Technology Update on IEEE 1588:

The Second Edition of the High Precision Clock Synchronization Protocol

Prof. Hans Weibel
Zurich University of Applied Sciences
Institute of Embedded Systems (InES)
Technikumstrasse 9
CH-8401 Winterthur, Switzerland
Tel +41 58 934 75 52
Fax +41 58 934 75 52
hans.weibel@zhaw.ch

Abstract

A high precision time base is important in many distributed systems. The Precision Time Protocol (PTP) specified in IEEE 1588 is able to synchronize networked clocks with an accuracy down to the nanosecond range. The mechanism combines high accuracy and fast convergence with low demand on clocks and on network and computing resources.
A second generation of PTP has been developed and was approved in March 2008. It was published as standard document IEEE 1588 – 2008, also known as PTP version 2 (PTPv2). This new protocol offers some additional interesting features and improvements which open the door to new applications. The paper introduces the concept of IEEE 1588 synchronization mechanisms and explains then in more detail how PTP was enhanced, e.g. by Transparent Clock (TC), peer-to-peer delay measurement, unicast operation, pure layer 2 operation, enhanced accuracy, and extension mechanisms. Application examples show how these enablers are used by industry. Compatibility between PTP version 1 and version 2 is discussed.
The semiconductor industry has created different solutions how PTP can be supported by hardware. The implementation options are outlined and discussed.

Keywords: Clock Synchronization Protocol, Time Dissemination, Ethernet, IEEE 1588, Precision Time Protocol (PTP)

1 IEEE 1588 Time Synchronization Protocol

1.1 What is IEEE 1588?

IEEE 1588 [1, 2] defines the Precision Time Protocol (PTP) which enables precise synchronization of clocks via packet networks. Compared with alternative synchronization mechanisms such as NTP, GPS, or IRIG, IEEE 1588 provides high precision combined with easy installation. Synchronization and data transfer use the same standard network. No expensive extra cabling or line of sight to satellites is required.

IEEE 1588 was developed with the following goals:

- Accuracy to at least microsecond and preferably nanosecond levels.

- Minimal network, computing and hardware resource requirements so that it can be applied to low-end as well as high-end devices.
- Applicable with minimal or no administration to systems defined by a single subnet.
- Applicable to common and inexpensive data networks including but not limited to Ethernet.
- Applicable to heterogeneous systems where clocks of different capabilities and qualities can synchronize to each other in a well ordered manner.

1.2 Where is IEEE 1588 used?

PTP is applied in very different areas.

- Test and measurement: In test and measurement systems, data is acquired by polling the sensors. Sampling timing heavily depends on application program timing and communication latency. A more flexible approach is to equip sensors with a synchronized clock. Each sampled value can then be timestamped for later analysis, or the clock can be used for time-triggered sampling. The LAN eXtensions for Instrumentation (LXI) consortium [5] specifies an instrumentation platform based on industry standard Ethernet technology. LXI makes use of IEEE 1588 to allow triggering directly over the LAN.
- Industrial automation: Ethernet is going to replace field buses more and more. The lack of determinism is compensated with some protocol extensions. IEEE 1588 plays an important role to coordinate communications and actions, and to decouple communication from execution. The presence of precise time information in every device enables distributed synchronous processes to be realized in control applications or in all kind of machinery. For this reason high-precision clock synchronization is considered as a basis for many real-time automation protocols.
- Power industry: In power plants and substations, voltage and current sensors are used to control and protect the equipment. Event timestamping and data correlation facilitates applications including fault localization, network disturbance analysis, and detailed recording of events (exact sequence of events facilitates diagnosis). Synchronized sampling, event timestamping, and other advanced functions require precise synchronization. Traditionally a separate synchronization network is used. Being able to transmit synchronization and data over the same network is a big advantage and saves a lot of cabling.
- Telecommunications: In telecommunication networks service quality depends on accurate synchronization. Such networks are traditionally circuit switched and allow the distribution of clock signals over the physical layer. While the networks migrate more and more to packet switching, many traditional circuit switched services continue to exist. An important telecommunication application is wireless networks. In cellular networks, the handover capability requires precise synchronization of all base transceiver stations. In digital TV broadcast systems (DVB-T), multiple transmitters operating at the same frequency need to be synchronized (in terms of both time and frequency).
- Aerospace, navigation, and positioning: In telemetry, radar, and sonar systems, synchronized clocks are generally of importance. Since GPS is expected to be jammed or spoofed in conflict situations, some independence from GPS may be advantageous.
- Audio and video networks: Low latency audio and video transmission over Ethernet enables new applications in residential and studio applications. The IEEE 802.1 working group Audio and Video Bridging (AVB) [6] works on this topic. Synchronization of endpoints and bridges is an important building block of the solution.

2 IEEE 1588 Operational Principle

This section provides a short overview of the most important mechanisms and characteristics of IEEE 1588.

2.1 Clock Synchronization

The synchronization mechanism is based on a master/slave protocol. PTP instances exchange messages in order to determine the offset between master and slave clocks but also the message transit delay through the network (see figure 1).

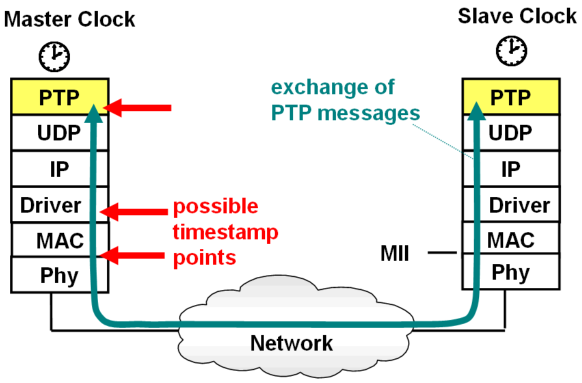

Figure 1: PTP message exchange

Two procedures take place in parallel:

(a) The first task, called syntonization, is responsible to run the slave clock at the same speed as the master. This is achieved by sending a continuous flow of Sync messages from master to slave (see figure 2).

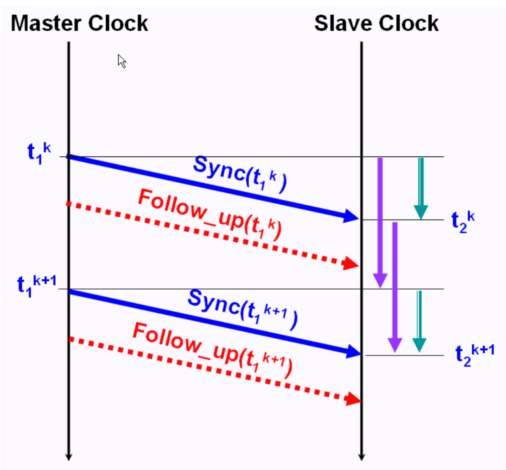

Figure 2: Syntonization

Send time t_1 and receive time t_2 of these Sync messages are measured with the local clocks and processed by the slave. The slave's clock has to be adjusted until time intervals are equal on both clocks, i.e.

$$t_1^{k+1} - t_1^k = t_2^{k+1} - t_2^k$$

$$t_2^{k+1} - t_1^{k+1} = t_2^k - t_1^k$$

There are two options to transport timestamp t_1 to the slave: two-step clocks use the separate Follow_Up message, while one-step clocks deliver t_1 with the Sync message itself. This option requires that the master is capable to insert t_1 into the Sync message on the fly. Because oscillators are susceptible to environmental changes, Sync messages are sent continuously at a constant rate of typically one or a few messages per second.

(b) The second task determines the slave's offset from the master, i.e. the difference of time of day between master and slave. This is achieved by measuring the two-way delay (round trip time). For the downlink, t_1 and t_2 are available from the last Sync. The uplink is measured with a Delay_Req message providing timestamps t_3 and t_4 (see figure 3).

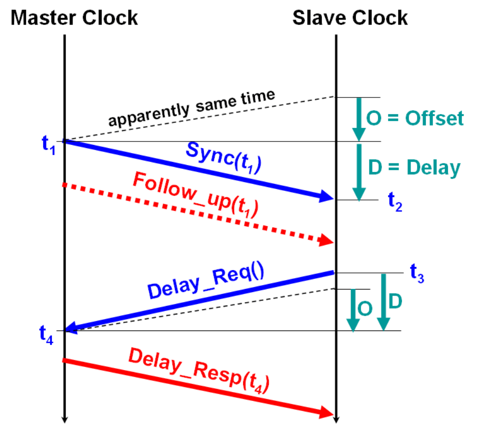

Figure 3: Offset and Delay Measurement

The Delay_Resp message is used to bring t_4 to the slave. Under the assumption of a symmetric transmission path for Sync and Delay_Req, one-way delay and offset from master are computed according to:

$$\text{Delay} = [(t_2 - t_1) + (t_4 - t_3)] / 2$$

$$\text{Offset} = [(t_2 - t_1) - (t_4 - t_3)] / 2$$

Since environmental conditions can change, a continuous correction of the slave clock is required. For this purpose the slave is controlled by a servo loop (typically a PI loop minimizing the slave's deviation).

2.2 PTP Communication and Network

PTP messages are sent to reserved multicast addresses. Therefore PTP clocks do not need an individual IP configuration.

When the delay of the Sync path varies due to queuing in bridges, the individual measurement results are not very useful.

One approach to overcome this problem is the concept of IEEE-1588-aware bridges, known as Boundary Clocks (BC). A BC is a bridge equipped with a PTP clock synchronized by the master over one of its ports (see figure 4). Over the other ports, the BC synchronizes slave clocks attached to it.

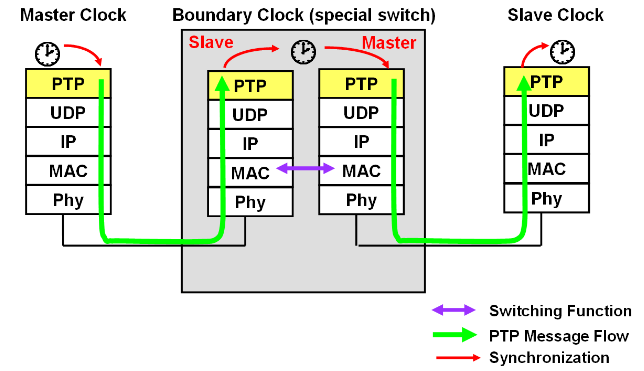

Figure 4: Boundary Clock

Such a configuration represents a synchronization hierarchy (see figure 5) which is established automatically by the so called Best Master Clock (BMC) algorithm. This algorithm takes clock quality and priority settings into account and guarantees that the best available master, the Grandmaster, is the root of the synchronization tree.

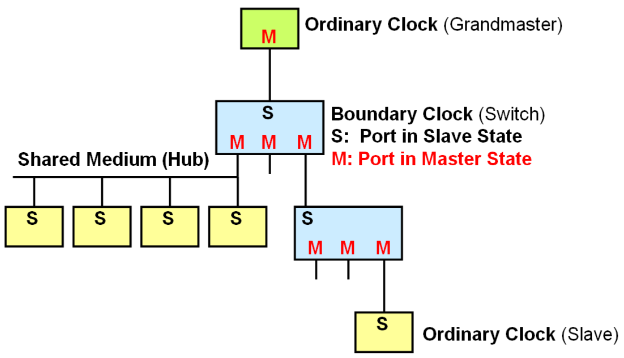

Figure 5: Network topology and clock types

3 History of the IEEE 1588 Standards

The origins of IEEE 1588 are in test and measurement systems, proposed by Agilent Technologies. The method developed there was submitted as a suggestion for standardization to the IEEE. The automation and control industry has joined the community in an early stage. The standard IEEE 1588 – 2002 [1], denoted as version 1 in this paper, was approved in September 2002 and adopted as an international standard by IEC under the label of IEC 61588 in 2004 [3]. In response to new requirements the project P1588 was started to specify a version 2 of the protocol, which was approved in March 2008 under the title IEEE 1588 – 2008 [2], denoted as version 2 in this paper. IEC has adopted this standard as well as IEC 61588 Edition 2 [4].

4 PTPv2 Features

4.1 Short Sync Message and higher Message Rates

Telco applications may require a high Sync rate of up to 128 messages per second. A shorter Sync message saves considerable bandwidth in this case. The 124 octets long v1 Sync message combines two purposes: it provides timestamps for clock synchronization as well as additional information required to run the distributed Best Master Clock (BMC) algorithm. In v2 these functions are split into two separate messages: a 44 octets long v2 Sync message which is purely dedicated for synchronization plus an announce message for BMC algorithm. Since the message rate can be configured individually for all message types in v2, a Sync will typically be sent more often than an announce message.

4.2 Mappings

IEEE 1588 specifies synchronization mechanisms independent of the underlying transport protocol. Annexes describe how PTP messages are mapped to a specific network technology. In v1 there is only one mapping specified: PTP over UDP/IPv4 over IEEE 802.3. The v2 specification adds mappings for PTP over UDP/IPv6 and for pure IEEE 802.3 operation without UDP/IP. PTP messages are identified in this case by a special Ethertype rather than by a port number. Other mappings are defined for fieldbus protocols such as PROFINET, DeviceNet and ControlNet.

4.3 Timestamp Representation

Timestamps are taken whenever a PTP event message (i.e. a PTP message which has a measurement purpose) is sent or received by a clock. The precision and resolution of such a timestamp depends on the implementation. Where timestamps have to be communicated between clocks, the timestamp representation within the PTP message sets the precision limit. Timestamp resolution is 1 ns in v1 and 2^{-16} ns (i.e. 15 femto seconds) in v2. This enhanced resolution paves the way to sub-nanosecond precision and is achieved by adding a new field to the PTP messages, the so called correction field. This field not only improves the timestamp resolution but also supports a new concept for an IEEE-1588-aware bridge type, the Transparent Clock (TC).

4.4 Transparent Clock

The physical layout of a machine determines the topology of an automation network, which is in many cases a daisy chain. When such a topology is built up with BCs, the result is a chain of control loops which is susceptible to error accumulation. That's why the automation community has proposed the new clock type TC. This is an Ethernet bridge which is capable to measure the residence time of PTP event messages, i.e. the time the message has spent in the bridge during transit. Because the residence time is the difference of two timestamps, the TC does not need to be synchronized. It is sufficient if it can measure short time intervals with reasonable accuracy. Syntonization of the local timer improves accuracy. The residence time of the traversed TCs is summed up in the correction field of the Sync message, if the TC is capable to modify the correction field on the fly, or in the respective Follow_Up message. TCs come in two flavors:

(a) In the case of end-to-end (e2e) TCs, the slave measures the delay to the master with an end-to-end delay request / delay response message exchange as described in section 2.1 (see figure 6 and 7).

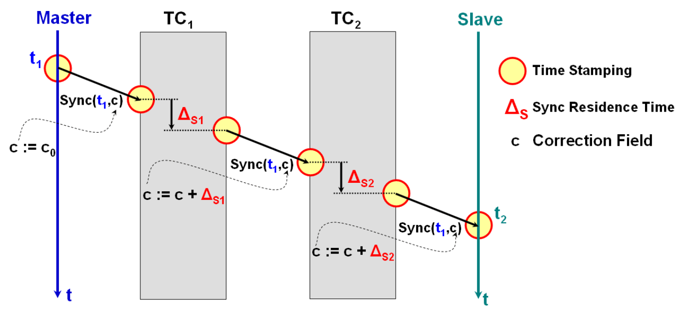

Figure 6: Sync message traversing two end-to-end TCs

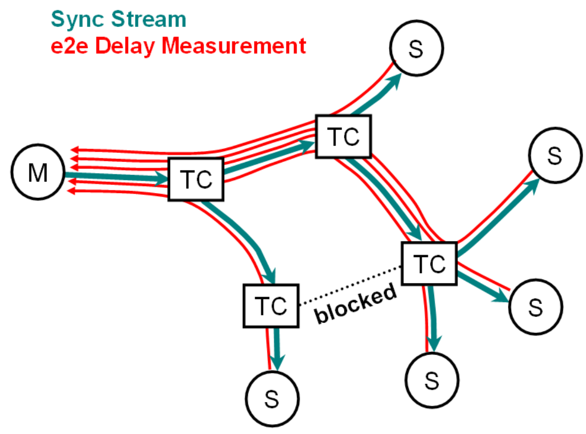

Figure 7: End-to-end TCs in ring topology

(b) The peer-to-peer (p2p) TCs measure the link delay to all neighboring clocks with Pdelay_Req / Pdelay_Resp messages. A third message type may be required for this purpose, the Pdelay_Follow_Up. When a Sync traverses a p2p TC, not only the residence time is added to the correction field but also the uplink delay, i.e. the delay of the link over which the Sync has been received (see figure 8 and 9).

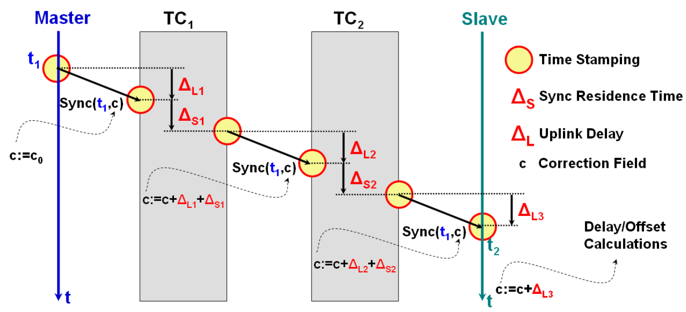

Figure 8: Sync message traversing two peer-to-peer TCs

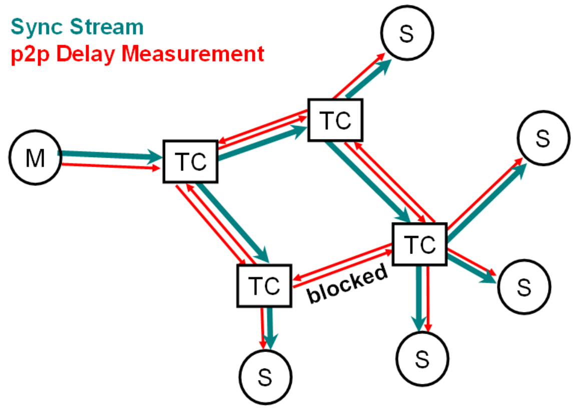

Figure 9: Peer-to-peer TCs in ring topology

Since the link delay is measured over all links, even over links blocked by redundancy protocols like Rapid Spanning Tree Protocol (RSTP), a network reconfiguration is seamless with respect to synchronization. No new delay measurement is required when the Sync path changes. A Sync message always reports its own delay, independent of the path it has passed through.

4.5 Unicast Operation

Multicast is the default addressing mode of PTP. The multicast address is registered and known by all clocks. Therefore no network specific configuration is required. This method has the disadvantage that clocks receive messages destined for other clocks. The required filtering raises a scalability issue. Telco networks may consist of a huge number of slaves and do not always support multicast. Unicast operation has been specified for this purpose. The slave needs to know the addresses of available masters, either by configuration or a dynamic mechanism such as DHCP. A slave can then negotiate the delivery of a PTP message type with a specific rate. The negotiated rate is granted for a limited duration and can be renewed if required. For the purpose of unicast negotiation, IEEE 1588 specifies a signaling protocol.

4.6 Extension Mechanisms

A type, length, value (TLV) construct is used to give PTP messages specific or additional functions. PTP defines e.g. only one signaling and only one management message. The meaning of the message is given by the TLVs it carries. PTP messages can also be extended by means of this TLV mechanism.

The type space is segmented in standard, extension, experimental, and reserved ranges.

Vendor and standard organization extension TLVs can be used by vendors and standard organizations, respectively, to extend the protocol for their specific needs.

Experimental TLVs are intended to facilitate operational experience with extensions that are likely to evolve into future standard extensions. Organizations or companies may apply to the Precise Networked Clock Working Group for experimental type values.

4.7 Profiles

An ample set of operation modes, clock types, parameter values, attributes, and options creates some interoperability issues. An application field typically requires only a subset of what is specified in IEEE 1588, but different fields require different subsets. In order to overcome this problem IEEE 1588 version 2 introduces the notion of profiles. Such a profile defines the range and default values of all configurable attributes as well as all required, permitted, or prohibited clock types and options for a specific application area. Profiles can be created by standards bodies, industry trade associations, or other appropriate organizations. IEEE 1588 defines two default profiles in Annex J.

4.8 Compatibility and Coexistence of the two Versions

IEEE 1588 v1 and v2 clocks can not directly synchronize to each other because they use a different message format.

Islands of different IEEE 1588 flavors can interoperate by means of Boundary Clocks providing different versions or different profiles over its ports.

It is however expected that v2 will be dominant in future applications.

5 Comparison between PTPv1 and PTPv2

Table 1 summarizes the properties and characteristics of the two PTP versions.

Criteria	**PTPv1**	**PTPv2**
clock types	Ordinary Clock (OC) Boundary Clock (BC)	Ordinary Clock (OC) Boundary Clock (BC) end-to-end Transparent Clock (e2e TC) peer-to-peer Transparent Clock (p2p TC) Management Node
time representation	epoc number (16 bit) seconds (32 bit) nanoseconds (32 bit)	seconds (48 bit) nanoseconds (32 bit)
time interval resolution	1 ns	2^{-16} ns (15.26 fs)
message types	Sync Follow_Up	Announce Sync Follow_Up
	Delay_Req Delay_Resp	Delay_Req Delay_Resp
	Management	Management
		Pdelay_Req Pdelay_Resp Pdelay_Resp_Follow_Up
		Signaling
message rates	small choice	bigger range and selectable per message type
addressing	multicast	multicast unicast
mappings	UDP/IPv4 over IEEE 802.3	UDP/IPv4 over IEEE 802.3 UDP/IPv6 over IEEE 802.3 directly over IEEE 802.3 PROFINET DeviceNet/ControlNet
extensions	none	by Type/Length/Value (TLV)
redundancy	BMC	BMC, Alternate Master, Master Cluster
	no	yes
multiple domains	by 4 multicast addresses	by Domain Number (8 bit)
What else?		profiles
		unicast message negotiation
		security protocol (experimental)

Table 1: PTPv1 / PTPv2 comparison

6 Implementing PTP

High precision requires hardware assistance for timestamp generation and clock adjustment while the protocol is implemented in software.

Synchronization accuracy directly depends on timestamp accuracy. The most accurate method is to detect and timestamp PTP messages with hardware assistance as near as possible to the physical layer. Different solutions are applied:

(a) Tap or intercept the Media Independent Interface (MII), where frames can easily be captured, decoded and probably modified (in order to implement a one-step clock). The accuracy of this method is limited by the PHY chip timing characteristics. The required logic can be located in an FPGA or be part of a microcontroller. Figure 10 depicts a block diagram of such a solution.

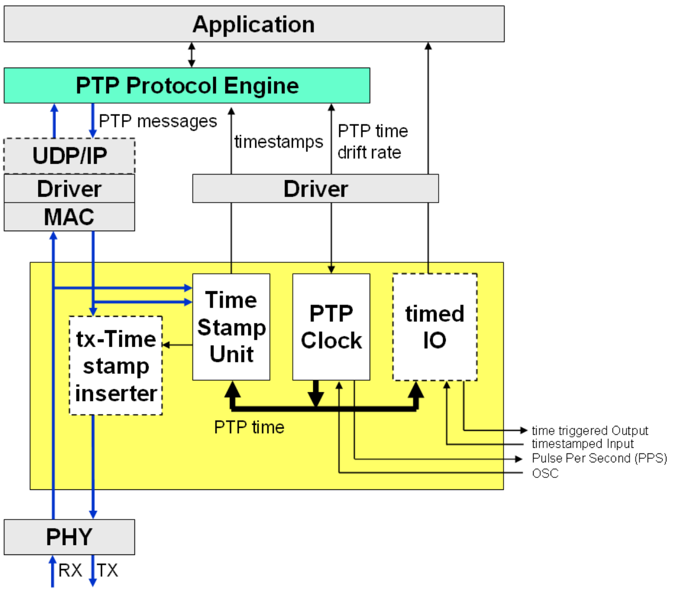

Figure 10: FPGA-based implementation

(b) Parse and timestamp PTP messages in an IEEE-1588-capable PHY. With respect to precision, this is the best place for timestamping because the transmission clock is accessible and buffer effects can be avoided.

The timestamps have to be delivered in some way to the protocol software, together with a message fingerprint (address, sequence number) in order to correlate the timestamp and the respective message.

A slave clock needs to be tunable. It will be accelerated or slowed down according the measurements to reproduce the speed of the master clock a precise as possible.

The protocol software sends and receives PTP messages, fetches the respective timestamps, and carries out the calculations and corrective measures.

The hardware assistance often includes custom logic to make use of the precise time in order to timestamp external events or to generate one-time or periodic external signals (e.g. frequencies locked to time of day).

More implementation details and hints can be found in [7] and [8].

7 Conclusions

PTPv2 standardized in IEEE 1588-2008 has from the protocol point of view the potential to reach synchronization accuracy in the sub-nanoseconds. The rich set of features enables a broad range of application scenarios and fulfills a variety of different requirements.

A growing choice of components, protocol stacks, and tools facilitates the integration of PTP into end products. It is expected that version 2 will displace version 1.

References

[1] IEEE Std 1588™-2002: "IEEE Standard for a precision Clock Synchronization Protocol for Networked Measurement and Control Systems"

[2] IEEE Std 1588™-2008: "IEEE Standard for a precision Clock Synchronization Protocol for Networked Measurement and Control Systems"

[3] IEC 61588 Ed.1: "Precision Clock - Synchronization Protocol for Networked Measurement and Control Systems"

[4] IEC 61588 Ed.2: "Precision Clock - Synchronization Protocol for Networked Measurement and Control Systems"

[5] http://www.lxistandard.org/

[6] http://www.ieee802.org/1/pages/avbridges.html

[7] Weibel, Hans: High Precision Clock Synchronization according to IEEE 1588 - Implementation and Performance Issues. Embedded World 2005, Nürnberg

[8] http://ines.zhaw.ch/ieee1588/