TIMING IN PACKET NETWORKS

STEFANO RUFFINI – WSTS 2016

CONTENTS

- Background
- Frequency Sync over the Physical Layer
- Frequency sync via packets
- Two-Way Time Transfer
- Time Protocols: NTP/PTP Details
- Impairments when delivering timing via packets
- Packet-based Metrics for frequency and time

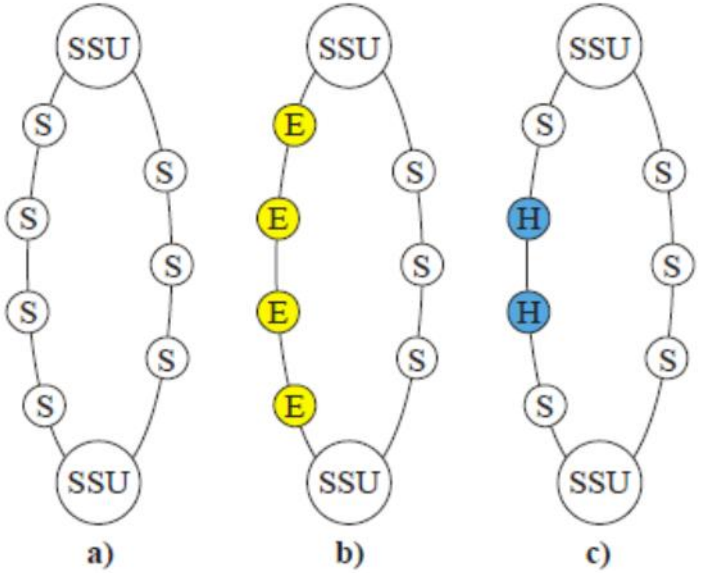
  - Note: some of this material is based on earlier presentations from Christian Farrow and Kishan Shenoi

HISTORICAL BACKGROUND

- Packet switching network does not require sync itself (at least traditional packet networks ..)
- CBR (Constant Bit Rate) services over ATM, one of the first packet–sync related examples
  - Methodologies to recover the CBR sync rate (e.g. 2 Mbit/s services, including 50 ppm frequency deviation):
    - **Network Synchronous**
    - **Adaptive**
    - Differential
- Generalization due to **migration to packet networks** (Ethernet-IP; Ethernet Physical layer traditionally defined as «asynchronous»):
  - Support timing requirements of the connected networks (e.g. **Mobile applications**)
  - **Circuit Emulation** detailed performance analysis
  - Frequency sync distribution via dedicated protocols (NTP, PTP)
  - Standardized performance objectives over reference networks (e.g. ITU-T Recc. G.8261)
  - Definition of a synchronous Ethernet (syncE) physical layer (G.8261, G.8262, G.8264)
- Increased interest to also deliver **time/phase sync** reference
  - **Packet-based sync technologies** required (may be combined with synchronous physical layer)
- Recent efforts for «Deterministic» packet networks (e.g. **TSN**-IEEE, **Detnet**-IETF)

SYNCE: INTRODUCTION

- Several applications requiring **accurate frequency reached by Ethernet**
  - Since the very start of timing over packet network activities, it was proposed to define possible use of synchronous Ethernet physical layer
  - Not in contradiction with IEEE (10^{-11} within the +/-100 ppm - 20 ppm)
  - Only in full duplex mode (continuous signal required)
- **Based on SDH** specification (for interoperability and simplifying the standardization task)
  - Synchronous Ethernet equipment equipped with a **synchronous Ethernet Equipment Clock – EEC** (G.8262). Synchronous Ethernet interfaces extract the received clock and pass it to the system clock.
  - Synchronization Status Message as per G.8264
  - Ongoing work to defined **enhanced SyncE** (G.8262.1)
- It does not transport Time (but it has been proposed)
- All nodes must support SyncE: sync chain as per G.803
  - Cannot be transported transparently across network boundaries



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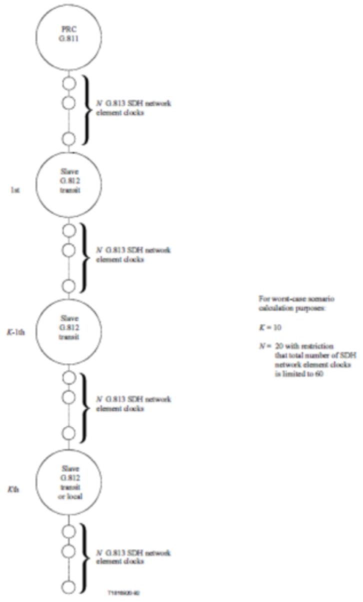
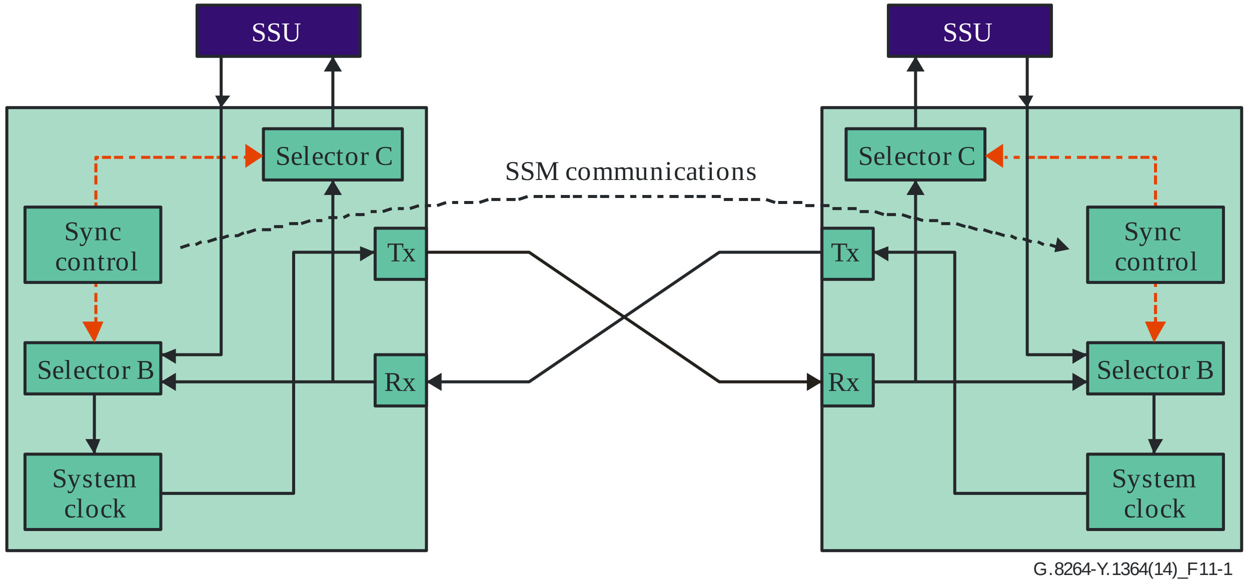


Figure 8-5/G.803 – Synchronization network reference chain

SSM (SYNCHRONIZATION STATUS MESSAGE) IN SYNCE

- SSM required to prevent timing loops and to support reference selection (as per SDH);
  - details according to G.781 and G.8264
- In SDH SSM delivered in fixed locations of the SDH frame
  - Packet based mechanism required in case of SyncE
- OUI (organizationally unique identifier) from IEEE reused to specify exchange of QLs over the OAM specific slow protocol (OSSP)
- EEC option 1 clock treated as G.813 option 1 (QL-SEC), EEC option 2 as an G.812 type IV clock (QL-ST3).
- Two types of protocol message types are defined
  - "heart-beat" message (once per second)
  - Event message generated immediately
- SSM QL value is considered failed if no SSM messages are received after a five second period.



ETHERNET SYNCHRONIZATION MESSAGING CHANNEL (ESMC) FORMAT

› ESMC PDU with QL TLV always sent as the first TLV in teh Data and padding field

Octet number	Size/bits	Field
1-6	6 octets	Destination Address = 01-80-C2-00-00-02 (hex)
7-12	6 octets	Source Address
13-14	2 octets	Slow Protocol Ethertype = 88-09 (hex)
15	1 octet	Slow Protocol Subtype = 0A (hex)
16-18	3 octets	ITU-OUI = 00-19-A7 (hex)
19-20	2 octets	ITU Subtype
21	bits 7:4 (Note 1)	Version
	bit 3	Event flag
	bits 2:0 (Note 2)	Reserved
22-24	3 octets	Reserved
25-1532	36-1490 octets	Data and padding (See point j)
Last 4	4 octets	FCS

NOTE 1 – Bit 7 is the most significant bit of octet 21. Bit 7 to bit 4 (bits 7:4) represent the four-bit number for the ESMC.

NOTE 2 – The three LSBs (bits 2:0) are reserved.

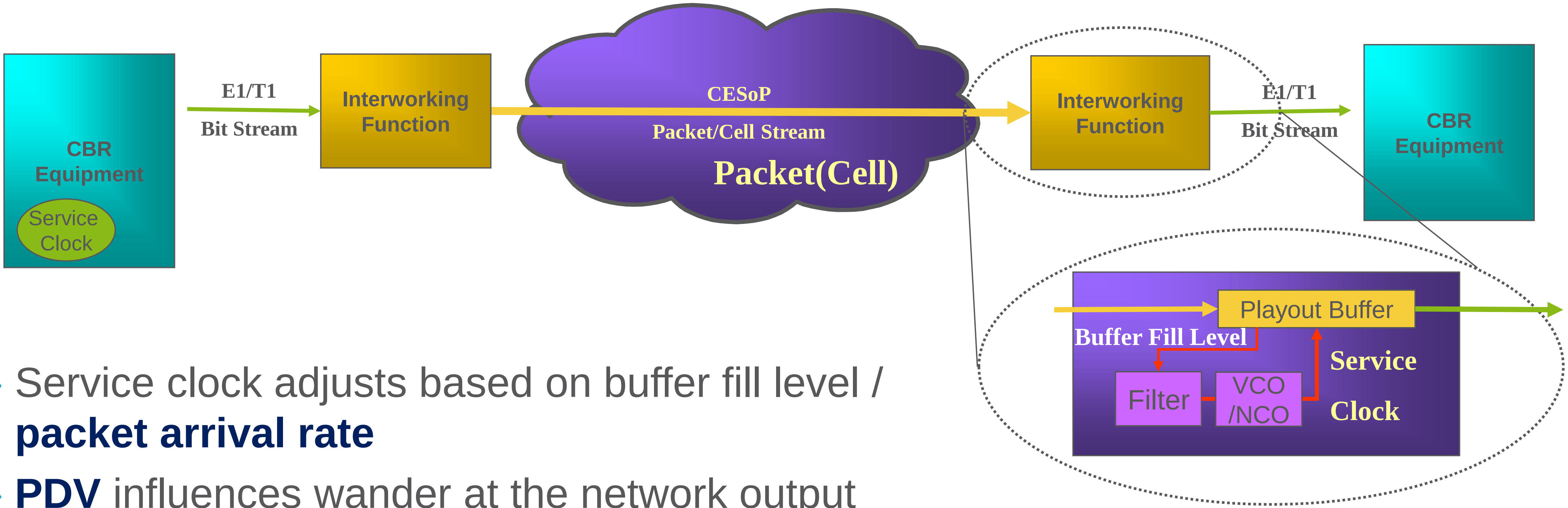
Octet number	Size/bits	Field
1	8 bits	Type: 0x01
2-3	16 bits	Length: 00-04
4	bits 7:4 (Note)	0x0 (unused)
	bits 3:0	SSM code

NOTE – Bit 7 of octet 4 is the most significant bit. The least significant nibble, bit 3 to bit 0 (bits 3:0) contains the four-bit SSM code.

› Recently extended to carry new clock types (and inform on PRTC traceability)

– Extend Ql TLV

PACKET-BASED TIMING: ADAPTIVE CLOCK OPERATION

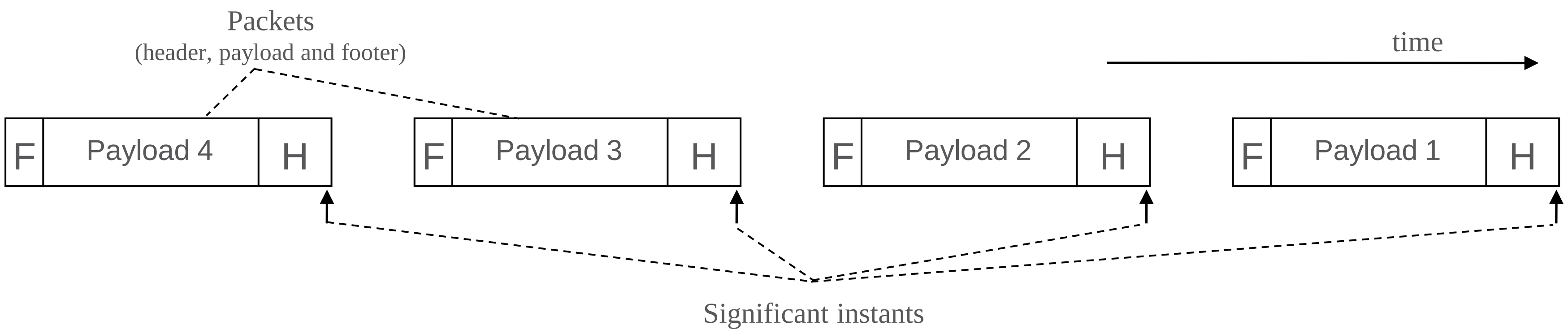


› Service clock adjusts based on buffer fill level / **packet arrival rate**

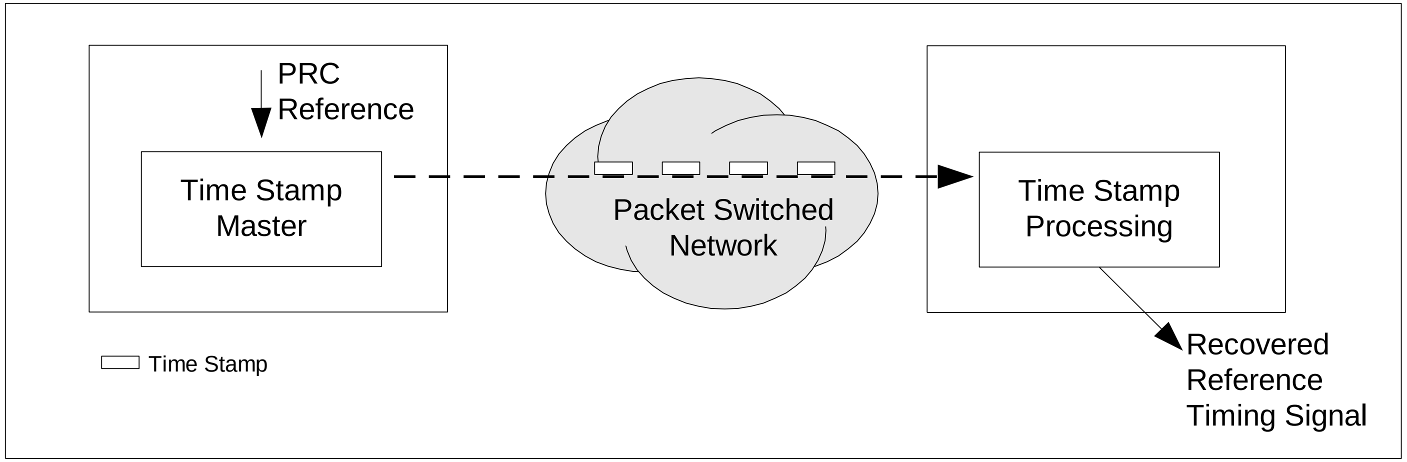
› **PDV** influences wander at the network output

FROM CLOCKS TO “PACKET CLOCKS”

- “**Packet clocks**” can be described in a similar way …
- CES Packets do have a regular rhythm
- Extension to using dedicated protocols: **NTP, PTP**
  - Packets may not arrive regularly, but **timestamps** mean time information can be extracted
  - Timing information contained in the arrival/departure time of the packets
  - **Two-way or one-way** protocols
  - Timing recovery process requires **PDV filtering**
- Time and frequency can be distributed from point A to point B



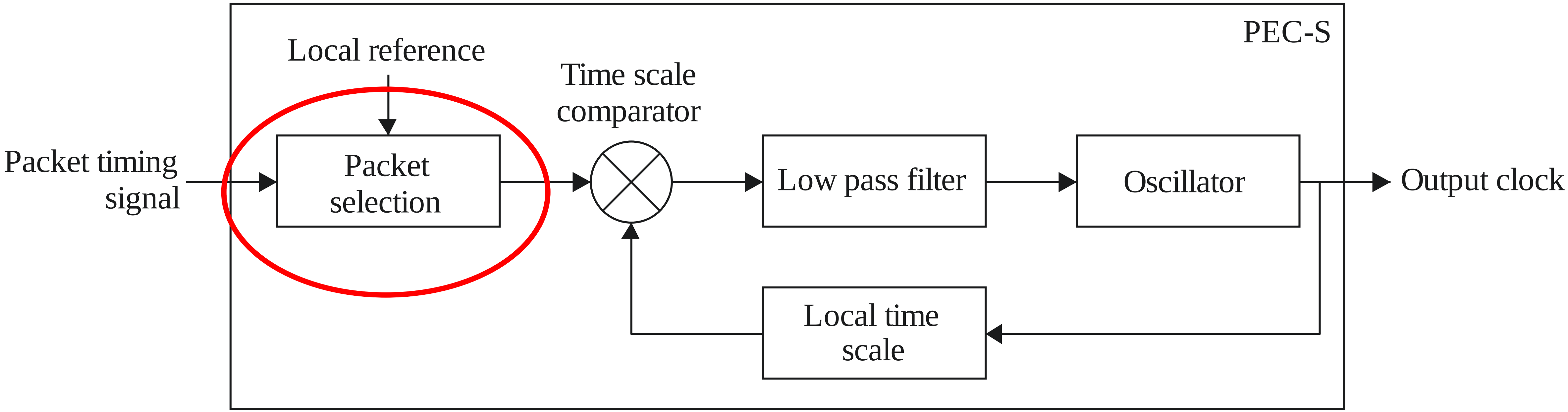
PACKET-BASED METHODS



From ITU-T Recc. G.8261

- Timing information carried by **dedicated timing packets**:
  - Network Time Protocol (NTP) – IETF RFC 5905
  - Precision Time Protocol (PTP) – IEEE1588-2008

PACKET-BASED EQUIPMENT CLOCK



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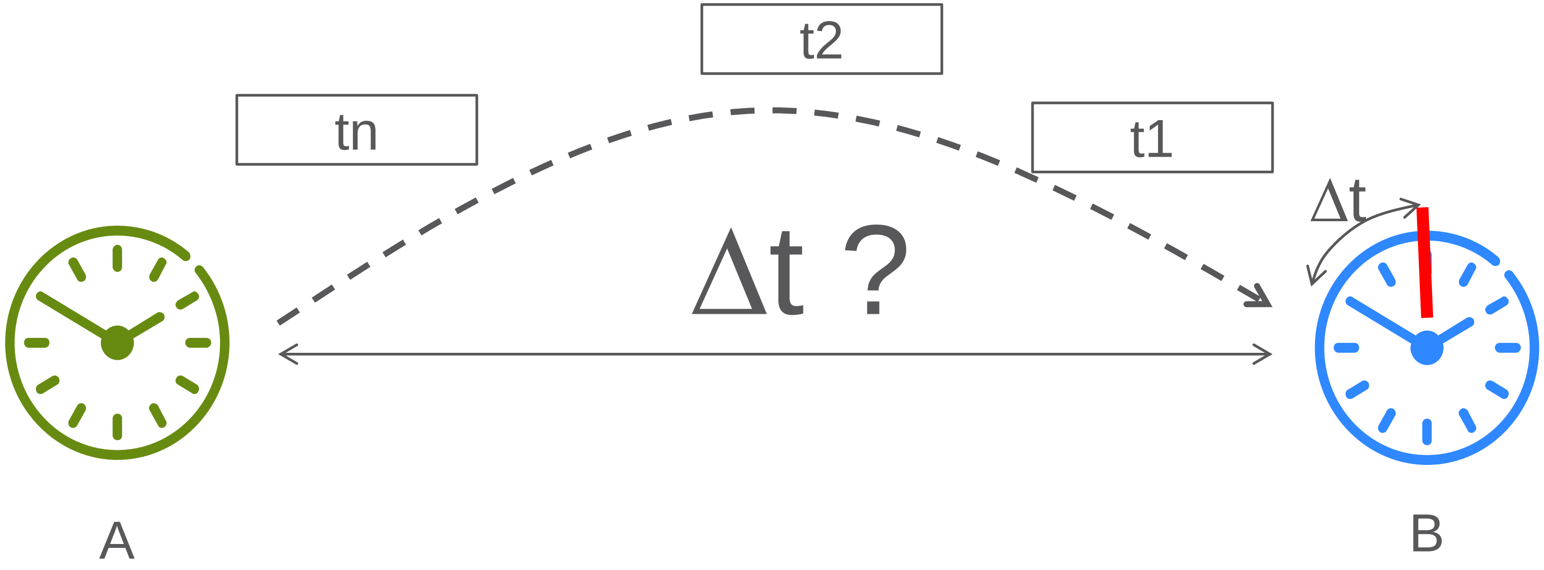
- Concept of «**Packet Selection**»:
  - Pre-processing of packets before use in a traditional clock to handle PDV

TWO-WAYS TIME TRANSFER

- Delivery of Time synchronization requires also the knowledge of «transit delay» from A to B

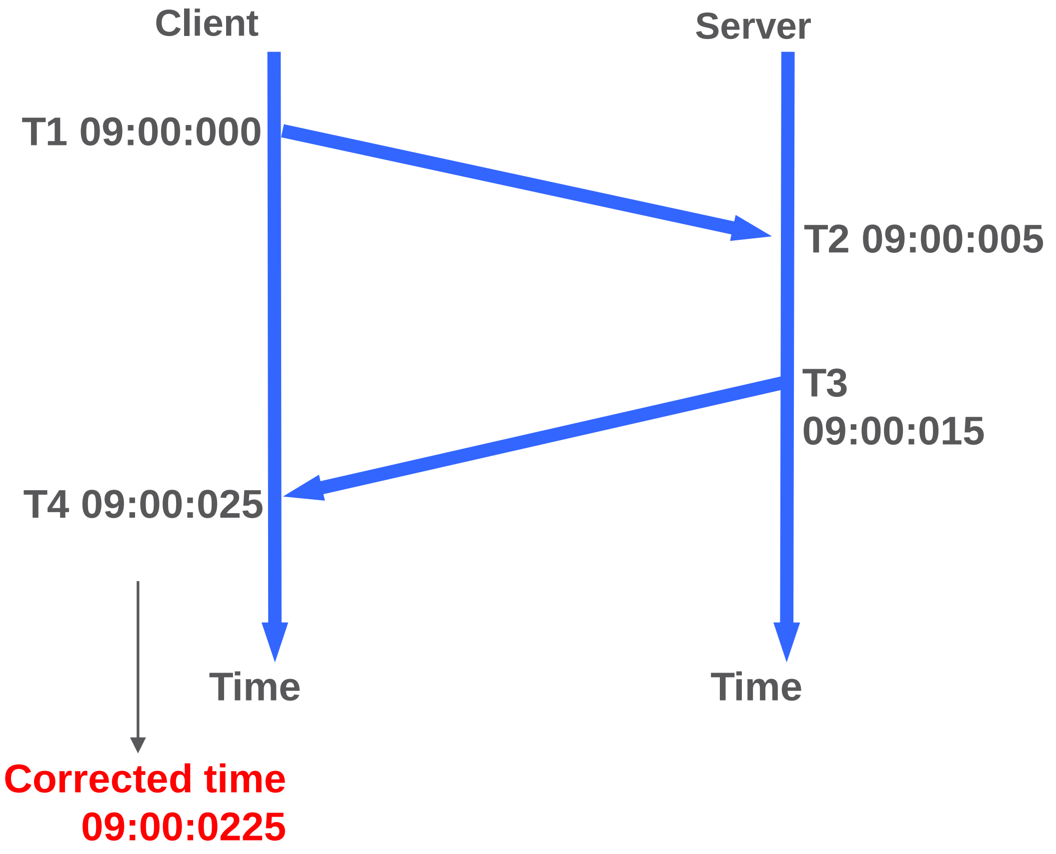


- **Two-ways transfer protocols** (round trip delay)
  - Assumption for **symmetric channel**

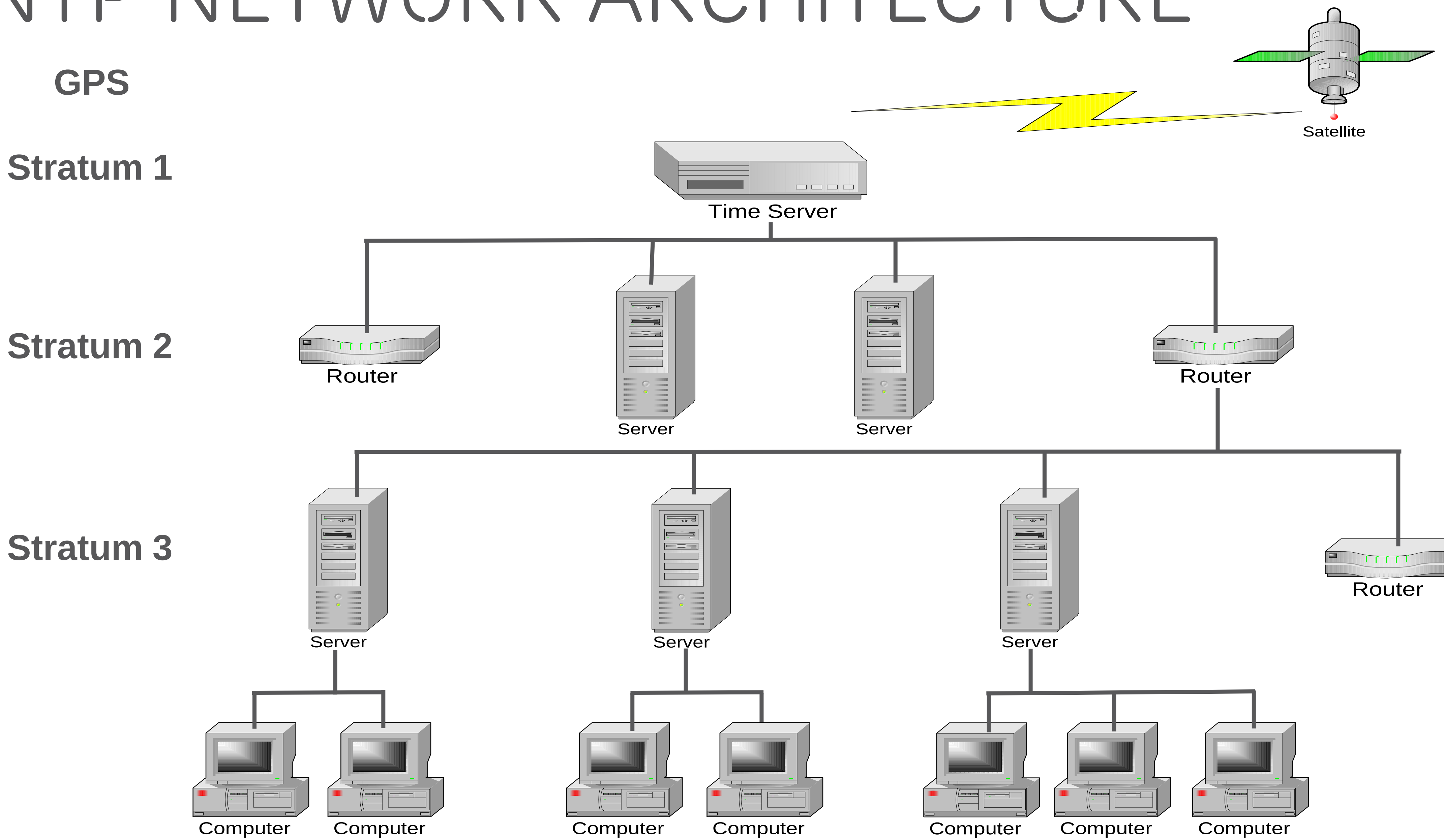
HOW NTP WORKS

- T1 Originate Timestamp
  - Time request sent by client
- T2 Receive Timestamp
  - Time request received by server
- T3 Transmit Timestamp
  - Time reply sent by server
- T4 Destination Timestamp
  - Time reply received by client
- Round Trip Delay=(T4-T1)-(T3-T2)
  - Round Trip Delay =25-10=15
- Clock Offset= [(T2-T1)-(T4-T3)]/2
  - Clock Offset =[5-10]/2= **-2.5** (Clients actual time when reply received was therefore **09:00:0225**)

- **Key Assumptions:**
  - **One way delay is half Round Trip (symmetry!)**
  - Drift of client and server clocks are small and close to same value
  - Time is traceable

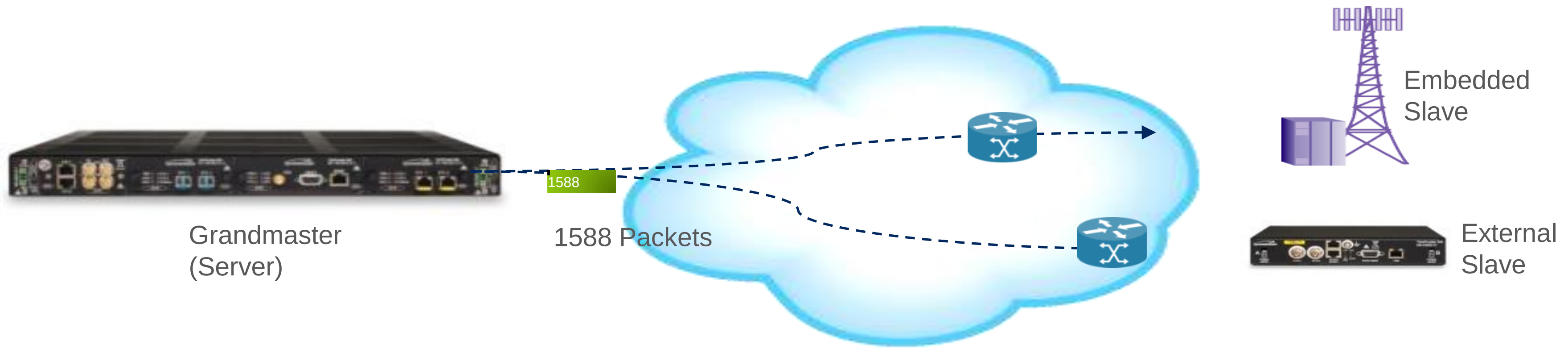


NTP NETWORK ARCHITECTURE



IEEE 1588-2008 PTPV2 OVERVIEW

- The **Grandmaster** “reference clock” sends a series of time-stamped messages to slaves.
- Slaves process the round-trip delay & synchronize to the Grandmaster.
- Frequency can be recovered from an accurate time of day reference (but **L1 can also be used** …)
- **Best Master Clock Algorithm** to define the hierarchy
- Accuracy is possible by means of:
  - Proper packet rate (up to 128 per second)
  - **Hardware time-stamping** (eliminate software processing delays)
  - **Timing support in the network** (e.g. transparent clocks, boundary clocks)

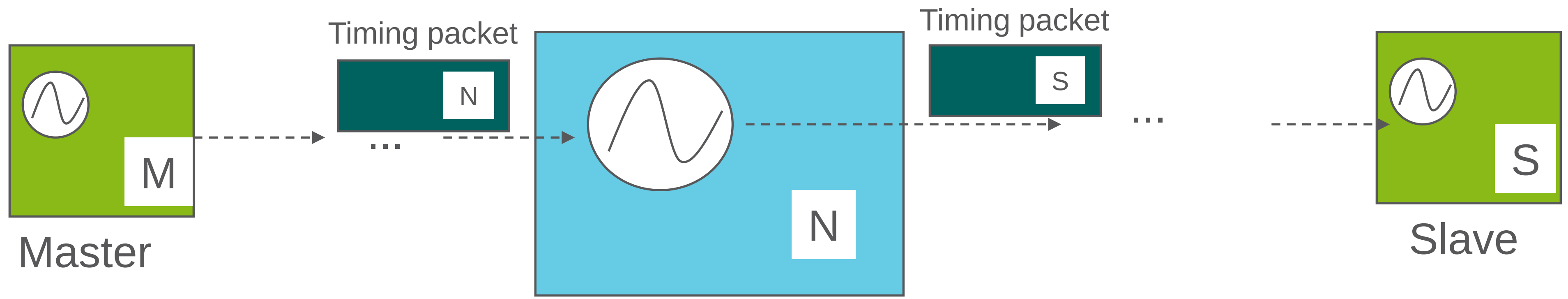


Packet Slave clocks can be either stand-alone or embedded in network equipment

- Note: IEEE 1588 under revision (planned 2017)

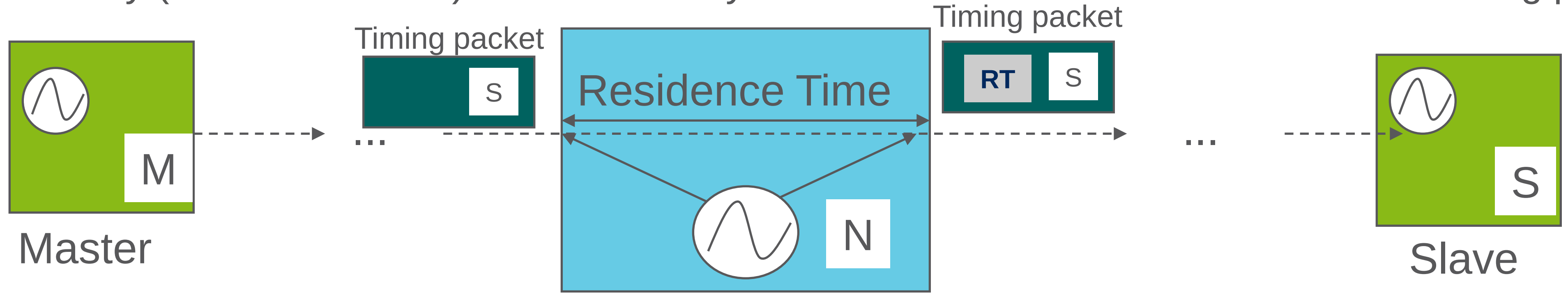
TIMING SUPPORT

Timing packets are terminated and regenerated by N



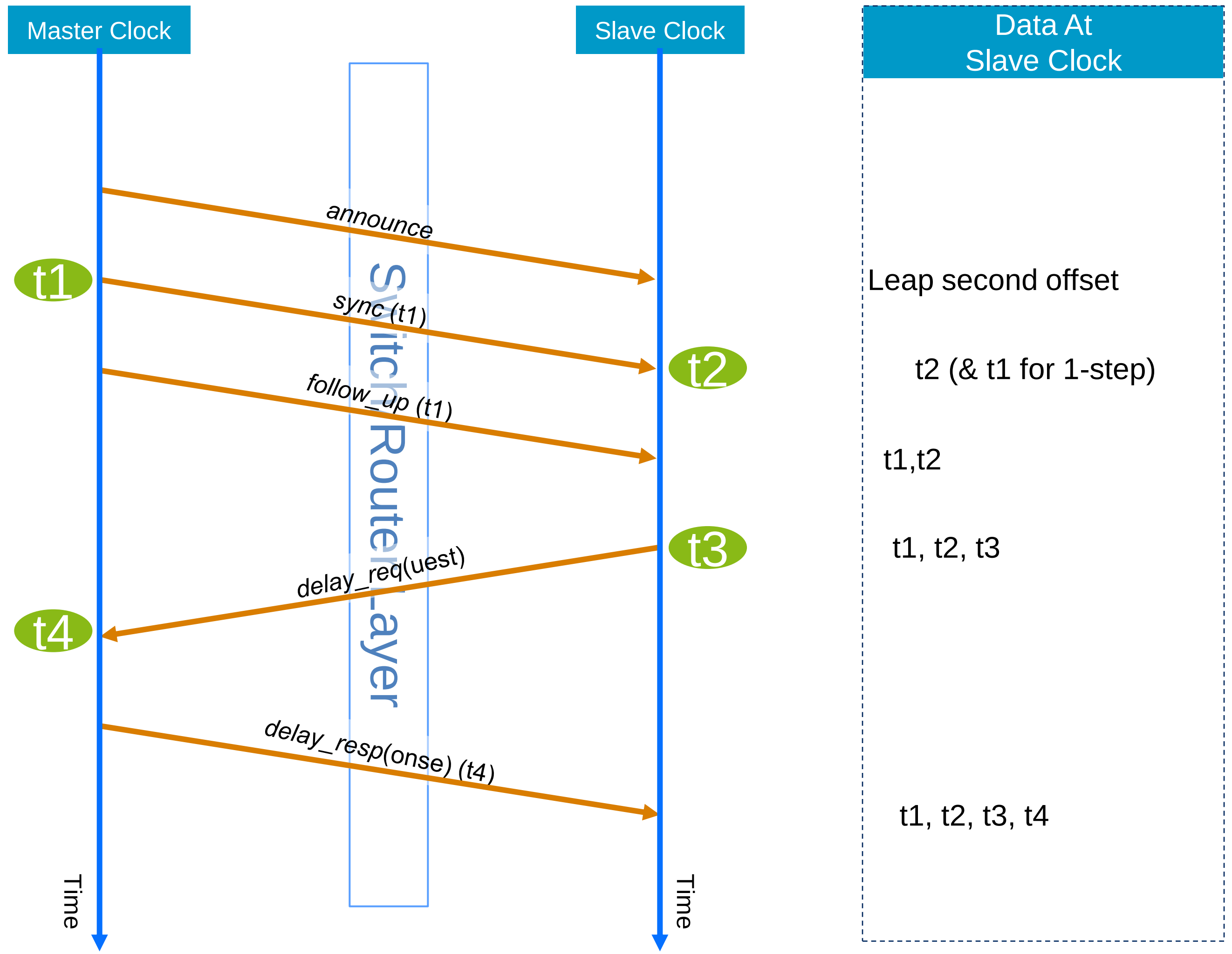
e.g. **IEEE1588 Boundary Clock**, NTP Stratum Clock

Latency (Residence Time) is calculated by NE and the information is added in the timing packet



e.g. **IEEE1588 Transparent Clock**

PTP TIME TRANSFER TECHNIQUE



The process is repeated up to 128 times per second.
(Announce rate is lower than Sync rate)

Round Trip Delay

RTD = (t2 - t1) + (t4 - t3)

Offset:

(slave clock error and one-way path delay)

Offset_{SYNC} = t2 – t1

$\text{Offset}_{DELAY\_REQ}$ = t4 – t3

We assume path symmetry, therefore

One-Way Path Delay = RTD ÷ 2

Slave Clock Error = (t2 - t1) - (RTD ÷ 2)

Notes:

1. One-way delay cannot be calculated exactly, but there is a bounded error.
2. The protocol transfers TAI (Atomic Time).
   UTC time is TAI + leap second offset from the *announce* message.

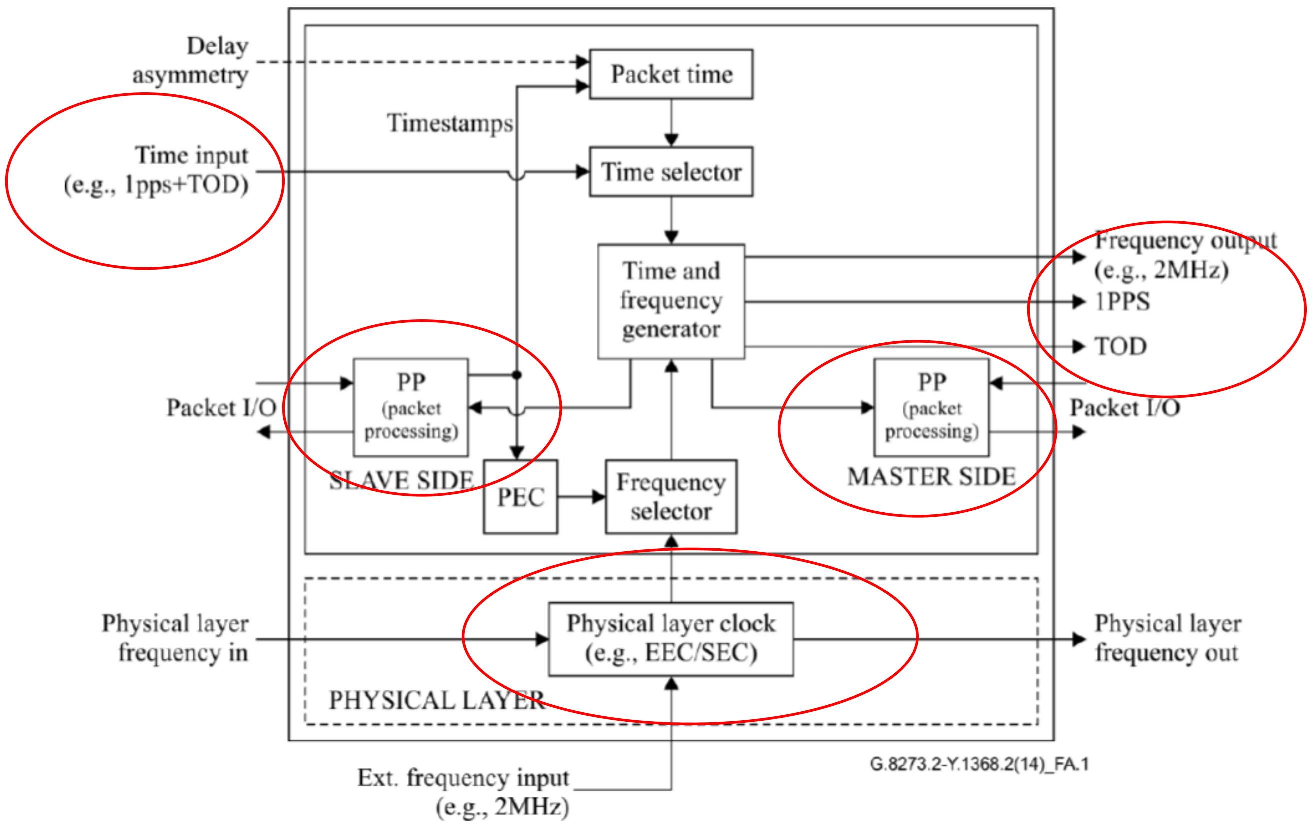
"THE TELECOM PROFILE" (G.8265.N/G.8275.N)

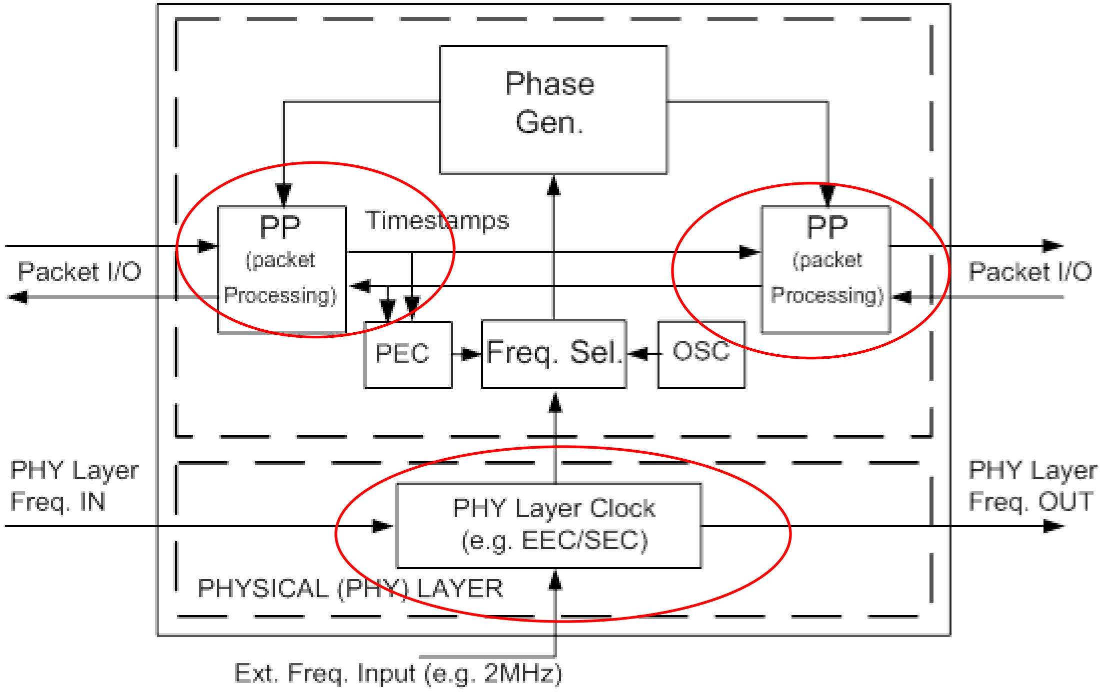
- A **profile** is a subset of required **options**, prohibited options, and the ranges and defaults of configurable attributes
  - e.g. for Telecom: Update rate, unicast/multicast, etc.

- PTP profiles are created to allow organizations to specify selections of attribute values and optional features of PTP that, when using the same transport protocol, **inter-works** and achieve a **performance** that meets the requirements of a particular application

- Other (non-Telecom) profiles:
  - IEEE C37.238 (Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications,)
  - IEEE 802.1AS (Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks); Under revision (targeting a full compliance with the next IEEE 1588 revision)

T-BC AND T-TC CLOCK MODELS

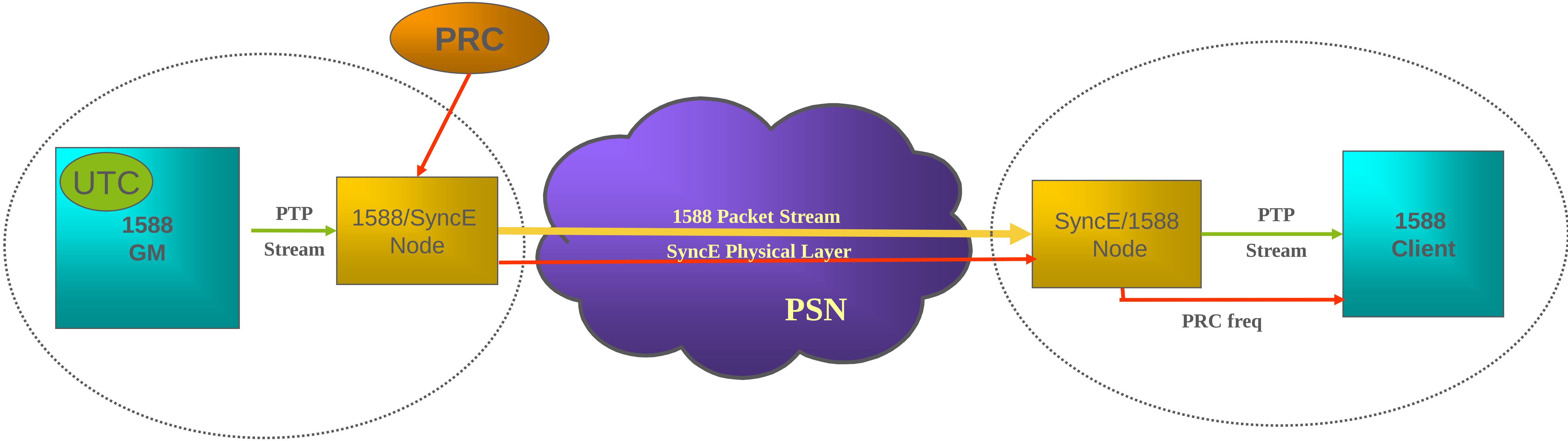




- **G.8273.2** and **G.8273.3** provide models for the Telecom Boundary and Transparent Clocks
  - **Frequency sync via physical layer** initially considered

COMBINED PTP-SYNCE

- SyncE as "frequency assistance" to 1588



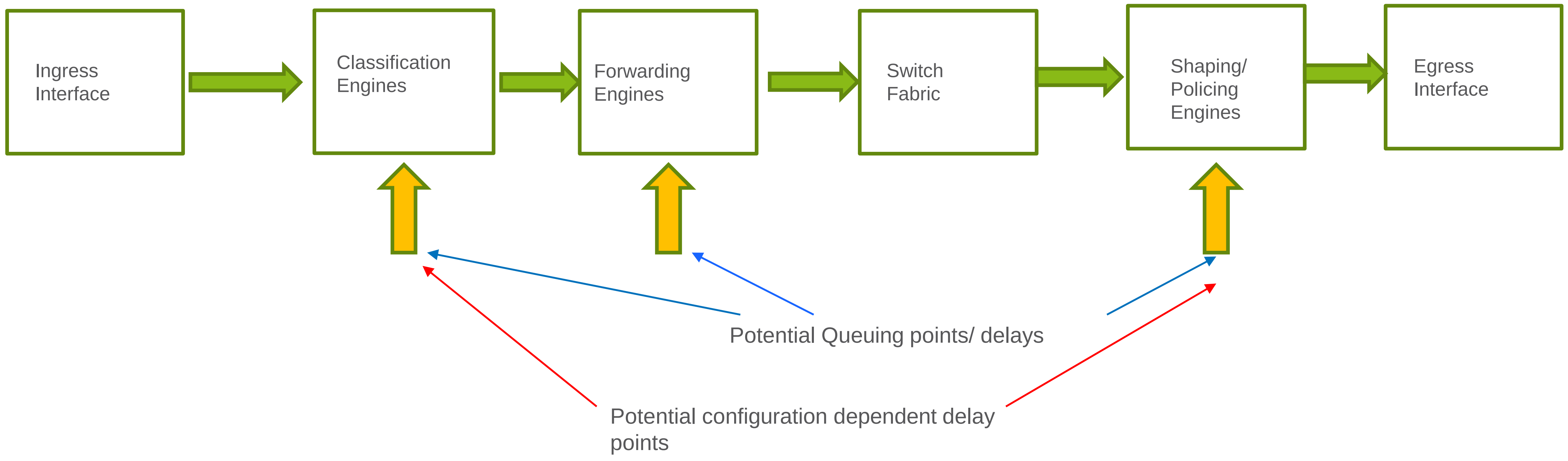
- Gives immediate "frequency lock" to 1588 client
- SyncE & 1588 functionality may be in the same node/element
- SyncE might be used for "**Time sync holdover**"

IMPAIRMENTS IN PACKET NETWORKS

- **Packet delay variations** [PDV], depending on
  - Network dimension
  - Traffic load
  - QoS
- Path dependent aspects
  - Physical path **asymmetry** (*particularly relevant for time synchronization*)
  - **Path rerouting**
- Interactions between the packet streams

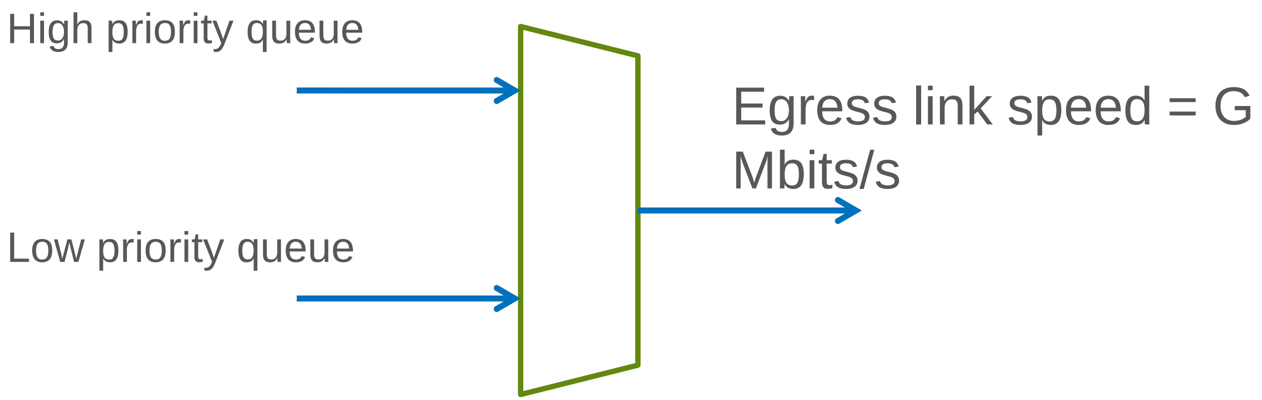
PACKET DELAY VARIATION (PDV)

- Queuing
- Equipment Configuration
- Priority/ QoS



PACKET DELAY VARIATION (PDV), CONT.

› Head of line blocking



MTU size M byte
Strict priority queue

$$(\Delta_{pp})_{max} \geq \left(\frac{M}{G}\right) \mu s$$

- A packet arrives in the HPQ, just when a packet from the LPQ has begun transmission
- The packet from HPQ is blocked till the LPQ packet is transmitted
- With more complex prioritization scheme the delay due to head of line blocking could vary significantly
- Tools being specified by IEEE 802.1 to address this issue (e.g. frame preemption, scheduled traffic)

Ex. : at 1Gbit/s,
1000 byte packet = 8 x 1000 / 1000 x 10^6 = 8 µs

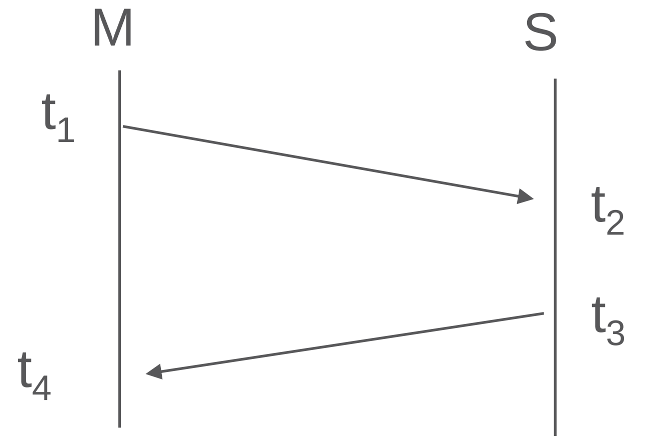
PATH DEPENDENT IMPAIRMENTS

- Asymmetry
  - Static difference in paths between the forward and reverse paths. E.g difference in lengths of fiber
  - Forward and reverse paths pass through different node
- Rerouting
  - Leads change in path delays and can “confuse” the algorithms.

TIME SYNCHRONIZATION VIA PTP: ASYMMETRY RELATED IMPAIRMENTS

- The basic principle is to distribute Time sync reference by means of two-way time stamps exchange

Time Offset= $t_2 – t_1$ – Mean path delay
Mean path delay = $((t_2 – t_1) + (t_4 – t_3))/2$



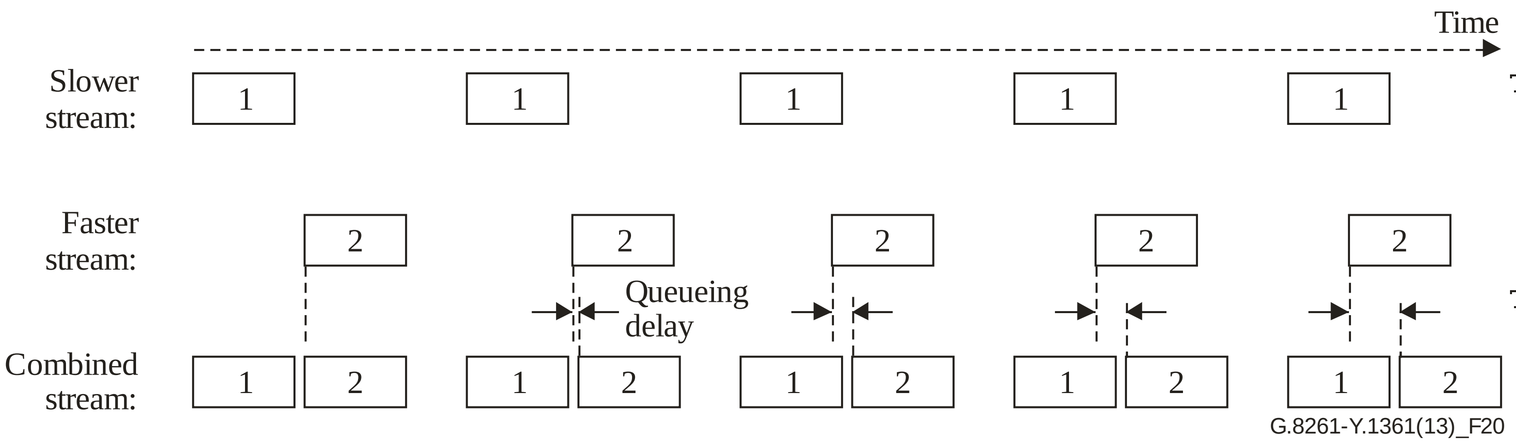
- As for NTP, also in case of PTP, symmetric paths are required:
  - Basic assumption: $t_2 – t_1 = t_4 – t_3$
  - Any asymmetry will contribute with half of that to the error in the time offset calculation (e.g. 3 μs asymmetry would exceed the target requirement of 1.5 μs)

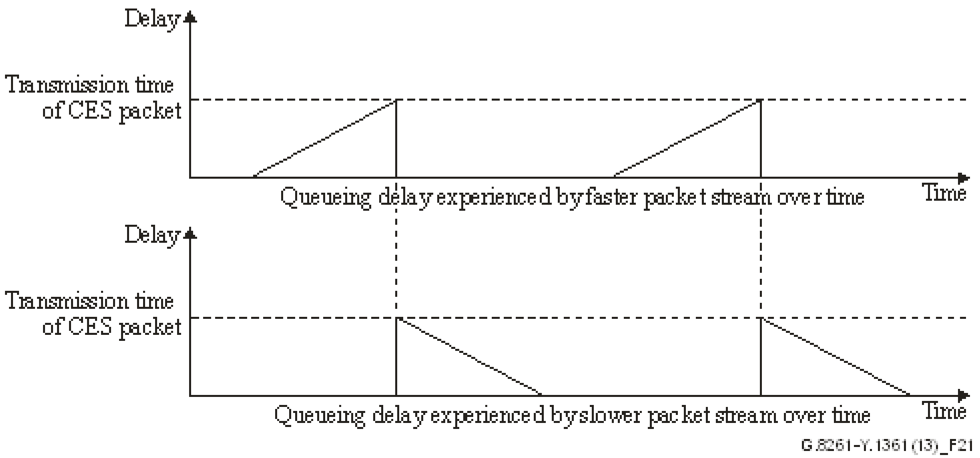
ASYMMETRY DUE TO THE TRANSPORT TECHNOLOGIES

- Different paths in Packet networks
  - Traffic Engineering rules in order to define always the same path for the forward and reverse directions
- Different Fiber Lengths in the forward and reverse direction
  - Additional problem: DCF (Dispersion Compensated Fiber)
- Different Wavelengths used on the forward and reverse direction
- Asymmetries added by specific access and transport technologies
  - GPON
  - VDSL2
  - Microwave
  - OTN

INTERACTION OF FLOWS

- This phenomenon occurs whenever two “non random” packets share a common path or transmission resource
- Two illustrative examples
  - 2 streams converging on egress of CES Functions
  - The PTP Grandmaster & (Multiple slaves) (OCs) communicating over “unaware” networks
    - Could easily create “bottle necks” even on unloaded networks



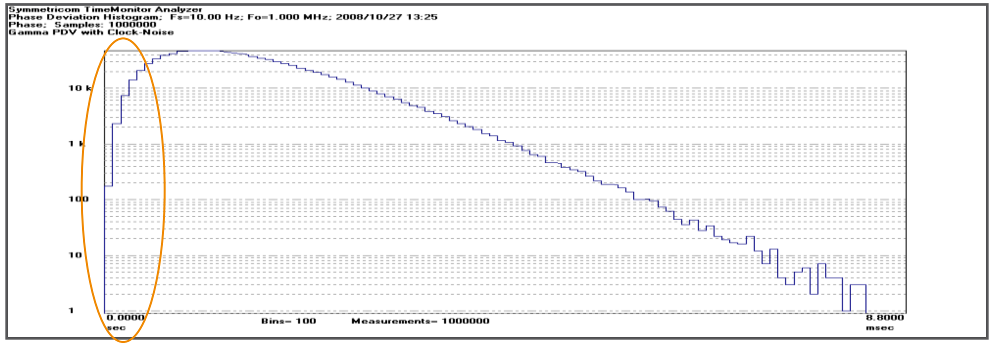


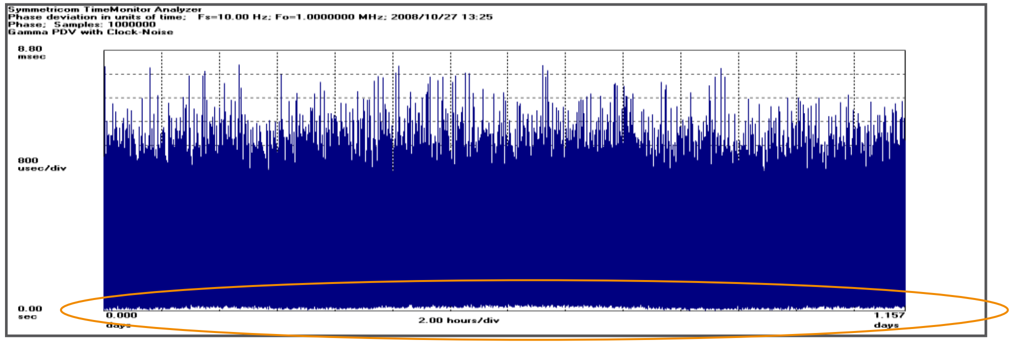
KEY ASPECTS OF PERFORMANCE

- **Packet Delay Variation** (PDV) is a major contributor to “clock noise”
  - Related to number of hops, congestion, line-bit-rate, queuing priority, etc. Time-stamp-error can be viewed as part of PDV
- Clock recovery involves low-pass-filter action on PDV
  - **Oscillator** characteristics determine degree of filtering capability (i.e. tolerance to PDV)
    - Higher performance oscillators allow for longer time-constants (i.e. stronger filtering)
    - Lower performance (less expensive) oscillators may be used (may require algorithmic performance improvements)
- Performance improvements can be achieved by
  - Higher packet rate
  - Controlling PDV in network (e.g. network engineering, QoS)
  - Timing support from network (e.g. *boundary clocks* in PTP)
  - Packet selection and/or nonlinear processing

NOTION OF “BEST PACKETS”

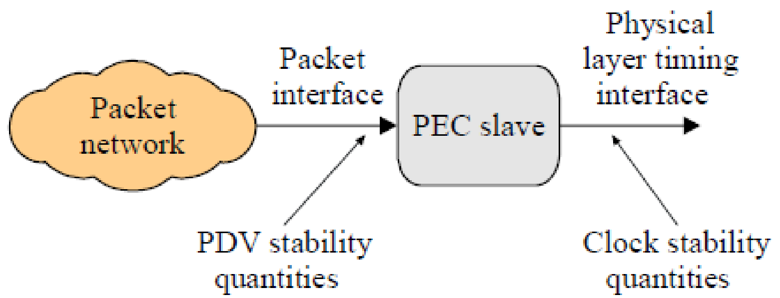
- Impact of PDV can be mitigated by means of a suitable classification and **selection** of packets
- The “**minimum delay**” approach is presented as an example. Depending on the network characteristics other approaches may be more suitable
- The assumption that the path is constant over the interval of observation implies a PDV with a distribution function with a slowly changing floor (i.e. minimum delay that a packet can experience)
- In many cases it has been observed that a reasonable **fraction (e.g. x%) of the total number of packets** will traverse the network at or **near this floor**
- Using only these packets in the timing recovery mechanism would allow to significantly reduce the impact of the PDV on the quality of the recovered reference timing signal





SYNC METRICS IN PACKET NETWORKS

- The Network Element clock output metrics as per TDM networks (e.g. MTIE/MRTIE/TDEV)
  - Some distinctions are required in case of packet clock integrated in the Base Station (no standardized output MTIE/TDEV by 3GPP)
- Specific Metrics have been defined to better characterize the behavior of packet networks (PDV) delivering the timing reference
  - Metrics that associate PDV with Frequency Offset or phase variation
  - Tolerance masks/Network limits are used by network operators and clock manufacturers
  - Packet selection methods can be justified



[*Clock stability quantities estimation*] = *function* (*PDV stability quantities*)

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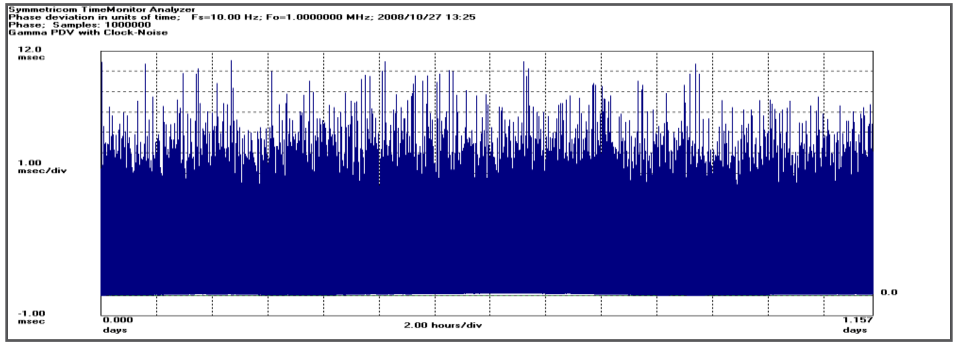
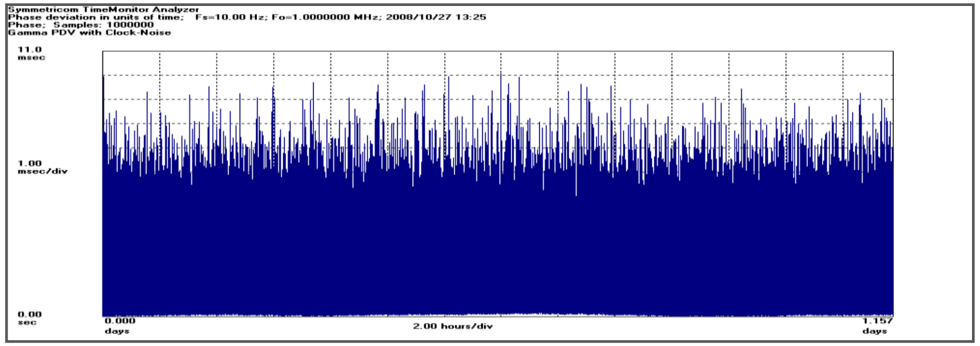
NEED FOR NEW METRICS

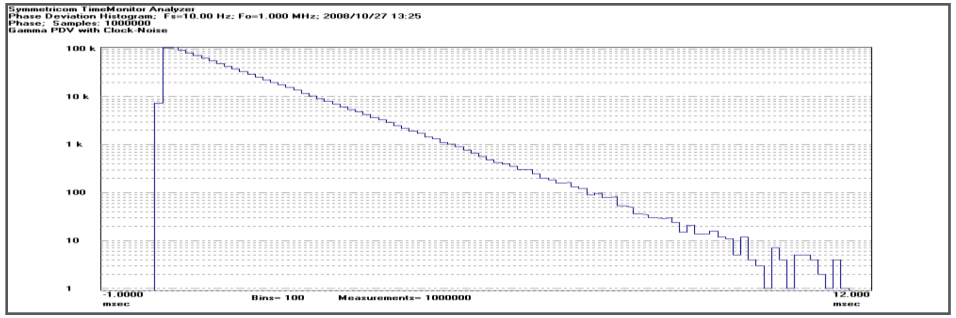
- Traditional IP networks utilized just peak-to-peak “jitter” as the sole time/timing related performance metric (e.g. 95% of delay variation samples <10 ms)
- This is generally not sufficient for the purpose of timing recovery as is seen in the following example.
  - The synthetic PDV sequence has a peak-to-peak measure of approximately 10ms and packet rate of 10Hz
  - The PDV, pdf, and TDEV/minTDEV are shown in the following charts
  - One TDEV mask (ETSI SEC) is shown in the charts to provide a frame of reference
  - Exception: Stable oscillator (e.g. Stratum 2) and only frequency required
- Timing is generally recovered using selected “best” packets; this is not visible in the peak-to-peak measurements
  - Other variations include metrics derived from the distribution of the packet-arrival times (e.g. Mode, median, etc.)
- Suitable metric sets must include those that characterize amplitude distribution (including peak-to-peak) and spectral distribution.

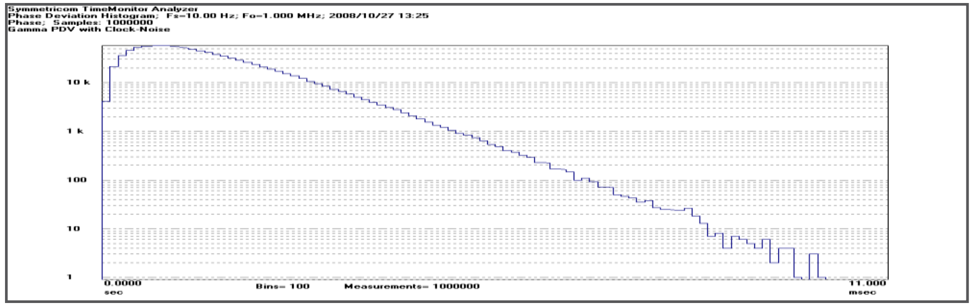
PEAK-TO-PEAK JITTER NOT SUFFICIENT



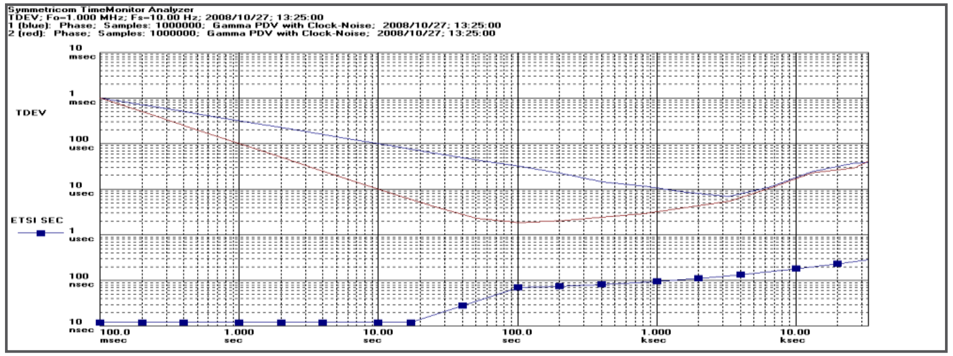


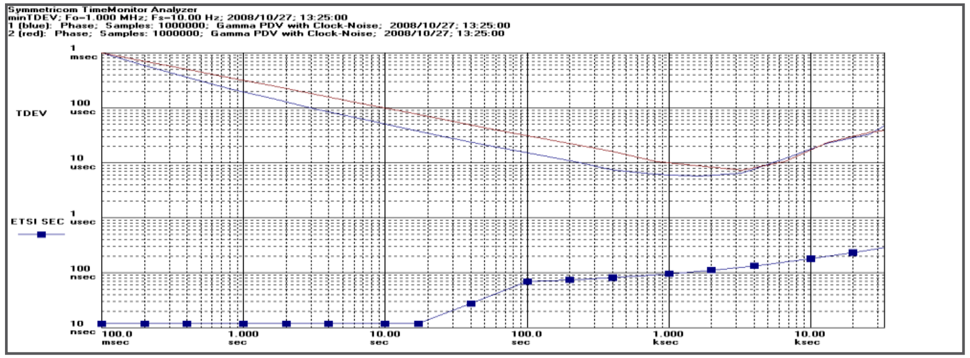
phase





pdf





TDEV and minTDEV

Peak-to-peak jitter = 11.5ms

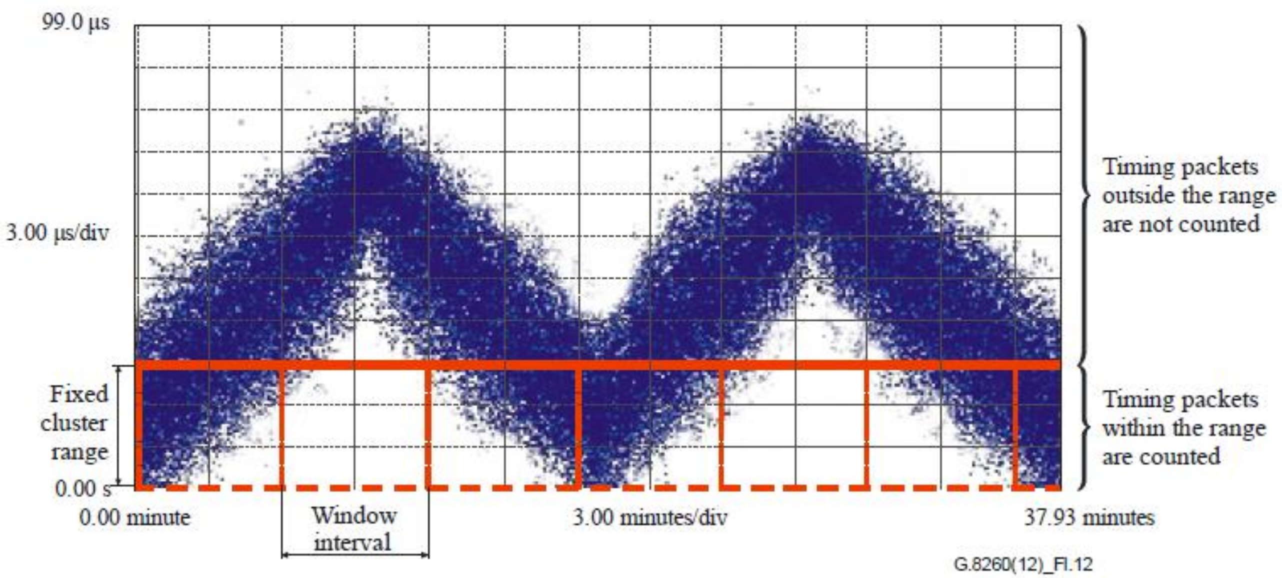
Peak-to-peak jitter = 10ms

PDV METRICS

- Several metrics have been defined by ITU-T:
  - These include minTDEV, MATIE, MAFE, percentileTDEV, bandTDEV, clusterTDEV, FPP, etc.
- minTDEV is analogous to TDEV
  - TDEV utilizes the average over windows
  - minTDEV utilizes the minimum over windows
- MATIE is related to MTIE
  - MTIE computed directly on the time error sequences $\{x_k\}$ or $\{y_k\}$ is not that meaningful because of large “jitter” (PDV)
  - MATIE is computed on the sequence following the pre-filtering (packet-selection) and emulates the low-pass nature of the traditional clock model (bandwidth / time-constant)
- Metrics Studying floor delay packet population
  - **FPP, Floor Packet Percent** (selected for defining network performance objectives for frequency sync)

FLOOR PACKET PERCENTAGE

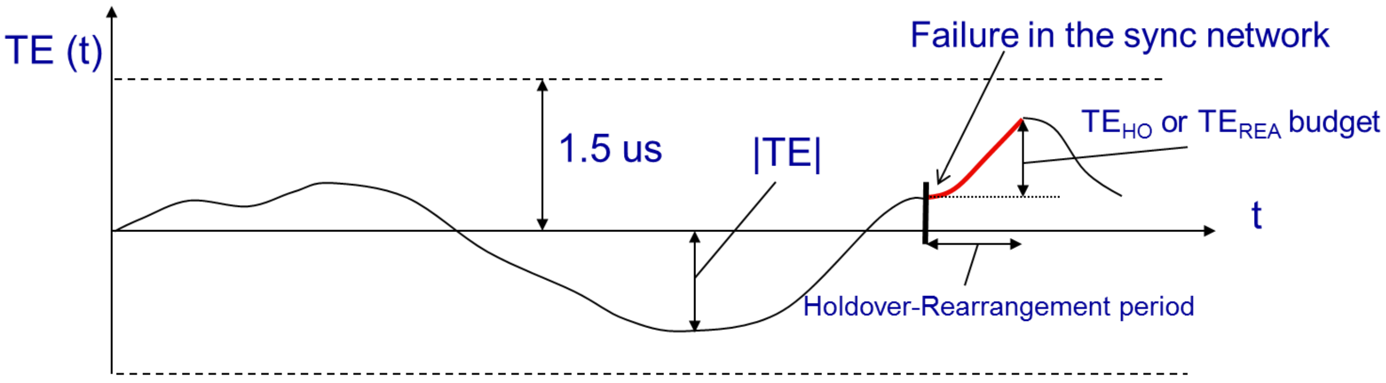
- Family of metrics based on counting amount of packets, observed for any window interval of t seconds within a fixed cluster range starting at the observed floor delay and having a size δ



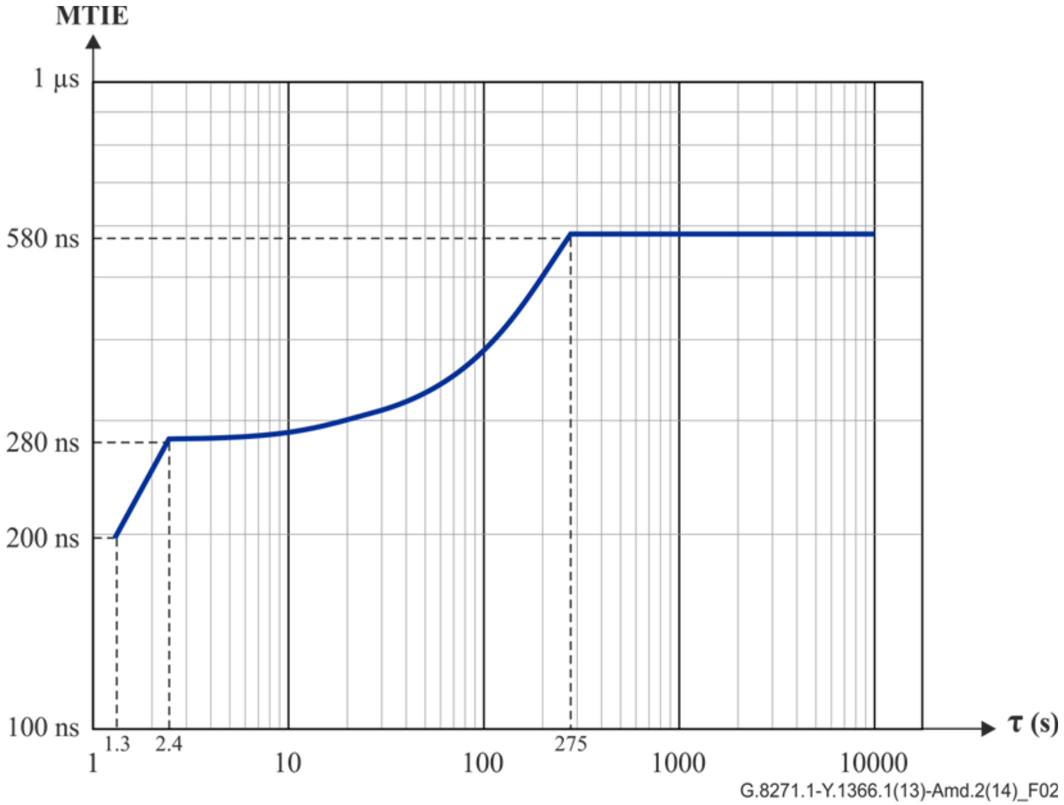
- Floor Packet Percent (FPP) defined in terms of percentage of packets meeting these criteria
- Basis for the G.8261.1 network limits (150 / 75 us)

TIME SYNC PERFORMANCE METRIC: FULL TIMING SUPPORT

- Max abs(TE) for combined **dynamic** and **constant time error**
- MTIE (low frequency) and «peak-to-peak TE amplitude» (high frequency) for dynamic time error

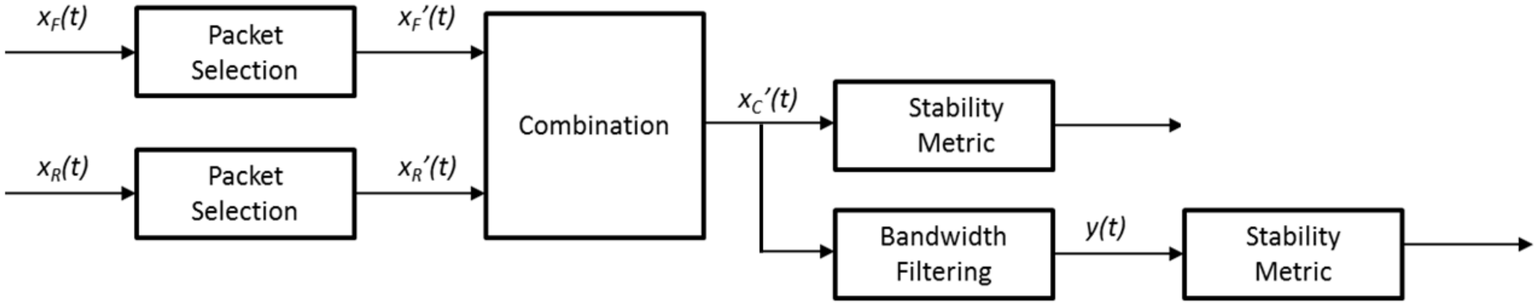


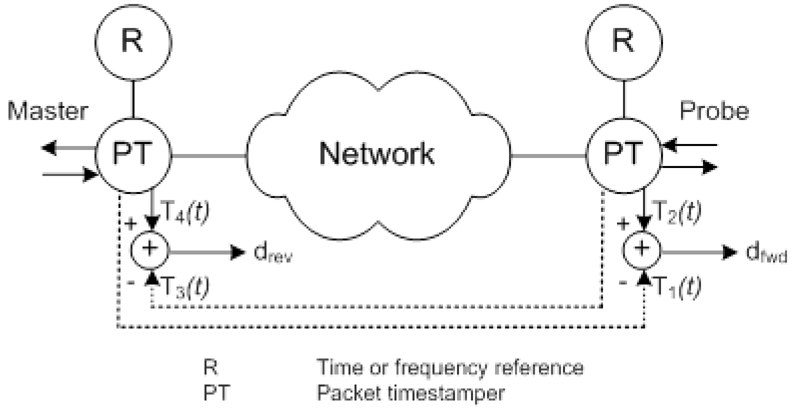
TE_{HO} applicable to the network (End Application continues to be locked to the external reference)
TE_{REA} applicable to the End Application (End Application handles short rearrangement periods)



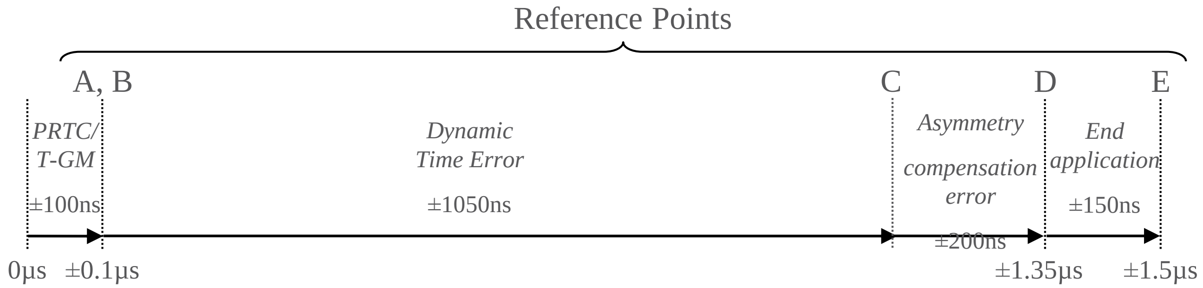
TIME SYNC PERFORMANCE METRIC: PARTIAL TIMING SUPPORT

- Metric agreed : «**Packet selected TE**»
  - Packet Selection criteria ;
    window interval of 200s and a percentage of 0.25% as initial assumptions for high stability clocks
  - Applicable to both «APTS» (Assisted Partial Timing Support) and «PTS»:
    - Peak-to-peak pktSelectedTE for APTS, max |pktSelectedTE| for PTS.





- 2 classes of network limits addressing different end applications cases.
- APTS Network Limit: 1.35µs in terms of maximum absolute time error (at the output of the clock).
- PTS Network Limits: under study
- MTIE mask also needed

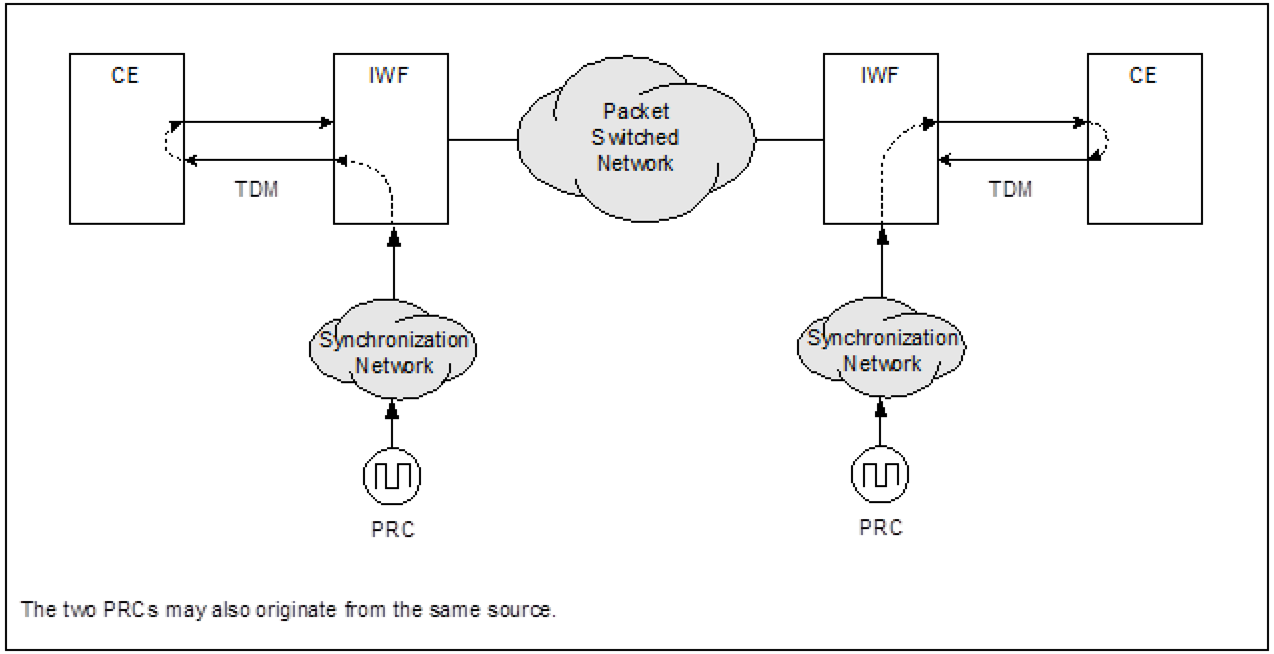


REFERENCES

- Packet Timing in ITU-T: ITU-T G.826x series, G.827x series,
- ITU-T general definitions: G.810, G.8260
- NTP: IETF RFC 5905/6/7/8
- PTP: IEEE 1588-2008
- CES: RFC 5087, RFC 5086, RFC4533, ITU-T Y.1413, ITU-T Y.1453, MEF3, MEF 8

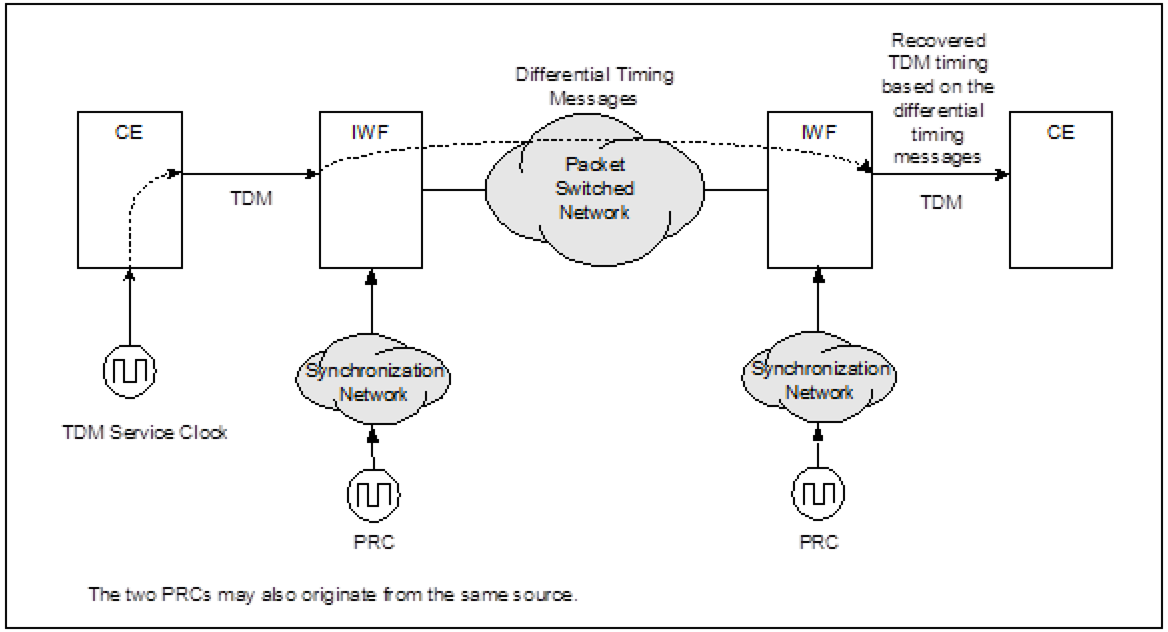
ERICSSON

CIRCUIT EMULATION SYNC SOLUTIONS: PRC AVAILABLE AT THE EDGES OF THE PACKET NETWORK



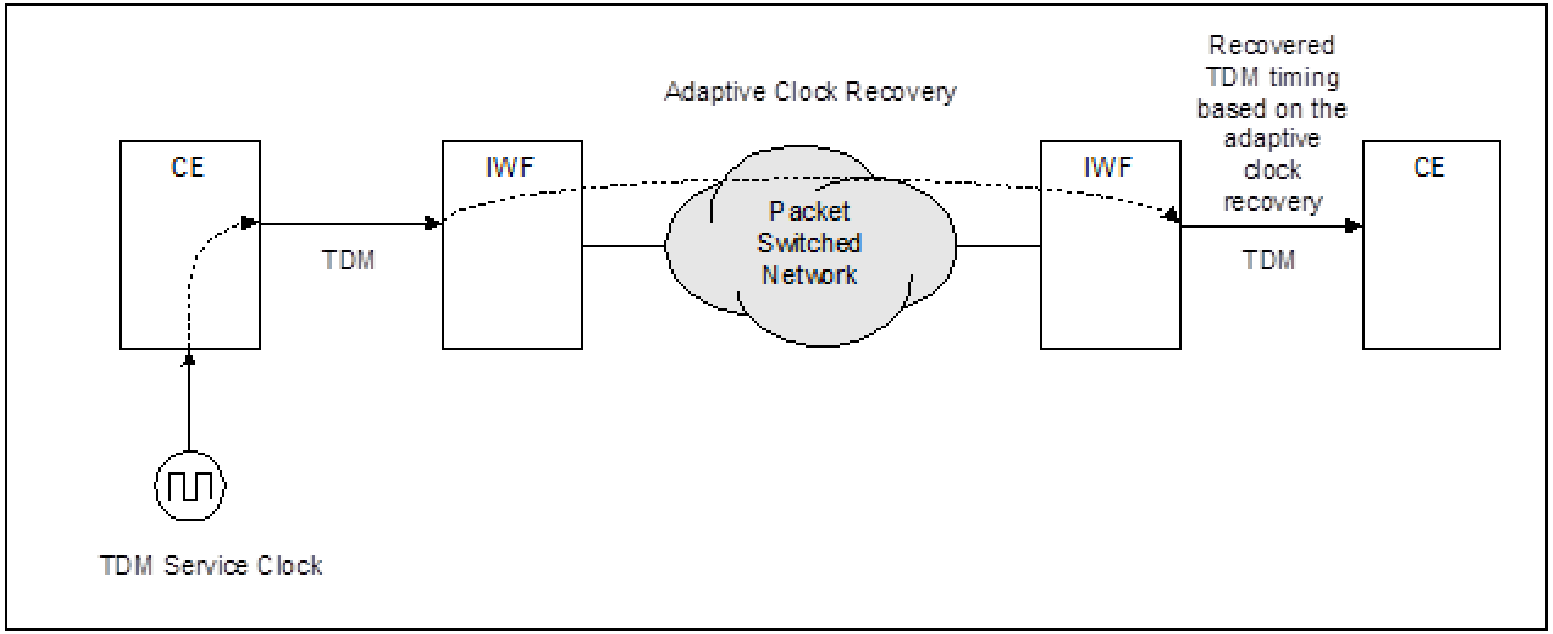
Network Synchronous

Differential



From ITU-T Recc. G.8261

CIRCUIT EMULATION: ADAPTIVE METHODS



From ITU-T Recc. G.8261

- No PRC traceable reference available at the edge of the packet network !
  - Frequency sync recovered based on arrival time of the packets ...

NTP PROTOCOL HEADER AND TIMESTAMP FORMATS

NTP Protocol Header Format (32 bits)

Cryptosum	LI	VN	Mode	Strat	Poll	Prec
	Root Delay					
	Root Dispersion					
	Reference Identifier					
	Reference Timestamp (64)					
	Originate Timestamp (64)					
	Receive Timestamp (64)					
	Transmit Timestamp (64)					
	Extension Field 1 (optional)					
	Extension Field 2… (optional)					
Authenticator (Optional)	Key/Algorithm Identifier					
	Message Hash (64 or 128)					

Authenticator uses DES-CBC or MD5 cryptosum of NTP header plus extension fields (NTPv4)

LI	leap warning indicator
VN	version number (4)
Strat	stratum (0-15)
Poll	poll interval (log2)
Prec	precision (log2)

NTP Timestamp Format (64 bits)

Seconds (32)	Fraction (32)

Value is in seconds and fraction since 0^h 1 January 1900

NTPv4 Extension Field

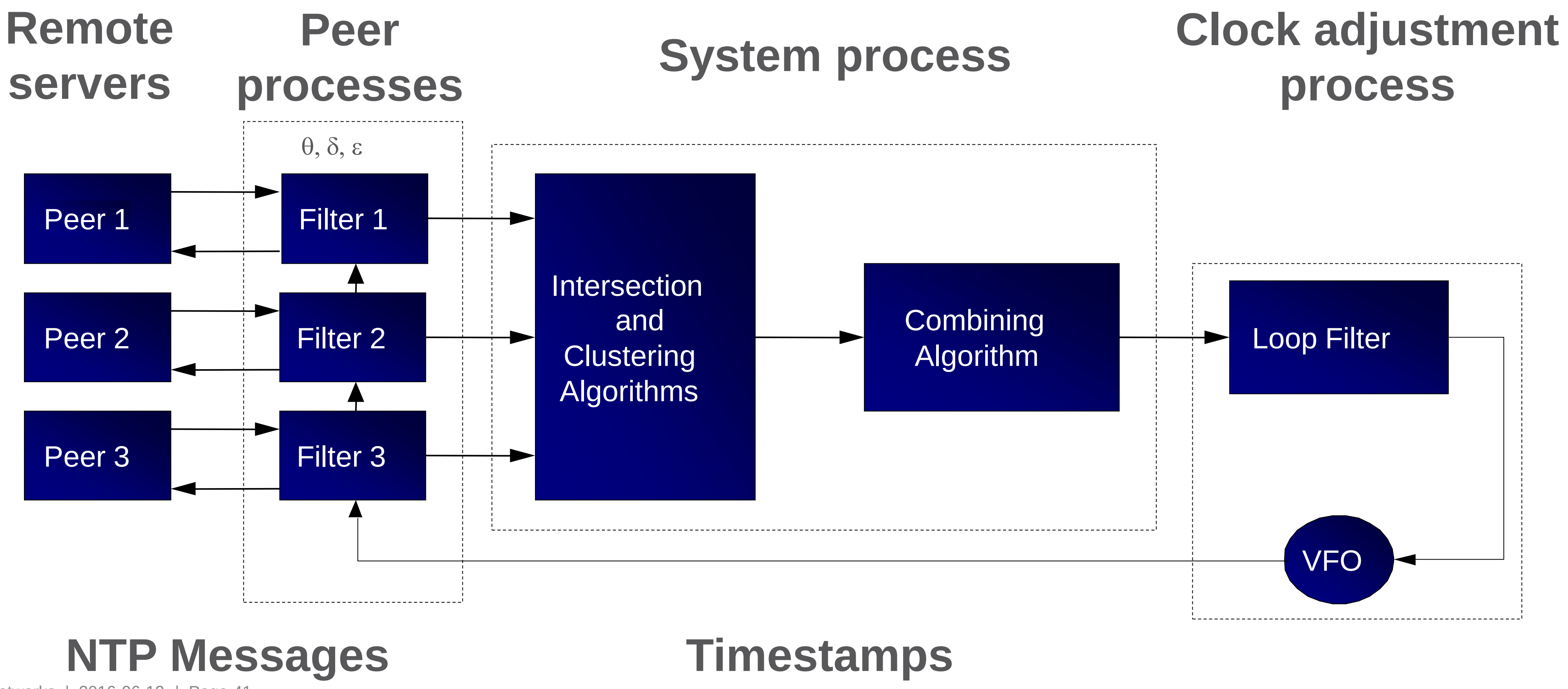
Field Length	Field Type
Extension Field (padded to 32-bit boundary)	

Last field padded to 64-bit boundary

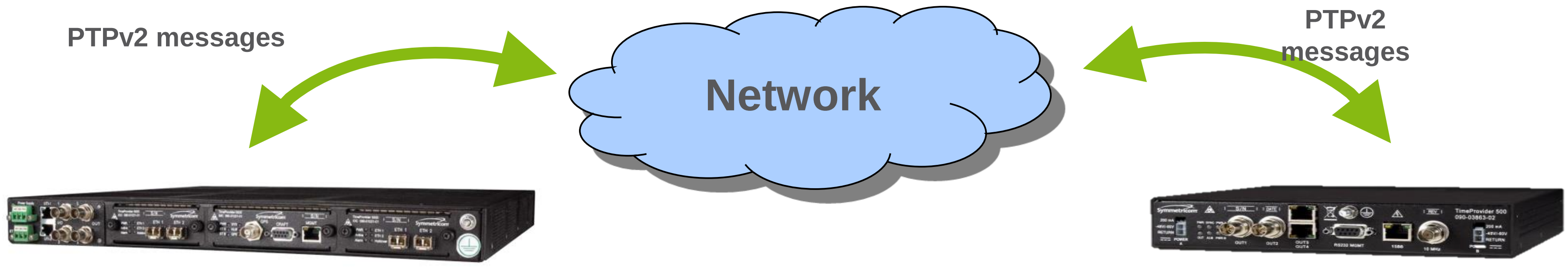
NTP v3 and v4
NTP v4 only
authentication only

NTP INPUTS AND OUTPUTS

Inputs - 3 x sources of equal or higher quality time from peers or servers
Output - Adjusted time available to peers and clients



PTPV2 TIMING MESSAGE TYPES



- The **Grandmaster** (Server) sends the following messages:
- Timing Messages (3 types):
  - **Sync** message
  - **Follow_Up** message (optional)
  - **Delay_Resp**(onse)
- **Announce** message (GM status)
- **Signaling** (2 types)
  - Acknowledge TLV (ACK)
  - Negative Acknowledge TLV (NACK)

- The **Slave** (Client) sends the following messages:
- Timing Messages
  - **Delay_Req**(uest)
- **Signaling** (3 types)
  - Request announce
  - Request sync
  - Request delay_resp(onse)

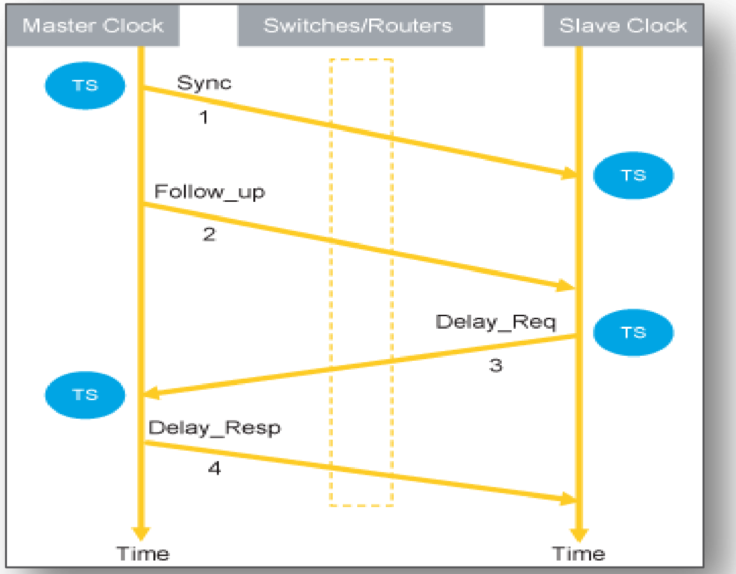
PTP PROTOCOL AND HW TIMESTAMPING

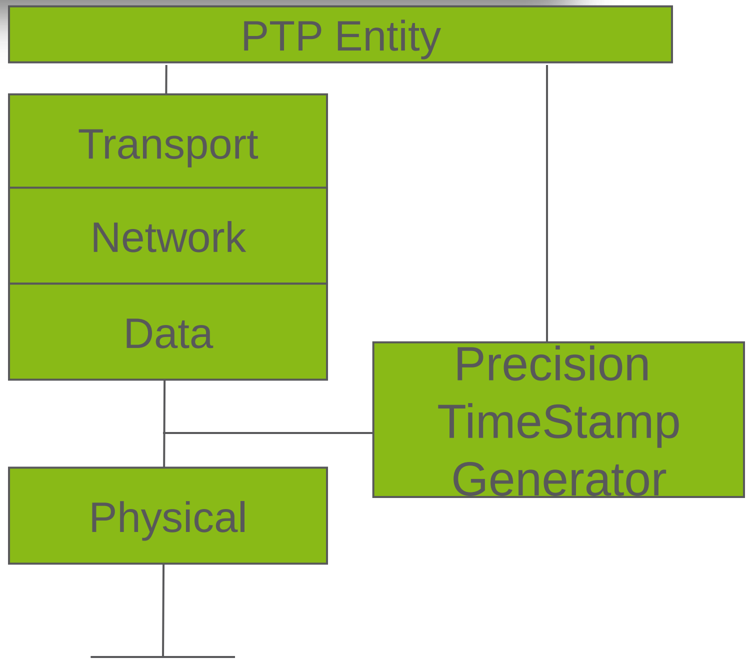
› **Message Exchange Technique**

- Frequent “Sync” messages broadcast between master & slaves, and…
- Delay measurement between slaves and master.

› **Hardware-Assisted Time Stamping**

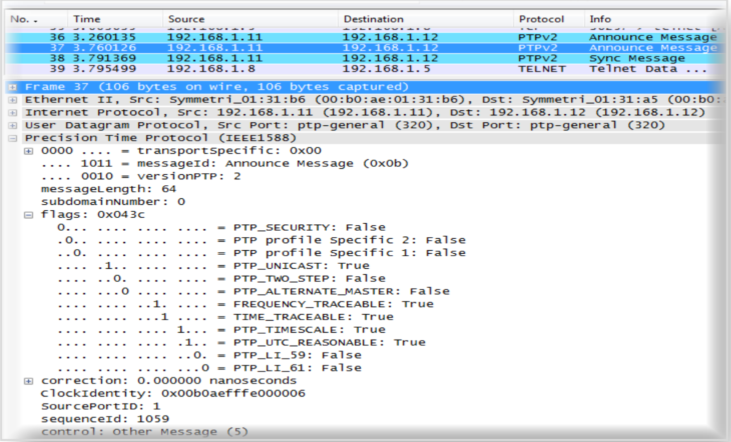
- Time stamp leading edge of IEEE 1588 message as it passes between the PHY and the MAC.
- Removes O/S and stack processing delays.
- Master & Slave use hardware assisted time stamping.





PTPV2 ANNOUNCE MESSAGES

- Announce messages hold information about the status, precision and accuracy of the Grandmaster
  - Changes in values within Announce packets reflect changes in conditions at the GM
- Transmitted to all Slave clocks at regular intervals (1 per second is normal)
  - Slave clocks use information in the Announce message in the Best Master Clock algorithm or to switch GM if
- Holds the following information used by Slave clocks:
  - Leap second information
  - **GM clockClass** – lower values mean a higher class of clock
  - **GM Accuracy** – ranges from 100ns to Unknown
  - **GM TimeSource** – GPS, Arbitrary, Unknown
  - **Time Traceable Flag** – True/False
  - **Frequency Tracable Flag** – True/False
  - **PTP TimeScale Flag** – True/False



- Other information held also: Leap second indicator, Two-step clock mode, etc.

PACKET DELAY VARIATION (PDV), CONT.

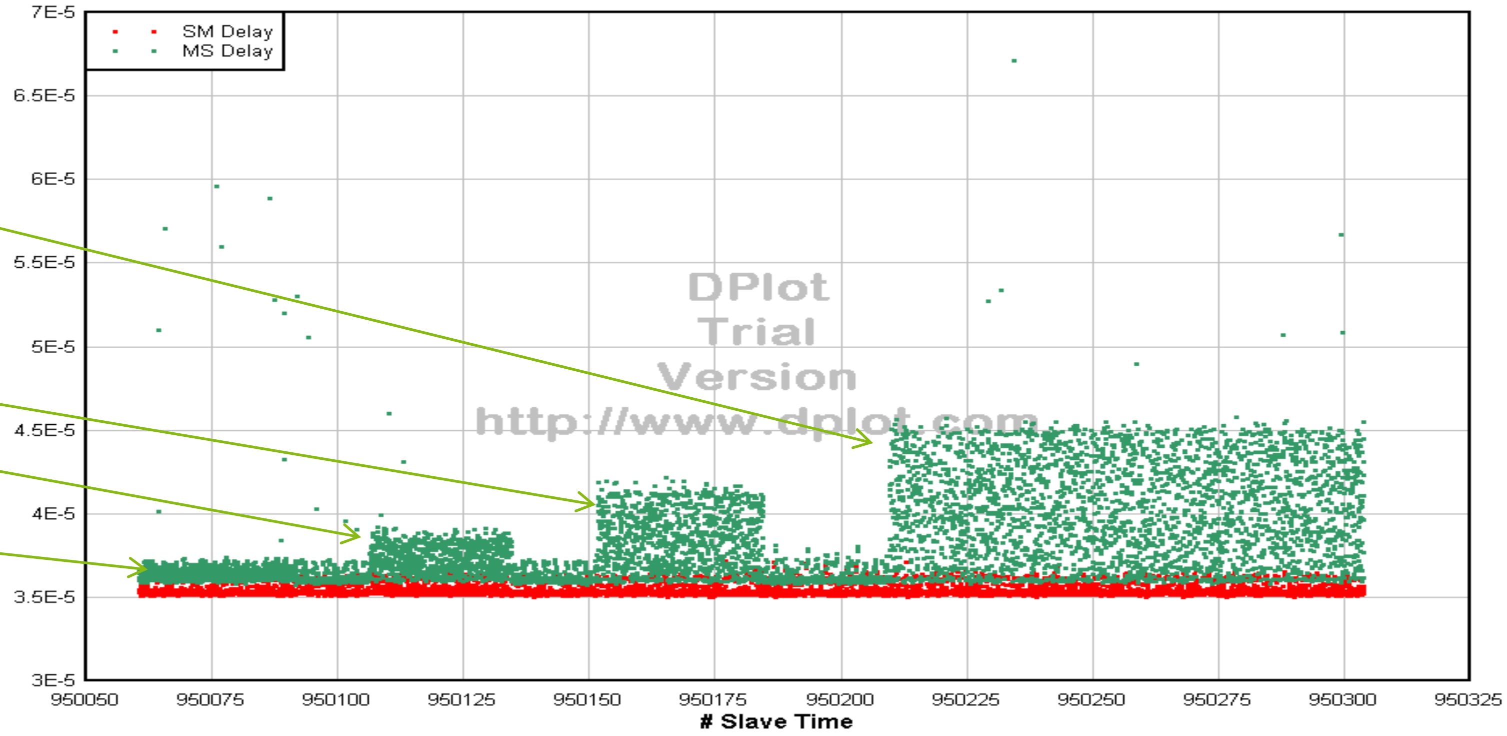
Equipment implementation specifics
e.g. the Delay variation through a single piece of equipment, with packet sizes

1024byte

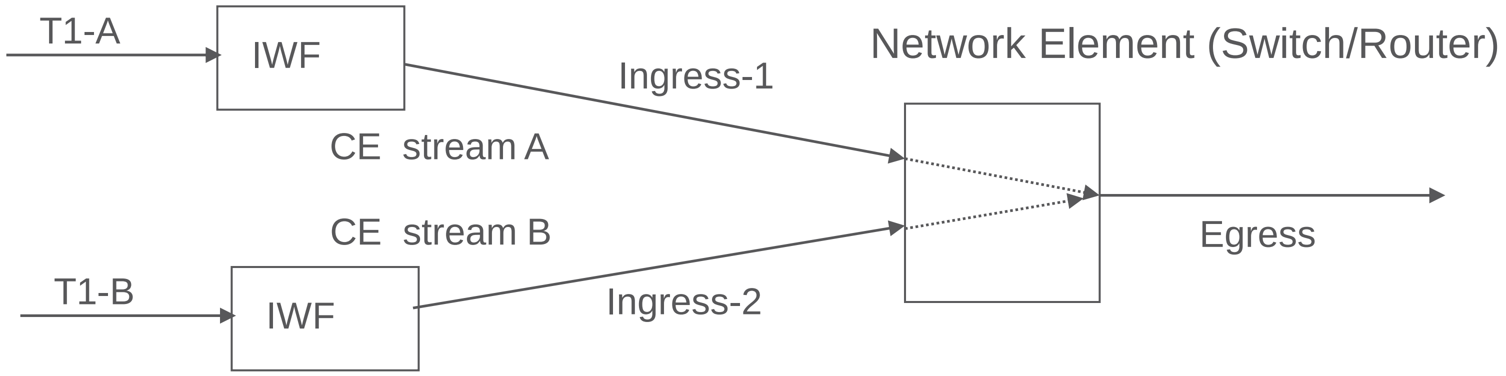
576 byte

256 byte

64 byte

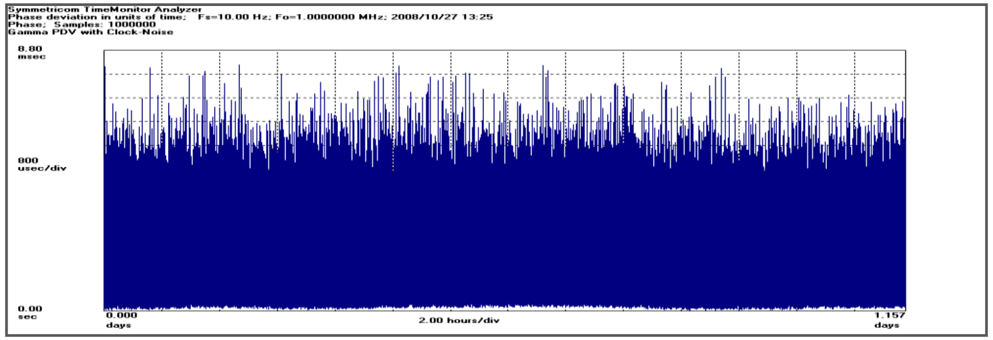


INTERACTION OF CBR STREAMS

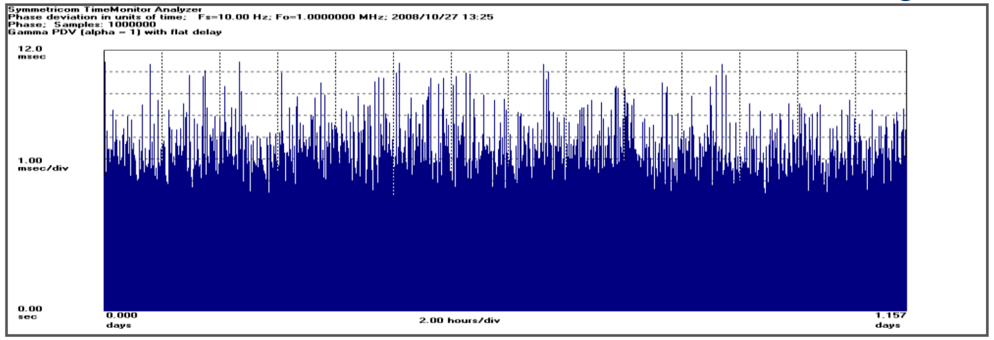


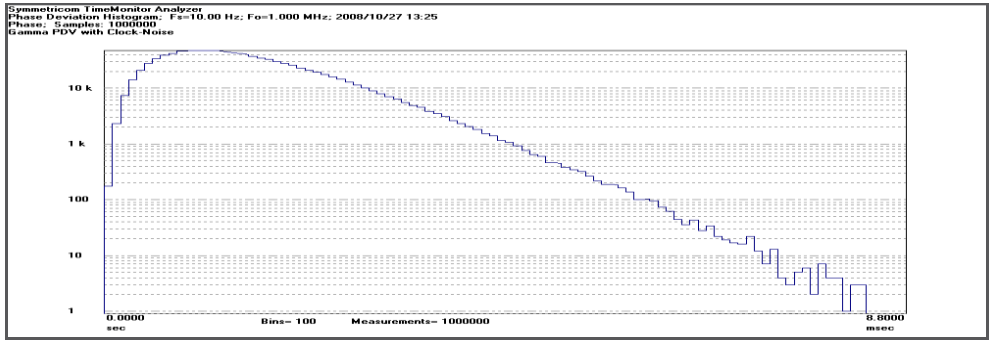
- Assumptions:
  - Streams A and B represent Circuit Emulation of T1 / E1-A and T1/ E1-B
  - Each packet is same size and the packet rates are nominally equal
  - The bandwidth of the egress is high (~ 1 Gbps) (NO bandwidth starvation). Each packet occupies ~ 2 μsec in the egress stream
- Stream A will experience a (variable) delay if it arrives when a stream B packet is being transmitted and viz.

PEAK-TO-PEAK JITTER NOT SUFFICIENT



phase





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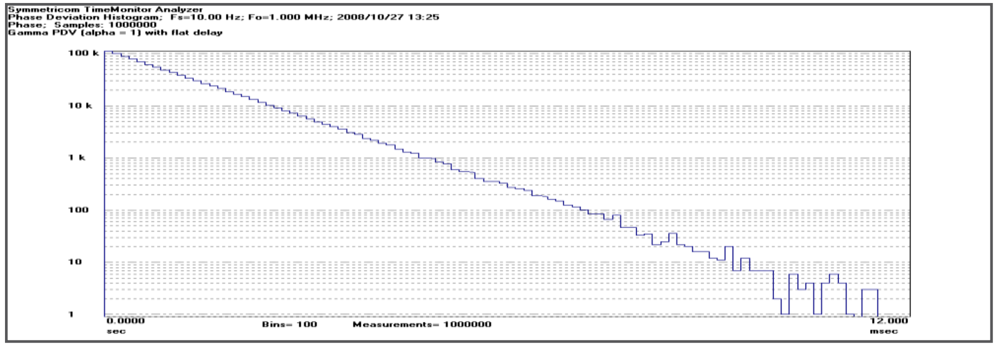
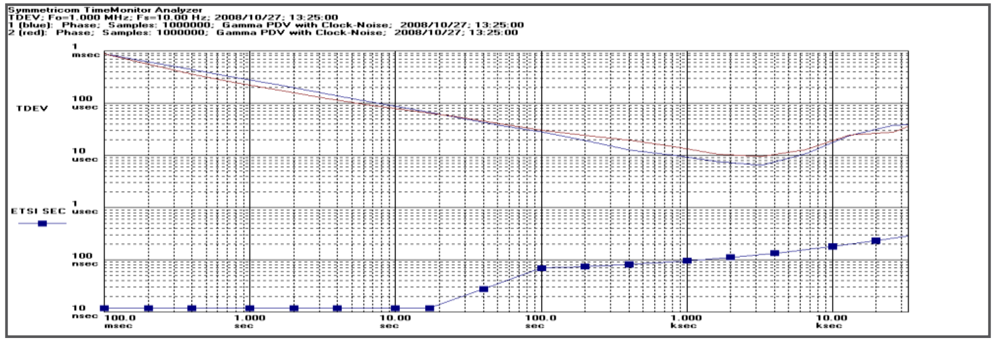
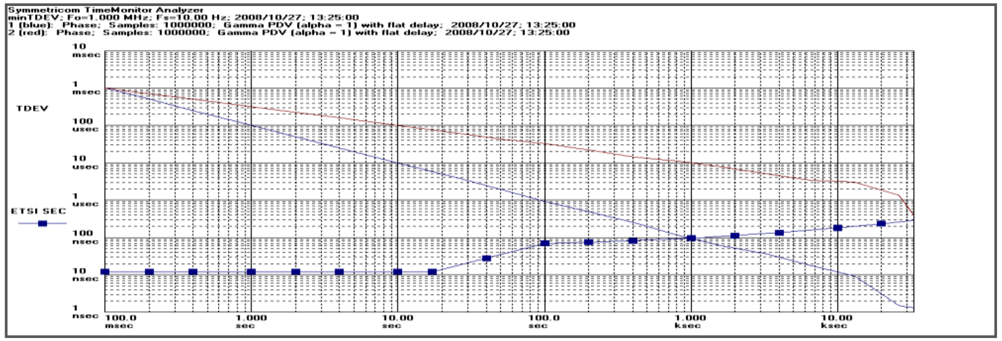




TDEV and minTDEV

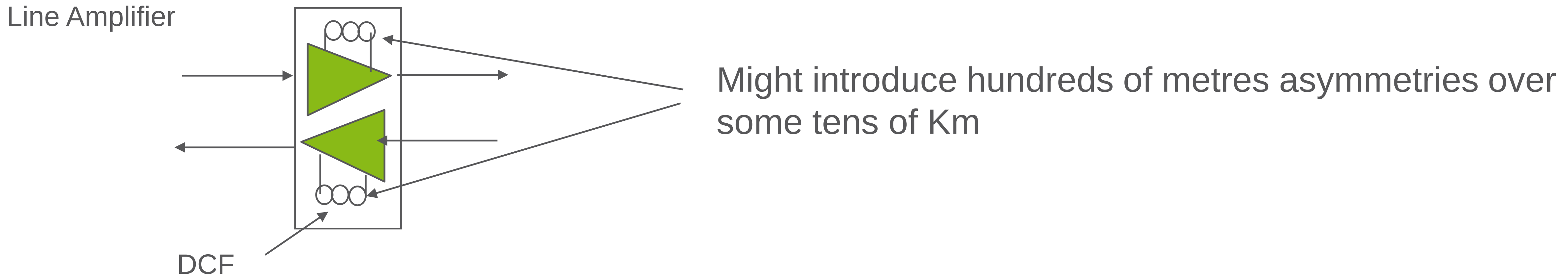


Peak-to-peak jitter = 8.3ms

Peak-to-peak jitter = 11.5ms

DIFFERENT FIBER LENGTH AND DCF

- Fiber length asymmetry is one major issue
  - About 2.5ns of inaccuracy per meter of asymmetry (related to group delay, about 5 ns/m)
- A line amplifier may embed a Dispersion Compensating Fiber (DCF) to compensate for the chromatic dispersion of the different wavelengths
  - the length of the fiber within DCF modules to compensate the same length of line fiber may vary significantly



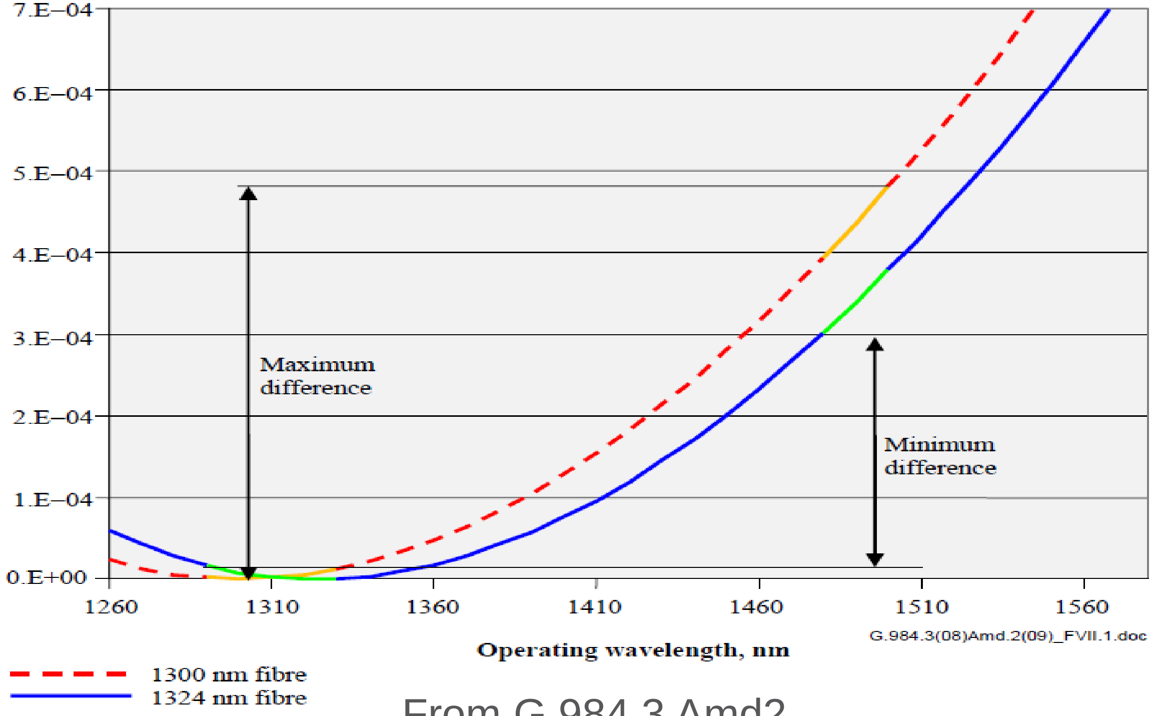
USE OF DIFFERENT WAVELENGTHS

- Group Delay depends on the wavelength and different wavelength are used on the forward and reverse path
  - −V = c/n (c= speed of light, n = group refractive index, depends on λ)
- $A = d_f – d_r = L * (n_r – n_f)/c$,
  - −d_f and d_r are the forward and reverse tra

    the related refractive indexes

Example:
λ_r = 1529.94 nm; n_r / c= 2000 ps/Km
λ_f = 1611.79 nm; n_f / c = 3700 ps/Km
L= 50 Km
A= 1700 x 50 ps = 85 ns

Refractive Index difference



From G.984.3 Amd2