IMPLEMENTATION AND TRANSITION CONCEPTS FOR IEEE 1588 PRECISION TIMING IN IEC 61850 SUBSTATION ENVIRONMENTS

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ABSTRACT

This paper presents a general introduction to the Precision Time Protocol (PTP), defined in the IEEE 1588-2008 standard [1] and its novelties in comparison to existing time synchronization and distribution concepts so far used in the electric power industry. Subsequently the paper provides an overview on the so-called power profile according to IEEE C37.238-2011 [2] which has been defined for integrating PTP time synchronisation into modern power systems applications. The next section of the paper focuses on implementation and transition scenarios in power utilities including infrastructural requirements to allow a successful deployment of PTP time synchronisation in such environments. The paper ends with an outlook on discussions and possible future developments with regard to time synchronization in the electric power industry.

INTRODUCTION

Due to the on-going implementation of the IEC 61850 [3] the substation communication infrastructure is changing drastically. The majority of communication between Intelligent Electronic Devices (IEDs), as well as between the IEDs and the station controller is now handled via Ethernet-based networks. Consequently it is logical that also the time synchronisation of these devices should take place over the same network infrastructure to avoid separate wiring for distributing the time synchronisation signals. As a first step in this direction the Network Time Protocol (NTP) [4] was specified in IEC 61850 as a time distribution mechanism to be deployed via Ethernet networks. Since NTP is only sufficient for applications which require time synchronization accuracies in the millisecond range still additional time synchronization methods providing higher accuracies, such as IRIG-B [5], had to be used in parallel. As a result, still separate time synchronization infrastructures were needed.

The Precision Time Protocol is the first accurate and safe way to distribute reference time information throughout the substation's Ethernet network. PTP provides time synchronization accuracies in the sub-microsecond range and is therefore suitable to be used for all timing applications in power utility automation.

TIME SYNCHRONIZATION IN A SMART SUBSTATION

Before touching base on the basic functionalities and advantages of IEEE 1588-2008 PTP it is helpful to understand what technical and regulatory requirements apply for time synchronized measurements and time stamping of data in the modern power grid. Further on this section also provides a short overview on the so far used and implemented time synchronization methods.

Substation Time Accuracy Requirements

As long as all processes and events in a facility like a substation are controlled from one singular central point, the absolute accuracy of the stations system time is not really important. But as soon as time synchronized switching events involving more than one substation have to be performed the absolute accuracy of each station's time reference gains significant importance.[6]

The North American Blackout back in August 2003 visualized how painful and time consuming it can be to align data, whose time stamps are derived from inaccurate time references. As a result the task force investigating the blackout demanded a regulation that ensures a minimum absolute accuracy for time stamped disturbance event data. With the adoption of the NERC[1] Standard PRC-018-1 [7] in 2006 it is now a legal obligation that all recorded data has to have an accuracy of 2 ms or better in relation to UTC[2].[6]

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[1] North American Electric Reliability Cooperation

[2] Universal Coordinated Time Scale

Nowadays, a lot of measurement and control data in the power grid have to have an absolute accuracy of approximately 1 ms:

- SCADA[3] Data
- Data from Event and Disturbance Recorders
- Time Stamped Data from IEDs
- Lightning Strike Correlation

A time accuracy of 1 ms is relatively easy to reach. But some current and emerging future measurement applications require a much higher accuracy. The applications mentioned below for example require an absolute accuracy of 1 µs or better:

- Sampled Values
- Synchrophasor[4] Measurements
- Travelling Wave Fault Location

To time synchronize all devices involved in the processes and measurements mentioned above usually GPS disciplined time references, commonly called substation clocks are used. [6]

In the IEC 61850-9-5 the time accuracy requirements for time tagging of events and time synchronized measurements are summarized in five time performance classes which range from 1 ms to 1 µs and are shown in TABLE 1 and TABLE 2.

TABLE 1: Time performance classes for time tagging of events according to IEC 61850-9-5

Time Performance Class	Accuracy	Purpose
T1	± 1 ms	Time tagging of events
T2	± 100 µs	Time tagging of zero crossings and of data for the distributed synchrocheck. Time tags to support point on wave switching

TABLE 2: Time performance classes for instrument transformer synchronization according to IEC 61850 9-5

Time Performance Class	Accuracy
T3	± 25 µs
T4	± 4 µs
T5	± 1 µs

Classic Time Synchronization Methods

Depending on the applying regulatory requirements and performed measurements a variety of time distribution methods has been implemented to distribute the time reference signal provided by the substation clock to the connected IEDs. Most classic distribution methods require a separate time distribution infrastructure as shown in FIGURE 1.

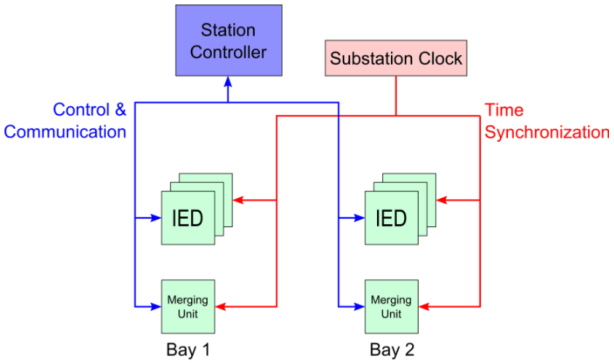

FIGURE 1: Simplified block diagram of a time synchronization signal distribution via a separate time distribution network

The following methods are commonly used for the distribution of time synchronization signals in substations.[6][8]:

IRIG-B. The IRIG[5] Time Codes were originally developed by a working group of the US Military to allow standardized time coding of measurement data originating from different locations. Today mostly the IRIG-B Code is used for civilian applications including the electric power industry. The IRIG-B Code transports the time synchronization signal with 100 bits/s and depending on the used distribution method[6] synchronization accuracy between 1 ms and 10 µs can be reached. For the distribution of the IRIG-B

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[3] Supervisory Control & Data Acquisition

[4] Synchronized phasor measurements of sinusoidal quantities synchronized in time and expressed as phasors.

[5] Inter Range Instrumentation Group

[6] Unmodulated Code (0/+5 V Shift) or modulated Code (1 kHz Carrier)

code either twisted pair wires or coaxial cables are used.

One Pulse per Second (1 PPS). The digital 1 PPS signal is a widely used reference signal for time synchronization and is provided by a lot of substation clocks. The signal is a simple rectangular 1 Hz pulse, whose rising or falling edge marks the beginning of a new second. The synchronization accuracy of the pulse is in the range of a few nanoseconds. If the cable delays occurring during the distribution of the signal are taken into consideration the achievable overall accuracy is about 1 µs. The 1 PPS signal itself does not contain any additional time information which allows linking the edge of the pulse to a specific absolute time. As a result, additional time information needs to be transported to the IEDs via a separate system (e.g. NTP). Due to this fact the importance of 1 PPS for time synchronization in substations is constantly declining.

Serial (ASCII) Broadcast Time Codes. These time codes are just mentioned for completeness. Due to better alternatives they are very seldom used in the electric power industry. In such systems the reference clock distributes the actual time in ASCII string format via a serial interface. The achievable synchronization accuracy is strongly depending on the used bit rate plus firmware and software latencies. For bitrates of 19200 Baud or higher, a typical system accuracy of approximately 1 ms can be reached.

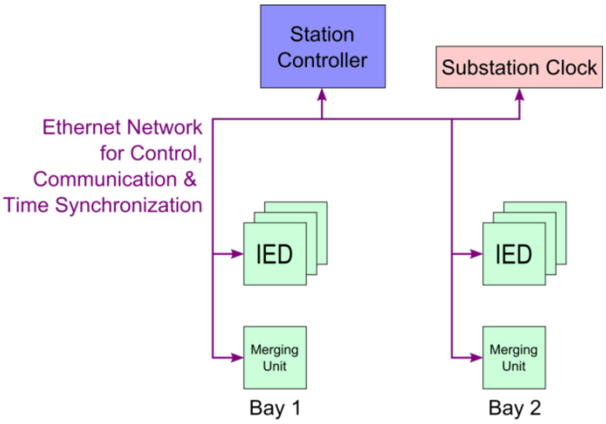

FIGURE 2: Simplified block diagram of time synchronization signal distribution via the station network

As already mentioned in the introduction of this paper the availability of substation-wide Ethernet networks is constantly increasing. Therefore time synchronization systems that can make use of such existing network infrastructures (as shown in FIGURE 1 and FIGURE 2) are constantly becoming more important. Prior the availability of the IEEE 1588-2008 the NTP was the only widely used time synchronization system that could be implemented without the need of a designated separate time distribution network.

NTP. The Network Time Protocol (NTP) is used to synchronize clocks in computer networks and was especially developed to allow reliable time synchronization in networks with variable packet runtime, such as the Internet. The achievable synchronization accuracy is mainly a function of the network traffic and the latencies in the used operating systems. Special algorithms are used to estimate the average delay time between the NTP server and each individual client in the network. In the Internet a time accuracy of approximately 10 ms can typically be reached. In local area networks like used in substations the achievable accuracy is in the range of a few milliseconds. This accuracy is sufficient to assign a certain absolute point of time to the rising edge of a 1 PPS signal. However, since two separate time reference signals (e.g. NTP & 1 PPS), distributed via two separate cablings are required, such combined solutions are very seldom implemented.

TABLE 3: Key characteristics of classical time synchronization methods

System	Typical accuracy	Separate cabling needed	Ambiguity
IRIG-B	10 µs to 1 ms[7]	yes	1 year
1PPS	1 µs	yes	1 second
ser. ASCII	1 ms	yes	none
NTP	1 ms to 10 ms	no	none

In TABLE 3 the key characteristics of the classically used time synchronisation methods are summarized. From the experiences made with these systems the following requirements for an improved time synchronisation method can be derived:

- High synchronization accuracy (1 µs or better)
- Using the existing Ethernet network infrastructure in the smart grid
- Automatic compensation of propagation delays
- No ambiguity
- Support of redundant configurations

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[7] Depending on the chosen distribution method (modulated or unmodulated)

PRECISION TIME PROTOCOL (PTP)

With the Precision Time Protocol, the IEEE 1588-2008 standard [1] defines a solution for synchronizing clocks in a computer network, for example via Ethernet. Like for NTP a common cabling for data communication and time synchronization is used which results in reduced cabling requirements and allows the use of the existing network cabling. Contrary to systems with separate distribution infrastructures the cable distribution delays cannot be simply calculated by measuring the used cable lengths during installation. The route a data packet takes in a computer network can change dynamically and the network infrastructure can be changed very easily, which requires dynamic correction of the network time delay for each data packet. Network components such as switches can cause additional delays for data packets, which can be significantly higher than the delay caused by the cabling. The Precision Time Protocol offers a method that allows determining and compensating the above mentioned dynamic time delays automatically. [6]

Time Synchronization with PTP

The basic principle of the method is shown in FIGURE 3. Two clocks, a Master Clock M (e.g. a GPS disciplined time reference) and a Slave Clock S (e.g. of a protection relay or an intelligent merging unit) are connected via a computer network. The target is to synchronize the Slave S to the Master M with the result that both clocks synchronously provide exactly the same time information. [6]

The time deviation between the two clocks is expressed by the value Δt_{ms}. In FIGURE 3 this deviation is also shown by the shifted zeros on the time axes. The target is to measure Δt_{ms}. To achieve this, a data packet A is sent from the Clock M via the Ethernet network to the Clock S. Thereby the Master M notes the point of time t_1, at which the data packet was sent. Thus, t_1 is a time stamp containing the absolute point in time the master's internal clock showed when the data packet was sent. The data packet requires some time to travel through the computer network before it reaches the Slave Clock S. This time delay is called Δt_{p} in FIGURE 3 and is the sum of all delays caused by the cabling and the network components such as switches. After this time delay the data packet arrives at the Slave S which now generates the time stamp $t_2{}'$.[6]

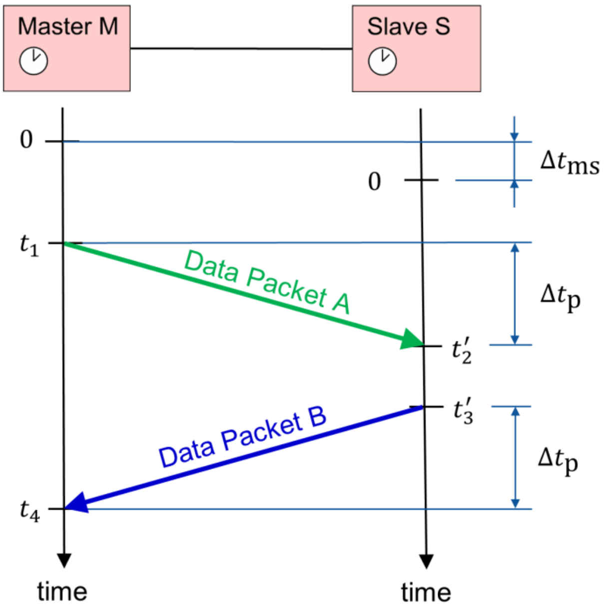

FIGURE 3: Determination of the time between master clock and slave clock using two data packets which are sent in opposite directions

This means that the Slave S notes the time his inner clock shows at the time of arrival of the data packet A. Thus, the relationship between t_1 and $t_2{}'$ is given by

$$t_2' = t_1 + \Delta t_{\mathrm{p}} - \Delta t_{\mathrm{ms}}. \tag{1}$$

Subsequently the Slave S sends back the data packet B to the Master M. The times at which the packet has been sent out by the slave ($t_3{}'$) and at which it has been received by the master (t_4) are recorded for the further calculation. If both data packets take the same path through the network we can assume an identical network time delay Δt_{p} and get

$$t_4 = t_3{}' + \Delta t_{\mathrm{p}} + \Delta t_{\mathrm{ms}}. \tag{2}$$

At each clock two timestamp values are now available, t_1 and t_4 at the clock M as well as $t_2{}'$ und $t_3{}'$ at clock S. As soon as the master forwards his time stamps (t_1 and t_4) to the Slave in a data packet the Slave is able to solve the system consisting of equations (1) and (2) to calculate Δt_{ms}. It obtains the deviation of his time from the master's time as

$$\Delta t_{\mathrm{ms}} = \frac{t_1 - t_2' - t_3' + t_4}{2}. \tag{3}$$

The Slave S can now use this information to correct its inner clock [11]. By continuous repetition of this measurement (typically once every second) and correction of the slave clock the deviation between the master and the slave clock can be reduced to typically 100 ns. [1]

For the delay measurement method described above it is crucial that the propagation delay of both data packets A and B is the same and therefore independent from the direction the data packet travels through the network. In standard network topologies this requirement does not hold due to the fact that standard Ethernet switches store incoming packets before they forward them. This residence time[8] of a data packet inside the switch is depending on a variety of factors including the network traffic which results in inaccuracies. To overcome this problem the IEEE 1588-2008 standard introduces the concept of so-called transparent clocks (TC). These clocks are switches that measure the time a PTP message needs to transit the switch and provide this information to clocks that receive the corresponding PTP message.

Delay measurement mechanisms

Based on the principle introduced above two time delay measurement mechanisms have been defined in IEEE 1588-2008: The end-to-end (E2E) and the peer-to-peer (P2P) mechanism. To ensure trouble-free time synchronization the same delay measurement mechanism needs to be selected for all involved clocks in a network.

End-to-end Delay Measurement Mechanism. When E2E is used, a transparent clock in the system measures the residence time of the PTP message inside the transparent clock and writes it into a special correction field of the PTP event message. If the PTP message travels through several transparent clocks before it arrives at its designated target all residence times are accumulated in this correction field.

Peer-to-Peer Delay Measurement Mechanism. While E2E transparent clocks only measure the residence time inside the clock a P2P transparent clock in addition measures the link delay between the port the message has been received and the port the message originates from. As a result the correction field inside the used PTP messages contain the residence time of all transparent clocks plus the link delays of all links the PTP message has travelled through.

For the E2E configuration the delay measurement takes place separately between the master and each connected slave as shown in FIGURE 4.[9] This results in increased traffic towards the master clock since the master “sees” all connected slaves.

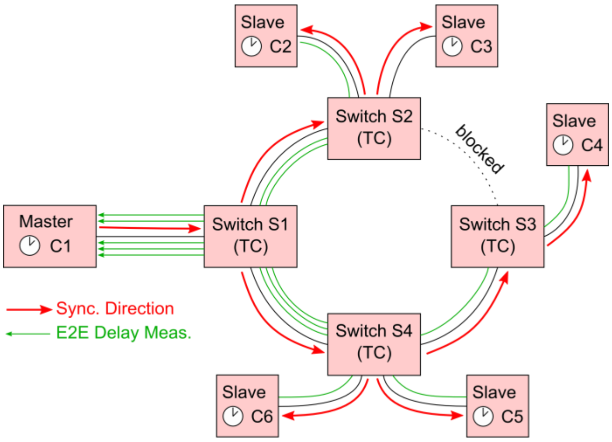

FIGURE 4: End-to-End in a ring topology

For the P2P configuration the Transparent Clocks measure the link delays to all neighbouring clocks as shown in FIGURE 5

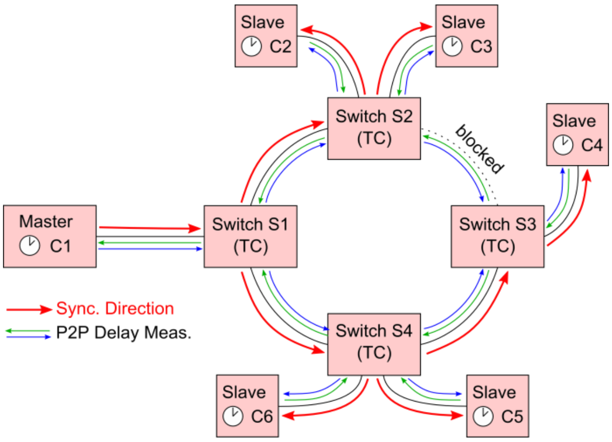

FIGURE 5: Peer-to-Peer in a ring topology

This delay measurement is also performed over links which are blocked by redundancy protocols (such as Rapid spanning tree). This allows a seamless reconfiguration with respect to synchronization since no new delay measurement is required when the synchronization path changes. [9]

Best Master Clock Algorithm

Another special feature of the protocol defined in IEEE 1588-2008 is the Best Master Clock Algorithm (BMCA). This algorithm is used to automatically determine the current best clock, which is the one to provide the reference time in the network. This clock becomes the grandmaster clock in the network and all other clocks synchronize their time to the grandmaster clock’s time. A special manual configuration to define

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[8] The time a data packet is stored in a switch before it is forwarded.

which clock takes over the grandmaster role in the network is therefore not needed. Backup solutions are also covered by the Best Master Clock Algorithm. If the grandmaster clock of the network has a malfunction the second best clock in the network becomes the new grandmaster clock without the need of any special interaction. The protocol ensures that also in complex network infrastructures a unique grandmaster is determined and used for further synchronization.[6]

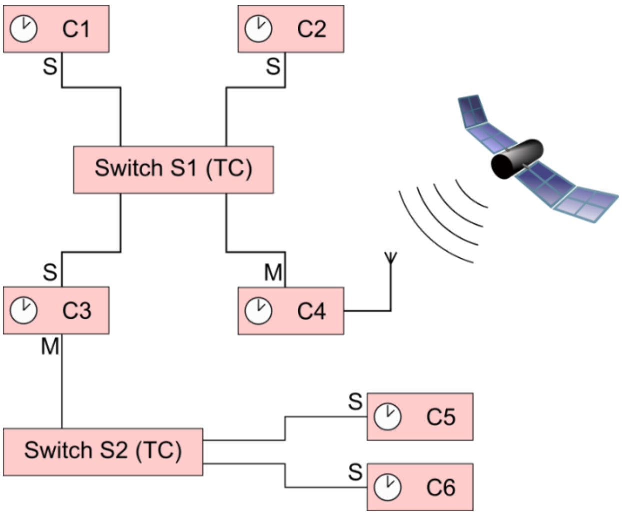

FIGURE 6: Best Master Clock Algorithm (BMCA) in a two-part network with six clocks (C1 to C6).

FIGURE 6 shows a network consisting of 6 clocks (C1 to C6), which are connected to each other via two switches (S1 and S2). Among the six clocks the clock C4 has an outstanding characteristic. This clock has a GPS receiver and is therefore in the position to obtain highly accurate time information from the satellite navigation system. Since this clock possesses the most accurate time in the network the BMCA ensures that clock C4 becomes the grandmaster clock in the network. All other clocks in the network (C1, C2 … which for example can be included in IEDs or intelligent merging units) are synchronizing their time to the time provided by C4. [6]

C3 is a special clock. This clock has two network ports and is therefore in the position to interconnect the two networks around the two switches S1 and S2 with each other. Due to the BMCA the network port of Clock C3 connected to Switch S1 is configured as slave (indicated in FIGURE 6 by the letter S) and as a result C3 receives its time from the grandmaster clock C4. In the network around Switch S2 the clock C3 takes over the master role and forwards the time received from C4 to the slaves C5 and C6. In the IEEE 1588-2008 terminology a clock like C3 is called a Boundary Clock. Such a clock allows for example to synchronize the time in two fully isolated networks to one common grandmaster.[1] The described configuration of the clocks is automatically performed by the BMCA. If a clock removed, added or replaced, the network timing structure is reconfigured automatically.[6]

PTP Profiles

The IEEE 1588-2008 is a very comprehensive standard with many user definable settings to ensure that PTP can be used for a high variety of applications. To ensure interoperability and an easy setup of the PTP equipment the standard introduces the notion of profiles. These profiles define default values and ranges for all configurable attributes, as well as the permitted clock types for a specific application area. The IEEE 1588-2008 standard defines two default profiles in Annex J: The Request-Response Default PTP profile (commonly known as the E2E default profile) and the Peer-to-Peer Default PTP profile. Additional profiles can be created by standardization bodies and industry organizations or other appropriate organizations. [1][7]

THE PTP POWER PROFILE

To ensure the seamless interoperability of PTP equipment for applications in the power industry the so-called Power Profile was defined in IEEE C37.238-2011.[2] This profile was developed by the Working Group (WG) H7 of the IEEE Power Systems Relaying Committee and the WG C7 of the Power Systems Substation Committee. Both groups belong to the IEEE Power and Energy Society.[10]

The PTP power profile was defined to ensure that IEE 1588-2008 time synchronization can be used in mission critical power system applications in 24/7 operation. To reach this target additional profile specific parameters where defined in addition to the chosen IEEE 1588-2008 parameters.

IEEE 1588-2008 Parameters of the PTP Power Profile

This section summarizes the most important IEEE 1588-2008 parameters that have been chosen for the PTP power profile. The complete parameters can be found in the standard [2].

Clock Types. The PTP power profile allows the usage of one-step[9] and two-step clocks. However, it recommends to use one-step clocks since these clocks are state of the art, while two step clocks have been only included due to their early availability on the market. Further on all clock types defined in the IEEE-1588-2008 standard such as ordinary clocks, transparent clocks and boundary clocks are allowed to be used.

Best Master Clock Algorithm. The PTP power profile utilizes the BMCA. The main difference to the default BMCA is that only grandmaster-capable clocks[10] are allowed to advertise themselves as potential grandmasters, while all other ordinary clocks should remain in the slave-only mode. This means that only a grandmaster-capable clock linked to an external time reference can become grandmaster of the substation.

Peer to Peer delay mechanism. The peer-to-peer delay mechanism is defined for use in the PTP power profile. This has the advantage that due to the pre-measurement of all link delays PTP message path changes due to failures of network elements can be resolved quickly and the network load on the grandmaster clock is drastically reduced.

Local Time Type-Length-Value (TLV). Grandmaster-capable clocks compliant to the PTP power profile need to add a Time Offset Indicator TLV to its announce messages[11]. This TLV is used to send time zone related settings and other additional information that allow the IEDs to convert the provided UTC time into local time.

PTP Power Profile Specific Parameters

This section summarizes the most important profile specific adaptations that have been made to ensure seamless integration of IEEE 1588-2008 into IEC 61850 substation environments [2][10]:

Steady-State Performance. To ensure sufficient time accuracy even for the most demanding substation applications, such as synchrophasors and sampled values, a steady-stated performance for delivering the time synchronization information to the slave clocks (e.g. IEDs) has been defined.

The total error at the input of a slave clock is not allowed to be greater than 1 µs after 16 network hops. As shown in FIGURE 7 the grandmaster clock itself is allowed to introduce a maximum error of less than 200 ns and transparent clocks can add a maximum error of 50 ns each. This steady state performance is defined for network loads of 80% of the wire-speed. To achieve this steady-state performance the transparent clocks need to be at least syntonized[12].

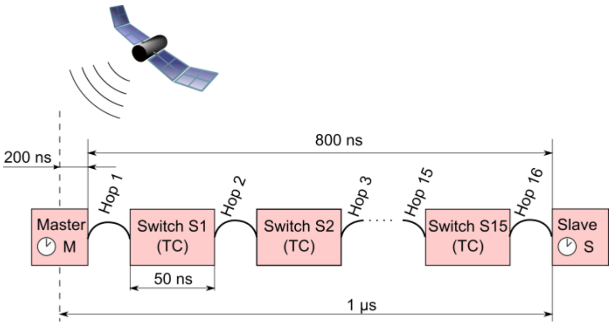

FIGURE 7: IEEE C37.238-2011 steady-state performance requirements

Hold over time for grandmaster clocks. While the IEEE 1588-2008 standard does not define a holdover drift for grandmaster clocks the PTP power profile defines a maximum drift of 2 µs within 5 seconds at constant temperature. This means that in case of time reference loss the current grandmaster is not allowed to drift more than 2 µs for 5 seconds. This time period has been defined to ensure enough time for another grandmaster-capable clock in the system to become grandmaster.

IEEE 802.1Q Tags. The PTP power profile demands that all PTP messages comply with the definitions of IEEE 802.1Q [11]. A tag is inserted into each frame that indicates the frames priority and the frames VLAN[13] membership. The priority field ensures that mission critical traffic such as substation protection messages have a higher priority than less important traffic. The VLAN fields allow partitioning the physical network in a way that the links to each application's IEDs only carry messages designated for these IEDs. The usage

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[9] A one-step clock writes the time stamp directly into the PTP message (e.g. Sync) while a two-step clock sends the time stamp in a separate Follow_Up message.

[10] Grandmaster capable clocks are clocks that are linked to a highly accurate time reference such as GPS.

[11] Announce messages are defined in IEEE 1588-2008 and contain information on the clock it originates from (e.g. Clock quality, Identity …)

[12] Two clocks are syntonized if the duration of the second is the same on both. They may or may not share the same epoch.[1]

[13] Virtual local area network

of VLANs allows increasing the networks security by blocking security threats and ensuring message confidentiality. Further on, it reduces the over-all traffic in the network.

IEEE C37.238 MIB. The PTP power profile specifies a Management Information Base (MIB) for the Simple Network Management Protocol (SNMP). SNMP Traps are included in the MIB to announce events such as grandmaster changes.

IEEE C37.238 TLV. The PTP power profile defines profile specific TLVs which contain the grandmaster identity, the grandmaster's time inaccuracy and the network time inaccuracy. These parameters can be used by the IED to determine its current worst-case time error and therefore the quality of the time stamped data it provides to other applications.

IMPLEMENTATION & TRANSITION SCENARIOS FOR THE SMART SUBSTATION

The comprehensive nature of the IEEE 1588-2008 standard allows developing individual, tailor-made time synchronization concepts for each facility.

PTP Implementation for new Substations

If a new substation can be planned from scratch it is easy to implement IEEE 1588-2008 precision timing since the entire network infrastructure can be planned to ensure that the needs of the IEC 61850 as well as the PTP can be fulfilled.

Network Infrastructure. The engineering of the network infrastructure can take place like for standard IEC 61850 substations. All safety aspects like redundant network structures (e.g. such as ring infrastructures) can be considered. The only timing related requirement is that PTP capable network devices (= transparent clocks) are used to build up the network infrastructure. To ensure interoperability all network devices have to be compliant to the PTP power profile.

Redundancy. To ensure secure availability of PTP it is recommended to have 2 to 3 grandmaster-capable clocks available in the network. The GPS antennas of these grandmaster clocks should be mounted at different locations to minimize the risk of GPS signal loss due to reception problems.

Cyber Security. In general the same regulations and recommendations apply like for standard IEC 61850 infrastructures. In addition it is strongly recommended to use the VLAN capability of the IEEE 802.1Q tags introduced by the PTP power profile. This requires that the used network switches support the ingress and egress of IEEE 802.1Q-tagged traffic.[10]

Mapping of time performance parameters. Substation applications such as synchrophasors and sample measured values require accurate information on time quality and synchronization. PTP power profile clocks provide this information (see IEEE C37.238 TLV). The informative Annex C of the PTP power profile describes how the provided time performance parameters can be mapped into IEC 61850 applications such as IED data time stamping and sampled value services.

Since there are a high variety of substation infrastructures no general implementation recipe can be provided.

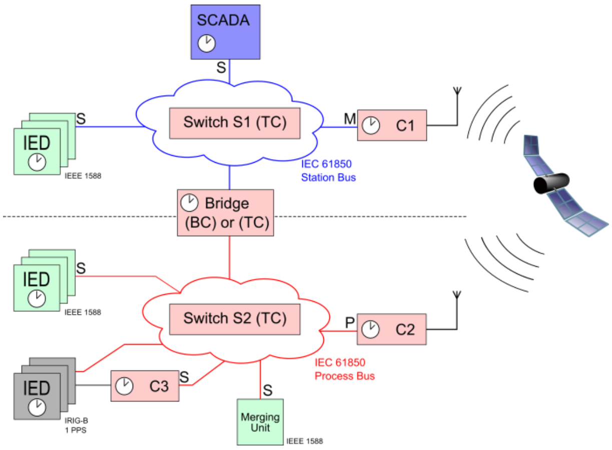

FIGURE 8: PTP implementation example for a smart substation

FIGURE 8 shows a simplified implementation scenario for an IEC 61850 substation. For simplicity the IEC 61850 station bus and the IEC 61850 process bus are symbolized by the two transparent clocks S1 and S2[14]. To each bus a GPS disciplined ordinary clock (C1 and C2) is connected. In our example the clock C1 delivers the best time and therefore it was automatically selected as grandmaster clock by the BMCA. All clocks in the system except clock C2 are synchronized to C1. C2 is in passive mode.

It has been widely discussed how and if the process and station bus should be implemented. Solutions range from two totally separated network infrastructures to one shared network

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[14] In reality a number of switches will be used to provide the bus infrastructure.

infrastructure. From the IEEE 1588-2008 point of view all clocks in a substation should be synchronized to the same Grandmaster clock. Therefore the station bus and the process bus need to be connected somehow. This can happen via a transparent switch, a PTP capable router or a boundary clock as shown in FIGURE 8. A boundary clock allows avoiding a direct connection between the IEC 61850 station bus and the IEC 61850 process bus if this is required by the substation architecture. The shown setup also provides full redundancy. If the clock C1 loses its accuracy the next best clock in the system, which is very likely C2, will become the grandmaster of the entire substation.

Transition considerations for existing Substations

Implementing IEEE 1588-2008 for an IEC 61850 substation that just has been built up a short time ago can be very painful. While the network cabling can be re-used all network devices have to be replaced with PTP capable switches (=transparent clocks). The good news is that not all network components have to be changed at once. The implementation of PTP can be limited to areas where high time synchronization accuracy is required. Modern PTP grandmaster clocks can provide NTP in parallel to PTP over the same network infrastructure. Therefore areas where lower time accuracy is sufficient can be served easily with NTP.

The integration of non-PTP capable IEDs and other vintage equipment can be achieved over various ways. One option is to generate the required time synchronization signals locally as shown in FIGURE 8. The clock C3 is synchronized to the grandmaster clock and locally provides time synchronization signals like IRIG-B or 1 PPS to non-PTP capable IEDs. These IEDs (colored grey in FIGURE 8) communicate via the IEC 61850 process bus and receive their time synchronization signal from clock C3 via a separate wiring. Transparent Clocks with additional IRIG-B outputs to connect vintage equipment are available on the market already.

Non-PTP capable IEDs are not equipped with Ethernet interface hardware that allows for hardware time stamping, which is required to utilize the full synchronization accuracy of PTP. But in principle it is possible to upgrade the firmware of a modern IED to allow PTP time synchronization. By using software-only time stamping an overall accuracy in the range from 20 µs to 100 µs can be achieved [12]. This is sufficient for general time stamping purposes outlined in IEC 61850-9-5 (see TABLE 1) but insufficient for the accuracy classes T3 to T5 (see TABLE 2). As a result IEDs that need to meet the accuracy classes T3 to T5 either need to be upgraded to allow hardware time stamping or exchanged with new devices. Since many substation applications requiring time synchronization are currently using IRIG-B the IEEE C37.238-2011 provides guidance how such applications can be adapted to use the PTP power profile in the Annexes C and D. [2]

The last remaining cable delay

It has been shown that with the implementation of PTP all infrastructure-related delays between the clocks in the network are automatically compensated. Only the time delay caused by the cable that connects the GPS Antenna with the grandmaster clock still needs to be compensated manually. Further on, even special HF antenna cables have high cable attenuation at the GPS reception frequency[15], which limits the maximum cable length to a range from 50 m to 100 m. If difficult reception conditions or other local circumstances (e.g. in a cavern power plant) require to cover longer distances, additional measures, such as the use of in-line amplifiers or signal mixing to an IF frequency, need to be taken.

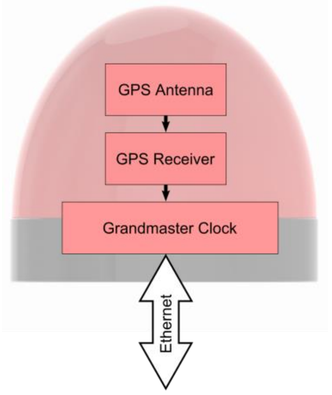

FIGURE 9 Block diagram of an antenna integrated grandmaster clock

By directly integrating the PTP grandmaster clock into the Antenna as shown in FIGURE 1FIGURE 9 the use of a coaxial antenna cable is no longer needed. The connection to the clocks which shall be synchronized to the master can be simply established via Ethernet. The power supply of the grandmaster clock can also be done via the Ethernet cable using Power over Ethernet (PoE). With standard Ethernet cables already a distance of 100 m can be covered. By using optical Ethernet the distance between the outdoor mounted antenna-integrated grandmaster clock and the network clocks to be synchronized can be

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[15] 1.57542 GHz

extended up to two kilometres. Due to the omission of the antenna cable there is no need to manually compensate its cable delay anymore.

ACTUAL DISCUSSIONS AND FURTHER DEVELOPMENTS

The IEEE 1588-2008 standard in combination with the PTP power profile according to IEEE C37.238 provides a comprehensive solution for accurate Ethernet-based time synchronization. Therefore industry discussions typically focus on general problems that either do not directly or only partly relate to IEEE 1588-2008.

Such a general problem, in relation to time synchronization, is the dependability on the global positioning system (GPS). At the moment GPS is the only currently used time reference for power system applications that provides accuracy in the sub microsecond range. The use of backup systems using other time references such as the Russian GLONASS System or the use of local high stable oscillators to bridge GPS reception losses are possible solutions. [10]

Another topic is the network security in general. It is strongly recommended to use a communication path selection process (circuit isolation) by using IEEE 802.1Q tags as proposed by the PTP power profile. This is also compliant to the security standard IEC 62351-6 (clause 4.1) where it is recommended to use a communication path selection process instead of encryption for time critical applications. [10].

Due to the growing trend toward IEEE 1588-2008 for Ethernet-based networks a high variety of network devices and time reference clocks is available. The integration of PTP into IEDs is already either done or on the development roadmap of all major IED manufacturers. Therefore it is strongly recommended to consider IEEE 1588-2008 when new substation infrastructure is planned.

SUMMARY

The IEEE 1588 standard provides all building blocks to implement a reliable, safe and easy time synchronisation system. Since no separate cabling is required the cost of installing and maintaining a separate time distribution network can be saved. The PTP power profile according to IEEE C37.238-2011 ensures that IEEE 1588-2008 fully integrates with IEC 61850. Therefore it can be justifiably claimed that the precision time protocol is an optimum and flexible technology for the time synchronisation in the smart grid.

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