On the Seamless Interconnection of IEEE1588-based Devices using a PROFINET IO infrastructure

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Abstract

Several types of industrial Real-Time Ethernet (RTE) networks could be present in the same plant. This work deals with the clock synchronization problems that arise when different RTE network infrastructures are interconnected. Specifically, the paper is focused on the exploitation of PROFINET IO Conformance Class C infrastructure for the interconnection of other industrial communication devices or measurement instruments that use IEEE1588 for clock synchronization. Actually, such devices (e.g. LXI instruments, EtherNet/IP devices etc.) cannot be satisfactorily synchronized if directly connected to the PROFINET infrastructure, because of the large time errors (up to 100µs). The solution proposed in this paper is an intelligent clock synchronization converter that has fewer limitations if compared with other systems, like boundary clocks. The basic idea is the creation of a “black-box” (a sort of remote bridging device) for the interconnection of IEEE1588 nodes through a PROFINET IO host plant, with zero-configuration on both systems. The proposed approach differs from boundary clock since its goal is to keep the PROFINET IO and the IEEE1588 synchronization domains separated, exploiting the possibility to tunnel the IEEE1588 time information through the PROFINET IO infrastructure with sufficient precision.

In order to verify the practical feasibility of the proposed solution, LXI Class B instruments have been connected to the infrastructure of a real PROFINET IO network. The results show that the standard deviation of the synchronization accuracy is only 10ns higher than the one measured in the case of a dedicated (separated) network for the LXI instruments.
Keywords

Real-Time Ethernet, Clock synchronization, Embedded system, Simulation, Performance evaluation
1. Introduction

A typical industrial plant hosts a plurality of devices in addition to the components necessary for the factory automation. In the last years, Ethernet networks expanded from the higher level of the plant infrastructure down to the shop floor; today, many factory automation devices have an Ethernet port. Furthermore, such a diffusion makes easier the use of additional, ancillary, devices and instruments in the factory plant that exploit the existing network infrastructure. For instance, there could be temporary installations of monitoring equipment, or general-purpose instruments [1, 2] for in-production quality control. In this case, the added instruments can use the Ethernet network and TCP/IP to transport measurement data and also to synchronize the measures/acquisitions. Thanks to recent protocols like IEEE1588-PTP (Precision Time Protocol) [3], the clock synchronization of multiple instruments in an Ethernet network is now possible, although the synchronization performance is limited if the network infrastructure is not compliant with IEEE1588-PTP, as in [4]. Another typical example is the distributed instrumentation based on the well accepted LXI (LAN eXtension for Instrumentation) standard [5].

Generally, the automation components require the use of dedicated protocols in order to fulfill the stringent constrains of the automation (determinism, low latency, etc.). The “Real-Time Ethernet” (RTE) networks satisfy such constrains, since they use the legacy Ethernet (Physical layer as well as Data Link layer) to guarantee real time communications [6, 7]. Moreover, most of them are compatible with TCP/IP and thus, theoretically, the seamless connection of any device should be possible.

In the practical case, many problems arise when the previously introduced mixed scenario is realized. As an example, the following situation can be considered. The user needs to utilize some LXI devices in order to make some measurements on a tool machine while it is running. The LXI Class A/B instruments must be networked in order to be synchronized by PTP. The tool machine is managed by an RTE network, so the user decides to connect the LXI instruments to the machine.
infrastructure using the most accessible free ports of the RTE switches. The user does not take care of modifying neither RTE nor PTP configurations, but he expects that both the tool machine continues working properly (with the same production quality) and the LXI system successfully achieves its synchronization. On the contrary, some conflict situations can occur in the case of devices with different clock synchronization protocols trying to share the same network infrastructure.

Normally, the RTE protocols enhance the traditional MAC (Medium Access Control) layer of Ethernet in order to minimize the communication jitter and gain the real-time behavior. Hence, if the network has been primarily designed for factory automation, the frames of time-critical automation components always have a sort of “high priority” against the frame of the other protocols (e.g. TCP/IP, etc). Therefore, any protocol that does not take part in the real-time control program may have its timing completely distorted due to the low transmission priority along the common infrastructure. For instance, such a situation has been illustrated in [8], where EtherNet/IP devices with the CIPsync profile for the real-time motion control [9, 10] have been connected to a PROFINET IO Conformance Class C (CC-C) network infrastructure. The CIPsync profile uses IEEE1588-PTP for clock synchronization and cannot obtain good accuracy since the PROFINET IO network is based on strict time division access rules; the result is a synchronization jitter of some tens of microseconds for the EtherNet/IP devices instead of few nanoseconds of a system with only EtherNet/IP components.

While the clock synchronization in industrial networks has been already investigated by several contributions [11, 12], the behavior of a mixed scenario has not been exhaustively addressed yet and, consequently, it needs to be studied more in detail. Indeed, the interconnection of networks based on different synchronization methods can be highly probable in typical situations, due to causes that could be either intentional (for exploiting an existing infrastructure) or unintentional (an error of the users). In [13], the authors propose a method, based on simulations as well as real
measurements, to settle on the parameters of the IEEE1588 algorithm in order to reduce side effects when devices using such algorithm are connected through a PROFINET IO CC-C infrastructure. The method is based on a filtering action that discards the PTP messages excessively delayed by the PROFINET network. However, a great configuration effort of the PTP-based devices is required when the method is applied in practice.

Considering that PROFINET IO is one of the most widespread RTE network in the factory automation and that the IEEE1588 is the widely accepted standard for clock synchronization over a packet network, the objective of this work is to provide a method to allow IEEE1588-nodes to be interconnected in a seamless way using a PROFINET IO network infrastructure. The idea behind this work is the definition of a “synchronization converter” that does not require configuration neither for stable nor for temporary use. The use of the converter enables the integration of IEEE1588 based devices in a time division MAC infrastructure, like the PROFINET one, with a small decrease of the IEEE1588 synchronization accuracy balanced by the great convenience of the proposed “zero configuration” approach. The proposed solution differs from a IEEE1588 boundary clock since the converter keeps the PROFINET IO and the IEEE1588 synchronization domains both separated and independent.

The proposed approach depends on the premise that the IEEE1588 time information can be transported through the PROFINET IO infrastructure with sufficient precision and without altering the PROFINET IO system.

Initially, the PROFINET IO concepts and the difficulties of the IEEE1588 integration are illustrated, followed by a simulation example of the bad behavior of a mixed scenario. Then, the synchronization converter architecture, partially introduced in [14], is presented and discussed. Thereafter, a practical implementation of the converter concepts, which uses FPGA hardware, is described. Last, several experiments demonstrating the converter effectiveness, applicability and high accuracy in a real case (LXI instruments) are reported and discussed.
2. Connection of IEEE 1588 devices to a PROFINET IO infrastructure

Given two protocols, their ability of sharing the same infrastructure maintaining their respective performance can be defined as the “coexistence” property. There is a “strict coexistence” if each protocol can maintain the same performance, otherwise there is a “partial coexistence” when the performance (of at least one protocol) gets worse. Since the severity of the performance worsening can be evaluated, strategies for the maximization of the coexistence (i.e. minimization of the performance worsening) can be studied and applied.

The aim of this section is the description of the coexistence related aspects of a network where the IEEE1588 traffic uses a PROFINET network infrastructure. Since the main obstacle in connecting devices that use an IEEE1588 clock synchronization to a PROFINET IO infrastructure is related to the PROFINET IO MAC, a brief overview of PROFINET concepts must be given. Afterwards, the standard means that the IEEE1588 suggests to overcome such a situation are illustrated and discussed in depth.

2.1. PROFINET IO overview

The PROFINET IO protocol corresponds to the communication profile specifications CP 3/4, CP 3/5 and CP 3/6 of the standard IEC61784-2 [15] that refers to the related IEC61158 [16] parts. PROFINET IO components can belong to three conformance classes (A, B, and C) depending on characteristics and performance. Devices belonging to class C must support all the three communication profiles and have the maximum performance. PROFINET IO defines three kinds of components: IO-Controllers (i.e. intelligent devices running automation control programs); IO-Devices (i.e. sensors, actuators, IO module etc.); and IO-Supervisors for diagnostics and configuration. Considering only PROFINET IO CC-C, there are three classes of communication protocols:
- RT_Class 1 (also known as RT, Real-Time) is used for automation systems requiring cycle time of about tens of milliseconds and with jitter (maximum cycle time minus minimum cycle time) on the order of few milliseconds;

- RT_Class 2 and RT_Class 3 (often called IRT, Isochronous Real-Time) are used when the application needs a cycle time in the range of 250µs - 4ms with extremely low jitter; indeed, the maximum allowed synchronization jitter is 1 µs for RT_Class 3 devices.

PROFINET IO uses a time division MAC strategy to allow for coexistence of its different types of protocols. Hence, the PROFINET IO data exchange among IO-Controllers and IO-Devices is cyclic. The cycle is divided into several phases (in time) as described in IEC61158-5-10:

- **RED phase**: in this phase, the whole network infrastructure is reserved for RT_Class 3 frames. The transmission is time scheduled on “a priori” defined paths. Other kinds of traffic (e.g. TCP/IP) are blocked (waiting) inside the switch buffers for the entire duration of the RED phase. It is important to say that the RT_Class 3 communication requires a rigid network topology (decided during the configuration) and purposely designed switches, in order to create the frame scheduling.

- **ORANGE phase**: the infrastructure is reserved for RT_Class 2 frames that use standard routing based on Ethernet MAC addresses. This means that for RT_Class 2 the network topology is free provided that the available network bandwidth is not exceeded in any point of the network.

- **GREEN phase**: this is the “open” communication phase that is used by RT_Class 1 messages and any other Ethernet messages, including IP based communication (TCP, UDP). The frames are transmitted and routed according to their Ethernet priority (IEEE 802.1Q).

The time left in the GREEN phase for non real-time protocols (like TCP or UDP) is, at least, the greater between 40% of the total cycle duration and 124 µs (i.e. the time for serving at least one Ethernet frame of the maximum size @ 100 Mbit/s). As stated in the introduction, such a traffic has low priority and experiences variable delays in crossing the network. Generally, this is not a
problem because the IP traffic is used for transferring considerable amounts of data and only the average bandwidth is important.

In PROFINET IO the network infrastructure must be synchronized in order to manage both the cycle and the frame scheduling; this requires the use of purposely designed switches. The PTCP (Precision Transparent Clock Protocol) is used for the clock synchronization. PTCP is very similar to the PTP described in the last release of the IEEE1588. The PTCP uses a transparent switch approach (similar to PTP V.2 transparent clock – TC- [17] ) with the peer delay mechanism to measure the link delay (i.e. the port-to-port propagation delay between two ports). The synchronization process is always independent of the classes of communication protocols: all PTCP synchronization traffic can be transmitted in the GREEN, ORANGE or RED phases. Usually the synchronization interval is 30 ms, even if many products, for ease of implementation, send the PTCP sync frame every cycle (during RED phase).

It should be highlighted that at the moment of writing, the PROFINET specifications [15, 16] are under revision. The main topics of the working group are the optimization of PROFINET performance using the Dynamic Frame Packing [23], and a general revision of the synchronization mechanism. The approach proposed and developed in this paper refers to the current PROFINET specifications [15, 16]. This means that the proposed approach is applicable to the totality of the currently available PROFINET components.

2.2. Coexistence of IEEE1588 devices and PROFINET IO devices

In case a PTP message generated by an IEEE1588 device travels through a PROFINET IO network, it will be treated as a “generic” UDP message since the implementation of the IEEE1588 protocol over Ethernet, as defined in the standard [3], specifies UDP as transport layer. Therefore the PTP messages will be transmitted from switch to switch only in the GREEN phase, while they wait inside the switch memory during both the RED and ORANGE phases. Since the PROFINET
IO cycle and the PTP protocol have no relations, the propagation delay of the PTP messages is random and in these conditions the PTP synchronization algorithm produces very poor results.

The coexistence of PTP and PROFINET over the same infrastructure may cause several risks to an industrial plant and it should be evaluated before the installation. The analysis of this situation can be suitably carried out by means of simulations in order to take also into account complex network structures. In [13], the authors proposed useful simulation models of PROFINET IO CC-C components (with PTCP) and EtherNet/IP components (with PTP V1). The simulation of these nodes implies an accurate model of the local oscillators, because time related parameters are mainly analyzed.

As an example, the network depicted in Fig. 1 has been simulated. There are four EtherNet/IP devices (E_IP0-1-2-3) connected to two PROFINET IO CC-C devices: PNIO_0 and PNIO_1. The oscillator model, described in [20], has the following parameters, typical of rugged devices [21]: Oscillator Frequency = 10MHz, Oscillator Class =100ppm, Aging Factor = $10^{-10}$/day.

The start-up time is different for each node in order to analyze the capability of the PTP synchronization protocol to dynamically synchronize new nodes inserted at different instants. The last node starts working 30 s after the beginning of the simulation. The node E_IP0 is the PTP master clock that synchronizes the nodes E_IP1-2-3 with a PTP sync_interval of 2 s, the default value, typically adopted in instrumentation applications. In fact, this sync_interval is a compromise between synchronization accuracy and throughput required by the synchronization messages. In this simulation, the EtherNet/IP nodes are exchanging only implicit messages, transported over UDP layer [22]. The data exchanged simulate a periodic data transfer between sensors, actuators and the controller of the network (E_IP0). This is the case of an industrial environment, where the data exchanged are limited (in this simulation: 16 byte). A sufficiently long period (greater then 500 ms) has been chosen in order to limit the load over the network due to the EtherNet/IP traffic. The EtherNet/IP nodes produce only real time traffic. In this simulation the PTP Sync frames use the
high IEEE802.1Q priority in order to obtain a better quality of service, hence additional non real-time traffic does not critically affect their propagation time. It is worth mentioning that the PROFINET switches support IEEE802.1Q priority. The PROFINET IO CC-C components have been configured with a communication cycle time equal to 1 ms and the RED phase duration of 30.5 µs. During the RED phase, the two PROFINET IO nodes are exchanging a small amount of data (124 bytes long frames) in both the directions. From the synchronization point of view, the PNIO_0 is the master clock of the PROFINET IO network, whereas the PNIO_1 is the slave clock. The synchronization frames of PROFINET IO are sent in every communication cycle (i.e. 1 ms).

The performance indicator to be evaluated is the clock offset of the EtherNet/IP devices. Initially, the nodes, both the EtherNet/IP as well as the PROFINET IO ones, are unsynchronized. During the first stage of the simulation, the PTP nodes exchange management messages in order to select the master of the network. Therefore the time readings of each clock are unrelated. In Fig. 2, the clock offset of the slaves with respect to the master time is reported during the steady state, i.e. after the election of the master and the correction of the initial offset. In the simulation reported in Fig. 2, no additional network traffic (such as TCP/IP), except PROFINET IO and PTP, is present. As expected, the variable propagation delay of the PTP synchronization messages over the PROFINET IO infrastructure heavily affects the synchronization capability of EtherNet/IP nodes. For instance, the offset error of devices, that seems constant for some time, is due to a delayed PTP Delay_Req message, causing an error in the calculation of the One_way_delay value.

In reality, the two synchronization networks, PTP and PTCP, are not synchronized together; their clocks drift away of about 10 µs/s, as measured on a real system [8]. Therefore periodically (about every 150 s) the PTP sync transmitted by the E_IP0 master clock arrives at the first PROFINET switch during the RED phase and has to wait for forwarding in the GREEN phase, heavily affecting the estimate of the offset error in the slave clocks. As a result, peaks of more than 70 µs are present in the chart of the offset errors.
2.3. The coexistence solution proposed by the IEEE1588 standard

The IEEE1588 offers a possibility for assuring coexistence. As previously introduced, PTP and PROFINET PTCP use analogous concepts to achieve synchronization over the network. The Normative Annex I of the IEEE 1588 [3] shows the correspondence between names given by the PTP to the synchronization variables/parameters and names given by PTCP to the same objects. In most cases, the values of the message fields are expressed with the same numerical representation,
giving the opportunity to simply copying from one message to the other. Moreover, the Annex I of IEEE1588 introduces the use of a Boundary Clocks (BC) as the reference method to safely connect a PROFINET IO network (called “region” in the standard) and a PTP region, creating a unique clock synchronization region. The BC is a device with at least two IEEE1588 enabled ports and a double clock synchronization stack. It behaves like an ordinary clock (OC) on a port and as a master clock (MC) on the other one. Inside the BC, the ordinary clock synchronizes itself to the (unique) GrandMaster Clock (GMC) of the network, and then at the master clock side the clock synchronization is propagated to the region that does not contain the GMC. A BC is able to choose on which port it has to behave as ordinary or master clock on the basis of the Best Master Clock (BMC) algorithm [3]. To our knowledge, today Annex I is implemented by some Siemens commercial products of the line SIMOTION. The use of a BC for the connection of a PROFINET region to a PTP region requires the configuration of both the systems: from the PROFINET point of view, the BC must be inserted into the network configuration; from the PTP point of view, there are several PTP parameters that are not-used, or undefined, in the PTCP and must be decided before the connection of the BC (see conversion tables in Annex I).

The analysis of a typical situation, shown in Fig. 3, can raise up other concerns. In the example case, two groups of IEEE1588-based devices are connected to a PROFINET IO CC-C infrastructure in different places. For instance, this is the case of two measurement instrument groups placed at the opposite ends of a production line. Since the goal is to have PTP regions A and B synchronized, the solution of IEEE 1588 Annex I is to synchronize all the clocks of PTP region A, PTP region B, and PROFINET region to the same (unique) GMC that could be located in any of the three regions. This situation could be undesirable for at least two reasons. Generally, the automation unit that controls the process (i.e. the PROFINET IO-Controller that drives the PROFINET IO-Devices) is required also to define the clock synchronization of the entire automation network (i.e. the PROFINET region). If the grandmaster clock is outside the PROFINET region, the timing is not under the direct
control of the IO-Controller. Hence, it cannot survey and guarantee any quality of the final product that is dependent on the time accuracy during the manufacturing process. The second problem is the lack of time reference during the BMC algorithm execution when a grandmaster clock in the PTP region is disconnected, as shown in [18]. Such situations can cause unacceptable errors in the automation application, or reduced product quality.

As a conclusion, the solution proposed by the Annex I is fully functional and standardized, but has some drawbacks if it is used in real systems.

![Figure 3. Connections between PROFINET region and PTP regions.](image)

3. The proposed method

The objective of this work is to seamlessly interconnect IEEE1588-based devices by means of a PROFINET IO CC-C network infrastructure obtaining good synchronization accuracy without requiring any configuration. Hence, the best approach to the problem is to maintain the PTP regions and the PROFINET region completely separated and autonomous from the clock synchronization point of view.

The proposed solution is shown in Fig. 4, and it is based on transparent “synchronization converters”. The property of the proposed converters is to create only two regions from the synchronization point of view: the PROFINET region and the “unified PTP region”. Any IEEE1588
device connected through a converter to the PROFINET IO infrastructure will become member of the “unified PTP region”. The location of the IEEE1588 devices does not require any planning in the PROFINET IO infrastructure. Since the “unified PTP” region and the PROFINET region are separated and independent, the presence of two GMCs (one for PTP and one for PROFINET) is allowed.

The PROFINET IO CC-C infrastructure is made of transparent clocks only and the converter operates on the PTP Sync messages that are transformed into “pseudo PTCP Sync” messages. Therefore, the PROFINET IO infrastructure transports them taking into account the propagation delay (i.e. line delay and the bridge delay) over the backbone. When one of the pseudo PTCP Sync messages arrives at another synchronization converter, the reverse conversion is applied and a PTP Sync message is forwarded to the locally attached IEEE1588 devices. The additional advantage of the proposed solution is that the propagation delay of pseudo PTCP Sync messages is measured by the PROFINET IO infrastructure itself.

The pseudo PTCP sync messages originated by the conversion of a PTP Sync must have no meaning for the host PROFINET IO infrastructure; they must be suitably coded in order to differ from the real PTCP Syncs used by PROFINET IO devices. The use of a different value for the clock domain unique identifier (i.e. the field of the PTCP message that identifies each

![Figure 4. Unified PTP region created by means of the proposed converter.](image-url)
synchronization region) and the assignment of the converter MAC address as master clock source address (i.e. the Master PTP identifier), can solve this problem. Moreover, such a solution has the advantage that the lower layers of the PTCP stack (usually implemented in hardware) deal with this pseudo PTCP message as a real PTCP message; on the contrary, the upper layers consider it as a foreign message and discard it.

The delay that the pseudo PTCP Sync message takes to travel from the entry point to the exit point of the PROFINET IO network is available in PROFINET. Referring to Fig. 5, the PROFINET IO infrastructure automatically encodes the total time delay of the PTCP sync message into a dedicated field of the frame (i.e. $PTCP_{delay10ns}$). The last part of the delay (LastDel - between the converter and the first PROFINET device it is connected to) may be estimated by both the PROFINET device and the proposed converter using the standard peer delay mechanism of PROFINET [16]. In order to be non-invasive on the PROFINET network, the LastDel estimation is done by the converter only. The propagation delay of the converter (ConvDel) is calculated by the converter itself for each frame. Summarizing, the original timestamp of the PTP Sync message ($OriginTimestamp$, $OTS$) coming from the PTP region containing the PTP Master clock is modified in the following way:

$$\text{modOTS} = OTS + PTPLineDel + \text{ConvDel}_A + \text{ConvDel}_B + PTCP_{delay10ns} + \text{LastDel}_A + \text{LastDel}_B$$

(1)

If the PTP devices require the use of PTP Follow-up messages, the previously described time modifications are applied to the relevant fields ($preciseOriginTimestamp$) of the Follow-up message.

The proposed synchronization converter is completely transparent from the TCP/UDP/IP point of view, and it behaves like a store & forward switch with two ports only. On the contrary, any PROFINET message is blocked (firewalled) by the converter and cannot enter the unified PTP region.
From the IEEE1588 point of view, in the PTP region side, the converter must operate only on the Sync, Follow-up and Delay_Req messages. Other PTP management messages (including BMC algorithm transactions) are transparently forwarded, since they are transported over UDP. Specifically, the BMC algorithm of the “unified PTP” region is completely independent of the BMA algorithm of the PROFINET region, because the PTP devices simply cannot perceive the presence of PROFINET devices, thanks to the converter firewalling action. The PROFINET region ignores the BMC algorithm messages of the PTP since they are coded in a different way.

The proposed synchronization converter is bidirectional; the direction of the Sync messages is not fixed, i.e. the IEEE1588 Master Clock can be placed in any PTP region. At the beginning, the PTP regions A and B are separated (each one with its own time); when they are initially connected to the PROFINET region, the converter allows the PTP sync messages to flow between the two regions. Then, the BMC algorithm of the PTP takes care of “electing” a unique Master Clock for all the PTP regions, creating a single “unified PTP region”, as shown in Fig. 4.

Last, in the proposed solution the number of PTP nodes and relative converters is limited only by the free bandwidth available in the PROFINET IO network. For a correct computation of the required bandwidth, all the messages of the hosted PTP nodes that pass through the PROFINET infrastructure must be considered, including PTP as well as non-PTP traffic, e.g. LXI protocol messages.

It is worth noting that, depending on the extent of the modifications that will be introduced into the forthcoming PROFINET IO specifications, the proposed converter could be prevented from working in some situations. The converter will work appropriately with PROFINET devices compliant with the current version of the specifications defined in [15, 16].
In order to verify the feasibility of the proposed solution and to experimentally characterize the performance, the prototype of the synchronization converter of Fig. 4 has been described in VHDL and realized using a FPGA (Stratix II by Altera).

### 3.1. General architecture of the intelligent clock synchronization converter

The general architecture of the synchronization converter has been developed referring to PTPv1 even if the approach proposed in this paper can be used also with PTPv2 with end-to-end delay measurement.

Fig. 6 shows the internal block diagram of the proposed converter. According to Fig. 4, it must be inserted between the PROFINET region and each PTP region to be unified. Hence, the converter has two dedicated Ethernet MII ports (“Media Independent Interface”), called respectively PN-port (PROFINET IO) and PTP-port, which are interfaced with 10/100 Ethernet PHYs. The MII port block manages the communication physical level and provides several other services, which are useful for the synchronization conversion. For instance, each port is able to identify and timestamp the incoming sync frames (both PTP and PTCP) in both directions, for measuring and adjusting the delay introduced by the converter.
Afterwards, the received messages are managed by the Switch logic block. This module identifies the messages and routes them on the right output. The synchronization messages, both PTP and PTCP, are sent to the Sync_Messages_Manager module for the conversion, whereas the other frames are sent to the right physical output port, minimizing the internal routing delay. The Sync_Messages_Manager converts the fields of the incoming messages into the correct fields required by the output synchronization protocol, following the Annex I of [3]. The converted frames are then sent back to the switch logic and then routed to the right output port.

The converter is based on a single local oscillator, but it should provide two different clocks in order to translate the time information from PROFINET time domain into the PTP time domain. In details, the propagation delay of the synchronization frame through the PROFINET network, as measured by the PROFINET infrastructure (switches), must be translated to the PTP domain time in order to take into account the drift and the offset of the two different regions.

The PN clock block is (at least) syntonized to the PROFINET region time through the PTCP sync frames provided by the PROFINET IO Controller (i.e. the GMC of the PROFINET region). However, in order to perform any synchronization interaction with the PROFINET network, the IO-Controller has to identify the converter as a PTCP capable device, exchanging suitable LLDP messages (“Link Layer Discovery Protocol”) with the PN port. It should be noted that, in theory, the converter should be registered as a PROFINET IO-Device in the configuration tool of the PROFINET network, in order to be recognized by the IO-controller and treated as a PROFINET slave. Actually, as explained in the following section, if a local information about the PROFINET region time is not required, the registration of the converter in the PROFINET configuration tool is not needed, simplifying its connection to the infrastructure.

On the other hand, the PTP clock block is synchronized to the PTP region time, which is common to all the converters.
The controller block manages all the information related to time: it synchronizes the clocks to the respective regions; it measures the drift and the offset between the synchronization regions; and it estimates the parameters used to convert the delay measures from PROFINET region into the related PTP delay. The PN and the PTP clocks of this converter are synchronized respectively to the PROFINET and the PTP regions; therefore the time information of both the regions is available. Table 1 summarizes the timestamping action carried out using the PN clock and PTP clock blocks. The timestamp values are then combined to carry out the actions described both in this section and in section 3. The PTP Sync is timestamped by both clocks, the PN and the PTP clocks, when entering the converter. These timestamps are respectively called Sync\_TS\_PN and Sync\_TS\_PTP. The Sync\_TS\_PTP timestamp is used to synchronize the PTP clock of the converter connected to the PTP region in which the PTP Master Clock is located. The PTCP Sync is also timestamped by both clocks: the PTCP\_Sync\_TS\_PTP timestamp is used only if the incoming packet is a pseudo PTCP Sync resulting from the conversion of a PTP Sync. In such a case, it is used to synchronize the PTP clock of the converter connected to the PTP region without the PTP Master Clock. On the other side the PN clock timestamps are used to synchronize the PN clock to the PROFINET Master clock, and to estimate the conversion delay (ConvDel) and the delay between the converter and the first PROFINET device (LastDel).

In detail, the difference between the rate of the PTP region to the rate of the PROFINET region is periodically estimated only by the converter directly connected to the PTP region with the PTP Master. The interval between two consecutive PTP sync messages timestamped by the PN clock is measured as follow:

\[
SyncInt_{PN} = Sync\_TS\_PN(k) - Sync\_TS\_PN(k-1)
\]  \[(2)\]

whereas the same interval, measured by the PTP clock, is:

\[
SyncInt_{PTP} = Sync\_TS\_PTP(k) - Sync\_TS\_PTP(k-1)
\]  \[(3)\]
The drift\(R\)ATE, defined as the ratio between the rates of the PTP and the PROFINET regions, can be expressed using the Eq. (2) and the Eq. (3):

\[
drift\text{\textsc{R}}\text{ATE} = \frac{\text{SyncInt}_{\text{PTP}}}{\text{SyncInt}_{\text{PN}}}
\]  

(4)

The calculated drift\(R\)ATE information is periodically transmitted to other converters by means of a dedicated messages over UDP (non real-time). In this way, the other converters can synchronize their respective PTP clocks using both the information derived from the pseudo PTCP Sync and the following relationship between every delay calculated by PROFINET and the correspondent delay in the PTP domain:

\[
\text{PTP} \text{Delay} = \text{PN} \text{Delay} \cdot \text{drift\text{\textsc{R}}ATE}
\]  

(6)

The equation to adjust the OriginTimestamp of the PTP Sync can be derived from the Eq. (1) after converting all the delays in the PTP domain using the Eq. (6)

\[
\text{modOTS} = \text{OTS} + \text{PTPLineDel} + (\text{ConvDel}_A + \text{ConvDel}_B + \text{PTCP} \text{delay10ns} + \text{LastDel}_A \cdot + \text{LastDel}_B) \cdot \text{drift\text{\textsc{R}}ATE}
\]  

(7)

The converter implements the Sync I/O module for debugging and testing purposes; it can be used either to receive an external 1-PPS (pulse per second) synchronization source (such as a GPS or an atomic clock) or to generate a periodic signal for testing the synchronization performance.

<table>
<thead>
<tr>
<th>Message type</th>
<th>Direction</th>
<th>PTP region ↓ Converter</th>
<th>Converter ↓ PN region</th>
<th>PN region ↓ Converter</th>
<th>Converter ↓ PTP region</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTP Sync</td>
<td></td>
<td>PTP clock</td>
<td>-</td>
<td>-</td>
<td>PN clock</td>
</tr>
<tr>
<td>PTP Delay_REQ</td>
<td></td>
<td>PTP clock</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PTCP Sync</td>
<td></td>
<td>-</td>
<td>PN clock</td>
<td>PTP clock</td>
<td>PN clock</td>
</tr>
<tr>
<td>PTCP Delay_REQ</td>
<td></td>
<td>-</td>
<td>PN clock</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Clock used to timestamp the synchronization related messages (names refer to the relevant Standards).
3.2. Architecture optimizations

The architecture proposed in the previous subsection requires the use of a high performance FPGA because of the complex operations that have to be implemented. For instance: the controller has to synchronize the PN and the PTP clocks to their respective time regions; any time related measure taken by the converter (such as the internal propagation delay) must be converted; finally, high level protocols must be managed in order to make the converter recognizable by the IO-controller as a PROFINET IO-Device.

After rigorous considerations, some architecture improvements can be introduced to optimize the proposed solution under certain assumptions.

3.2.1. Optimization related to the internal propagation delay calculation

Large part of the modules described in the previous block diagram is dedicated to the measure of the internal propagation delay of the converter. This delay is due to the conversion of Sync messages from a synchronization protocol to the other. The hardware is described and synthesized...
using the VHDL language; high priority can be assigned to synchronization messages in the switch logic, hence the internal delay can be predicted. Therefore, a constant internal delay may be assumed, instead of measuring it every time. In other words, the upper limit of the overall internal delay due to the conversion is known and, during the design a slightly greater (but constant!) delay can be used (e.g. in this implementation such a delay is set to 50µs). This implies that the timestamp logic, needed for the calculation of the ConvDel, can be eliminated and the time fields of Sync messages are updated with a constant value (i.e. a much simpler design and routing of the adder stage).

It should be noted that, since the internal frame conversion delay is constant, the maximum drift error between the local oscillator (used to create the fixed delay) and the PTP (or PN clock) can be “a priori” estimated. Even using a COTS oscillator with medium drift performance (100ppm), the drift error is small if the delay is short. For instance, a maximum error of 5ns is expected when the conversion delay is fixed to 50µs.

3.2.2. Optimization related to the conversion of the propagation delay through the PROFINET network

The propagation delay is transparently measured by the chain of PROFINET IO switches and it is available in the PTCP_delay10ns field of a PTCP Sync. When a PTP Sync is converted into a pseudo PTCP Sync and transmitted over the PROFINET IO infrastructure, the value of the propagation delay must be converted and combined into the re-generated PTP Sync at the destination converter. As discussed in section 3.1, this conversion must take into account the time drift between the PN and the PTP clocks.

However, the pseudo PTCP Sync messages have the higher priority among Ethernet frames and they wait inside the switch only if: the switch is in the RED phase; or the output port is busy. On the other hand, in [14] the bridge delay of a PTCP_Sync message in a PROFINET IO switch has been
measured under typical traffic conditions; usually, it is lower than 10 µs. Hence, the propagation delay upper and lower boundary may be effectively estimated.

As an example of the worst case situation, a PROFINET IO network with a communication cycle of 250 µs (125 µs RED phase plus 125 µs GREEN phase) and a typical topology of 10 cascaded switches, has been considered. The worst bridge delay through a switch is 250 µs when the pseudo PTCP message arrives just at the beginning of the GREEN phase and the output port is occupied by the longest Ethernet frame (125 µs). In this case the pseudo PTCP message must wait also for the entire duration of the next RED phase before being transmitted. If the described situation is verified in every switch of the cascaded structure, the worst propagation delay is 2500 µs. On the other hand, the shortest propagation delay along the cascaded structure can be considered 100 µs. In this example, drift error is small since the propagation delay is short; considering 100ppm oscillator in the devices, the expected drift error is between 10 ns and 250 ns.

In conclusion, if the uncertainty related to this drift error is acceptable, the propagation delay estimated by the PROFINET infrastructure can be directly used in the PTP domain without a conversion.

3.2.3. Optional optimization

The PTCP devices could automatically generate a Follow-up message when propagating a PTCP Sync. This event requires the converter to manage/convert a further message, the PTCP Follow up. The processing of this frame is straightforward (e.g. conversion from PTCP to PTP) but requires additional space on the FPGA.

In order to demonstrate the feasibility of the proposed solution, the implementation has been kept as simple as possible and additional features have been limited, when possible. Thus, the PTCP Follow-up handling is not included in the optimized prototype. Anyway, Follow-ups are not generated by the PROFINET IO devices used in the experimental setup considered in this paper.

3.2.4. Optimized architecture
Following the considerations of the previous sections, the proposed architecture can be optimized if a worsening of the synchronization accuracy on the order of 50 ns is acceptable for the final application.

The double clock (PN and PTP clocks) architecture is needed for the correct conversion of time measures from a time domain to the other; if the drift of the local oscillator and of the synchronization region can be ignored, the PN clock block can be removed.

In the optimized architecture the PTP clock block can be used to timestamp only the following messages: PTP Sync, PTP DelayReq, PTCP Sync.

The final equation to adjust the OriginTimestamp of the PTP Sync can be derived from Eq. (7) after applying the aforementioned optimization

\[
modOTS = OTS + PTPLineDel + 2 \cdot ConstConvDel + PTCP\_delay10ns + LastDel_A + LastDel_B
\]

Moreover, as a further positive side-effect of the elimination of the PN clock, the converter is not required anymore to be identified as a PTCP clock in the PROFINET configuration tool and, therefore, it can be inserted on the PROFINET infrastructure with zero-configuration.

Using the optimizations described in this section, a lighter implementation can be obtained; only a small part of the resources of the Stratix II device are used (i.e. less than 10% of registers and 30% of the total bits of RAM). In this way, the converter could be implemented also using lower performance, lower cost and more rugged FPGA devices, like the Altera Cyclone series. On the other hand, a small decrease of the synchronization accuracy of the PTP system is expected.

4. Experimental evaluation of the proposed architecture

The practical feasibility of the proposed synchronization converter and its performance have been experimentally evaluated. The goals of the experiments are:
• to assess the capability of the proposed converter of reducing the coexistence problems between real-time protocols that use different synchronization approaches;
• to evaluate the effect on the synchronization accuracy when the optimized converter is used.

A specifically designed setup has been created, where two IEEE1588 devices are interconnected by means of a PROFINET infrastructure. The IEEE1588 devices selected for the test are LXI class B instruments. Such a choice is due to two reasons. First, because the PTP protocol is used by these devices to synchronize their reference time. Moreover, because the introduction of Ethernet for industrial as well as measurement (LXI) applications makes highly probable the occurrence of several coexistence problems in the near future. In details, two Agilent LXI Class B “trigger boxes” (model E5818A) have been used as PTP-enabled reference devices. The functionalities of the “trigger box” include the generation of trigger signals based on PTP clock, a very suitable feature for performance assessment.

During the first experiment, the synchronization capability of LXI devices has been evaluated, connecting them by means of a simple network topology (point to point connection through a cross cable). In this way, the propagation delay jitter of frames due to network components (such as hub or switches) and other network traffic, has been minimized; thus, the best synchronization accuracy can be obtained.

During the first experiment, the synchronization capability of LXI devices has been evaluated, connecting them by means of a simple network topology (point to point connection through a cross cable). In the second experiment, they were connected using a dedicated network device, the Hirschmann PTP switch (Hirschmann Mice MS30 with real time RT MM3 module). In the third experiment the LXI instruments were interconnected through a PROFINET IO CC-C infrastructure, in order to investigate the effects of such a network on their synchronization performances. Finally, the proposed solution has been verified; the two LXI devices were interconnected through the same PROFINET infrastructure using two prototypes of the proposed synchronization converter.

4.1. Synchronization accuracy of Class B LXI devices using a simple network topology

During the first experiment the synchronization performance of Agilent LXI trigger boxes has been evaluated, connecting the two LXI devices directly via a cross cable. In this way, the propagation delay jitter of frames due to network components (such as hub or switches) and other network traffic, has been minimized; thus, the best synchronization accuracy can be obtained. The
measure of the time difference between the devices is equivalent to the synchronization accuracy of the specific implementation of the protocol. An estimation of this time difference can be obtained programming the two devices for generating a trigger output signal at the same instant (i.e. the same PTP time). Then, the synchronization accuracy is the time offset error between the two trigger outputs.

The distribution of the offset error, measured using a high stability counter (Agilent 53132A, option 010), is reported in Fig. 7 and statistical parameters are summarized in Table 2. The measures are performed over 6000 samples, about 2 hours, with a PTP sync_interval of 2 s. As shown in Table 2, the synchronization accuracy the devices can achieve in ideal network conditions is of few tens of nanoseconds.

![Figure 7. Distribution of the offset error between the two LXI instruments connected by means of a cross-cable.](image)

4.2. Synchronization accuracy of Class B LXI devices linked through a boundary clock

With respect to the experimental setup of the previous section, a real instrumentation network has a more complex network topology. Usually LXI devices are connected using network components, such as hubs and switches, in order to deploy a structured network. The use of such network devices can cause a significant decrease of the synchronization performances, especially with high network load conditions [19]. For this reason, IEEE1588 introduces network devices, boundary and transparent clocks, for distributing time reference also in a complex network.
A more realistic experimental set-up has been carried out by connecting the two LXI devices through a PTP Boundary clock, the Hirschmann MICE MS30 modular switch with the real time module MM3. In this case as well, the offset error between the trigger output signals of the devices has been used for measuring the synchronization accuracy. The distribution of the offset error (6000 samples) is reported in Fig. 8. As shown in Table 2, the PTP compliant Ethernet switch slightly affects the synchronization performances of the LXI devices (the maximum error is about 40 ns).

![Figure 8. Distribution of the offset error between the two LXI instruments connected through a Boundary Clock.](image)

4.3. Synchronization accuracy of Class B LXI devices connected through a PROFINET infrastructure

The following experiment has been carried out in order to verify the worsening of synchronization accuracy of LXI devices interconnected by a PROFINET IO infrastructure, as already highlighted in the simulation results of section 2.2. The two communication protocols used during the tests (LXI and PROFINET IO) create two different synchronization domains with different timing parameters. The former (LXI) creates a PTP network with a sync_interval of 2 s. The latter is a PTCP network with a sync_interval of 10 ms.

The PROFINET IO CC-C network comprises two IO-Controllers (PNIO C1 and C2 - Siemens CP1616) and two IO-Devices (PNIO D1 and D2 - Siemens EB400) connected in a line topology (also called daisy-chain), in which each node is connected in series to the next. One of these controllers is also the master of the PTCP domain and sends the Sync message every 10 ms. The
PROFINET IO bus cycle time is 10 ms as well, with 330 µs reserved for isochronous real-time communication and the rest for normal TCP network traffic. The two LXI trigger boxes have been connected to free ports of the network infrastructure. The two entry point ports are at the opposite ends of the infrastructure, so the PTP synchronization frames have to travel through the entire real-time network. As in the previous experiments, the synchronization accuracy of the LXI instruments has been tested measuring the offset error between the output trigger signals provided by each device. The medium access policy (TDMA) used by PROFINET introduces additional jitter on the propagation delay of non real-time frames that depends on several parameters (e.g. network architecture, number of devices, etc). The propagation delay of LXI frames (including PTP) over the PROFINET backbone is variable, with peaks up to 70 µs, as shown in Fig. 9.

As a consequence, the PROFINET infrastructure heavily affects also the synchronization capability of the LXI instruments; the standard deviation of the offset error is on the order of 15 µs (as reported in Table 2), three orders of magnitude greater than the previous experiments. Moreover, the offset error distribution, shown in Fig. 10 (obtained using 6000 samples), is in accordance with simulation results [13]. Since the propagation delay affects also the Delay_Req messages, the clock can experience a prolonged bias error in the estimation of the One_way_delay. The bias error persists for a long time until a new delay request is sent. Since the bias error has always the same sign, the distribution is asymmetrical.

Therefore Class B LXI instruments can not be directly linked to a PROFINET IO CC-C infrastructure because a reliable PTP synchronization is impossible due to the particular medium access policy of PROFINET, confirming the simulation results of section 2.2.
4.4. Experimental evaluation of the Converter synchronization accuracy

Since the PTP Sync frames (used by LXI instruments) are handled by PROFINET IO CC-C switches as non real-time traffic, they are heavily affected by propagation delay jitter. The proposed converter should be able to dynamically measure and then to compensate this jitter.

The experimental setup used to test the proposed synchronization converter has been depicted in Fig. 11. The PROFINET IO network, used to interconnect the two LXI devices, is composed of two
IO-Controllers (PNIO C1 and C2) and two IO-Devices (PNIO D1 and D2), similarly as the one described in the previous section. One of the controllers is the GMC for the PROFINET region. The two LXI trigger boxes are connected to the PROFINET infrastructure through two synchronization converters (Conv1 and Conv2).

Similarly to the previous experiment, the synchronization accuracy of the optimized solution has been tested measuring the offset error between the output trigger signals provided by the trigger boxes (M and S in Fig. 11). The offset error distribution, shown in Fig. 12 (6000 samples) demonstrates that the proposed synchronization converter can greatly improve the synchronization accuracy of LXI devices with respect to direct connection to the PROFINET infrastructure. In that case, the improvement is more than three orders of magnitude. On the other hand, the results summarized in Table 2, are slightly worse than those obtained using a dedicated measurement and synchronization network for LXI instruments (section 4.2). However, the synchronization accuracy is well under the upper limit of the expected drift error during a typical PROFINET domain traversal, as discussed at the end of section 3.2.2. Therefore, a good network simplification and the
zero-configuration insertion of the LXI devices in pre-existent PROFINET infrastructure can be achieved at the expense of a small decrease of the synchronization accuracy (i.e. on the order of 10 ns).

Figure 12. Distribution of the offset error between the two LXI instruments connected to the PROFINET IO infrastructure by means of the proposed converter.

<table>
<thead>
<tr>
<th>Offset error (ns)</th>
<th>Experiment</th>
<th>Ave.</th>
<th>Std. dev.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cross-cable</td>
<td>-1</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Boundary Clock</td>
<td>-5</td>
<td>13</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>PROFINET IO</td>
<td>-1000</td>
<td>15000</td>
<td>58000</td>
</tr>
<tr>
<td></td>
<td>PROFINET IO and synchronization converter</td>
<td>1</td>
<td>22</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 2. Offset error between the two LXI instruments during the experiments.

5. Conclusions

The paper dealt with the coexistence problems that can arise when different types of industrial Real-Time Ethernet (RTE) protocols and networks are installed in the same plant. The main problems are related to the clock synchronization accuracy of the coexisting devices. The main objective of this work is the demonstration that a PROFINET IO Conformance Class C infrastructure can be advantageously exploited for the transparent interconnection of RTE devices that use IEEE 1588 for clock synchronization.

Thanks to the synchronization converter approach described in this paper, industrial communication devices or measurement instruments (e.g. EtherNet/IP devices, LXI instruments) can use the
PROFINET IO infrastructure as a black box. Moreover, the zero-configuration required by the proposed solution enables the easy creation of temporary measurement installations, directly located on the production line for the assessment of product quality.

The practical feasibility of the proposed solution has been demonstrated by means of experiments involving converter prototypes based on FPGA, LXI Class B instruments and IEEE1588 devices. The experimental comparison between a private network with boundary clocks for the LXI instruments only, and the proposed application with the LXI instruments connected to the infrastructure of a real PROFINET IO network, showed a small difference of 10ns in terms of standard deviation and 30 ns in terms of jitter.

In conclusion, the proposed approach can be successfully applied in any situation where the network infrastructure must be greatly simplified or the temporality of the installation does not justify the high cost of a separate network. In these cases, a little worsening of the performance with respect to a separate network with boundary clock can be accepted.

References


