14.05.2012

DRAFT

Dual Time Scale in Factory & Energy Automation

White Paper about Industrial Requirements @ Time Synchronization

(IEEE 802.1ASbt)

Authors and contributors:

Franz-Josef Goetz, I IA ATS, Siemens AG, (franz-josef.goetz@siemens.com)

Clemens Hoga, IC SG AE, Siemens AG, (Clemens.hoga@siemens.com)

Dr. Karl Weber, Zurich University of Applied Sciences, (Karl.Weber@ieee.org)

1 Introduction

During the last decade, lots of work has been done in order to increase the accuracy of time sync via Local Area Networks. A major step was the involvement of bridges to eliminate the variance of transmission time of delay request and delay response caused by the nature of unpredictable Ethernet traffic. Specified in IEEE 1588, the current version V2 offers comprehensive functions to fulfill almost all requirements of today's applications. Unfortunately, the increasing number of different application fields led to a number of profiles and derivates, which imply incompatibilities in detail. An additional challenge, the mandatory high performance media redundancy of such Industrial Ethernet applications increases the complexity. On the other hand, lots of successful implementations and plugfests, which have demonstrated the interoperability of the dedicated solutions, have already created the new potential fields of application for IEEE 1588. Today, it is possible to support different PTPv2 profiles in one switch or edge device, however this is not quite optimal.

Currently in IEEE 1588 a discussion about PTP version 3 is open. Within IEEE 802.1 AVB task group requirements for industrial are collected for further discussion in PTP working group.

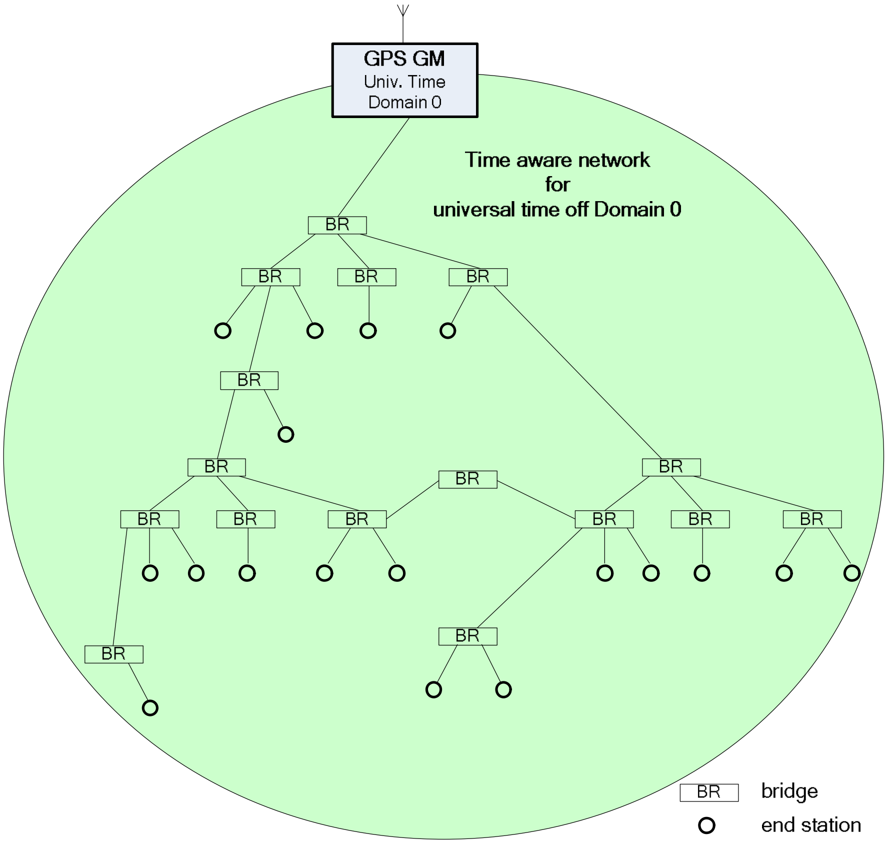
This paper elaborates the typical use cases in the various industry domains and introduces a novel way how to structure the time sync domains by introducing so called "working clocks".

This paper also describes how time synchronization is used in factory automation. Typical applications using time synchronization over Industrial Ethernet are introduced and their requirements will be described. The reasons why dual time scales may be necessary are listed.

If this paper will be officially published, I would make a note here that a reader is assumed to be familiar with IEEE1588 and 802.1AS standards. Otherwise you may need to define universal time, PTP, gPTP and other terms and abbreviations.

2 Universal time

Typically universal time is distributed by GPS satellites. To make universal time available in a factory network GPS receivers are used. The gPTP protocol is used to distribute universal time over bridged network.



The increasing production speed and requirements for high product quality are among reasons for increasing requirements on higher accuracy for synchronization of universal time. These increased requirements can not met by Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP).

2.1 Reasons for using gPTP (IEEE 802.1 AS-2011) to Synchronize Universal Time

- Universal time should be available over the whole network
  - One common sync domain

- Little configuration effort (plug & play)

- Inherent loop prevention mechanism (Best Master Clock algorithm used creating sync tree)

- Use COTS bridges with little hardware support and low CPU utilization
  - Announce message is used to establish port roles for sync tree with fast configuration and reconfiguration of sync tree
  - The cumulative frequency offset mechanism and the sync tree mechanism guarantees fast startup und fast reconfiguration
  - Only one reserved group multicast address for all gPTP messages, all messages are peer-to-peer messages (announce, sync, follow up, P-delay request, P-delay response, P-delay follow up response, signaling)

  - Peer-to-peer path delay measurement is time scale independent
    (free running timer / counter are used for peer-to-peer path delay measurement)
  - Sync messages have to follow sync tree
  - Sync messages are only forwarded over links
    - which supports the path delay measurement and
    - where path delay measurement was successful
  - Only one sync message per port within one sync interval (no overload) at startup

- Can cross router borderlines with gPTP capability
  (forwarding mechanism for gPTP messages is independent of L2 and L3 forwarding mechanism because it has specified own forwarding rules for announce, sync and follow up messages by best master clock algorithm (BMCA))

2.2 Typical Applications Using Universal Time for Time Stamping

- **Universal Time (wall clock)**

- **Sequence of events or events**

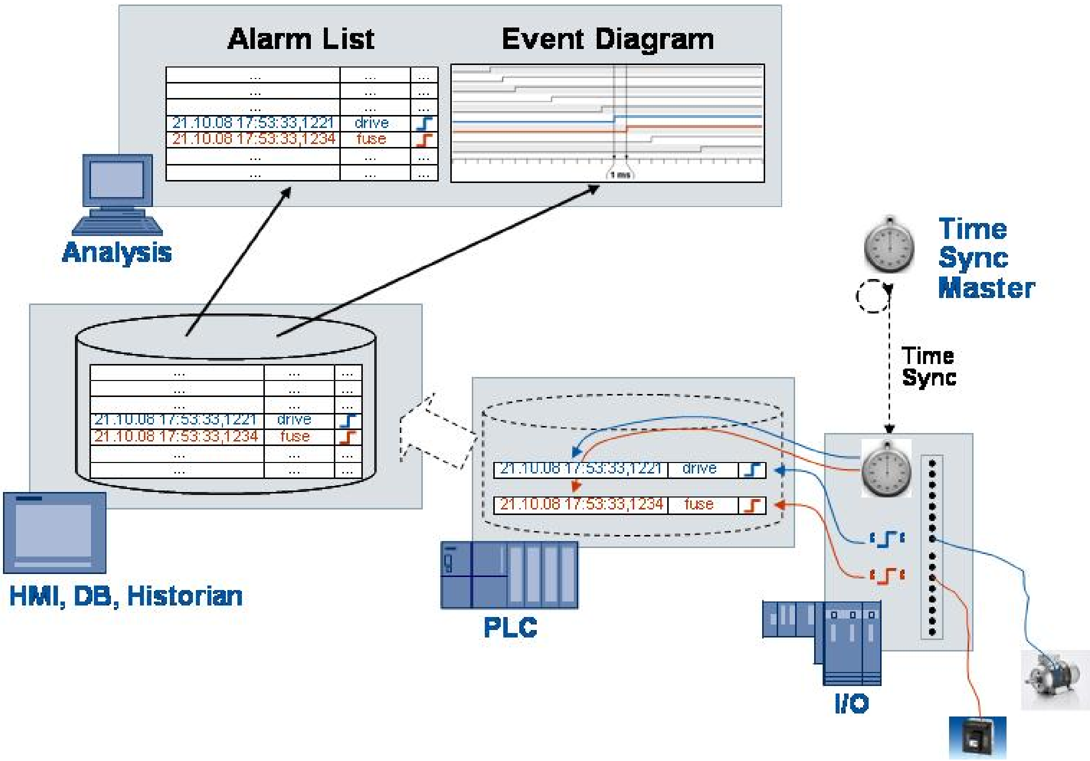
- **Latency measurement**

- **Measurement systems (sampled values)**

- **Time stamp production data**

- **…**

Detailed view for use case “sequence of events”



Distributed systems which are composed of Actuators, Sensors, PLCs and other nodes are time stamping events. All events are stored in a database. Analysis tools visualize the chronological sequence of the events.

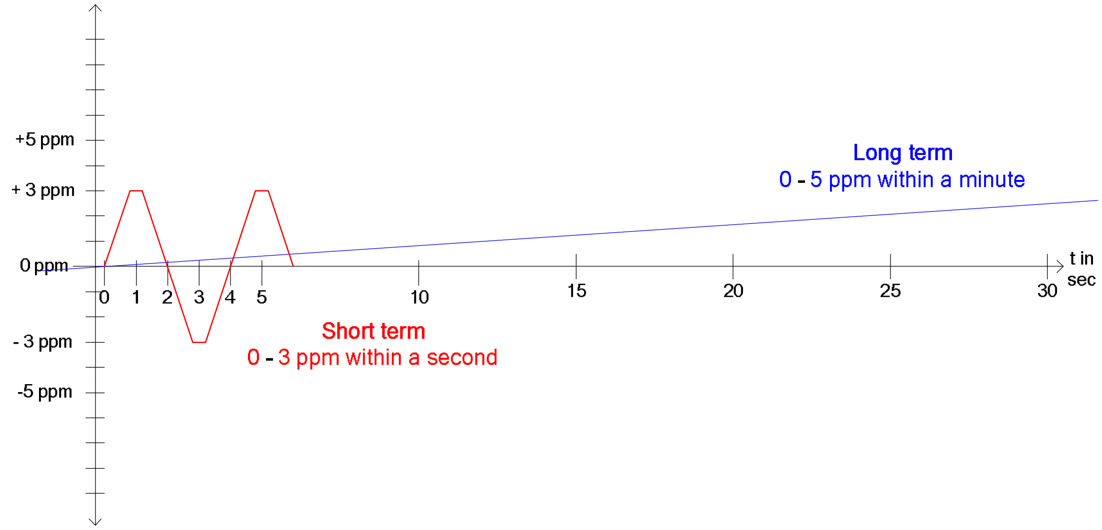
2.3 Requirements for Synchronizing Universal Time

(by a given sync interval of125ms)

1) **Accuracy**
    - Accuracy <100µs over 128 hops @ industrial automation
    - Accuracy <1µs over 16 hops @ energy automation (IEEE C37.238-2011 standard)

2) **Interval for sync messages is 125ms (default for gPTP)**

3) **Frequency change (Δf / f) / +Δt @ industry**
    - Short term 0 – 3 ppm within a second
    - Long term 0 – 5 ppm within a minute



4) **End-to-End GM rate measurement** (to follow frequency GM change very quick)

5) **Plug & play**

6) **Usage of low cost oscillators in end stations and bridges**

7) **Open standard (e.g. IEEE)**

8) **Independent loop prevention mechanism**

9) **Media independent and also long distance**
    - ***Wired***
        - Long distance with fiber optic (multi mode, single mode)
        - Polymeric optical fiber
        - Copper
        - …
    - ***Wireless***
        - Wi-Fi (Wireless LAN, IEEE 802.11)
        - WPAN (Wireless Personal Area Networks IEEE 802.15)
        - …

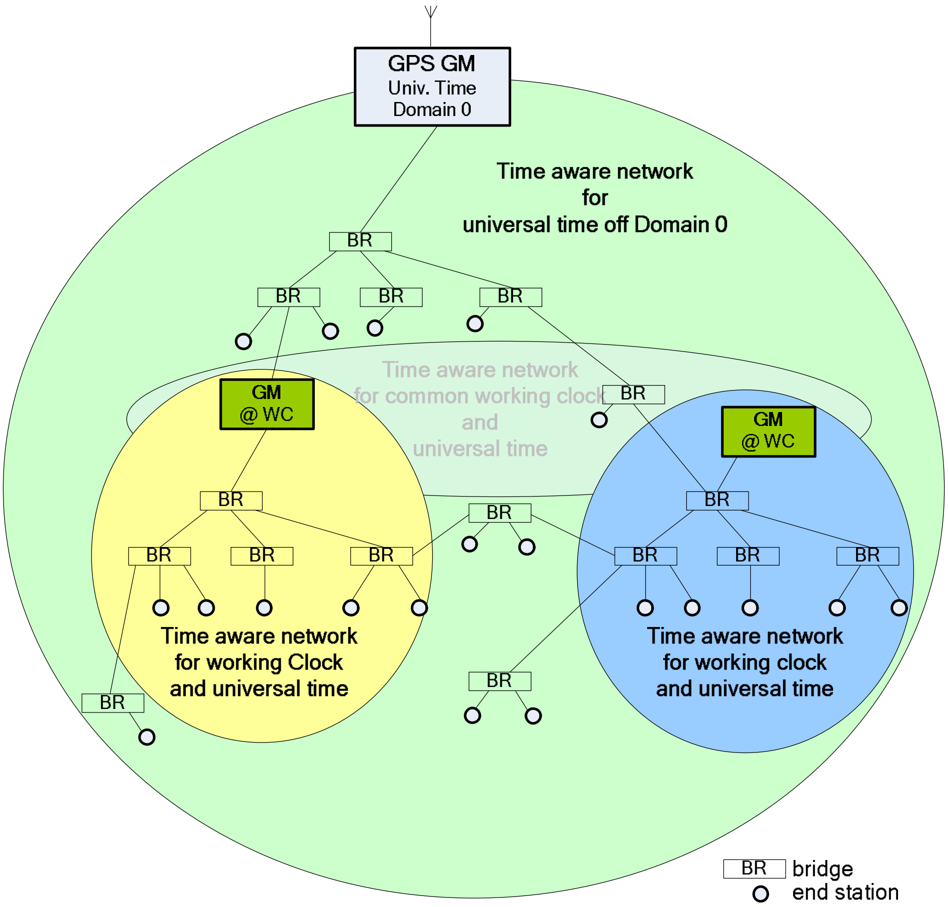
10) **When different network parts are joined to one network automatically reconfiguration for synchronization is expected**

11) **Universal time shall be able to cross IP router borderlines**

12) **Security concept for universal time synchronization**

3 Working Clock

Typically working clock is distributed by PLC's in factory automation. PLC's are used as clock source to distribute local time as working clock within a working clock domain. A working clock domain covers only a restricted area of a factory network. Within a factory network there can exist multiple independent working clock domains but also the hierarchical (max. two hierarchical level) working clock domains are conceivable.



Unlike the universal time domain, a working domain is typically engineered and configured (PLC's, sensors and actuators which belong to a working clock domain). Clock source for working clock is a local oscillator..

3.1 Reasons for Using Working Clock

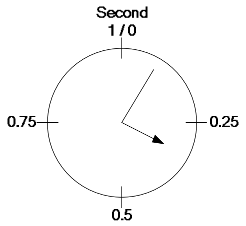
- Synchronization of scheduled control data traffic
  - Time aware traffic shaper in end stations
  - Time aware blocking shaper in bridges (if required)

- Synchronization for data sampling
  - Input system (e.g. sensors of an Energy Automation Process Buss IEC 61850-9-2)

- Synchronization of actuators
  - Output System

- Synchronization of applications
  - Motion control loop

- Different cyclic time-scales for working clock (e. g. 1 second in energy automation)

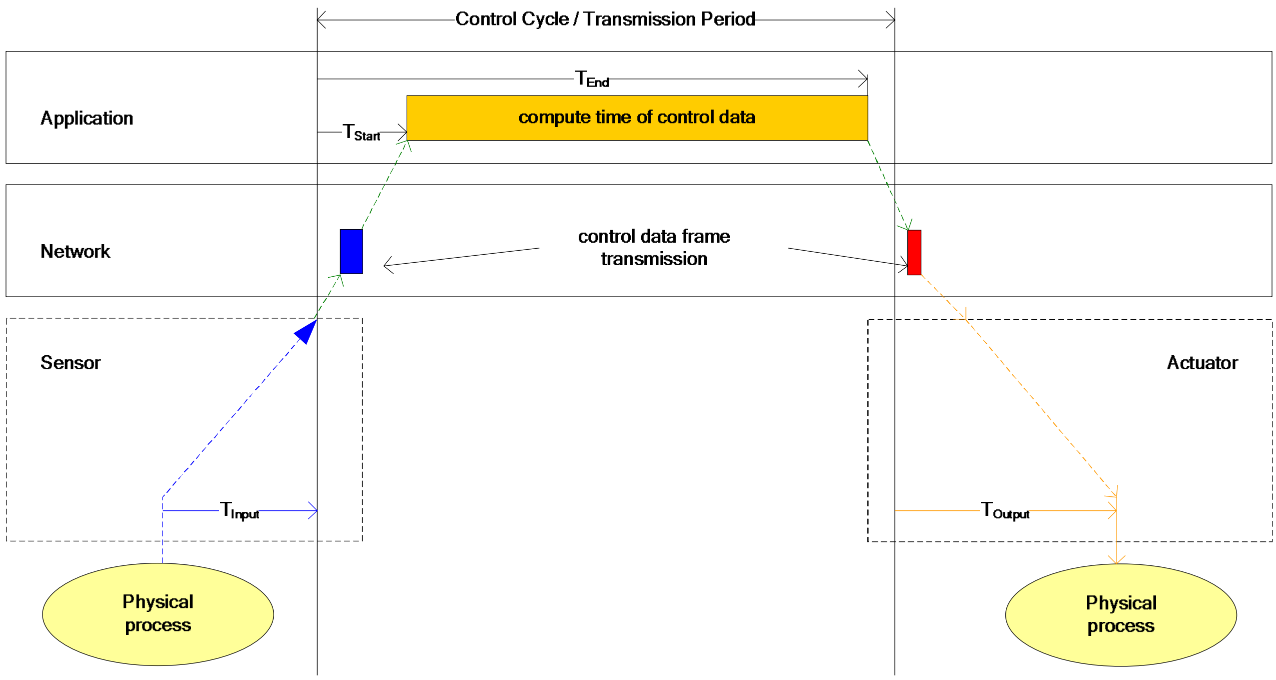


Some applications e.g. energy automation for working clock they do have no need for time of day information. Working clock wrap around at 1 second is sufficient.

3.2 Use Case for Working Clock

3.2.1 Motion Control Application

The following figure shows a typical traffic pattern for motion control applications. Motion control applications are closed control loops. Within each control cycle before a motion control application can compute new output data for actuators sensor data must be exchange over network.



- Synchronized measurement of sensor control data
- Scheduled transmission of control data traffic (simultaneously input and output control data)

3.2.2 Scheduled Control Data Traffic

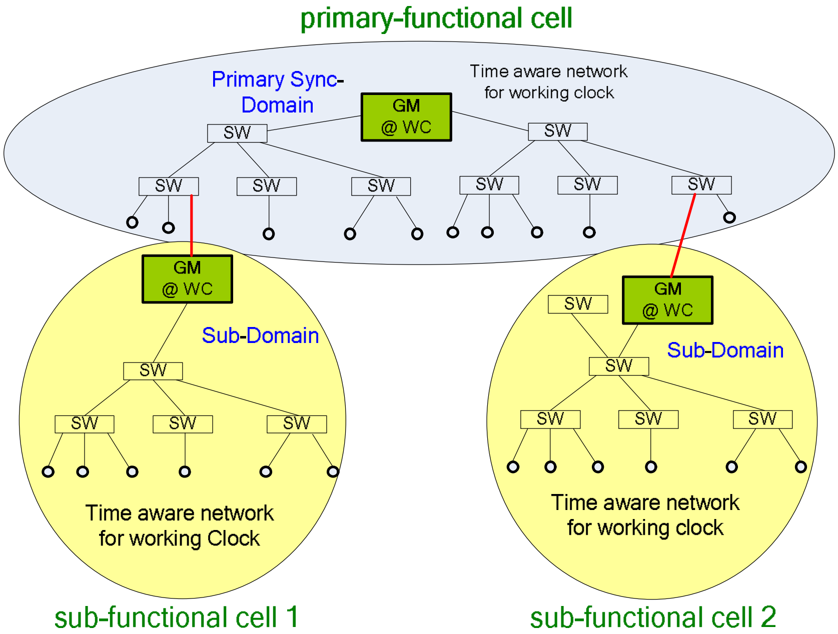
Control data traffic specifies a time sensitive traffic class for control data with guaranteed quality of service (QoS). In industrial automation control data are exchange between PLC's, actuators and sensors.

- To avoid packet lost in bridges,
- to guarantee latency control data traffic and
- to minimize time for exchange a certain amount of control data,

In convergent networks control data traffic are scheduled (transmission time and transmission) in end stations. Time based control data transmission in end stations helps to minimize make span and resources for control data within bridges.

3.2.3 Joining and Separating Synchronization Islands

3.2.3.1 Industrial Automation

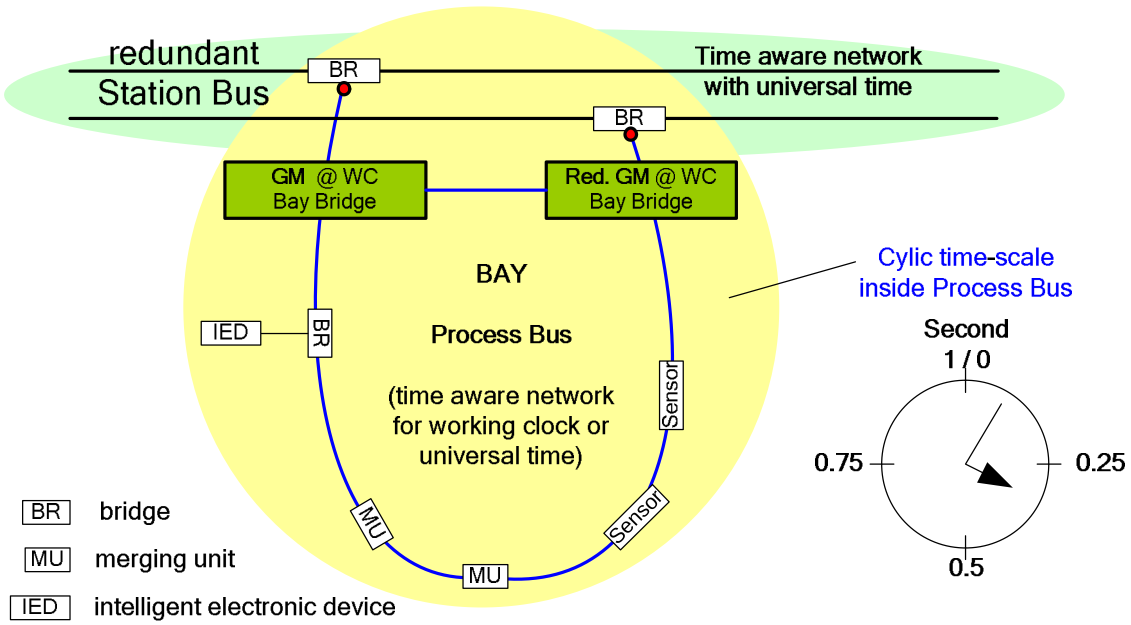


When independent synchronized sub-functional cells are joined to a primary functional cell, merging to one working clock domain should happen manually and be driven without reconfiguration for synchronization. As long as an operator has not approved merging to one working clock domain, synchronized sub-functional cells should work independently from each other.

Typical use case:

- Pre-commissioning for functional cells
- Printing machines with multiple printing and folding units
- Production lines which consists of a lot of different components

3.2.3.2 Energy Automation



The typical cyclic time-scale for working clock in energy automation's Process Bus is one second. A Process Bus is a subnet in a substation, typically allocated to branch of the substation (a BAY) with its voltage and current sensors. Currents and voltages are typically sampled with 4 kHz, each sample tagged by a sample counter. This sample counter will be reset every second and incremented every sample. If a protection relay (IED) needs the input of different sensors, it can explicitly identify the different values sampled at the same point of time.

As long as BAY's are not connected to the station bus, they are operating independently. While operating independently, all components inside a BAY are synchronized with working clock (local time).

When a BAY is connected to the station bus, which provides universal time, all components within a BAY shall be synchronized to universal time (Some protection functions need sensor data from various BAYs). Synchronization of a BAY to universal time is the manually driven procedure and should happen by the following steps:

1. BAY is synchronized with local time (working clock, cyclic time-scale of 1 second)
2. Slewing to universal time (Clock Boundary functionality)
3. When synchronized to the second of universal time, switch role to time aware system
4. All nodes (Station Bus & Process Bus) are synchronized by GM over universal time

(Comment: More details must be specified. Overall slow time can take about 1 hour.)

3.3 Requirements for Synchronizing Working Clock

1) Accuracy

- < 1µs over 64 hops@ industrial automation and energy automation
- < 100ns over 8 hops for special use cases like frequency converter

2) Interval for sync messages in a range of 15,625ms - 31,25ms

3) Usage of low cost oscillators in end stations and bridges

4) Frequency change (Δf / f) / Δt @ industry

- short term 0 – 3 ppm within a second
- long term 0 – 5 ppm within a minute

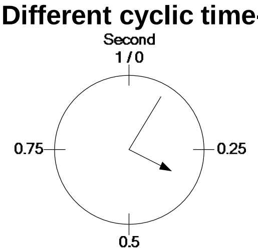
5) Low latency for sync messages to minimize PLL reaction time (1ms / hop)

6) End-to-End GM rate measurement (to follow frequency GM change very quick)

7) Media independent and also long distance (e.g. production line)

- ***Wired***
  - Long distance with fiber optic (multi mode, single mode)
  - Polymeric optical fiber
  - Copper
  - …

8) Different cyclic time-scales for working clock



(e. g. 1 sec in energy automation)

9) Clock source for working clock is typically local time and not traceable to TAI (option)

10) Guaranteed seamless working clock operation

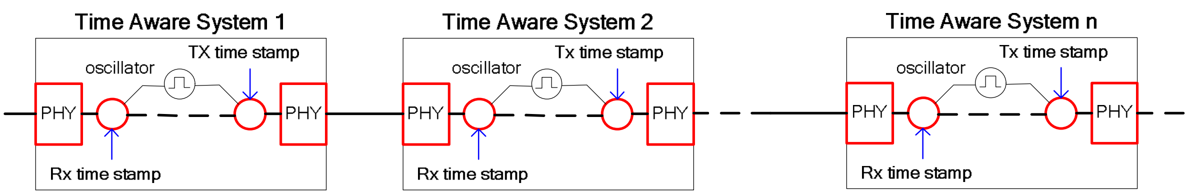
- *Grandmaster change*
  - guaranteed take over time < 200ms
  - switch over time for slaves < 250ms
- *Path change*
  - Guaranteed path reconfiguration time

=> Deterministic failure behavior for seamless working clock operation is required

11) High availability of working clock to handle single point of failure (robustness) and guaranteed take over time

Synchronization with multiple sync messages (forwarded over disjoint path) from one grand master to avoid offset jumps after sync tree reconfiguration (long daisy chains)

Impact of sync path change on accuracy



Time stamp inaccuracy (e. g. 8ns by 125 MHz)
PHY jitter ~ 2 - 3 ns

Time stamp accuracy causes an error in path delay measurement on each link which causes offset error. When receiving sync message, which is transmitted over one path, the offset error can not make visible. Only when receiving multiple sync messages from the grandmaster, which are forwarded over disjoint path, an offset error can make visible.

The effect can be measured when doing synchronization with PTP over large number of hope counts and long distances.

12) Working clock domains can be located anywhere in the network

13) GM of working clock domains can be located anywhere in a working clock domain

14) Each working clock GM capable device has mostly the same clock quality which fulfil the clock source quality requirements for working clock grand master

- The "active" GM has highest priority
- GM changes only triggered by failure and ***not*** by source clock quality
- Only a few numbers (typical 2) of GM capable within a working clock domain

15) Multiple (in)dependent working clock domains within one network

16) Maximum two hierarchical levels for working clock domains

17) Manually driven merging to one working clock domain of two independent synchronized functionally cells without reconfiguration

18) While configuring a working clock domain synchronization of universal time shall not be disturbed

19) Topology independent

20) No requirement to cross router borderlines

21) Security concept for working clock synchronization?

3.4 Clock Boundary Function and Alternate Timescale TLV

Clock Boundaries are required when a synchronized sub-domain is joined to a synchronized primary time domain and,

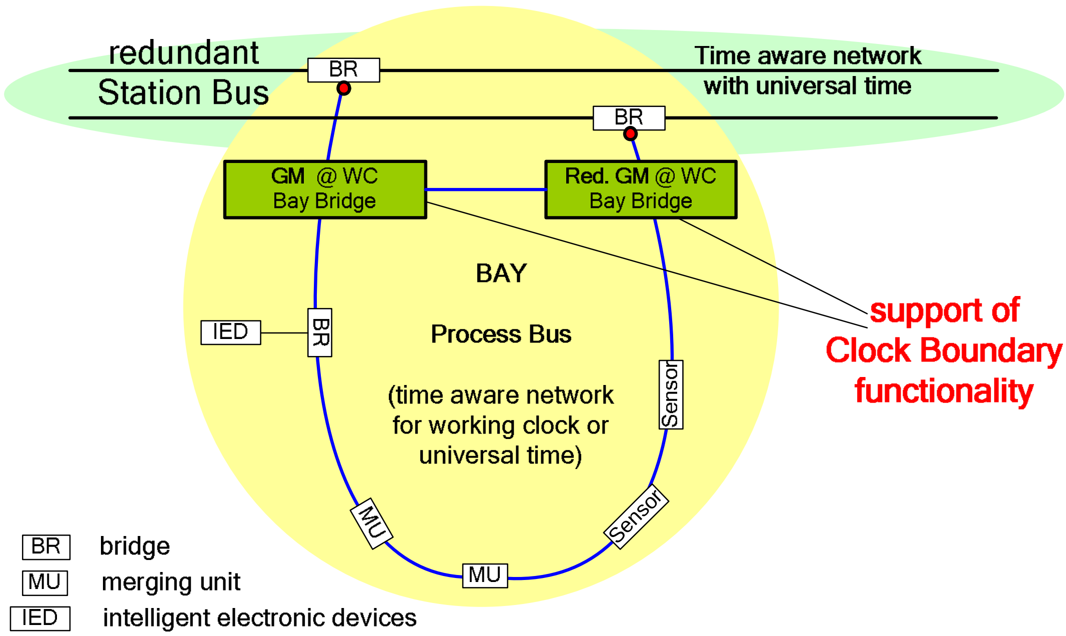
a) syntonization to universal time

b) or synchronization to universal time (for e.g. short cycle tines-scale of 1 second inside the working clock domain) is required.

Time jumps within the working clock domain must be avoided. A mechanism for slewing to primary time domain is required. Only grandmaster capable nodes shall support clock boundary functionality.

Also a mechanism, which supports manually driven joining operation to one common sync domain, is required.

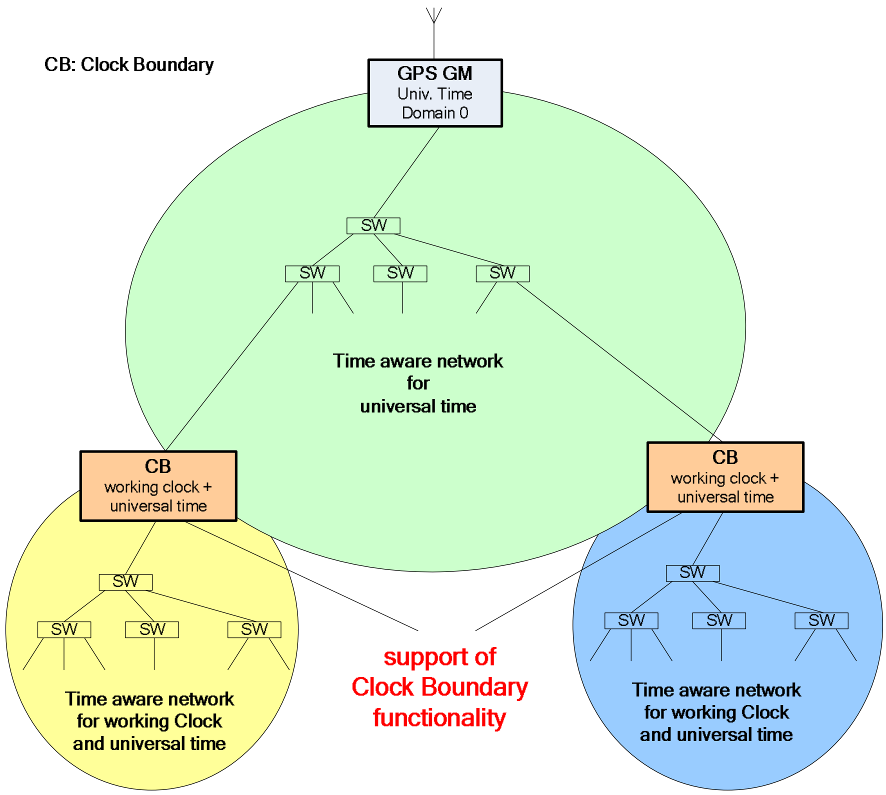
3.4.1 Energy Automation Use Case



Clock boundary function makes slewing to second of universal time possible.

3.4.2 Hierarchical Clock Use Cases

To guarantee accuracy within a working clock domain the working clock domain is separated by clock boundaries (CB's).



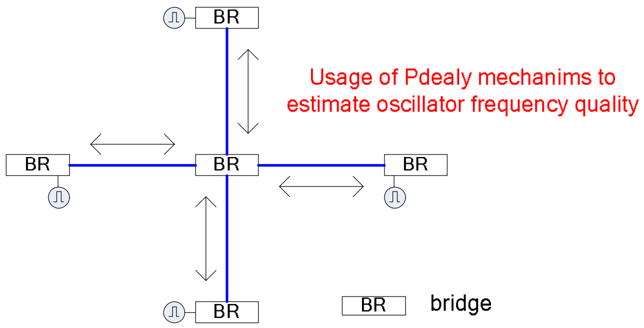
Time offset between universal time and working clock is announced by Alternate Timescale TLV.

4 Diagnostic for Clock Quality

For synchronization diagnostic a standardized algorithm to estimate frequency quality of time in bridges and end stations is required.

Without diagnostic information about oscillator frequency stability it is very difficult to locate frequency instable nodes.

To measure frequency stability, each node needs knowledge about its own frequency quality. The mechanism specified in IEEE802.1AS can be used to compare its own frequency quality with the neighbor's frequency.



Furthermore, an algorithm is required to estimate the quality of synchronized time dependent on its own local oscillator quality and on the information of grandmaster quality which is provide by the synchronization protocol.

5 Conclusions:

The recent different solutions and derivates of IEEE 1588 all have their validity for their dedicated applications; they are optimized and fulfill their dedicated application needs.

In the IEEE 1588 version 3, parallel to the trend to convergent networks, time sync function has to become convergent too. A common stack of solutions should be defined, which covers all the necessary functions of industrial and other high precision time sync applications. This can prevent parallel solutions of IEEE 1588 on a convergent Ethernet network which is designed for a common use of multiple services like real-time application parallel to standard IP-traffic.

The combination of a UTC clock with a working clock system described in the offers a comprehensive solution for various use cases of modern industrial networking. It provides a solution for the issue of combination of time stamp aware applications and cycle driven applications which eventually have to work in a combined manner.
The working clock can solve the problems combining parts of an application pre-commissioned to another part or extending an existing application with new parts.

Therefore the description of such a working clock solution can become an important function of the future Version 3 of IEEE 1588.