Synchronization in Time-Sensitive Networking: An Introduction to IEEE Std 802.1AS

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Abstract

Synchronization has become key in many applications. It is a key aspect of Industrial Automation networks, as those applications depend on synchronized time. It is also important for automotive applications, as synchronization is used for infotainment and handling sensor data. In Telecommunications networks, synchronization has been used for many years, and it is very important to fulfill 5G technology requirements. The Time-Sensitive Networking (TSN) Task Group (TG) of IEEE 802.1 has developed several base standards to allow a deterministic network with bounded latency. IEEE Std 802.1AS, "Timing and Synchronization for Time-Sensitive Applications," is part of these base standards developed by the TSN TG. This article gives an introduction of IEEE Std 802.1AS, and addresses synchronization concepts and its applications. IEEE Std 1588 defines a precision time protocol (PTP), and IEEE Std 802.1AS includes a profile of IEEE Std 1588; therefore, some concepts of IEEE 1588 are also described in this article.

Introduction

Synchronization is critical to several applications, and it has become one of the key topics in several industries, such as Audio/Video, Industrial Automation, Automotive, Telecommunications, Power, and Finance.

Over several years, synchronization has been used in many applications; the Network Time Protocol (NTP) [1] has been widely used around the world since the 1980s and has been supplying time for applications that need time error on the order of milliseconds. The required worst-case time error is dependent on the application and the type of network. Some applications, such as Industrial Automation, need a better accuracy, on the order of one microsecond for 64 hops, and therefore a more precise time protocol was needed.

The TSN set of base standards developed by the Time-Sensitive Networking (TSN) Task Group (TG) of IEEE 802.1, allows a deterministic network with bounded latency, and it includes one key standard for the transport of time synchronization: IEEE Std 802.1AS.

IEEE Std 802.1AS includes a profile of IEEE Std 1588, and it also includes requirements related to audio and video applications. IEEE Std 1588 defines the precision time protocol (PTP) and was first published in 2002, mainly addressing test and measurement applications. Soon after its publication, the development of IEEE 1588 version 2, published in 2008, was underway to address a wide variety of applications, such as Test and Measurement, Telecommunications, Power, Industrial Automation, and Military. In 2019, a new edition (version 2.1) of IEEE Std 1588 was approved, and was published in 2020.

The first version of IEEE Std 802.1AS was published in 2011, and is based on IEEE Std 1588-2008; its focus was audio and video applications. The second version of IEEE Std 802.1AS was published in 2020, and is based on IEEE Std 1588-2019; it was developed to include other TSN applications, such as Industrial Automation, Automotive, and Aerospace. Even though IEEE Std 802.1AS includes performance requirements intended for Audio and Video, the performance requirements for new applications will be addressed as part of new TSN profiles, such as IEC/IEEE 60802 TSN Profile for Industrial Automation.

The authors recognize the sensitive nature of some words used in IEEE Std 1588 and IEEE Std 802.1AS. At the time of the preparation of this article, an amendment to IEEE Std 1588 (P1588g) is in its final stage of approval to include alternative terminologies for offensive words. Also, an amendment to IEEE Std 802.1AS (P802.1ASdr) is under development to replace offensive words in the standard. P802.1ASdr is dependent on the terminology chosen by P1588g. Whenever possible, this article uses timeTransmiter for master, and timeReceiver for slave, as these are the terms that are being considered in the P1588g amendment to IEEE Std 1588-2019.

IEEE Std 802.1AS has been described previously; see, for example, [2] and references cited there. However, those descriptions were limited to the 2011 edition of IEEE Std 802.1AS and audio/video applications. The present article focuses on IEEE Std 802.1AS-2020, new amendments to 802.1AS under development, and the newer TSN applications.

This article first addresses some basic concepts of IEEE Std 1588, followed by an introduction to IEEE Std 802.1AS, the synchronization details, and the architecture layering. Next, it describes the differences between IEEE Std 802.1AS-2011 and IEEE Std 802.1AS-2020, and a hot standby feature being considered by a few TSN applications. Finally, synchronization aspects of IEC/IEEE 60802,

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P802.1DG, and IEEE P802.1DP / SAE AS6675 TSN profiles are summarized. Conclusions are presented in the final section.

IEEE Std 1588 Basic Concepts

The PTP protocol is executed to synchronize clocks that are part of a PTP network within a particular domain. It first organizes the PTP network to create a synchronization hierarchy by using the Best Master Clock Algorithm (BMCA) to determine the best clock of the network, the Grandmaster (GM). The GM exchanges PTP timing messages with its time receiver devices to synchronize their clocks to the GM clock.

The development of IEEE Std 1588-2008 (version 2) involved many industries, and several features were included in that version of the standard to address different applications. The notion of PTP profile was first introduced allowing different industries to use features that best suit their application. It is also important to allow interoperability between PTP Instances using a particular profile that targets a specific application.

The PTP profile specifications are defined in Clause 19.3 of IEEE Std 1588-2008, and in Clause 20.3 of IEEE Std 1588-2019, and it is defined as follows: "A PTP Profile is a set of required options, prohibited options, and the ranges and defaults of configurable attributes."

Version 2 of IEEE Std 1588 defined two default PTP profiles ("Delay Request-Response Default PTP Profile" and "Peer-to-Peer Default PTP Profile"), and a third default profile was defined in version 2.1 ("High-Accuracy Delay Request-Response Default PTP Profile").

Other standard development organizations (SDOs) have defined profiles to target their applications, such as the IEEE Std 802.1AS profile, the profile developed by the Society of Motion Picture and Television Engineers (SMPTE) [3] for professional broadcast applications, the Telecommunication profiles developed by the International Telecommunication Union (ITU).

A profile identifier carried on-the-wire was not part of version 2 of IEEE Std 1588, therefore, it was not possible to identify a particular PTP message with a particular profile; this could create some issues if two different profiles are used in the same network. Version 2.1 fixed this issue by introducing an SDO identifier (sdoId) to allow isolation of profiles.

IEEE Std 1588 defines a default BMCA, and it also allows a profile to define an alternate BMCA.

PTP defines two mechanisms for measuring the propagation delay between two PTP ports:
- The delay request-response mechanism using the Sync, delay request (Delay_Req) and delay response (Delay_Resp) messages
- The peer-to-peer delay mechanism using the peer delay request (Pdelay_Req), peer delay response (Pdelay_Resp), and optionally the peer delay response follow-up (Pdelay_Resp_Follow_Up) messages.

A profile should define which of these two mechanisms is implemented, as an example, IEEE Std 802.1AS uses the peer-to-peer delay mechanism with Pdelay_Resp_Follow_Up message being mandatory, even though it is optional in IEEE Std 1588.

IEEE Std 1588 defines several transport mechanisms, and it allows a profile to use a different one that is defined by an organization that has jurisdiction over that transport mechanism. For example, one Telecommunication profile [4] allows the transport of PTP over the Optical Transport Network (OTN); as of the date of preparation of this article, there is an amendment to IEEE Std 1588 to include PTP over OTN, which is in its final stage of approval.

IEEE Std 1588-2019 defines a PTP Instance as an instance of the PTP protocol, operating in a single device, within exactly one domain. Five types of PTP Instances are defined: 1) Ordinary Clock (OC) is defined as a PTP Instance that has a single PTP Port in its domain; it could be a time transmitter or a time receiver; 2) Boundary Clock (BC) is defined as a PTP Instance that has multiple PTP Ports in its domain; it could be a time transmitter and a time receiver; 3) End-to-end Transparent Clock is a Transparent Clock (TC) that supports the delay request-response mechanism; 4) Peer-to-peer TC is a TC that supports the peer-to-peer delay mechanism; 5) PTP Management Node for management.

IEEE Std 1588 defines several optional features, and which one(s) is/are implemented should be specified by a profile.

IEEE Std 1588 can be extended by the use of a TLV (type, length, and value) that could be defined in a profile.

IEEE Std 802.1AS Introduction

IEEE Std 802.1AS includes a PTP profile and adds protocol features beyond those specified by IEEE Std 1588. It specifies the generalized precision time protocol (gPTP). It also specifies performance requirements addressing audio and video applications. The concept of a time-aware system is introduced to specify a device implementing gPTP; a time-aware system contains one or more PTP Instances and/or PTP services (e.g., the common mean link delay service). It also introduces two types of PTP Instances: PTP End Instance, which is defined as a PTP Instance that has exactly one port; and PTP Relay Instance, which relays time information that it receives from a GM, compensates for the delay through the network, and transmits the corrected time information; it has more than one port. A PTP End Instance might, or might not, be a GM; a PTP End Instance that is not a GM receives time information that originates at the GM.

The first step of the protocol is to establish the synchronization hierarchy via external port configuration or through the use of BMCA. If external port configuration is used to construct the desired synchronization hierarchy, then the PTP port states are configured by an external entity to be either TimeTransmitterPort, TimeReceiverPort, PassivePort, or DisabledPort (see Table 10-2 of [5]). If the BMCA is used, then Announce messages are used to convey information between the PTP instances to select the GM and to decide the PTP port states. The BMCA is based on the default BMCA defined in IEEE Std 1588 with a few differences (e.g., there is no premaster state, no foreign master qualification, and the clock attribute priority1 is used to determine whether or not the PTP instance is GM-capable). Figure 1 shows an example of a synchronization hierarchy.

In Fig. 1, each PTP Relay Instance runs the BMCA independently. Each port on each PTP Relay Instance receives information about the

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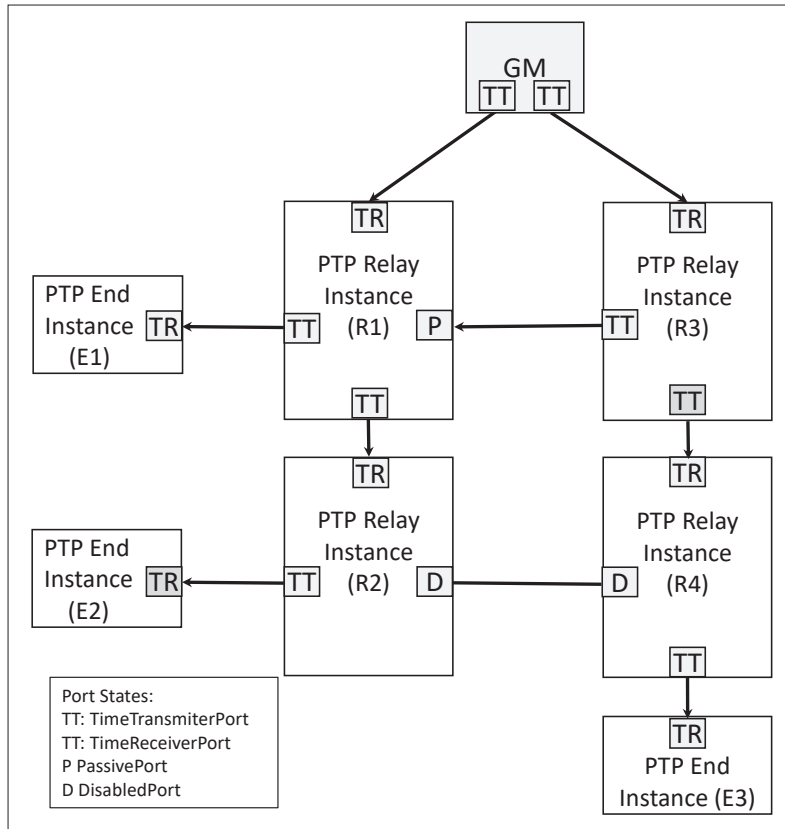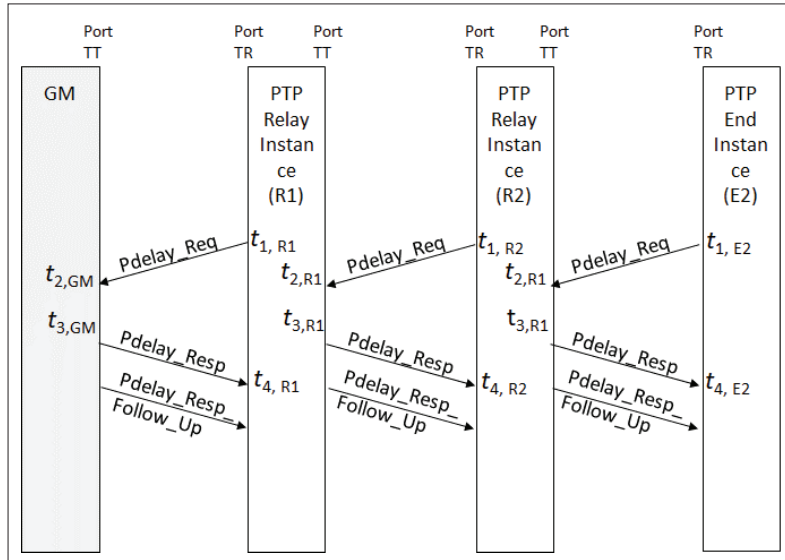
FIGURE 1. Example of synchronization hierarchy.

FIGURE 2. Example of mean link delay and the neighbor rate ratio measurement.

best GM in the network through Announce messages. Each PTP Relay Instance compares received clock quality information with its own quality. If the received clock quality, at a particular port, is better than the quality of the current PTP Instance[1] and the received quality on other ports, then that port is deemed to receive time information from a better clock. If the quality of the current PTP Instance is better than the received quality in all of the received Announce messages on all ports, then the current PTP Instance is deemed to be the best clock and it becomes the grandmaster. Thus, the BMCA forms the synchronization hierarchy.

The second step of the protocol is to synchronize the PTP instances. The details are given in the next section for full-duplex Ethernet transport.

TIME SYNCHRONIZATION

Once the BMCA forms the synchronization hierarchy, the PTP Instances can synchronize to the grandmaster.

For full-duplex Ethernet, the synchronization is based on PTP messages exchanged between the PTP Instances.

Using the example network shown in Fig. 1, the following text describes the synchronization steps that take place to synchronize the PTP End Instance E2 to the GM, through PTP Relay Instances R1 and R2.

Figure 2 shows the timing messages exchanged between the ports on each node to calculate the mean link delay and the neighbor rate ratio, using the Pdelay mechanism. Note that in Fig.2 the ports are still labelled as TimeTransmitterPort and TimeReceiverPort, but any port in any state other than DisabledPort can be the initiator or the responder of Pdelay messages, which are used to calculate mean link delay and neighbor rate ratio.

In the example shown in Fig. 2, the following steps are taken to calculate the mean link delay and the neighbor rate ratio between the GM and PTP Relay Instance R1. The neighbor rate ratio is the ratio of the frequency of the local clock of the responder (e.g., GM in Fig. 2) to the frequency of the local clock of the initiator (e.g., PTP Instance R1 in Fig. 2) of the Pdelay messages. The steps are:

1. The initiator, R1 in Fig. 2, sends a Pdelay_Req to the GM, the Pdelay_Req is timetamped ($t_{1,R1}$) using its free-running local clock, and it is recorded.
2. The responder, GM, receives the Pdelay_Req and timestamps ($t_{2,GM}$) it using the GM time and sends ($t_{2,GM}$) back to R1 in a Pdelay_Resp.
3. The Pdelay_esp, originating as a response to the received Pdelay_Req, is timestamped ($t_{3,GM}$) using the GM time, and a Pdelay_Resp_Follow_Up message containing ($t_{3,GM}$) is sent to R1.
4. When R1 receives the Pdelay_Resp, it timestamps ($t_{4,R1}$) it using its local clock.
5. The exchange of Pdelay messages is periodic, and the timestamps generated by successive Pdelay_Resp messages (t_3 and t_4) are used to calculate the neighbor rate ratio. The neighbor rate ratio (r) is calculated using the following equation.

$$r = \frac{t_{3,GM}(N) - t_{3,GM}(N-1)}{t_{4,R1}(N) - t_{4,R1}(N-1)}$$

where N is the Nth Pdelay message sent/received, and ($N - 1$) is the prior Pdelay message sent/received.

6. The initiator, R1, has all four timestamps and it calculates the mean link delay (D) relative to the GM timebase using the following equation:

$$D = \frac{1}{2}\left[r(t_{4,R1} - t_{1,R1}) - (t_{3,GM} - t_{2,GM})\right]$$

7. This process takes place in all of the PTP instances in order to calculate the mean link delay and the neighbor rate ratio for all neighboring PTP instances in both directions. Note that the mean link delay measurements can be done in any direction on all ports that are not blocked, and they are independent of the direction of the sync messages. This allows for faster resynchronization after a reconfiguration of the network.

Figure 3 shows the timing messages exchanged between the ports on each node to transport time synchronization.

In the example shown in Fig. 3, the following steps are taken to synchronize the PTP End Instance E2 to the GM:

1. GM generates a Sync message and time-stamps it at a precise time ($t_{1,GM}$) based on the GM local time, and sends it to the TimeTransmitterPort (Port TT) either in a Sync message (in one-step mode), or in a Follow_Up message (in two-step mode); the example in Fig. 3 is based on two-step mode.

2. After some time, PTP relay instance R1 receives the Sync message at its TimeReceiverPort (Port TR), and timestamps it based on its local clock at a precise time ($t_{2,R1}$). Shortly after receiving a Sync message, the associated Follow-Up message is received; the Follow_Up contains the GM time ($t_{1,GM}$) and the delay asymmetry if known. After some time, the PTP relay instance R1 sends a Sync message in its TimeTransmitterPort (Port TT), and timestamps it at a precise time ($t_{1,R1}$). A Follow_Up message will follow the Sync message, and it contains: the GM time ($t_{1,GM}$); a correction field containing the difference between the time that the Sync message was sent from the TT port in R1 and the GM time ($t_{1,GM}$), this is based on the R1 residence time ($t_{1,R1} - t_{2,R1}$), and the mean link delay between GM and R1; it also accounts for the rate ratio, which is the ratio of the GM clock frequency to the local clock frequency of R1. The neighborRateRatio is accumulated in a TLV appended to the Follow_Up message and is sent to the next node (R2).

3. After some time, PTP relay instance R2 receives the Sync message in its TimeReceiverPort (Port TR in Fig. 2), and timestamps it based on its local clock at a precise time ($t_{2,R2}$). Short after receiving a Sync message, the associated Follow-Up message is received; the Follow_Up contains the GM time ($t_{1,GM}$), the delay asymmetry if known, correction field, and the rate ratio between R1 and GM. After some time, the R2 sends a Sync message at its TimeTransmitterPort (Port TT), and timestamps it at a precise time ($t_{1,R2}$) based on its local clock. A Follow-Up message will follow the Sync message, and it contains: the GM time ($t_{1,GM}$); a correction field containing the difference between the time that the Sync message was sent at the TT port in R2 and the GM time; this is based on the correction field of the Follow_Up message received at the TR port of R2, the R2 residence time ($t_{1,R2} - t_{2,R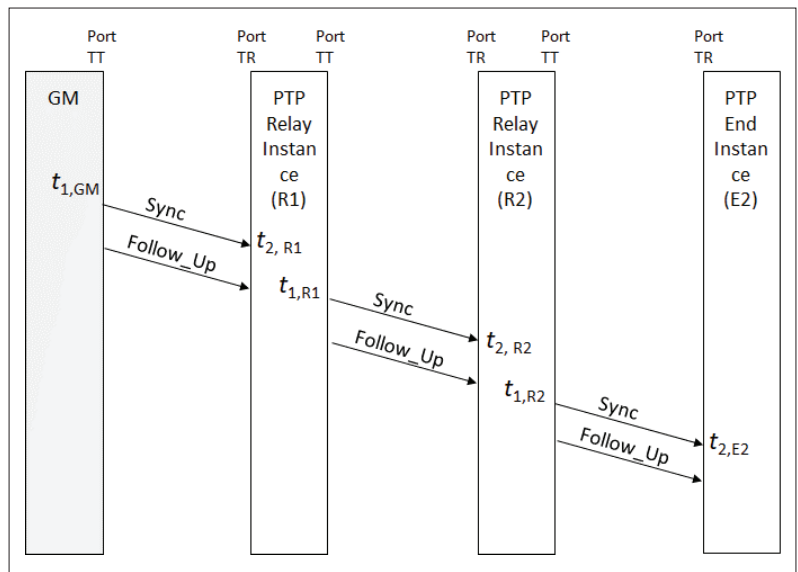2}$), the mean link delay between R1 and R2, and the rate ratio, which is the ratio of the GM clock frequency to the local clock frequency of R2. The neighborRateRatio is accumulated in the TLV attached to the Follow_Up, and it is sent to the next node (E2).

4. After some time, PTP End instance E2 receives the Sync message at its TimeReceiverPort (Port TR in Fig. 2), and timestamps it based on its local clock at a precise time ($t_{2,E2}$). Shortly after receiving a Sync message, the associated Follow-Up message is received; the Follow-Up contains the GM time ($t_{1,GM}$), the delay asymmetry if known, accumulated residence time, and the rate ratio between the previous node and the GM. It now has all the information needed to correct its time with respect to the GM. Depending on the application, a low-pass filter may be used at the PTP end instance to filter the noise accumulated throughout the network.

The example above covers the case of two-step clocks. If one-step clocks are used the synchronization steps are similar; the difference is that the information in the Follow-Up messages is carried in the Sync messages.

FIGURE 3. Example of the transport of time synchronization.

IEEE Std 802.1AS
Architecture Layering

The architecture of a PTP instance is modeled in IEEE Std 802.1AS with media-independent and media-dependent layers. This is important in order to support certain media, such as IEEE Std 802.11 [6], IEEE Std 802.3 EPON [7], and Coordinated Shared Network (CSN), where their inherent time transport mechanisms are used rather than adding a separate timing mechanism based on IEEE Std 1588 messages.

For IEEE Std 802.11 links, the protocols Timing Measurement (TM), or Fine Timing Measurement (FTM), as defined in IEEE Std 802.11-2016 [6], are used to transfer time to the end application.

For EPON, a "slow protocol" is used to transfer time to the end application.

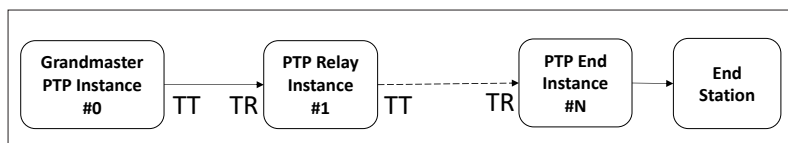For full-duplex Ethernet, IEEE Std 1588 timing messages are used as described above.

FIGURE 4. HRM used for simulations.

For CSN (e.g., MoCA), the same communication system is used as for full-duplex Ethernet; however, there also is an option to use inherent mean path delays and an inherent CSN reference clock if the CSN provides them.

IEEE Std 802.1AS defines primitives to transfer information between media-dependent and media-independent layers.

IEEE Std 802.1AS defines a Boolean asCapable to determine that two PTP instances connected by a link can interoperate with each other using the IEEE Std 802.1AS protocol, and that there are no non-IEEE-802.1AS in between them. The determination of asCapable is medium dependent.

Differences between IEEE Std 802.1AS-2011 and IEEE Std 802.1AS-2020

The first version of IEEE Std 802.1AS was published in 2011, and was developed for audio/video applications. It also included performance requirements. It was limited to one gPTP domain, with domain number 0.

The latest version of IEEE Std 802.1AS was published in 2020, and was developed taking into consideration new applications such as industrial automation and automotive. Several new features were added to support these new applications.

The following new features were added to IEEE Std 802.1AS-2020.
- The use of multiple domains: the total number of domains may be specified by a profile. In order to keep backward compatibility with the 2011 edition, domain zero must be supported by the time-aware system and the timescale of domain zero must be PTP.
- External port configuration: with this option, the BMCA is disabled and the port states are set externally and are static. External port configuration is disabled by default for domain zero for backward compatibility with the 2011 edition. One use-case of this feature in combination of multiple domains is for hot standby (see more details below).
- One-step clock: a flag in a signaling message is set to true if the port can receive one-step Sync messages. This will trigger a state machine on the transmit side to send one-step Sync messages if supported by the port.
- Common mean link delay service: this allows a common mean link delay measurement between two ports to be done across all domains, as the mean link delay is dependent on the physical characteristic of the link, and is not dependent on the PTP domains.
- Fine Timing Measurement (FTM) per IEEE Std 802.11-2016, to improve accuracy.
- A gPTP capable TLV indicating that its neighbor is capable of executing the gPTP protocol.
- Management support for delay asymmetry measurement based on line-swapping.

Hot Standby

At the time of the preparation of this article, the TSN WG is working on an amendment to IEEE Std 802.1AS-2020 to support hot standby (P802.1ASdm).

PTP instances that operate in hot standby do not support the BMCA; they use the external port configuration, so PTP ports are statically configured. Two independent GMs (primary and secondary) operate simultaneously, each in its own PTP domain, and therefore two independent domains are used.

The change from one GM to another GM must be done seamlessly, without any disruption in the time, and therefore it is assumed that the primary and the secondary GMs are fully synchronized. To do so, the secondary GM takes time from the primary domain, and if the primary GM fails, then the secondary GM provides synchronization.

A split function is being defined to provide an enhanced mitigation scheme for GM and link failures. In order to avoid any synchronization disruption at the end application, this scheme defines an interworking function (IWF) to transfer time from the primary domain to the secondary domain in case of failure of the secondary domain (i.e., of the secondary PTP Instance TimeReceiverPort, and vice-versa).

The failure or fault conditions of a GM for a hot standby system is not specified in IEEE Std 802.1ASdm; it is expected that a TSN profile or an application specifies those conditions. It is expected that the fault conditions are repaired by a higher-layer entity (such as a management node) outside of the scope of P802.1ASdm.

Hot standby is especially important for industrial automation in case of GM failure in the network.

Industrial Automation Synchronization

At the time of the preparation of this article, work is being done to develop a profile for Industrial Automation. This project (IEC/IEEE 60802 TSN Profile for Industrial Automation) [8] is a joint effort between IEC SC65C/WG18 and IEEE 802.

Industrial automation contains control loops with multiple tasks, including data flows that are based on time or cycles. A data flow relies on regular updates based on a local or network time base, making latency and time synchronization very critical for the proper operation of the system; therefore latency and time error need to be minimized and bounded.

The profile defines Global Time and Working Clock. Global Time is synchronized time traceable to a known source (e.g., International Atomic Time (TAI)), and Working Clock is synchronized time traceable to an arbitrary (ARB) timescale. Industrial automation devices need to ensure that time is always available; it could be based on a grandmaster or an internal clock. Simulation work is being done to define specifications for the Working Clock. Figure 4 shows the hypothetical reference model (HRM) used by the simulations.

The number of nodes between the Grandmaster PTP Instance and the end station must be at least 64 nodes, and it is desirable to be 100

nodes. The synchronization requirement has been defined for this network, and the maximum absolute time error of any End Station relative to the Grandmaster PTP Instance must be below 1 µs.

The main purpose of the simulation work is to define parameters to be used in the profile to guarantee that the maximum absolute value of time error of 1µs is not exceeded.

The simulation model includes 101 nodes, and it takes into consideration:
- Temperature profile for the local clock: this is important for GM and local clock frequency drift rate. The clock frequency drift being used in the simulation is between −1.35 ppm/s and +1.35 ppm/s.
- Mean Sync message interval: 125 milliseconds.
- Mean Pdelay message interval: different intervals of 31.25 milliseconds. 250 milliseconds, and 1 second are being considered.
- Timestamp granularity of 8 nanoseconds.
- Dynamic timestamp error of 8 nanoseconds and 4 nanoseconds.
- Residence time: two values of 1 millisecond and 10 milliseconds are being considered.
- Endpoint filter bandwidth of 2.6 Hz.

These simulations are being run at the time of the preparation of this article, and, based on the results of these simulations, key parameters (e.g., residence time, mean Sync and Pdelay_Req message interval) may be defined as normative parameters in the profile.

AUTOMOTIVE AND AEROSPACE SYNCHRONIZATION

At the time of the preparation of this article, work is being done to develop a profile for Automotive (IEEE P802.1DG), and a profile for Aerospace (IEEE P802.1DP / SAE AS6675).

The synchronization work for these profiles is still in early stages, as noted in the next sub-sections.

AUTOMOTIVE PROFILE (P802.1DG)

P802.1DG [9] is a profile for automotive in-vehicle Ethernet communications. It is being developed based on Ethernet network to support in-vehicle applications.

Unlike the Industrial Automation networks, in-vehicle networks are well defined at design time, and should not change unless these changes were already planned during the design. P802.1DG currently defines three profiles.

Base Profile: it defines a minimum set of requirements to support TSN inside the vehicle. From the time synchronization perspective, it is important to support IEEE Std 802.1AS-2020, as time synchronization is needed for some key features, such as synchronizing media streams, and for handling sensor data for advanced driver assistance systems (ADAS).

Extended Profile: it supports all the requirements of the base profile and adds TSN capabilities to support autonomous driving and next generation architecture. Fault tolerance and deterministic low latency are key aspects of this profile.

Profile for Audio Systems: it defines requirements for in-vehicle audio systems. From the time synchronization perspective, it is important to support IEEE Std 802.1AS-2020 to deliver quality audio.

Discussions are being held on the following points:
- Synchronization requirements: a maximum absolute value of time error of 1µs has been suggested to address in-vehicle audio and video applications.
- BMCA: whether or not there is a need to use BMCA and Announce messages.
- PTP message rates to meet specific requirements to address several in-vehicle applications.
- Hot standby: need a simple backup mechanism; may need a simpler version of 802.1ASdm hot standby.

AEROSPACE (IEEE P802.1DP/SAE AS6675)

This profile is a joint project of IEEE 802 and SAE Avionics Networks AS-1 A2. Similar to P802.1DG, it is being developed based on Ethernet network to support aerospace applications. Time synchronization is in early discussions within this project and IEEE Std 802.1AS is being considered to be used.

CONCLUSION

TSN includes several base standards, and the associated technologies have been evolving and improving. Several new applications are making use of TSN standards, and synchronization is a key part of TSN technology. New profiles are being developed based on TSN standards, and as the work progresses and evolves, some new features to IEEE Std 802.1AS have been identified, which are included in several amendments to IEEE Std 802.1AS; they are:
- P802.1ASdn: amendment to specify a YANG data model to support configuration and state reporting via the managed objects of IEEE Std 802.1AS.
- P802.1ASds: amendment to support IEEE Std 802.3 Clause 4 Media Access Control (MAC) operating in half-duplex. This is particularly important for the Automotive profile to support the 10BASE-T1S type of technology.
- P802.1ASdm: amendment to support hot standby as described above.

It is expected that TSN technologies will be widely used in several industries addressing different applications, and time synchronization is a key aspect of these applications.

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The number of nodes between the Grandmaster PTP Instance and the end station must be at least 64 nodes, and it is desirable to be 100 nodes. The synchronization requirement has been defined for this network, and the maximum absolute time error of any End Station relative to the Grandmaster PTP Instance must be below 1µs.

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[7] IEEE Std 802.3-2022, IEEE Standard for Ethernet.
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ADDITIONAL READING

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BIOGRAPHIES

Silvana Rodrigues is a senior principal engineer at Huawei. She holds an Electronic and Electrical Engineering degree from University of Campinas, Brazil. She has been working on network synchronization and actively contributing to synchronization standards development for more than 15 years. She has been the secretary of IEEE 1588 Precision Time Protocol (PTP) Working Group since the beginning of the work of IEEE 1588 version 2. She is the editor of P802.1ASdr and P802.1ASds, she participates and contributes to several IEEE 802.1 TSN working groups. She is currently the associate rapporteur and editor of several recommendations at ITU-T SG15 Q13 (the synchronization experts group).

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