IEEE 1588, Standard for a Precision Clock Synchronization Protocol

IEEE 15888 Tutorial

Conference on IEEE 1588
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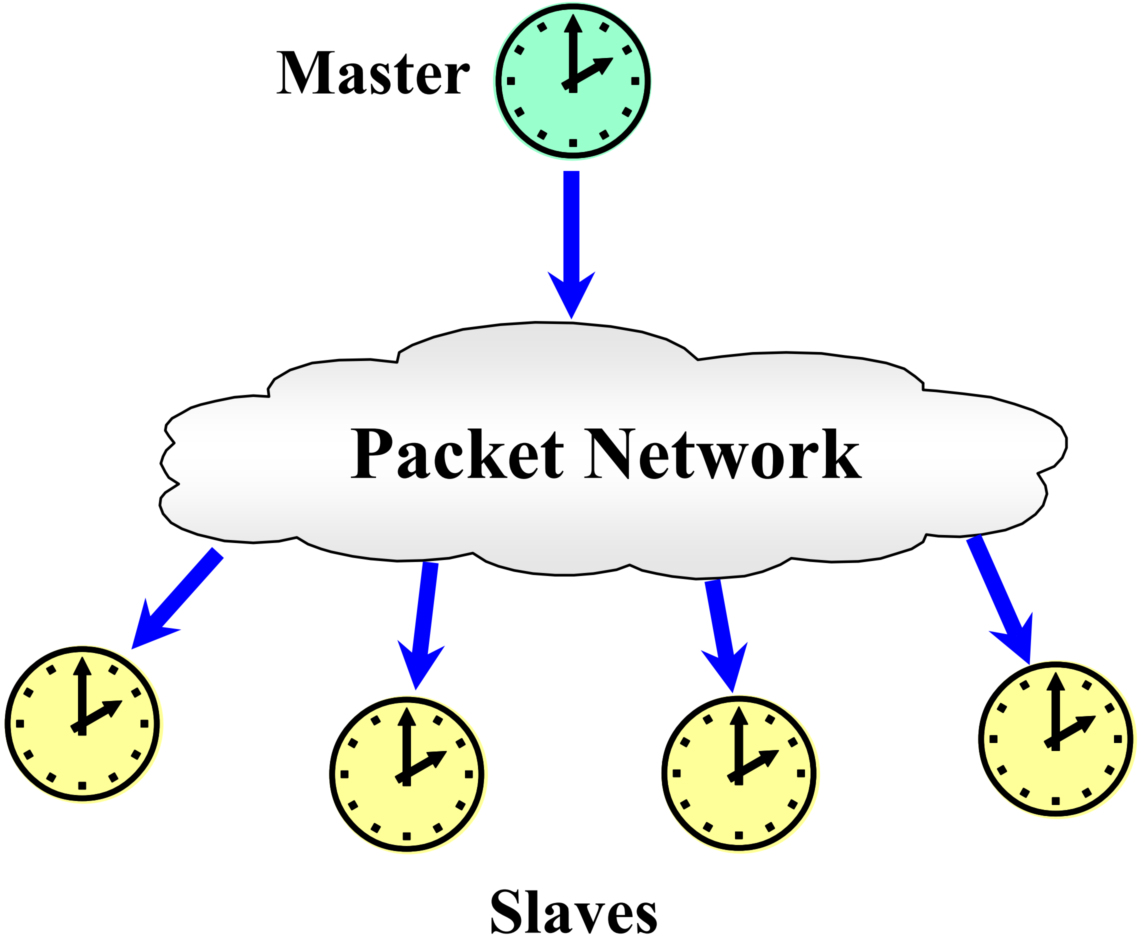
IEEE 1588
What is it all about?



Distribution of
- frequency and
- time

over a packet network (main focus is on Ethernet)

IEEE 1588 and other Time Dissemination Networks
Why a new standard?

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- NTP does a good job since many years
  - runs on legacy data networks
  - but some applications demand for much higher accuracy
- Specialized sync networks can do this job more accurate
  - but at much higher cost
  - e.g. IRIG-B, a specialized dedicated sync network
  - e.g. GPS, allows for global synchronization, requires outdoor antenna

- IEEE 1588 offers high accuracy (< 1 µs) over a data network
  - but requires hardware assistance
  - applicability restricted to local area (or may be metropolitan area)

IEEE 1588 and other Time Dissemination Networks

Comparison of different Syncronization Methods

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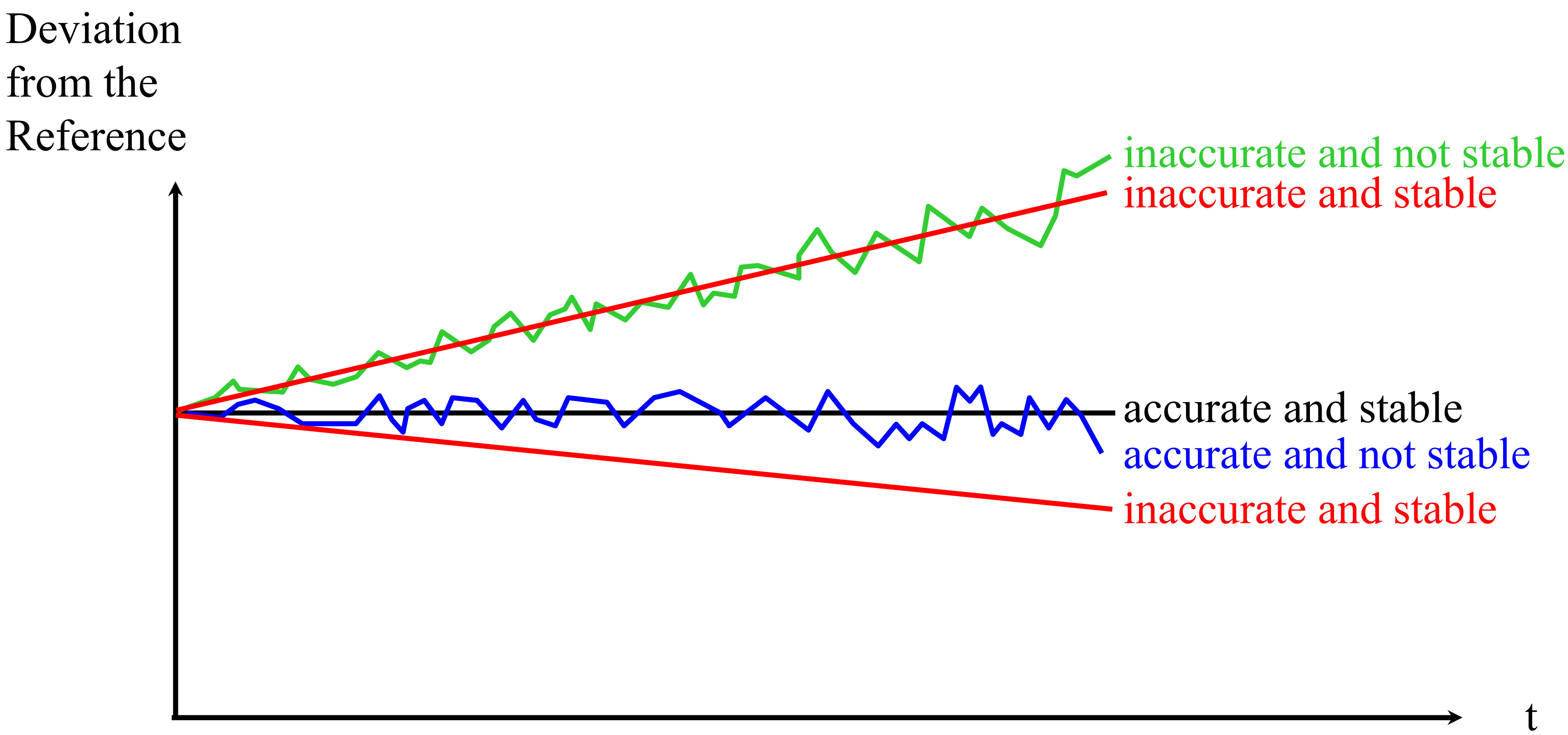
	NTP/SNTP	GPS	IEEE 1588
Application Area	Wide Area	Wide Area	a few Subnets
Communication	Internet	Satellites	LAN
Accuracy	some ms	< µs	< µs
Administration	configured	n/a	self-organized
special Hardware	no	Receiver	with or without

NTP Network Time Protocol (RFC 1305)
SNTP Simple Network Time Protocol (RFC 2030)
GPS Global Positioning System

Nature and Importance of System Time

- Explicit system time is represented by a clock providing a time reference
- In a distributed system, system time may be required in different nodes
- System time is usefull
  - to coordinate measurement instants (sampling, triggering)
  - to measure time intervals (and to calculate derived quantities)
  - as a reference to determine the order of events
  - to reconstruct complex, fast and distributed activities
  - to determine the age of data items (data correlation; data base replication)
  - as a basis for the execution of coordinated actions (time based behaviour)
  - to decouple communication from execution
- The system wide provision of exact system time offers new approaches to design distributed systems

Some important Definitions
Accuracy and Stability



Application of synchronized Clocks
Where is sub-µs Accuracy required?

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- Automation and control systems
  - Synchronize multi axis drive systems
  - Synchronize subsystems with cyclic operation
- Measurement and automatic test systems
  - Correlation of decentrally acquired values
  - Timestamping of logged data
- Power generation, transmission and distribution systems
  - Control of switching operations
  - Reconstruction of network activities and events
  - Isolation of problems (distinguish cause and impact)
- Ranging, telemetry and navigation
  - Triangulation
  - Large sensors for seismic or submarine applications
- Telecommunications
  - distribution of frequency and time in Next Generation Networks
  - Emulation of TDM circuits through packet networks
  - Synchronization of wireless base stations
  - Backup for other time sources (loss of GPS signal)

Data collected during a 707 test flight

(Poster at the Air and Space museum in Washington)

Remarks

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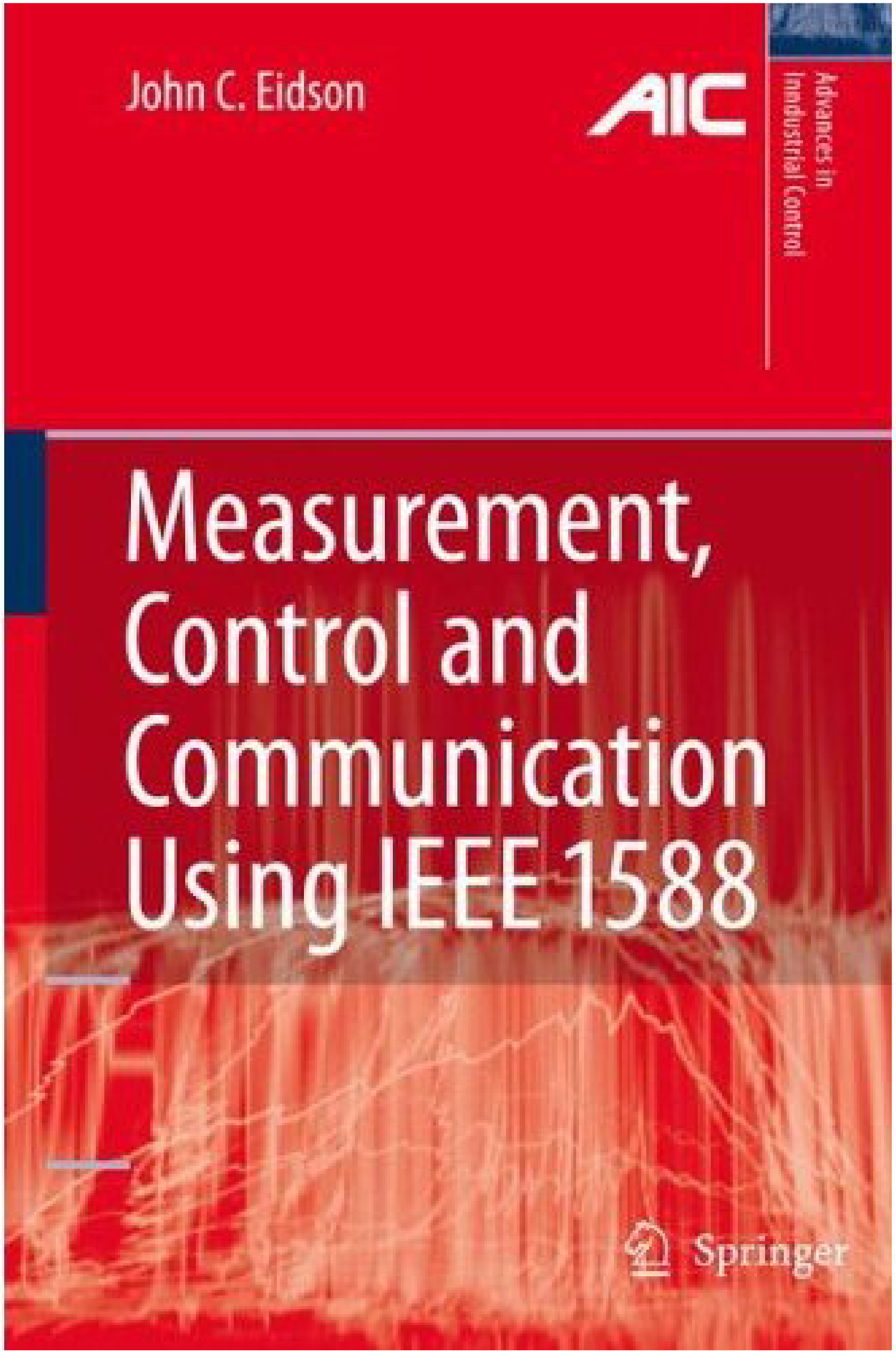
- IEEE 1588 can be applied in different kinds of network technologies
  - All examples in this tutorial are with respect to Ethernet
- Basis of the tutorial is PTP version 1.
  - PTP version 2 will be presented by John C. Eidson.
  - Nevertheless, some forwad references will be given
- Where learn more about IEEE 1588?
  - The Standards Document IEEE Std 1588-2002: “IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems”
  - Proceedings of the 2003, 2004 and 2005 Conferences on IEEE 1588 see http://ieee1588.nist.gov
  - The upcoming 2006 Conference



John C. Eidson: Measurement, Control, and Communication Using IEEE 1588.

Springer,
ISBN: 1846282500

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General overview of time dissemination techniques

PTP basic operations

- Transfer of frequency and time
- Basic operation of clock adjustment
- Influence of the network and the protocol stack

Guide to the the standard

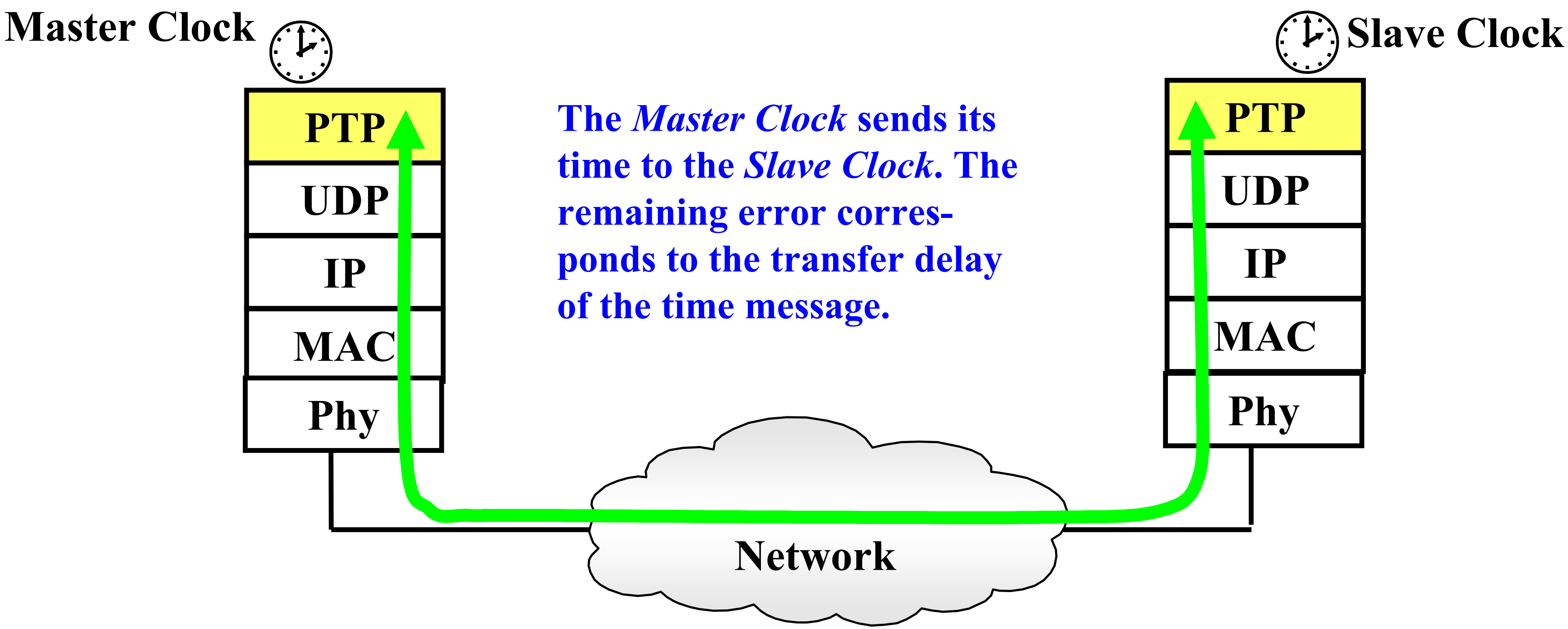
Implementation and performance aspects

Status of PTP version 2 activities

Applications

PTP basic operations

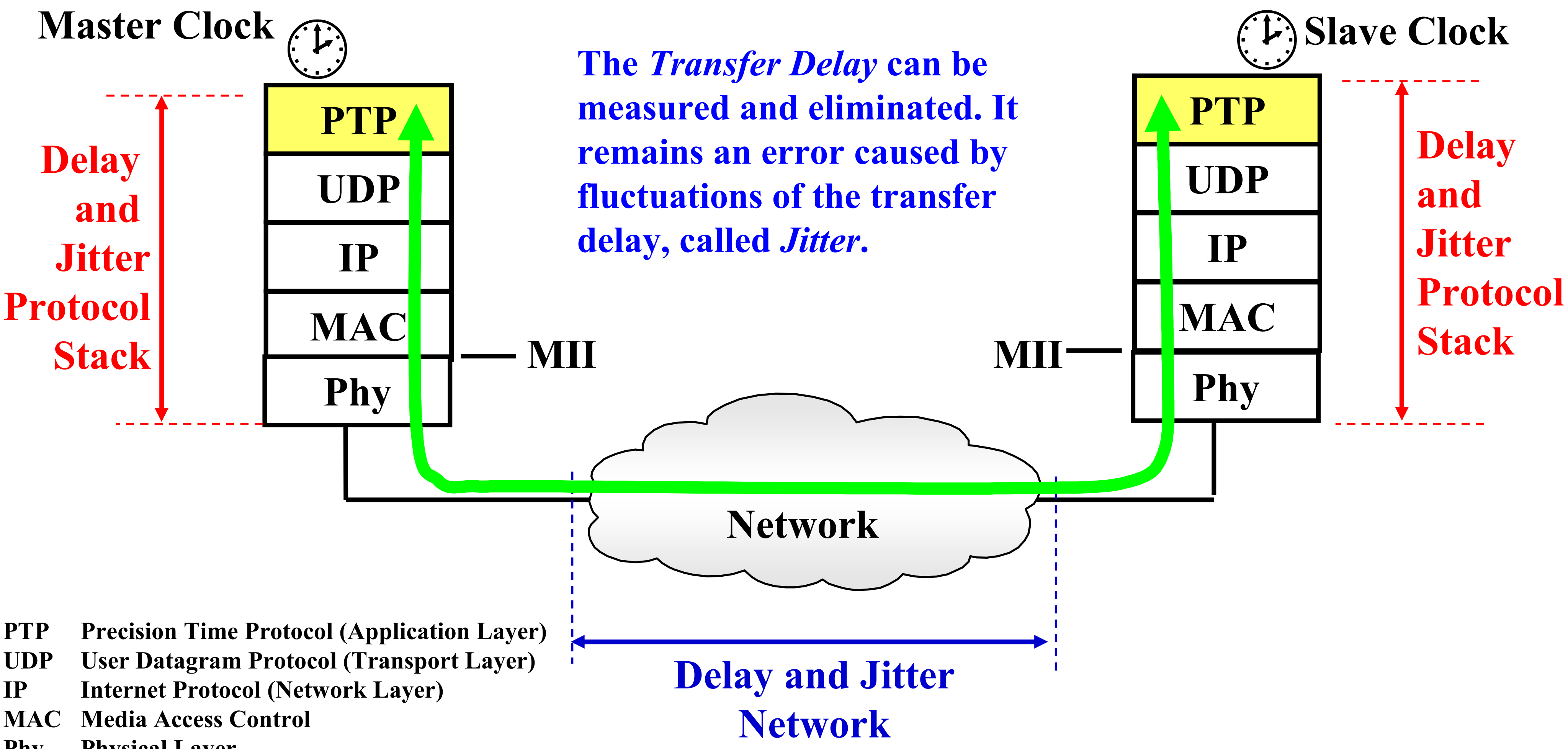
Principal Operation of Clock Adjustment



The *Master Clock* sends its time to the *Slave Clock*. The remaining error corres-ponds to the transfer delay of the time message.

PTP	Precision Time Protocol (Application Layer)
UDP	User Datagram Protocol (Transport Layer)
IP	Internet Protocol (Network Layer)
MAC	Media Access Control
Phy	Physical Layer

PTP basic operations
Main Problems are Delay and Jitter

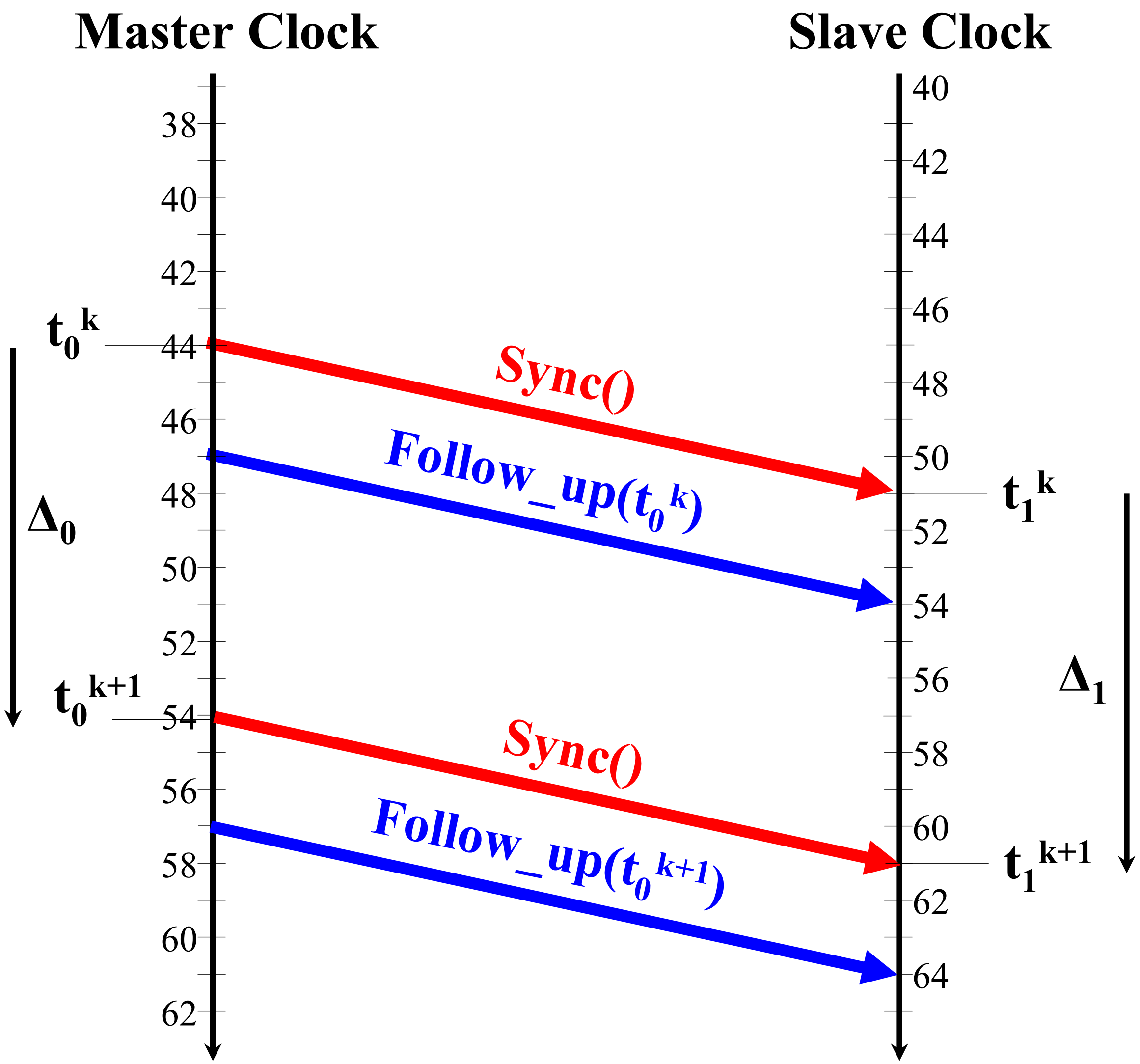


The *Transfer Delay* can be measured and eliminated. It remains an error caused by fluctuations of the transfer delay, called *Jitter*.

PTP	Precision Time Protocol (Application Layer)
UDP	User Datagram Protocol (Transport Layer)
IP	Internet Protocol (Network Layer)
MAC	Media Access Control
Phy	Physical Layer

PTP basic operations

Determination of Phase Change Rate (Drift)



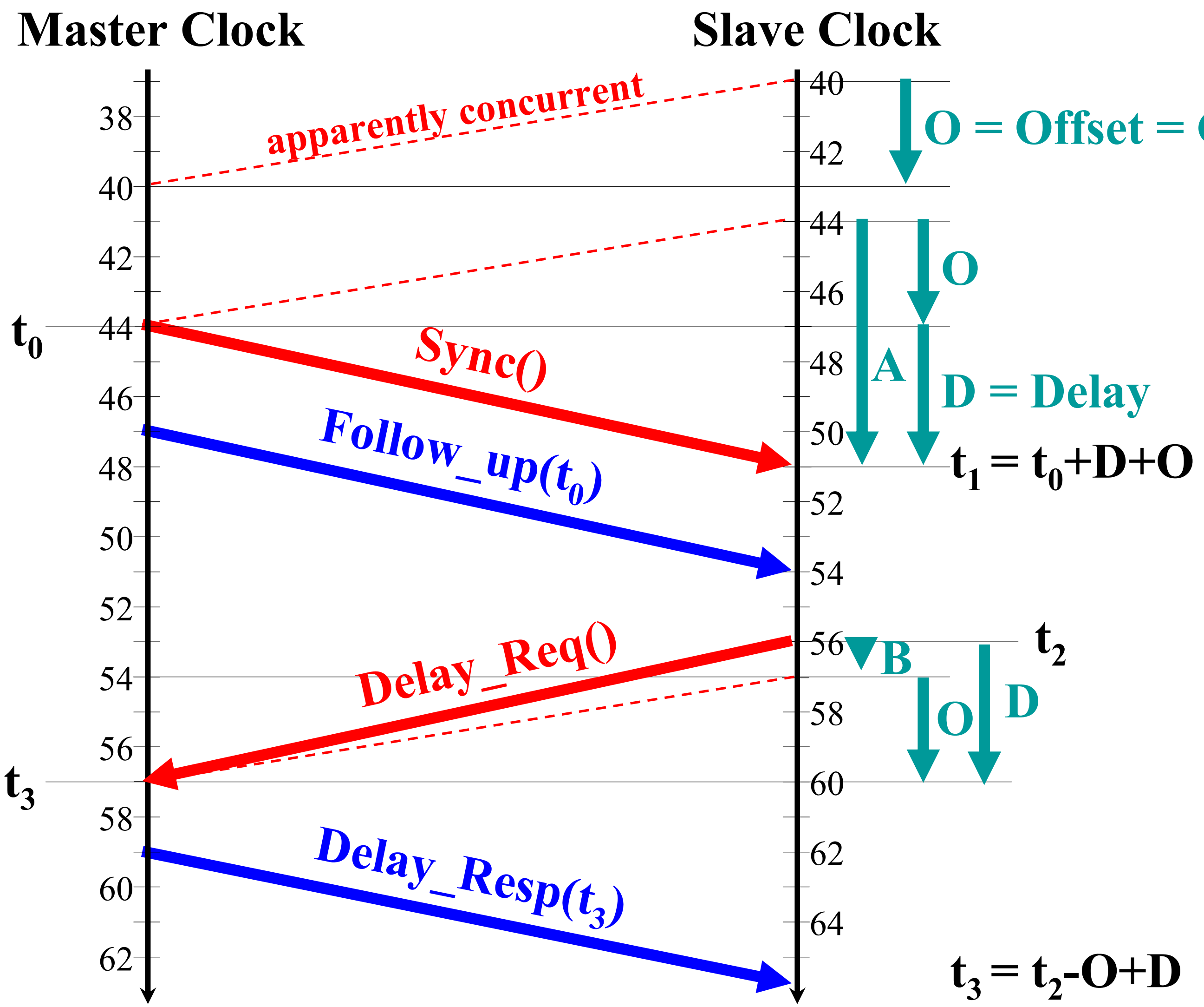
$\Delta_0 = t_0^{k+1} - t_0^{k}$

$\Delta_1 = t_1^{k+1} - t_0^{k}$

$$\text{Drift} = \frac{\Delta_1 - \Delta_0}{\Delta_0}$$

PTP basic operations

Delay and Offset Determination



measured values t_0, t_1, t_2, t_3

$A = t_1 - t_0 = D + O$

$B = t_3 - t_2 = D - O$

$$\text{Delay } D = \frac{A + B}{2}$$

$$\text{Offset } O = \frac{A - B}{2}$$

PTP basic operations
Frequency and Time Transfer

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- Phase Change Rate (Drift) Compensation → Frequency Transfer
  - The slave‘s oscillator does (when running free) not have exactly the same frequency as the master
  - The frequency varies over time (due to environmental conditions)
  - Consecutive timestamped Sync messages allow to determine and compensate the deviation (accelerate or slow down the oscillator)
  - This compensation is repeated regularly (interval depending on oscillator stability and desired accuracy)
  - A frequency aligned slave clock is called "syntonized„ (i.e. it‘s second is the same as in the reference clock)
  - Remember: 1 ppm results in 1 µs / s

- Offset Correction → Time Transfer
  - Set the slave‘s time (of day) to the master‘s time
  - Correction is based on the round trip time measurement (carried out by timestamped Sync and Delay_Req messages)

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The Standard IEEE 1588
Objectives

- synchronization of distributed system clocks with high precision (< µs)
- applicable in any multicast capable network
  - main focus is on Ethernet
- easy configuration
- fast convergence
- support of a heterogeneous mix of different clocks with different characteristics (accuracy, resolution, drift, stability)
- moderate demand for bandwidth and computing resources

Contents of the Standards Document

IEEE 1588 Standard
Status and Future

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- Standard was approved 12th of September 2002 and published in Nov 2002
- IEC has adopted the standard under the label IEC 61588 in 2004
- Application of IEEE 1588 was announced by different standards organizations and interest groups
- First commercial IEEE 1588 enabled products are on the market
- Several implementations have proved interoperability during plug fests
- Components with integrated HW assistance, IP cores and PTP protocol support were announced or are available
- Increasing interest in new application areas
- The standard revision working group P1588 has been established to elaborate enhancements and improvements to meet new requirements

Clock Types

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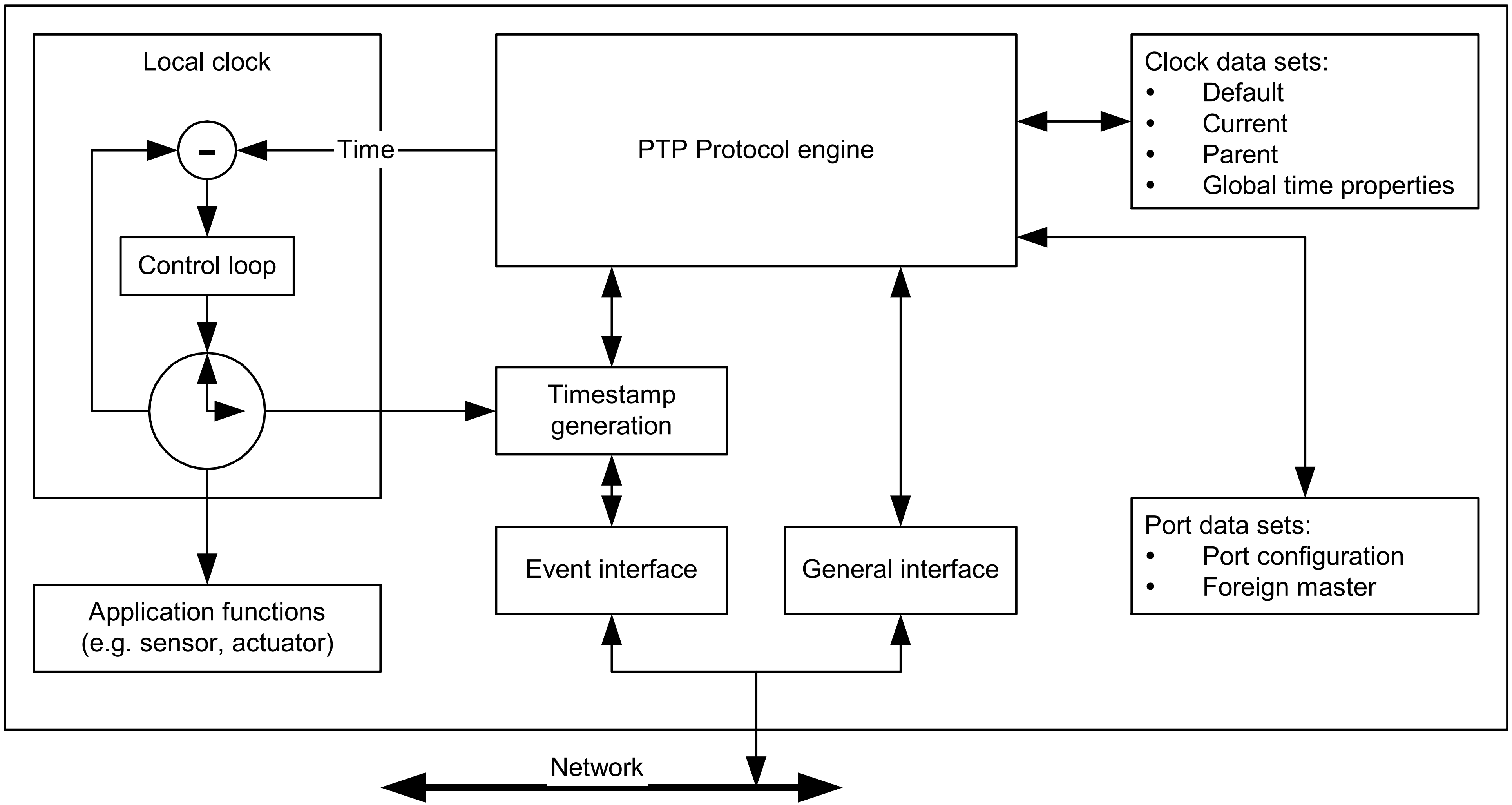
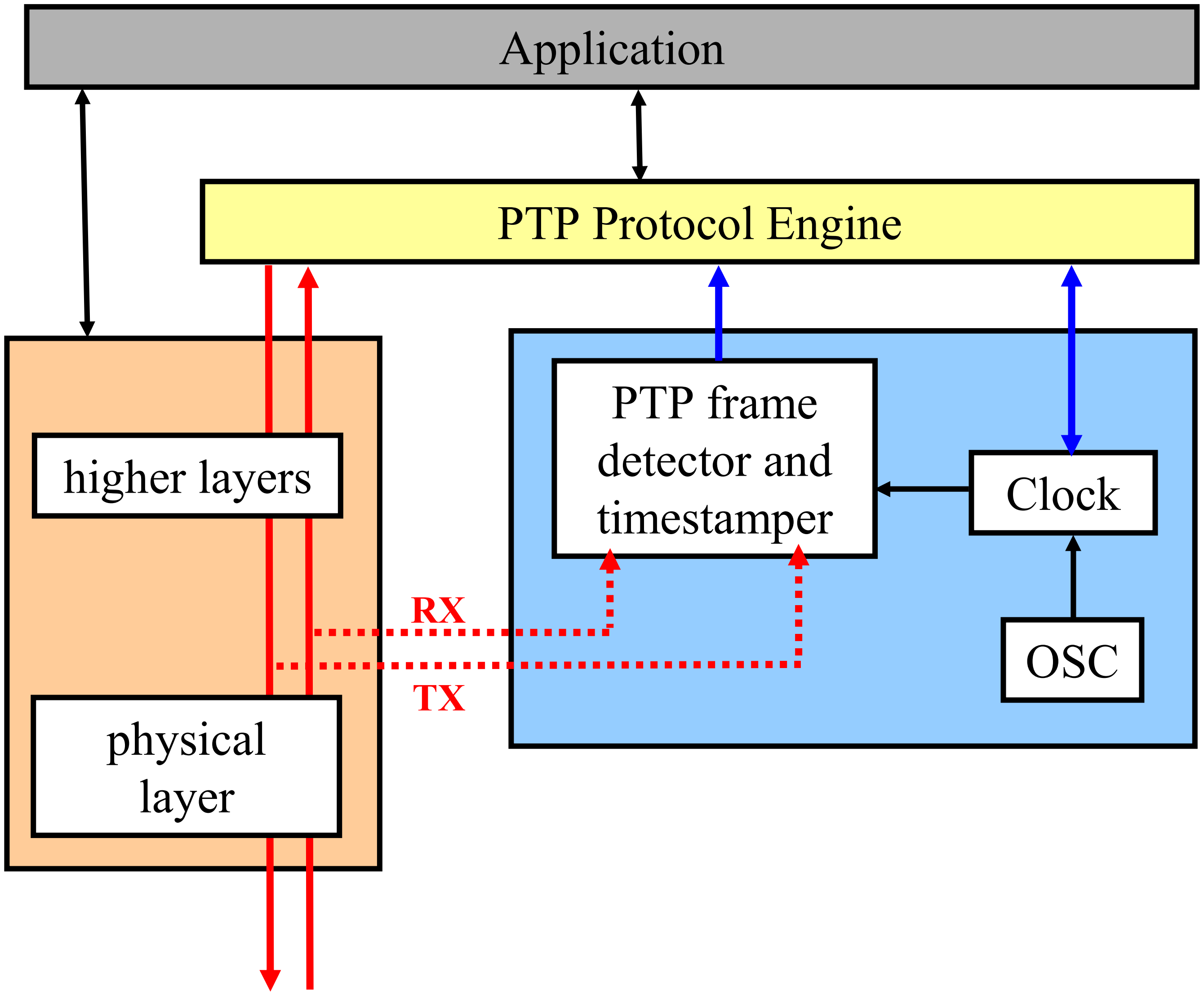
IEEE 1588 version 1 defines 2 clock types

- **Ordinary Clock (OC)**
  - A PTP clock with a single PTP port
  - Typically an end system
- **Boundary Clock (BC)**
  - A clock with more than a single PTP port
  - Typically a switch/bridge of the communication network with its own clock

IEEE 1588 Standard
Ordinary Clock Model



IEEE 1588 Standard
Ordinary Clock Model



The Standard IEEE 1588
Hardware assisted Timestamping

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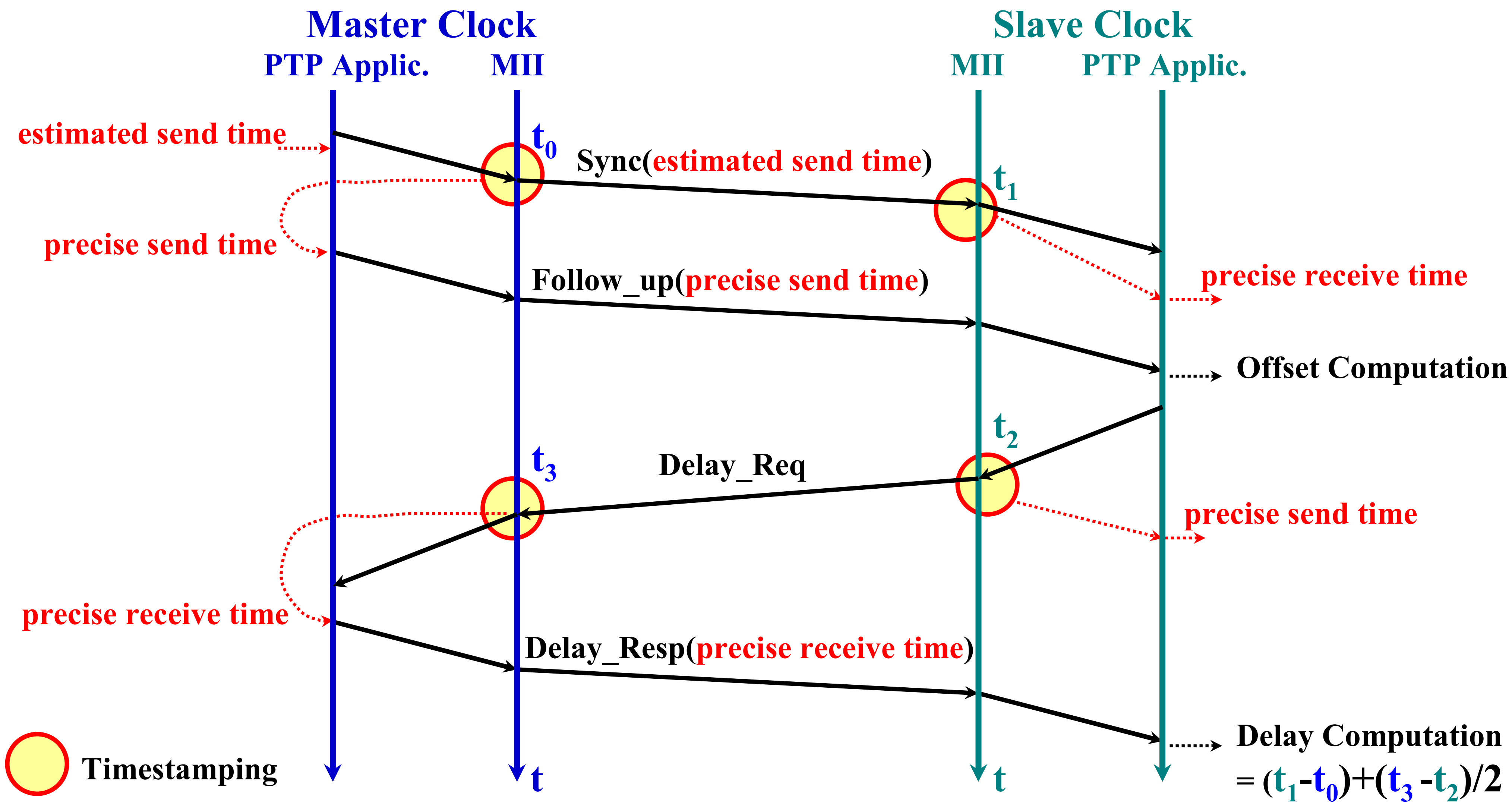

IEEE 1588 Standard
Offset Computation and Correction

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- The standard says how the slave can determine its offset from the master

- The standard says nothing about how to correct the slave clock

  - It may immediately be overwritten with the computed time
    → the clock steps forward (result is a time gap) or
    → the clock steps backward (clock runs through a time period again)

  - Its oscillator may be accelerated or slowed down for a while in order to achieve a smooth correction
    → How fast should this happen?

IEEE 1588 Standard
Kinds of Messages

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The set of event messages consists of:

- **Sync messages**: The appearance of a Sync message at the clock timestamp point interface of a clock shall be an event to which a local clock must assign a timestamp, the sync-event-timestamp, based on the value of the local clock.
- **Delay_Req messages**: The appearance of a Delay_Req message at the clock timestamp point interface of a clock shall be an event to which a local clock must assign a timestamp, the delay-event-timestamp, based on the value of the local clock.

The set of general messages consists of:

- **Follow_Up messages**: Follow_Up messages communicate the local value of the sync-event-timestamp for a particular Sync message to another clock in the PTP system.
- **Delay_Resp messages**: Delay_Resp messages communicate the delay-event-timestamp marking the receipt by a master clock of a slave's Delay_Req message from the slave clock.
- **Management messages**: Management messages communicate information used to manage individual clocks and a system of clocks.

IEEE 1588 Standard
Sync Message

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- Event message (i.e. sending and receipt timestamps are generated for this message)
- Issued by clocks in the Master state
- Contains clock characterization information
- Contains
  - the sending time t_0 → this requires an on the fly modification of the message

  or
  - an estimate of the sending time $\sim t_0$ → typical for standard transmitter logic
- When received by a slave clock the receipt time t_1 is noted
- Can be distinguished from other legal messages on the network
- For best accuracy these messages can be easily identified and detected at or near the physical layer and the precise sending (or receipt) time recorded

IEEE 1588 Standard
Follow_Up Message

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- General message (i.e. no timestamps are generated when the message is sent or received)
- Issued by clocks in the Master state
- Always associated with the preceding **Sync** message
- Contain the precise sending time t_0 as measured as close as possible to the physical layer of the network
- When received by a slave clock the precise sending time is used in computations rather than the estimated sending time contained in the **Sync** message
- If the **Sync** provides a sending time with sufficient precision, no **Follow_Up** message is required (this is indicated with a flag in the **Sync** message)

IEEE 1588 Standard
Delay_Req Message

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- Event message (i.e. sending and receipt timestamps are generated for this message)
- Issued by clocks in the Slave state
- The slave measures and records the sending time t_2
- When received by the master clock the receipt timestamp t_3 is generated
- Can be distinguished from other legal messages on the network
- For best accuracy these messages can be easily identified and detected at or near the physical layer and the precise sending (or receipt) time recorded

IEEE 1588 Standard
Delay_Resp Message

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- General message (i.e. no timestamps are generated when message is sent or received)
- Issued by clocks in the Master state
- Always associated with a preceding Delay_Req message from a specific slave clock
- Contains the receipt time t_3 of the associated Delay_Req message
- When received by a slave clock the receipt time is noted and used in conjunction with the sending time of the associated Delay_Req message as part of the delay calculation

IEEE 1588 Standard
Message Fields

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The messages carry different fields depending on their type. The list is not exhaustive:

- PTP version
- Subdomain: A subdomain is a group of synchronized clocks. A network can have more than one subdomain.
- Message Type and control: the kind of message
- Source UUID and source port: The source of the message. The universally unique identifier (UUID) is the MAC address in Ethernet.
- Sequence ID: A sequence number
- Timestamp
- Info about Grandmaster clock
- Info about Parent clock

The Standard IEEE 1588

Data Types - Time Representation

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15 … 0	31 … 0	31 … 0
epoch_number	seconds	nanoseconds
unsigned integer	unsigned integer	integer magnitude/sign reperesentation

- time scale is defined by Grandmaster clock
- PTP epoch starts 1st January 1970, 00:00
- the variable `seconds` overflows after about 126 years (i.e. in January 2106)
- `seconds` overflows are counted in variable `epoch_number`, which will overflow after 8‘925‘512 years
- conversion to other time systems
  - `PTP_Seconds = NTP_Seconds - 2'208'988'800 + currentUTCOffset`
  - `PTP_Seconds = GPS_Seconds +   315'964'819`

The Standard IEEE 1588

Boundary Clock eliminates the Network's Fluctuation

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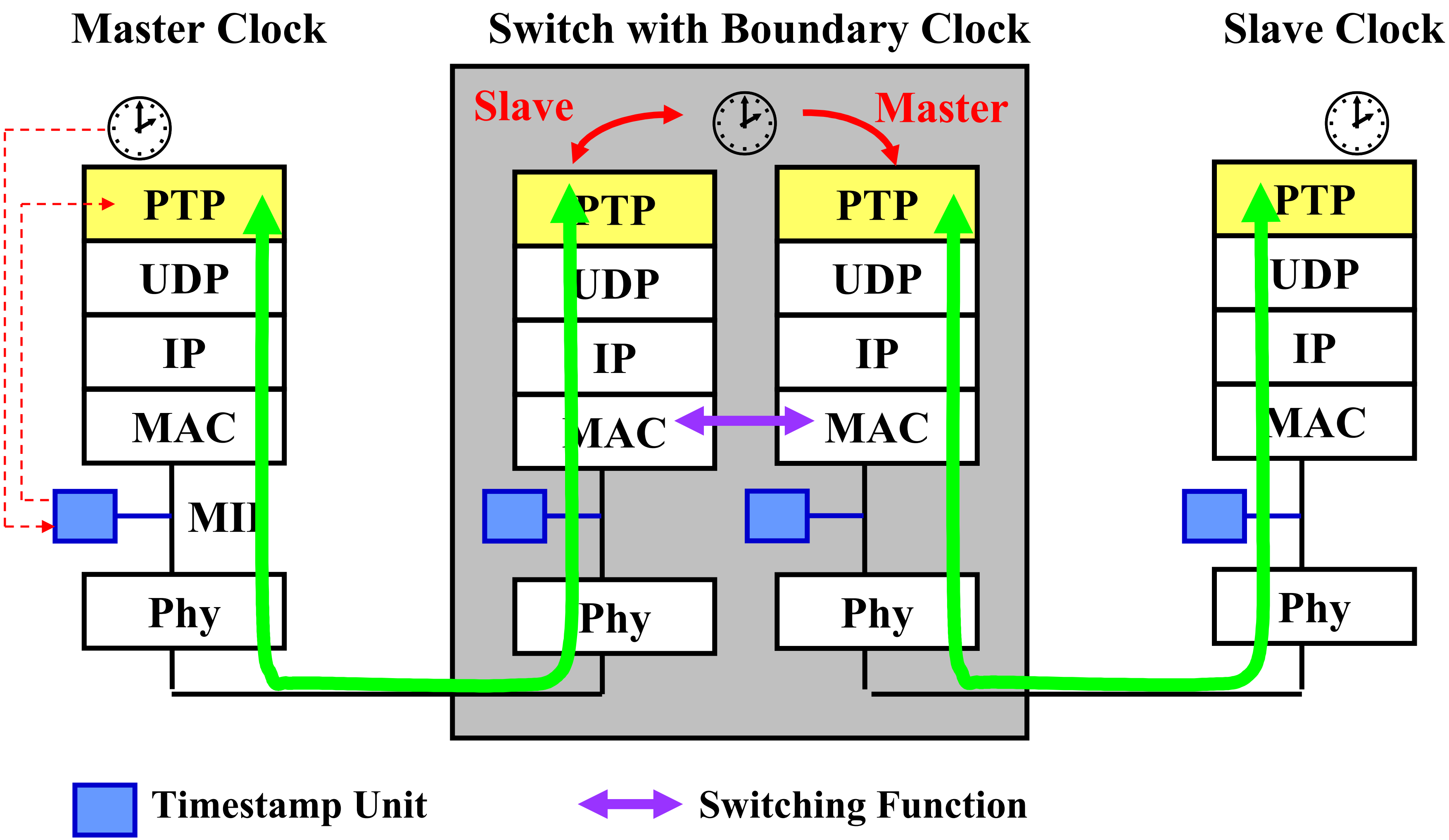
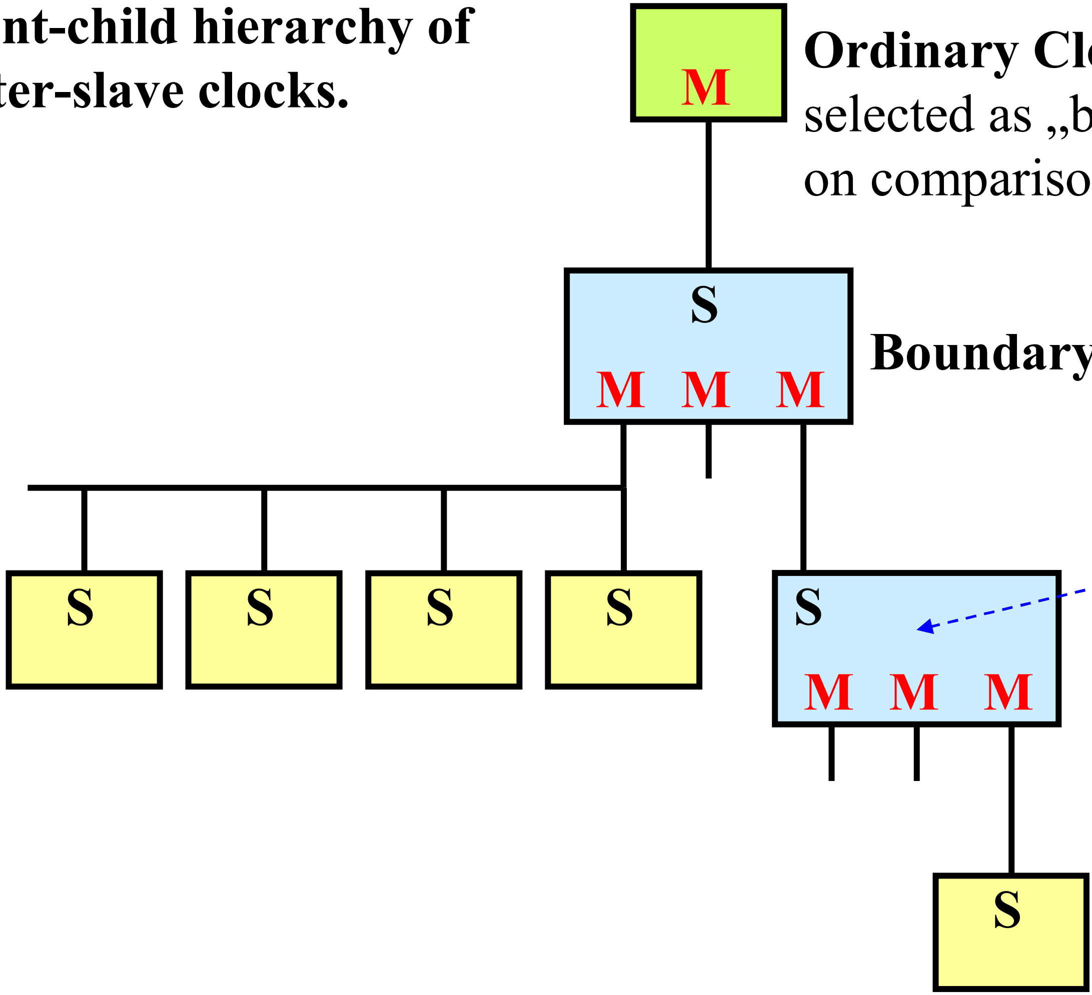


The Standard IEEE 1588

Topology and „Best Master Clock“

Boundary clocks define a parent-child hierarchy of master-slave clocks.



Ordinary Clock, Grandmaster: clock selected as „best Master“ (selection based on comparison of clock descriptors)

Boundary Clock, e.g. Ethernet switch

S: Port in Slave State
M: Port in Master State

Ordinary Clock

„Best Master Clock“ Algorithm

- The Best Master Clock (BMC) algorithm runs independently on all ports of every clock in a subdomain.
  - The purpose of the BMC is to determine the state of each port of a PTP system.
  - Clocks do not negotiate which should be master and which should be slave—instead, each computes only its own state.
  - Since it runs continually, it continually readapts to changes in the network or the clocks.
- Self-configuring is based on clock characteristics and network topology
- Port state determination is based on information contained in Sync messages received at the ports of a given clock and on the default data set values of the given clock, such as
  - Preferred: designates a set of clocks from which the Grandmaster is selected
  - Stratum: primary or secondary standard
  - Identifier: accuracy of clock’s time base
  - Variance: stability and noise of clock
  - “Closest”: minimum spanning tree algorithm
  - UUID: tie-breaker

Data Sets

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The following are per clock data sets:

- Default data set: Properties of the local clock that determine its behavior and performance when it is the grandmaster clock
- Global time properties data set: Time base properties
- Current data set: Current synchronization and topological operational properties

The following are per clock port data sets:

- Parent data set: Properties of the parent and grandmaster
- Port configuration data set: Clock port properties
- Foreign master data set: Identification of Sync messages from potential master clocks-part of a qualification scheme to reduce thrashing

Clock States

State	Description
PTP_INITIALIZING	The associated port shall initialize the data sets, hardware and communication properties of the clock.
PTP_FAULTY	The fault state of the protocol. The associated port shall not participate in the synchronization aspects of the protocol but may take implementation-specific measures to clear the fault.
PTP_DISABLED	The associated port shall not place any messages on its communication path.
PTP_LISTENING	The associated port is waiting for the Sync message receipt timeout to expire or to receive a Sync message from a master. The purpose of this state is to allow orderly addition of clocks to a subdomain.
PTP_PRE_MASTER	The associated port shall behave in all respects as though it were in the PTP_MASTER state except that it shall not place any non-Management messages on its communication path.

IEEE 1588 Standard
Clock States

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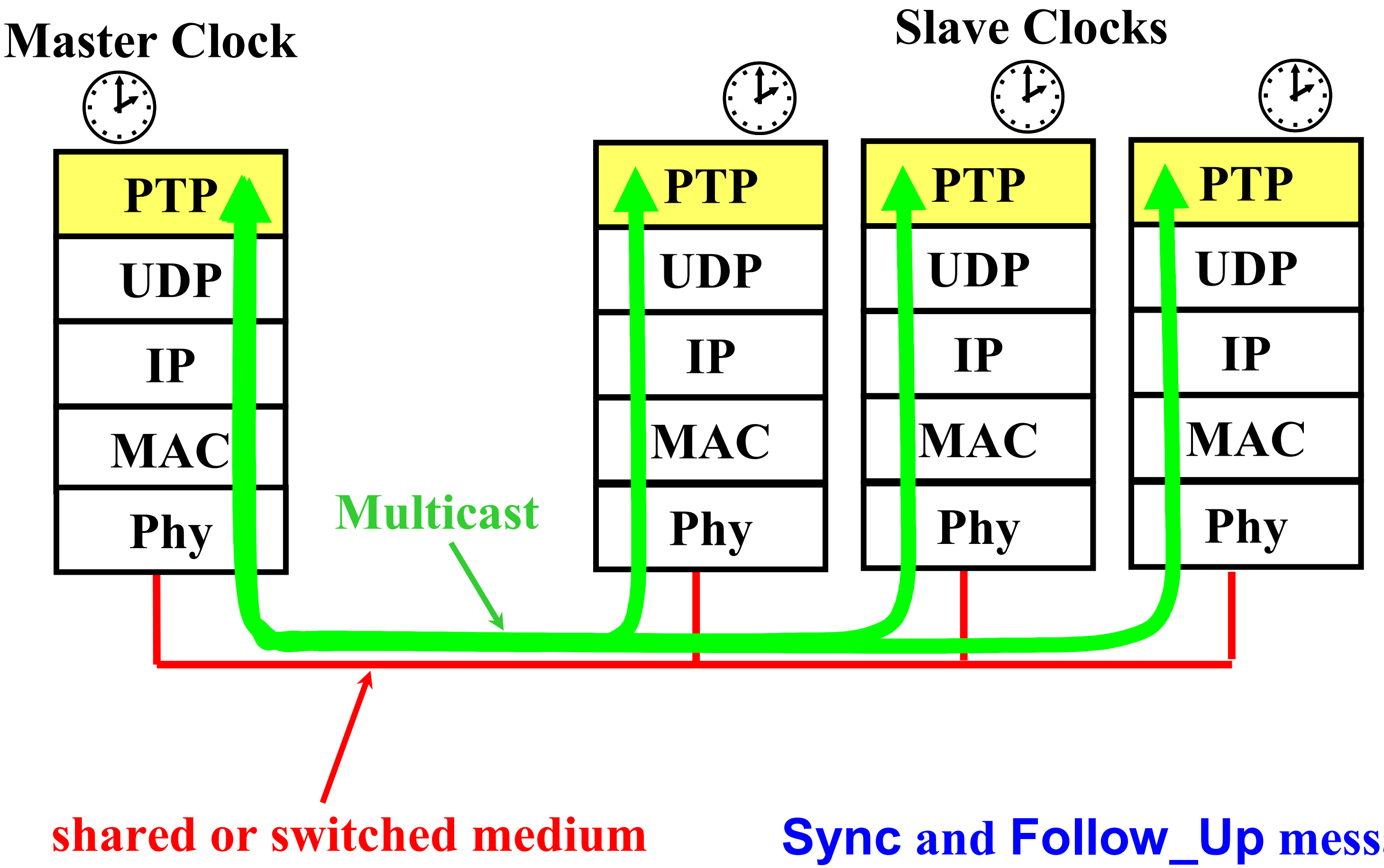
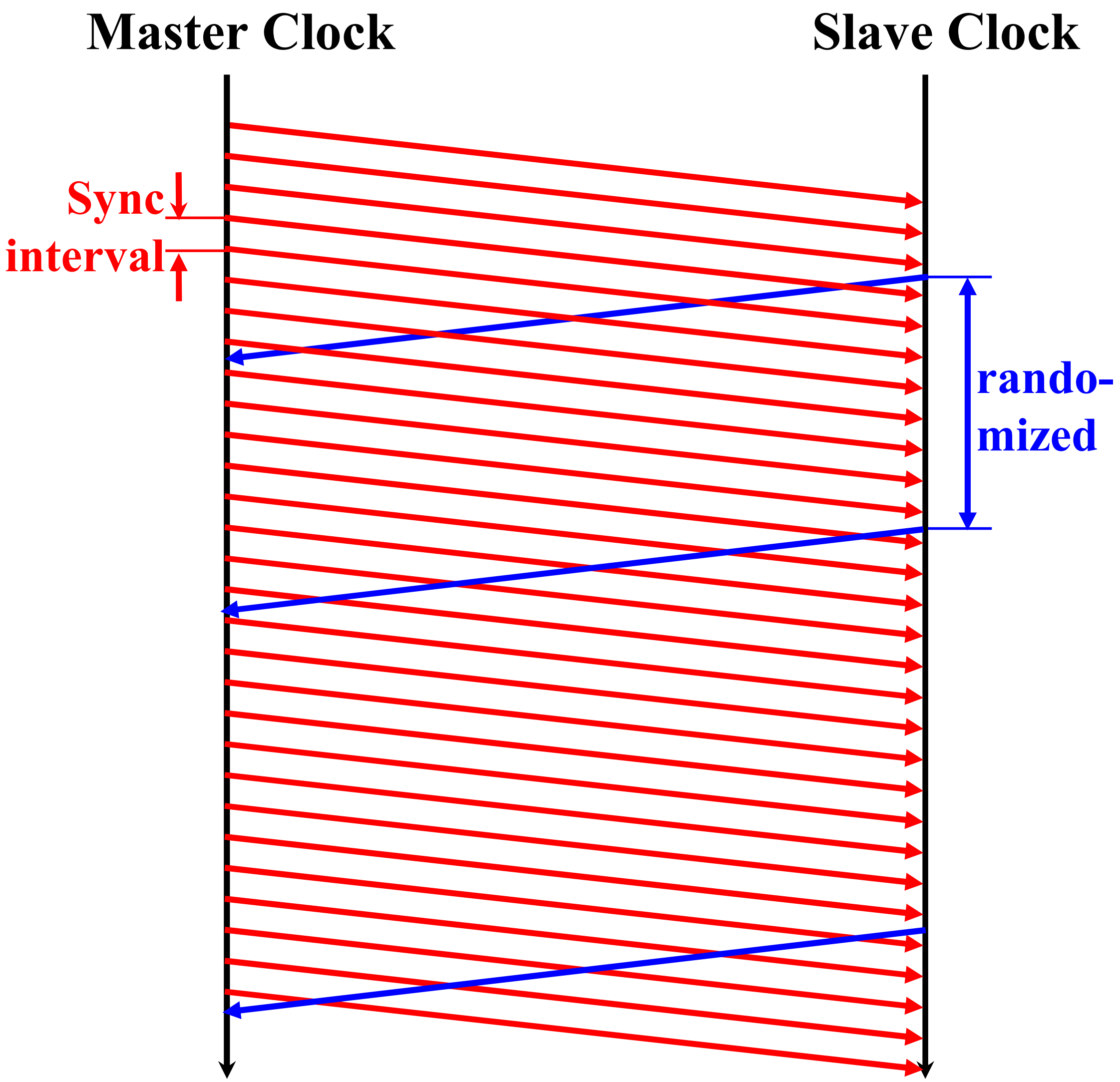
State	Description
PTP_MASTER	The associated port is behaving as a master port. The local clock is used to timestamp the receipt or departure of messages associated with the port.
PTP_PASSIVE	The associated port shall not place any messages on its communication path unless otherwise specified.
PTP_UN-CALIBRATED	One or more master ports have been detected in the subdomain. The appropriate master port is being selected and the local port is preparing to synchronize to the selected master port. This is a transient state to allow initialization of synchronization servos, updating of data sets when a new master port has been selected.
PTP_SLAVE	The associated port shall synchronize to the selected master port.

The Standard IEEE 1588
Multicast Operation



Sync and Follow_Up messages are 1-to-n

The Standard IEEE 1588
Frequency of Meassage Exchange



Sync
- allows continuous frequency corrrection
- in a cyclic interval of 1, 2, 4, 8, 16 or 64 s, default is 2 s
- interval choosen according to oscillator stability and expected environmental conditions

Delay_Req
- for Delay measurement
- in an irregular pattern (randomized interval)
- much less frequent than **Sync**

Sync Interval and Network Load

- Dimensions
  - 1 ppm of deviation corresponds to 1 µs per second (1 µs/s results in 1s/12 days)
  - a cheap quartz has a temperature dependency of 1 ppm/^{0}C or more
- In order to achieve high accuracy, frequent adjustments are required
  - the standard allows for Sync intervals of 1, 2, 8, 16 and 64 seconds
  - it is proposed to extend this choice to ⅛, ¼ and ½ seconds
- Sync and Follow_Up messages are sent as multicasts
  - the master can serve all slaves of a segment with one single message
  - this enables each slave to calculate its offset individually (provided that the delay is known)
- Delay_Req and Delay_Resp messages are with point-to-point significance, but sent with the multicast addresses as well (no address administration required)
  - this enables the slave to calculate the delay (assumed that transmission is symmetric, i.e. same transit delay for both directions)
  - because delay is assumed not to change quickly, it is not measured as frequent as the offset is → resulting network load is fairly low

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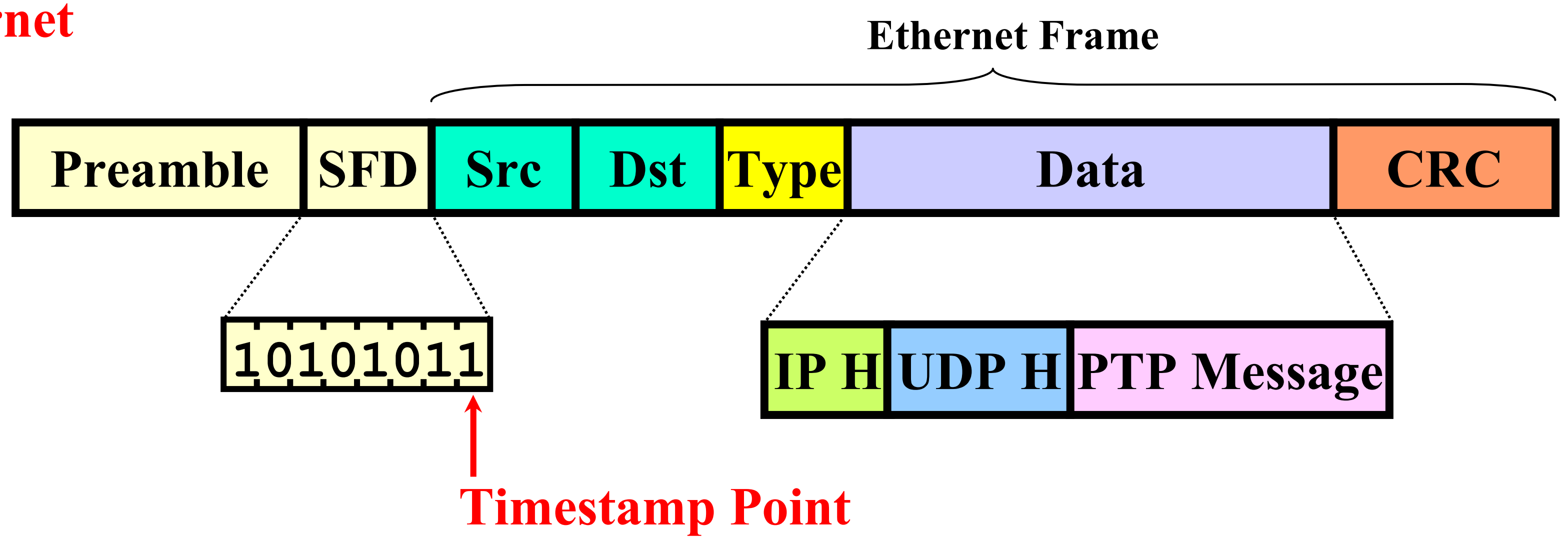
- **Implementation and performance aspects**
  - Event message detection and timestamping
  - Adjustable clocks
  - Timed I/O (generating events, timestamping of events)
  - Servo loop
  - Performance issues
- Status of PTP version 2 activities
- Applications

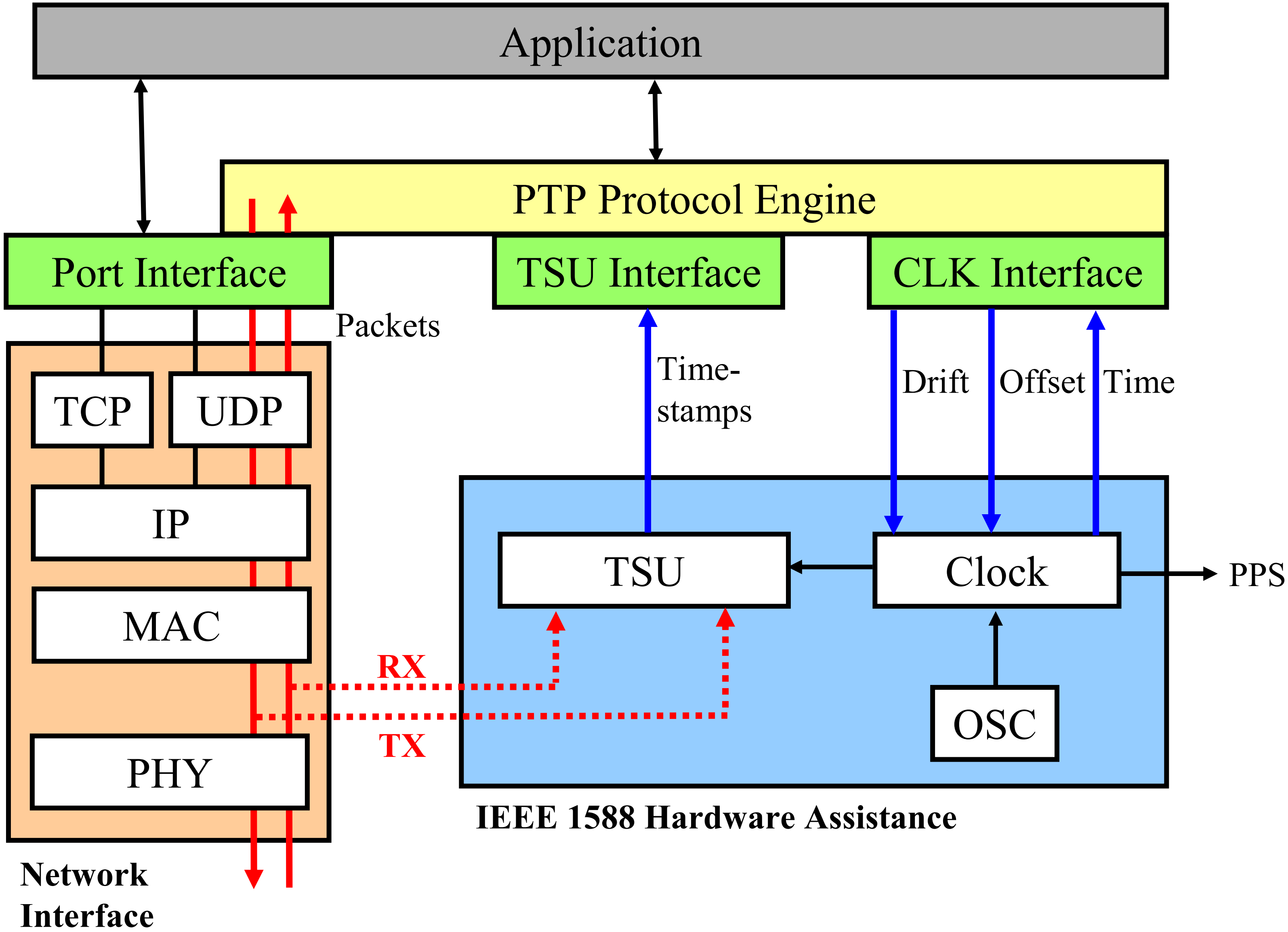
Implementation
PTP over UDP / IP / Ethernet

- **UDP** Port **319**: event port for Sync und Delay_Req messages
  Port **320**: general port for Follow_Up, Delay_Resp and Mgmt messages
- **IP** Time To Live = 0, i.e. will not be forwarded by routers
  multicast dest addresses 224.0.1.129 for *PTP-primary* (default Domain)
  224.0.1.130 for *PTP-alternate1* (alternate Domain)
  224.0.1.131 for *PTP-alternate2* (alternate Domain)
  224.0.1.132 for *PTP-alternate3* (alternate Domain)
- **Ethernet**



Implementation

Ordinary Clock Design with Hardware Assistance



Implementation
How to achieve high Accuracy?

- **Timestamps have to be taken as near as possible to the physical layer, in order to eliminate the impact of protocol stack and operating system software**
  - **Implementiation with HW assistance:**
    - **Install a PTP message detector and timestamp unit at the MII (Media Independent Interface, connecting MAC and PHY).**
    - **Exact timestamp has to be taken for every emission and reception of relevant PTP messages (i.e. Sync and Delay_Req).**
  - **Implementiation without HW support:**
    - **Timestamps taken by SW, at the entry/exit point of the interrupt service routine serving the MAC controller or at the application layer**
- **Provide Boundary Clocks in switches (and routers)**
  - **switch has its own clock which is synchronized with the master**
  - **plays the slave role at one port and the master role on all remaining ports**
- **Use statistical methods to reduce jitter**
  - **filtering, averaging, ...**
  - **such methods slower the convergence**

Reasons of residual Inaccuracies?

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Even with HW assistance, some fluctuations can still be observed

- **Quantization effects due to timestamp resolution**
- **Jitter in the data path (PHY chips, eventually hubs)**
- **Oscillator instabilities**
- **Asymmetries**
  - **Cable: up to 50 ns per 100 meter twisted pair cable (IEC 11801)**
  - **Transceivers: different send and receive path delay (difference of 150 ns and more)**
- **Phase between different asynchronous clock domains of all involved functional building blocks**
- **Limited observation capabilities**
  - **the PPS output subject of quantization effects as well**

Implementation
Statistical Methods

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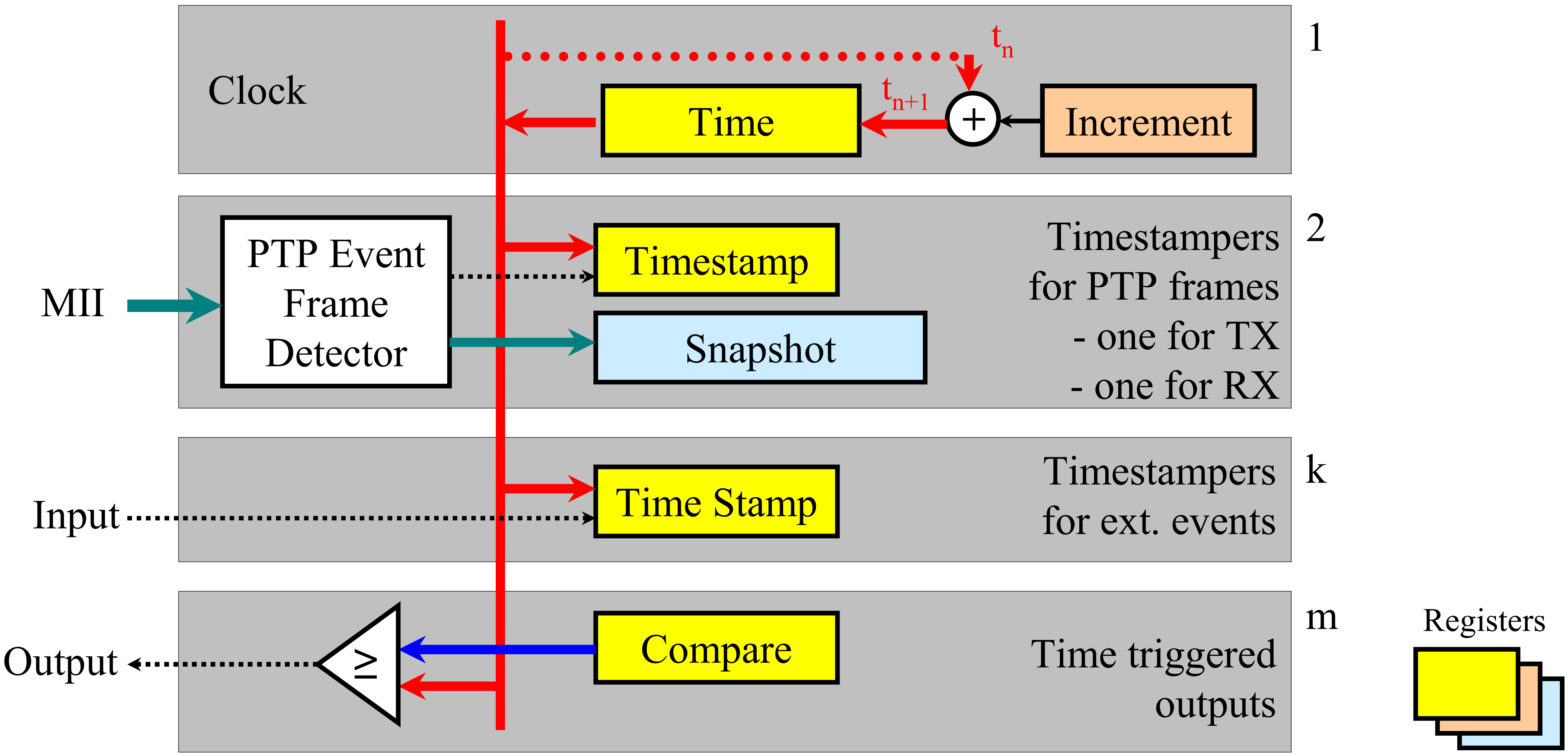
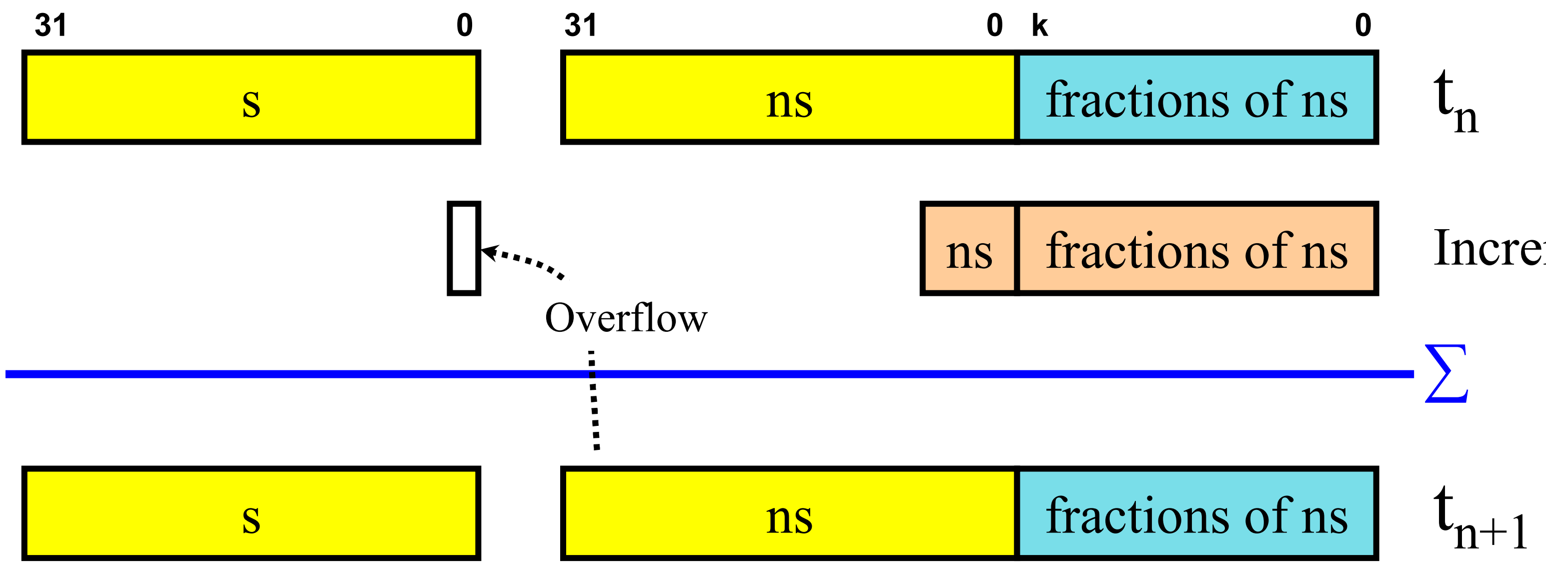
- Even with HW assistance, some fluctuations can still be observed
- Stochastic fluctuations may be removed by statistical methods
  - filtering and averaging algorithms
  - long-term averaging requires demands for a reasonable oscillator stability
- If a topology change occurs (e.g. fast reconfiguration in ring topology)
  - filtering and averaging slower the convergence
  - if reconfiguration can reliably detected, filtering and averaging should be bypassed to accelerate convergence
- Systematic effects remain
  - e.g. imperfect symmetry

Implementation
Hardware Assistance - Overview



Hardware Assistance – Clock Design Details



- The nominal increment is choosen according to the nominal oscillator frequency
- The phase change (drift) is compensated by slightly increasing or decreasing the increment

Implementation
Start-up Period

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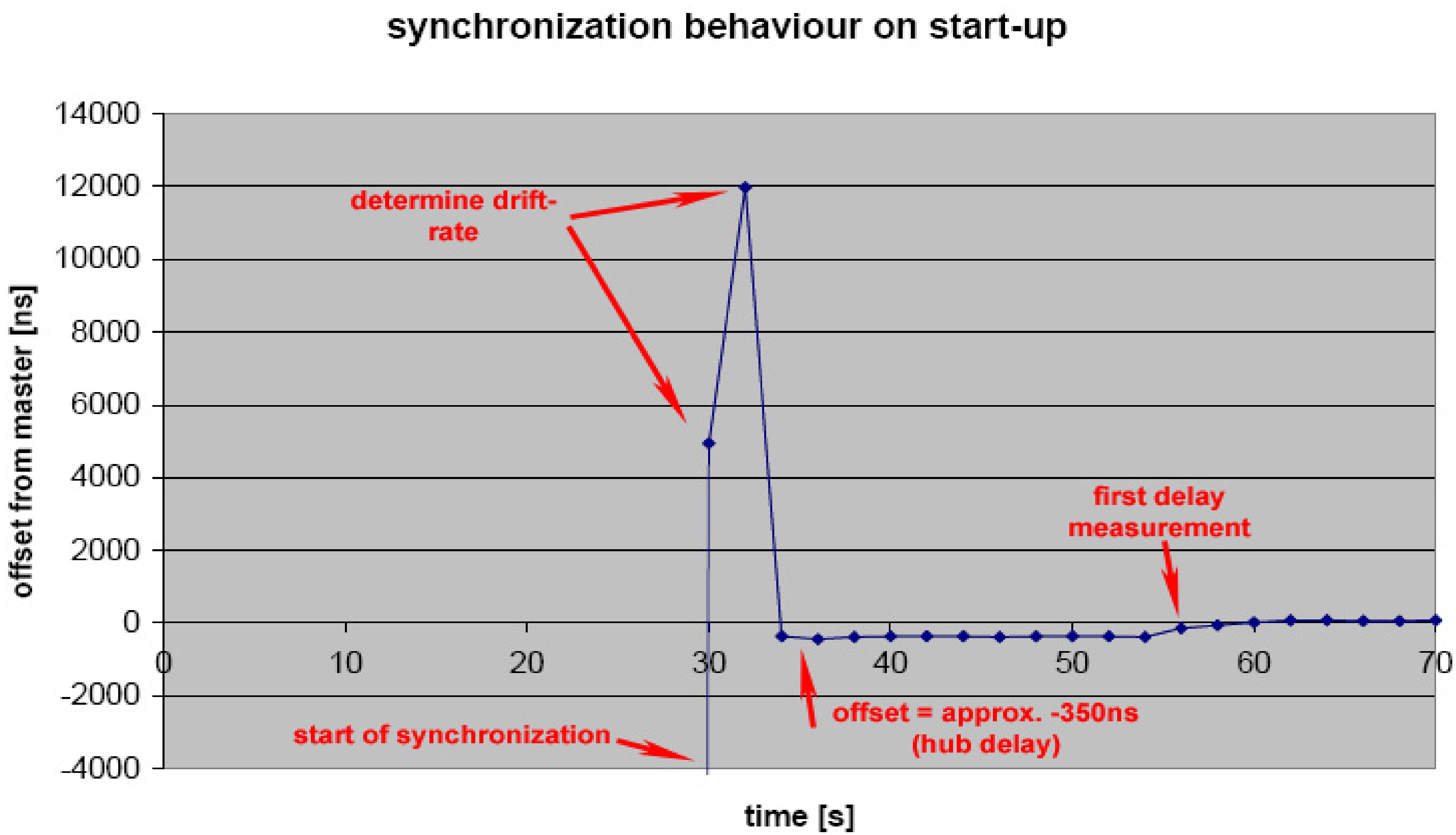

Performance

Deviation between two synchronized Clocks

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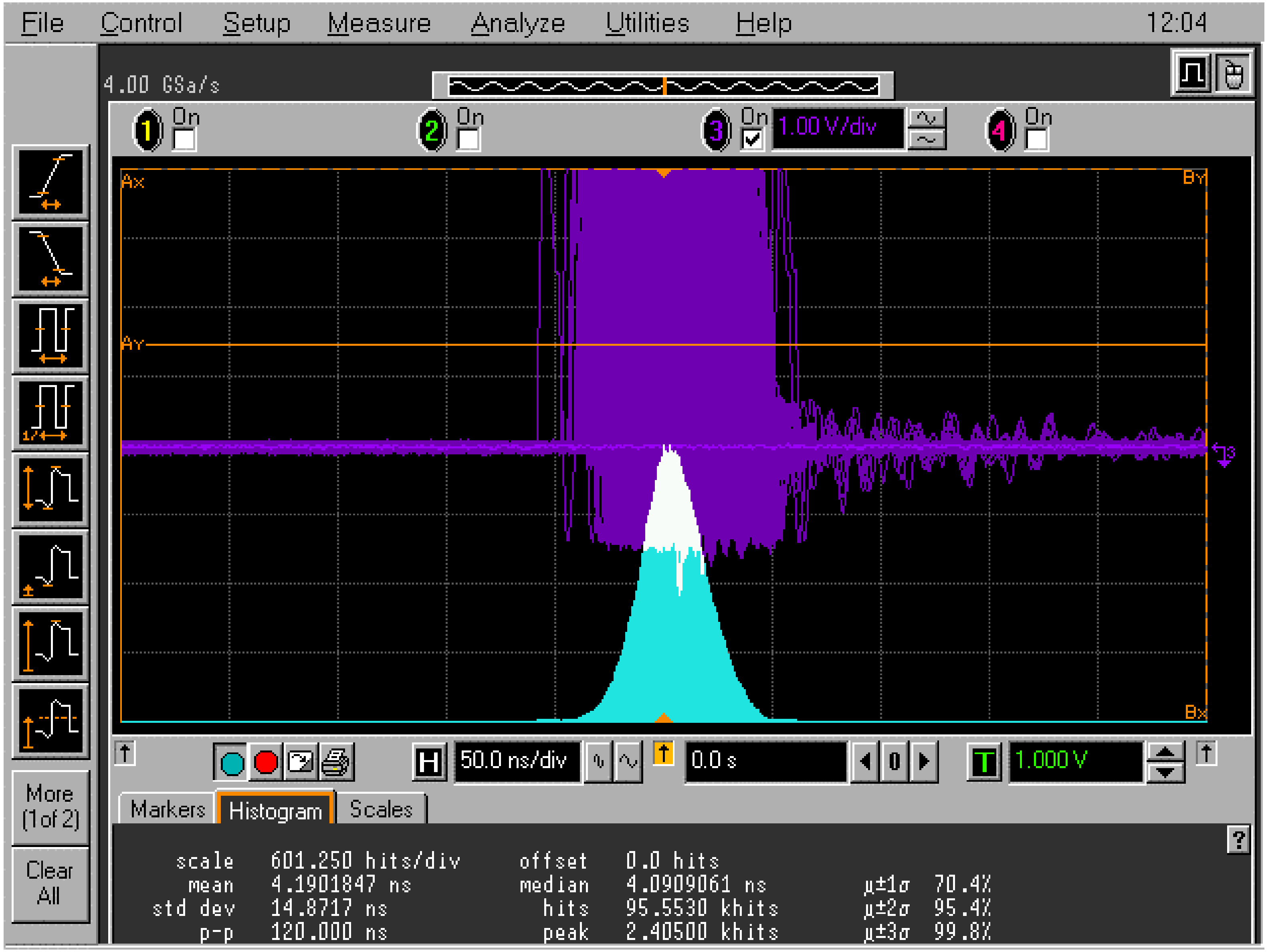

Offset between Master and Slave

+ / - 60 ns

Std deviation: 15ns

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  - Test and Meaurement (John C. Eidson)

Many thanks for your attention!

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