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White Paper

Precision Clock Synchronization

The Standard IEEE 1588

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Precision Clock Synchronization
The Standard IEEE 1588

1 Introduction

Precise time information is especially important for distributed systems in automation technology. With the Precision Time Protocol (PTP) described in IEEE 1588, it is possible to synchronize distributed clocks with an accuracy of less than 1 microsecond via Ethernet networks for the very first time. The demands on the local clocks and the network and computing capacity are relatively low.
This White Paper provides you with an overview of the application possibilities and function of the Precision Time Protocol.

2 Why time synchronization

We use clocks to synchronize ourselves with persons or processes. The necessary accuracy of the clock depends on the application. Anyone wanting to catch a train has to have his eye on the clock to within a minute. In competitive sport, a hundredth of a second can be decisive and drives in a packing machine need synchronization in the microsecond range.

Many technical systems have a sense of time. An implicit system time exists when there is no actual clock and the timing behavior is determined by processes in the hardware and software. This is often sufficient in a lot of systems. An implicit time system is implemented, for example, by regular trigger events to every user which indicate the beginning of a unit of time and then trigger the appropriate actions.

The system time is explicitly available when it is represented by a clock. This is often necessary in complex systems especially. This decouples the communication from the execution. But not every clock is exact. Now and again it has to be checked whether the deviation is tolerable and whether the clock needs to be corrected. Communication between the individual clocks is necessary for this.

Two effects are in evidence when setting or synchronizing clocks: independent clocks initially run at an offset for one thing. To synchronize them, the more inaccurate clock is set to the more accurate one (offset correction). Another thing is that real clocks do not run at exactly the same speed. Therefore, the speed of the more inaccurate cock has to be regulated constantly (drift correction).

3 Previous solutions

There have previously been different ways to synchronize distributed clocks through a network. The most common of these are the Network Time Protocol (NTP) and the simpler Simple Network Time Protocol (SNTP) derived from it. These methods are widely distributed in LANs (Local Area Networks) or in the Internet and allow accuracies into the millisecond range. Another possibility is the use of radio signals from GPS satellites. However, this necessitates relatively expensive GPS receivers in every clock as well as the appropriate antennae. This theoretically gives you high-precision clocks but the high costs and effort often prevent it.

Another solution is to send a high-precision time pulse (e.g. pulse per second signal) to every user on separate lines. However, this entails an enormous additional wiring effort.

This is where the Precision Time Protocol (PTP) described in IEEE 1588 comes in. It has been developed with the following aims:

- Synchronization accuracy in the sub-microsecond range
- Minimum requirements of the processor performance and network bandwidth which enables it to be implemented on simple and low-cost devices
- Low administration effort
- Use via Ethernet networks but also via other networks
- Specification as an international standard

4 PTP applications

The idea for PTP was born at the end of the 90s in the USA at Agilent Technologies in the field of measuring technology. The process principle developed there was submitted to the IEEE as a suggestion and created the basis for the IEEE 1588 standard. At the end of 2002 PTP was passed as a standard under the name of "1588™ - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems". In addition, PTP was also adopted as an IEC standard in May 2004 and was published under the name of IEC 61588.

PTP is arousing interest in many different applications. In automation technology, PTP is in demand wherever processes need to be synchronized exactly. Here Motion Control is an important field of application in the broadest sense. Because PTP helps to synchronize drives in a robot or a printing, packing or paper processing machine for example. Interactive robots are also connected by high-precision clocks or whole machine or plant parts are linked closely by PTP so that the processes that run can be synchronized exactly. Clocks running synchronously in every component enable distributed structures to be set up and the processes to be decoupled from the communication and processing of the control commands.

For this reason, the time synchronization according to IEEE 1588 has since become a part of almost all future real-time automation protocols. CIPsync, part of the Ethernet/IP frameworks of the ODVA, relies totally on PTP for Motion Control applications. PROFInet (PNO) uses PTP as a synchronization protocol (Transport of PTP over IEC 61158 Type 10, Annex I in IEEE1588-2008) and ETHERNET Powerlink (EPSG) will also use PTP for synchronizing real-time segments in a future version.

Also, many companies are working on the evaluation and implementation of PTP outside of automation technology. For test and measurement applications the new LXI standard (LAN eXtension for Instrumentation) defines methods and protocols to connect devices with Ethernet and synchronize those devices using PTP version 2. Generally, wherever measured values are detected and need to be put in relation to each other, PTP is a popular solution. In energy distribution systems, parameters such as currents and voltages are measured in distributed sensors, linked centrally and evaluated. Turbine controls use the PTP protocol to set up even more efficient plants. And, for monitoring processes, de-central detected events are marked with precise time stamps and transferred to the control station for logging and analysis. In high-frequency measuring applications PTP is used for correlating de-central detected physical variables. Geo-scientists use PTP to synchronize seismic measuring instruments over great distances and to be able to localize earthquake epicenters more exactly. In telecommunications, PTP is being considered for synchronizing networks or supplying mobile radio base stations with precise time pulses. There is also interest in time synchronization in accordance with IEEE 1588 in the fields of safety technology, digital audio / video transport, automotive technology or military applications.

Many of these applications are currently in the development or prototype stage. However, in the next few years, these applications will come onto the market as regular products and PTP will find wide distribution.

In 2004 the IEEE1588-2002 standard was undergoing revision to meet the interest of additional applications like Telecom, Wireless and others. The P1588 project was started in February 2005 in the IEEE Committee with the aim of extending the IEEE1588-2002 standard. The outcome of this IEEE Committee is the new IEEE1588-2008 standard which will be available in March 2008 with the following new features:

- Better accuracy to achieve sub nanosecond ranges and below
- Faster synchronization (in version 1 SYNC messages occur no faster than 1 second, with version 2 SYNC messages can occur up to several 1000 messages)
- Shorter messages to reduce network bandwidth
- New messages (Announce message, PDelay_Req, PDelay_Resp, Pdelay_Resp_Follow_Up, Signaling messages and also new Management messages)
- Introduction of one-step-mode (no follow-up messages are sent/needed)
- Introduction of Transparent Clocks (End-to-End and Peer-to-Peer) to prevent error accumulation in cascaded topologies
- Introduction of profiles (to define features and settings for different applications and markets, e.g 802.1 AVB Task Group as P802.1AS or PROFInet)
- New mappings to other transport mechanisms like DeviceNet, PROFInet, ControlNet and IEEE802.3/Ethernet (direct mapping)
- Introduction of TLVs to extend the protocol with new features and options to meet the requirements of future applications
- (Optional) Unicast messaging
- (Optional) Path Trace
- (Optional) Alternate Timescales
- (Optional) Master Cluster Tables
- (Optional) Alternate Master
- Security features (experimental only in IEEE1588-2008)
- Conformance specifications
- Configuration options
- Requirements for compatibility between IEEE1588-2002 (PTPv1) and IEEE1588-2008 (PTPv2)

5 The functional principle of PTP

PTP knows different types of clocks and acts as a master to slave protocol. A clock in an end device is known as an ordinary clock, a clock in a transmission component like an Ethernet Switch is a boundary clock (BC) or transparent clock (TC). A master which is controlled ideally by a radio clock or a GPS receiver, synchronizes the respective slaves connected to it.
The synchronization process is divided into two phases. First the time difference between the master and the slave is corrected, this is the offset correction.

Two modes (with IEEE1588-2008) are known for the synchronization process:

Two-step-mode:
In two-step-mode the master sends a synchronization message – SYNC message – with an estimated value of the time cyclically to the connected slaves. Parallel to this, the time at which the message leaves the sender is measured as precisely as possible, if possible by hardware support directly on the medium. The master then sends this actual exact transmission time of the corresponding sync message to the slaves in a second message - follow-up message. These also measure the reception time of these messages as exactly as possible and can correct the correction value (offset) to the master from it. The slave clock is then corrected by this offset. If the transmission line were to have no delay, both clocks would be synchronized.

One-step-mode:
The master sends a synchronization message – SYNC – message with the precise value of the time cyclically to the connected slave. Other than in two-step-mode, the precise time is inserted into the SYNC message "on-the-fly" by the hardware. No FOLLOWUP – messages are needed in this mode. The calculation of the offset is the same as in two-step-mode.

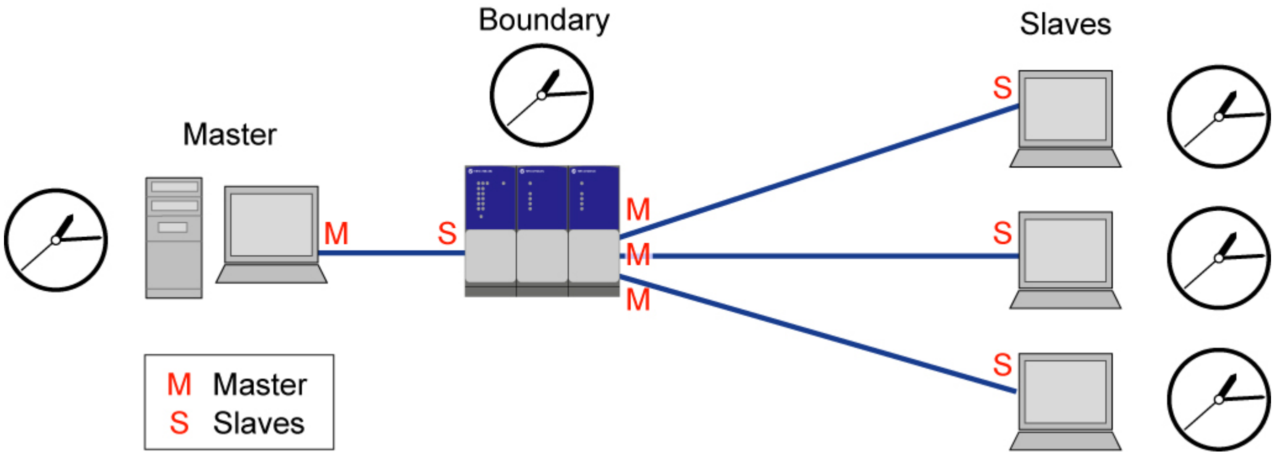

***Figure 1*: Boundary clock switches works as slaves in relation to the master clock and supply the other connected slaves as a master.**

The second phase of the synchronization, the delay measurement, determines the run time between slave and master. This is determined by so-called Delay Request and Delay Response messages in a similar way and the clocks adjusted accordingly. This can also be achieved in one-step or in two-step mode.

Boundary clocks are required wherever there is a change of the communication technology or other network elements block the propagation of the PTP messages. Furthermore it is recommended that a Boundary clock be used wherever there is a network component that inserts significant delay fluctuation. Boundary clocks have typically more than 2 ports, with one port serving as a PTP slave port to an upstream master clock, and the other ports serving as PTP clock masters to downstream PTP clocks. So with Boundary clocks you get time distribution trees. [Figure 1]

The Boundary clocks (BC) defined in both versions of the IEEE1588 Standard respectively Draft Standard [2] evidence two problems when used in (highly) cascaded networks. Namely, there is nonlinear decreasing synchronization accuracy and rising resynchronization time after network reconfiguration. To eliminate these effects the concept of transparent clocks (TC) has been introduced in the IEEE 1588 standard version 2. Transparent clocks were added in IEEE1588 - 2008 to correct the “residence time” of the network device like an Ethernet Switch. The residence time is accumulated in a field (correction field) of the SYNC (one-step) or FollowUP (two-step) message. [Figure 2]. Since transparent clocks are stateless they have no impact on the reconfiguration time of e.g. ring topology networks.

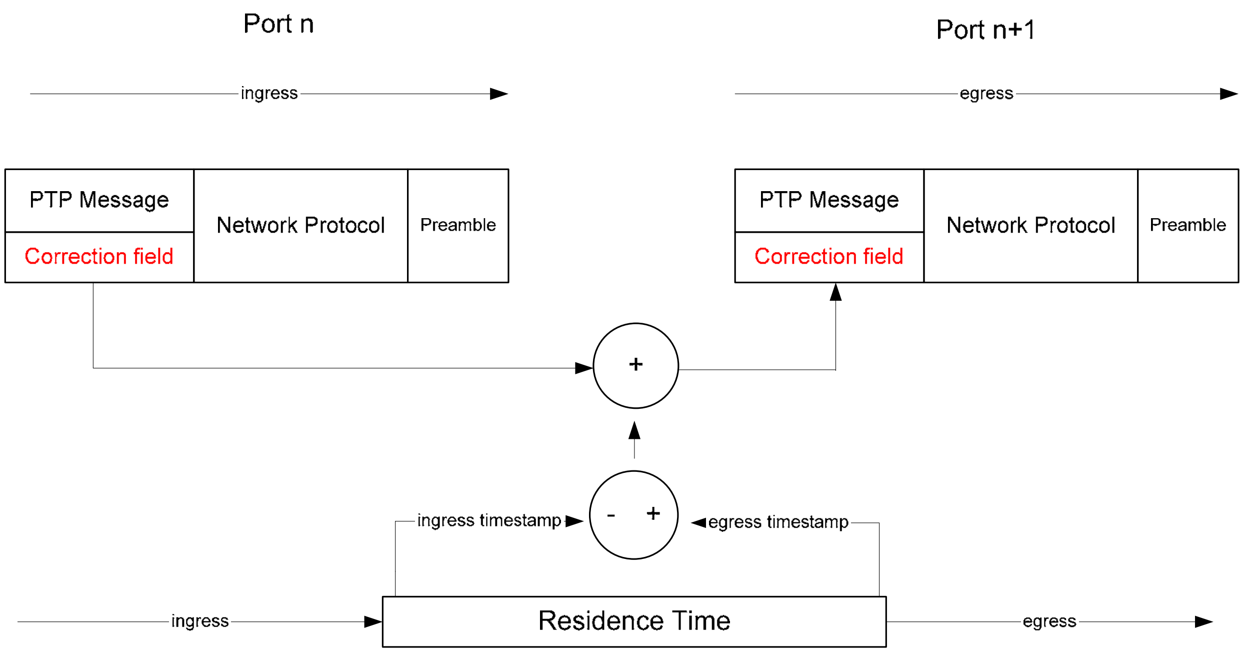

***Figure 2*: Transparent clock residence time calculation**

The IEEE1588-2008 standard knows to types of transparent clocks, namely: End-to-End (E2E) and Peer-to-Peer (P2P).

- End-to-End TCs only measure the time taken for a PTP event message (those who get time stamped) to transit the bridge and provide this information to the receiving clocks in the correction field. No propagation delay of the link connected to the port is corrected by the E2E TC. E2E TCs use the delay request / delay response mechanism for the delay measurement whereby the residence time of the delay request / delay response messages are corrected in the same way stated above.

- Peer-to-Peer TCs use the peer delay mechanism (Figure 3) for the delay measurement. In addition to providing PTP event transit time information the P2P TC also provides corrections for the propagation delay of the link connected to the port receiving the PTP event message (correction field).

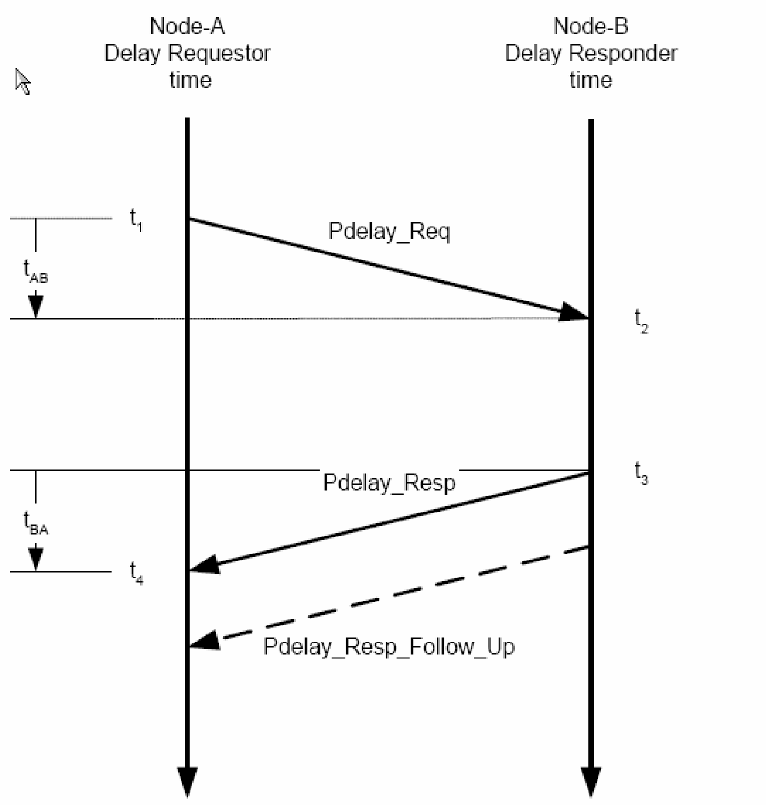

***Figure 3*: Peer Delay Mechanism (taken from [2])**

- The peer delay mechanism measures the port to port propagation delay time between two directly connected ports sharing the same communication technology. The peer delay mechanism is independent of the state of a port (master or slave). It operates separately in both directions of the link.

6 Implementation of PTP

If the Precision Time Protocol is to be used in a system, the PTP protocol stack must be implemented. This can be done very compactly and only makes minimum demands on the processor performance and the network bandwidth. This is very important for the implementation in simple and low-cost devices. PTP can even be implemented without any trouble in embedded systems with simple 16 or 32 bit microcontrollers. The only requirement for achieving a high precision is as exact a measurement of the PTP message transmission and reception times as possible. This must take place very close to the hardware (e.g. directly in the driver software) and with as great an accuracy as possible. In implementations as a purely software solution, therefore, the architecture and performance of the system restrict the attainable accuracy directly.

When using additional hardware support for time stamping, the precision can be increased considerably and effected virtually independently of the software. A little logic is necessary for this which can be integrated, for example, as FPGA or in ASICs directly at the network input.

If PTP is used through Ethernet networks, special attention must be paid to the network infrastructure. Since hubs have almost no influence on the accuracy of the protocol due to their practically constant throughput time, the run times must be taken into account when using switches, as already described in chapter 5. PTP measures the run times in the network and measures the clocks accordingly. However, run time variations, as they always occur in switches, lead to inaccuracy.

Since switches store the received data packets completely and queuing effects can considerably delay the transmission under certain circumstances, significant fluctuations may occur here. At low network load, this effect hardly has an influence, but at greater network load or in temporary load situations, this can considerably worsen the synchronization accuracy.

This is counteracted by using so-called boundary clock switches. These contain their own PTP instance which operates as a PTP slave in relation to the connected master clock and is therefore exactly synchronized by it. In relation to the connected terminating devices, the PTP slaves, every single switch port then operates in turn as a PTP master and synchronizes these slaves with its internal time. This compensates all run time fluctuations and wait times in the switches and enables maximum accuracy to be achieved even through larger Ethernet networks. In highly cascaded networks the cumulative effect of multiple servos (one in each BC), can significantly decrease the clock accuracy. The introduction of transparent clocks in IEEE1588-2008 solves this drawback by measuring the residence time of each network transmission device. It does not matter if an E2E or P2P TC is used. Both correct the residence time of event messages.

7 Results

Hirschmann was one of the first manufacturers to implement and optimize the Precision Time Protocol. A software stack was developed which implements the protocol very efficiently and a chip (FPGA) which supports the process for maximum precision.

In a system in which several ordinary clocks connected by an Ethernet switch with boundary clock function, a typical accuracy of +/-60ns was achieved, practically independently of the network load or workload of the CPU. Variants of the PTP boundary clock are available for the Industrial-Ethernet switches of the MICE family from Hirschmann.

Figure 4 shows the result of 30 boundary clocks cascaded in a linear chain.

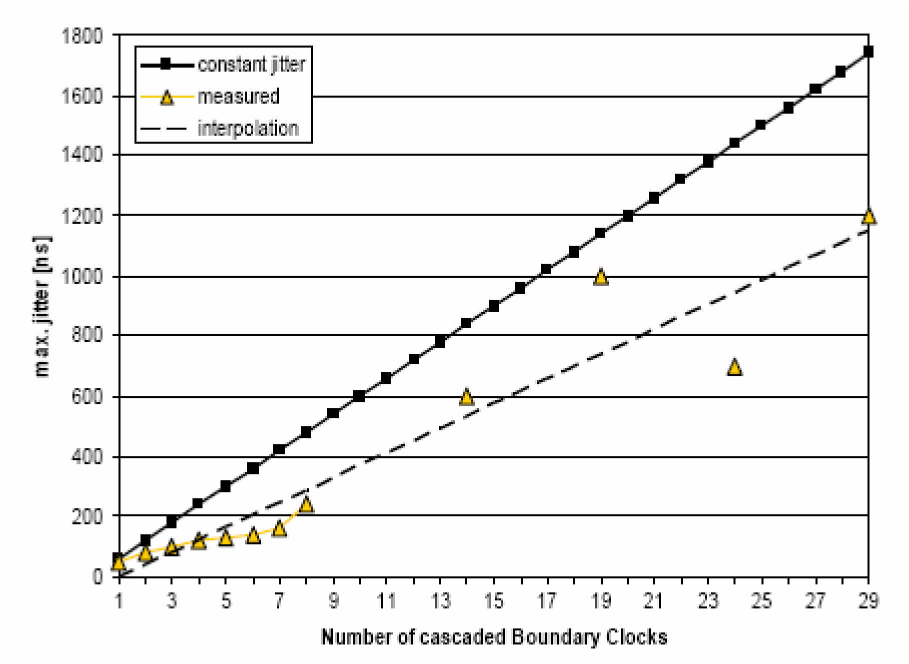

***Figure** 4: Error accumulation / degrade of clock accuracy*

Figure 5 shows the result of 30 boundary / transparent clocks cascaded in a linear chain.

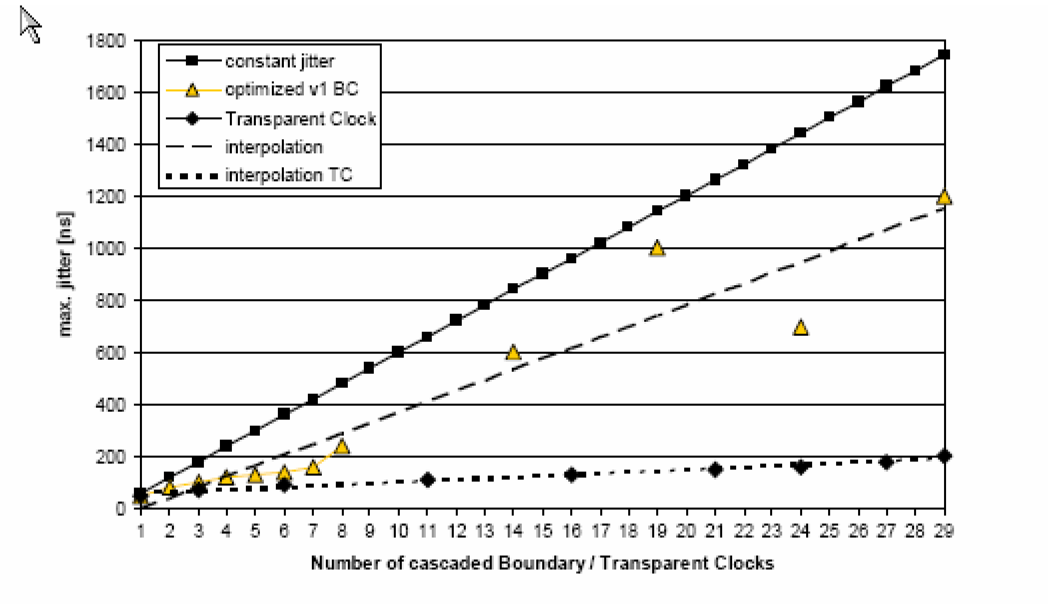

Figure 5: **improved synchronization using TCs**

Due to the missing control loops in transparent clocks the diagram shows clearly the improved synchronization behaviour.

Hirschmann Automation and Control has implemented PTP v1 and v2 Boundary clocks and transparent clocks in his MICE family of Industrial Ethernet switches

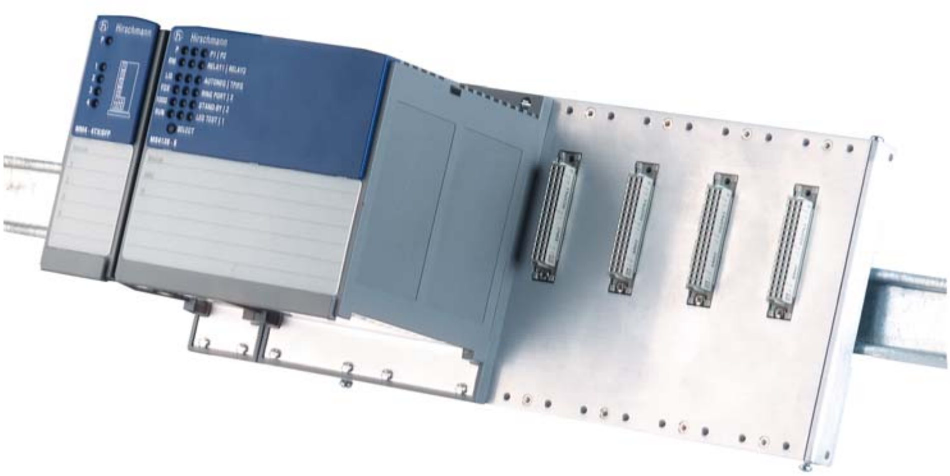

Figure 6: The Industrial Ethernet switches of the MICE series support the Precision Time Protocol according to IEEE 1588-2002 and IEEE1588-2008.

8 Cooperation between Hirschmann and the Zurich University of Applied Sciences (ZHAW)

In cooperation with the Zurich University of Applied Sciences (ZHAW), Hirschmann has been working for a long time of the development and optimization of IEEE 1588 - 2002 and IEEE1588 - 2008. In the scope of this cooperation, the ZHAW offers interested users support in the implementation of PTP products. This includes software stacks and VHDL designs which are based on the technology developed by Hirschmann / ZHAW and additional services such as evaluation kits, training or design support. For further information, see the web site "www.ines.zhaw.ch/ieee1588".

9 Summary

PTP has already proven its capabilities in the lab and is now ready to make the leap to practically applications. You can be assured that PTP will find further distribution over the next few years and that many applications can be implemented much easier and more efficiently than with existing technology.

Further information:

http://www.hirschmann.com	Hirschmann Automation and Control GmbH
http://ieee1588.nist.gov/	IEEE 1588 Standardization Group
http://ines.zhaw.ch/ieee1588/	Zurich University of Applied Sciences, PTP Stacks and Services

Annex 1 – References

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