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IEEE 1588 High Accuracy Default Profile: Applications and Challenges

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ABSTRACT Highly accurate synchronization has become a major requirement because of the rise of distributed applications, regulatory requests and position, navigation and timing backup needs. This fact has led to the development of new technologies which fulfill the new requirements in terms of accuracy and dependability. Nevertheless, some of these novel proposals have lacked determinism, robustness, interoperability, deployability, scalability or management tools preventing them to be extensively used in real industrial scenarios. Different segments require accurate timing information over a large number of nodes. Due to the high availability and low price of global satellite-based time references, many critical distributed facilities depend on them. However, the vulnerability to jamming or spoofing represents a well-known threat and back-up systems need to be deployed to mitigate it. The recently approved draft standard IEEE 1588-2019 includes the High Accuracy Default Precision Time Protocol Profile which is intensively based on the White Rabbit protocol. White Rabbit is an extension of current IEEE 1588-2008 network synchronization protocol for sub-nanosecond synchronization. This approach has been validated and intensively used during the last years. This paper revises the pre-standard protocol to expose the challenges that the High Accuracy profile will find after its release and covers existing applications, promising deployments and the technological roadmap, providing hints and an overview of features to be studied. The authors review different issues that have prevented the industrial adoption of White Rabbit in the past and introduce the latest developments that will facilitate the next IEEE 1588 High Accuracy extensive adoption.

INDEX TERMS GPS backup, high accuracy profile, IEEE 1588, time dissemination, precision time protocol, PTP, white rabbit.

I. INTRODUCTION

Historically, cities have been the core of the technological development in our society. Different factors, as convenient locations or resource access, facilitated the development of densely populated areas with better economic and social conditions. These communities took advantage of their economic capabilities to create industrial and innovation hubs thanks to better civil infrastructures and higher education levels.

Therefore, metro areas around the world concentrate most of the population and technology-related industries, e.g. finance, telecommunications or broadcasting. For this reason, significant distributed applications from different industries can be found in metro scenarios. This fact results in massive communication infrastructures. Nowadays, this concept is evolving to Smart Cities that integrates many innovative advances to make large and densely populated cities more efficient and sustainable.

In the telecom industry, i.e. with the implementation of the fifth generation (5G) cellular network technology, different metro areas are playing a pioneering role in the deployment of new technologies. It is noteworthy that, in order to attend the potential number of customers, the telecom infrastructure will evolve dramatically to a higher capillarity in these locations where the number of deployed cells will be much higher than in rural areas. This fact leads to more demanding operation conditions due to the coexistence and integration of more complex networks, including higher synchronization requirements [1]. Furthermore, new services will require higher bandwidth and, at the same time, lower latency and

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improved data delivery determinism. This will impose very exigent specifications for telecommunication networks and will require enhanced mechanisms for network analysis, test and monitoring [2]–[4].

In the finance segment, most of the trading activities are located close to financial centers involving a few intensively connected datacenters where the different trading actors are co-located. Satellite-based systems are used as their main time reference. In this framework, synchronization through wired links provides a coherent time reference for coordinated trading within "the low-latency race" [5] or as a countermeasure against jamming or spoofing attacks. Furthermore, this is also motivated by some new regulations as MiFID II in Europe [6] or SEC and FINRA in USA [7].

Following this thread, different companies are deploying time synchronization services in datacenters developing a service to datacenter-centric applications or distributed databases [8]. For this purpose, atomic clocks are combined with network synchronization protocols, as Network Time Protocol (NTP), IEEE 1588 Precise Time Protocol (PTP) or others [9]–[11]. The adoption of evolved network equipment based on Graphics Processing Units (GPUs) or Field Programmable Gate Arrays (FPGAs) is leading to a scenario where nanosecond-level time synchronization is useful both for the internet service providers and the co-located customers in the datacenters. Likewise, future ExaScale High Performance Computing (HPC) systems could benefit from tight synchronization to improve the application execution time and energy efficiency.

In other sectors, as Smart Grid and broadcasting, network-based synchronization is already in use and typically works over IEEE 1588-2008 protocol profiles [12]. Here, accurate profiles can be used in order to improve this time synchronization, deploying virtually zero-time budget links in specific parts of the network helping to meet the synchronization accuracy specifications, enhance some features such as Traveling Wave Fault Location (TWFL) in Smart Grid or even replacing the whole synchronization network [13].

Time Sensitive Networking (TSN) requiring stable time references is also expected to be increasingly implemented to provide deterministic latency in data transmissions for control applications and wireless communications in industrial networks [14], [15]. New features for telecom networks were inspired by this technology, as the traffic shaping capabilities in the fronthaul network defined in the Common Public Radio Interface (CPRI) specification for the eCPRI protocol [16].

Nanosecond-level accurate time synchronization can be used for monitoring purposes using visibility networks in all these sectors. These networks allow monitoring the synchronization performance in the production network, facilitating the detection and forensic analysis of failures. This is key to define any Service Level Agreement (SLA) with end customers using timing related services. In this framework, a proper monitoring of the production network time-related services benefits of a better accuracy as well as deterministic behavior [17].

In this paper, the authors perform a review of existing synchronization technologies and present the White Rabbit (WR) protocol as pre-standard implementation of the IEEE 1588-2019 High Accuracy Default PTP Profile (HA) and some of its potential applications. Then, they enumerate the main obstacles that have prevented the WR technology adoption during the last years which also represent barriers to this new profile. After that, the latest developments in terms of reliability, interoperability and deployability for industrial applications are exposed. Reference literature about this technology is condensed in the different sections complementing the addressed topics.

II. INDUSTRIAL TECHNOLOGY REVIEW

Typical deployments in aforementioned sectors include a stable time reference which is used to provide a time basis, allowing the correlation of the local time resources in different places. Global Navigation Satellite Systems (GNSS), are the main source of time because of its price, accuracy, easy deployment and global coverage. This technology allows to obtain time and frequency references with tens of nanosecond accuracy in remote places traceable to Coordinated Universal Time (UTC). Nevertheless, it is vulnerable to accidental or malicious signal disruption, natural interferences due to weather conditions or urban constrains in terms of signal coverage and integrity.

Apart from satellite-based technologies, network-based protocols arose as a complementary solution to distribute time and frequency signals at a lower cost using a primary time reference. Thanks to these protocols, time information can be distributed to nodes which have no satellite coverage through a reliable physical infrastructure with improved accuracy. The significant extension of wired communications supports the scalability and feasibility of this approach providing a solution with increasing capillarity and availability.

The most extensively used protocols are NTP and IEEE 1588-2008, typically known as PTP. In terms of synchronization accuracy, under well controlled conditions, NTP can provide microseconds scale accuracy using a software-based solution, while PTP can provide up to tens of nanoseconds using hardware timestamps and well controlled scenarios based on time-aware switches and nodes [18].

Although these technologies are well supported with commodity solutions for the respective industries, the problem arises when the accuracy requirement is lower than 100 nanoseconds. Path asymmetries, temperature changes, cable length delays and other variables represent very complex issues that require careful design and adopting smart solutions.

In order to improve the synchronization accuracy offered by previous protocols, WR was designed to provide subnanosecond time synchronization accuracy in Ethernet networks to thousands of nodes with high reliability and determinism.

Due to the increasing requirements for time synchronization in different sectors as science, finance or telecom, WR is being adopted for time synchronization in multiple applications [19]. WR is considered an emergent trend for finance applications in the last update of the Report on Time & Synchronization User Needs and Requirements released by the European GNSS Agency motivated by the deployment in Deutsche Börse stock exchange [20]. Additionally, the technology is under evaluation by the United States Department of Transportation as Global Positioning System (GPS) backup [21] and several telecom companies as Deutsche Telekom [22] or Orange [23] have presented preliminary results in the International Timing and Sync Forum (ITSF) or the International IEEE Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS). In the scientific side, an overview of applications is listed in [24].

It is noteworthy that wide area WR deployments have been excluded from this review. Although WR links above one thousand kilometers have been deployed, they are still a matter of study in the community because of different optical phenomenons which affect the fiber signal reliability [25], [26].

III. WHITE RABBIT

WR is a synchronization technology developed as an open source project [27]. It was born in 2009 and involves multiple international public scientific facilities, i.e. European Organization for Nuclear Research (CERN), Helmholtz Centre for Heavy Ion Research (GSI) or University of Granada (UGR), and private companies, as Seven Solutions which was responsible for the WR switch hardware design.

The main characteristic of the WR technology is that it ensures sub-nanosecond time synchronization accuracy in conventional optical fiber networks [28]. For this purpose, it was based on standard technologies as Ethernet, PTP or Layer 1 syntonization, similar to Synchronous Ethernet (SyncE). The capability to improve the timing performance without requiring a complete change of the fiber infrastructure is the reason why it has been adopted in different scientific facilities and industrial applications.

Another important feature of the WR technology is the frequency distribution with a precision better than 50 picoseconds as stated in its specification. The typical WR link has a master/slave model where the time information from the master is distributed to the slave node. In order to distribute very stable external time references, the WR devices can also be configured as grandmasters. Under this configuration, the devices use the analog 1 Pulse Per Second (1PPS) and 10 MHz clock signals to obtain the time reference and NTP for the Time of Day (ToD) information.

In its original version, WR supports 1 Gigabit (G) Ethernet connections and shows no time synchronization degradation when combining data packets with WR packets.

The main mechanisms used in the WR technology are enumerated below:

- Layer 1 syntonization. In a similar way to SyncE, the clock reference from the master is distributed to the slave. A Clock Data Recovery (CDR) is used to retrieve the transmission clock from the received physical data stream. This recovered clock is used to adjust the local transmission clock, creating an internal copy of the reference clock.
- Network time packets exchange: WR uses an extension of standard PTPv2 packets to perform time synchronization. It includes specific signaling messages to establish the WR link, where additional information, as calibration parameters, is aggregated to the event messages. Lately, WR uses this packet exchange to generate hardware timestamps both in the transmission and the reception, and uses this information to compute the clock offset between the master and the slave.
- Phase measurement: In order to avoid the resolution limitation of hardware timestamps, WR takes advantage of the syntonization to perform phase measurements with picosecond resolution between the received and transmission clocks in the master and the slave. This information is used to enhance the timestamp information, improving the clock offset calculation accuracy.

The typical WR connection estimates the propagation delay asymmetry to avoid uncompensated synchronization offsets, simplifying the setup procedure by applying precalibrated values to compensate different propagation speeds and fixed delays [29]. Its default precalibration allows a maximum link distance up to 10 kilometers.

IV. ADOPTION ISSUES

WR started as a collaborative effort between public scientific facilities and science-oriented companies. During the last 10 years it has evolved from an academic technology, that was deployed in controlled scenarios with highly specialized personnel, to a mature technology that provides very accurate time synchronization which eases the deployment as it avoids in-situ calibration. During this process, several adoption issues have arisen:

A. TECHNOLOGY INMATURITY

As a novel technology, WR had some issues that prevented it to be adopted by the industry. Due to its complex design, based on FPGAs with specific clock circuitry including both the hardware and the software creation, WR has had a slow and expensive development stage. For this reason, the technology was mainly oriented to scientific applications and was funded by public projects in its beginning.

Although WR has a fast-growing user community as exposed in Section II, the main development efforts have been carried by few teams around the world which have pushed the technology in different directions depending on their goals. In this context, private companies have mainly oriented the technology to industrial applications, diversifying the features in the devices or integrating the technology in previous designs. Other users have focused on the management capabilities and different projects have designed specific functionalities to fit their requirements.

B. DEPLOYMENT

As can be seen in the references from section I, one of the main issues to adopt this technology has been that it usually exceeded the synchronization requirements of telecom or finance industries in the past. This fact converted WR in a niche technology whose main applications were very exigent distributed scenarios or networks with a lack of accuracy because of the distance or the number of hops.

For this reason, the WR ecosystem was focused on custom implementations, especially in particle accelerators [30] or distributed telescopes [31], where a homogeneous WR-based synchronization network is deployed.

In that context, a lack of general purpose WR devices, the limitation in the maximum distance because of the optic equipment and the absence of pre-calibration or feasible calibration procedures made some potential industrial applications reject this technology.

C. INTEROPERABILITY

The interoperability capabilities of the WR technology are a remarkable issue when it is integrated with different equipment that needs time information. Originally, WR was created to replace previous synchronization networks and provide high accuracy synchronization in a WR compliant scenario. Nevertheless, many applications still require ‘‘last mile’’ links which use standard protocols as IEEE 1588-2008 profiles with minimum degradation of the timing performance.

Although it was developed to work over Ethernet networks, its default bandwidth, limited to 1Gbps connections, or the supported synchronization mechanisms show that the initial goal was to work in homogeneous environments where a single organization was responsible of the fiber network and the whole WR network.

This fact originally affected the WR integration capabilities in heterogeneous networks, where the fiber network is not easy to adapt to fulfill the plug-and-play conditions with dedicated WR links. Consequently, although WR presents a realistic alternative for next technological infrastructures such as 5G mobile telecommunications networks, its massive adoption is not straightforward as indicated in [32].

Another integration issue is presented in the industry because GNSS devices with different implementations manufactured by different vendors are widely used as time source. Several facts as the stabilization period of the GNSS device timing outputs, the phase relationship between the 1PPS and the frequency outputs or the physical cable distance that connect the analog reference signals to the WR grandmaster device need to be considered.

Lastly, the existing fiber infrastructure is usually shared with other services or based on Dense or Coarse Wavelength Division Multiplexing (WDM) technologies, which makes harder to deploy a WR link based on bidirectional transmission over the same fiber.

D. ROBUSTNESS

As a novel technology, WR did not offer enough mechanisms or industry driven test results that certified its robustness. Reliable operation under non-controlled environmental conditions, as temperature or humidity changes, during long periods needed to be proved.

In this context, the validations performed by several metrology institutes and scientific applications which have generated extensive literature about WR has been a remarkable factor to improve the credibility of this technology [33], [34].

On the other hand, different features as holdover capabilities, automatic source switching, or redundancy support are important functionalities that complement the time synchronization and are key for industrial support. Several examples of developments focusing on these capabilities will be exposed in the following section, although they are not included in all WR devices.

E. DATA TRANSMISSION

WR was designed to share data with time synchronization packets. This way, WR devices support switching or data forwarding. However, its 1G link speed capability, its limited switching performance and a platform design focused on low traffic conditions have avoided this technology to be used for data traffic in different industries.

This issue is overcome deploying time dedicated WR networks, but it implies an extra cost in infrastructure and management resources that in some cases discourage potential users [35].

In this context, the main challenge to achieve higher link speeds is that it requires major modifications in the original WR design, as the FPGA models or the Ethernet modules in use need to be replaced [36]. Additionally, the reference frequencies recovered from the Ethernet interfaces will vary between different link speeds affecting the layer 1 syntonization explained in Section III.

Finally, WR uses specific transceiver configurations and specific clock circuitry which prevents the design of completely software PTP stacks which could be easily integrated on industrial network equipment supporting higher bandwidths.

V. WHITE RABBIT TECHNOLOGY EVOLUTION AND ROADMAP

WR has progressively evolved solving bugs and extending the technology functionalities. From its beginning, different WR development teams have been created, encouraging the development of different WR devices focused on different applications, i.e. Cherenkov Telescope Array (CTA) [37], Square Kilometre Array (SKA) [34], Cubic Kilometre Neutrino Telescope (KM3NET) [38]. Thus, the available portfolio of products has increased, the existing devices have been adapted to the requirements from different industries and the technology robustness has improved.

Furthermore, the accumulated experience during the development and deployment for different projects has helped to provide better user experiences and to ease the deployment in industrial scenarios.

It is also remarkable the dissemination effort made by the community, which has included tens of papers and conference presentations, promoting this technology beyond the scientific field [39]. It is noteworthy that the community has tried to make innovation not only in the technology domain but also in the open hardware approach as stated by the Open Hard*w*are Repository concepts promoted by CERN [40].

A. IEEE 1588 STANDARDIZATION

IT has been announced that the IEEE 1588 Precision Time Protocol standard will include a new HA profile in its new revision. This HA profile is based on the current WR technology and it is expected to be publicly released in early 2020. The fundamental principles of WR are kept in the standard implementation but the protocol has been revisited and adapted to be coherent with other IEEE 1588 profiles, showing similar nomenclature, state machines or general mechanisms. This significantly improves the interoperability, as well as consider industrial cases which were not addressed in the original WR implementation.

For example, control of layer 1 syntonization, estimation of delay asymmetry and hardware delays correction or calibration are generalized and integrated in the following sections:

- Optional features: Clauses 16, 17 and Annex O combines HA-specific with other generic features regarding packet exchange, state configuration and layer 1 syntonization.
- Default PTP Profile: Annex J.5 defines the new profile.
- Informative annexes: Annex P describes the sub-nanosecond implementation of the new "High Accuracy Delay Request-Response Default PTP Profile" and annex Q the calibration procedures.
- Additionally, a number of changes to core parts of the standard were made to allow the optional features.

This fact has helped to spread the WR capabilities and justifies that it is a mature technology which has implemented certain mechanisms which have been proved reliable and useful to achieve better synchronization accuracy. An extensive adoption of the WR mechanisms in the future is foreseeable. The integration into the standard will facilitate the adoption of this protocol principles by a wider user community and promote the competition between different vendors.

B. CALIBRATION

One of the main aspects of WR is the fiber asymmetry and fixed delays compensation. This compensation is performed following a calibration procedure based on a bidirectional link scheme where two different wavelengths are used to transmit information between both ends using the same fiber. By default, this distance link is limited to 10 km due to the precalibrated Small Form-factor Pluggables (SFP) that are used in the research facilities.

For this reason, local area deployments are straightforward, but calibration has been a recurrent topic to deploy long distance links or using different optics, which eases the WR integration in existing infrastructures. Several calibration methods are presented below:

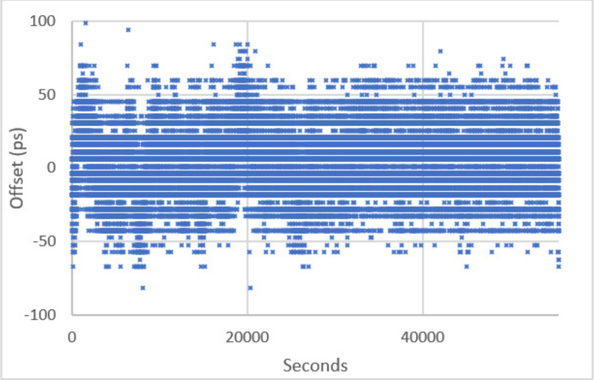

FIGURE 1. Time offset results in a 120 kilometers WR link with two hops using WR-ZEN TP devices after calibration.

- Precalibration in dedicated links: The distance limitation for WR links is caused by the SFP transmission power. Long distance SFPs supporting up to 120 km links can be calibrated following the standard calibration procedure for a specific fiber type as shown in Figure 1. This distance can be extended by using multiple WR nodes [41] or bidirectional amplification, although this last option also requires calibration for each amplifier. Absolute calibration has been studied to ease the deployment of network components [42], [43].
- Precalibration in shared WDM links: WDM technology can be used to deploy bidirectional links reducing asymmetries. Additionally, this technique allows to introduce different optical equipment as Dispersion Compensation Modules (DCM), optical multiplexers or optical amplifiers and, at the same time, share the physical medium with other applications. The maturity of the approach has been shown with solutions as 44] and nowadays this improvement is fully supported by leading WR companies. The temperature impact in WR WDM links has been studied by the community [45].
- GNSS based calibration: Once the link has been deployed, on site calibration can be performed using GNSS receivers in each end [44], [46]. The accuracy depends on the instantaneous offset between both receivers, which could be affected by different factors as the antenna position or the internal delays. Accuracy close to the nanosecond level can be achieved with calibrated GNSS receivers, making this method a feasible alternative due to the WR synchronization stability.
- Swapping based calibration: Depending on the deployments, swapping based methods can be performed to measure link asymmetries using a stable time reference [25]. This technique allows to achieve sub-nanosecond accuracy when working in bi-fiber links where the distance asymmetry cannot be compensated. The downsides are that it requires to have access to both ends and no unidirectional equipment can be installed in the link.
- Network effect calibration: When extensive WR networks are deployed with redundant topologies,

several loopbacks conformed by multiple links can be closed, measuring the offset in each location with different configurations. This procedure allows to calculate and compensate the asymmetry in each of the deployed links when a minimum of three locations are connected. This methodology, exposed for the first time in the literature in this paper, is used by other timing techniques and can be also applied to WR calibration. Although WR has been typically approached from a point to point perspective, there is no reason to extend this concept to more general approaches.

C. ROBUSTNESS

Driven by the scientific applications where WR has been integrated, i.e. particle accelerators or radio telescopes, where a synchronization system malfunction can lead to a major failure, the robustness of the WR technology has been another point of interest in the community.

Different network redundancy mechanisms have been studied based on different network topologies. For instance, tree topology redundancy can be easily achieved using multiport WR devices as the WR-switch or several WR nodes. In this case, monitoring tools such as Simple Network Management Protocol (SNMP) or Remote System Log (Rsyslog) can be used to detect synchronization losses and automatically change the time source using basic scripts if occasional disruptions are assumable.

Other more complex techniques as High availability Seamless Ring (HSR) topologies [47], [48] with zero-time recovery capabilities have been also developed. In this case, a ring topology was able to change its reference maintaining sub-nanosecond accuracy independently of the active synchronization path.

HSR was partially possible because of the seamless switchover capabilities in WR devices [49]. Although this mechanism is still under development and is not included in most of the current devices, it allows to keep track of multiple backup WR time sources, switching from the main reference to the secondary sources without affecting the synchronization performance.

Subsequently to the definition of the HA profile in IEEE 1588, other resiliency mechanisms based on existing PTP technologies have been also proposed to be integrated in WR. A main example is the Best Master Clock Algorithm (BMCA), where the devices can switch between different synchronization sources depending on the clock characteristics from different time references. It also provides automatic source switching in case of connection failure [44].

Besides that, holdover capabilities have been included in WR devices to fulfill industry standard requirements, i.e. 1.5 μs drift after 24 hours in telecom. Initial tests have been performed showing that this accuracy level can be obtained in WR devices when the fiber connection is disrupted as shown in Figure 2. Thanks to the WR stability, WR devices can learn from remote stable references reducing the drift from the source and reducing the local dependencies [44].

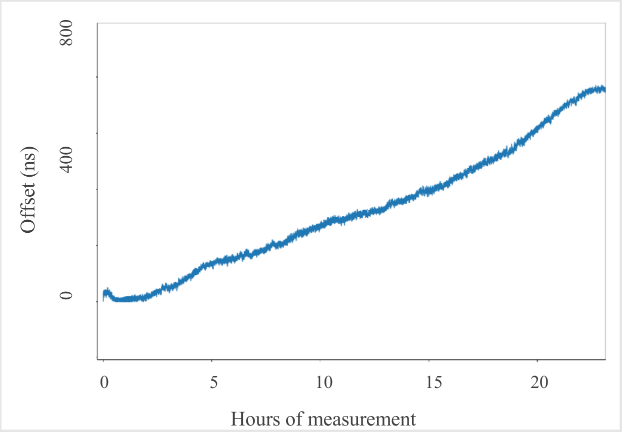

FIGURE 2. Holdover time offset results in WR-ZEN for 24 hours.

Lastly, several devices have included previously commented features as BMCA or holdover with redundant power-supply systems to be protected against power failures making possible to have reliable devices for industrial applications. In Figure 2, holdover capabilities in a WR-ZEN Time Provider are shown.

D. INTEROPERABILITY

As was presented above, the interoperability issues can be related to different use cases or device configurations. The time reference, the time synchronization distribution to non-compliant WR equipment or the network integration need to be considered. In the following list it is stated how these different issues have been addressed:

- GNSS reference alignment: WR grandmaster devices are designed to syntonize their internal clock to an external 10 MHz clock reference and use an external 1PPS signal at the beginning to set its notion of time.
  This fact affects the time synchronization accuracy in comparison to GNSS receivers, because they typically generate the 1PPS signal reference based on the 10 MHz clock but there could be slight drifts and the phase relationship between both is not guaranteed. Due to that, a 1PPS alignment module that ensures sub-nanosecond dynamic alignment to the 1PPS input has been developed and can be optionally enabled by the user [46].
  Additionally, different cable distances connecting the time source and the WR grandmaster device can lead to uncontrolled offsets. In order to solve this issue, some WR nodes allow to configure a programmable delay correction to the 1PPS input that removes any undesired difference or control their 1PPS outputs to configure its delay in comparison to the internal WR 1PPS reference.
- Non-compliant WR devices time synchronization: In contrast to scientific deployments, industrial applications usually integrate WR as an auxiliary network that allows to improve the time synchronization between the devices in the production network. Consequently, WR needs to interface the already deployed production devices using standard synchronization mechanisms.

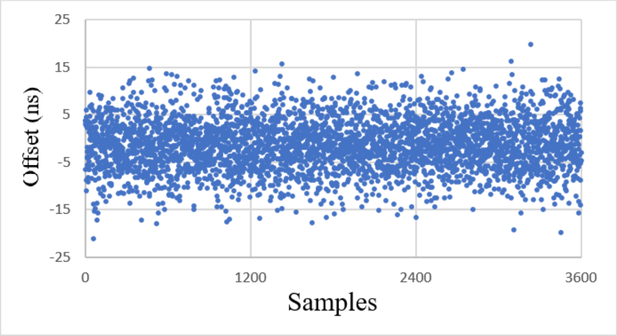

FIGURE 3. Time offset results between two boards synchronized using PTP by two different WR-ZEN TP connected to a shared WR reference.

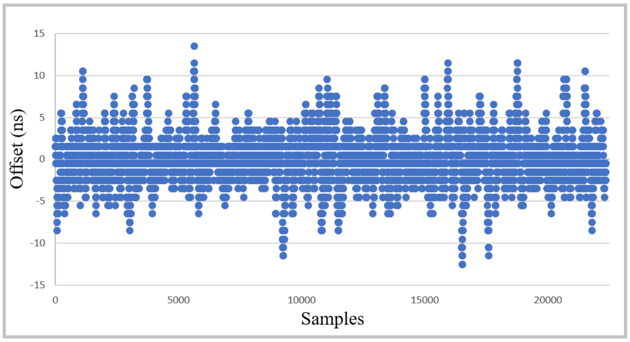

FIGURE 4. Time offset results between a time reference and one board synchronized using 1PPS by one WR-ZEN TP device.

In this scenario, extended network-based synchronization protocols as PTP or NTP must be supported by the WR-compliant devices, allowing to distribute the time reference in heterogeneous networks.

PTP is the preferred interoperability option because of the enhanced synchronization accuracy which allows to achieve tens or hundreds of nanoseconds accuracy using specific equipment integrated in some industrial scenarios. In these cases, WR can be used to save time budget caused by multiple PTP hops or link asymmetries that significantly degrade the PTP accuracy when multiple devices are cascaded. As shown in [50], there are existing commercial solutions capable of providing such interoperability. The provided accuracy is comparable to a direct connection from the end node to the network time reference without any penalty caused by the network timing distribution as shown in Figure 3. It representsa significant advantage compared with existing alternatives.

NTP compliance, although it provides a synchronization accuracy several orders of magnitude worse than WR, is an important feature because it enables general purpose devices synchronization, offering a comprehensive solution where only one synchronization network is used in the facility.

Furthermore, NTP can be used to provide ToD when 1PPS distribution is used as primary synchronization method as shown in Figure 4. In fact, depending on the PPS receiver clock circuitry, this method has been proved to be the most accurate alternative, achieving even sub-nanosecond synchronization accuracy levels.

On the negative side, 1PPS distribution demands consciously deployments, where cable distance delays must be accounted and compensated. Accordingly, multiple 1PPS output support and delay configuration has allowed to decrease the deployment cost and to ease the installation procedure.

Accordingly, multiple 1PPS output support and delay configuration has allowed to decrease the deployment cost and to ease the installation procedure.

- High bandwidth networks support: WR was conceived as a 1G Ethernet-based technology. Nonetheless, the increasing data bandwidth requirements in most industries, including telecom and finance, has led to network deployments based on 10G, 25G, 40G or even 100G in datacenter scenarios. On this basis, standard WR devices are becoming outdated in different niches.

  Motivated by this fact, a new implementation of WR supporting 10G capabilities [51] has been recently presented. As can be seen in Figure 5, this technology shows comparable time and frequency distribution performance in comparison to standard 1G nodes evaluated in [31], while supporting higher bandwidths.

  The new design has been conceived to support generic communication modules in its endpoint, facilitating its integration with different commercially available developments. In parallel, it has confirmed the flexibility of the WR design to work with different internal frequencies that was explored in different 1G WR reference platforms, suggesting that it could evolve to support 25G or 40G bandwidths in the future.

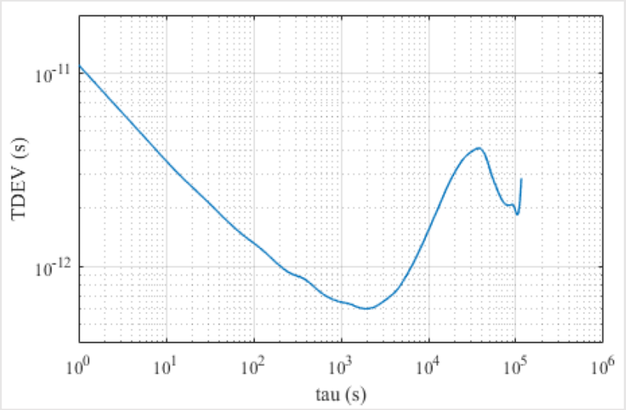

FIGURE 5. Time Deviation results for a point-to-point 10G WR link.

- Digital high accuracy time integration: Even though the majority of non-compliant WR devices use standard synchronization mechanisms, a software-defined synchronization solution which enables FPGA based devices to synchronize with sub-nanosecond accuracy over optical fiber links to WR devices was presented in [52].

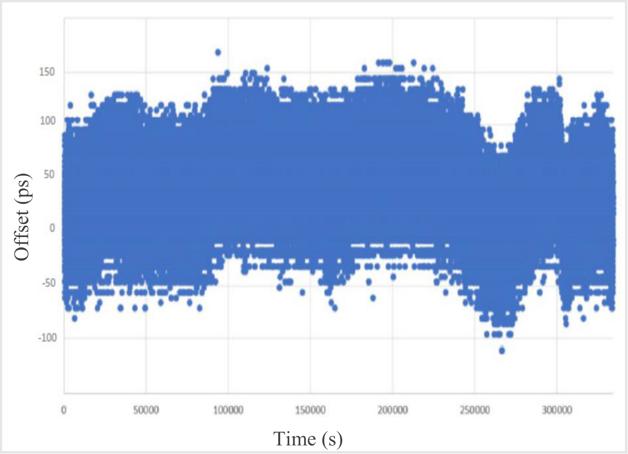

FIGURE 6. Time offset results for a point-to-point 1G link between a WR node and a HATI.

This design called High Accuracy Timing IP (HATI) is an ad-hoc solution interoperable with WR devices which allows to improve the synchronization performance to the sub-nanosecond level. This shows that some of the stated mechanisms presented in the WR section could be reused to enable FPGA based network equipment, complementing its functionality without requiring a complete substitution.

HATI supports 1G and 10G optical links with distances over 80 kms and it is capable to share the medium with data packages.

As can be seen in Figure 6 the time synchronization performance for this design exceed the sub-nanosecond accuracy, automatically compensating asymmetries caused by weather conditions and allowing to correct asymmetries in the link.

E. PRODUCT PORTFOLIO

As explained in previous points, WR has been mainly used in the industry in parallel to the production networks. For this reason, the first WR boards, designed to be plugged in production machines, were useless in these scenarios.

In order to overcome this inconvenience, several WR standalone nodes that could fulfill the industry requirements have been designed. The latest versions of them are based on Linux operating systems (OS), allowing to perform remote management and monitoring.

Some of the tools that have been supported by different devices include SNMP, Rsyslog or Wireshark packet capturing for monitoring purposes, but also integrate different Linux management tools as Internet Protocol (IP) filters or Dynamic Host Configuration Protocol (DHCP), and multiple connection interfaces, i.e. serial ports, Ethernet or mini Universal Serial Bus (USB).

Additionally, including Graphical User Interfaces (GUI), command line interfaces and physical screens in some of the devices has made WR a more user-friendly technology.

Beyond the current synchronization specifications, the WR community is working in new low jitter versions [53] that could be useful in long distance deployments or the most demanding applications in terms of time and frequency distribution. This also impacts and benefits the calibration and deployment on long distance links, simplifying the installation process.

At the moment, the WR products portfolio covers most of the current requirements. More devices are expected to be released but the solution ecosystem is growing very fast. This will help and motivate the growth and adoption of the technology beyond its original niche applications.

VI. CONCLUSION

This paper reviewed WR as the pre-standard implementation of IEEE 1588 HA network-based synchronization protocol capable to obtain sub-nanosecond accuracy levels in metro areas industrial applications.

As a reference, telecom, finance or datacenters need resilient and nanosecond-level time synchronization services as these applications are conceived as critical distributed networks. Common time or frequency references are vital to deploy new services specially in metro areas environments where the number of synchronized nodes is larger.

Thanks to the accumulated experience in the technology, several mechanisms to overcome the integration issues have been developed and presented in the previous sections.

On the technical side, the improvements in the robustness and interoperability capabilities enable this technology to work in critical heterogeneous networks. Reutilization of mechanisms included in the WR definition which enable sub-nanosecond synchronization accuracy over fiber links to help on the integration side made has been discussed. Additionally, advanced calibration techniques which allow to deploy WR networks in different fiber infrastructures with several synchronization accuracy levels have been presented. Furthermore, a network-based approach for calibration purposes in WR links has been introduced as an alternative.

On the business side, the synchronization requirements increase due to the evolution of other products, the dissemination performed by the WR community and its involvement in the release of the HA profile in the new PTP revision, added to an extended device portfolio including standard management and monitoring tools, have made WR to be considered as a fully functional technology.

In summary, a clear roadmap is presented together with hints about the technological needs and the set of features to be implemented in the next generation of devices. Altogether, it is foreseeable an increase of the adoption of WR-based synchronization mechanisms as they will be part of the IEEE 1588 standard.

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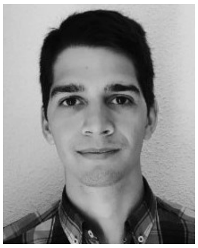

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