Revision of IEEE Std C37.238, Power Profile for IEEE-1588: Why The Big Changes?

IEEE PSCC Task Force P1 Members and Guests

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***Abstract*—**Revision and renewal of standards is normally a routine process. This paper describes why revision of the Institute of Electrical and Electronics Engineers (IEEE) C37.238 standard was anything but routine, the reasons why a new approach was needed, and the impacts of the changes on users. By far the most significant change was splitting this standard into two standards: the new joint standard International Electrotechnical Commission (IEC)/IEEE 61850-9-3 and the now revised IEEE C37.238-2017.

The reason for this split was that the two main sponsoring organizations IEC Technical Committee (TC) 57 Working Group (WG) 10 and IEEE Power and Energy Society (PES) Power Systems Relay Committee (PSRC) expressed significant differences in their expectations from this work. The result was that IEC/IEEE 61850-9-3 became the technical specification document, providing the baseline performance level required for all applications. Additional requirements supported by the revised IEEE C37.238 include real-time updates of the delivered time's quality (inaccuracy), plus inclusion of the time's data needed to support the migration of substation time-distribution networks from IRIG-B.

The paper will describe why re-arranging the standard this way has advantages and disadvantages; discuss the consequences of these changes to the users of the standard(s), and reveal important issues users must keep in mind when migrating to the new version.

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 Inter-Range Instrumentation Group (IRIG)-B or 1 Pulse Per Second (PPS) 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 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems [1] specified another network-based time synchronization protocol – Precision Time Protocol (PTP) 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.

Time synchronization sources and interfaces of modern IEDs are shown on Figure 1. Ethernet-based time distribution over PTP that meets requirements of power system application allows replacing commonly used IRIG-B time distribution, and reducing the number of direct Global Positioning Systems (GPS) connections. Both require dedicate cabling, installation, maintenance, and placement, that can be reduced or eliminated by switching to Ethernet-based technology. The users' benefits, therefore, include system design simplification and reduced installation and maintenance cost.

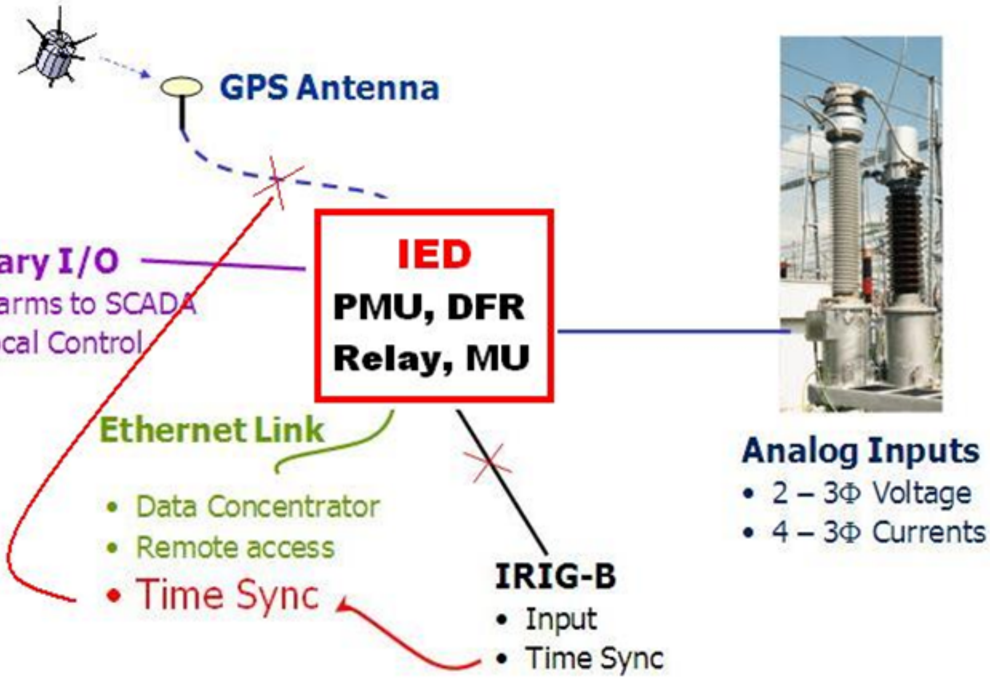

Figure 1. Time synchronization alternatives

The first PTP profile for power system applications was specified in IEEE C37.238-2011 standard by Institute of Electrical and Electronics Engineers (IEEE) Power Systems Relay Committee (PSRC) Working Group (WG) H7/SubC7 in coordination with International Electrotechnical Commission (IEC) Technical Committee (TC) 57 Working Group (WG) 10 and other interested organizations [2].

A summary paper was published in 2012 to introduce PTP Power profile to the industry [3]. The paper provides a complete description of IEEE C37.238-2011 parameters and rational for their selection. The reader is encouraged to study that first WG paper before reading this paper that covers IEEE C37.238-2011 revision.

The paper also briefly describes other IEEE 1588 profiles specified to date such as default profiles, per IEEE 1588-2008 Annex J, Audio/Video bridging profile per IEEE 802.1AS-2011, Telecom profiles per International Telecommunications Union (ITU) G.8275, and Timing over Internet Protocol (IP) Connection and Transfer Of Clock (TICTOC) profile developed by the Internet Engineering Task Force (IETF) Community.

After the first implementations of IEEE C37.238-2011, comments were brought forward by IEC TC57 WG10 and other implementers and users, with suggestions to start a revision process in a timely manner.

In the meantime, IEC TC57 WG10 opted for a profile already developed for industrial automation. This profile offers the same basic services as IEEE C37.238-2011, but provides more flexibility of the network engineering and seamless fault-tolerance. It was published in IEC 62439-3, Industrial communication networks – High availability automation networks – Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) [4].

To avoid the emergence of two competing standards and a de facto split between the North American (NA) market and the rest of the world, IEC and IEEE decided on an IEC/IEEE Joint Development in which the requirements of both communities are considered, while allowing for extensions to further profiles. The result was the base PTP profile specified in IEC/IEEE 61850-9-3:2016 [4], a dual logo international standard specifying a PTP profile for power utility automation.

Additional requirements of the NA market were further developed as an extended PTP profile and are now specified in IEEE C37.238-2017 [5]. The extended profile is based on the base IEC/IEEE 61850-9-3 profile and extends the base profile capabilities.

Thus, the revision of IEEE C37.238-2011 standard includes two standards: a dual-logo IEC/IEEE 61850-9-3:2016 standard and the IEEE C37.238-2017 standard. The content of these standards, their comparison and interoperability are described in Sections below.

II. IEEE C37.238 Revision

As explained in the Introduction, revision of IEEE C37.238-2011 led to generation of two standards: IEC/IEEE 61850-9-3 [5] that specifies base PTP profile, and IEEE C37.238-2017 [6] that specifies extended PTP profile. The reason for the split is inherited differences in market requirements over the world. Agreements, however, were reached on base features that are common to all markets, and these are now specified in the base PTP profile developed under IEC/IEEE Dual Logo Agreement Joint Development. A single standard for base PTP profile addresses users' needs globally, and reduces confusion that could be caused by multiple industry standards. The base PTP profile is described in Section II A.

Additional features specified in the extended PTP profile include dynamic time inaccuracy reporting and extended support for IRIG-B converters. These are explained in details in Section II B.

This paper is organized as follows. Section II below describes features of base and extended PTP profiles and highlights the difference with the first power profile specified in IEEE C37.238-2011. Section III summarizes differences between first PTP power profile, base PTP profile and extended PTP profiles. Section IV describes profiles testing and certification activities.

A. Base profile IEC/IEEE 61850-9-3:2016

For time distribution over Ethernet using PTP IEEE 1588 allows a number of options, including 1-step/2-step correction, End-to-End or Peer-to-Peer delay measurement, and Layer 2 or Layer 3 operation, different LANs, etc., but does not specify performance.

The IEC/IEEE 61850-9-3:2016 Standard [5] is a profile of IEC 61588:2009 ¦ IEEE Std 1588-2008 [1] for the power utility automation, i.e. it is a subset of IEEE 1588 except for the (optional) redundancy method. It is derived from the profile in IEEE 1588 Annex F (Ethernet) and the default profile Annex J.4 (peer-to-peer).

Furthermore, this standard specifies performance requirements that allow compliance with the highest synchronization classes of IEC 61850-5:2013, Communication requirements for functions and device models, and with the highest synchronization classes of IEC 61869-9:2016, Instrument transformers – Part 9: Digital interface for instrument transformers.

In addition to normative references, terms, definitions, abbreviations, acronyms, and conventions, this Standard gives details of supported clock types, protocol specifications, seamless redundancy, default settings, Protocol Implementation Conformance Statement (PICS) and management objects.

Note that a full comparison between the different profiles (IEEE C37.238-2011; IEC/IEEE 61850-9-3:2016; IEEE C37.238-2017) is presented in Section III of this paper. Note also that changes from IEEE C37.238-2011 version are also captured in the Introduction of IEEE C37.238-2017 standard.

1) Base parameters

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

TABLE 1. IEC/IEEE 61850-9-3 MAIN PARAMETERS

Parameter	Value
Profile identifier	00-0C-CD-00-01-00
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 except peer delay mechanism messages) 01-80-C2-00-00-0E (peer delay mechanism messages)
Virtual Local Area Network (VLAN)	out-of-scope
Ethertype	0x88F7 (1588)
Subtype	0 (version 2)
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
Best Master Clock Algorithm (BMCA)	Default and IEC 62439-3 when redundancy is used.
Backup master	Parallel operation defined in IEC 62439-3, multiple masters allowed
Priority1	128 (255 for slave-only clocks)
Priority2	128 (255 for slave-only clocks)
Medium converters inaccuracy	50 ns (steady-state)
GM inaccuracy	250 ns (steady-state)
TC inaccuracy	50 ns (steady-state)
BC inaccuracy	200 ns (steady-state)
Syntonization	Implicitly required
Holdover time	5 s
Signaling	Not specified
Management	1) IEC 62439-3 Annex E 2) IEC TR 61850-90-4 3) other
Management Information Base (MIB)	Optional, e.g. IEC 62439-3
Local Time	Optional ATOI (1588 16.3)
Security	Optional, e.g. IEC 62351

Note that core parameters, such as Layer 2 mapping, multicast messaging, peer delay mechanism and 1 second Sync interval are the same as in IEEE 1588 Power Profile specified in IEEE C37.238-2011 standard.

To meet requirements of the highest synchronization class, accurate real time measurements and compensation of variable delays are needed. IEEE 1588 peer delay mechanism is used to measure the delay variation primarily caused by three sources. The peer delay mechanism compensates for the delay asymmetry, which can degrade clock synchronization performance, in real time. Figure 2. shows these variable delay sources: PTP protocol stack, cable delay and residence time of intermediary network nodes, i.e. time that a given Sync message spends inside an Ethernet switch with transparent clock (TC) functionality.

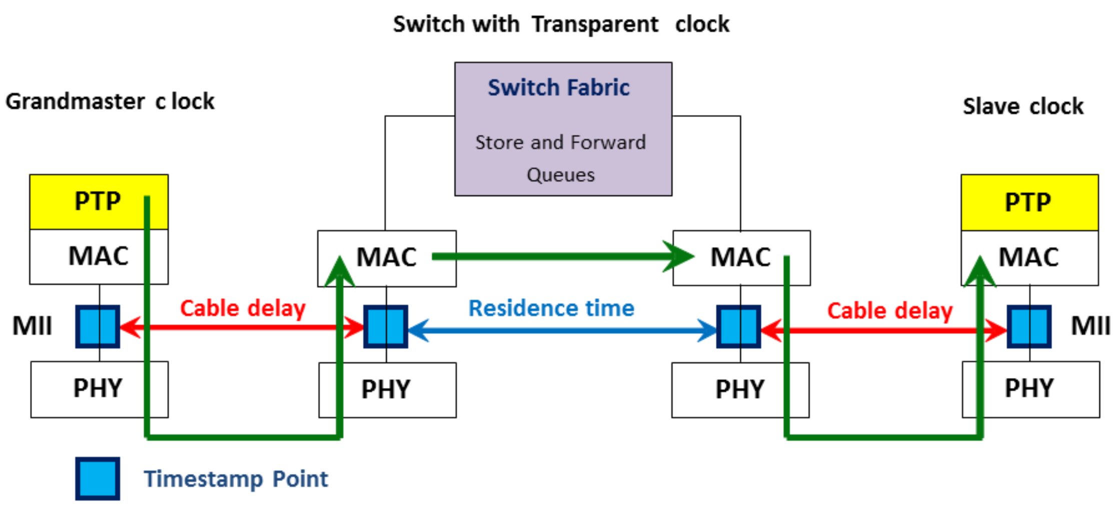

Figure 2. Peer delay measurement and compensation

2) Performance requirements

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

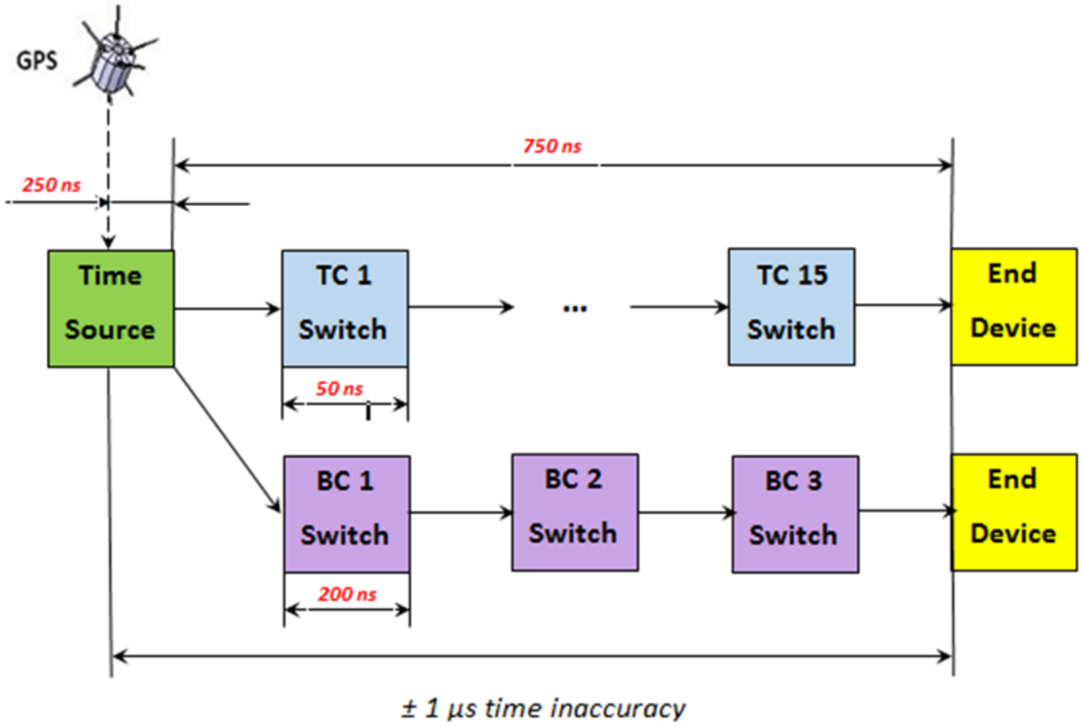

Figure 3. Maximum steady-state time error

Note that IEEE C37.238-2011 specified maximum steady-state time error of +/- 1 µs after 15 TCs (with no BCs). IEC/IEEE 61850-9-3:2016 added that this could also be achieved after 3 BCs (if no TCs). Figure 3. below provides graphical representation of IEC/IEEE 61850-9-3:2016 steady-state performance requirements. Note that performance requirements for Ethernet media converters were also added to base PTP profile.

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 (GM) accuracy, which can degrade due to loss of reference signal. A GM is supposed to maintain its specified accuracy for 5 s after loss of reference signal (e.g. GPS).

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

3) Best Master Clock Alrorithm and check for profile-specific extension

Best Master Clock Algorithm (BMCA) is used for selecting the best master clock, the GM, in a PTP time distribution system. IEEE C37.238-2011 standard required to check for presence of profile-specific extension, called Time Length Value (TLV) before processing PTP Announce messages used for BMCA. While this was introduced as a means of separating a IEEE C37.238 network from other PTP profiles, it was also a departure from the standard IEEE 1588 BMCA and caused confusions. During the IEEE C37.238-2011 revision it was decided to use PTP domain numbers for profiles isolation. Thus, the profile-specific TLV check is not anymore needed for BMCA. The profile-specific TLV check was removed, and standard IEEE 1588 BMCA was re-stored.

4) IEEE 802.1Q tags

IEEE C37.238-2011 standard required PTP frames to have IEEE 802.1Q tags. While these tags are useful, and are commonly used by many utilities in North America discussions revealed that for a benefit of having a single common standard it was best to remove this requirement, and treat VLAN tagging as a common Ethernet feature that is out of scope of time distribution standard covering a PTP profile.

5) Default PTP domain number

Default domain number remains as 0, the same as in IEEE C37.238-2011. However, a recommended domain number for base PTP profile is 93. Refer to Section II B for information on domain number for the extended PTP profile.

6) Alternate Time Offset Indicator extension

Alternate Time Offset Indicator (ATOI) extension (TLV) is used to communicate local time information, such as local time zone offset and daylight saving from master to slave devices. IEEE C37.238-2011 specifies mandatory support and optional use of ATOI TLV, while for the base PTP profile ATOI TLV both support and use are optional. Further details on ATOI TLV differences between PTP profiles are listed in a standards comparison table, see Section III.

7) Management mechamisn

IEEE C37.238-2011 standard contains an IEEE C37.238 Management Information Base (MIB) specification, and allows vendor specific reporting of various management and performance parameters. A modified version of IEEE C37.238 MIB is now captured in IEC 62439-3 Annex E. Base profile does not include any MIB specification and allows the use of IEC 62439-3 Annex E MIB, IEC 61850-90-4 objects or a vendor specific management mechanism.

8) Redundancy principle

Substation automation systems require a very high availability. Therefore, Local Area Network (LAN) redundancy is required. IEC 61850 specifies to use the redundancy schemes of IEC 62439-3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). While the details of redundant operation are not covered in standards specifying PTP profiles, the base PTP profile IEC/IEEE 61850-9-3 can utilize the redundancy schemes specified for IEC 61850 systems.

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.

When a master clock sends a Sync message to a slave clock, the principle of PRP is defeated 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 message and the corresponding Follow_Up message.

Therefore, IEC 62439-3:2016 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.

IEC 62439-3 also applies this principle to HSR. Within the HSR ring, the Sync frames travel in both directions and are corrected by each HSR node. Since corrected Sync frames are not duplicates any more, they are removed from the ring by their source, using the back-up mechanism of HSR. Each node selects the Sync messages from one direction and uses the other direction to monitor availability.

B. Extended profile IEEE C37.238-2017

The extended PTP profile, specified in IEEE C37.238-2017 standard, is based on the base PTP profile, and extends its capability by adding several features explained below. Specifically, explanations are given to dynamic time inaccuracy reporting and extended support for IRIG-B converters. Default domain number, and mixed profiles operation are also described.

1) Dynamic Time Inaccuracy reporting

Dynamic time inaccuracy reporting is one of the key features of the extended PTP profile. Time inaccuracy requirements for different power system applications when clock is locked, and distributed or drifting are shown on Figure 4.

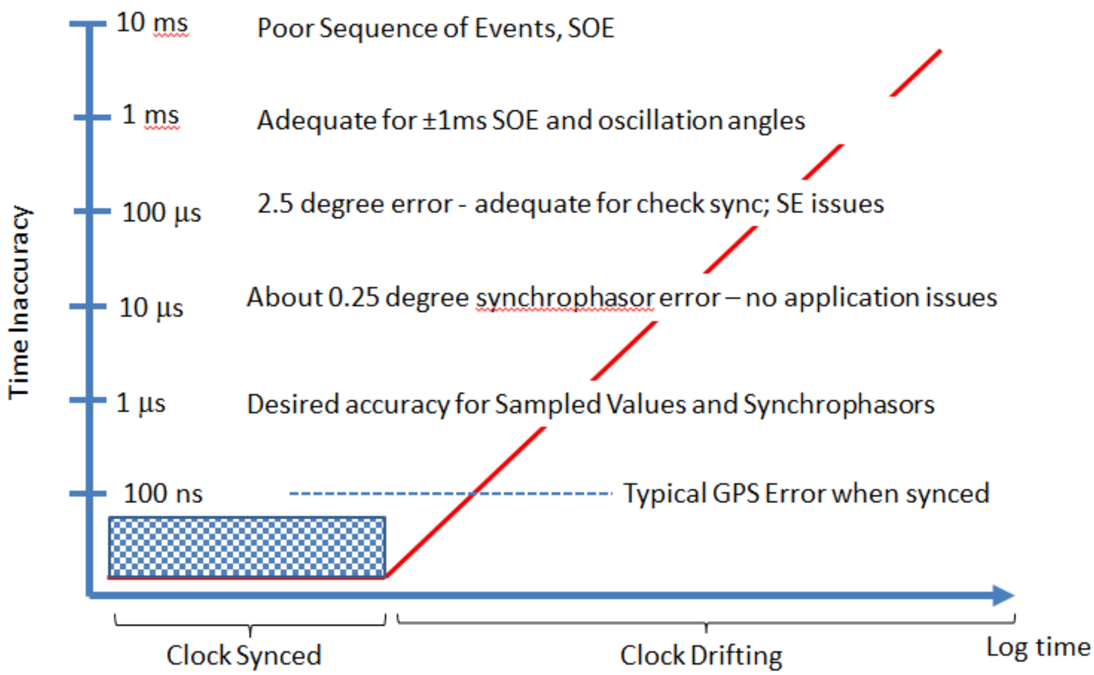

Figure 4. Clock drift time and Time Inaccuracy

Synchrophasor measurements are one of the first widely deployed, power system applications that need distributed precise time source to operate successfully. The time reference translates directly to the measured phase angle. This can be seen by looking at the basic formula defining the synchrophasor. The following equation represents the waveform signal *x(t)* (which could be a voltage or current) and the nominal power system frequency f_0:

$$x(t) = X_m \cos[2\pi f_0 t' + \phi]$$

The synchrophasor value is:

$$\boldsymbol{X}(t) = \frac{X_m}{\sqrt{2}} e^{j\phi}$$

When actual time $t = t'$, the synchrophasor value is the correct phase angle ϕ. However, if the reference time t' being used for the estimate has an error of Δt seconds from the actual time t ($t' = t - \Delta t$), the phasor angle will be similarly displaced:

$$x(t) = X_m \cos[2\pi f_0 t' + \phi] = X_m \cos[2\pi f_0 (t + \Delta t) + \phi] = X_m \cos[2\pi f_0 t + 2\pi f_0 \Delta t + \phi]$$

Therefore the synchrophasor value with time uncertainty contribution is as follows:

$$\boldsymbol{X}(t) = \frac{X_m}{\sqrt{2}} e^{j(2\pi f_0 \Delta t + \phi)}$$

Synchrophasor definition is graphically depicted in Figure 5.

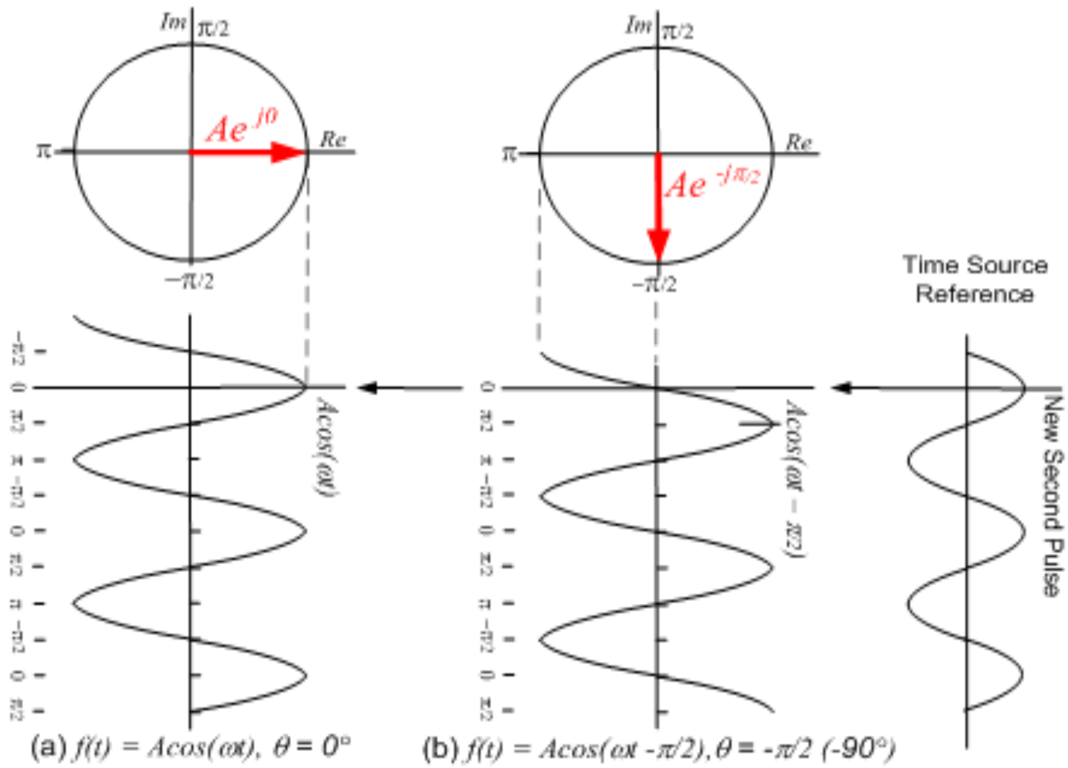

Figure 5. Synchrophasor definition

The basic accuracy requirement for synchrophasors is specified in the measurement qualification standards, IEEE C37.118, IEEE C37.118.1, and IEEE/IEC 60255-118-1. Synchrophasor accuracy, called total vector error (TVE), is determined as the root mean square (RMS) difference between the modulus of the measured and reference (ideal) phasors. This comparison includes both the magnitude and phase angle of the phasor. Steady state measurements are required to have TVE ≤ 1%. A time error of 26 μs in a 60 Hz system or of 31 μs in a 50 Hz system will produce a TVE = 1%. In order to provide an error margin for magnitude and other error sources, a time reference should be at least 10x more accurate than these minimums. To be sure there is enough margin through the phasor estimation processes, 1 μs is widely accepted as the target accuracy for the time input.

In order to assure users that the Phasor Measurement Unit (PMU) is using time that is synchronized to a reference, there are two time quality indicators in the C37.118 communication format. The first one, called message time quality (MSG_TQ), is a 4-bit quality indication. The binary value 0000 indicates the time is locked to a reference signal and is at maximum accuracy. Indications 0001 to 1011 indicate time is within 1 ns to 1 s of Coordinated Universal Time (UTC) by decade. An indication of 1111 indicates the time is unknown. The decade time indication is active only when the clock is in an unlocked or holdover state. The states 0000 and 1111 are usable at any time. The second indicator is the PMU time quality (PMU_TQ) which indicates the clock time quality at all times. This 3-bit indication tracks time error from <100 ns through >10 ms, the most useful range for determining the usability of the synchrophasor phase angle. Both of these TQ indicators should be created by the clock and communicated to the PMU for inclusion in the data message. The PMU needs to have a time message from the clock that supports this information transfer.

The basic question of a synchrophasor application's user is: "Is a synchrophasor is usable?" Figure 4. gives an indication of the "usability" of a timestamp – based on the estimated time error. For a Synchrophasor, measurements with up to a 100 µs error are typically usable. Time errors larger than this make synchrophasors unusable for most applications.

To address this question, the IEEE C37.118.2 Synchrophasor standard makes the following statement: "The Message Time Quality indicator code contained in the lowest 4 bits (of the Time Quality byte in the timestamp) indicates ***the maximum time error*** as determined by the PMU/ Phasor Data Concentrator (PDC) clock function." The IEEE 1588 standard does define a clockAccuracy field, however, it is defined to the "expected accuracy of a clock when it is the grand master". By definition, the expected value of a number the accuracy is the "average" of the accuracy and not the worst case.

To address the need for the "maximum time error" requirement of the Synchrophasor standard, the extended PTP profile, specified in IEEE C37.238-2017 standard, supports communicating dynamic time inaccuracy estimates from master to slave devices in real time. For this, a profile-specific extension – Time Inaccuracy field in the IEEE C37.238 TLV is used. The idea is to estimate the various sources of time inaccuracy in real time and place current time inaccuracy estimates into a cumulative field included in the PTP message sent from master clock to slave devices.

Dynamic time inaccuracy concept is depicted in Figure 6. The following sources of time inaccuracy are considered: grandmaster time inaccuracy, time source inaccuracy and distribution time inaccuracy. Time source time inaccuracy is time accuracy of the GPS source itself. Grandmaster time inaccuracy is the time error introduced by the grandmaster. Distribution time inaccuracy includes time errors introduced by intermediate network devices, e.g. transparent clocks. It should be emphasized that the totalTimeInaccuracy field in the time Inaccuracy TLV appended to PTP Announce messages is a cumulative field which upon arrival to the end device contains the sum of time inaccuracy contributions from all devices in the time distribution chain.

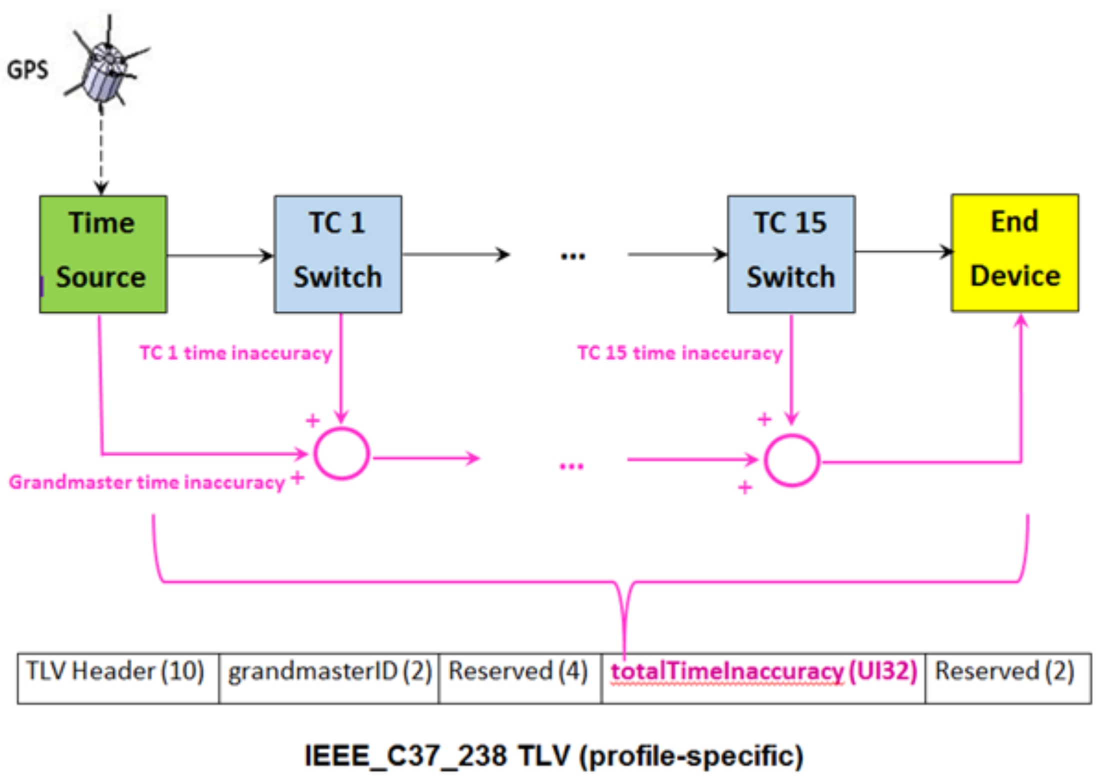

Figure 6. Cumulative dynamic time inaccuracy concept

Next, the Time inaccuracy estimate received in Time Inaccuracy field is mapped into the synchrophasor's Time Quality (TQ) and continuous time quality fields (CTQ) fields. Such mapping is specified in Annex C of IEEE C37.238-2017 standard, and is captured Table 2 below.

TABLE 2. TIME INACCURACY MAPPING BETWEEN IEEE STD C37.238 AND IEEE C37.118.1 AND IEEE C37.118.2 FIELDS

IEEE C37.238 totalTimeInaccuracy,	IEEE C37.118.2 MSG_TQ field IEEE C37.118.1 IRIG-B TQ field	IEEE C37.118.2 PMU_TQ field IEEE C37.118.1 IRIG-B CTQ field
If FFFFFFFF hex (unknown, or > ~4s) else use below	15	7
If TAI-UTC offset "unknown" (currentUtcOffsetValid flag= 0) (e.g., due to expiry of last IERS bulletin-C)	11 (for 1 s to >10 s) else use below	7 else use below
If clock is "locked" (clockClass= 6)	0 else use below	ignore (use below)
100 000 001 to 1 000 000 000	10	7
10 000 001 to 100 000 000	9	7
1 000 001 to 10 000 000	8	6
100 001 to 1 000 000	7	5
10 001 to 100 000	6	4
1001 to 10 000	5	3
101 to 1000	4	2
11 to 100	3	1
1 to 10	2	1
0	1	1

Thus, synchrophasor data arrives together with its current time inaccuracy information mapped into TQ and CTQ fields. Synchrophasor applications can now make a determination as to whether to use the synchrophasor based on the estimated ***maximum time error*** in the timestamp.

As TQ and CTQ fields are also used in IRIG-B control characters, time inaccuracy mapping in Table 2 can also be utilized for IRIG-B converters.

The users should be aware that time inaccuracy concept was supported in the first PTP profile, specified in IEEE C37.238-2011 [2]. The revised 2017 standard specifies a modified IEEE C37.238 TLV format identified as version 2 that is not fully compatible with version 1 TLV.

2) Short Grandmaster Identity

In addition to Time Inaccuracy information, the IEEE C37.238 profile-specific TLV also includes a short grandmaster identifier to use a 16-bit ID for grandmasters' identification as an optional addition to the 64-bit grandmaster ID in the Announce message. The size of this field was changed from 8-bit field in 2011 to 16-bit field in 2017 version to support larger systems.

3) Local time and IRIG-B replacement support

As local time is required for many power utilities applications, and IRIG-B is commonly used in power substations today, local time and IRIG-B replacement support were detailed in IEEE C37.238-2017 extended profile. IEEE 1588-2008 Alternate Time Offset Indicator (ATOI) time length value (TLV) extension is used for these features.

The following three challenges were identified by vendors when using IEEE 1588-2008 ATOI TLV: a possibility of sending incorrect local time, for lack of definition for node's time (the reference time for local time offset); an incomplete support for IRIG-B converters, due to the absence of daylight savings time (DST) in effect flag; and a possible inability to pass ATOI TLV through more than 1 boundary clocks (BC), as advance information on offset changes may be only provided for 4 messages. To overcome these limitations IEEE C37.238-2017 clause 6.2.2 contains a profile-specific ATOI fields' specification.

To provide correct local time IEEE C37.238-2017 specifies that ATOI's currentOffset field value shall be the current offset of the local time, in seconds, relative to the PTP timescale, including both accumulated leap seconds and local offset. This clarifies the specification for IEEE 1588-2008 clause 16.3.3.4 which defines the ATOI's currentOffset field as the offset of the alternate time, in seconds, from the node's time, where node time is undefined. Note that different interpretations of this field have led to reception of incorrect local time during interoperability testing and real time operation.

To support daylight savings time (DST) for end devices and IRIG-B converters, a DST in effect indication was added. IEEE C37.238-2017 specifies that ATOI's jumpSeconds field value shall be 0 when the local time is not using Daylight Saving Time (DST), else it shall be Nx900 with N an integer <> 0; except that jumpSeconds shall be ±1 when, and only when, a leap second is within the next 10 s ± 30%. Note that though the jumpSeconds field provides a leap second indication, IEEE 1588-2008 specifies that this must not be used (the Leap59 and Leap61 flags are to be used).

To allow ATOI TLVs to traverse chains of 2 or more BCs, IEEE C37.238-2017 specifies that ATOI's timeOfNextJump field shall be provided for at least the 10 s prior to each event. With the standard's 30% tolerance on message intervals, this allows the use of this ATOI on networks with as many as 7 cascaded BCs.

Note that since all these IEEE C37-238-2017 requirements only tighten the IEEE 1588-2008 ATOI specification, devices compliant to the IEEE C37.238-2017 ATOI are also compliant to the IEEE 1588-2008 ATOI; and all end devices correctly designed to accept the IEEE 1588-2008 ATOI will also work correctly when receiving the IEEE C37.238-2017 ATOI.

4) Default PTP domain number

Default PTP domain number was changed in the revised PTP profiles. PTP power profile IEEE C37.238-2011 specified default PTP domain 0, and used profile-specific TLV check for profile isolation. Revised version relies on domain number for profile isolation instead. The extended PTP profile IEEE C37.238-2017 specifies default PTP domain number 254, with configurable range of 0-127, and 254.

5) Mixed profile operation

The extended profile IEEE C37.238-2017 Annex E described mixed profiles operation. Specifically it covers the use of IEC/IEEE 61850-9-3 slave devices and the use of other profiles master clocks.

A visual representation of devices in time distribution network and requirements of end users for different profiles is presented in Figure 7.

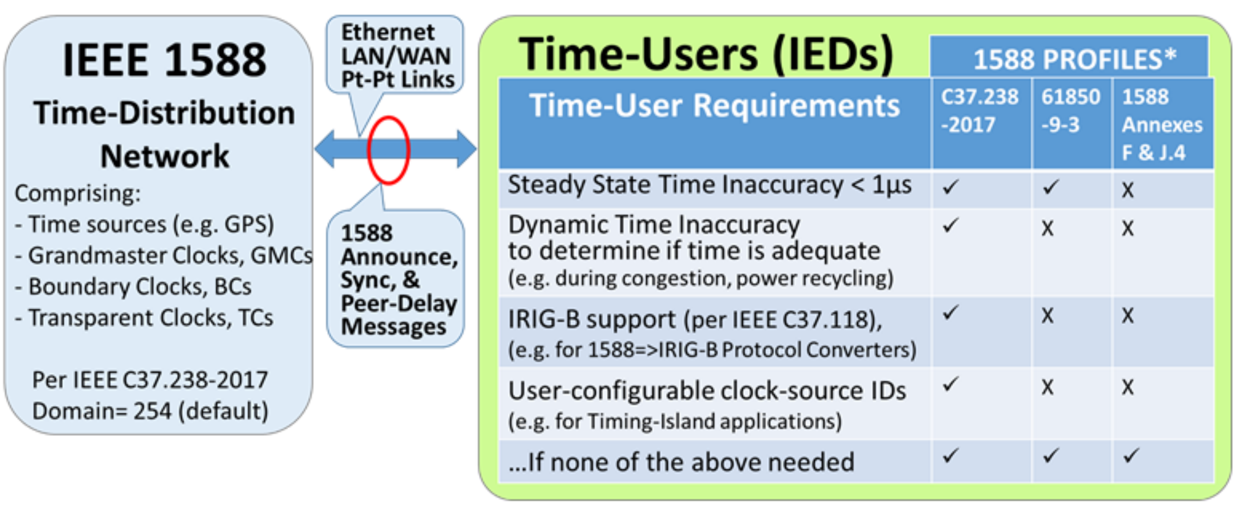

Figure 7. Mixed profile operation

NOTE - Other 1588 Profiles can co-exist on the network (since they will use a different domain (not 254)), e.g. IEEE 802.1AS for "Time Sensitive Networks" and ITU G.8275 for Telecom (domains 44 to 63).

Figure 8. is a network diagram showing interoperation of the base PTP profile (subnets #2 and #3) and the extended profile (subnets # 1 and #2) when using an extended PTP profile grandmaster.

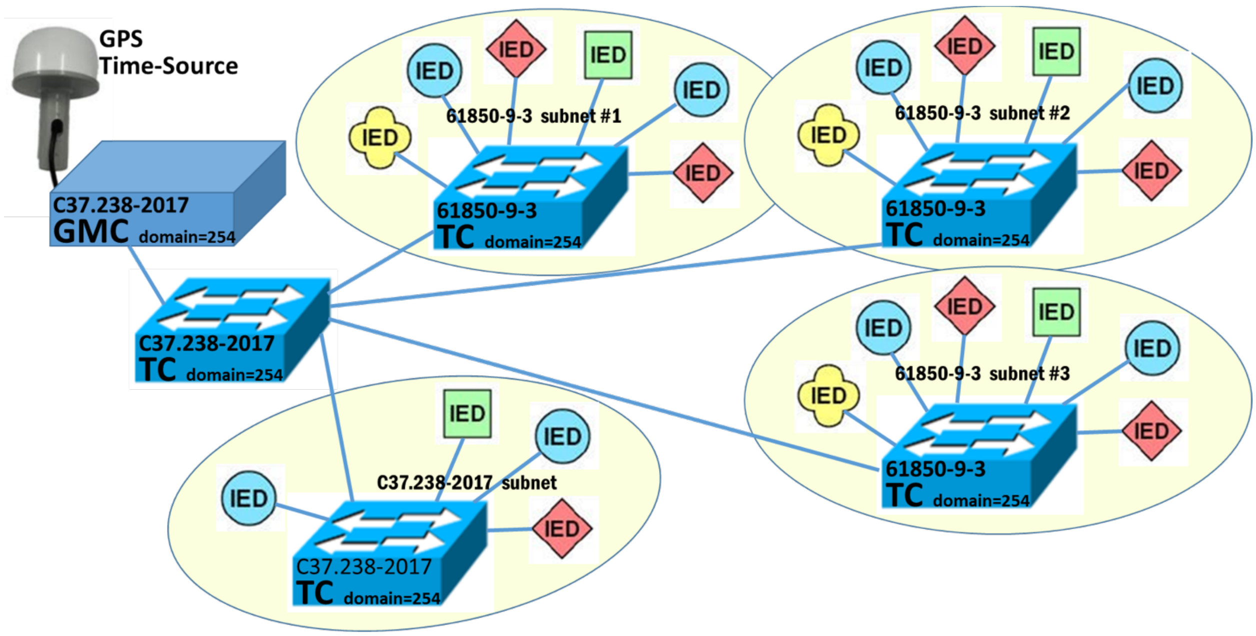

Figure 8. Profiles interoperation

NOTE – For all C37.238-2017 IEDs, the chain of TCs, BCs (if used) and Grandmaster Clock (GMC) to the GPS time source must all support the C37.238-2017 profile.

III. PTP Profiles Comparisson

To assist the reader differences between PTP Power Profile (IEEE C37.238-2011), the base PTP profile (IEC/IEEE 61850-9-3) and the extended PTP profile (IEEE C37.238-2017) are summarized in Table 3 provided at the end of this paper.

IV. IEEE Conformity Assessment Program (ICAP) Test and Certification for IEC/IEEE 61850-9-3:2016 and IEEE C37.238-2017

Distributed measurement and control automation capabilities rely on well characterized clock synchronization and time-stamps within a known uncertainty. Inaccurate timestamps can propagate its uncertainty into measurements and control decisions. In the 2016 workshop on Timing Challenges in the Smart Grid, industry stakeholders identified timing integrity assurance as a key priority to address for the power industry [7]. A rigorous conformance and interoperability test process for industry can help provide a level assurance in meeting industry time synchronization performance requirements among the myriad of device vendors available.

One of the first steps to interoperability is to ensure conformance to industry standards. To add a level of compliance assurance to practical implementations of IEEE C37.238-2017 and IEC/IEEE 61850-9-3:2016 IEEE 1588 Power Profile requirements, the IEEE Conformity Assessment Program (ICAP) [8] is developing a test and certification program. IEEE ICAP has convened a group of industry experts, including device engineers and end users, to review and reach consensus on the PTP Power Profile Test Suite Specification (TSS) [9] developed by the University of New Hampshire InterOperability Laboratory (IOL), which includes tests for both the IEC/IEEE 61850-9-3:2016 and IEEE C37.238-2017 standards.

As IEEE C37.238-2017 is based on IEC/IEEE 61850-9-3, it provides a super set of features to be tested, as shown on Figure 9.

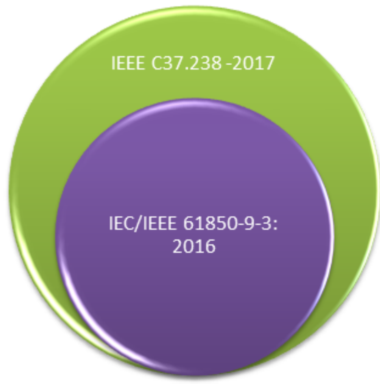

Figure 9. IEC/IEEE 61850-9-3:2016 and IEEE C37.238-2017 test and certification scope

The TSS covers conformance tests for the default BMCA, Power Profile attributes, message intervals, clock holdover, time discontinuities (leap second) and both static and dynamic time error, based on device specifications, current reference source, as well as clock signal output, such as 1 PPS. When 1 PPS signals are not available, the dynamic estimation of time error would be based on peer delay request and response messages. Additional interoperability tests, outside of standard requirements, such as VLAN testing was also identified to be of interest to end users. Some of the optional features such as security and redundancy are not currently covered, but can be part of a future iteration of the TSS.

IEEE Conformity Assessment Program (ICAP) IEEE 1588 Power Profile Test and Certification development process is shown on Figure 10. Once the TSS draft is complete and as device implementations become available, the plan is to begin the experimentation of test methodologies to ensure results are traceable and repeatable to a known uncertainty and statistically valid. The results will help inform the Conformity Assessment Steering Committee (CASC) group on the need to specify general tolerances regarding environmental conditions and test equipment specifications.

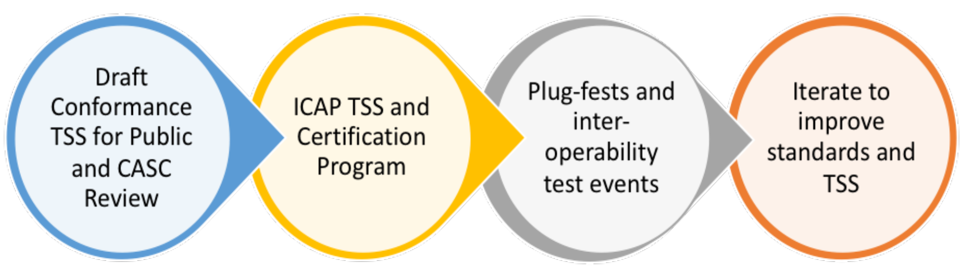

Figure 10. ICAP IEEE 1588 Power Profile Test and Certification Program Development Process.

Interoperability test events and plug-fests also provide the opportunity to evaluate clock response behavior, ensure profile attributes are accurately populated and disseminated with timely response to time events and dynamic topology and performance changes. The test events also provide the ability for different implementations and vendor devices to cooperate and still meet or exceed industry requirements [10]. Interoperability test events provide a means to detect implementation issues, such as watchdog, to enhance overall reliability of devices available to end users.

Through the experimental and interoperability test processes, the objective is to develop a robust test framework upon which a certification program can be launched. The results from the tests will be used to continuously improve the power profile standards as well as the test methodologies in the TSS.

V. Conclusions

IEEE C37.238-2011 standard specifying IEEE 1588 Power Profile for Power Industry Applications was revised. During revision the standard was split into two parts: IEC/IEEE 61850-9-3:2016 that specifies base PTP profile and IEEE C37.238-2017 that specifies extended PTP profile.

This paper explained the reasons for the split, described the features of both profiles and compared them with the original version. Mixed profile operation was described. Differences between three PTP power profiles were presented in Table 3.

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Trademarks are identified in this paper in order to foster understanding. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology.

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TABLE 3. DIFFERENCES BETWEEN IEEE C37.238-2011, IEC/IEEE 61850-9-3:2016 AND IEEE C37.238-2017

Difference	IEEE C37.238-2011	IEC/IEEE 61850-9-3:2016	IEEE C37.238-2017
Mode setting	Not settable to IEEE C37.238-2017 mode	Not settable to C37.238 modes	Settable to IEC/IEEE 61850-9-3 mode, not settable to C37.238:2011 mode.
Backward compatibility and interoperability between profiles	Not compatible with IEEE 1588 clocks that do not support the C37.238 TLVs	Master cannot synchronize C37.238:2011 slaves. Slave can synchronize itself to a C37.238:2011 master with BMCA. Slave can synchronize itself to a C37.238:2017 master (using domain=254).	Master cannot synchronize C37.238:2011 slaves. Master can synchronize 61850-9-3 slaves (when slave is set to domain=254). Slave needing extended features cannot synchronize itself to a C37.238-2011 master Slave needing extended features cannot synchronize itself to a 61850-9-3 master Slave not needing extended features can synchronize itself to a 61850-9-3 master.
PTP time domain	Range: Table 2 of IEEE 1588-2008; Default domainNumber = 0.	Range: Table 2 of IEEE 1588-2008; Default: domainNumber = 0; Recommended: domainNumber = 93.	Range: 0 ...127 + 254 Default domainNumber = 254. 0 ... 127 for basic-profile (61850-9-3) domains 254 mandatory for extended-profile.
Slave clocks with no peer delay measurement	Allowed	Refers to IEEE 1588 that is ambiguous.	Allowed
Startup	TCs do not forward before they reach their specified accuracy	TCs and BCs start to operate immediately after power up with no indication of their inaccuracy.	TCs and BCs start to operate immediately after power up, and signal their inaccuracy in the C37_238_TLV.
Time Inaccuracy information	Through C37_238_TLV v1	Through IEEE 1588 §7.6.2.5 grandmaster.clockQuality (estimated time error) as in the BMCA.	As IEC/IEEE 61850-9-3 and through C37_238_TLV version 2.
C37_238_TLV (time inaccuracy	Mandatory for GM-capable devices, adjusted optionally by TCs	Forwarded by TCs without adjustment, but not by BCs, ignored by slaves.	Mandatory for GM-capable devices, forwarded and adjusted by TCs and BCs.
C37_238_TLV Short GM identity)	8-bit GM short identity v1 incompatible with IEEE C37.238-2017	None	16-bit GM short identity, version 2 incompatible with IEEE C37.238-2011.
ALTERNATE TIME OFFSET TLV	Mandatory support, optional use as 1588 §16.3 [1].	Optional support and use as 1588 §16.3 [1].	Mandatory support, optional use as 1588 §16.3 [1], with extensions: • keyField=0 represents an invalid offset • jumpSeconds always non-zero when daylight time is observed, whether in effect (summer) or not (winter) • leap seconds announced 7 s in advance.
Compatibility	N/A	61850-9-3 slaves fully compatible with a	C37.238-2017 slaves can sync to a 61850-9-

		C37.238-2017 GM	3.GM, but without TLV extensions.
TLV order	TLV order mandatory at GM, slaves ignore Announce messages with incorrect TLV order.	As IEEE 1588	TLV order mandatory at master
Network auto discovery	Limited support. Slaves do not recognize a GM without the C37_238_TLV attached.	Optional check of peers by time-out on Pdelay_Resp messages, according to IEC 62439-3 Annex E or IEC 61850-90-4.	As IEC/IEEE 61850-9-3 and by explicit use of domain 254.
BMCA	Qualified by C37_238_TLV	As IEEE 1588, extended by time quality when redundant ports are used	As IEC/IEEE 61850-9-3
Clock classes	Transitions not specified	Transitions specified	As IEC/IEEE 61850-9-3
Preferred grandmaster	Shorter timeout = 2 × Announce interval	Not supported	As IEC/IEEE 61850-9-3
Grandmaster accuracy	Specified (200 ns)	Specified (250ns)	As IEC/IEEE 61850-9-3
Grandmaster holdover	Accuracy within 2000 ns for 5 s after loss of time reference.	Accuracy within 250 ns for 5 s after loss of time reference.	As IEC/IEEE 61850-9-3
PTP attributes	IEEE C37.238-2011 Table 1	As IEEE 1588 J.3.2 except logAnnounceInterval = 1	As IEC/IEEE 61850-9-3 except default domainNumber = 254.
Boundary clocks	Out-of-scope	Inaccuracy specified (200 ns)	As IEC/IEEE 61850-9-3
Transparent clocks	Inaccuracy specified (50 ns)	Inaccuracy as C37.238-2011 (50 ns)	As IEC/IEEE 61850-9-3, except default domainNumber = 254.
Media converters	Not defined	Inaccuracy specified (50 ns)	As IEC/IEEE 61850-9-3
Double attachment	Not foreseen	Uses IEC 62439-3 Annex B	As IEC/IEEE 61850-9-3
IEEE 802.1Q Tags	Mandatory	Optional (used when VLANs desired)	As IEC/IEEE 61850-9-3
Management	C37_238 MIB	IEC 62439-3 Annex E MIB, IEC 61850-90-4 objects or manufacturer defined.	As IEC/IEEE 61850-9-3