# Standard Profile for Use of IEEE Std 1588-2008 Precision Time Protocol (PTP) in Power System Applications

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***Abstract*—**This paper provides a summary of the IEEE C37.238-2011 standard, which specifies a subset of PTP parameters and options to provide global time availability, device interoperability, and failure management. This set of PTP parameters and options allows IEEE 1588-based time synchronization to be used in mission critical power system protection, control, automation, and data communication applications utilizing Ethernet communications architecture.

Keywords: IEEE 1588, PTP, protective relaying, smart grids, time distribution.

## I. INTRODUCTION

Until relatively recently the time synchronization of electronic devices in power systems has been realized via dedicated wiring used for distribution of IRIG-B or 1PPS signals. IRIG-B has the accuracy for the newest substation application technologies: however it requires dedicated cabling to distribute the timing signals, which while providing a simple and reliable connection, imposes limitations on scalability, and increases deployment and maintenance costs. 1 PPS is an even simpler method of distributing time which relies on precise time pulses every second distributed over dedicated wiring. These pulses however do not carry time-of-day information.

Modern intelligent electronic devices (IEDs) capable of Ethernet communications presented an opportunity for the introduction of new methods of time synchronization based on network protocols, such as Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP); however, these protocols do not meet the required accuracy for all power system applications.

IEEE 1588 is another network-based time synchronization protocol that meets the sub-microsecond accuracy requirements for the most demanding substation applications such as IEC 61850-9-2 Process Bus or IEEE C37.118.1-2011 Synchrophasors; however it needed a PTP profile customized for power system applications which is now available with the IEEE C37.238-2011 Standard.

### *IEEE 1588 and PTP Profiles*

IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control System was initially released in 2002 and revised in 2008, the IEEE Std. 1588-2008 [2]. The standard describes a protocol for distributing time with sub-microsecond time accuracy over various communication technologies, such as Ethernet, UDP/IP, DeviceNet, etc. The key advantages of this standard are that timing can be distributed over the same network as application data, and time accuracies generally not achievable by other time distribution protocols become possible.

### *PTP Profiles*

The IEEE Std 1588-2008 standard specifies many new features of the Precision Time Protocol (PTP), mandatory and optional, including conceptually new devices (transparent clocks), new message formats, etc. Development of this version was driven by five main industries: test and measurement, telecom, industrial automation, power and military. As a result, it was impossible to specify a single set of interoperable functions, as requirements for these industries differ significantly. To address this challenge a concept of PTP profile was introduced, as a clearly defined subset of protocol features, the use of which will meet specific industry requirements. Two default profiles are defined in the Annex J of the IEEE 1588-2008 [2]. Industries were encouraged to define their own PTP profiles to address specific requirements of their applications. Currently active PTP profile developments are briefly described below.

The PTP profile specified in IEEE Std. 802.1AS-2011 is for time-sensitive applications in bridged Local Area Networks [13]. It was developed by the 802.1 AVB (Audio/Video Bridging) Task Group of the IEEE 802 standards body which is responsible for Bridging [14], Ethernet [15], and Wi-Fi [11, 12], among others. The initial applications include professional A/V studios and “live sound”, home theatre, and automotive infotainment systems. The profile defines a Simple Network Management Protocol (SNMP) Management Information Database (MIB) for configuration, status and control.

PTP profiles for telecom industry are being developed under ITU-T Study Group 15 Question 13. An approach was chosen to develop multiple profiles and devices to address specific application services. These services fall into two classes:

- Frequency-only services – required to support the wander requirements of PDH or SONET/SDH transport and support the synchronization needs of frequency division duplex (FDD) cellular communications systems. ITU-T Recommendation [16] contains the telecom profile for frequency based services.
- Frequency, time and phase-based services – required to support the synchronization needs of time division duplex (TDD) cellular communications systems, enhanced multimedia broadcast/multicast service (MBMS), Long Term Evolution (LTE) Advanced services and other applications required high precision time or phase-based synchronization [17].

Other industries have also developed or are developing PTP profiles. PTP profile for test and measurement industry was developed by LAN eXtensions for Instrumentation (LXI) consortium [20]. Society of Motion Pictures and Television Engineers (SMPTE) currently is developing a PTP profile [21].

The Internet Engineering Task Force (IETF) community in TICTOC (Timing over IP Connection and Transfer Of Clock) Working Group, is currently not developing a PTP profile [18]. It works on an SNMP MIB for generic PTP, security issues related to packet-based timing, and on transport of PTP over Multiprotocol Label Switching (MPLS).

### *PTP Power Profile*

The primary need for developing a specialized PTP profile for power system applications is based on the specific substation network architectures, data exchange mechanisms, and performance of time distribution service required for power system applications. The profile is optimized for operation on isolated Ethernet networks with strict segregation of functions and a small number of dedicated grandmaster-capable clocks. Such networks are typical for power substation environment and are normally engineered (pre-configured) with static master / slave assignments, etc. It is important to note that these networks have to operate continuously (24/7) and need to exhibit deterministic (pre-programmed) failure behavior (scenarios include formation of operational islands, change of a grandmaster, etc)

The performance of a time distribution service and required time accuracy depend on power application needs and vary from 100 ms (for substation monitoring), 1 ms (for IED event recording) to 1 µs (for synchrophasor measurements and IEC 61850 sampled values service). The accuracy requirements for time synchronization messages are defined in IEC 61850-5 standard [3]. Since all of these applications require performance which can be supported by synchronization at the 1 µs level of accuracy (corresponding to ~0.02 degree error at power line frequency), the Working Group chose that level of performance for IEEE C37.238. Therefore a single time distribution service based on IEEE C37.238 can meet the requirements for all local and wide-area power system applications. Sections below describe timing requirements for two applications: IEC 61850 process bus and synchrophasors. The process bus can operate with local or relative time synchronization with the ability to create operation islands, while synchrophasors applications require synchronization to the global time.

### *Timing requirements for IEC 61850 process bus*

IEC 61850 introduces the concept known as “process bus” to substation automation systems. Although not necessarily implemented as a physically separate communication network, process bus concept introduces the possibility of connecting process equipment, such as switchgear and sensors, directly via a digital interface to the rest of the system. Instantaneous current and voltage measurements are transmitted using the IEC 61850-9-2 “Sampled Values” (SV) service. At the point of use individual measurement samples must be synchronized to each other.

The easiest way to achieve sample synchronization is to digitize all mutually dependent signals (complete protection zone) within the same device (“merging unit”). Unfortunately this concept does not scale (has difficulties addressing large substations). Multiple merging units can further be synchronized to each other by using 1 PPS pulses, IRIG-B or PTP based technologies.

IEEE C37.238 fulfills the requirements of IEC 61850-5 for all synchronization classes. It is expected to replace point-to-point and other solutions which also fulfill these requirements since it does not require additional wiring. A concept of how to deploy a synchronization network based on IEEE C37.238 is suggested in IEC 61850-90-4 [22]. The handling of redundant paths is described in IEC 62439-3 Annex A [23].

The advantages of the PTP power profile include Layer 2 transmission, message priority, *GrandmasterID* TLV etc. and are described in this document.

### *Timing requirements for synchrophasors*

Phasors are used to represent periodic signals in power system and other signal analysis. Synchrophasors are phasors that are synchronized to Coordinated Universal Time (UTC) or International Atomic Time (TAI) using a precise reference such as GPS or IEEE 1588. The standard IEEE C37.118.1-2011 [7] defines synchrophasors for power systems and describes their estimation from power signals using a phasor measurement unit (PMU). Synchrophasors measured using a common time reference can be compared directly for power system analysis. PMUs thus allow measuring power system signals over a wide area and using the measurements directly for real time and off line analysis.

The C37.118.1 standard defines a cosine at the nominal frequency synchronized to UTC as synchrophasor time reference. Thus if the power signal is exactly at the nominal frequency and has a positive maximum at the UTC second rollover, the phase angle will be 0 degrees. Since the phase angle is determined by the time reference, any deviation time will result in a phase angle displacement. For example, with a 60 Hz power signal, a 50 μs time deviation will displace the phase angle measurement by 1.08 degrees.

This standard also describes measurement requirements and validation methods for assuring the measurement. Accuracy for synchrophasor measurements is determined by Total Vector Error (TVE) which compares the true and estimated phasor values. Both magnitude and phase angle are included in the TVE calculation. 1% TVE is the basic required accuracy (at steady state). A phase angle error of 0.57 degrees gives a 1% TVE. This translates to a time error of ± 26 μs for 60 Hz system and ± 31 μs for 50 Hz system. Since this is the maximum error that is allowed, the timing input must be much more accurate than this. The more accurate the time reference is, the more accurate the PMU measurements; and an accurate source of time can also allow reduction in cost of the PMU. It has been generally agreed that since ± 1 µs time accuracy is readily achievable, that this is a reasonable target accuracy for PMU timing inputs.

Whereas IEEE C37.118.1 calls for synchrophasor timestamps from a timescale using leap-seconds, the IEC deprecates this, calling instead for the use of a timescale without leap-seconds. Though the epoch chosen (start of 1984) is different from PTP (start of 1970, TAI), the offset is an easily-handled constant by IEDs using IEEE 1588 clock sources (not so by IEDs using IRIG clock sources). This change avoids future problems due to satellite clocks, IEDs, data formats and applications software incorrectly handling leap-second events.

PTP power profile achieves the above goals by relying on Layer 2 Ethernet transport mapping, selecting the peer-to-peer delay measurements to improve and bound the convergence time on grandmaster change and establishing the overall steady-state synchronization requirement of 1 µs worst-case time error over 16 network hops.

The IEEE C37.238 Standard Profile for the Use of IEEE 1588 Precision Time Protocol in Power System Applications was developed by the Working Group (WG) H7 of the Power System Relaying Committee (PSRC) jointly with WG C7 of the Power System Substation Committee, both belonging to the IEEE Power and Energy Society (PES) in coordination with IEC Technical Committee 57 Working Group 10.

## II. IEEE C37.238 PARAMETERS

IEEE 1588-2008 Clause 19 introduced the concept of a PTP profile, as a clearly defined subset of PTP protocol features, the use of which will meet specific industry requirements. Following this guidance, IEEE C37.238-2011 standard specifies PTP power profile that consists of IEEE 1588-2008 parameters and additional profile-specific parameters. Comparison between PTP power profile, and the peer-to-peer default PTP profile, specified in IEEE 1588-2008 Annex J.4, is given in Table I. These parameters and IEEE C37.238 selections are discussed in more details in the subsequent sections.

IEEE 1588-2008 parameters included into IEEE C37.238 PTP Power Profile are:

- 1 s intervals for PTP messages
- Multicast communications and Layer 2 mapping
- Peer-to-peer path delay measurement
- One-step and two-step clocks
- Default Best Master Clock Algorithm, and
- Local Time Type Length Value (TLV) extension

Profile-specific parameters include:

- Pdelay option for slave-only clocks
- IEEE 802.1Q tags
- IEEE_C37_238 TLV
- IEEE C37.238 MIB
- Steady-state performance requirements
- Mappings for IEEE C37.118 and IEC 61850 protocols
- IRIG-B replacement mode

TABLE 1. COMPARISON BETWEEN PEER-TO-PEER DEFAULT PTP PROFILE PER IEEE 1588-2008 ANNEX J. 4 AND PTP POWER PROFILE PER IEEE C37.238-2011.

| | ***Peer-to-Peer Default PTP Profile per IEEE 1588-2008 Annex J.4*** | ***PTP Power Profile per IEEE C37.238-2011*** |
|---|---|---|
| ***PTP Attributes*** | | |
| defaultDS.domainNumber | 0 | 0 |
| portDS.logAnnounceInterval | 1 (2s), range from 0 to 4 | 0 (1s) |
| portDS.logSyncInterval | 1 (2s), range from -1 to +1 | 0 (1s) |
| portDS.logMinPdelayReqInterval | 0 (1s), range from 0 to 5 | 0 (1s) |
| portDS.announceReceiptTimeout | 3, range from 2-10 | 2 for all preferred grandmaster clocks,<br>3 for all other grandmaster-capable devices |
| defaultDS.priority1 | 128 | 128 for grandmaster-capable devices<br>255 for slave-only devices |
| defaultDS.priority2 | 128 | 128 for grandmaster-capable devices<br>255 for slave-only devices |
| defaultDS.slaveOnly | FALSE | FALSE for grandmaster-capable devices<br>TRUE for slave-only devices |
| transparentClockdefaultDS.primaryDomain | 0 | 0 |
| $\tau$ | 1.0 s | 1.0 s |
| ***PTP Options*** | | |
| IEEE 1588 Clause 15.5.4.1.7 and Clause 17 | Permitted, inactive by default | Not required, except the Local Time TLV |
| Management | IEEE 1588-2008 Management | IEEE C37.238 MIB required for grandmaster-capable devices only |
| Best Master Clock Algorithm | Default per IEEE 1588-2008 clause 9.3.2 | Default, only preferred grandmaster clocks are required to send Announce messages, Announce messages shall use C37_238 TLVs |
| Path delay measurement | Default is peer delay, delay request response is permitted | Peer delay mechanism only. Optional for slave –only devices. |
| Profile specific | None | Profile specific IEEE C37.238 TLV |
| ***Clock physical requirements*** | | |
| Frequency accuracy | 0.01 % from the SI second | 0.01 % from the SI second |
| Frequency adjustment range | At least +/- 0.025% | At least +/- 0.025% |
| Time accuracy in the steady state | Not specified | +/- 1µs over 16 network hops |
| Grandmaster clock TimeInaccuracy | Not specified | < 0.2 µs |
| Transparent clock TimeInaccuracy | Not specified | < 50 ns |
| Holdover, grandmaster-capable devices only | Not specified | within 2 µs for up to 5 s at a constant temp |

### A. *IEEE 1588 Parameters*

IEEE C37.238 specifies the following IEEE 1588-2008 parameters.

#### 1) *Sync and Announce messages interval values*

IEEE 1588-2008 specifies a message-based Precision Time Protocol (PTP). PTP messages can be divided into 3 categories based on their function, as messages for

- Distributing time (*Sync*, *Follow_Up* messages)
- Selecting the best clock (*Announce* messages)
- Measuring path delay (*Pdelay* messages)

The IEEE 1588 allows for a wide range of message intervals, to accommodate the large variety of applications the standard is expected to support. However, to guarantee interoperability and simplify device configuration IEEE C37.238 sets each of the message interval to once per second, support for other intervals is not required. This selection is based on WG philosophy to use mandatory and fixed choices whenever possible.

TABLE 2. INTERVALS FOR IEEE C37.238 MESSAGES

| ***Message Type*** | ***Interval, s*** | ***Message Function*** |
|---|---|---|
| *Sync* | 1 | Carries the time from the grandmaster to the slaves. |
| *Follow_Up* | 1 | Used in two-step clocks only. Carries a more accurate time stamp for the corresponding *Sync* message. Triggered by sending a *Sync* message. May be created by a two-step transparent clock passing a one-step *Sync* message. |
| *Announce* | 1 | Lists the grandmaster's properties. Used to select the best master in the network. |
| *Pdelay_Req*<br>*Pdelay_Resp*<br>*Pdelay_Resp_Follow_Up* | 1 | Used to measure the communication link delay between PTP aware devices.<br>*Pdelay_Resp_Follow_Up* only used in two-step clocks. |

In addition the IEEE C37.238 profile sets the announce timeout interval to 2 s for preferred grandmaster clocks and 3 s for other devices. This provides faster grandmaster recovery using the Best Master Clock algorithm.

#### 2) *Communication Model and Transport Mapping*

PTP messages can be carried over different underlying communication protocols. IEEE 1588-2008 specifies transport mapping to UPD/IP, Layer 2 / Ethernet, DeviceNet, etc. A given PTP profile should specify transport mapping, type of addressing (e.g. multicast or unicast) and addresses used.

The IEEE C37.238 standard specified the use of multicast messages and IEEE 802.3/Ethernet transport mapping, specified in Annex F of IEEE 1588-2008. In addition, it requires the use of IEEE 802.1Q tags, described in Section II B on profile-specific parameters.

#### 3) *Path delay measurement mechanism*

The IEEE 1588 standard includes two different methods to measure message delays in the network, so that the effects can be corrected in the clocks. With End to end delay measurements, masters and slaves exchange messages to measure the delay between them. Alternatively in the peer delay measurement method, messages are exchanged between adjacent devices on the network to calibrate the link delay between them. In the peer delay mechanism each network element corrects for the delay of inbound sync messages using the previously measured link delay.

In IEEE C37.238 only the peer-to-peer delay mechanism is used. The advantage of this approach is that all link delays are pre-measured as a background task by network elements. Therefore, if the *Sync* messages abruptly change paths, due to the failure of a network element, then the message delay of the new path is already measured, and is immediately corrected. This is achieved by devices exchanging peer delay messages on network ports that are otherwise blocked by Spanning Tree protocols. In addition, network loading on the grandmaster is reduced since it does not have to respond to *Pdelay_Req* messages from every slave.

The peer-to-peer delay mechanism requires both devices on a link to exchange *Pdelay_Req* and *Pdelay_Resp* messages in both directions. Further, requests and responses must be correlated. Because of the desire to accommodate simpler slave protocol logic, the IEEE C37.238 standard gives the slave-only devices the option of not executing peer delay measurements. This is further explained in Section II B.

#### *4) Clock types: one-step and two-step*

The IEEE 1588-2008 standard specifies two types of clocks: one-step and two-step clocks. The main difference between them is that one-step clocks update *Sync* messages that carry grandmaster's time on-the-fly, by overwriting the "approximate" timestamp with the actual precise time of when the *Sync* message is egressing the clock and is hitting the communication media, while two-step clocks require an additional message called *Follow_up* to transmit this precise time, One-step clock require special hardware assistance to update *Sync* messages on-the-fly.

The IEEE C37.238 standard specifies the use of both one-step and two-step clocks. It also recommends the use of one-step clocks, as it results in less network traffic and potentially simpler implementations. The use of two-step clocks is also supported because of their early availability and use. Expanding use of PTP has driven continued development and presently both one-step and two-step clock chips are commercially available.

All peer-to-peer transparent clocks accurately measure the residence time that is the time that *Sync* messages spend inside an Ethernet switch (transparent clock), as well as the communication link delay between devices. One-step transparent clocks provide residence time value in the *correctionField* of the *Sync* message, while two-step transparent clocks put this value in the *correctionField* of the *Follow_Up* message. A similar process applies for *Pdelay_Resp* and *Pdelay_Follow_Up* messages that are used to measure communication link delay.

If a two-step transparent clock is connected to a one-step clock, it should operate as defined in subclasses 11.5.2.2 and C.3.6 of the IEEE 1588 [2]. When it receives a *Sync* message from one-step clock with the *twoStepFlag* set to False, it should set the *twoStepFlag* to True and send an updated *Sync* message. As it will not receive a *Follow_Up* message from the one-step clock, the clock should generate a new *Follow_Up* message with the *correctionField* information. PTP fields *sequenceId* and *domainNumber* should be copied from the *Sync* message to the new *Follow_Up* message.

As specified in subclass 11.2 of the IEEE 1588 [2] a slave clock should use the sum of the *CorrectionField* values in the *Sync* and *Follow_Up* messages to compensate for delays in communication links and Ethernet switches.

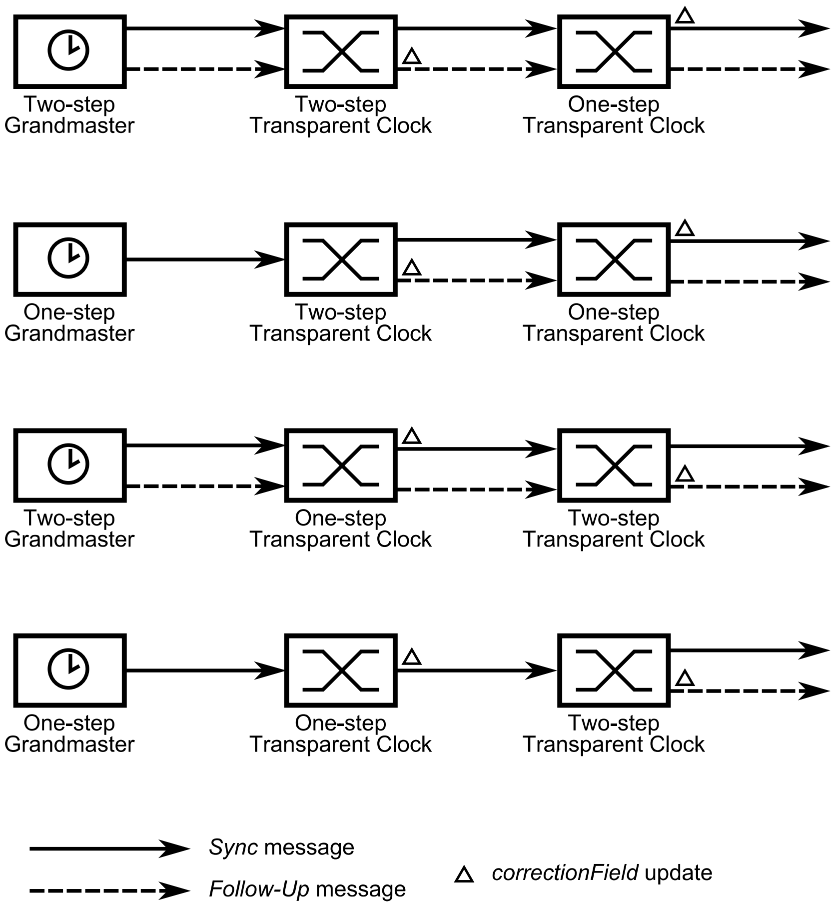

Figure 1. Conversion between one-step and two-step clocks

### 5) *Best Master Clock Algorithm*

IEEE 1588-2008 supports automatic selection of the best master clock in the system, upon initial setup and any reconfiguration / changes. It specifies default Best Master Clock Algorithm (BMCA) that uses *Announce* messages to select the best master. *ClockClass*, *ClockAccuracy*, and clock's MAC address can be used for selecting the best clock. Configurable Priority fields are provided for controlled best master selections.

IEEE C37.238 standard specifies the use of default best master selection algorithm with one addition: only preferred grandmaster clocks shall advertise themselves as potential grandmasters by sending Announce messages. This is selected to reduce network traffic and network convergence time during grandmaster selection. It is expected that substation networks would have 2 or 3 preferred grandmaster clocks for redundancy; other devices should be slave-only.

### 6) *Local Time TLV*

IEEE 1588-2008 specifies Type Length Value (TLV) mechanism for protocol extensions, if needed. It also defines a number of IEEE 1588 TLVs that can be used by industry-specific PTP profiles. One of these TLVs is ALTERNATE_TIME_OFFSET_INDICATOR TLV specified in the IEEE 1588 Section 16.3. The TLV allows the grandmaster clock to send time zone related settings to slave devices.

It is a requirement for IEEE C37.238-compliant grandmaster clocks to add an ALTERNATE_TIME_OFFSET_INDICATOR TLV to its *Announce* messages. A node (for example an IED) requires additional information if it needs to relate its own local time to UTC time. This TLV has a current Offset data field and therefore can provide the data required to convert the UTC-based time information into local time the requirement to include this TLV ensures that all applications migrating their time synchronization solution from IRIG-B to IEEE C37.238 can rely on receiving this information when switching to IEEE C37.238.

The ALTERNATE_TIME_OFFSET_INDICATOR TLV also supports indicating a time jump (e.g. an upcoming daylight savings time change event).

A grandmaster clock is allowed to send multiple ALTERNATE_TIME_OFFSET_INDICATOR TLVs (although additional TLVs have to be added after the two mandatory TLVs, i.e. after the first ALTERNATE_TIME_OFFSET_INDICATOR TLV and the IEEE_C37_238 TLV which is also mandatory is described in Section II B). A possible scenario for this is a network environment that spans more than one time zone.

### B. *Profile-specific Parameters*

IEEE C37.238 standard includes the following profile-specific parameters.

#### 1) *Pdelay option for slave-only clocks*

IEEE C37.238 standard supports simple slave-only devices, e.g. fault recorders, etc. To maintain simple implementations for such slave-only devices, Pdelay measurement on the last communication link to these devices is optional. This means that the delay of the last link in the path between the master and slave is not required to be compensated when setting the time at the slave. Often this error in the overall path delay calculation is acceptable for the length of this link and the accuracy desired. For example, the delay in a CAT 5 UTP or silica glass fiber optic network cable is approximately 5 ns/m, and therefore the error introduced by a 5 m long cable is only 25 ns. (IRIG-based timing systems do not automatically compensate for cable delays.)

#### 2) *IEEE 802.1Q tags*

The IEEE C37.238 standard requires that all messages comply with the IEEE 802.1Q protocol which inserts a tag into each frame; these tags have two fields of interest:

- The frame’s priority (3 bits).
- The frame’s VLAN membership (12 bits).

The main reason is to include the priority field that enables mission-critical traffic (like substation protection messages) to have priority over less critical traffic (like file transfers), when competing for the same switch port.

The VLAN field enables applications to be separated so that the cables to each application’s IEDs only carry messages intended for these application’s IEDs (thereby enhancing the messages’ security and dependability). Note that this does not preclude distribution to all IEDs if it is required by the applications.

The WG felt that some, but not all, installations would require the use of these IEEE 802.1Q tags.

The guiding philosophy that “all options must be justified” (and no justification surfaced) then drove the decision to mandate the use of this IEEE 802.1Q protocol. Default values of the parameters in the IEEE 802.1Q tags were selected to be the same as those in IEC 61850-9-2 specification: the default priority is equal to 4 and the default VLAN ID (VID) is equal to 0 (priority only frames).

VLANs can offer the following benefits:

- Blocking security threats.
- Improved message dependability (from the reduction of traffic).
- Message confidentiality (IEDs cannot monitor messages from other applications).

- Allowing several IEEE 1588 time-distribution systems on the same network, e.g.
  - IEEE 802.1AS and IEEE C37.238 (to simultaneously support audio/video networked applications).
  - A plurality of IEEE C37.238 systems (each IED receives multiple sources, for extra dependability).

Note that the use of VLANs is not a panacea for the dropped-packets and latency-jitter arising from network congestion (it only helps); good traffic engineering is still needed. For more information on VLANs refer to [14].

Note also that as with many other performance features, no assumptions should be made regarding the ability of switches under consideration to support the ingress and egress of IEEE 802.1Q-tagged traffic (some switches always remove tags from the frames egressing “edge” ports). By default, all devices are expected to accept IEEE C37.238 messages that have had their IEEE 802.1Q tags removed, and tagged IEEE C37.238 messages with their configured VID value.

### *3) IEEE_C37_238 TLV*

IEEE C37.238 standard specifies mandatory profile-specific IEEE_C37_238 TLV.

It contains

- GrandmasterID
- GrandmasterTimeInaccuracy
- NetworkTimeInaccuracy

IEEE C37.238 slave clocks may find themselves in the position of serving time (timestamped data) to other applications. In doing so, slaves must be able to accompany their data with precise indication about their clock quality and the exact identity of the grandmaster clock to which the slave is synchronized at that time.

Under stationary conditions any given IEEE C37.238 time distribution network can have only one grandmaster. However, during transient conditions (such as fragmentation and rejoining of islanded network segments caused by unexpected network failure) it is possible that the data from different slaves may reach their destination before IEEE C37.238 has time to re-elect the new grandmaster. Power system applications using such data must be able to identify that the data supplied by different slaves is not synchronized with each other and to correctly react to this situation.

Both IEEE 1588 and therefore IEEE C37.238 have a unique 8-octet field called *clockIdentity.* This field is sufficient to uniquely identify the applicable grandmaster clock. Unfortunately, message payload limitations of several power grid applications; most notably the IEC 61850-9-2 SMV data exchange make it necessary to transmit this information using a single octet field. To enable such applications the IEEE C37.238 mandatory TLV includes a 2-octet field named *GrandmasterID*. On any given network *GrandmasterID* must be unique and is normally assigned (set) during configuration. Most significant octet of the *GrandmasterID* is reserved and must be set to 0. Other values are illegal and indicate *GrandmasterID* field is not configured.

The dynamic indication of the received clock quality can be deduced from the *TimeInacuracy* parameters. IEEE 1588 has 8-bit clockAccuracy parameter to communicate clock quality, however this parameter is often set once in clock hardware and does not change depending on current conditions. It also has predefined allowed values with large steps, thus its resolution is insufficient. IEEE C37.238 *TimeInaccuracy* is defined as a device’s estimate of current worst-case time error (its magnitude) between time that the device provides and traceable time. There is *GrandmasterTimeInaccuracy*, provided by grandmaster-capable devices, and optional *NetworkTimeInaccuracy,* provided by the time distribution network. The *NetworkTimeInaccuracy* is a compound field that allows accumulation of time errors provided by each network device. This allows capable network devices (transparent clocks) to report their current worst-case time error, so that the slave devices can account for the time error introduced by the network. Note that if network devices are not capable of adding their current worst-case time error, they can add their maximum time error of 50ns, as specified in IEEE C37.238 Annex B,

To estimate the current quality of the received clock, slave devices can add received *GrandmasterTimeInaccuracy* and *NetworkTimeInaccuracy,* if provided. Note that for network engineering purposes the IEEE C37.238 standard also provides *EngineeredTimeInaccuracy*, which contains the worst *NetworkTimeInaccuracy* from a given device to all preferred grandmasters. All these parameters are 32-bit unsigned integers in nanoseconds that allows for a range of 0 to approximately 4.29 s, with one nanosecond resolution.

In addition to distributing *GrandmasterID* and *TimeInaccuracy* parameters, the IEEE C37.238 TLV provides a mechanism for PTP Power Profile Identification.

### *4) IEEE C37.238 MIB*

For system-wide configuration and status monitoring of the devices over a communication network, the IEEE C37.238 standard specifies the IEEE C37.238 MIB for use by SNMP. The MIB is required only for grandmaster-capable devices. It includes objects for boundary / ordinary clocks and transparent clock objects that are aligned with IEEE 1588-2008 datasets, plus profile-specific parameters. Among profile-specific parameters are GranmasterID, TimeInaccuracy, discussed earlier, as well as OffsetFromMasterLimit, which should be set to the max allowed time error for a given application, for example it could be set to 1us. In addition, the MIB includes SNMP events (traps) that report a change of grandmaster, that another PTP profile is detected, that offset from master exceeded configured OffsetFromMasterLimit, etc. Note that local configuration and status monitoring could be added and supported by implementations, if it is required by the application(s).

### *5) Steady-state performance*

The IEEE C37.238 standard defines steady-state performance requirements for the time distribution service to the end devices. Requirements for the end devices are application-specific and are not specified. Annex B of the IEEE C37.238 standard states that a time shall be distributed over 16 network hops with 1 µs time accuracy at the input to the end device. The time reference source can contribute less than 0.2 µs to the total time error, and network devices (transparent clocks) can contribute up to 50 ns each. The steady-state performance is defined for network loads at 80% of the wire-speed. IEEE C37.238 time distribution network is shown on Figure 1.

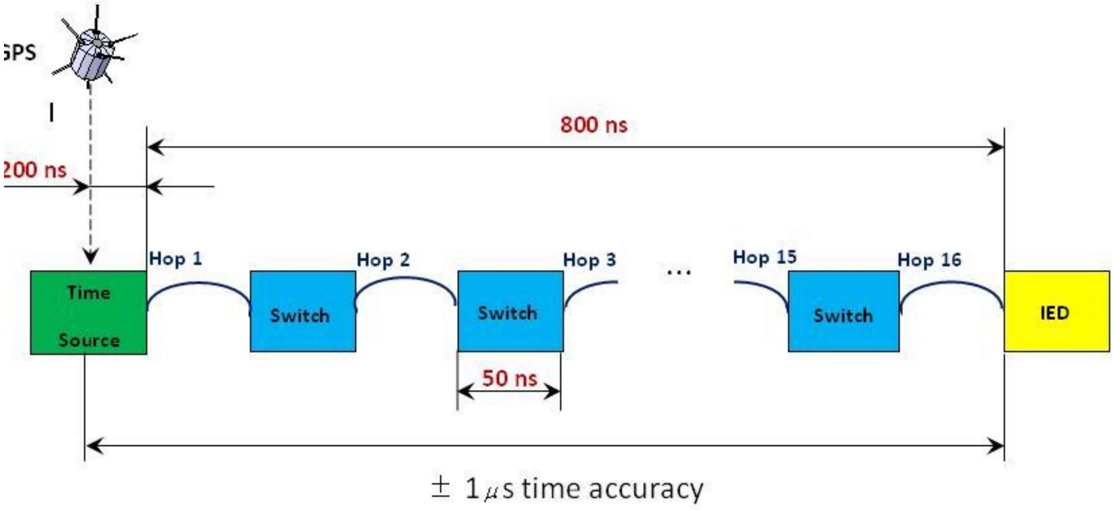

Figure 2. IEEE C37.238 steady-state performance requirements

In addition, to support quality of time distribution service during grandmaster change, the IEEE C37.238 standard specifies holdover drift for grandmaster-capable devices to be within 2 μs for up to 5 s at a constant temperature.

#### 6) *Mapping into IEEE C37.118.1/2 and IEC 61850*

The IEEE C37.238 standard's Annex C suggests the mapping of IEEE C37.238 parameters into IEC 61850 family of standards (IEC 61850-7-2 IED timestamping, IEC 61850-8-1 GOOSE messages and IEEE 61850-9-2 SMV) and IEEE C37.118.1/2-2011 synchrophasor formats. It suggests the mapping of the time error estimate and traceability to a recognized standard time source. This information is required for both IEEE C37.118.1/2 and IEC 61850 applications, thus a guidance is provided to facilitate the use of IEEE C37.238 for these applications.

#### 7) *IRIG-B replacement*

IEEE C37.238 standard provides an informative Annex C to suggest how slave-only IEDs could decipher the IEEE C37.238 messages into any of the timescales in common use; namely PTP, UTC, and local time (with DST when in use); plus how to correctly handle leap-second events. This is because many substation applications requiring time distribution currently use IRIG-B technology the standard provides specific guidance on how such applications can be changed to use the IEEE C37.238 technology.

As mentioned, the latency of cables (~5μs/km) is normally insignificant for IRIG-B IEDs, it is therefore also normally insignificant for IEEE C37.238 IEDs (and in both cases this latency can be compensated if desired). This is why there is no requirement for the slave-only IEDs to support the IEEE 1588 *Pdelay* algorithm.

## III. FURTHER DISCUSSIONS

### A. *GPS Security*

Though sourcing the time to IEEE C37.238 networks is out of scope, users should be aware of the risks using the only sub-microsecond accuracy time source in current use, namely the USNO's NAVSTAR global positioning satellite (GPS) system[1].

#### 1) *Loss of timing due to RF interference, both natural and man made.*

The very weak received power level at the GPS receivers (typically –130 dBm) can be easily overpowered by solar bursts[2], adjacent-spectrum services[3] and jammers (legal or otherwise).

#### 2) *Loss of timing due to satellites not sending signals*

e.g. from owners suspending the service, or from malicious attacks by others.

#### 3) *Loss of timing due to antenna not receiving signals*

e.g. from growth of trees and buildings, or from antenna or cable failures.

#### 4) *Wrong Time*

e.g. from GPS network faults or from malicious signal spoofing.

Some mitigation technologies to consider include a backup antenna, alternate timing sources (e.g. GLONASS[4], WWVB[5]), a local high-stability oscillator (a tradeoff between cost and outage-duration tolerance), and terrestrial based distribution methods based on SONET or IEEE C37.238 / PTP systems in the future.

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[1] http://tycho.usno.navy.mil/gps.html

[2] Cornell University, (2008, February) Solar Radio Bursts and Newly Discovered Effects on GPS Receivers

[3] David Schneider, (2012, February) GPS- Interference Controversy Comes to a Boil. IEEE Spectrum, 13-14

[4] http://en.wikipedia.org/wiki/Global_Positioning_System

[5] http://tf.nist.gov/general/pdf/2429.pdf

Although these concerns are real, presently many hundreds of thousands of GPS receivers are in use in the power and telecom industries with outstanding reliability and availability. GPS and other GNSS systems including GLONASS and Galileo will likely be, for the foreseeable future, the most reliable and cost-effective means to provide accurate time and frequency distribution to geographically-diverse locations.

### B. *Network security*

The use of a network protocol (Ethernet) obviously makes the IEEE C37.238 time-distribution more susceptible to disruptions than would be expected in the traditional IRIG-B installations.

There are two approaches for guaranteeing the integrity of traffic on Ethernet networks:

- Cipher security.
- Circuit isolation.

IEEE C37.238 does not provide a cipher security algorithm since none is provided by the IEEE 1588 standard. (IEEE 1588-2008 does provide an informative Annex K with an “experimental” protocol, but this has not been considered useful.)

The second approach is the one recommended by the IEC security standard IEC 62351-6, which in clause 4.1 states: “For applications …… requiring 4 ms response times, multicast configurations and low CPU overhead, encryption is not recommended. Instead, the communication path selection process (e.g. the fact that GOOSE and SV are supposed to be restricted to a logical substation LAN) shall be used to provide confidentiality for information exchanges.”

The requirement for IEEE C37.238 messages to be IEEE 802.1Q compliant enables this approach.

The network switches must of course have their ports configured securely (e.g. using SNMPv3) and appropriately (the correct VLAN assignments to the ports’ blocking, and passing, VLAN lists).

EEE C37.238 time-distribution networks can therefore be secured using IEC 62351-6.

### C. *Timescales*

The purpose of IEEE C37.238 is for IEDs to provide timestamps for events; however the PTP timescale use differs from the timescales in general use by substation IEDs; for this reason the IEEE C37.238 standard provides guidance for the conversions to these timescale in informative Annex C.

The PTP timescale was created around the start of the current millennium by the IEEE 1588 Working Group when it was found that there was no standard timescale (from an approved standards organization) with a defined epoch (start). (A common view that TAI has a defined epoch is incorrect.)

The WG chose their PTP epoch to be the start of 1970 on the TAI timescale. (This was 8.000082 seconds before the start of 1970 on the UTC timescale.)

To support applications requiring UTC time (the majority of power applications presently use UTC time), the PTP messages contain a “currentUtcOffset” field whose value is the number of seconds by which TAI is ahead of UTC. (This changed from 34 to 35 seconds at the start of July 2012.)

Though both IEEE C37.118 and IEC 61850-7-2 specify that their timestamps’ epoch shall be the start of 1970 on the UTC timescale, in practice all implementations use an epoch 82 µs later (when the UTC second rollover was aligned with the TAI second rollover), allowing the simple conversions:

IEEE C37.118 “SOC” = PTP Time (s) – “currentUtcOffset”

IEC 61850 “SecondsSinceEpoch” = PTP Time (s) – “currentUtcOffset”

with IEC 61850 “LeapSecondsKnown” field = “True”

For syncrophasor IEDs, IEC 61850-90-5 specifies the transport of syncrophasor messages using both the IEC 61850-8-1 protocol (for events, e.g. GOOSE) and the IEC 61850-9-2 protocol (for streaming data, e.g. SV), with the recommendation that for both cases TAI be used for all timestamps. The demonstrated difficulty (e.g. satellite clock hiccups) of correctly handling leap-second events, plus the timestamp ambiguities arising from seconds being repeated, has motivated many groups to deprecate the use of UTC for timestamps (handling the conversions only when presentations in UTC (or local time) are required on HMI displays).

For IEC 61850 this can be handled by setting:

IEC 61850 “LeapSecondsKnown” = “False”

with IEC 61850 “SecondsSinceEpoch” = PTP Time (s).

### D. *Future support for wireless links*

The communication of precise time over wireless links is an area of interest for a future version of IEEE C37.238, and is under study. Unlike modern Ethernet links, which are full duplex and maintain a consistent bit rate and link delay over time, wireless network links provide no such guarantees. Indeed, retransmissions, frame aggregation (MAC or PHY) and bit rate variability can result in orders of magnitude worse jitter which is are not comprehended in the current version of IEEE 1588, making interoperable sub-microsecond accuracy difficult.

One promising option under investigation for IEEE 802.11 links [11] is a recent amendment to the wireless standard that defines measurement of transmit/receive times and wireless link delays that are independent of the sources of perturbation listed above. It’s called the TIMINGMSMT primitive and is defined in IEEE 802.11v [12].

It should be possible to satisfy the requirements of IEEE C37.238 over wireless links using this approach, but few measurements from devices that implement IEEE 802.11v TIMINGMSMT have been published at this time. Also, this time measurement approach must be harmonized with Ethernet PTP measurements and synchronization. It is promising that an audio-video profile of IEEE 1588 specified in IEEE 802.1AS [13] has demonstrated the feasibility of such harmonization.

## IV. CONCLUSIONS

The IEEE C37.238-2011 standard specifies the PTP power profile for power system applications. The profile is optimized for use in specific power substation network architectures and meets timing requirements of the most strenuous power system applications.

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