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Ethernet-based timing system for accelerator facilities: The IFMIF-DONES case

Carlos Megías [a,*], Víctor Vázquez [a], Eduardo Ros [a], Mauro Cappelli [b], Javier Díaz [a]

[a] *Department of Computer Engineering, Automatics and Robotics, CITIC, University of Granada, Granada, Spain*
[b] *Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Rome, Italy*

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ABSTRACT

This article presents the design of a timing system for accelerator facilities, which relies on a general networking approach based on standard Ethernet protocols that keeps all the devices synchronized to a common time reference. The case of the IFMIF-DONES infrastructure is studied in detail, providing a framework for the implementation of the timing system. The network time protocol (NTP) with software timestamping and the precision time protocol (PTP) with hardware timestamping are used to synchronize devices with sub-millisecond and sub-microsecond accuracy requirements, respectively. The design also considers the utilization of IEEE 1588 high accuracy default PTP profile (PTP-HA) to provide sub-nanosecond accuracy for the most demanding components. Three different solutions for the design of the timing system are discussed in detail. The first solution considers the deployment of one time-dedicated network for each synchronization protocol, while the second one proposes the integration of the synchronization data of NTP and PTP into the networks of the facility. The third solution relies on the single distribution of PTP-HA to all the systems. The final design aims to be fully based on standard technologies and to be cost-efficient, seeking for interoperability and scalability, and minimizing the impact on other systems in the facility. An experimental setup has been implemented to evaluate and discuss the suitability of the solutions for the timing system by studying the synchronization accuracy obtained with NTP, PTP and PTP-HA under different network conditions. It includes a timing evaluation platform that tries to resemble the network architecture foreseen in the facility. The measured results revealed that PTP is the most limiting protocol for the second solution. Using the default PTP configuration, it tolerates less than 20% of maximum bandwidth utilization for symmetric bidirectional flows, and around 30% in the case of unidirectional flows (server to client or client to server), with the current setup and using switches without enabled timing support. This case study provides a better understanding of the trade-off between bandwidth utilization, synchronization accuracy and cost in these kinds of facilities.

1. Introduction

Time synchronization is an essential part in industrial plants and scientific facilities to ensure efficient scheduling of tasks and time-consistent collection of measurements among all devices. These infrastructures are usually made up of a large number and heterogeneous types of systems, most of which need to be tightly coordinated in time and are therefore time-sensitive with different synchronization requirements depending on their individual application and criticality. To meet the synchronization needs of each system, it is necessary to regularly adjust their local clocks (synchronize) with respect to a shared time reference provided by the facility's time server. This continuous synchronization requires the repetitive transfer of data over the network [1]. The specific route followed by this information may have an impact on the synchronization quality obtained and on the features of the switching devices to be used. The evaluation of the synchronization quality is performed by obtaining direct measurements or estimations of the difference between the time reported by the synchronized system and the time at the server.

The timing system is responsible for the synchronization of all the devices. It has three main roles: time generation, time distribution and time consumption. Firstly, the time reference for the whole

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Abbreviations: IFMIF-DONES, international fusion materials irradiation facility - DEMO oriented neutron source.

* Corresponding author.

E-mail address: narg@ugr.es (C. Megías).

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infrastructure must be generated. This is typically implemented by using a global navigation satellite system (GNSS) receiver together with a high stability oscillator. The time, frequency, and phase are then distributed to all the devices in the facility. Finally, the end devices process time-based control actions (triggers) and timestamp different signals (events) which are coherently coordinated between the different actuators and sensors of the facility. Our focus in this contribution is on the time distribution.

The design of the timing system of large facilities is mainly determined by the requirements and the disposition of the systems in the plant, and the synchronization technology. The most adopted solution for the time distribution is the deployment of a time-dedicated network that distributes the synchronization data between the time server and all the systems in the facility [2]. This network can guarantee the joint coordination of the systems and the precise timestamping of the measurements obtained by the different devices, since the timing signals are not interfered by other data traffic coming from the different systems of the facility (active communication sessions between nodes). There are two main strategies regarding the utilization of the timing network depending on the nature of the signals distributed from the time server: event-based and time-based. In the former one, the time server typically sends a signal to the systems at the precise time when an action must be performed, using the timing and control network for triggering the events (control commands). The time server also distributes its clock signal to all the systems through this network, so that each system can use this time reference to perform the timestamping. On the other hand, a time-based solution ensures that the clocks of the systems are continuously synchronized to that of the time server, establishing active messaging sessions and distributing a common notion of time throughout the facility. A timing system may adopt one of these strategies or combine both.

Another important consideration for the design of the timing system is the technology to be used. The utilization of standard synchronization technologies allows the joint integration of devices from different manufacturers and facilitates the collaboration with different academia and industry partners in the design and operation of the facility. The international thermonuclear experimental reactor (ITER) experiment has adopted a general networking approach for the distribution of timing data by the utilization of the precision time protocol (PTP), defined in the IEEE 1588-2008 standard, which raises the possibility of using the timing network to aggregate the synchronization data with control and monitoring traffic [3]. Several other scientific facilities rely on standard technologies such as the European organization for nuclear research (CERN) or the GSI Helmholtz center, whose timing systems also use time-based Ethernet networking technology. Moreover, they have been working on the development of white rabbit (WR), a sub-nanosecond technology that is compatible with Ethernet and that has been adapted to be included in the latest specification of the IEEE 1588-2019 standard as a high accuracy (HA) default PTP profile [4]. Other facilities such as the European spallation source (ESS) and the Swiss free electron laser (SwissFEL) have opted for an event-based approach and the use of non-standard and time-specific hardware devices [5,6].

The international fusion materials irradiation facility - DEMO oriented neutron source (IFMIF-DONES) research infrastructure is expected to contribute to the development of fusion as a source of energy, by testing and qualifying the materials that will be used in future fusion power reactors. The facility consists of different groups of systems, which are: a) accelerator systems, b) lithium systems, c) test systems, d) central instrumentation and control systems, and e) site buildings and plant systems [7]. The central instrumentation and control systems, hereinafter referred as instrumentation and control (I&C) system, coordinates the operations of the entire facility, and it is the system to which the timing server and synchronization network belong. From the point of view of the I&C system and at a local level, the basic subsystems in the facility would be the local instrumentation and control systems (LICSs), each of which would comprise several devices interconnected by their own local network. These subsystems would be centrally controlled from the central instrumentation and control system (CICS) and grouped into larger systems. Since there are many devices involved in very different systems and applications, the timing requirements of each LICS differ from each other.

A time-based timing system built on top of Ethernet technology is proposed to efficiently handle the timing requirements of each subsystem of the facility. This solution is based on the utilization of different standard network protocols: the network time protocol (NTP) with software timestamping and the basic profile and high accuracy default PTP profile of IEEE 1588 (or PTP) with hardware timestamping. The basic profile of IEEE 1588 corresponds to PTP Version 2 and is noted from now on as just PTP. The high accuracy default PTP profile of IEEE 1588 is defined in the specification of 2019 of the standard and is noted from now on as PTP-HA. PTP-HA is not yet fully implemented by the industry but is likely to be available when the facility is deployed. NTP with software timestamping can guarantee a synchronization accuracy in the order of milliseconds or even microseconds [8]. PTP with hardware timestamping can achieve a clock offset between the time server and the end devices on the order of nanoseconds [9]. It is the hardware support that enables the generation of timestamps at the hardware level (hardware timestamping), between the media access control (MAC) and physical (PHY) layers. The major difference between software and hardware timestamping lies in the place where the timestamps are generated for the NTP or PTP packets. The basic modes of operation of NTP and PTP are very similar, both use a set of messages to measure the delay between the nodes and apply a correction to the distributed time reference so that the distributed clocks can be synchronized accurately. An overview of their network structures, message exchanges and security considerations can be found in [10]. Their main difference lies in their implementations, with the one with hardware timestamping being much more accurate than the one with software timestamping, due to reduction of the unpredictable behavior of the software components, such as interrupts. There are implementations of NTP that support hardware timestamping which can achieve comparable results to PTP under some conditions [11,12]. However, since PTP was conceived to be supported in hardware from its beginning, the number of available devices and configuration options when precise timing is required is greater. Both protocols satisfy the synchronization accuracy required in a wide range of applications in many different domains, such as high-performance computing (HPC) [13,14], or the cases summarized in [15] for testbeds for the internet of things (IoT). Finally, PTP-HA can provide an accuracy in the sub-nanosecond range by jointly using PTP, syntonization (similar to synchronous ethernet) and phase difference measurements [16]. Depending on the requirements of the devices in each subsystem, different protocols are considered more appropriate to forward the corresponding synchronization data to them.

The main performance limitation of the operation mode of PTP and NTP lies in the assumption of symmetric forward and reverse paths in the network, which may not be the case if the packets of the data flows experience a different propagation delay in each direction due to the implementation of the network or changes in its conditions. This assumption produces deviations in the calculation of the clock correction. The static (or constant) asymmetry in the network can be compensated by calibration. Packet delay variation (PDV), defined as the difference in the one-way delay between different packets of a traffic flow, is the main responsible for the dynamic degradation of the synchronization accuracy, since the delay experienced in both directions of the communications is different and changes over time [17–19]. To cope with PDV, IEEE 1588 standard provides the implementation of boundary clocks (BC) and transparent clocks (TC) when hardware support is available in middlebox devices. This allows the calculation and correction of the delays in a hop-by-hop basis, increasing the synchronization accuracy in large networks where there are many cascaded switches and routers. These time-aware options have been studied. However, they impose some restrictions on the type of devices that are useful for the design and therefore the utilization of these features has not been proposed. Therefore, when considering the utilization of PTP we have followed the end-to-end (E2E) delay measurement mechanism, solely involving the time server and the clients in the synchronization process, being the only devices with PTP hardware support in the network. Alternatively, when all the nodes in the network can perform hardware timestamping, the peer-to-peer (P2P) delay measurement mechanism can be used. In this last approach, the devices of the network keep track of the measured delays between themselves and their immediately attached devices [20]. Furthermore, it is worth mentioning that many of the different PTP profiles were analyzed as part of the previous work for the IFMIF-DONES facility. As a result, the most general and least complex (in terms of hardware) solution was chosen, which resulted in the use of the default profile.

1.1. Main outcome of the work

The major contributions of the present work are pointed out as follows:

- A solution based on the exclusive utilization of Ethernet technology for the design of the timing system of a scientific facility (composed of distributed instrumentation) is proposed. Specifically, three different design alternatives are analyzed and discussed in detail. To the best of our knowledge, this is the first time that a solution entirely based on Ethernet is used for the synchronization of all the devices of a large facility with diverse and very demanding timing requirements. With this approach, many other typical network protocols can be integrated together into a single network.
- These alternatives rely on three levels of synchronization, in which each device of the facility is provided with the synchronization accuracy that it needs to operate correctly. Thus, a combination of three protocols that can run over Ethernet has been used. The designs need to be able to handle the different levels of synchronization at any of these places: time generation, distribution from the central systems to the local systems and inside the local systems to synchronize each individual device. This is possible thanks to the interoperability provided by the underlying Ethernet technology.
- An experimental setup has been used to evaluate the different alternatives, helping in the design phase of the timing system for the facility, prior to the integration phase. The experiments carried out offer a fair comparison between the main protocols and technologies that can be employed in computer networks: NTP, PTP and recently PTP-HA. There is not any previous published work that provides this complete comparison with similar network traffic profiles (that are common in distributed instrumentation facilities) and justifies in a quantitative way the impact of the data traffic over the timing performance.

In this paper, we present a fully standards-based timing system for the IFMIF-DONES infrastructure. Three different architectures for the time distribution are discussed. The final objective of the design aims to be scalable with the number of devices and be integrated into the existing networks, with the objective of minimizing the impact on the control systems, the cost of deployment and the maintenance operations. The proposed designs and the given design considerations are intended to be useful for the implementation of the timing system in upcoming scientific facilities. A complete experimental setup has been developed that allows to separately evaluate the performance of each synchronization protocol and the feasibility of the solutions by obtaining several sets of hardware measurements and software estimations of the synchronization accuracy under different traffic (thus PDV) conditions.

2. Design

The IFMIF-DONES research infrastructure would use the I&C system for the control and monitoring of the plant. The CICS, located at the top level of the design of the I&C system, would guarantee the proper operation of the LICSs. The LICs would be responsible for the management of a group of application-related devices that acquire and process the signals. At the same time, the CICS would consist of three main systems: control data access and communication system (CODAC), machine protection system (MPS) and safety control system (SCS), which have their own communications networks [21]. These two-way networks interconnect the CICS with the LICSs and allow the exchange of data between the different systems. All the LICSs include a local controller for CODAC, MPS and SCS, according to their specifications. The CODAC network would be used for the coordination, control and monitorization of the LICSs (with all the plant signals). The traffic that traverses the MPS network would carry information regarding the interlock signals, which must be handled relatively quickly. Finally, the SCS network would be dedicated to the signaling and execution of personnel and environment safety processes. Additionally, the timing system and network are considered part of the I&C system, being the time servers located at the CODAC part of the CICS. This hierarchical implementation of the I&C system composed of a centralized CICS and distributed LICSs over the facility, is similar and analogous to that of other infrastructures such as ITER [22]. The total number of LICSs is expected to be less than fifty. A schematic representation of the I&C networks at the logical level is shown in Fig. 1.

From all the previous networks, the CODAC would be the one designed to have the highest bandwidth and based on standard Ethernet technology. Moreover, the CODAC network could be considered a soft real-time network, as it will require quality of service mechanisms and redundancy capabilities, but without strong requirements on latency compared to the MPS and SCS networks. On the other hand, MPS and SCS communications technologies are expected to be mostly based on fieldbus hardware and more specific protocols. The three local systems of each LICS: CODAC, MPS and SCS, must be synchronized to the time reference provided by the time servers.

All the LICSs of the facility have been independently analyzed in terms of timing requirements. The synchronization accuracy, defined as the absolute time difference between the time at the time server and that reported by the synchronized device, has been used to establish these requirements. Three different classes have been established to categorize the local systems of each individual LICS depending on the timing requirements of their devices, from the least demanding to the most demanding: information parameters (IP), loose time-related parameters

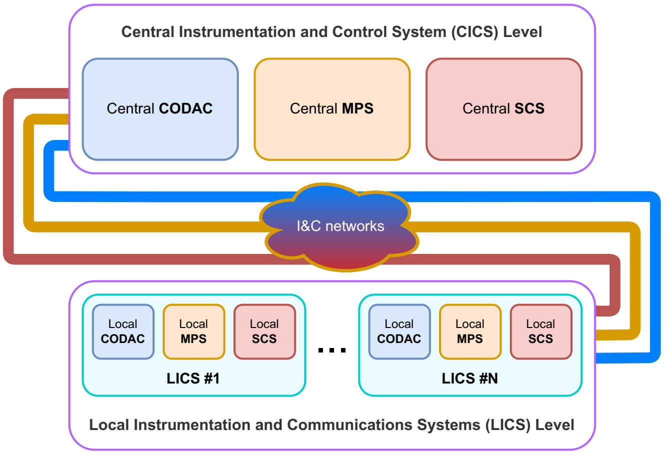


Fig. 1. Block diagram of the I&C system and networks of IFMIF-DONES: CODAC in blue, MPS in orange and SCS in red. The I&C network associated to each system interconnects the CICS with each LICS of the plant.

(LTP) and tight time-related parameters (TTP). The systems included in the IP class can perform well with a synchronization accuracy of up to 1 millisecond (ms) with respect to the time server. In the LTP class, the systems expect a maximum clock difference with the time server of about 1 microsecond (μs). The systems that belong to the TTP class need a maximum synchronization accuracy of approximately 1 nanosecond (ns). This analysis reflected that:

- The local MPS of all the LICSs have similar timing requirements, being most of them categorized in the LTP class (some of them in the IP class).
- The local SCS of all the LICSs have similar timing requirements, being most of them categorized in the IP class (some of them in the LTP class).
- The local CODAC of the LICSs have very heterogeneous timing requirements, thus, they can be included into the IP, LTP or TTP classes.
- Each local system of a LICS may belong to one or more synchronization classes.

The main challenge of the timing system is to properly (with low quality degradation) distribute the synchronization data from the time servers to the local systems of each LICS of the facility. As anticipated, a time-based general networking approach has been chosen for the design of the timing system, in which a suitable synchronization protocol has been assigned to each timing class according to their synchronization accuracy. The software implementation of the NTP protocol has been assigned to the least demanding systems, i.e., the ones included in the IP class. IEEE 1588 has been considered to obtain a synchronization accuracy in the order of a microsecond or below. Concretely, the hardware implementation of the basic profile of PTP and PTP-HA have been chosen to meet the timing requirements of LTP and TTP classes, respectively. Table I summarizes the results of the assignment by synchronization accuracy and protocol, and the order of the expected number of devices for each class in the IFMIF-DONES facility.

Three different architectures for the timing system are proposed. The final choice of one or another depends on the final design, network devices and bandwidth, and physical implementation of the network architecture of the facility. These are the main options considered, although they may be used as the starting point for some variants:

A It can be considered the most straightforward implementation of the timing system since it directly includes three time-dedicated networks for the distribution of the synchronization data, one for each protocol.
B This solution aims to minimize the impact of the timing system in the implementation of the I&C system and to be cost-effective, trying to integrate it as much as possible in the current network architecture of the facility.
C This last option guarantees that the best synchronization accuracy is delivered to each LICS, implementing a protocol gateway to satisfy the requirements of each device.

Note that similar approaches to the ones to be explained can be followed in other accelerator facilities that also have their networks, or at least part of them, based on Ethernet technology. The study of these designs has been performed mainly for the distribution of the synchronization data from the time servers to the LICSs, but the analysis presented would also be useful for the distribution inside each LICS.

Table 1
Timing requirements analysis of IFMIF-DONES.

Class	Devices	Accuracy	Protocol
IP	Thousands	≤ 1 ms	NTP
LTP	Thousands	≤ 1 μs	PTP
TTP	Hundreds	≤ 1 ns	PTP-HA

The generation of the time reference for the infrastructure is the same for all the proposed solutions. It will be explained by observing the top part (CICS level) of the diagram in Fig. 2. From top to bottom, the timing servers at the CICS level include the generation of the time reference (primary oscillator) for the whole infrastructure, which is based on an atomic clock such as a passive hydrogen maser (PHM). If required, the primary oscillator can replicate the time reference of another clock (for instance from a metrology institute) by performing the common view technique, that also requires the utilization of a GNSS receiver, a frequency stepper, and a processor for the calculations. This design guarantees long term stability, allowing the resilient operation in holdover mode in case of connection failure to the satellites or detection of jamming or spoofing on the GNSS signals. It also provides a low phase noise reference to disseminate frequency to the systems of the facility. On the bottom part of the timing servers lay the time servers for each synchronization protocol: NTP with software timestamping, PTP with hardware timestamping and PTP-HA. All of them take the time reference provided by the primary oscillator, obtaining a high quality and reliable reference to perform the calculations needed for the delay estimations and the frequency propagation. The time servers of NTP and PTP are also connected to the gateways of CODAC to reach the MPS and SCS systems.

2.1. Timing system based on time-dedicated networks: solution A

Typically, a time-dedicated network architecture is designed as physically independent from the rest of the communications, so that other traffic data do not interfere with the timing data. This design involves the deployment of a whole dedicated network architecture, with its switches, network cards and cable links. Moreover, it usually uses specialized hardware devices for timing, which increases the cost of the solution. The initial representation of the timing system at the logical level is represented in Fig. 2. This network diagram has been drawn on top of the CODAC system, in which the gateways subsystem at the CICS level provides connections to the MPS and SCS systems, and the server subsystem includes databases and the execution of run-time applications

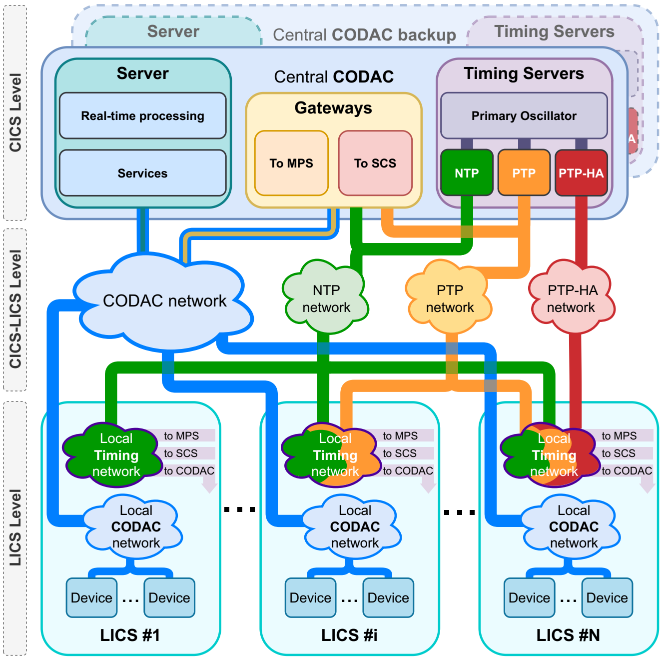


Fig. 2. Block diagram of a timing system that uses one time-dedicated network per synchronization protocol in the CODAC system of the I&C system at CICS, network and LICS levels. NTP is represented in green, PTP in orange and PTP-HA in red.

and other services. The CODAC system and network have been chosen to illustrate the timing system for the facility and the distribution of the synchronization data, since it is the most complete and complex one (more timing classes), compared to the MPS and SCS systems; and it is the system to which the timing servers belong. The MPS and SCS central and local systems have been omitted from the representations to ease the visualization of the timing system.

A common consideration for the three solutions of the timing system proposed is that once the synchronization data is received at the CODAC system of the LICS, there are two possibilities to distribute them to the MPS or SCS: a) it can be forwarded to the devices connected to the local MPS and SCS systems to optimize resources, b) alternative data paths that traverse the MPS and SCS systems at the CICS and CICS-LICS (network) levels can be used.

These are the main considerations for the distribution of the synchronization data of the implementation depicted in Fig. 2:

- CICS-LICS level: The three time servers have their own independent time-dedicated network to distribute their synchronization data. Specialized timing hardware is used to setup the PTP and PTP-HA networks. This implies a higher cost per device and reduces the options available from the manufacturers.
- LICS level: Each LICS has their own local timing network, which receives the synchronization data from the NTP, PTP and PTP-HA networks. Depending on the synchronization data demanded by the devices in each LICS, the local timing networks are connected to one, two or all these networks. The local timing network distributes the synchronization data to the devices connected to CODAC.

2.2. *Timing system integrated in CODAC network: solution B*

To reduce the complexity of the overall network architecture that yields the previous solution, the maintenance operations on the different communications links and the cost associated with the deployment of three different time-dedicated networks, a solution is proposed that seeks to mostly integrate the timing system in the already existing networks whenever it is possible.

Considering the three-network topology of the I&C system, it was concluded that the CODAC network is the one that best suites the conditions, in terms of technology, bandwidth and compatibility, to accommodate part of the traffic of the timing system. Because the proposed timing solution is based on standard packet-switched networks, the control and command network of CODAC can be used for synchronization. With a time-specific solution for the time distribution, this integration would not be possible.

The proposed solution for the timing system has been drawn starting from the network diagram of Fig. 2, leading to the representation of Fig. 3. This solution relies on a hybrid architecture for the distribution of the synchronization data. The objective of this solution is to distribute the synchronization data to each subsystem in the facility according to their timing requirements, using the CODAC network as the main forwarding vehicle and keeping the size of the high precision time-dedicated network as small as possible. These are the main considerations for the distribution of the synchronization data of the implementation depicted in Fig. 3:

- CICS-LICS level: On the one hand, the synchronization data of NTP and PTP are incorporated to the CODAC network without any change in the features and number of network devices. The time servers periodically distribute the synchronization data of NTP and PTP as any other traffic in the network. The bandwidth required for their distribution highly depends on the number of clients of their synchronization data, since the timing messages are exchanged between the time server and each individual device. On the other hand, a small time-dedicated network is deployed for the distribution of the PTP-HA traffic. This network only interconnects the time server with those LICSs demanding the highest synchronization precision and frequency dissemination. Specialized timing hardware is needed to correctly setup this time-dedicated network.
- LICS level: Each LICS integrates the traffic of NTP and PTP with their local CODAC network. Only those LICSs requiring PTP-HA synchronization for some devices have a small local timing network connected to the PTP-HA network. Depending on the synchronization data demanded by the devices at each LICS, the local CODAC and timing network takes the data of just NTP, or NTP and PTP, in addition to the CODAC data. This network distributes the synchronization data to the devices connected to CODAC.

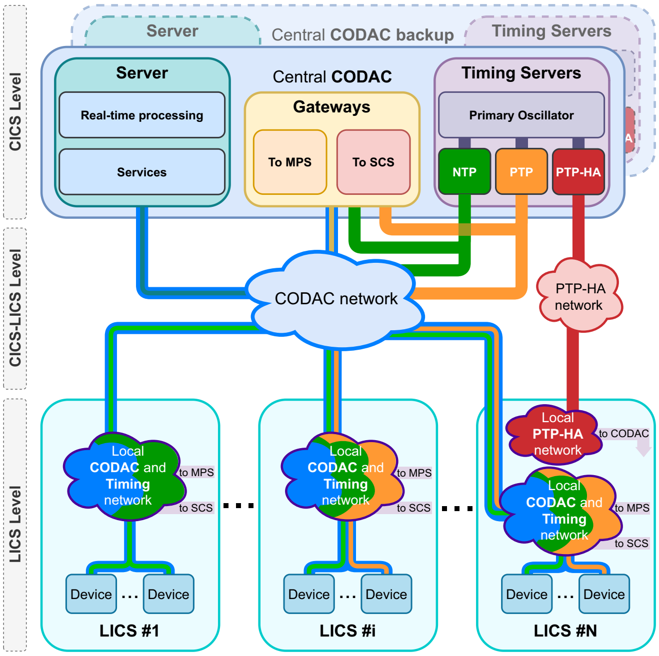


Fig. 3. Block diagram of a timing system that integrates into the existing network of the CODAC system of the I&C system at CICS, network and LICS levels. NTP is represented in green, PTP in orange and PTP-HA in red.

Some problems may appear in the distribution of NTP and PTP synchronization data in this design. The first one is due to the great number of active sessions that the NTP and PTP time servers establish with each individual device of each LICS of the facility. These traffic flows may require a high bandwidth of the total available in the CODAC network, which in the end can degrade the overall synchronization accuracy or even block other operations of the CODAC system. To solve this problem, a local boundary clock device must be included for those LICSs that require a high bandwidth utilization of the CODAC network for the synchronization of their devices. These time boundary devices are synchronized to their corresponding time server with the objective of reducing the communications domain of the synchronization data, limiting the messaging exchange to the local CODAC network of the LICS. For those LICSs including a time boundary device, the corresponding time server only keeps one single synchronization session, greatly reducing the traffic of the CODAC network. This solution also reduces the maximum number of PTP or NTP flows that the time servers must support. The boundary clock devices are called BC in PTP and stratum 2 time servers in NTP.

The second problem that may appear mainly concerns the hardware implementation of PTP. Since no changes have been performed to the initial CODAC network, its switches are not expected to have time-aware capabilities nor hardware timestamping that make the calculations to correct for the time spent in it (when acting as TC) or to be synchronized (when acting as BC). This fact may have a huge impact in the PTP synchronization performance if the PDV becomes large, since the dynamic asymmetry between the forward and reverse path may become larger. This PDV is not static because the traffic and other network conditions vary over time, so it cannot be calibrated. NTP with software timestamping would also be influenced by this delay variation, but since it is already based on software estimations the degradation is expected to be relatively much lower than for PTP with hardware support. Two solutions may be adopted to address this problem in PTP. The first one is to directly replace the standard Ethernet switches of the CODAC network with ones which are PTP-aware and support hardware timestamping. These switches can be configured to minimize the impact of PDV by making accurate corrections to the time that is being distributed from the time server to the devices. This solution is not generally available for NTP distribution since NTP standard does not consider the correction of the time distributed using the calculations of delay in each node. The second solution relies on an additional advantage of having the PTP-HA network, which can relax the capabilities required in the switches used in the CODAC network. For those LICSs requiring PTP accuracy for which the degradation of the PTP data distributed over the CODAC network is very high, a direct connection to the high-accuracy time-dedicated network can be deployed to obtain cleaner and more accurate timing signals.

As stated, this solution relies on the capability of NTP with software timestamping and PTP with hardware support to handle the traffic of the network and the number of switches between the central system to the local subsystems. A simple way to add redundancy features to this solution is to establish a link connection between the CODAC and PTP-HA networks. This provides an alternative path to the LICSs to be synchronized if there is a large degradation of NTP or PTP data, or a link or server failure.

2.3. Timing system based on high accuracy network: solution C

Another solution for the design of the timing system consists in the distribution of the maximum synchronization accuracy to all the subsystems of the I&C system. The representation of this solution is shown in Fig. 4. This implementation aims to solve the problem of the degradation of the synchronization data coming from the NTP and PTP servers of the previous solution. These are the main considerations for the distribution of the synchronization data of this implementation:

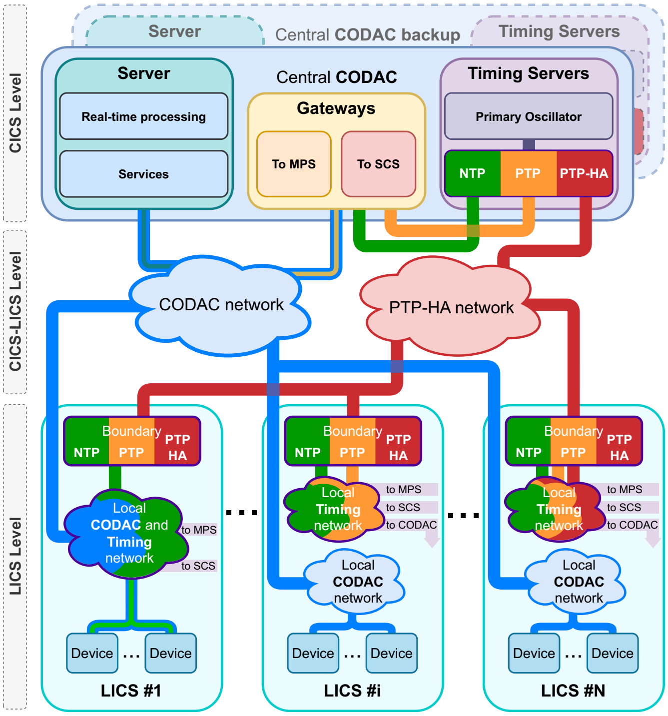


Fig. 4. Block diagram of a timing system based on PTP-HA (red) in the CODAC system of the I&C system at CICS, network and LICS levels. Protocol gateways are needed at subsystem level for NTP (green) and PTP (orange) compliance.

- CICS-LICS level: A time-dedicated network based on PTP-HA is used to synchronize all the LICSs to the time server. This network architecture guarantees sub-nanosecond synchronization accuracy for all the LICSs of the facility. However, it implies the development of a larger independent network and the utilization of more specific hardware devices for the intermediate nodes compared to the solution presented in Fig. 3, which in the end increases the cost of the solution.
- LICS level: Each LICS includes a boundary device that receives the information of the PTP-HA network. This device can provide the synchronization data of NTP, PTP and PTP-HA to match the time requirements of each device of the LICS. Each LICS manages the timing data depending on its necessities. They can mix the data coming from the boundary device with the CODAC data (as solution B) or they can opt for a separated local timing network (as solution A).

The physical separation of the CODAC and the timing data in two different networks overcomes the problem of PDV. Moreover, there is a simplification in the distribution of the synchronization data, as it uses only one protocol instead of three and each LICS receives similar data. However, the deployment of a large time-dedicated network that reaches all the LICSs implies a moderate cost.

An additional benefit of this solution is that it provides the possibility to monitor the synchronization quality of the devices of a LICS that use NTP and PTP, even though the LICS does not require PTP-HA for typical synchronization purposes.

2.4. Discussion

The proposed solutions for the timing system have been analyzed in terms of cost and network complexity, scalability, and accuracy. Table II shows a qualitative comparison of the three solutions.

Scalability has been considered as the capability to synchronize a large number of clients. In that sense, since the timing system proposed in **A** uses dedicated networks, it has no restrictions coming from other components or networks. This makes it possible to add as many clients or boundary devices as needed to increase the number of clients that this solution can serve (reduce synchronization domain and regeneration of the timing signals). The same applies to solution **C**. On the contrary, solution **B** relies on a shared network for the distribution of the timing signals, thus, it directly depends on what is available in the network. This shared network may restrict the number of boundary devices that can be added to it. The inclusion of additional time servers can partially solve this problem. Another concern is that, as the number of devices demanding NTP or PTP accuracy increases, the traffic traversing the CODAC network may become very large, degrading its performance.

When measuring accuracy, the number of hops between the clients and the devices to which they are immediately synchronized has been taken into account. Similar to the analysis performed for the scalability, the fact that solutions **A** and **C** use dedicated networks provides the possibility of reducing the number of hops to one by adding boundary

Table 2
Qualitative comparison of the solutions for the timing system.

Solution	Cost and complexity	Scalability	Accuracy
A	High	High	High
B	Low	Medium	Medium
C	Medium	High	High

devices. Since solution **B** may present some limitations to add many boundary devices, it is possible that the number of hops may increase. Moreover, the timing signals may suffer degradation in the presence of large CODAC traffic.

Finally, the cost and complexity has been evaluated in terms of the number of time-specific devices that are needed to set up the different topologies at each level: CICS, CICS-LICS and LICS. Solution **A** requires three time servers at the CICS and another three servers for redundancy, making it six servers. At the LICS level, those LICS demanding PTP synchronization need one boundary device. The same applies to PTP-HA at the LICS level. For NTP, the time server would be able to handle many clients, so the number of NTP-specific devices at the LICS will not directly scale with the number of LICS. In addition to these devices, the dedicated networks at the CICS-LICS level (as well as the possible local timing networks) must also be considered for the cost estimation. The analysis for solution **B** is similar to that of solution **A**, with the exception of the time-dedicated networks. This design, based on network sharing, can save much of the total cost of the timing system. On the other hand, solution **C**, only needs one time server plus another one for redundancy at the CICS level, and one boundary device per LICS at the LICS level since it can serve the synchronization for the three protocols. However, the need for a PTP-HA dedicated network at the CICS-LICS level (larger than the one needed by solution **B**), would likely increase the cost with respect to solution **B**.

From this analysis we concluded that the most attractive solution in terms of cost and complexity is the timing system **B**. However, the synchronization accuracy that it can provide to the LICSs must be evaluated under different network conditions. This will be examined in the next section. The experiments performed are used to study the feasibility of the solution and give some insights into the overall performance and problems that it may encounter.

Intermediate solutions between the three solutions discussed can also be considered. The synchronization data required for NTP with software timestamping is not expected to be highly degraded in conditions of large amount of network traffic, since the delays needed for the calculation of the clock offset are already not very accurate because they are obtained by software. Because of that, the NTP data may always be suitable to be distributed using the CODAC network, according to the time requirements of the subsystems included in the IP class. This approach may prevent the deployment of the NTP network in the solution **A**, simplifying the network architecture and saving costs. In the case of the timing system **C**, it results in a combination of the solutions schematized in Fig. 3 and Fig. 4, where the time-dedicated network is used for the LICSs demanding PTP and PTP-HA, and the NTP shares the network with the data of the CODAC system. The number of devices at the CICS-LICS network level, boundary devices at the LICSs and features of the time-dedicated network, in terms of switching capabilities and number of ports, may be reduced with this solution. The resulting designs of the timing system may be more affordable than the solutions depicted in Fig. 2 or Fig. 4.

3. Evaluation

For the design of the timing system of a critical infrastructure like IFMIF-DONES, it is essential to know how the different components that are involved in the distribution of the timing signals interact. To this end, an experimental setup has been designed to study the performance of the different synchronization protocols under different network conditions. Several network parameters, which may have an impact on the synchronization accuracy, can be modified with this setup. It has been mainly used to evaluate the feasibility of the proposal for the timing system of IFMIF-DONES depicted in Fig. 3 (solution **B** of the timing system). Moreover, the experiments carried out demonstrate that the NTP and PTP-HA time-dedicated networks (considered in solutions **A** and **C**) can provide the expected synchronization accuracy in the presence of large amounts of traffic. The results obtained in this section also allow us to quantitatively compare the different solutions for the timing system presented.

The three Ethernet-based protocols have been tested independently, while trying to use the same network devices between experiments when possible. The synchronization data of NTP with software timestamping and PTP with hardware timestamping are distributed without employing devices with enabled time-aware features and considering similar conditions as the ones that are going to be present in the final architecture of the CODAC network. On the other hand, for the time-dedicated network of PTP-HA profile, specific time-aware hardware that implements the WR technology, which is considered its pre-standard [16], has been considered for the experiments. The objective of the experiments carried out is to study how PDV, generated by setting different values of bandwidth utilization on the network, impacts the synchronization accuracy. The influence of the data traffic on the PDV is studied under different network configurations in [23] and on the synchronization accuracy in [24], showing more degradation and larger delay variation as the load in the network increases. However, these works do not look for the maximum bandwidth utilization that the network may support for a specific timing requirement. Moreover, most of the available literature focuses on PTP, leaving NTP and PTP-HA (or WR) technology aside.

There are many network parameters that may influence the synchronization accuracy achieved at the LICSs and at the final devices. The parameters that have been identified to influence more the synchronization performance are the following: bandwidth utilization of the links, number of hops between the time server and its clients, total number of traffic flows and clients, ratio of traffic in each direction of the communications, and the networking capabilities and performance of the different nodes. These parameters may directly influence the latency and the jitter in the communications, producing PDV, which in the end generates network asymmetry that varies over time. All the parameters mentioned should be considered and evaluated for the final design once the network architecture is fully defined at the physical topology level.

Concretely, in our experiments we aim to determine the maximum bandwidth utilization that guarantees the timing requirements for each subsystem class and protocol (see Table I). The remaining network parameters that may also impact the performance of the timing solution have been fixed. Note that the experimental setup described in this section enables the study of many different timing solutions based on Ethernet protocols without major modifications in its design.

3.1. Experimental setup: design and methods

The experimental setup resembles a local network made up of commercial devices. The complete overview of the proposed topology for the evaluation of the different synchronization protocols is depicted in Fig. 5.

Since the CODAC network is expected to follow a tree topology, a three-hop switched network with a time server (*server*: Raspberry Pi 4 for NTP and WR Z16 from Orolia for PTP) at one end and its corresponding client (*client*: Raspberry Pi 4 for NTP and syn1588 PCIe NIC from Oregano Systems for PTP) at the other end has been chosen to try to fairly represent it. For NTP and PTP, the switches employed either do not have time-aware options or do not have them enabled, acting as standard Ethernet devices. The three switches lay on the managed category (*sw01*: μFalcon-MX/G from FibroLAN, *sw02*: Catalyst 9300-24T from Cisco, *sw03*: Falcon-MX/G from FibroLAN). Additional Ethernet-compliant devices have been included at both ends of the network to establish traffic flows that traverse the whole network (*ndXY*: Raspberry Pi 4*)*. The connection between the switches is performed by a single link between each other, so that all the traffic originated by a device at one end of the network with destination to a device at the other end, shares the same link bandwidth. Three traffic flows with different source and destination network nodes have been established in the current setup, using the *iperf3* tool [25], to simulate the traffic of the CODAC network

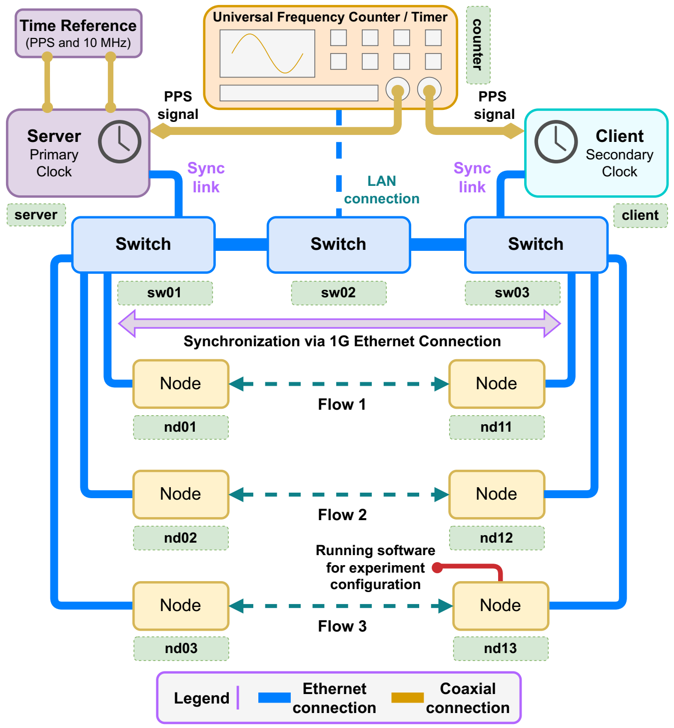


Fig. 5. Experimental setup for evaluation of synchronization quality of the three Ethernet-based time protocols: NTP, PTP and PTP-HA (or WR).

regarding control and monitoring signaling of the communications between the CICS and the LICSs. The traffic flows can be configured as bidirectional, so that the traffic in each direction is almost the same in each experiment; or unidirectional, so that the traffic mainly follows one direction (from client to server or from server to client). Unidirectional flows are representative when the traffic in each direction of the communications is not balanced. The synchronization data originated at the server go through all the switches before arriving to the client, and the data generated by the client follow the reverse route, sharing the link with the traffic flows.

A similar experimental setup has been used to evaluate the synchronization accuracy of a high precision time-dedicated network based on PTP-HA. The main difference with respect to the described one is that the intermediate switches have been replaced by specialized hardware compliant with WR technology and with time-aware options enabled (*sw0Y* are all WR Switch from Orolia, *server*: WR Z16 from Orolia, *client*: WR LEN from Orolia).

On the measurement side, a universal frequency counter (*counter*) device has been connected to the time server (*server*) and to the client (*client*) by means of coaxial cables that transmit the analog pulse per second (PPS) signals, allowing the evaluation of the synchronization quality of PTP and PTP-HA. The PPS signal is a squared or sinusoidal signal that is periodically generated by a clock to indicate the passing of a second. The counter device has been configured to take the PPS differences, which corresponds to a time interval measurement starting at the rising edge of the PPS signal of the clock of the time server and finishing at the rising edge of that of the client. This phase error of the PPS signals is commonly known as time error (TE). These measurements give very confident estimations of the deviation of the client clock over time. This device has also been connected to the network, so that it can be remotely controlled from any node or from an external connection. In the case of NTP, the synchronization quality has been estimated using software-based offsets, which are looked up each second, imitating a PPS differences measurement.

A software tool has been developed to automatize the measurements, the configuration of the devices and the setup of the traffic flows, according to the experiment to be performed. This tool is based on a centralized implementation running on one node that establishes secure shell (SSH) sessions with the devices and measuring instruments that make up the network. Its objective is to improve the scalability of the experiments and reduce the manual interaction with the experimental setup.

The current setup allows the incorporation of more intermediate switches between the time server and the client, as well as more devices to generate additional traffic. Moreover, other routes for the data could have been configured, such as redundant paths to increase resiliency of the synchronization data or additional traffic flows that only traverse a portion of the network. The current maximum bandwidth of the link is 1 Gb/s, but the results obtained can give good insight into how the synchronization accuracy behaves with faster networks, such as 10 Gb/s bandwidth.

3.2. Results

All the synchronization protocols have been independently evaluated using their corresponding network configuration and measurement method. As stated before, the synchronization accuracy has been analyzed for different bandwidth utilizations of the link. Note that with the current setup, the *iperf3* tool was not able to reach the theoretical maximum bandwidth of 1024 Mb/s, saturating at about 90%. In the case of bidirectional traffic, for bandwidth utilizations above 90% the traffic in each direction of the flows was not fully symmetrical. This relation between the desired bandwidth utilization and the total obtained (accumulation of the three traffic flows) is shown in Fig. 6.

The absolute value of the TE is used to analyze the synchronization quality of each protocol, which here is referred as the synchronization accuracy. An overview of the main results obtained for the three protocols is represented in Fig. 9, where the maximum time interval error (MTIE) [26] has been obtained for a bidirectional bandwidth utilization of 18% of the maximum link bandwidth. The time deviation (TDEV) is also shown in Fig. 9 for completeness. Both statistical measures are used to analyze the stability of a time distribution network and give an insight into the stability of the synchronization accuracy over time [27]. For all the results shown in this section, the case with no traffic on the network of each protocol has been taken as baseline, so that all the measurements obtained of each bandwidth utilization within each protocol are referred

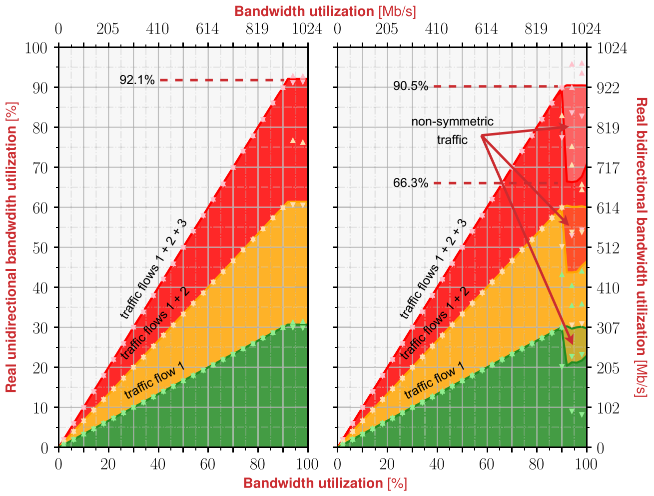


Fig. 6. Relation between the desired and the obtained mean bandwidth utilization (the output of the iperf3 tool have been used) using the three different traffic flows (green, orange and red) of Fig. 5 for about 1 hour. The left part represents the case of unidirectional flows and the right part the case of bidirectional flows. Markers indicate maximum and minimum values (averaged over 1 second intervals) obtained for each bandwidth utilization and flow.

to its baseline (similar to calibration). The experiment configuration and analysis of the results for each protocol are explained below.

3.2.1. Network time protocol (NTP)

The *chrony* open-source implementation of NTP [12] has been employed to study the synchronization accuracy for clients with loose time requirements. This implementation allows to setup the NTP server and its corresponding client by means of configuration files in computers with standard network interfaces.

The influence of the amount of bidirectional traffic traversing the network on the synchronization accuracy is drawn in Fig. 7. The three traffic flows represented on the bottom part of Fig. 5 have been established to set the bandwidth utilization. For the evaluation of NTP, bidirectional flows have been used instead of unidirectional flows for representation, because they place greater demand on the intermediate switches, thus representing the worst-case scenario for the synchronization data. It can be observed how the variability of the maximum values obtained increases when the bandwidth utilization is larger than 16% (163.84 Mb/s out of 1024 Mb/s). Part of the large variability obtained for similar amounts of bandwidth utilization may be attributed to the unpredictable behavior of the software-based timestamping used by the protocol. This fact makes it difficult to strictly correlate the influence of the bandwidth utilization with the PDV, and with the synchronization accuracy. In NTP with software timestamping, the processor workload will probably influence more the synchronization than the network traffic itself. On the other hand, these results ensure that the synchronization accuracy remains below 56 μs with a worst-case mean of about 4.2 μs (whatever the level of bandwidth utilization), thus fulfilling by far the desired timing requirement of 1 ms for this protocol.

3.2.2. Precision time protocol (PTP)

The PTP basic profile has been evaluated by setting the time server and its corresponding client using network devices with hardware timestamping support. A proprietary implementation of the protocol has been used on the client side and the *PTPd* [28] open-source implementation was running on the time server. The default protocol settings provided by the device manufacturers have been used, so the results obtained are subject to them. The rate of the *sync* and the *delay request* messages was fixed to one packet per second, and the operation mode was two-step. The optimization of these parameters (among others), the usage of additional hardware components or the consideration of delay filtering techniques may improve the results obtained.

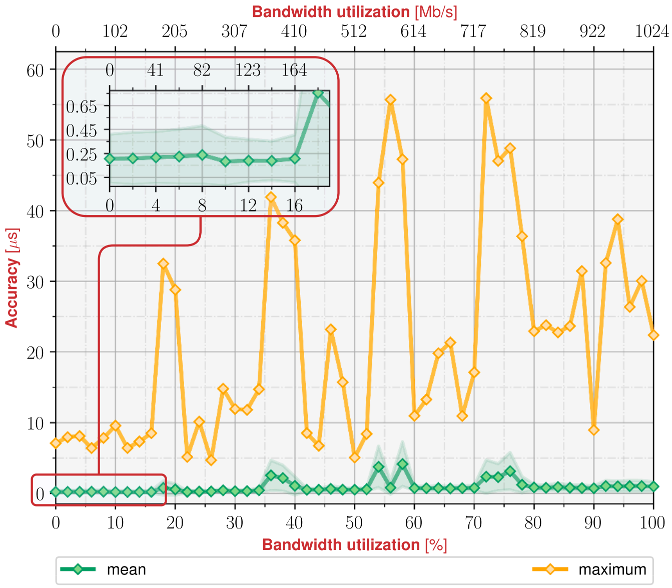
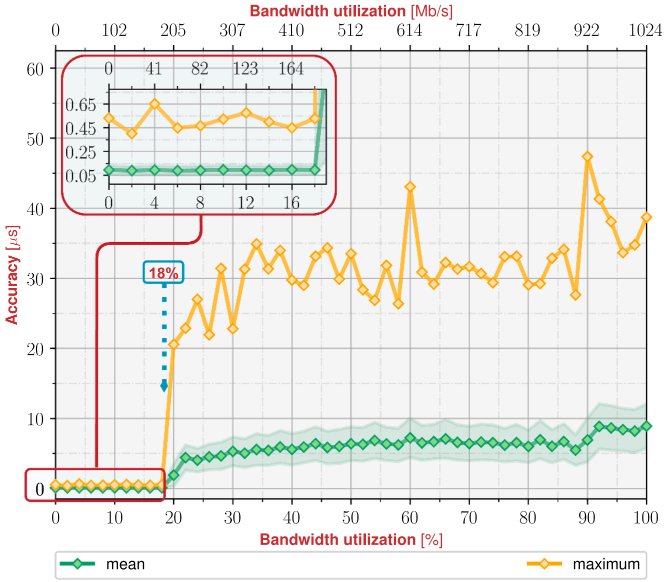
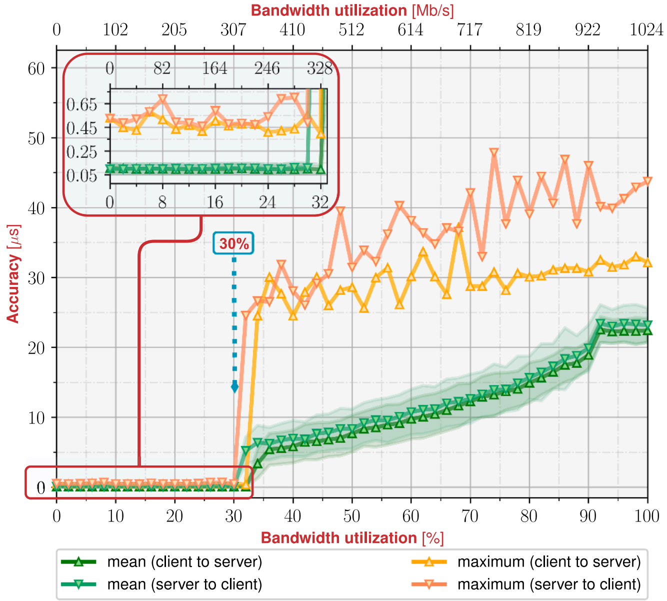


Fig. 7. Analysis of synchronization accuracy of NTP for different bidirectional bandwidth utilizations (increasing in steps of 2%). One hour of measurements (3600 samples) have been obtained for each value of bandwidth utilization. For completeness, the standard deviation has been drawn in shadowed green around the mean. A zoom is shown on the lower bound of the bandwidth utilization.

The synchronization accuracy of PTP has been studied separately for bidirectional (Fig. 8(a)) and unidirectional (Fig. 8(b)) traffic flows. In this case, the relationship between the synchronization accuracy and the bandwidth utilization becomes clearer than in the case of NTP, since the PDV of the network is the main factor influencing the instant in which to perform the timestamping of the packets. The asymmetry between the forward and reverse propagation delays produced by the traffic load is



(a) Bidirectional bandwidth utilization.



(b) Unidirectional bandwidth utilizations.

Fig. 8. Analysis of synchronization accuracy of PTP for different bandwidth utilizations (increasing in steps of 2%). One hour of measurements (3600 samples) have been obtained for each value of bandwidth utilization. The cyan dashed markers indicate the maximum bandwidth utilizations to ensure the synchronization accuracy of 1μs. For completeness, the standard deviation has been drawn in shadowed green around the mean. A zoom is shown on the lower bound of the bandwidth utilization.

the main responsible for the degradation of the accuracy. The results obtained with symmetrical bidirectional traffic show how the synchronization performance of PTP starts to degrade rapidly (becoming the maximum worse than 1 μs) when the bandwidth utilization is higher than 18% (184.32 Mb/s out of 1024 Mb/s).

As shown in Fig. 8(b), when unidirectional flows are used, the maximum bandwidth utilization before the degradation of the synchronization accuracy is increased from 18% to 30% (307.2 Mb/s out of 1024 Mb/s), when the traffic data is established from the server to the client; and to 32% (327.68 Mb/s out of 1024 Mb/s), when the traffic data is established from the client to the server. This difference between the bidirectional and unidirectional traffic profiles implies that the maximum bandwidth utilization tolerated by PTP fulfilling 1 μs of synchronization accuracy depends on the nature of the traffic of the network.

These results reflect the impact of the PDV in the offset calculations of PTP. Since no time-aware options are used in the intermediate switches of the network, no delay compensation is performed for the asymmetry between the reception and transmission directions. These asymmetries are mainly due to the difference in the residence times in the intermediate switches of the network generated by the traffic in the network. For large amounts of traffic, the variability of the queueing and switching times increases, leading to a worse synchronization accuracy and more unpredictable offset.

The main reason why PTP degrades with a lower bandwidth utilization in the case of bidirectional flows is the overload of the intermediate switches, which have to handle the double of data than for the cases of unidirectional flows. However, as it can be observed, the values of the mean curve of Fig. 8(a) are in the range from 4.4 μs to 7.22 μs for a bandwidth utilization between 22% and 90% (the trend of the maximum curve also seems to be stabilized). In the case of unidirectional flows, the mean curves of Fig. 8(b) always increase from 30–32% until reaching the 92% of bandwidth utilization (the maximum curves also seem to tend to increase slightly). This phenomenon may probably be due to the partial compensation of delay asymmetry between the forward and reverse paths when there is (almost) symmetric bidirectional traffic in the network. The values of the mean for the bidirectional case from 92% to 100% of bandwidth are probably higher due to the traffic asymmetry shown in the right part of Fig. 6. The mean curves of both cases also remain fairly constant over this same range (saturation).

The MTIE and TDEV of the synchronization accuracy of PTP and NTP have been studied under the network condition of a bidirectional bandwidth utilization of 18%, since it represents the limit of the worst-case tolerable by PTP that meets the requirement of a maximum synchronization accuracy of 1 μs. The results obtained for the MTIE and TDEV are shown in Fig. 9. For each protocol, 3 hours and half of measurements have been obtained.

The MTIE curve of PTP starts with relative low values but increases rapidly for short measurement periods. The curve starts to stabilize at around 2 minutes of integration time. In the case of NTP, the MTIE curve starts with a large value and stabilizes at about half an hour of measurement period. The maximum peak to peak deviation obtained for PTP is 1059 ns, and 60308 ns for NTP. The fact that the last part of the curves is almost flat makes the measurement time significant to characterize the synchronization accuracy over time. With these results, the desired performance of PTP with hardware support and NTP with software timestamping is guaranteed if we constraint the bandwidth utilization to 18% of 1 Gb/s (maximum bandwidth of the link).

3.2.3. High accuracy default PTP profile (PTP-HA)

To characterize PTP-HA, a proprietary implementation and specialized hardware (for the intermediate switches and end devices) compliant with WR technology (since it can be considered its pre-standard) have been used. This protocol requires the transmission of PTP basic profile and frequency dissemination of the hardware clocks of the devices.

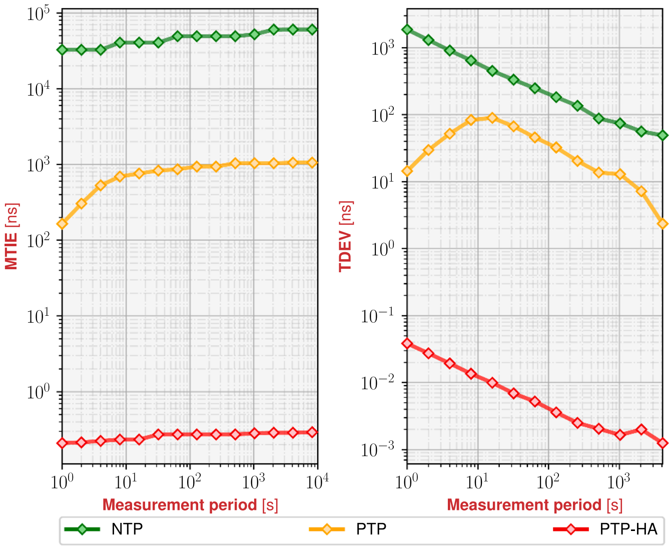


Fig. 9. MTIE and TDEV curves for the evaluation of the synchronization accuracy of the three protools for a symmetrical bidirectional bandwidth utilization of 18% (maximum bandwidth tolerated by PTP fulfilling 1 μs of accuracy). 3 hours and a half of measurements (about 12600 samples) have been obtained for each curve.

It was observed that the synchronization accuracy was always kept below the nanosecond, regardless the bandwidth utilization of the link. This synchronization quality obtained is mainly due to the calibration, delay compensation, frequency syntonization and clock phase difference measurements, that these devices perform and that make them resilient to PDV.

For completeness, the results obtained for PTP-HA using different bidirectional bandwidth utilizations have been included in Fig. 10. Note that the units on the y-axis are in picoseconds (ps). These curves demonstrate that the synchronization accuracy obtained with this protocol is not degraded in the presence of additional traffic.

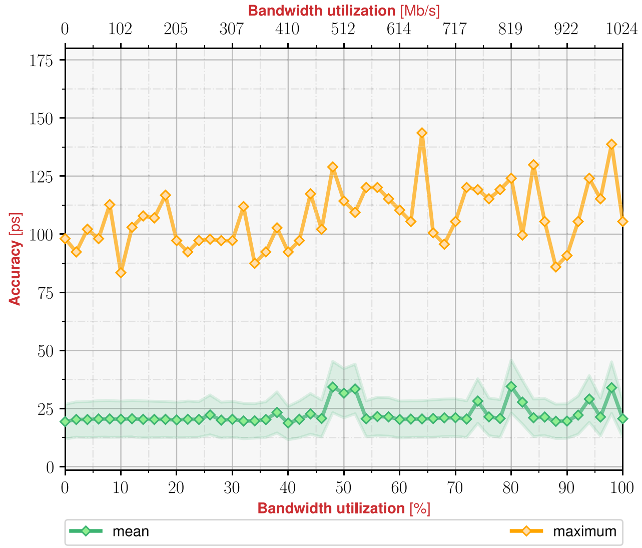


Fig. 10. Analysis of synchronization accuracy of PTP-HA for different bidirectional bandwidth utilizations (increasing in steps of 2%). One hour of measurements (3600 samples) have been obtained for each value of bandwidth utilization. For completeness, the standard deviation has been drawn in shadowed green around the mean.

PTP-HA has also been evaluated for the 18% of bidirectional bandwidth utilization, since even if it will have a time-dedicated network, some configuration data is usually exchanged between nodes. The MTIE curve of the PTP-HA profile in Fig. 9 starts in 210 ps and ends up below 293 ps. Finally, the TDEV curve shows the best stability compared to NTP and PTP. These curves reflect the great synchronization performance that can be obtained when distributing PTP-HA (or WR).

3.3. Interpretation and considerations

As it has been observed, the synchronization accuracy of PTP is highly dependent on the traffic traversing the network because of the time-changing asymmetry produced between the reverse and forward directions. The main point of interest corresponds to the value of bandwidth utilization at which the maximum curve of the synchronization accuracy becomes worse than 1 μs. On the other hand, although the variability of NTP with software timestamping increases for large bandwidth utilizations (compared to the lower bound), the software nature of its implementation partially masks the effect of the network conditions (it makes accuracy dependent on the workload of the processor). The final case of the PTP-HA profile is more special, since all the devices used for its network were able to account for the PDV and the asymmetry of the network.

The experiments reflected that PTP is the most limiting synchronization protocol according to the fixed 1 μs accuracy requirement when used in a network made up of non-time-aware devices (or disabled options) and with variable traffic conditions. Because of that, for the integration of the timing system in CODAC (solution **B**), the maximum bandwidth utilization of this network will be fixed by the maximum value tolerated by PTP (NTP was able to always meet the requirement of 1 ms synchronization accuracy). It must be noted that in accelerator facilities such as the current case, the network traffic in the client to server (LICS to CICS) direction is expected to be higher than in the reverse path (monitoring data). Because of that, although the focus has been set on bidirectional traffic (as it is considered the worst-case scenario that led to a maximum bandwidth utilization of 18% for PTP), the requirement imposed for the maximum bandwidth utilization of the CODAC network can be placed somewhere between 18% to 32% with relative confidence. The additional amount of traffic that is incorporated to the network due to the NTP and PTP synchronization sessions of the devices should also be taken into account for the final design. Different configurations of the NTP or PTP implementations can be applied to the time servers and clients to fine-tune their performance (e.g., to control the messaging rate).

Another important consideration is the final hardware that will make up the CODAC network, especially the intermediate switches. The utilization of basic switches with low computation and switching capabilities may reduce the maximum bandwidth utilization of the network allowed by PTP. A simple experiment was carried out to evaluate this dependency on the hardware by replacing one of the switches of the setup in Fig. 5 by an unmanaged one (*sw01*: DGS-1005D from D-Link). It was observed a reduction from 18% to 13% in the case of symmetric bidirectional traffic and a large difference between the curves with asymmetric traffic (compared to the ones shown in Fig. 8(b)). The selection of high-performance switches for the network, in terms of communications bandwidth (e.g., 10 Gb/s) and computation, or the oversizing of the network, may probably increase the maximum bandwidth utilization supported by PTP. Moreover, since time-aware options in the switches are nowadays more common, using them would make the PTP data more resilient to the influence of the PDV observed in the experiments. However, their utilization would limit the solution to more specific hardware devices and incur in higher costs.

4. Conclusion

In this paper, three different solutions for the design of the timing system for accelerator facilities have been presented and evaluated using the network architecture of IFMIF-DONES. All of them are based on standard Ethernet synchronization protocols. The most attractive solution in terms of cost and complexity is the one that relies on the distribution of NTP and PTP synchronization data over the networks of the facility, and on the deployment of a small high accuracy network. The experimental results show that PTP constraints the maximum bandwidth utilization of the (non-time-aware) network for a specified synchronization accuracy (1 μs in this case) between the time server and the clients. On the other hand, NTP and PTP-HA always meet their respective (1 ms and 1 ns) requirements of synchronization accuracy under any bandwidth utilization condition. These results compromise the feasibility of this solution, highlighting constraints that need to be taking into account for the final design of the network and its hardware. This represents a disadvantage with respect to the other solutions for the timing system, which do not impose any restriction on the networks of the facility but incur in a higher cost. Concretely, the solution based on a single high accuracy (PTP-HA) network may be the one that best balances the complexity and cost of the network with the confidence of the synchronization accuracy and the scalability.

Further experiments should be carried out to analyze the influence of multiple NTP and PTP clients on the saturation of the network and the time servers, and its impact on the synchronization accuracy. Redundancy is also another aspect that the design must consider to make the synchronization resilient to link or device failures. The definition of the network architecture at the physical level is needed to finally design the timing system that best suits the facility.

An additional noteworthy contribution of this work is the performance analysis of the most typical standard Ethernet-based synchronization protocols for different network traffic conditions. Moreover, the current experimental setup that has been implemented can be used to evaluate the influence of other network parameters on the synchronization accuracy without major modifications and explore different ways to improve it. This includes the evaluation of different parameters that can be configured in the synchronization protocols and that can improve the results obtained. These actions will be part of future work to fully determine the best solution to be implemented in IFMIF-DONES.

In conclusion, we have shown that an Ethernet-based solution for timing distribution with high performance and configurability in linear particle accelerators with diverse and very demanding synchronization requirements, such as IFMIF-DONES, can be possible. The approach followed allows us to take full advantage of network design techniques without the need to use very specific and technologically complex alternatives. The presented design process for the timing system and the given implementation considerations are intended to provide guidance and serve as a reference for upcoming scientific facilities.

CRediT authorship contribution statement

Carlos Megías: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Víctor Vázquez:** Conceptualization, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Eduardo Ros:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mauro Cappelli:** Conceptualization, Writing – original draft, Supervision. **Javier Díaz:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Antonio Javier Diaz Alonso reports a relationship with Seven Solutions S.L. that includes: board membership, consulting or advisory, and equity or stocks. Eduardo Ros Vidal reports a relationship with Seven Solutions S.L. that includes: board membership, consulting or advisory, and equity or stocks.

Data availability

The data (measurements) and logs of the experiments are included in an attached file with a small "readme". The code can be obtained on request and we are considering also attaching it in the future.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.comnet.2023.109897.

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Carlos Megías received his B.Sc. and M.Sc. degrees in Telecommunications Engineering from the University of Granada, Granada, Spain, in 2019 and 2021, respectively. He also holds a M.Sc. degree in Industrial Electronics from the same university. He is with the Department of Computer Engineering, Automatics and Robotics, and is currently a Ph.D. student of the program in Information and Communication Technologies at the University of Granada. His main research interests concern communications networks, deterministic networks, timing and synchronization, and FPGA-based systems design.

Víctor Vázquez is with the Department of Computer Engineering, Automatics and Robotics at the University of Granada, Spain. He received his M.Sc. degree in Computer Engineering in 2020 and is currently a Ph.D. Student at the University of Granada. He works on industrial communications, focusing on time synchronization and deterministic networks.

Prof. Eduado Ros received his M.Sc. and Ph.D. degrees in Physics, Electronics Engineer and Computational Neuroscience from the University of Granada (Spain) in 1992, 1995 and 1997 respectively. He is currently Full Professor in the Department of Computer Engineering, Automation and Robotics (ICAR) at the University of Granada. He is part of the Time Transfer and Synchronization team. He is co-founder of a start-up acquired by Safran. He is the author of more than 110 articles. His main research interests include time transfer and synchronization, computational neuroscience and machine learning, robotics and VR.

Mauro Cappelli is a Researcher at ENEA (Italy), Frascati Research Center, Adjunct Professor of Instrumentation for Control of Energy Systems at the University of L\220Aquila, Adjunct Professor of Monitoring and Control of Energy Systems at the Sapienza University of Rome and Affiliate at the DEWS Center of Excellence, University of L\220Aquila. He got a Laurea (B.Sc. + M.Sc.) in Electrical Engineering from the University of Perugia, a PhD in Electrical Engineering from the Sapienza University of Rome, a Master in Nuclear Safety at the University of Pisa, a Master in Fusion Energy at the University of Rome Tor Vergata.

Javier Díaz holds a Ph.D. degree in Electronics obtained from Granada University. His primary expertise lies in time transfer and frequency dissemination techniques, control for particle accelerators, FPGA and embedded systems for image processing or safety-critical applications. Currently, he serves as full Professor at the University of Granada, where he actively collaborates with facilities such as SKA (White-Rabbit timing) and IFMIF-DONES (CODAC, RH and timing systems in the framework of WPENS project). Additionally, he has participated in multiple EU-projects. Notably, he has also founded Seven Solutions and engaged in close collaboration with Safran as part of his technology transfer activities.