical background for the extensions.
2. Hardware requirements to implement the extensions.
3. Protocol additions/changes to support the extensions.
4. Formal definition of the WR PTP Profile.

Such a definition of the WR synchronisation method meant that in a distant future the WR PTP Profile could be standardised on its own or it could be incorporated into the base standard - an ambitious task that CERN decided to undertake.

PATHS FOR WR STANDARDISATION

There is no crash-course at CERN on how to standardise new technologies. All had to be learned from scratch on a trial and error basis. The WR standardisation effort was started by setting up a project [9] with the goal *"of standardising the White Rabbit extension to the IEEE1588-2008 standard"* and gathering a Study Group [10] to advise on how to do so.

First, potential WR standardisation paths were identified:

1. Standardisation in ITU-T:
    (a) within an existing Telecom PTP Profile,
    (b) as a new Telecom PTP Profile.
2. Standardisation in IEEE:
    (a) as a new PTP Profile included in IEEE 1588,
    (b) as part of AVB Gen2[1] in the 802.1AS PTP Profile.
3. Standardisation by a WR consortium acting as an SDO.

Second, each of the paths was studied in terms of cost, effort and prospects of success. As such, WR was presented at relevant ITU-T and IEEE meetings to the respective communities. Attendance in these meetings allowed to evaluate the operational procedures and dynamics of the groups, as

[1] Now known as Time Sensitive Networks.

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well as the level of interest in the extensions proposed by WR, and synergies with ongoing projects. The observations and conclusions from this phase were as follows:

1. The level of performance provided by WR exceeded the needs of industry at that time, thus companies would find it hard to justify efforts into WR standardisation.
2. The ITU-T path was considered infeasible.
3. Creating a WR Consortium was too costly and risky.
4. Many synergies were found between WR solutions and the AVB Gen2, which was encouraging.
5. WR inclusion into IEEE1588 was identified as the best and most feasible WR standardisation path.

At that time, WR was presented at important events such as the IEEE Plenary [11], as well as meetings of dedicated SDO working groups. The presentations were made by CERN and industry representatives and demonstrated applications outside of CERN, thanks to the open-source and collaborative nature of WR and its community. As a result of these efforts, WR became recognised in the industrial timing community. This, in turn, made it possible to consider WR for inclusion into the base standard - the best possible scenario.

WR STANDARDISATION IN IEEE 1588

IEEE Standard Lifecycle

Each IEEE standard must obey the *Standards Development Lifecycle* presented in Fig. 1 which for existing standards ensures that a new revision is published every 10 years. Luckily, step 1 in the lifecycle of IEEE 1588 was triggered in 2012 when WR standardisation paths were evaluated.

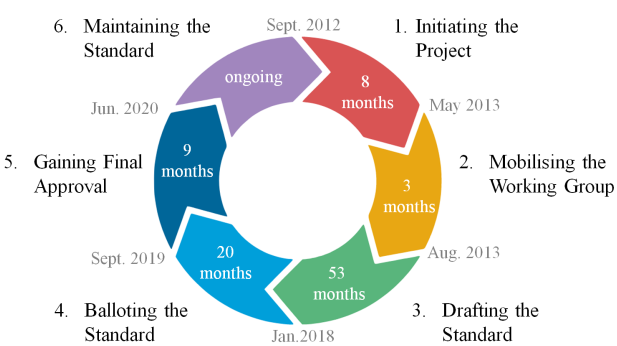

Figure 1: Standards Development Lifecycle, indicating times for the IEEE1588-2019 revision.

In the first step in Fig. 1, the scope of the project is defined in the Project Authorisation Request (PAR) which is submitted to IEEE for approval. For existing standards, the scope can be limited to a simple erratum or it can add new features. For the IEEE 1588, a Special Session at the ISPCS 2012[2] conference was held to evaluate the needs of the community. Among many contributions, it was proposed to include WR into the revised IEEE 1588 [12]. The feedback indicated that a major revision of the standard was needed, therefore a Study Group was formed to prepare the PAR which stated: *"The protocol enhances support for synchronization to better than 1 nanosecond"*. This sentence reflected group's enthusiasm to include WR into the standard, yet with no guarantees.

[2] The International IEEE Symposium on Precision Clock Synchronization for Measurement, Control, & Communication.

P1588 Working Group

In the second step in Fig. 1, a P1588 Working Group (P1588 WG, [13]) was mobilised to work on the new revision of IEEE 1588. Over 180 representatives from industry and academia jointed the group, though only around 40 actively participated. The P1588 WG was divided into 5 subcommittees (SC) to work on different aspects of the revision, namely Maintenance, Management, Architecture, Security and High Accuracy SCs were formed. The latter, was dedicated to including WR into the standard. Each SC met online twice a month and reported its progress monthly on an online Plenary of the entire P1588 WG. Two to three times a year, P1588 WG face-to-face (F2F) meetings were organised in different locations; one was held at CERN. The proposals prepared by SCs were reviewed by the entire P1588 WG.

P1588 High Accuracy Subcommittee

The High Accuracy SC was lead by CERN and included around 20 active representatives from such institutes and companies as NIST, Huawei, National Instruments, ADVA Optical Networking, Microsemi, Intel, Boeing, Ericsson, Meinberg and Cisco. The SC started step 3 in Fig. 1 by studying and understanding the WR PTP Profile [8]. This was important before deciding how to include WR into the standard. The study revealed a number of challenges:

1. There was no immediate need for the performance provided by WR which required hardware modifications. The interest was rather in using WR methods for improving performance of existing hardware.
2. WR is specified for a particular type of medium (1 Gbps Ethernet over single mode bidirectional fibre) while the standard is generic.
3. WR requires a particular hardware implementation while IEEE 1588 is purposely silent in these regards.

As a result, the WR PTP Profile could not be included into the IEEE 1588 standard in a straightforward way and the efforts for WR inclusion were questioned numerous times.

Eventually, a consensus was reached which proposed a method of including WR in the standard that encouraged contributions from the SC members. As described in Fig. 2:

1. WR was divided into a number of optional features that could be useful on their own for different industries, i.e. Layer 1 Syntonisation Enhancements (L1 Sync), Configurable correction of timestamps, Calculation of the delayAsymmetry, mechanism for external configuration and masterOnly mode.
2. These optional features were made generic and extended to accommodate the needs of some members [14]. Methods known to work for WR became a particle configuration of the generic feature and were presented as examples.

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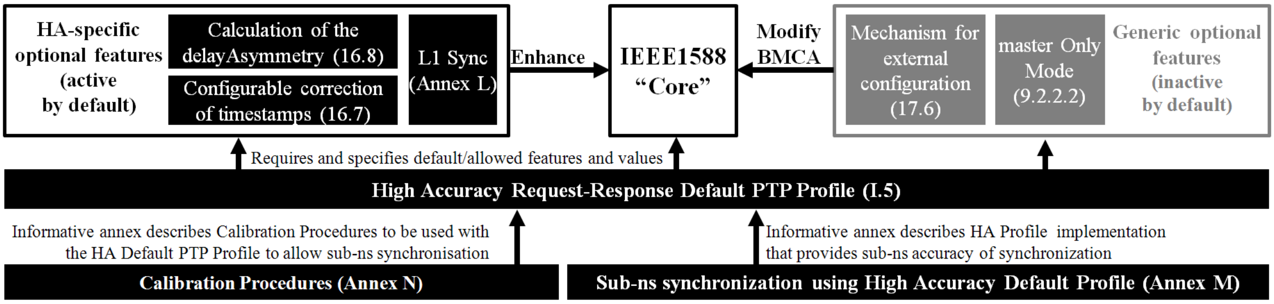

Figure 2: WR incorporation into IEEE1588-2019.

3. A new High-Accuracy Default PTP Profile (HA PTP Profile) was defined that makes use of the new optional features and specifies how a WR implementation should configure them.
4. While the WR methods included into the normative parts of the standard define only protocol aspects (no requirements on performance or hardware), the implementation details that allow achieving sub-ns accuracy of synchronisation were described in an informative annex, as an example implementation of the HA PTP Profile. Additionally, the WR calibration procedures [15] could be also included as an informative annex.

With the above compromise methodology, all aspects of the WR PTP Profile [8] and WR Calibration [15] could be included into the IEEE 1588 standard. WR was translated into three new annexes (L, M and N) and a number of additional clauses (e.g. 16.7, 16.8, 17.6, I.5) constituting a total of over 55 pages. Additionally, the core text of the standard (PTP "generic framework") had to be enhanced with more precise definitions (e.g. clock, clock signal, Direct PTP Link), as well as an improved specification of timestamp generation and medium asymmetry, see [16] for details.

This compromise means that the WR PTP Profile and the HA PTP Profile are not compatible at the protocol level. While the existing WR hardware can be used to implement the new profile, the software WR implementation of the PTP stack [17] had to be updated. Before submitting the final text for the HA features and PTP Profile to the P1588 WG, the updated protocol was prototyped and compliance tests were developed independently to ensure its high quality [18].

With the new text ready and the solutions thoroughly tested, the High Accuracy SC submitted the text to the P1588 WG, were it joined that of the other SCs - the draft of the entire new standard (which grew from 289 to 499 pages) was ready for balloting.

Balloting

Balloting is a voting and review process of IEEE standards in which each reviewer votes to either reject or approve the text. The approval can be made conditional on implementing voter's comments. Each comment must be precise, explain the problem, and suggest new text that solves it. All comments are reviewed by a dedicated committee and each comment must be addressed. An updated text of the standard is submitted for re-circulation. In re-circulation, the reviewers vote with the same rules as before, but comments can be made only to the text that changed. In this way, after a limited number of re-circulations, the voting converges.

For the revised version of IEEE 1588, there were three ballots internal to the P1588 WG, which are still step 3 in Fig. 1. In these WG ballots, 3352 comments were submitted in the first one, 1504 in the second one and 749 in the third one. It took 18 months to go through this step and have the draft ready for the next step, i.e. Sponsor Ballot.

The Sponsor Ballot, step 4 in Fig. 1, is the IEEE Standards Association Public Review process in which anyone in the world can take part and vote submitting comments. A group of 127 registered balloters submitted a total of 358 comments which took 2 re-circulations and a total of 16 months to resolve before getting the required number of affirmative votes.

Final Approval and Publication

The balloted draft was then approved by the IEEE Standards Review Committee and Standards Board in November 2019. At this point the new revision of the IEEE 1588 standard, IEEE1588-2019, superseded the previous IEEE1588-2008. However, the standard was not yet publicly available. It was passed to the IEEE Editor. The editing process took around 6 months and the new edition of the IEEE 1588 standard, WR included, was published on 16 June 2020.

COSTS, BENEFITS AND LESSONS LEARNED

On behalf of CERN, the author was heavily involved in each step of the IEEE *Standards Development Lifecycle* described in the previous section. His involvement included leading the High Accuracy SC, contributing to the work of the Architecture, Management and Maintenance SCs, as well as substantially helping in the ballot comments resolution and working with the IEEE Editor in the final stage.

The indicative costs of CERN's involvement in the work of the P1588 WG in order to standardise WR amounts to an estimated 2.25 person-years and 26 kCHF spread over 7 years. It includes participation in online and F2F meetings, preparation and review of documents and organisation of a F2F meeting at CERN; it excludes implementation of the HA PTP Profile and its compliance tests.

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The motivation for standardising WR was to achieve long-term benefits, such as wide adoption and support from industry to minimise costs for CERN installations. Although these benefits cannot yet be unequivocally claimed only 1 year after IEEE 1588-2019 publication, some clear initial indications can be observed. Moreover other benefits of WR standardisation are apparent.

WR technology has benefited technically from the transformation into the HA options and PTP Profile. Not only has a number of known shortcomings of WR been fixed but WR technology has also become a more generic and flexible solution – see [14].

Even before the WR standardisation was completed, many companies had enthusiastically acted on the premise that WR would become an integral part of IEEE 1588. This included companies already familiar with WR and newcomers. The prospective WR standardisation clearly motivated these companies to invest time and resources into WR technology, which was tested for future applications in telecommunication networks on this premise [19]. The increasing number of applications and companies producing and supporting WR devices is essential for healthy competition and technology evolution, e.g. commercial long-distance WR-based time transfer [20].

The IEEE 1588 standard benefited from CERN's contributions and expertise. The constantly growing number of WR users increases the popularity of the standard. The enhanced level of accuracy achievable by the IEEE 1588-2019 meets the increasing needs of the industry. While the accuracy required from IEEE 1588 devices by industry in 2012 was at sub-μs level, it has now increased to 4 ns [21] and will surely increase further. IEEE 1588-2019 is prepared to meet these requirements.

Finally, WR standardisation is a technology transfer that fulfils CERN's mission to *push the frontiers of science and technology, for the benefit of all* [22]. CERN has become a recognised player in the timing industry and continues its mission as the key driving force for innovation in the P1588 WG that continues to oversee the evolution of the IEEE1588 standard. As such CERN now leads the *P1588 New Features SC* mandated to add new features to IEEE1588, some of them inspired by new developments in the WR community.

WR AFTER STANDARDISATION

WR technology provides deterministic data transfer and accurate time transfer over an Ethernet Bridged Local Area Network using an extension to IEEE 1588. Initially this extension was the WR PTP Profile of IEEE1588-2008. After the WR standardisation described in this article, it will be the HA PTP Profile of IEEE1588-2019. This update requires only upgrade of the software implementation of the PTP used in WR devices, i.e. PPSi [17]. Currently the beta version of the HA PTP Profile is available, yet official releases of WR firmware still use the WR PTP Profile.

The migration of WR devices to use the HA PTP Profile is foreseen in the coming years and it is intended to be transparent for the WR users. WR Switches will support both PTP Profiles, WR and HA. The WR Nodes will use a profile of their choice, yet their support for the WR PTP Profile is meant to be deprecated at some point. On the other hand, the WR Switch is meant to support both profiles in the long-term. When connecting a WR device (switch or node) to a WR Switch, it will attempt to run the HA PTP Profile by default. If the HA PTP Profile is not detected on the adjacent WR device, the WR PTP Profile will be attempted. Thus, a WR Network can effectively use both profiles, WR and HA, in a manner transparent to the user.

The compliance of WR devices with the WR PTP Profile and the HA PTP Profile is ensured through extensive compliance tests developed using the Veryx ATTEST framework. While the framework is proprietary, the compliance tests are open-source [18]. The WR PTP Profile tests were purposely developed to ensure compliance of new WR firmware releases with the legacy devices/release. The HA PTP Profile tests were developed to verify the new profile during its development, and are meant to verify compliance with the HA PTP Profile of its implementations by CERN and the industry.

Notably, WR technology is a particular implementation of the HA PTP Profile that guarantees sub-ns accuracy of synchronisation. There might be other implementations of that profile without such guarantee.

CONCLUSION

Standardisation of a new technology is a long process which requires not only an excellent technical solution but also patience and an open-minded attitude which allows to reach consensus. The duration and dynamics of the standardisation process depend on the SDO, the particular standard and the group that works on it, thus each potential standardisation effort must be considered individually.

The author is convinced that for technologies which are meant to last for decades and be deployed in thousands of units, the benefits of standardisation clearly out-weigh the efforts. A decrease of price by a hypothetical 50 CHF for a single WR device, costing hundreds or thousands CHF, due to competition encouraged by the WR standardisation compensates the monetary cost of this standardisation as soon as 500 unites are purchased. The 2.25 person-years spent during 7 years on WR standardisation are more than compensated by 20 experts from industry scrutinising the technology ensuring its longevity and making it future-proof, while learning how to implement it in their companies.

Of course, standardisation is an investment which, by nature, brings profits with time and it is only in a decade or so that a true evaluation of the benefits of WR standardisation will be possible.

ACKNOWLEDGEMENTS

WR would not have made it into the IEEE 1588 standard without the strong support and invaluable help of John Eidson, called in the community "the father" of IEEE1588.

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REFERENCES

[1] White Rabbit Project – official CERN website, https://www.cern.ch/white-rabbit

[2] White Rabbit Project Open Hardware Repository, https://ohwr.org/project/white-rabbit/wikis

[3] M. Lipiński *et al.*, "White Rabbit Applications and Enhancements", in *Proc. ISPCS2018*, CERN, Geneva, Switzerland, Oct. 2018, pp. 106-112. https://ohwr.org/project/white-rabbit/uploads/7f9e67258850d5c036629a509bf2e124/ISPCS2018-WRApplicatoinsAndEnhancements.pdf

[4] *IEEE 1588-2019 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE Standard, New York, NY, USA, Nov. 2019; https://standards.ieee.org/standard/1588-2019.html

[5] Institute of Electrical and Electronics Engineers (IEEE), https://www.ieee.org/

[6] Precision Time Protocol Profiles, https://sagroups.ieee.org/1588/ptp-profiles

[7] M. Lipiński, T. Włostowski, J. Serrano, and P. Alvarez, "White Rabbit: a PTP application for robust sub-nanosecond synchronization", in *Proc.* ISPCS2011, Munich, Germany, Sep. 2011, pp. 25-30. doi:10.1109/ISPCS.2011.6070148

[8] E. Cota, M. Lipiński, T. Włostowski, E. van der Bij and J. Serrano, "White Rabbit Specification: Draft for Comments, version 2.0", CERN, Geneva, Switzerland, Jul. 2011; https://white-rabbit.web.cern.ch/documents/WhiteRabbitSpec.v2.0.pdf

[9] White Rabbit Standardization Project, https://ohwr.org/project/wr-std/wikis/home

[10] White Rabbit Study Group, https://ohwr.org/project/wr-std/wikis/std-group

[11] M. Lipiński, "White Rabbit - Ethernet-based solution for sub-ns synchronization and deterministic, reliable data delivery", *Tutorials*, IEEE 802 Plenary, Geneva, Switzerland, Jul. 2013. https://www.ieee802.org/802_tutorials/2013-07/WR_Tutorial_IEEE.pdf

[12] M. Lipiński, "High accuracy extension/option/profile", in *Special Session* ISPCS2012, San Francisco, USA, Sep. 2012. https://www.ohwr.org/project/white-rabbit/uploads/b0c0f513bf8734bc856f6860fa693201/ISPCS2012-specialSession-final.pdf

[13] P1588 Working Group – official website, https://sagroups.ieee.org/1588

[14] O. Ronen and M. Lipiński, "Enhanced Synchronization Accuracy in IEEE1588", in *Proc.* ISPCS2015, Beijing, China, Oct. 2015, pp. 76-81. doi:10.1109/ISPCS.2015.7324687

[15] G. Daniluk, *White Rabbit calibration procedure, version 1.1*, CERN, Geneva, Switzerland, Nov 2015; https://white-rabbit.web.cern.ch/documents/WR_Calibration-v1.1-20151109.pdf

[16] WR integration into IEEE1588-2019 as High Accuracy, https://ohwr.org/projects/wr-std/wiki/wrin1588

[17] PPSi: PTP Ported to Silicon, https://ohwr.org/project/ppsi/wikis/home

[18] White Rabbit Compliance Tests, https://ohwr.org/project/wr-compliance-tests/wikis

[19] H. Imlau, *Highly Accurate Time Dissemination and Network Synchronization at ISPCS 2019*, Telekom Technik GmbH, *keynote*, ISPCS20219, Portland USA, Sep. 2019, https://www.researchgate.net/publication/336013265_Highly_Accurate_Time_Dissemination_and_Network_Synchronization_at_ISPCS_2019

[20] T. Cozzens, "White Rabbit makes leap for time over fiber", *GPS World*, Online, Sep. 2021. https://www.gpsworld.com/white-rabbit-makes-leap-for-time-over-fiber

[21] *ITU-T G.8272.1 - Timing characteristics of enhanced primary reference time clocks*, ITU-T Recommendation, Nov. 2016. doi:11.1002/1000/13162

[22] WHAT IS CERN'S MISSION? https://home.cern/about/who-we-are/our-mission

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