IEC / IEEE

● PMU (Pilot Project)	● PMU (IPP)	★ Central PDC	☆ Regional PDC	★ Local PDC

A wide area monitoring system with more than 5000 PMUs deployed in India

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Precision Time Protocol Profile

for power utility automation application and technical specifications

Electrical utilities depend increasingly on precise clock synchronization to detect grid instability and protect the infrastructure. The IEC and IEEE collaborated on a profile of the Precision Time Protocol that suits the needs of the power utility industry and that is integrated in the IEC 61850 utility communication suite. The resulting standard IEC/IEEE 61850-9-3 provides sub-microsecond time accuracy and supports seamless redundancy.

Time Synchronization in the Grid

Electrical utilities have been one of the most demanding applications regarding time precision. Historically, the electrical grid was the primary provider of time for the synchronization of public clocks (synchronous clocks) and this remains true even today as the grid operators ensure that the number of periods at the end of the day matches the 86400 seconds times the grid frequency (this is a frequency distribution, so the clocks still need to be set).

To track back disturbances, for instance to reconstruct the sequence of events that led to a blackout, a precise time-stamping of events with respect to absolute time is needed. In this application, the time distribution over the network using the SNTP [13] protocol with an accuracy of some 10 ms was sufficient.

With the introduction of digital substations, e.g. based on IEC 61850-9-2, a precise time distribution with a better accuracy is needed. Differential protection schemes protect assets by detecting unbalances in the current flow. Current and voltage are sampled at different places at exactly the same time. This allows applying simple Kirchhoff's law to sense abnormal situations. To this purpose, a sampling accuracy of some microseconds is needed. Since only relative time matters here, the time distribution for differential protection could be done either via a dedicated link, e.g. carrying a 1 PPS signal. This works well within a substation, but for differential line protection between substations, it is impracticable to span dedicated synchronization lines. Rather, the communication network was used under the assumption that the delays were predictable and symmetrical. This was the case with the old analogue telephone lines, and also SDH/SONET networks, but this virtue went lost with the digital data communication packet switching networks, which need exact time to resynchronize the samples.

Synchronization to absolute time became indispensable to detect grid instabilities. Grid collapses announce themselves by variations in the grid frequency, so comparing the phases of voltage and current at strategic nodes of the grid allows to detect an incipient black-out and take measures.

To this effect, the phase of current is measured at strategic positions in the grid by Phasor Measurement Units (PMUs). India is deploying a wide area monitoring system with more than 5000 PMUs. Synchrophasor transmission over PSN (packet switching networks) is specified in IEC 61850-90-5.

The phase measurement in each PMU is time-stamped with respect to absolute time within a few microseconds. Indeed, a phase error precision of 0,1° corresponds to time error of 5 µs on the sampling. A clock accuracy of 1 µs is deemed more than sufficient for this application, since the instrument transformers and the filtering introduce a larger error.

Early PMUS were synchronized by radio receivers listening to broadcast of atomic clocks, e.g. WWV in the USA or DCF-77 in Europe. The devices in the substation were connected in star fashion to the receiver by dedicated lines, e.g. according to the IRIG-B protocol.

Synchronizing by a GPS receiver in each device has become cost-effective, but remains technically impracticable. The reason is that

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utilities do not trust the GPS signal. Some GPS clocks, especially in locations with restricted sky view, have shown degraded performance depending on the satellites that are visible. The antenna must also be deployed outside of the substation if the substation is entrenched or subterranean. Especially in northern countries, the GPS signal can be interrupted by aurorae. The signal could be spoofed, presenting a cyber-attack risk.

So, the solution that imposed itself, is to use atomic clocks, e.g. rubidium clocks, in dedicated network nodes. The time is transmitted over the wide area network (WAN) that controls the grid, as explained in IEC TR 61850-90-12. Similarly, the time signal is distributed within the substation using the same Ethernet as for the data communication, as explained in IEC TR 61850-90-4. This makes that an IED can be used as a PMU. In addition, the LAN transmission eliminates the dedicated 1 PPS or IRIG-B links within the substation.

Figure 1 shows an example of time synchronization in a substation. The primary reference comes from the wide area network (e.g. an SDH/SONET or MPLS network), where a number of atomic clocks maintains the absolute time. In case of WAN disruption, a local rubidium atomic clock maintains the time until WAN recovers. A GPS receiver is used for consistency check and to adjust leap seconds in UTC time. This diversity is also a protection against cyber-attacks that spoof time. As help for commissioning, the master clocks can generate 1 PPS signals to check that all IEDs are correctly synchronized.

Figure 1 shows three different types of bay that need synchronization: classical bays with no process bus, bays with merging units to classical instrument transformers and bays with a process bus and distributed digital instruments.

Principle of PTP

Precise time distribution relies on the estimation and correction of all transmission delays between a master clock giving the absolute time and a slave clock synchronized to it. When one hears Big Ben striking noon, it is noon past some seconds, depending where one is.

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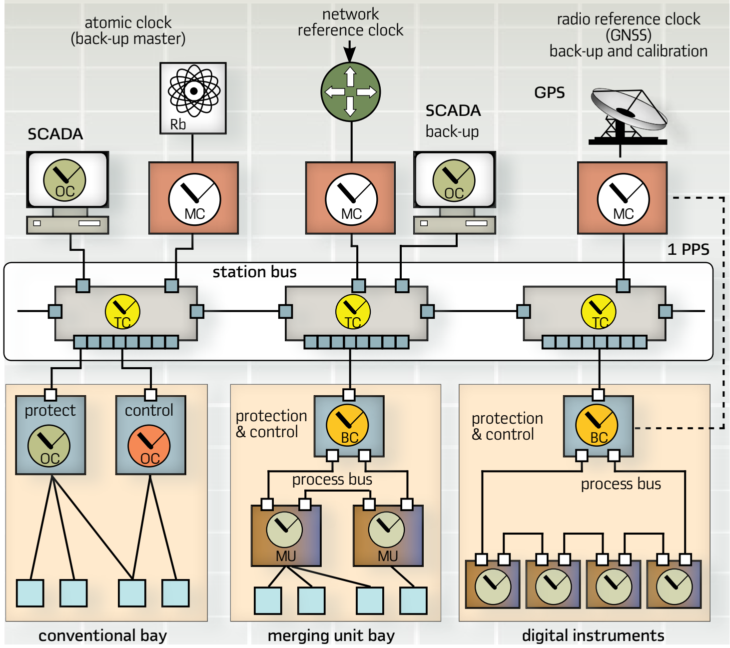
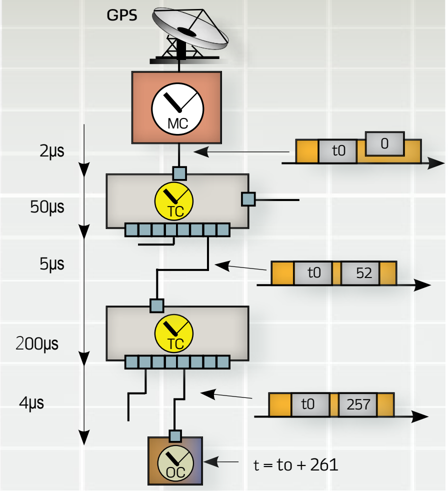
1 Time distribution in a substation



Note: Abbreviations are defined in Figure 8

2 PTP time transmission



In radio transmission, the distance between the sender and the slave clocks and the signal paths must be known to estimate the propagation delay. In long-wave radio such as DCF-77, surface propagation is assumed while in shortwave radio such as WWB the (quite variable) ionospheric path is considered. GPS greatly improves the precision by precise location of the slave clock with respect to the satellites and estimation of the signal path delay with an atmospheric model. In data networks, the delays consist of propagation delay over the medium (link delay, about 5 µs/km) and forwarding delay of the packets in the network nodes, bridges or routers (residence delay, in the order of milliseconds depending on traffic).

The IEEE 1588 Precision Time Protocol (PTP) distributes both TAI (atomic time) and UTC (legal time). It was standardized in 2008 and adopted by IEC as IEC 61588 in 2009. 1588 (for short) lets a master clock broadcast a Sync message that carries the exact time when the Sync left the egress port of the master. The Sync message travels through the network. Each network node that receives a message over a port forwards it on all its other ports, after correcting the time to account for its residence delay and the link delay (per port), as Figure 2 shows. A device that relays the Sync and corrects it is called a transparent clock (TC). TCs can be used in LANs (over Ethernet) and in WANs.

The transparent clocks are normally integrated in bridges (switches). However, the

IEEE 802.1D bridge functionality does not apply to 1588. So even ports blocked by the Rapid Spanning Tree Protocol send (modified) Sync messages.

The measurement of the residence time in each node requires that a port can precisely record the time at which a Sync enters the port and the moment the (modified) Sync message leaves the port. To this effect, a time-stamping mechanism is implemented directly in the Ethernet physical interface (PHY) as Figure 4 shows.

To this effect, the TC captures the egress time when the first bit of the header after the preamble is sent, calculates the difference between egress and ingress time, adds the link delay to it, sums it to the former correction field, modifies the correction field and finally adjusts the checksum of the frame all while the frame is being transmitted (Figure 5). This is called a one-step correction.

Since correcting a frame on the fly can only be done in hardware, 1588 foresees also a two-step correction in which a subsequent Follow_Up message transmits the correction, which is not considered here to simplify.

To correct for the link delay, each port of a clock node calculates the link delay to its peer by a request-response message, called a Pdelay_Req and Pdelay_Resp, as Figure 3 shows.

A port measures the link delay to its peer by calculating the time difference between sending the Pdelay_Req and receiving the Pdelay_resp, and deducing the residence time that the peer indicated in its Pdelay_Resp message, i.e.

$$\lambda = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$$

This method assumes a symmetrical delay. If an asymmetry is known beforehand, it can be compensated for. Here also, a two-step correction can be applied, and in this case the peer returns its residence delay in a subsequent Pdelay_Resp_Follow_Up message.

1588 also supports a different kind of clock nodes, called boundary clocks (BCs). The boundary clocks were the historical solution in 1588v1 before the advantages of transparent clocks became obvious.

A boundary clock is a network node in which one port is synchronized by another master clock and synchronizes the local clock. The other ports of the boundary clock act as master in their respective region. So a boundary clock separates regions within with a time distribution domain, each region having its own master. The master at the top of the hierarchy is called the grandmaster.

While BCs do not offer the same accuracy as TCs, because a chain of clocks need to be synchronized, they are effective to separate the network into islands should the main synchronization fail. They however cannot serve as protocol translator, e.g. between profiles of 1588. Figure 6 shows the elements of a 1588 time distribution scheme

Clock Accuracy

Each clock introduces a certain inaccuracy. The master clock accuracy depends on the quality of the reference and of the frequency stability of the local oscillator.

3 Link delay calculation by peer delay measurement

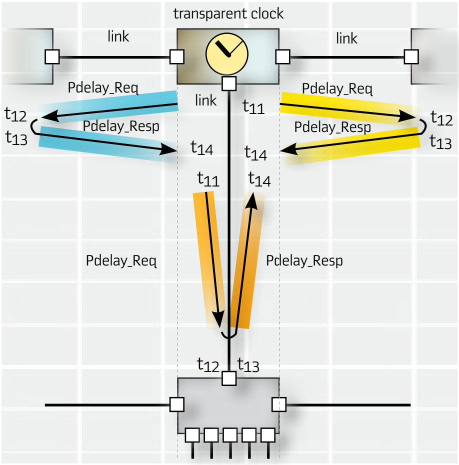


Figure 3: To correct for the link delay, each port of a clock node calculates the link delay to its peer by a request-response message, called a Pdelay_Req and Pdelay_Resp.

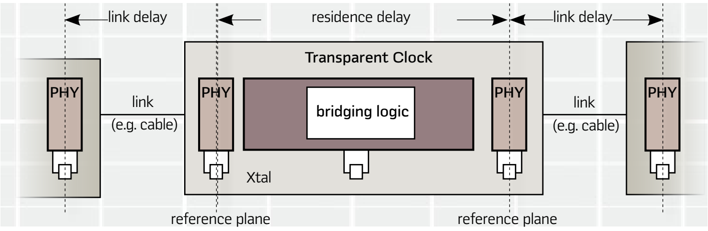
Each transparent clock introduces an error in the timestamping, since its local quartz frequency is not infinite and the local oscillator has only a limited stability. For implementation reasons, there are several quartzes and therefore quantification errors appear. And finally, the quality of the local oscillator of a TC is lower than that of the grandmaster, even if it is properly synchronized (tuned to the frequency of the master).

So inaccuracy increases with the number of TCs and BCs clocks in series. Figure 7 shows the time error histogram of the different clocks in function of their position in the Sync path. For the purpose of power utility automation, the PMUs and other demanding devices must be located so that the accuracy at their location is still sufficient.

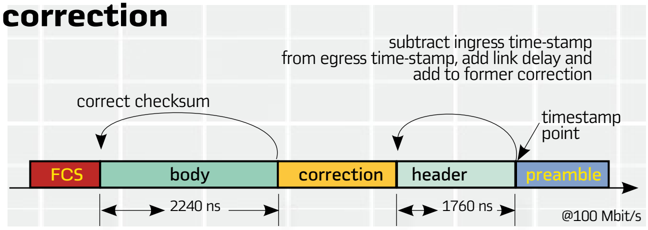
The IEC-IEEE 61850-9-3 Standard

1588 allows a number of options, including 1-step/2-step correction, end-to-end/peer-to-peer delay measurement, layer 2/layer 3 operation, different LANs, etc. but does not specify performance.

4 Time-stamping in a network node



5 Sync frame in 1588 with one-step correction



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The IEC/IEEE 61850-9-3 Standard is a profile of 1588 for the power utility automation, i.e. it is a subset of 1588 except for the (optional) redundancy method. It is derived from the profile in 1588 Annex F (Ethernet) and default profile Annex J.4 (peer-to-peer).

The main parameter of IEC/IEEE 61850-9-3 are summarized in Table 1.

The 1588 does not specify performance. IEC/IEEE 61850-9-3 specifies by how much the different components may degrade the time inaccuracy, so as to guarantee sub-microsecond accuracy after 15 TCs or three BC.

The network engineer knows from this information where to place the grandmaster and the slaves that require high accuracy. The manufacturer guaranteed clock inaccuracy is also part of the object model of each clock, which is also readable when the devices are in place. But discovering during commissioning that a substation network presents intolerable inaccuracy accumulation can cause high costs in re-engineering, so a worst-case approach was chosen.

There is no ongoing check of clocks degradation, except for the grandmaster accuracy, which can degrade due to loss of reference signal. A grandmaster is supposed to maintain its accuracy during 5 s after loss of reference signal (e.g. GPS)

Time accuracy depends on the interval between Syncs. Other 1588 profiles use shorter intervals, but it was shown that 1 s intervals are optimum. The grandmaster also issues an Announce message that indicates its characteristics; here also, 1 s was chosen to account for a master transfer within 5 s.

Redundancy Principle

Substation automation systems require a very high availability. Therefore, LAN redundancy is required. IEC 61850 specifies to use the redundancy scheme of IEC 62439-3 [8] Parallel Redundancy Protocol) (PRP) and High-availability seamless redundancy (HSR).

PRP operates on the principle that the nodes are attached to two separate, completely independent LANs operated in parallel. Such a doubly attached node sends a frame over both LANs simultaneously; the frames travel through both LANs; a receiving node takes the first frame and discards the duplicate.

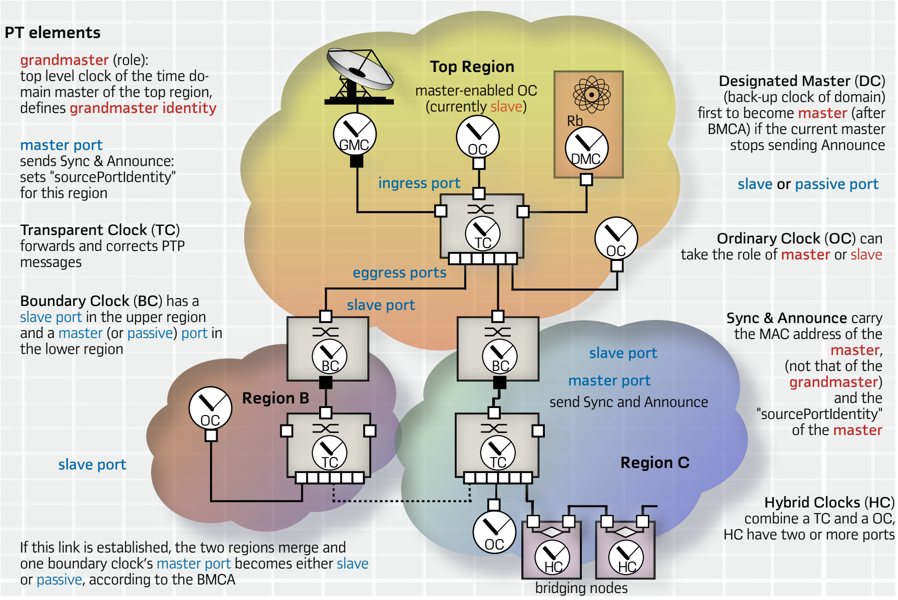
Figure 8 shows the principle of PRP, when a master clock sends a Sync to a slave clock. PRP defeats the principle of 1588 because the delay that a Sync frame experiences is different when travelling over one LAN or over the other LAN. The Sync frames will have different correction fields and therefore will not be duplicates of each other. Accepting both frames for synchronization would cause a significant jitter in the control loop of the oscillator of the slave clock. When 2-step correction is used, it would be difficult to pair the Sync and the corresponding Follow_Up.

table 1 IEC/IEEE 61850-9-3 main parameter

Parameter	Value
Profile identifier	00-1B-19-00-02-00
Clocks	MC, BC, TC, OC
Media	Ethernet Layer 2
Topology	full-duplex IEEE 802.3
Transmission	Multicast messages
Multicast address	01-1B-19-00-00-00 (all but pDelay) 01-80-C2-00-00-0E (peer delay)
VLAN	Allowed, not recommended
Ethertype	0x88F7 (1588)
Subtype	0 (version2)
Path delay measurement	peer-to-peer only
Correction	1-step and 2-step, may be mixed at will
Clock domains	All settable, default = 0, domain 93 recommended
Announce interval	1 s
Sync interval	1 s
Pdelay_req interval	1 s
Announce timeout	3 s
MBCA	Default and IEC 62439-3 when redundancy is used.
Backup master	Parallel operation defined in IEC 62439-3, multiple masters allowed
Priority 1	128
Priority 2	128
Medium converters inaccuracy	50 ns
GM inaccuracy	250 ns
TC inaccuracy	50 ns
BC inaccuracy	250 ns
Syntonization	Implicitly required
Holdover time	5 s
Signalling	Not specified
Management	1) IEC62439-3 Annex E 2) IEC 61850-90-4 3) other
MIB	Defined in IEC 62439-3 Annex E
Local Time	Optional ATOI (I588 16.3)
Security	IEC 62351

Figure 6 shows the elements of a 1588 time distribution scheme.

6 **Elements of a 1588 time distribution network**



Therefore, IEC 62439-3 Annex A modifies the 1588 principle exclusively for PTP messages. A slave treats the master clock seen on LAN A and LAN B as two different clocks and applies a Best Master Clock algorithm to select its master.

At the same time, the slave supervises the other LAN to detect failures of the other path. Since the identity of the master is the same over both LANs, the slave uses additional time quality information to select the master, for instance the one with the smallest correction field or the smallest jitter. (see Figure 8).

IEC 62439-3 also applies this principle to HSR as Figure 9 shows. Within the HSR ring, the sync frames travel in both directions and are corrected by each HSR node. Since corrected Syncs frames are no duplicates any more, they are removed from the ring by their source, using the back-up mechanism of HSR. Each node selects the Syncs from one direction and uses the other direction to check healthiness.

An HSR ring can be connected to a PRP double LAN, as Figure 9 shows. This could be the case if the station bus operates with PRP and the process bus operates with HSR. In this case, there are four Sync frames circulating every second. This does not cause a significant traffic load.

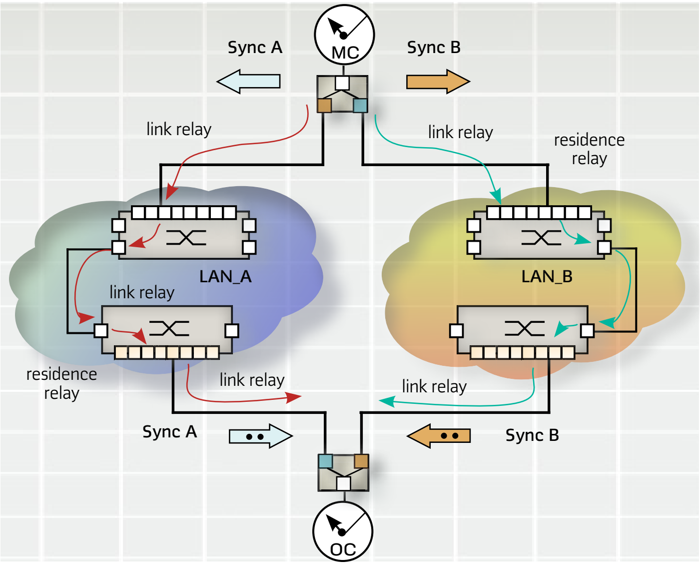
Since a slave selects its master, several masters could be active at the same time in each LAN. While this brings little in terms of availability, this diversity allows a consistency check and protects against cyber-attacks trying to spoof time.

Conclusion

With IEC/IEEE 61850-9-3 and IEC 62439-3, the power industry has a standardized, high performance, high-availability network capable of distributing sub-microsecond time synchronization for the most demanding applications. The precision time protocol allows additional services, such as deterministic data transmission by time slotting, if this should prove necessary.

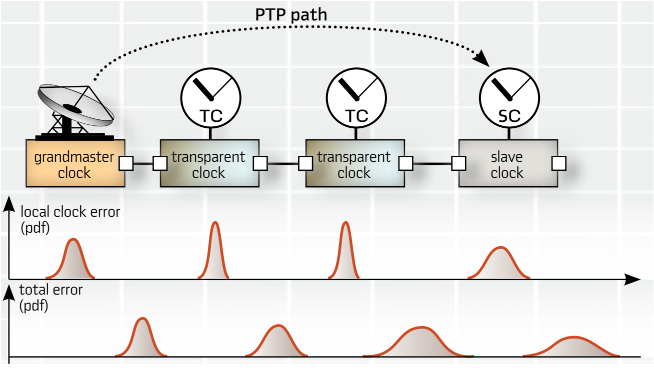
Return on experience is sought, indeed, the UCA organized a successful plug-fest and interoperability test in Brussels in November 2015 that showed that devices of different manufacturers could interoperate smoothly. ■

8 Principle of parallel redundancy with PTP



The precision time protocol allows additional services, such as deterministic data transmission by time slotting, if this should prove necessary.

7 Degradation of time accuracy



9 Principle of parallel redundancy with PRP (top) and HSR (bottom)