Using Time Synchronization to Improve Your Protection & Control System

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Time synchronization is essential in protection and control applications as process bus and line current differential. But more often, time synch is utilized in determining what happened and why during the forensic analysis of a system fault. But with so many time synch methods and network configurations, in this paper we will delve into various synchronization methods with a focus on the 1588-time Synchronization protocol.

In today's power systems, comprised of interconnected electronic devices, the inevitability of time drift. Each device, governed by its crystal oscillator's quality and environmental factors, undergoes subtle shifts in time. Yet, it is not the extent of each device's drift from absolute time or its start time that holds significance; rather, it is the synchronization of these devices with one another that determines operational accuracy. Thus, the need for a single reference point arises, enabling all devices to synchronize and maintain alignment, ensuring precision in relative time measurements.

Not all applications requires the same time accuracy, event time stamping for forensic analysis requires 1 ms , NERC requires 2ms to UTC for Monitoring disturbance equipment after the famous 2003 blackout

As you can see from the table the time accuracy relates directly to the phase angle and fault location and synchrophasor, traveling wave are one of the most demanding applications for time synch along with process bus. Traveling wave fault location can introduce error roughly I meter per 3 nano seconds of timing error.

- **Electrical Grid Time Synch Requirements:**
    - Sequence of events, post-disturbance analysis (1 ms). NERC recommendation after blackout of 2003, PRC-018-1 requires DME synchronize to within 2ms or less to UTC
    - Line current differential
    - Synchrophasor (1µs)
    - Traveling wave fault detection (300ns). The most demanding roughly 1-meter error per 3ns of timing error
    - Process bus (1µs)

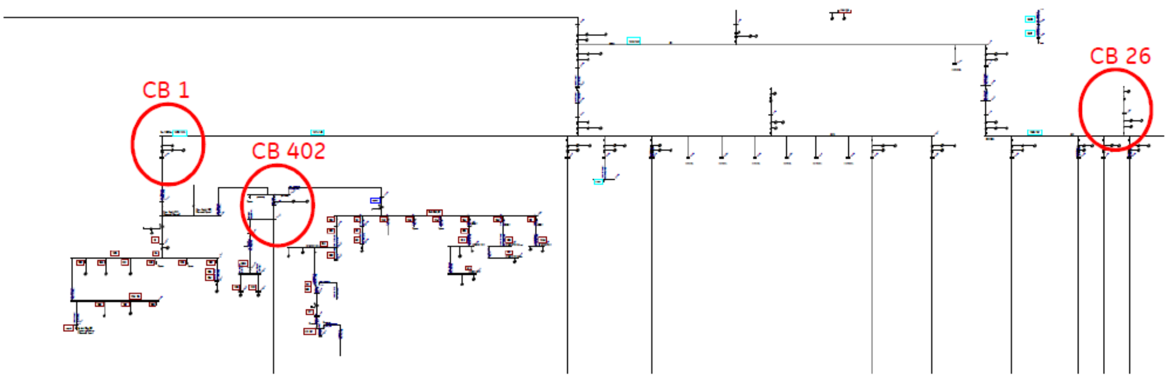
Time Class (IEC61850)	Accuracy (µs)	Phase Angle 60HZ	Fault Location %
T0	10000	216	NA
T1	1000	21.6	7.9
T2	100	2.2	.780
T3	25	.5	.0195
T4	4	.1	.031
T5	1	.02	.008

Table 1 Impact of Time Accuracy

pacworld Time in IEC61850

- **Case Study: Post Event analysis Snake causes a Distribution Fault:**

A snake caused a fault in the system showing below, triggering three relays. Despite being a single event, the log entries displayed three different timestamps because the relays were not synchronized to a single time reference. This discrepancy resulted in significant time being wasted during the analysis before it was realized that the multiple entries were related to just one event.



Event	Date	Time	Cause of Event
374	03/20/2014	22:00:48.232	Pickup: Ground Instantaneous OC
373	03/20/2014	22:00:48.232	Pickup: Ground Time OC
372	03/20/2014	22:00:48.232	Trip: Phase C - Phase Instantaneous OC 2
371	03/20/2014	22:00:48.232	Pickup: Phase C - Phase Instantaneous OC 2
370	03/20/2014	22:00:48.232	Trigger Trace Memory
369	03/20/2014	22:00:48.232	Trip: Phase C - Phase Instantaneous OC 1
368	03/20/2014	22:00:48.232	Pickup: Phase C - Phase Instantaneous OC 1
367	03/20/2014	22:00:48.231	
366	03/20/2014	22:00:48.231	
365	02/11/2014	07:37:38.182	

Event	Date	Time	Ca
48	03/20/2014	22:20:49.968	Dropout: Pha
47	03/20/2014	22:20:49.954	Alarm: Pha
46	03/20/2014	22:20:49.953	Dropout
45	03/20/2014	22:20:49.953	Dropou
44	03/20/2014	22:20:49.945	Input(C) ON-Block Neutral Time OC 1
43	03/20/2014	22:20:49.945	Input(C) ON-Block Ground Time OC
42	03/20/2014	22:20:49.945	Input(C) ON-User Input D / ABB 50D Blk
41	03/20/2014	22:20:49.937	Pickup: Negative Sequence Overvoltage
40	03/20/2014	22:20:49.921	Pickup: Phase B - Phase Time OC 2
39	03/20/2014	22:20:49.921	Pickup: Negative Sequence Time OC

Event	Date	Time	Cause of Event
46	03/22/2014	22:20:10.05	Differential Trip
45	03/22/2014	21:13:33.34	Differential Trip
44	03/22/2014	20:50:10.92	Differential Trip
43	03/21/2014	11:33:29.68	Differential Trip
42	03/21/2014	09:14:34.50	Differential Trip
41	03/21/2014	08:47:18.56	Differential Trip
40	03/20/2014	23:20:33.15	Differential Trip
39	02/11/2014	08:38:36.53	Cont. Power Applied
38	02/11/2014	08:38:35.74	Control Power Lost
37	02/11/2014	08:31:11.56	Cont. Power Applied

Figure 13 Relays TIME STAMPS

Continuing from our discussion on the necessity of time synchronization in substations and across the power system, the integration of the Global Navigation Satellite System (GNSS) emerges as a crucial solution. GNSS provides a reliable 24/7 accurate reference point for timing requirements.

GPS served as the primary operational GNSS with its constellation 24 satellites. However, additional satellite system such as the Russian GLONASS became available which also consist of 24 satellites and fully operational today. Utilizing a reference that spans both GPS and GLONASS systems offers resilience against potential spoofing, and Jamming attacks on either system and can significantly improve signal quality. SO access to both GPS and GLONASS can also enhance the accuracy and over all reliability of the synchronization process.

Now that we have established the importance of a single time reference with GNSS playing pivotal role, we will discuss the key time synchronization Methods, their advantage, and disadvantages.

- **Time Synch IRIG-B**

  IRIG-B is one of the most common time Synch methods in the Power System Industry with accuracy up to 1 microsecond which make suitable for most Power System applications.

  IRIG-B functions as a timing code, transmitted via copper wire through voltage pulses in either a modulated or unmodulated signal. Alternatively, it can be transmitted over fiber optic cable. Depending on the IRIG-B extension code utilized, it can convey various time-related parameters such as daylight savings, Time Occurrence, Time offset from UTC, and Time Quality.

  Advantage:

- Proven, IRIG-B has been used since 1960s under the Inter-Range Instrument Group.
- μs accuracy: It offers precision up to the microsecond.

  Disadvantage:

- The number of devices it can support.
- Distance limited by the voltage in the copper wire.
- Requires exclusive wiring and design.
- Redundancy is difficult.

  IRIG-B necessitates a specialized wiring design tailored to the specific IRIG-B signal being employed—whether modulated or unmodulated—accounting for factors such as wiring impedance, distance from the source to the last IED (Intelligent Electronic Device), and the configuration of a daisy chain setup. Fiber optic cable emerges as a preferable option for long-distance transmissions due to its enhanced immunity to electromagnetic interference (EMI). The number of devices supported for TTL is contingent upon variables like the clock's maximum current, the current draw of the connected IED, the termination resistor, and the total cable length from the clock to the last IED. For cable lengths exceeding 50 meters, it is advisable to incorporate a signal repeater.

- **IRIG-B Signal**
  IRIG-B Signal is 100 Pulse Pers second within 10 ms interval with available format as shown in the table below:

1st digit	***Modulation***
0	Unmodulated DC Level Shift
1	Amplitude Modulated
2	Manchester modulated
2nd digit	**Carrier Frequency/ Resolution**
0	No Carrier (DCLS)
1	100 HZ /10 ms
2	1 KZ / 1 ms
3	10 KHZ/ 100 microsecond
4	100 KHZ /10 microsecond
3rd Digit	**Code Expression**
0	BCDTOY, CF, SBS
1	BCDTOY, CF
2	BCDTOY
3	BCDTOY, SBS
4	BCDTOY, BCDYEAR, CF, SBS
5	BCDTOY, BCDYEAR, CF
6	BCTOY, BCDYEAR
7	BCDTOY, BCDYEAR, SBS

Table 2 IRIG Signal Numbering Scheme (3 digits)

In an IRIG-B signal, the BCDTOY expression code provides essential time information, including the day of the year, hour, minute, and second. Meanwhile, CF bits transmit additional details such as Time Zone and Daylight-Saving Time status. Additionally, the SBS component indicates the count of seconds elapsed since the beginning of the day (ranging from 0 to 86,400 seconds), while BCDYear specifies the year.

In the table above, I highlighted B004, which encompasses all IRIG-B options. Therefore, a clock supporting this code should be able to synchronize with any IED, regardless of its specific code requirements. However, caution is warranted, as some older legacy devices may fail to synchronize if the transmitted bits do not precisely match the IED's expectations. While ideally, IEDs should ignore unsupported bits transmitted by the clock, this may not always be the case due to vendor-specific implementations.

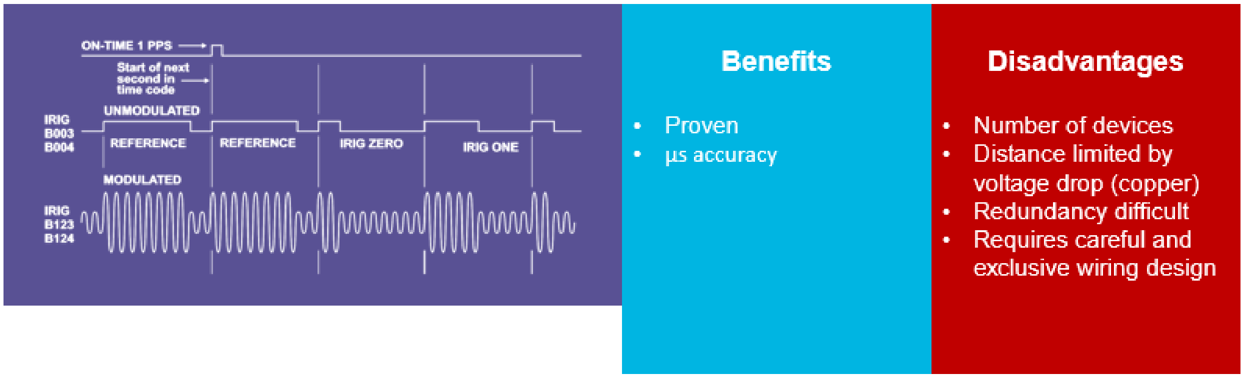


Figure 2 IRIG-B

- **NTP/SNTP Time Synchronization**

  NTP is a network-based time protocol used for time synchronization, where signals are transmitted over Ethernet networks. It operates within a hierarchical system of servers. Each server in the hierarchy synchronizes its time with higher-stratum servers until reaching primary time servers, which are directly connected to highly accurate time sources, such as atomic clocks. SNTP, on the other hand, is a subset of NTP, offering a simplified version of the protocol.

  A full-featured NTP server/client utilizes sophisticated mathematical algorithms and statistical methods to ensure smooth clock speed adjustments and high accuracy. In contrast, SNTP employs a polling scheme with simple time stepping, resulting in less precise time synchronization. SNTP is suitable for applications that do not require high accuracy and reliability.

  NTP Disadvantages

  - **Less Accuracy within Milliseconds**: While NTP provides accurate time synchronization, its precision within milliseconds may be lower compared to other time synchronization methods.
  - **No Hardware-Level Time Stamping**: NTP does not perform time stamping at the hardware level, which may affect the accuracy of timestamped events in certain applications.
  - **Does Not Recognize Time Zone and DST**: NTP does not inherently recognize time zone and daylight-saving time (DST) adjustments. However, these functionalities may be implemented at the level of the clock itself, depending on its capabilities.

Figure 3 NTP

- **Time Synch IEEE 1588 precision Time Protocol (PTP v2)**

PTP is a network-based time synchronization protocol that leverages hardware timestamping, allowing for more frequent time updates and accuracy to sub-microsecond levels. It operates within a Master-Slave architecture. The accuracy of PTP stems from its ability to precisely timestamp events using hardware timestamps for t1, t2, t3, and t4. These timestamps are then used to calculate the delay time between nodes accurately, employing the equation:

Delay = (t2 - t1 + t4 - t3) / 2.

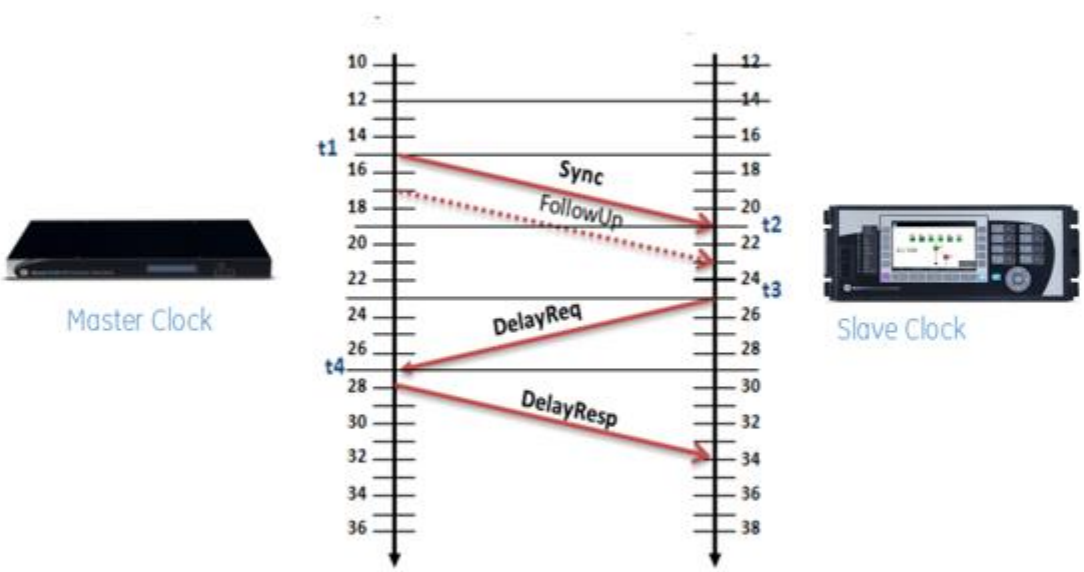


Figure 4 Master-Salve Time Synch

- Key Features and Terminologies of the PTP v2
  - Sync Messages: PTP utilizes Sync messages and Follow-Up messages to achieve precise synchronization of slave clocks. The Follow-Up message is included only in a two-step master clock configuration, where it transmits the t1 timestamp, representing the hardware stamp of the message leaving the master clock. The t2 timestamp corresponds to when the slave received the Sync message. In a one-step Master Clock configuration, t1 timestamp is sent with the Sync message, and no follow-up message is needed.
  - Grand Master Clock: Grand Master Clocks are high-precision clock, source of time for time sync.
  - Ordinary Clock: PTP clock with single PTP port, it can act as a Master or Slave clock, typically slaves at end devices.
  - Boundary Clock: Multiple PTP ports (1x slave, others master), can be master and slave at different ports, publish synch messages in case masters are lost.
  - Transparent clock: Mostly Ethernet Switch is used as transparent clock to compensate for the time spent in the switch.

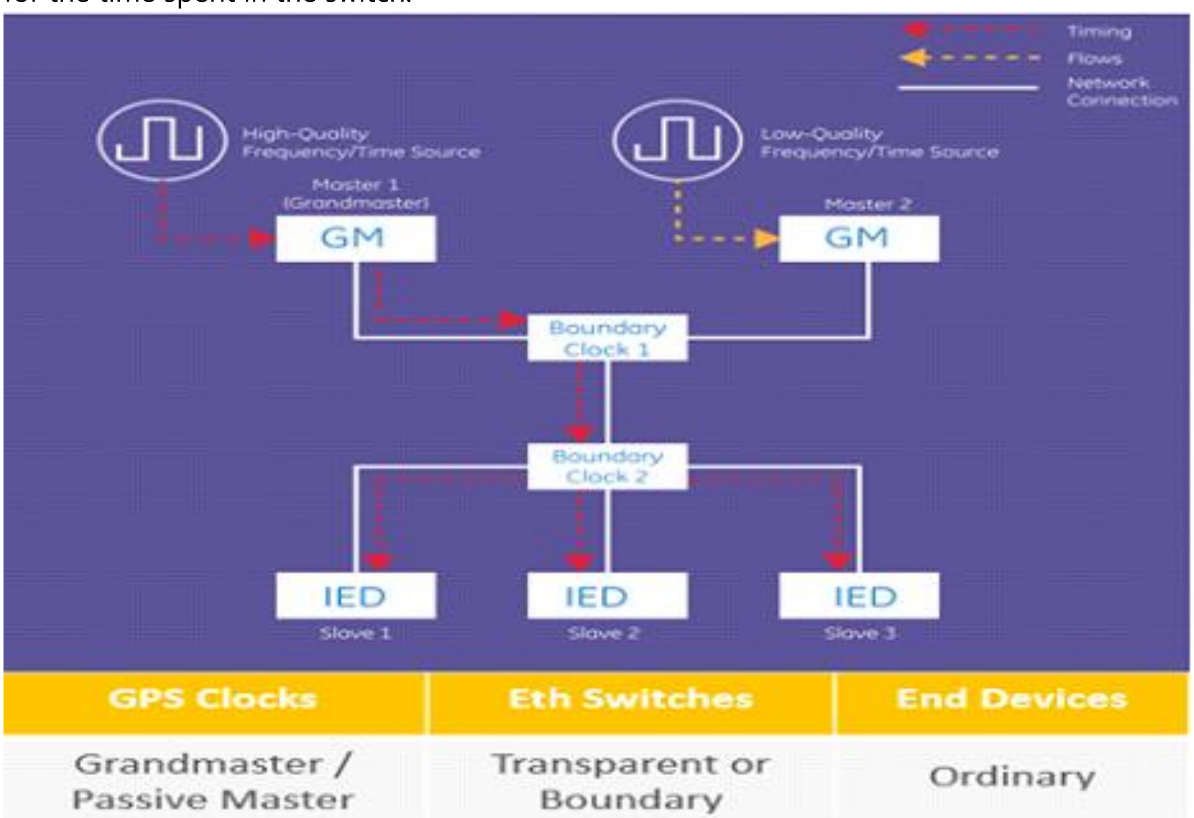


Figure 5 Cocks Type

- Best Master Clock (BMC): PTP incorporates unique features that allow any master clock to assume the role of the Grandmaster clock in case the Grandmaster loses its GPS signal or if a more accurate master clock is available in the network. An algorithm utilizing Announce Messages with special parameters is employed to determine which master should be selected as the Grandmaster clock. These parameters are transmitted in the Announce message and include:
  - Priority 1: An 8-bit user-settable value where the lowest number takes precedence. It is a configurable parameter within the clock.
  - Clock Class: An enumerated list of clock states, with a Grandmaster clock (GPS sync) typically assigned a higher class than a free-running clock.
  - Clock Accuracy: An enumerated list representing the range of accuracy to UTC, for example, 30-100 ns.
  - Clock Variance: Indicates the stability of the clock based on observations of its performance over time.
  - Priority 2: Similar to Priority 1 but lower in the decision-making hierarchy.
  - Clock Identity: A universally unique numeric identifier for the clock, typically constructed based on a device's MAC address, serving as a tie-breaker in case of priority conflicts.

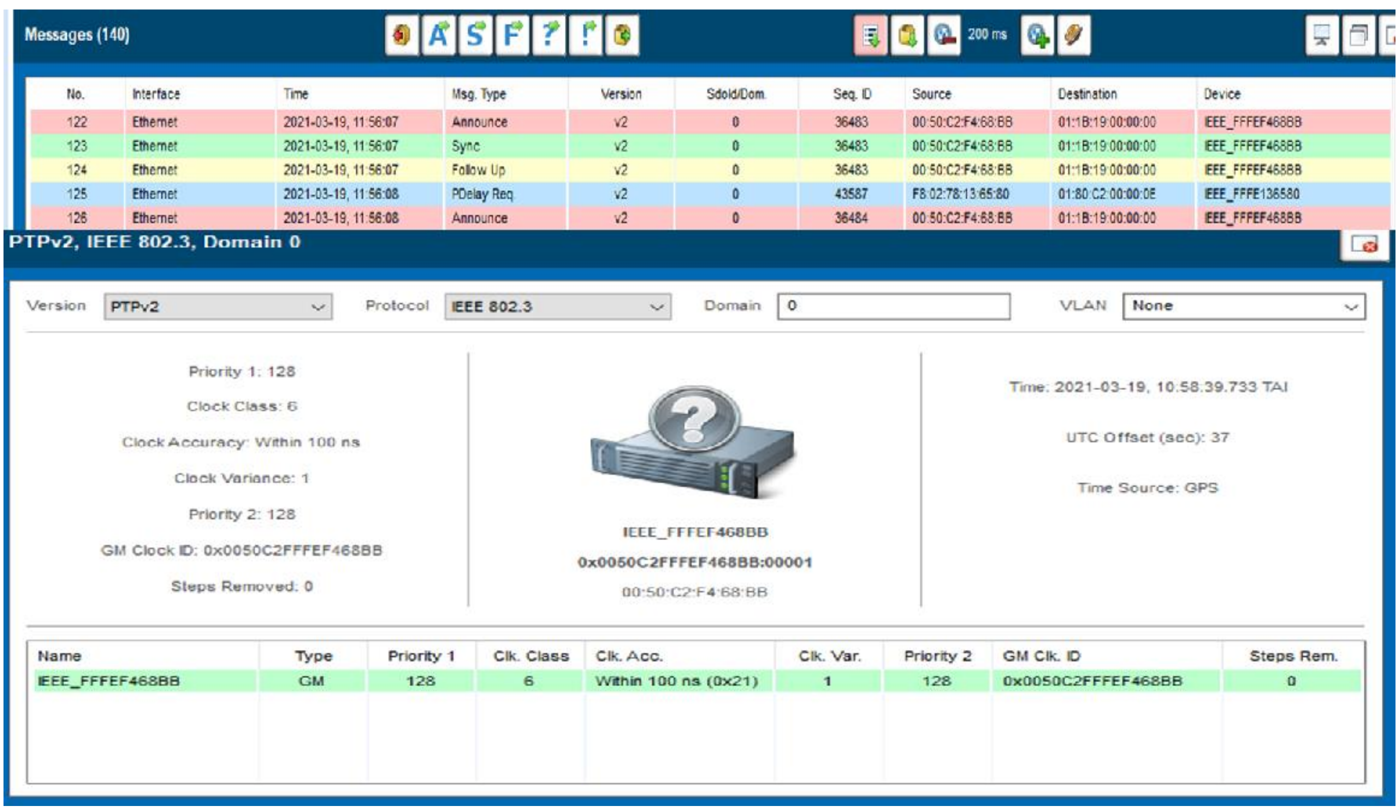


Figure 6 Announce Message

- Delay Mechanism: Peer-to-Peer and End-to-End. Peer-to-Peer measures the delay between adjacent clocks, including Ethernet-enabled PTP switches. End-to-End Delay measures the delay across the entire network. End-to-End Delay may be useful in scenarios involving non-PTP-enabled devices, but it is not allowed in PTP power profiles.

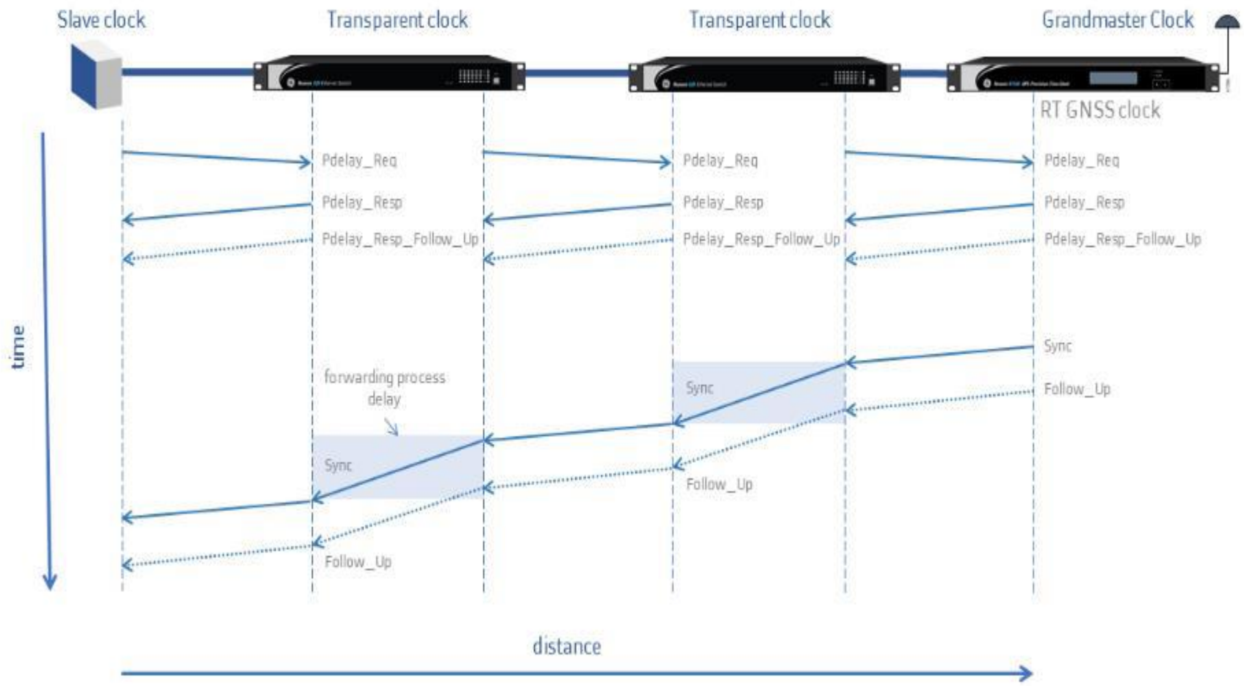


Figure 7 Peer to Peer

- PTPv2 Power Profile: PTP power profiles define specific characteristics for configuring PTP clocks, including PTP-enabled Ethernet switches, to ensure the highest accuracyand interoperability. The figure below shows the available power profiles:

	IEEE C37.238:2011 PTP Power Profile	IEEE C37.238:2017 PTP Power Profile	IEC 61850-9-3 PTP Profile for Power Utility Automation
Network Protocol	Ethernet Layer 2	Ethernet Layer 2	Ethernet Layer 2
Delay Mechanism	Peer-to-Peer (P2P)	Peer-to-Peer (P2P)	Peer-to-Peer (P2P)
Operation Mode	One Step	One or Two Step(s)	One or Two Step(s)
Sync / Announce Message Interval	1 per second / 1 per second	1 per second / 1 per second	1 per second / 1 per second
TLV messages	Required	Optional	Optional
Grandmaster Priority	#1 and #2 = 128 Equal for all Grandmaster	Selectable, allowing to choose the best grandmaster for holdover conditions	Selectable, allowing to choose the best grandmaster for holdover conditions

Figure 8 Power Profiles

Power Profile does not allow the following:

- Use of non-TAI time stamp
- End to end Time Delay Mechanism
- Unicast Operation
- Other Massage Rates

- PTPv2 over PRP: Some clocks support PTPv2 over Parallel Redundancy Protocol (PRP). While PTPv2 can benefit from Parallel Redundancy, it is important to note that PTP over PRP is handled differently than other protocols running over PRP networks. The IEC 62439-3:2016 standard defines the mapping for PTP over PRP.

- **Consideration for Clock Selection**:
    - Support for GNSS to mitigate jamming and spoofing.
    - Simultaneous support for IRIG-B, NTP, and PTP for compatibility with legacy and new devices.
    - Support for PRP (Parallel Redundancy Protocol) for enhanced redundancy.
    - Full-range power and redundant power supply for reliability.
    - SNMP support (v1, v2, v3) for remote monitoring of clock status.
    - Software-based licensing for adding additional features.
    - Software configurable for flexibility in configuration and management.
    - Integration of TCXO internal oscillator to maintain timekeeping in case of signal loss from satellites.
    - Relay contact that can be used to remotely signal the satellite locked state and to alarm if there is no power in the clock.
    - No internal battery for simplified maintenance and reliability.
- **Conclusion:**
    - Time synchronization is not optional - it is a critical functionality in protection and control and Control Systems.
    - IEEE 1588 Time Synchronization protocol allows for sub-microsecond synchronization and provide robust redundancy for application such as process bus, traveling wave.
    - Ethernet communication is the backbone of modern substations. With 1588 Time Synchronization protocol, it is that much more important.
    - As we modernize our infrastructure, we need to ensure newly sourced clocks and switches meet legacy and modern technology needs.

References

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Alexander Apostolov Time in IEC 61850 based substation protection and control systems

PTP Track Hound Meinberg