OSCILLOQUARTZ
An ADVA Optical Networking Company

IEEE 1588™ (PTP) in Communication Networks

White paper

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TELECOM NETWORKS
PROFESSIONAL COMMUNICATION
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1 Why PTP?

This Application Note is about the new Precision Time Protocol (PTP), also know by the name of the corresponding standard, IEEE 1588TM. PTP is used for distributing synchronization over packet-switched communication networks. This has become an important technology because of the recent move in telecommunications from traditional Time Division Multiplexed (TDM) networks to packet-switched networks (remark: in this document we often use the term ‘packet switching‘ to designate both L3 packet routing and L2 frame switching). In TDM networks the transfer of synchronization was a natural function of the physical layer of a traffic signal. With the introduction of packet-switched networks new protocol-based synchronization techniques were introduced because of the essentially asynchronous nature of packet switching. PTP is the result of a standardization effort which was initially done for industrial automation and measurement instrumentation. With the second version of the standard, known as IEEE 1588-2008TM, this technology became available for other application spaces, including telecommunications. PTP is now being used in cases where synchronous network elements (such as base stations and Nodes B) are connected to the rest of the network via a packet-switched network. PTP replaces the traditional TDM-based synchronization distribution using E1, T1, STM-n, or OC-n signals. At the same time PTP extends the synchronization capabilities: while traditional synchronization technologies distributed just a common frequency, PTP is now capable of distributing common frequency, common phase-alignment, and even common time-of-day (TOD).

The Application Note gives an overview of PTP technology and its applications. Companion Engineering Notes address more specific technical issues related to particular applications.

2 What Is PTP?

This section explains in simple terms what PTP is and how it works.

In a packet-switched network environment, information is transferred in the form of packets or frames (remark: in this document we use often the term ‘packet‘ to designate both L3 packets and L2 frames); each packet of a packet flow traverses the network (i.e. is switched/routed and transmitted) independently of the other packets of that flow. In the case of synchronization transfer, a master clock and a slave clock exchange information in both directions.

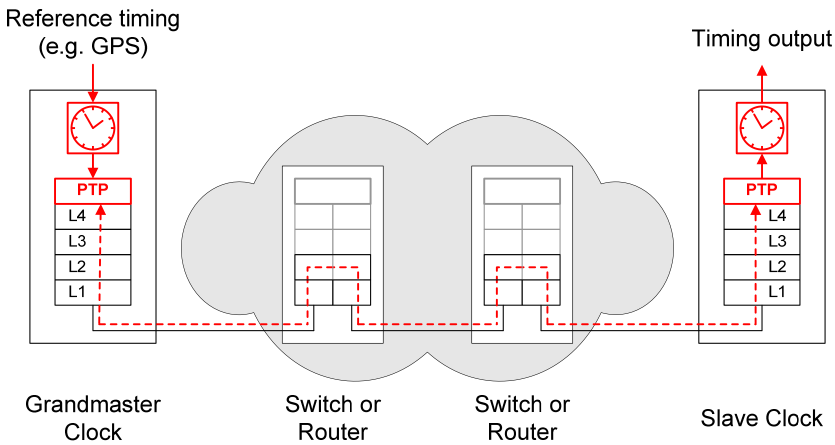

Figure 1: Basic PTP network architecture

The basic architecture is shown in Figure 1. The figure shows the two end systems, i.e. the PTP Grandmaster Clock and the PTP Slave Clock. On their way through the network the packets traverse transmission links (cables, microwave links, etc.) and switching respectively routing network elements. The figure also shows the protocol stacks inside the end systems and the network elements. This is to remind that the PTP protocol uses messages which are assembled and parsed in a layered fashion according the famous OSI principles (Open Systems Interconnection, see [9]).

In the end systems, the PTP protocol layer sits on top of layer 4 (the so-called Transport Layer). In the case of telecom applications, the layer 4 protocol is actually UDP (User Datagram Protocol), whereas the layer 3 protocol is IPv4. There are various mappings for the lower layers, the most popular being the various Ethernet stacks. There exists a number of other protocol mappings adapted to a wide variety of application domains (e.g. PTP over field bus protocols for industrial automation, etc.).

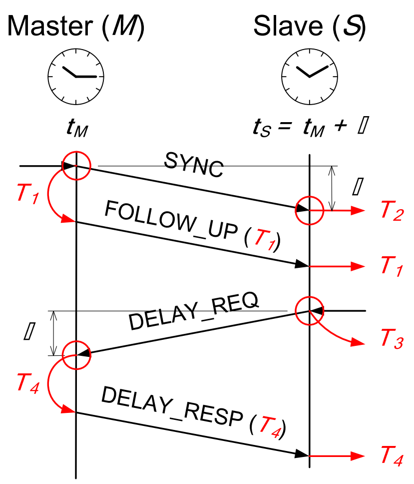

Figure 2: Basic PTP message exchange

Figure 2 shows the basic message exchange sequence. It consists of the following four message types: SYNC, FOLLOW-UP, DELAY_REQUEST, and DELAY_RESPONSE. This sequence is repeated at a certain rate (typically in the range of 8 per second to 64 per second). The FOLLOW_UP message is actually optional[1]. The critical packets in this sequence are the SYNC and the DELAY_REQUEST packets. The master and the slave measure the transmit and receive times of these packets with nanosecond resolution. The timestamps generated by the master are sent to the slave as data field in the SYNC (or FOLLOW_UP) and the DELAY_RESPONSE messages. Based on the four timestamps, the slave is then able to calculate and correct the time-offset which existed between the slave's and the master's time scales:

$$q = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

where θ = time offset between slave's and master's time scales

T_1 = transmit time of SYNC message

T_2 = receive time of SYNC message

T_3 = transmit time of DELAY_REQUEST message

T_4 = receive time of DELAY_REQUEST message

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1 There are two modes of operation in PTP : 'one-step' and 'two-step'. In one-step mode the SYNC message contains (as a data field) the timestamp T_1 corresponding to the transmit time of the message (the timestamp is inserted at the very last moment just before the message leaves the clock as a packet or frame). In two-step mode the timestamp is inserted in the FOLLOW_UP message.

2 The PTP time data fields contain timestamps related to TAI ; a separate data field contains the leap seconds. UTC time can be obtained by calculating UTC = TAI - leap second.

This way of transferring time is called 'Two-Way Time Transfer' or 'TWTT'. Once the slave has aligned its own time to that of the master, the slave derives time-of-day signals (e.g. IRIG-B), phase signals (e.g. 1PPS) and frequency signals (e.g. 10 MHz) from it.

A PTP master runs either a so-called 'PTP time scale' or a so-called 'arbitrary or ARB time scale'. The PTP time scale is related to the internationally defined time[1]. The ARB time scale, while running at the rate of the SI second, has its epoch set arbitrarily. The PTP time scale is used whenever phase or time-of-day synchronization is the objective. The ARB time scale may be used when frequency synchronization is all that is required.

Figure 1 shows switches or routers as network elements on the path between the master and the slave. It is possible to run PTP flows over 'standard' Ethernet switches, 'standard' IP routers, or 'standard' MPLS Label Switched Routers. By 'standard' it is meant that these network elements do not feature any specific PTP functionality; they simply forward PTP packets without modifying them.

The other possibility is to use network elements with specific PTP functions. The IEEE 1588TM standard defines three types of PTP functions for network nodes: 1) Boundary Clock, 2) End-to-end Transparent Clock, and 3) Peer-to-peer Transparent Clock. Let us briefly present these three functions. The presence or absence of such functions in the network has an impact on synchronization performance.

1) Boundary Clock

A Boundary Clock (BC) terminates the upstream PTP connection and initiates a downstream PTP connection. The BC is synchronized to an upstream PTP master or master port (the BC's ingress port acts as a slave), and in turn acts as master to downstream slaves and slave ports. In a case where all network elements on the path are BCs, we are in the presence of a chain of clocks interconnected by individual PTP connections, one connection per hop, where each clock of the chain is slave of its predecessor and master to its successor. Note that only the main message flows (those depicted in Figure 2) are segmented into separate hop-by-hop connections. There are other PTP message types such as the ANNOUNCE messages discussed further down which traverse the BC and are terminated in the PTP clock of the end system.

2) End-to-end Transparent Clock

An End-to-end Transparent Clock (E2E-TC) forwards PTP messages, but modifies SYNC, FOLLOW_UP[2] and DELAY_RESPONSE messages as they traverse the network element. The E2E-TC actually measures the residence times of the SYNC and DELAY_REQUEST messages, i.e. the time between their entering and their leaving the network element. The measured residence time of a SYNC message is added into a data field of the SYNC or the FOLLOW_UP message. This data field is called 'Correction Field'[3]. The residence time of a DELAY_REQUEST message is added into the Correction Field of the corresponding DELAY_RESPONSE message. Since all E2E-TCs on the path add their residence times into the Correction Field of the SYNC respectively the DELAY_RESPONSE message, the Correction Field ends up containing the sum of all the residence times that a SYNC respectively DELAY_REQUEST message has encountered on its way through all E2E-TC network elements on the path. The PTP slave uses this information in order to apply corrections to the calculation of the offset between the slave's and the master's time.

1 Only in case of two-step mode

2 In case of one-step mode the residence time is added to the Correction Field of the SYNC message; in case of two-step mode the residence time is added to the Correction Field of the FOLLOW_UP message.

3) Peer-to-peer Transparent Clock

The Peer-to-peer Transparent Clock (P2P-TC) resembles the E2E-TC. SYNC and possibly FOLLOW_UP messages traverse the clock (they are not terminated by it). The Correction Fields of the SYNC or the FOLLOW_UP messages are modified. The difference with the E2E-TC lies in the fact that the P2P-TC adds to the Correction Field the sum of the residence time and the upstream link delay (whereas the E2E-TC only adds the residence time). The upstream link delay is the estimated packet propagation delay between the neighbour P2P-TC upstream and the P2P-TC under consideration. Here again, the Correction Field of the message arriving at the slave contains the sum of all link delays and all residence times, which actually is equal (at least in theory) to the total end-to-end delay (from master to slave) experienced by the SYNC packet. Again, like in the case of the E2E-TC, the slave uses this information when determining the offset between the slave's and the master's time.

The measurement of the upstream link delay is done with another Two-Way Time Transfer process which takes places between the P2P-TC under consideration and the neighbor P2P-TC upstream (or the Grandmaster clock in the case of the first hop). This process makes use of a pair of messages called 'PDELAY_REQ and PDELAY_RESP (in the case of two-step mode there is also a PDELAY_RESP.FOLLOW_UP), which are repeated periodically.

The message exchange is shown in Figure 3 (the figure actually shows the two-step case[1], in the one-step case the FOLLOW_UP message is missing). The transmit times (T1, T3) and the receive times (T2, T4) of these packets are measured and the peer-to-peer link delay is calculated and then added to the Correction Field as mentioned above. The link delay is calculated using the following well-known formula:

$$d = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

where δ = peer-to-peer link delay

T_1 = transmit time of PDELAY_REQ message

T_2 = receive time of PDELAY_REQ message

T_3 = transmit time of PDELAY_RESP message

T_4 = receive time of PDELAY_RESP message

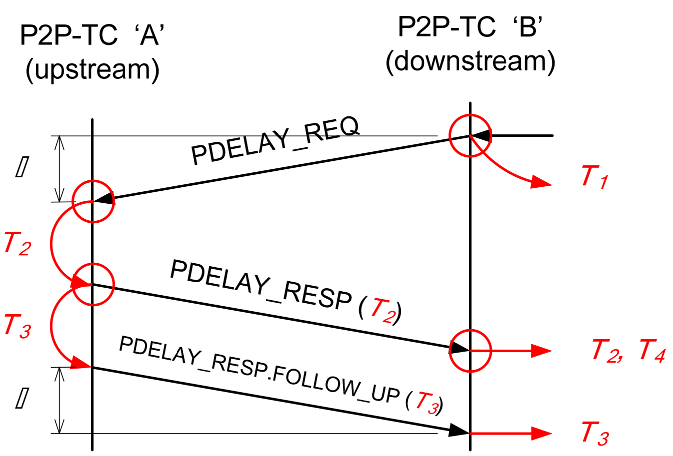


Figure 3: Peer-to-peer message exchange

1 In the one-step case the PDELAY_RESP.FOLLOW_UP message is missing, and the T3 timestamp is conveyed inside the PDELAY_RESP message.

Comment: The two formulae for θ and δ given in this section are based on the assumption that the packet delays in both directions are the same. Any asymmetry in the delays (delay in one direction is different from delay in the other direction) cause an error in the estimation of θ and δ. This in turn affects synchronization performance.

Best Master Clock Algorithm

IEEE 1588TM is more than just a protocol for transferring frequency, phase and time-of-day from one clock to another, as described above. IEEE 1588TM also contains mechanisms for the automatic ordering of a set of PTP clocks (i.e. a set of clocks communicating with each other using the PTP protocol). This mechanism is based on two elements, 1) a way of exchanging identity information between PTP clocks, and 2) a mechanism for ordering the set of clocks into a master-slave structure based on the exchanged information. The exchange of information about identity and properties (e.g. accuracy) between all participating PTP clocks is done via a special message called 'ANNOUNCE'. Once all clocks know each other's identities and properties, each clock runs a special algorithm called 'Best Master Clock Algorithm (BMCA)'. The BMCA decides which of the clocks is the Grandmaster and determines the states (master, slave, passive) of its own ports. IEEE 1588TM specifies a default BMCA. However, IEEE 1588TM also permits standards organizations to specify alternate BMCAs. Such an alternate BMCA is then described in the relevant PTP Profile (see section 4).

3 PTP Profiles

The IEEE 1588TM standard provides many optional features (e.g. unicast delivery) and many configurable parameters (e.g. message rate), which taken together allow PTP to be optimized for a specific application and network context. This flexibility of the IEEE 1588TM standard is the reason why PTP is used in so many different application spaces, including telecommunications. The set of options, together with the ranges and default values of configurable attributes adopted for a specific application form what is called a 'PTP Profile'. A PTP Profile may also contain the definition of an alternate BMCA (see previous section). The purpose of defining PTP Profiles is to assure interworking between clocks and required performance level for a specific application and a specific network context. PTP Profile documents are typically defined and published by standards organizations (after review by the IEEE).

In the field of telecommunications, PTP profiles are defined and published mainly by the ITU-T and by IETF. The first of a series of upcoming profiles is contained in ITU-T Recommendation G.8265.1: "ITU-T PTP profile for frequency distribution without timing support from the network" (see [8]). As the title indicates, this profile is targeted towards frequency synchronization. This is required for operating GSM base stations, UMTS Node Bs, WiMax-FDD base stations, etc. The profile is optimized for networks which do not contain any BC, E2E-TC or P2P-TC (this is what the term "without timing support from the network" in the title of the profile document means). ITU-T is also working on other profiles for other applications cases, e.g. for cases where phase delivery is required. IETF is presently considering the development of a PTP profile for MPLS and MPLS-TP networks (see [10]).

In the field of electric power systems two IEEE standards working groups called IEEE-PSRC (for Power Systems Relaying Committee) and IEEE-SUB (for Substation Committee) are working on a PTP Profile for their specific needs. This is being done in close cooperation with another standards body called IEC TC57. They will soon publish their profile as IEEE Standard PC37.238: "IEEE Standard Profile for Use of IEEE 1588TM Precision Time Protocol in Power System Applications" (see [11]). This profile is targeted at Smart Grid synchronization applications; see section 5.3 for more information.

4 Oscilloquartz Product Line

This section introduces the Oscilloquartz line of PTP products. The reader is encouraged to contact Oscilloquartz (www.oscilloquartz.com) for more detailed information on a specific product. Figure 4 depicts the main products of the line.

OSA 5330/31 PTP Grandmaster

The 5330/31 is a standalone Grandmaster driven by a GNSS-receiver. The GNSS-receiver is either GPS or Glonass. Additionally the 5330/31 can be driven by electrical input signals for frequency (2.048 MHz a.o.), phase (1PPS) and time-of-day (NMEA). In this way the 5330/31 can operate either locked to GPS or Glonass, or it can be connected to an SSU or to any other device capable of delivering the required reference signals.

The main output is the Ethernet port for PTP delivery (FE or GE, depending on the model type). The 5330/31 can serve a few hundreds of PTP Slaves (exact numbers depend on the model type and on the configured PTP message rate).

There are also additional electrical outputs for frequency, phase and time-of-day. It is for instance possible to use the 5330/31 as a GNSS-driven PTP Grandmaster and as a frequency reference source in front of an SSU. The unit can be managed locally or remotely using the Oscilloquartz SyncView Plus management system.

OSA 5320 PTP Slave

The 5320 is a standalone PTP Slave providing many output options. The 5320's PTP input is a 10/100 Mbit/s Ethernet port.

The 5320's PTP engine features very sophisticated algorithms which provide optimum performance in presence of packet delay variations caused by the network. When network conditions degrade beyond a certain level, the 5320 enters holdover mode and maintains good synchronization performance at the outputs until the network conditions have returned to normal.

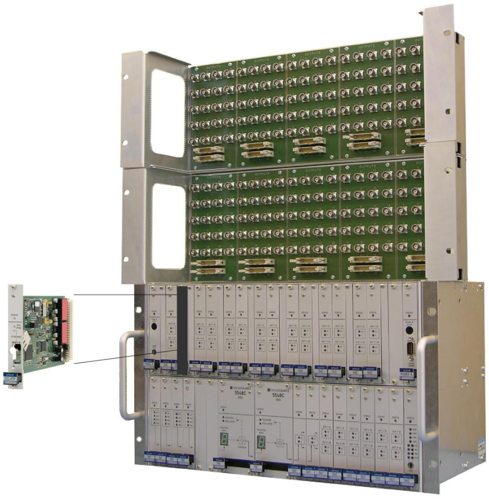
The 5320 can be ordered with three holdover performance options (frequency drift rate of $1 \cdot 10^{-10}$/day or $1 \cdot 10^{-9}$/day or $1 \cdot 10^{-8}$/day). Thus the customer can choose an optimal solution in terms of cost and performance. Another interesting feature of the 5320 is its flexibility in terms of outputs.

The 5320 has 5 separate output ports providing a mix of frequency, phase and time-of-day outputs.

There are several different output variants; each variant comes with a mix of output signals optimized for a specific application domain. Presently the available variants cover three application domains: 1) telecommunications, 2) audio and video broadcasting (e.g. DVB, DAB), and 3) Power Utilities (mainly phase and time-of-day outputs). As with other Oscilloquartz standalone products, the 5230 can be managed locally and remotely via SyncView Plus.

OSA 5330/31 PTP Grandmaster

OSA 5320 PTP Slave



TCC-PTP card for OSA 5548C SSU/TSG

PTP OEM Module

Figure 4: The Oscilloquartz PTP product line

TCC-PTP

The TCC-PTP is a card-level PTP Grandmaster designed for being integrated into Oscilloquartz modular products such as the OSA 5548C SSU/TSG. The TCC-PTP receives frequency, phase and time-of-day from the host product's internal bus. In a typical case the 5548C is equipped with one or two GPS-receiver cards which deliver frequency, phase and time-of-day to the internal bus and thus to the TCC-PTP. In another case, the 5548C is only synchronized in frequency (via one of its electrical input ports); in this case the TCC-PTP is used for distributing frequency only, using the operating mode called 'ARB' (for 'arbitrary time scale', see section 2 above). The TCC-PTP fits into any of the output slots of the host product. This makes the solution scalable. In an OSA 5548C SSU-60 there are three output slots which can receive a TCC-PTP. In the larger OSA 5548C SSU/TSG-200 there is space for 10 TCC-PTP cards. Often these output slots are used to provide diverse output signal types such as 2.048 MHz, 2.048 Mbit/s, 1.544 Mbit/s, 64 kHz C/C, NTP, IRIG-B, 10 MHz, PTP, etc. The modular structure allows customers to combine output card types which best fit their needs. The TCC-PTP is managed locally or remotely through the host product's management interface and SyncView Plus.

PTP OEM Module

The picture at the bottom of Figure 4 shows the possible shape and size of an OEM PTP module. Oscilloquartz has been active in OEM products (e.g. GPS-receiver modules) for many years. The PTP OEM product line is a continuation of this OEM offering. The success of the Oscilloquarz OEM product line is based on a set of outstanding R&D design capabilities. The PTP engines use very sophisticated algorithms for the mitigation of all sorts of impairments caused by the network. The internal oscillators are manufactured by Oscilloquartz. The control of the entire design and manufacturing process leads to exceptionally well behaved oscillators in terms of temperature sensitivity and ageing. These advantages are leveraged in innovative compensation techniques which improve holdover performance.

The PLL (Phase Locked Loop) and DDS (Direct Digital Synthesizer) designs are capable of smoothing out not only stationary noise (jitter, wander), but they also behave well under all sorts of abnormal transient conditions. There is a wide variety of output signal options available, including low phase noise frequency signals with exceptionally good phase noise performance.

5 Application Examples

This section describes some typical application cases where PTP is successfully used.

5.1 Telecommunication Networks

Telecommunication networks are evolving from TDM networks based on circuit-switched technology to so-called Next Generation Networks (NGN) based on packet-switching.

The driver of this evolution is cost reduction; the technical goal is the transport of all telecommunication services over a unified and packet-switched platform. This is generally called ‘network convergence’. Despite the asynchronous nature of packet switching, synchronization is still very much needed in converged Next Generation Networks. It turns out that many access network technologies require some form of synchronization.

This is the case for all cellular mobile networks. They require their base stations to be synchronized. There are other cases like some of the PON technologies used in Fiber-To-The-Home applications. Some of these technologies require synchronization of their equipment clocks in frequency, some in phase, some even require some form of time-of-day.

A useful overview of these synchronization needs can be found in a draft IETF document called “TICTOC Requirements” [17], as well and in Appendix IV of ITU-T Recommendation G.8261 [6]. Table 1 gives an overview of some common telecommunication technologies with the required frequency accuracies and phase accuracies (where applicable).

Table 2 gives more detailed specifications for the LTE case (LTE: Long Term Evolution). In LTE the synchronization requirements depend very much on the optional features implemented in the Node B.

Table 1: Synchronization requirements in telecommunications

Network Element type	Frequency accuracy[1)] (fractional frequency)	Phase-time accuracy[2)] [microsecond]
cdma2000 basestation	5E-8[5)] / 1.6E-8[6)]	3 µs
UMTS-TDD basestation	5E-8[5)] / 1.6E-8[6)]	1.25 µs
UMTS-FDD basestation	5E-8[5)] / 1.6E-8[6)]	
LTE basestation	See Table 2	See Table 2
WiMax basestation	8E-6	~ 1 µs[4)]
APON & GPON Optical Line Terminal	1E-11	
MGW/MSC, RNC/BSC	see Note 3)	

1): frequency synchronization
2): phase synchronization
3): depends on physical layers
4): mandatory for WiMax-TDD, optional for WiMax-FDD
5): specified for base station's air interface
6): commonly considered for base station's input

The key question is: how can all these network elements be supplied with synchronization when the underlying transport network uses an asynchronous switching mode? One of the answers to this question is PTP. Figure 5 shows the case of a 3G mobile network. The architecture shown here can be applied to any of the application cases mentioned above.

The figure shows different possibilities for implementing PTP Grandmasters and PTP Slaves. In the upper part of the diagram the Grandmaster is a TCC-PTP card inserted into an OSA 5548C SSU. The 5548C is located in an MGW / RNC site. It acts as a node or site clock and provides traditional synchronization signals to the MGW and the RNC. The PTP Ethernet port of the TCC-PTP is connected to an ordinary traffic port of a co-located Ethernet switch.

The PTP stream traverses the aggregation network and is terminated on the OSA 5320 PTP Slave located in the Node B station. Depending on what the Node B requires, the 5320 delivers a frequency signal (e.g. 2.048 MHz) and/or a phase signal (e.g. 1PPS) to the Node B. The number of Slaves which can be connected to the SSU-based Grandmaster depends on the PTP message rate and the number of TCC-PTP cards inserted into the SSU.

The possibility to later on add more TCC-PTP cards makes the solution highly scalable.

Table 2: Synchronization requirements for LTE

LTE feature	Frequency accuracy	Phase accuracy	LTE standard
eMBMS with SFN (enhanced Multimedia Broadcast Multicast Service, Single Frequency Network)	50 ppb	1 µs	3GPP Rel 9
Inter-cell interference cancellation	50 ppb	1 µs	3GPP Rel 10-11
N-cell search Femto/macro interference coordination	50 ppb	1 µs	3GPP Rel 10-11
Network MIMO (Multiple Input Multiple Output)	5 ppb	500 ns	3GPP Rel 10-11
Location Based Service	50 ppb	200 ns	3GPP Rel 9

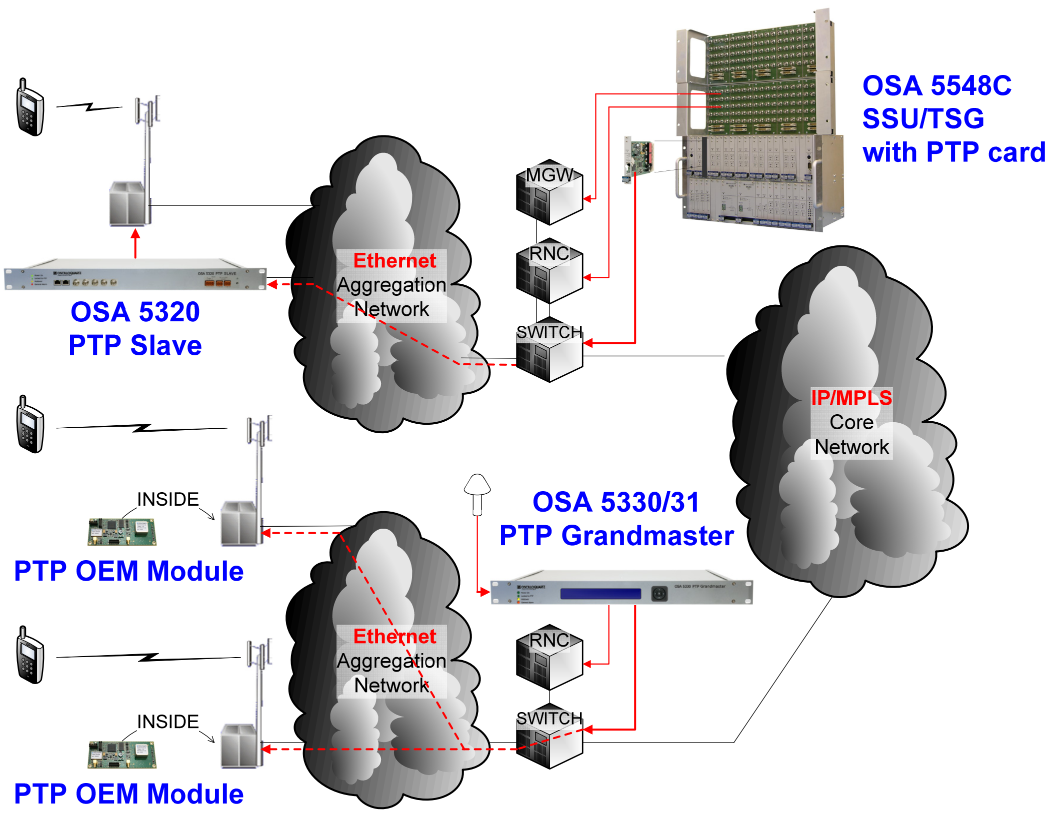


Figure 5: Base stations and Nodes B synchronized by PTP

The lower part Figure 5 shows a different possible implementation. Here the PTP Grandmaster is a stand-alone 5330/31. It is co-located with an RNC. Since the 5330/31 features a few extra traditional synchronization output ports, it can be used as a synchronization source for the RNC.

The PTP port (Gigabit/s Ethernet) is again connected to the co-located Ethernet switch. The 5530/31 serves a number of Node Bs (the maximum number depends on the exact model type and on the PTP message rate). The Nodes B (lower left corner of the diagram) contain an built-in PTP Slave based on an Oscilloquartz PTP OEM module.

The purpose of this section is just to illustrate a few possible implementations. There are of course other possibilities. For the full picture of the design of a PTP network refer to the accompanying Oscilloquartz Engineering Notes.

5.2 Digital Audio and Video Broadcasting

Digital broadcasting, be it audio or video (TV), is another area where synchronization is of paramount importance.

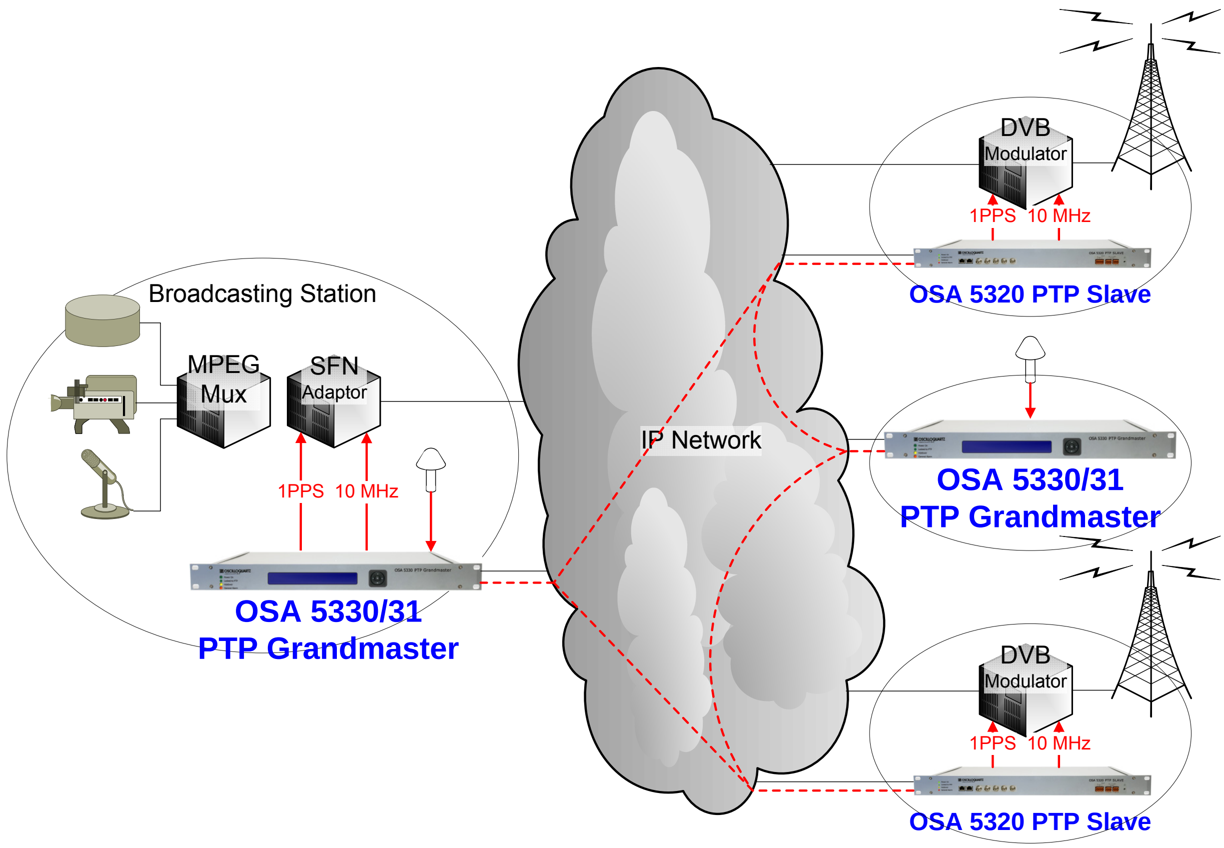


Figure 6: DVB broadcasting system synchronized by PTP

Digital Audio Broadcasting or DAB is a radio broadcasting standard initially developed and published by ETSI (see [14]). It has undergone several revisions (DAB, DAB+, DMB) and is now being adopted throughout the world under the heading WorldDAB and WorldDMB1 (DMB stands for Digital Multimedia Broadcasting; it is an evolution of the DAB standard which includes the broadcasting of video elements).

[1] www.worlddab.org

All three standards (DAB, DAB+, DMB) are based on the same base technology, i.e. they use the same physical layer modulation technique and protocol. The modulation technique used here is the Coded Orthogonal Frequency Division Multiplexing (COFDM) combined with Quadrature Phase Shift Keying (QPSK) and some additional technical tricks.

The main benefit of this technique is that of reducing multipath fading dramatically (the data stream is divided into multiple low-data-rate flows, modulating multiple RF carriers; because the individual flows have low data rates, the duration of the symbols and the additional guard intervals between any two symbols are long; multipath echoes fall within the long guard intervals and hence do not cause intersymbol interference).

An additional benefit of the technique is that it allows building so-called Single Frequency Networks (SFN). DAB transmitter networks are cellular networks; multiple transmitters cover an entire geographical area, each transmitter serving a limited portion or cell. Planning the network coverage is greatly simplified if one uses the same frequency on all transmitters.

Such an SFN is made possible by DAB's COFDM modulation technique (identical symbols emitted on the same frequency by two transmitters arrive at the receiver at slightly different times; if the time difference is within the guard interval, intersymbol interference is prevented - much like with multipath echoes). Building an SFN requires that all transmitters have their RF carrier signals synchronized with an accuracy of ± 10 Hz to a common frequency reference. An easy way of achieving this is by installing PTP Slaves in each DAB transmitter station, and having centrally located PTP Grandmasters serving the slaves.

The situation in the field of television broadcasting is similar to that in radio broadcasting. DVB (Digital Video Broadcasting) is an industry consortium which promotes the deployment of video (TV) broadcasting systems based on a set of ETSI standards. There are several DVB standards for different transmission contexts such as satellite (DVB-S), terrestrial (DVB-T), etc.

The radio interface technology used for the terrestrial version (DVB-T, see [15]) is very similar to what is used in DAB. Multipath fading issues are mitigated with COFDM. Single Frequency Networks are possible. They require that all transmitters have their RF carriers synchronized to a common reference frequency. But this is not enough. The data stream being broadcast (the so-called 'Transport Stream') is assembled in the Broadcasting Studio by the MPEG Mux, as shown in Figure 6.

The Transport Stream is distributed to all transmitters via a transport network (IP). The Transport Stream is structured into frames. These frames must be 'launched' simultaneously by all transmitters. To assure simultaneous transmission despite different and varying delays in the transport network, the frames are time-stamped in the Broadcasting Studio by a piece of equipment called 'SFN Adaptor'. Based on these time-stamps all transmitters align the launch times of the frames to a common time reference (this is done by the DVB Modulators in Figure 6).

A particularly efficient way a distributing common timing to the SFN Adaptor in the Broadcasting Studio and the DVB Modulators in the transmitter stations is PTP. In Figure 6 a PTP Grandmaster is installed in the Broadcasting Studio. A second Grandmaster is installed on a separate site in order to provide redundancy.

The Grandmasters send out PTP streams to all transmitter stations. Additionally a 10 MHz and a 1PPS output are used to synchronize the SFN Adaptor.

In the transmitter sites a PTP Slave recovers timing from the incoming PTP flows and provides a 10 MHz and a 1PPS signal to the DVB Modulator. Thus all equipment of the DVB network is synchronized to a common timing reference.

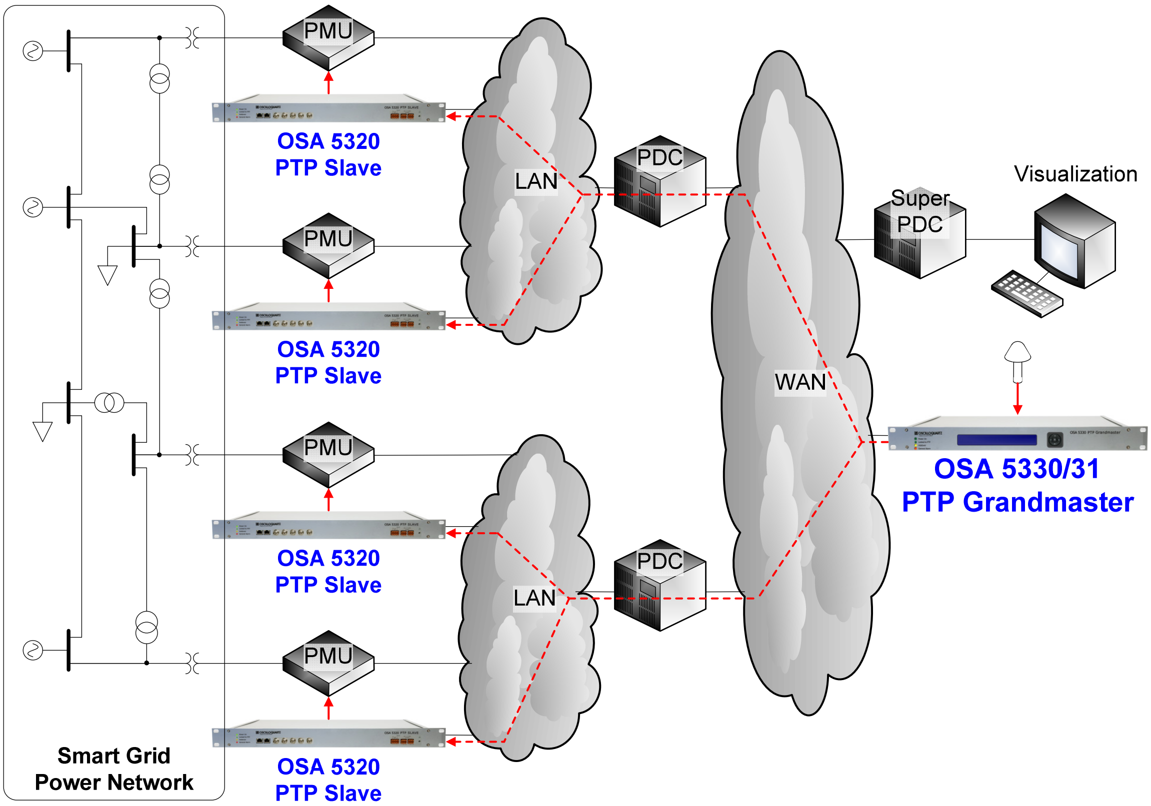


Figure 7: Smart Grid Synchrophasors synchronized by PTP

5.3 Power Utilities

A Smart Grid is an electric power network modernized by the addition of an information system used to monitor and control power flows from the power generators to the individual consumers. Smart Grid is being promoted by many governments in order to address today's challenges related to energy efficiency and system resilience.

There are many aspects of Smart Grid which involve synchronization. The most important one is the measurement of the phase of the 50 or 60 Hz power waves (sine voltages and currents are represented as phasors in the domain of complex numbers: $\bar{U} = U_{RMS} \cdot e^{j \cdot \varphi}$). Synchronized phasor measurements are addressed in the following international standards: IEEE C37.118 (see [12]) and IEC 61850 (see [13]). According to these standards, phasor angles must measured relative to UTC with an accuracy of ± 26 µs.

Figure 7 shows a typical architecture for the synchronization of synchrophasor measurements. Synchrophasor measurements are performed in many places of the power network by small boxes called Phasor Measurement Units (PMU). The measurement results are then transferred to a device called Phase Data Concentrator (PDC). Each PDC collects the phasor measurement results of a certain area. Finally the data of the entire power network are made available to a central management system called Super PDC.

Thanks to the microsecond accuracy and the high sampling rates (10 to 60 per second) of the measurements, the system is able to capture and represent the dynamic behaviour of the power network (earlier systems such as SCADA only represented the stationary behaviour). The hierarchical structure with PMUs, PDCs and Super PDCs allows control systems to be organized hierarchically: decisions with local scope or requiring fast reaction time are taken at the PDC level; decisions with a network-wide scope are taken at the Super PDC level.

Table 3: Smart Grid time synchronization requirements

(source: Fletcher & Moyne; *Smart Grid Time Synchronization requirements*; draft report to NIST)

Application	Need	Absolute Accuracy	Relative Accuracy	Data Sampling Interval	Precision
Substation Automation					
Fault detection / recording	Fault measurements (i.e. digital protective relays)	1 ms	1 ms	50 ms	1 ms
Event ordering	Chronological list of device change-of-state	1 ms	1 ms	event based	1 ms
Process bus synchronization	Synchronization across process bus	1 µs	1 µs	varies	< 1 µs
Energy management systems	Measurement and aggregation of data within process bays	1 ms	1 ms		1 ms
Local data acquisition		1 µs	1 µs	varies	< 1 µs
Transmission and Distribution Automation					
End-to-end line testing	Synchronized line testing requiring coordinated actions at both ends of the line	N/A	1 ms	N/A	1 ms
Wide area data acquisition [Synchrophasors]	Measurement and aggregation of data across a distributed network	26 µs	26 µs	33 ms	1 µs
Meter synchronization	Synchronization of meters for pricing	> 1 ms	> 1 ms		

Since the PMUs are required to measure phase angle relative to UTC, a UTC-traceable time reference must made available to each PMU. This is the role of the OSA 5320 PTP Slave in Figure 7.

The flexibility of the 5320 in terms of output port formats allows one to adapt it to the type of time-of-day signal required by the PMU. Traditionally the power industry has been using IRIG-B signals, sometimes combined with a 1PPS signal.

Synchrophasors are not the only application of Smart Grid requiring synchronization. Table 3 gives a short summary of other applications in need of some form of synchronization.

6 Conclusions

IEEE 1588™ or PTP is an answer to the synchronization challenge in the context of packet-switched networks. PTP is a way of distributing frequency, phase and time-of-day by exchanging PTP packets between a synchronization source (the Grandmaster) and a synchronization consumer (the Slave). This exchange of packets is an implementation of the well-known Two Way Time Transfer (TWTT). PTP can be run over ordinary packet-switched networks with ordinary switches and/or routers. PTP can also be run over networks containing switches and routers with specific PTP functions (Boundary Clock, Transparent Clock). So-called PTP Profile documents determine which PTP optional and configurable features are to be used in a given application and network context in order to achieve optimum performance and interoperability.

Oscilloquartz offers a complete line of PTP products ranging from stand-alone Grandmasters and Slaves, to Grandmaster cards for modular SSUs and TSGs, to OEM modules tailored to meet specific customer needs. Because of its flexibility, PTP is the technology of choice in many different application spaces.

This is supported by the already mentioned PTP Profiles, which allow PTP solutions to be adapted to a given application. This Application Note mentions a few typical application domains, namely telecommunication networks, broadcasting (e.g. DVB, DAB), and Power Utilities (e.g. synchrophasor measurements). There are many other applications where PTP can be used with great benefit.

7 Bibliography

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8 Abbreviations

BMCA	Best Master Clock algorithm
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IETF	Internet Engineering Task Force
ITU-T	International Telecommunication Union, Telecommunication Standardization Sector
LAN	Local Area Network
LTE	Long Term Evolution
MGW	Media Gateway
MSC	Mobile Switching Center
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PRC	Primary Reference Clock
PTP	Precision Time Protocol
PTRC	Primary Time Reference Clock
PTSG	Precise Time Stamp Generator
RNC	Radio Network Controller
TOD	Time-of-Day
UTC	Universal Time Coordinated