Fundamentals of Precision Time Protocol

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Abstract

This session will provide a general background on IEEE 1588 Precision Time Protocol (PTP), how it works, some basic terminology, and its main uses in the market. There will be a discussion on PTP implementations (with a primary emphasis on Industrial products). The session will also touch on other related timing protocols and future enhancements to PTP.

Objectives

Converse About PTP Basics…

Understand the different Time Protocols

Understand the various PTP Profiles and Standards

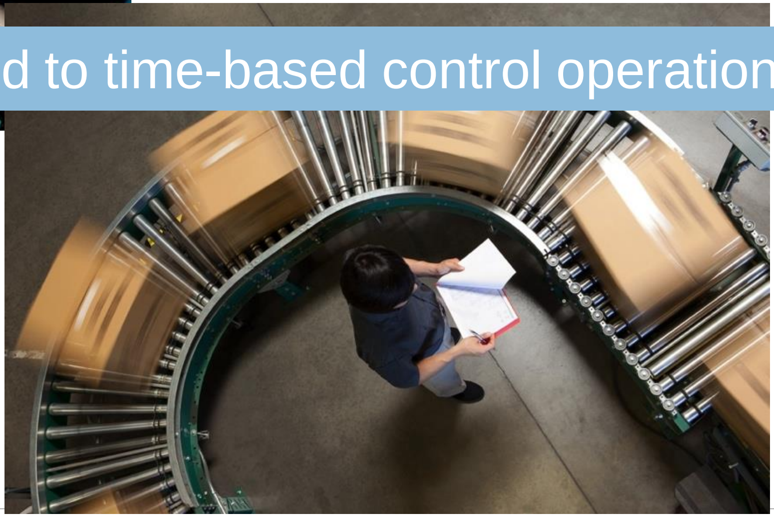
Understand how PTP relates to Controls Engineering

ODVA 2015
INDUSTRY CONFERENCE AND 17TH ANNUAL MEETING
ODVA'S 20TH ANNIVERSARY 1995-2015

"Timing is Everything"

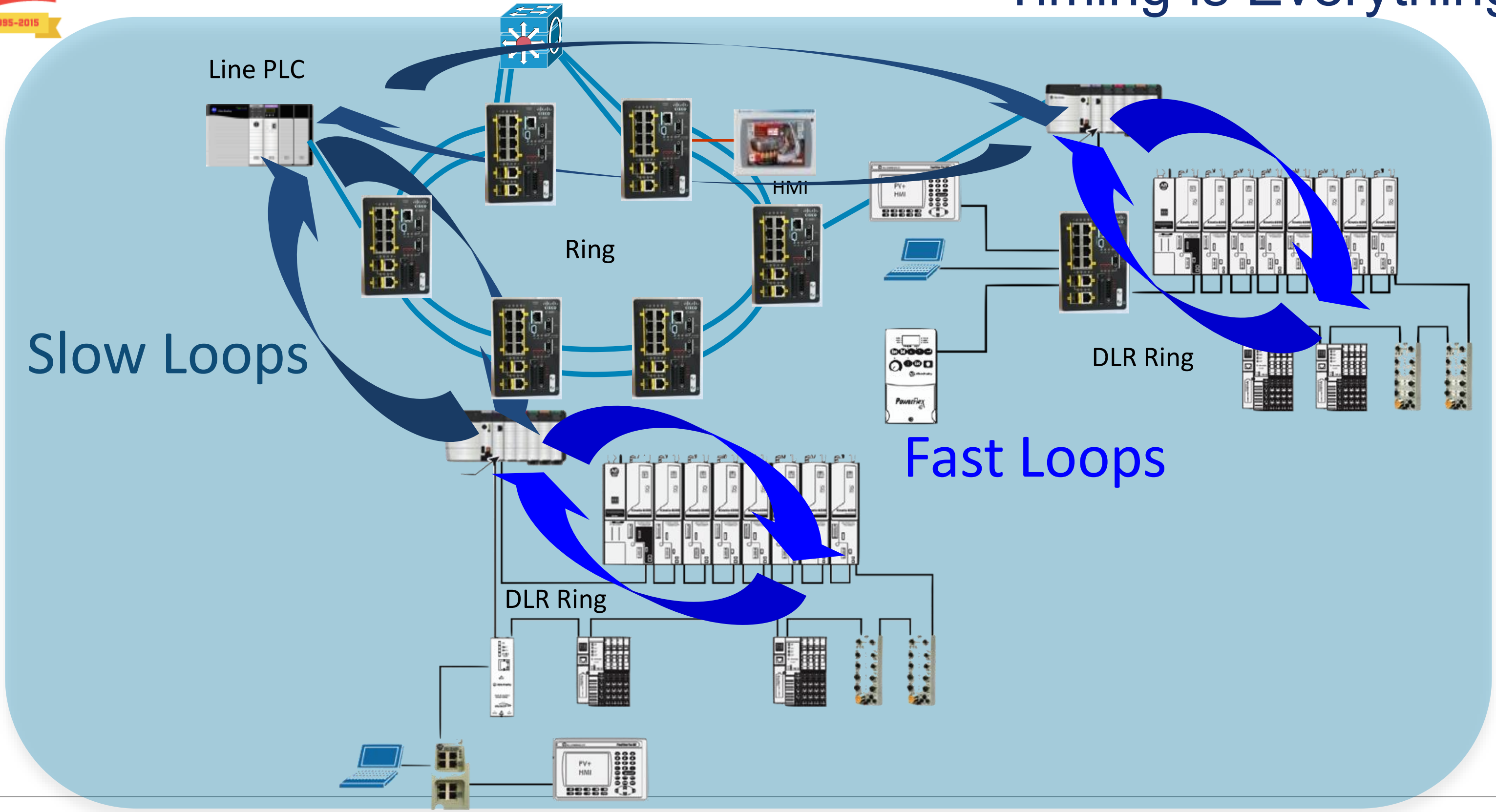
Motion Control

Load sharing of robots



Scan-based to time-based control operation

"Timing is Everything"



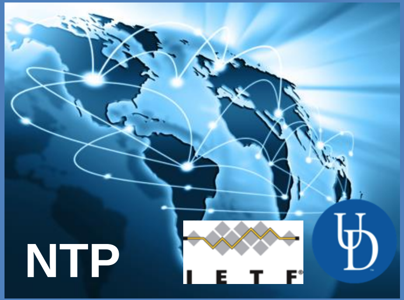
Various Time Distribution Protocols

One Way Time Transfer

IRIG

Range Commanders Council

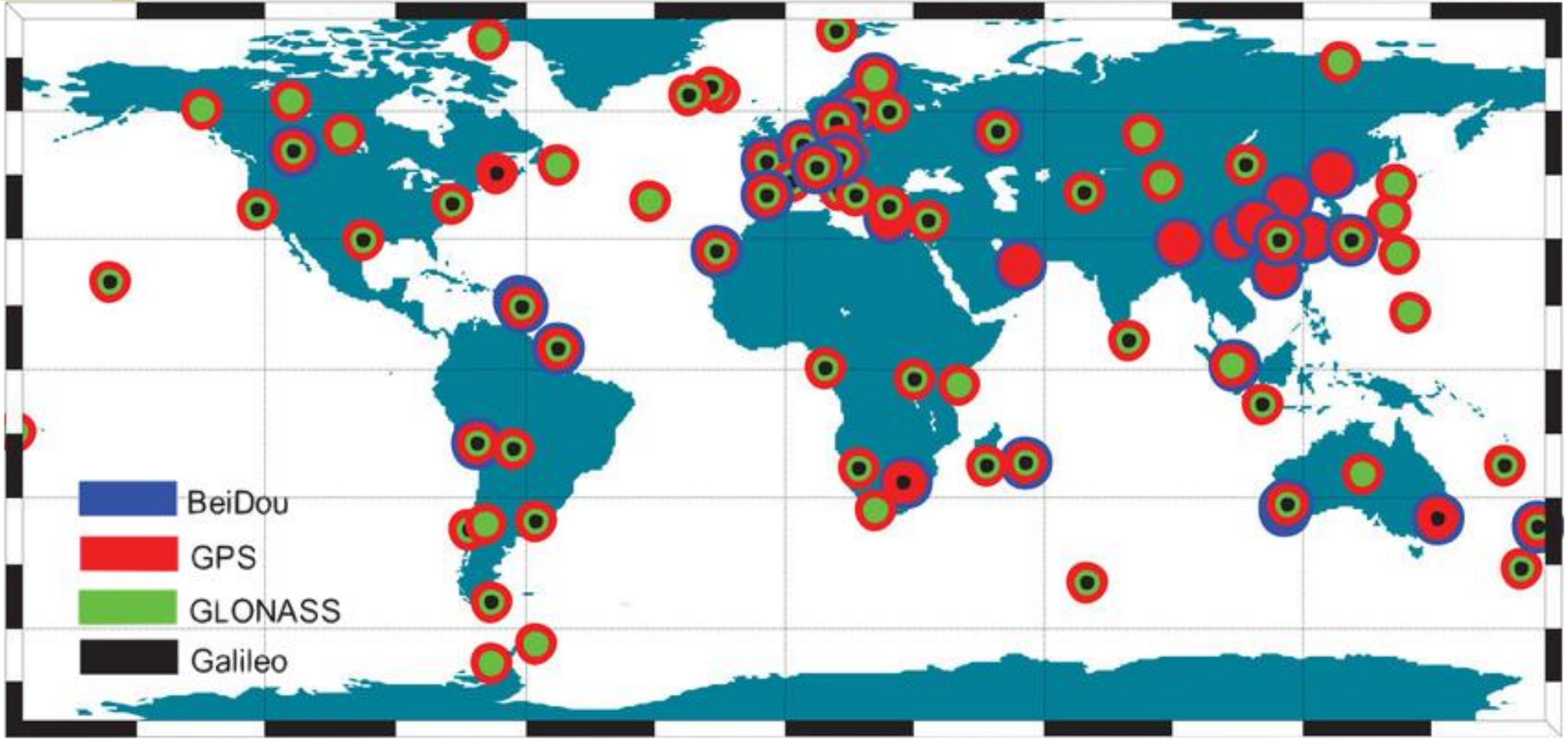
Two Way Time Transfer



PTP/1588

IEEE

GNSS – Systems Around the World



Why (and Why Not) GNSS…

Examples: GPS, GLONASS, COMPASS/BeiDou-2, Galileo, …

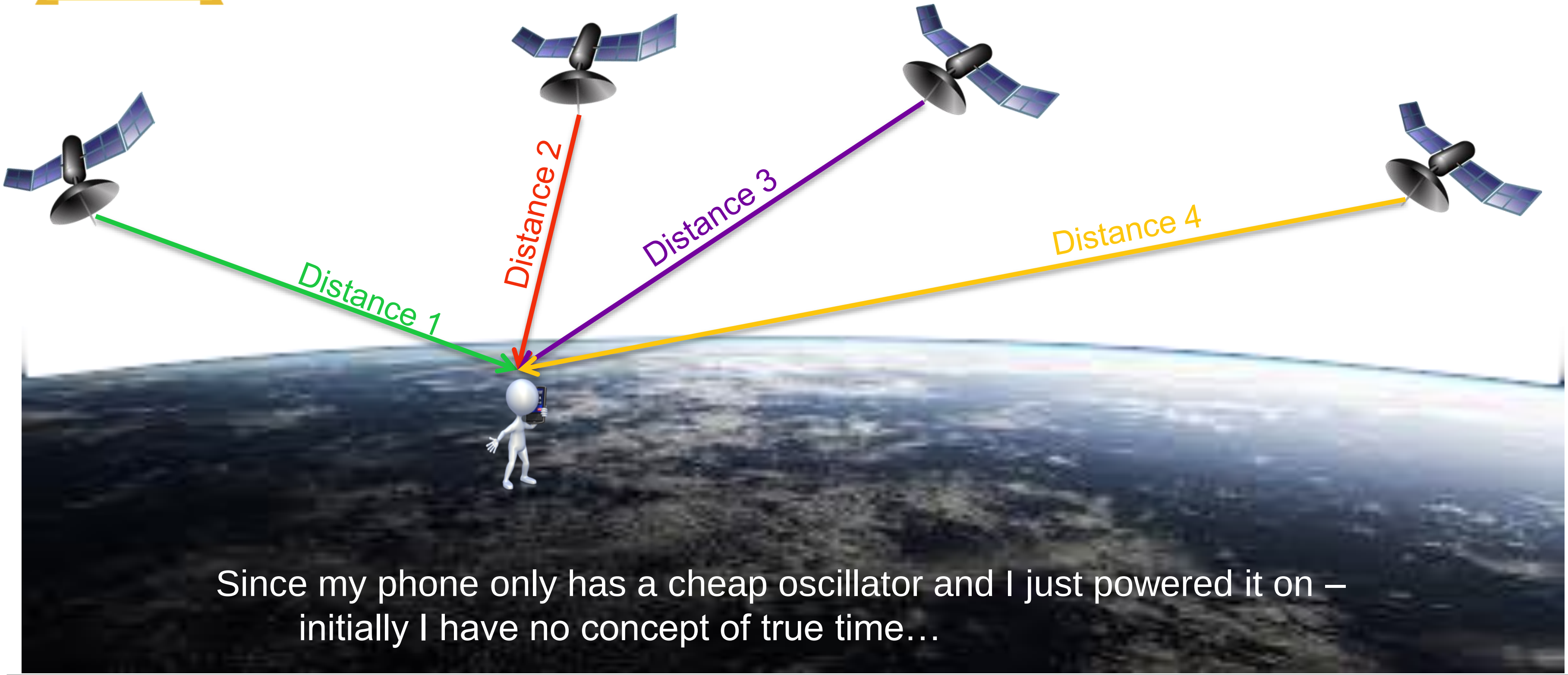
- ✓ Nearly globally available
- ✓ Traceable to UTC

- ✗ Reliability (weak satellite signal)
- ✗ Not available indoor (or urban canyons)
- ✗ Cost of Equipment

- ◆ Government Requirements for Backup

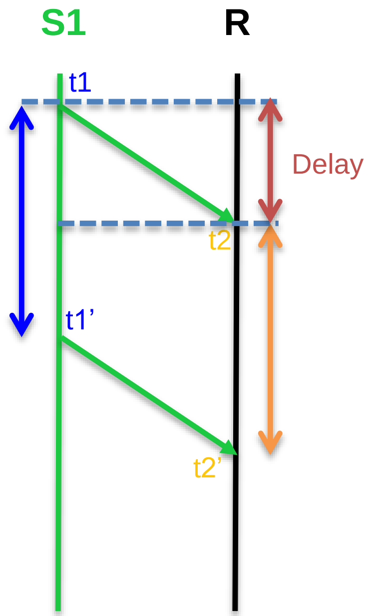
One Way Time Transfer Basics

One-Way Time Transfer (OWTT) Basics



Steps to GPS Time

1. Frequency Lock to Satellite 1



To Frequency Lock – only t1 & t2 timestamps are needed

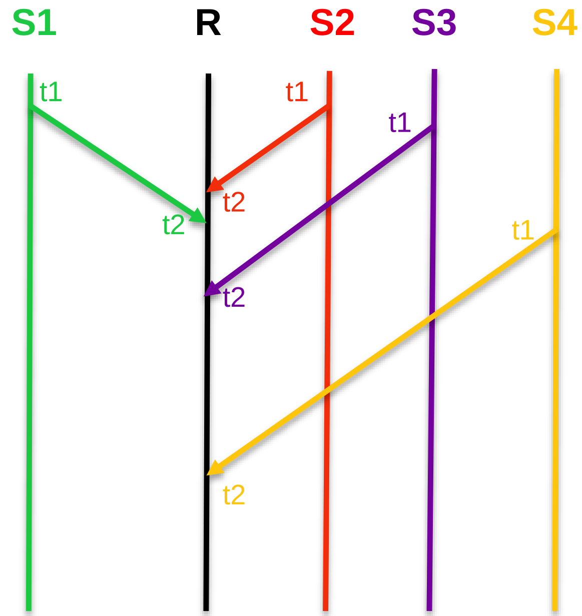
$$FFO = ((t_2' - t_2) - (t_1' - t_1)) / (t_1' - t_1)$$

Continually adjusting your frequency (yellow) until it matches GPS (blue)

This gets your cheap Cell Phone oscillator locked to a stable GPS frequency…

This will allow you to more accurately measure time differences (up next)…

Also note: the Delay here is constant – speed of light through atmosphere



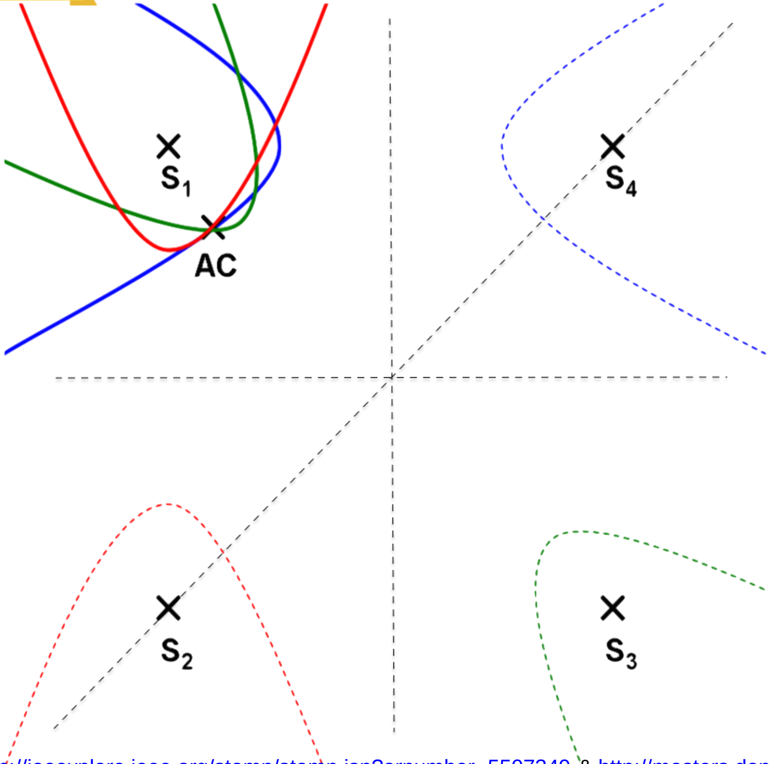
2. Find Time Differences of Arrival (TDOAs)

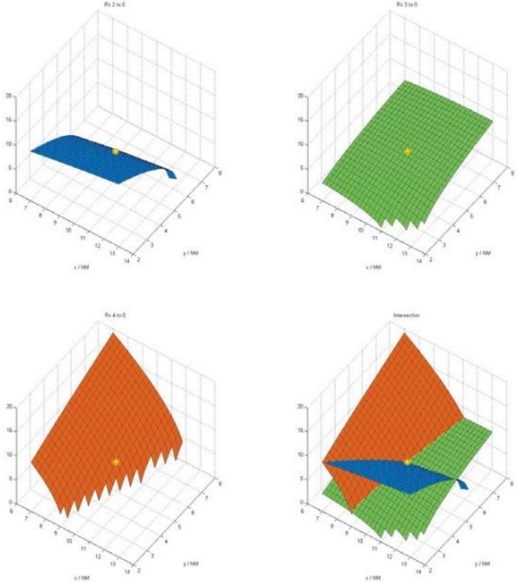
TDOA S1 – S2 = t2 – t2
TDOA S1 – S3 = t2 – t2
TDOA S1 – S4 = t2 – t2

These differences are Hyperboloids…

Note: angles on the arrows are the same as the delays through the atmosphere are the same

Multilateration – Overlapping Hyperboloids





It takes the intersection of 3 of the Hyperboloids to narrow it to a single point

Source: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5507349 & http://masters.donntu.org/2014/frt/gontsa/diss/indexe.htm

Two Way Time Transfer Basics

PTP v2 messages and transmission

A set of event messages providing significant instances and consisting of:

- Sync
- Delay_Req
- Pdelay_Req
- Pdelay_Resp

A set of general messages consisting of:

- Follow_Up
- Delay_Resp
- Pdelay_Resp_Follow_Up
- Announce
- Signaling
- Management

- Mappings: L2 Ethernet, IPv4, IPv6 (others possible)
- Transmission modes: either unicast or multicast (can be mixed)
- Variable rate and timeout values
- Various TLVs and flexible TLV extensions

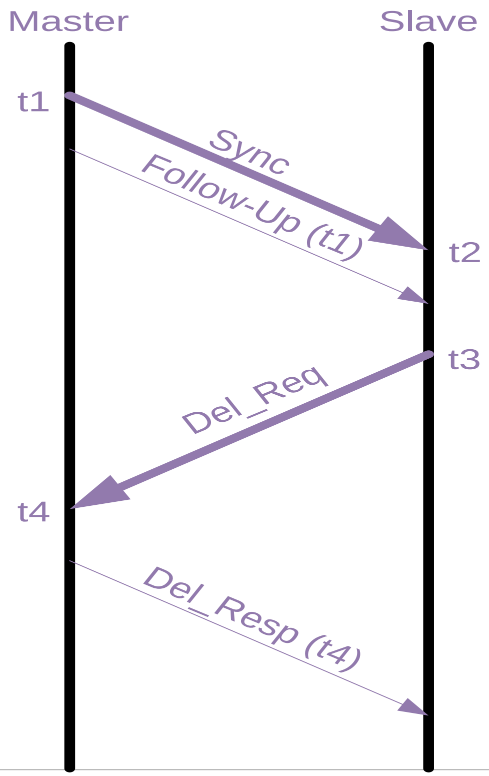
Basic Message Flow – PTP (TWTT)

Event Messages:

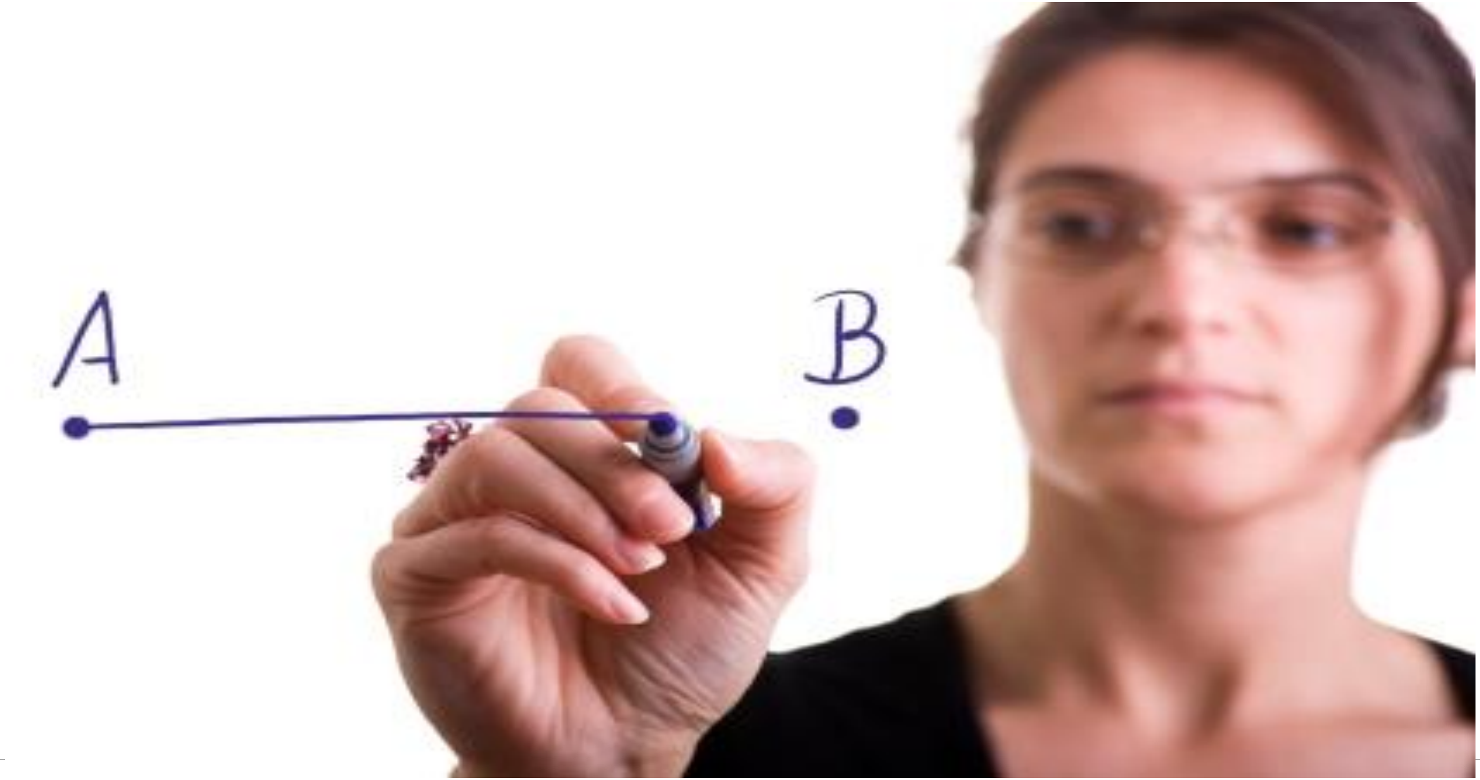
- Sync
- Del_Req
- Pdel_Req
- Pdel_Resp

General Messages:

- Follow_Up
- Announce
- Del_Resp
- Pdel_Resp_FU
- Management
- Signaling



How do we get there?



First – you Synchronize (or "Syntonize")

1. Frequency Lock to GMC

To Frequency Lock – only t1 & t2 timestamps are needed

FFO = $((t_2' - t_2)-(t_1' - t_1))/(t_1' - t_1)$

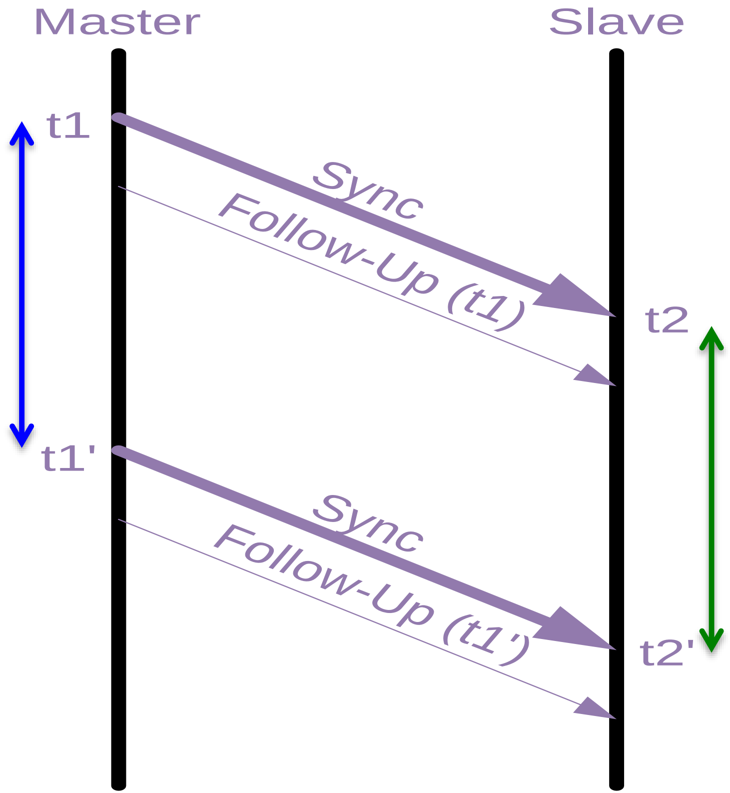
Think of a counter on each system.

From t1 to t1' the Master uses its clock to Count the time…

From t2 to t2' the Slave uses it clock to Count the time…

The difference in the number of counts is how different the two clocks are.

(Assuming the Delays are the same)



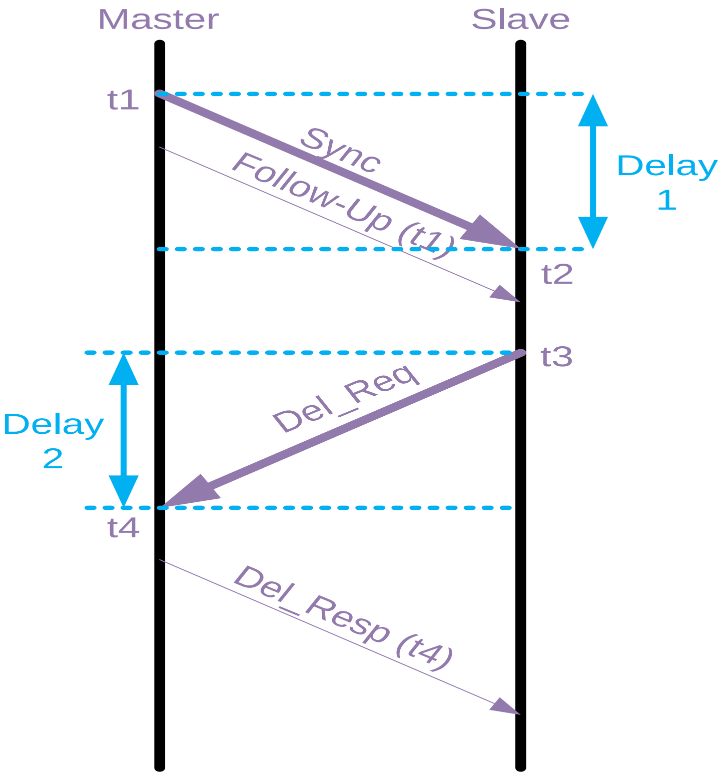
Fractional Frequency Offset (FFO) = diff in frequency from Master to Slave

Next – you Time (Phase) Align

2. Time Align

To Time Align you need t3 and t4 timestamps

Once you are Frequency Locked, you can Calculate the Delay and Offset from the Master



Calculating Delay

$$Delay = ((t_2 - t_1)+(t_4 - t_3))/2$$
$$= (Delay1+Delay2)/2$$

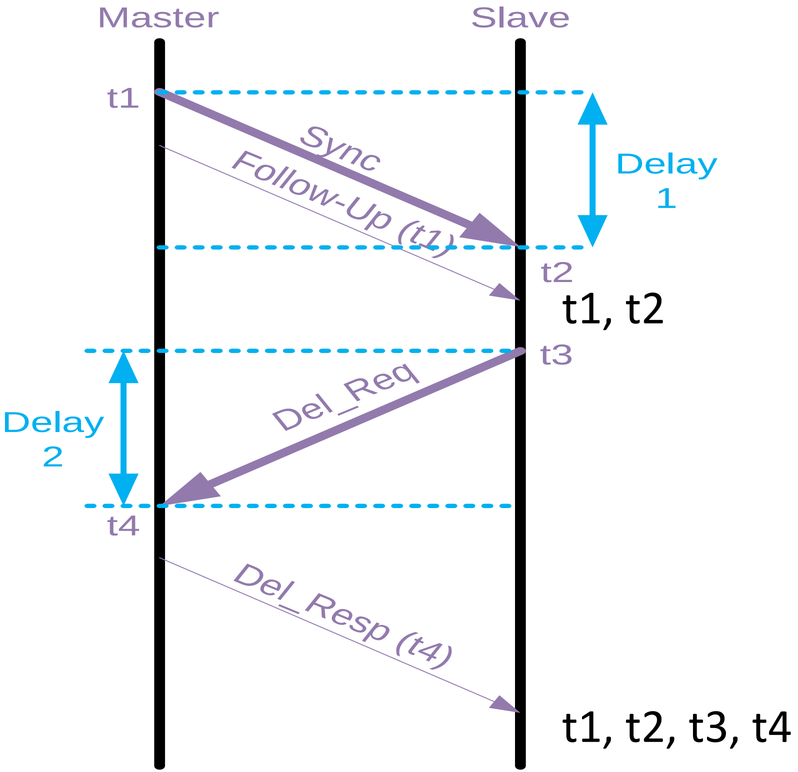
Delay is really an Average

An **assumption** is made:
Delay 1 = Delay 2

Assumption is usually **wrong**
(to some degree)

Protocol Mechanisms can correct
for **known** Asymmetry

Asymmetry cannot be detected



Calculating Time Offset

$$\text{Delay} = ((t_2 - t_1) + (t_4 - t_3))/2$$
$$= (\text{Delay1} + \text{Delay2})/2$$

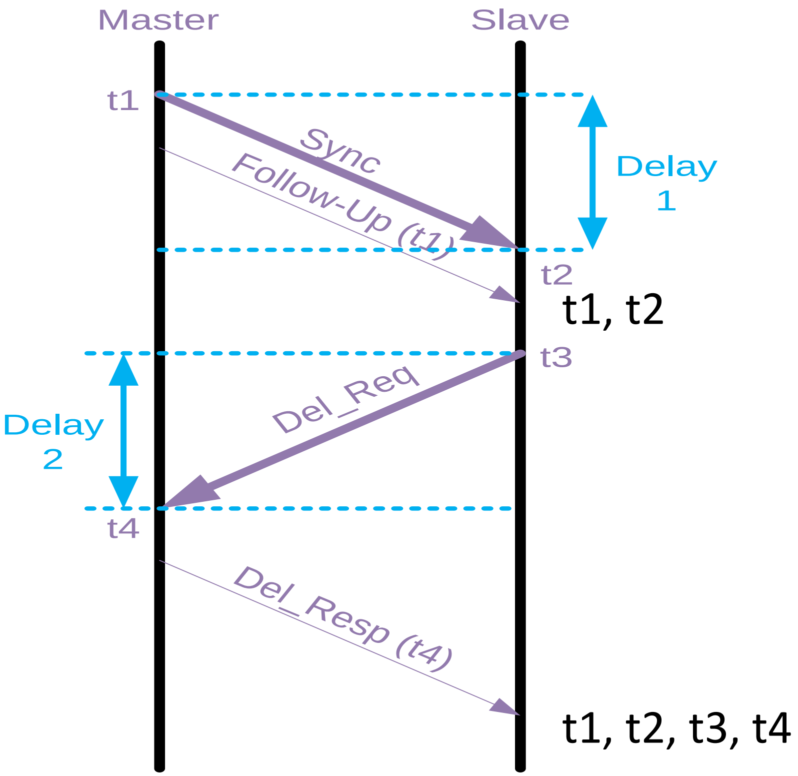
$$\text{Offset} = ((t_2 - t_1) - (t_4 - t_3))/2$$
$$= (\text{Delay1} - \text{Delay2})/2$$

or

= Master Time – Slave Time – Delay

In other words:

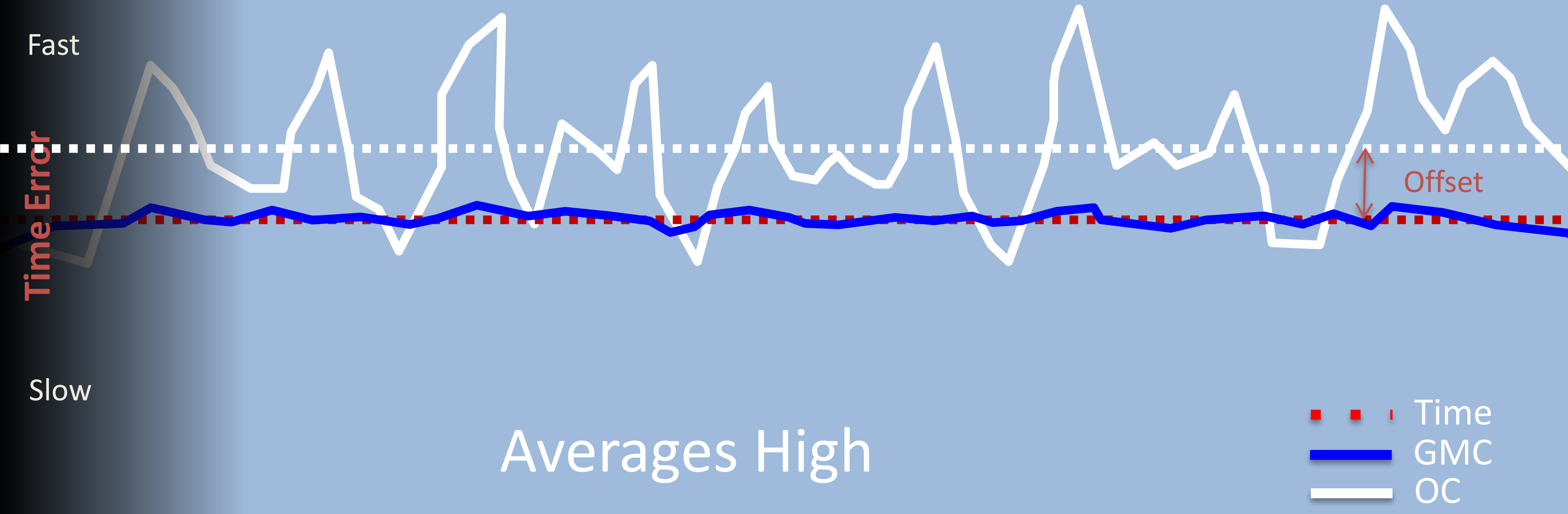
If you are Frequency Locked and you assume Delay1 = Delay2, then any difference is due to error in Time.



Visualizing Time Error

Averages to Zero

Visualizing Time Error



Real World Problems

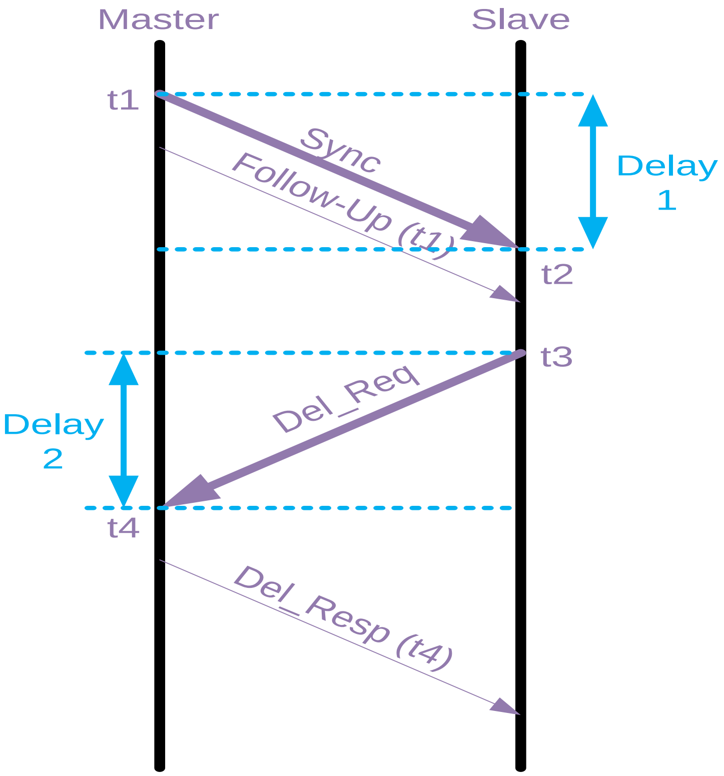
Assumptions we made:

1. Symmetrical Master/Slave & Slave/Master
2. Same delay each time

In the Real World – both are not true
to varying degrees…

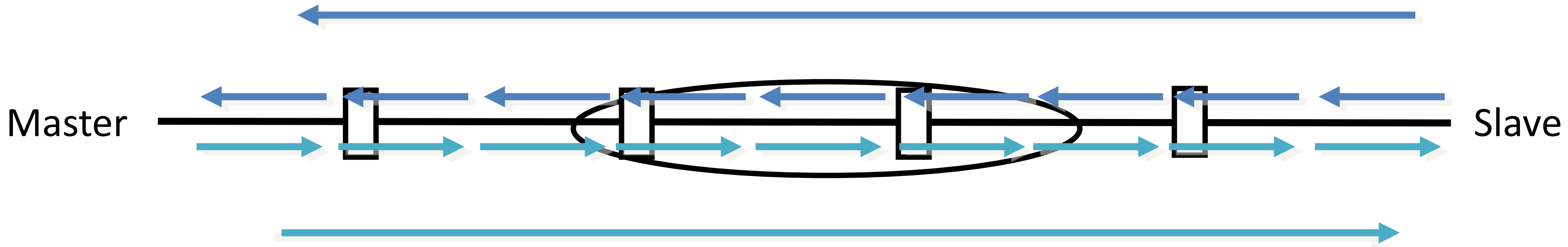
The Two Biggest Problems:

1. Asymmetry
2. Packet Delay Variation (PDV)



Asymmetry

- Forward and backward delays are not identical.
- Every Node and Link in the network can introduce asymmetry.



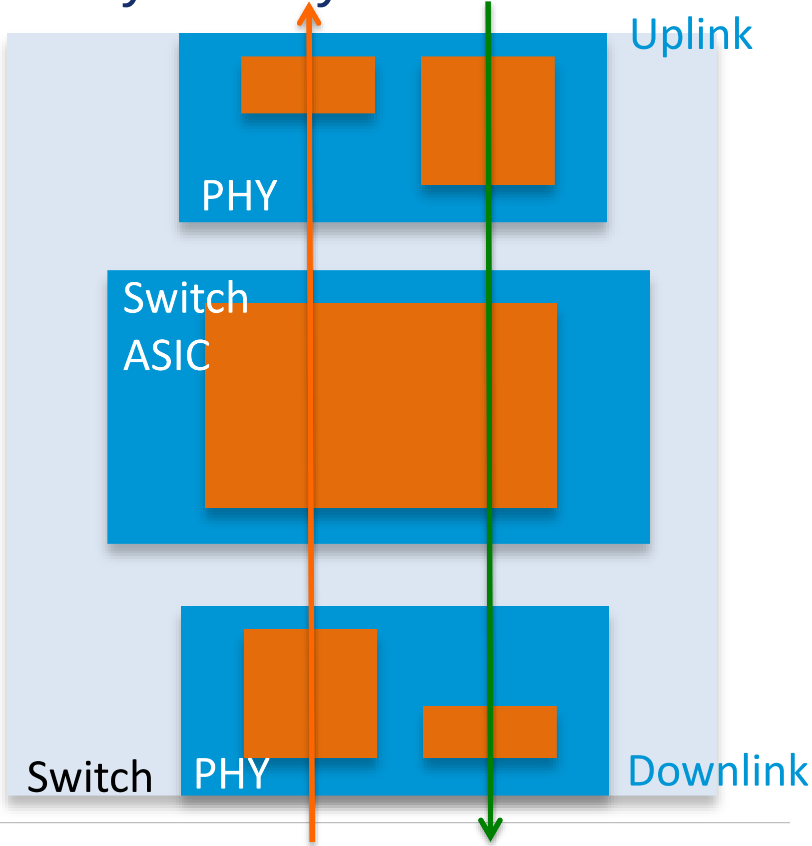
Primary source of Asymmetry is Queuing Delay

Secondary source is Transmission Delay

Asymmetry: Within a Node

If the internal components of the System are symmetrical, then the delays will be symmetrical.

However…

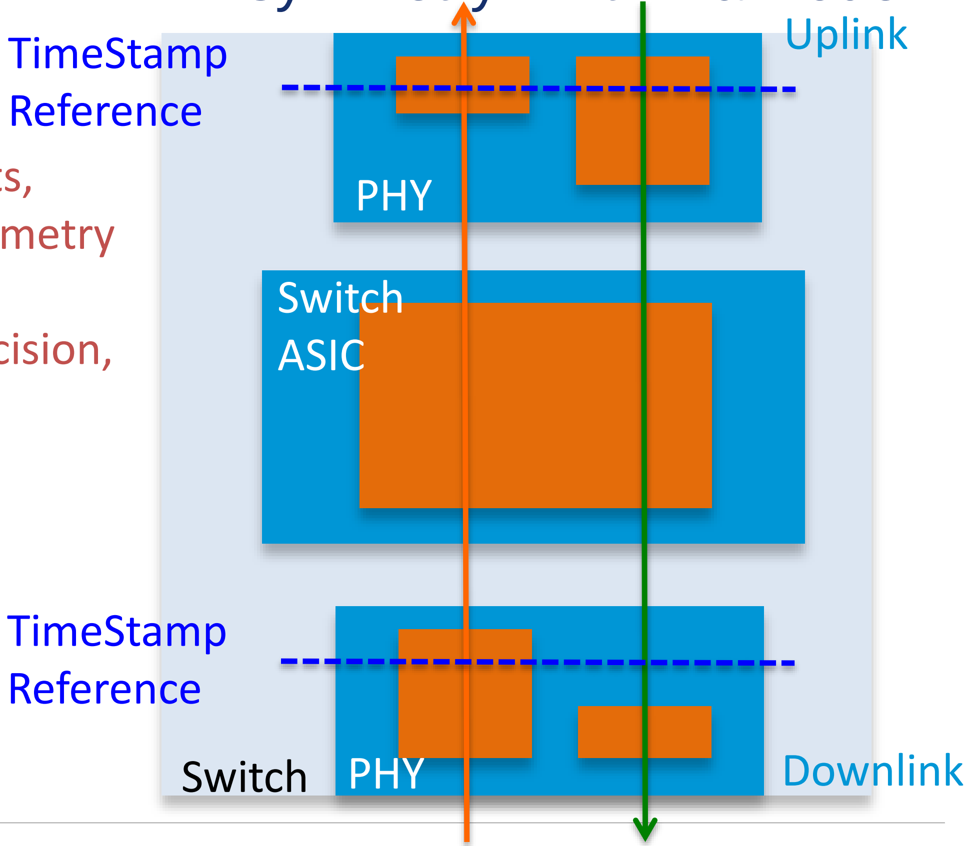


Asymmetry: Within a Node

If different PHYs are used on different ports,
Even that slight difference can cause asymmetry

When trying to get to nanoseconds of Precision,
Every little bit counts…

And where you time stamp matters.

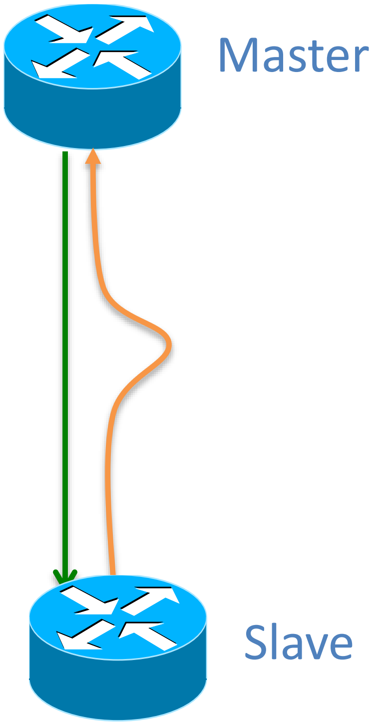


Asymmetry: Transmission

Typically, transmission delays are fairly symmetrical:
Bidirectional over same pairs, small differences in pair lengths

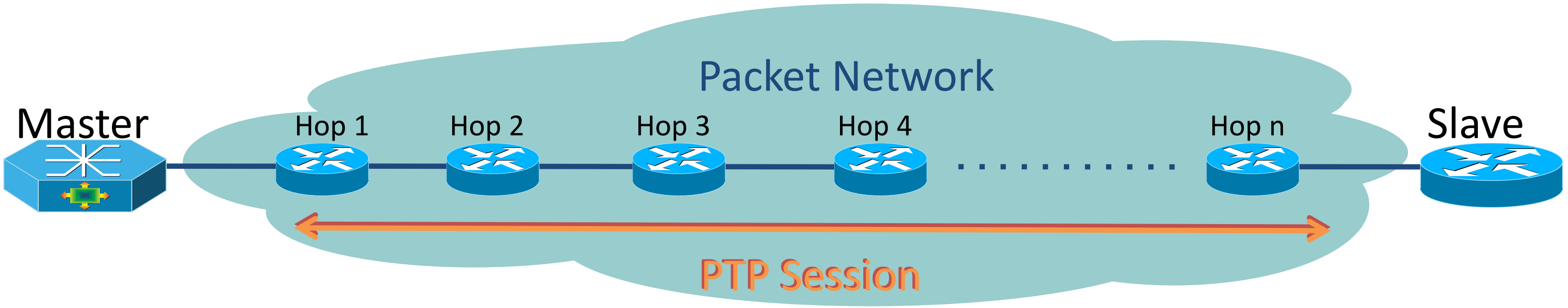
However, some things can make it more likely:
EtherChannel, Fiber (especially rings; East v. West)

Nanoseconds matter => Meters matter



Packet Delay Variation (PDV)

PDV is primarily due to Varying Queue Delays…

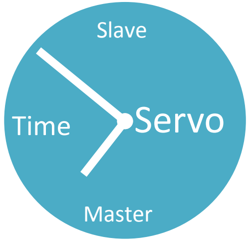


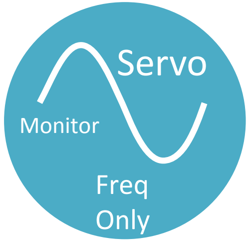
Even High Priority packets get behind a 1518 from time to time.

The variance comes from the fact that sometimes you do and sometimes you don’t.

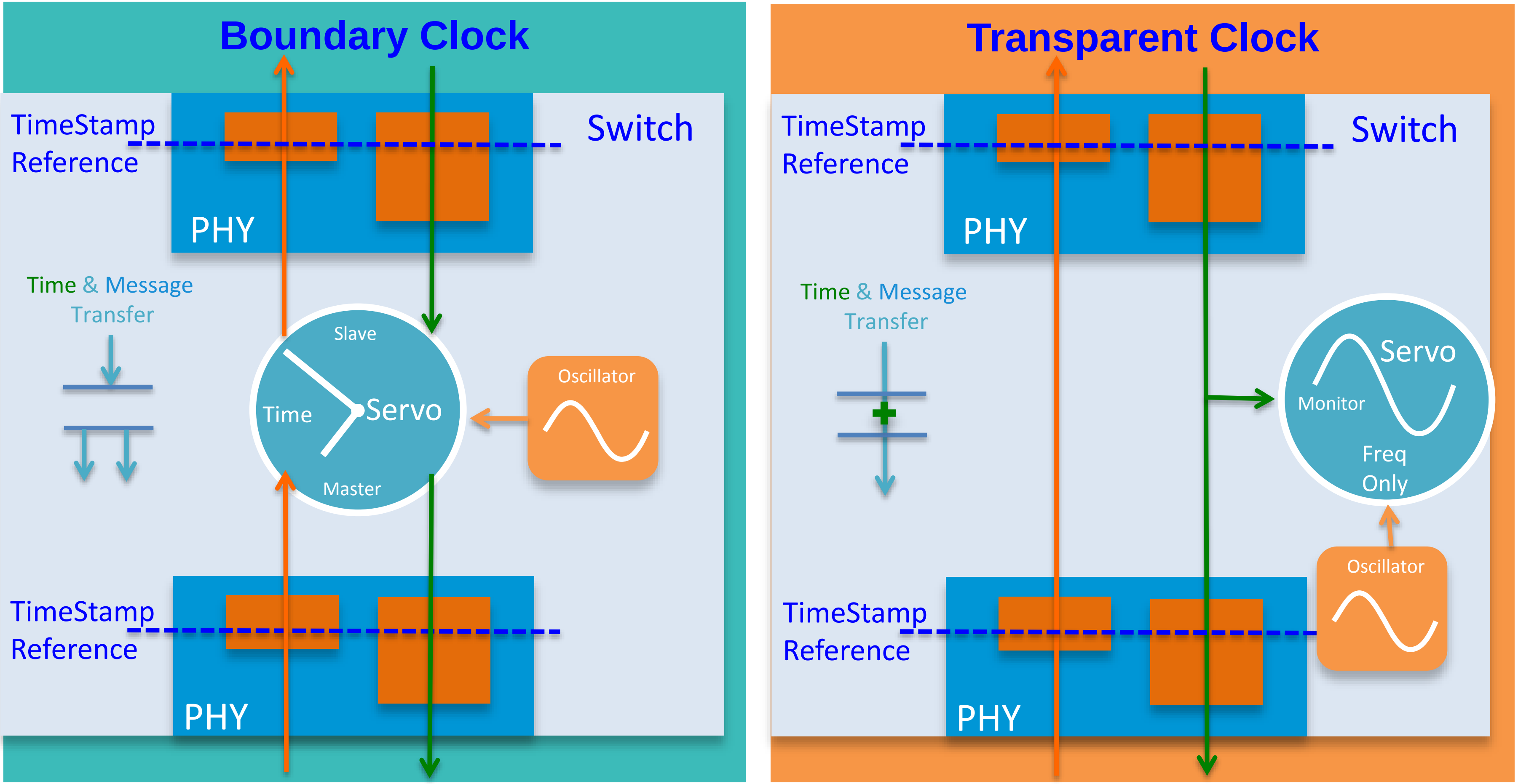
It’s all statistics…

Boundary Clocks and Transparent Clocks





Boundary Clock v. Transparent Clock – Error Sources



Pros and Cons of Boundary Clocks

Pros:

- Breaks up the PTP message domain
- Breaks up the PTP timing domain
- Spans across VLANs
- Shields Slaves from Transients due to hierarchy changes (BMCA)
- Filters PDV

Cons:

- Adds low frequency (wander) time error (hard to filter)

Message Transfer

Time Transfer

Pros and Cons of Transparent Clocks

Pros:

- Maintains tight timing throughout a domain
- Peer-to-Peer TCs can converge faster after network topology changes

Cons:

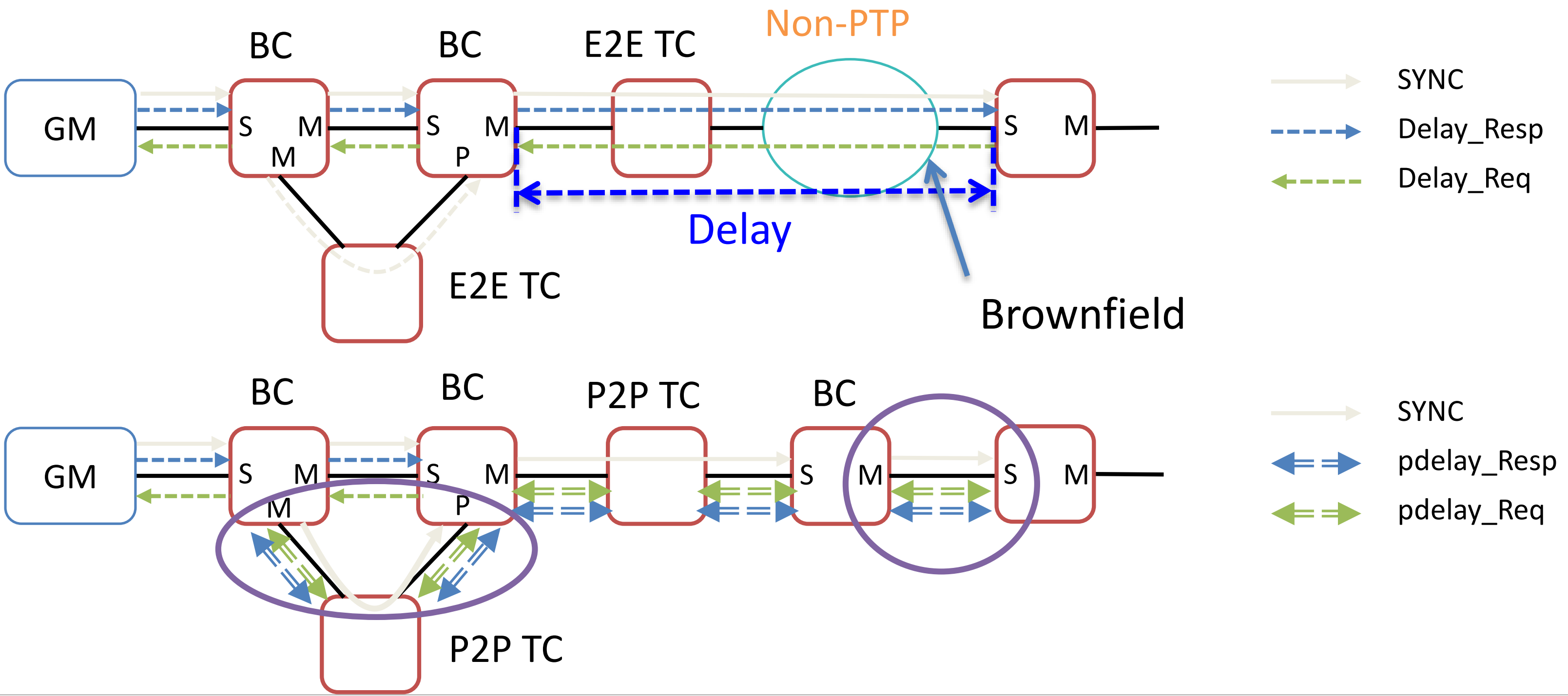
- End-to-End TCs can have scalability issues

Time Transfer

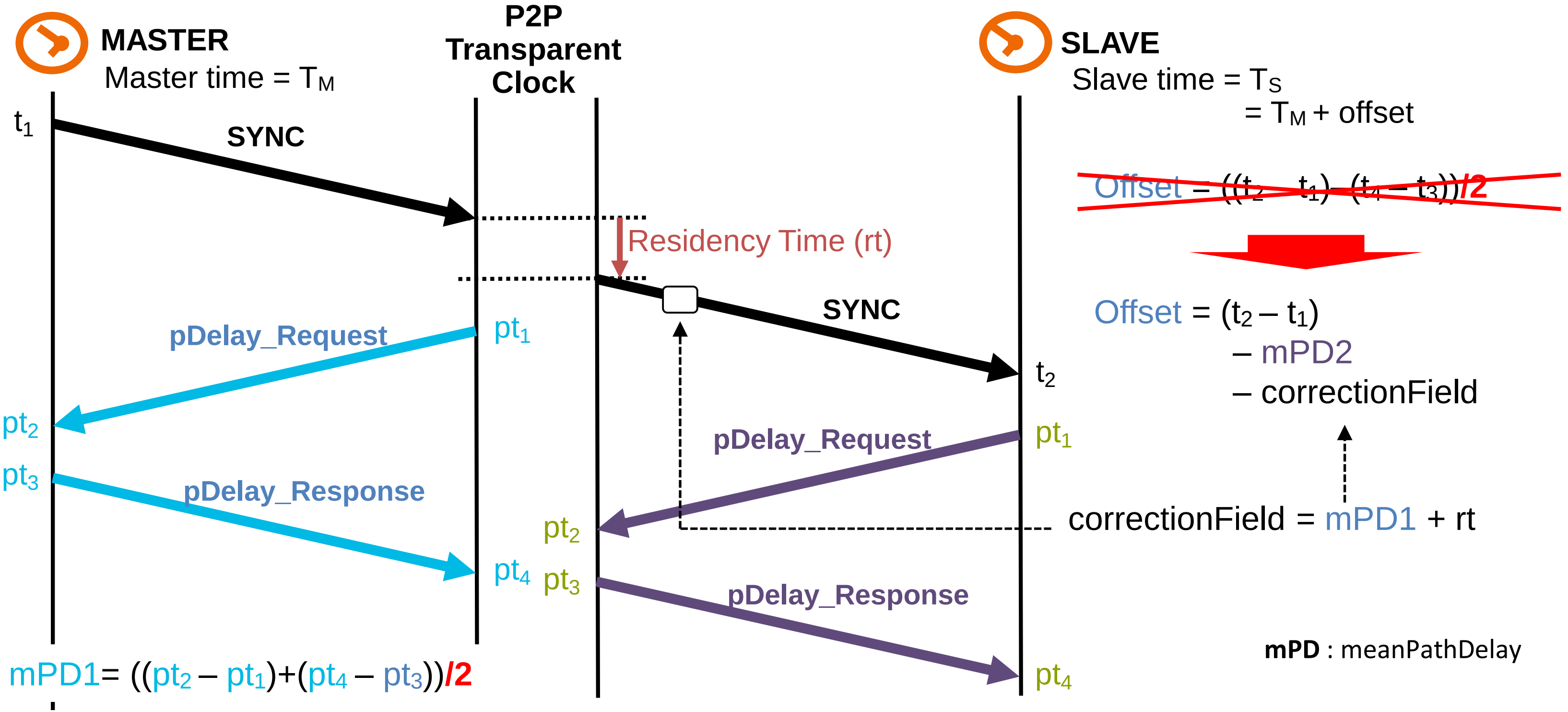
Message Transfer

Delay and pdelay Mechanisms

Two Types of TCs: End-to-End and Peer-to-Peer



Peer to Peer Transparent Clock



$$mPD1 = ((pt_2 - pt_1) + (pt_4 - pt_3))/2$$

$$mPD2 = ((pt_2 - pt_1) + (pt_4 - pt_3))/2$$

Thermal Changes Affect Base Oscillators

PTP Profiles

(And the Proliferation of said…)

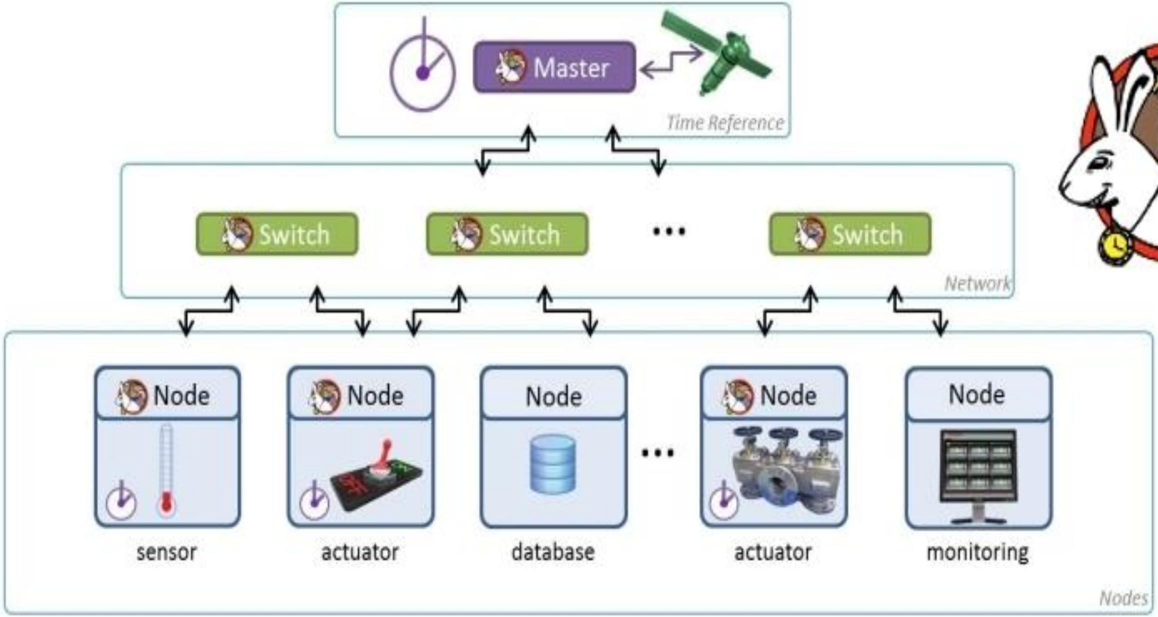
Main Current Industrial Profiles

	IEEE 1588-2008 Default (CIP Sync)	IEEE 802.1AS	IEEE C37.238	ITU-T G.8275.1
Segments	Industrial Solutions	AVB (residential) TSN	Power Industry (SmartGrid substation)	Telecom Mobile Backhaul Substation Backup
Transport	IP, L2 Ethernet, industrial specifics	L2 Ethernet	L2 Ethernet	L2 Ethernet
Transmission	Multicast (default)	Multicast non-forwardable	Multicast non-forwardable	Multicast (both address types)
Delay mechanism	Delay (Annex J.3) Pdelay (Annex J.4)	pdelay	pdelay	delay
Clock mode	One- & two-step	Two-step	Two-step	Any
BMCA	Default	Alternate	Default	Alternate
TLV Extensions	Optional	Yes	Yes	No
Clocks	OC, BC, TC	time-aware bridge and end station	OC, TC (BC in future revision)	T-GM, T-BC, T-TSC
Deployment model	Not defined	Full support	Full support	Full Support + PHY layer freq.

Performance Specifications

	IEEE 1588-2008 Default (CIP Sync)	IEEE 802.1AS-2011	IEEE C37.238-2011
Network limits	No	7-hop network: • time accuracy • jitter and wander	16-hop (TC) network
Clocks	No	LocalClock: • frequency accuracy • time granularity • noise generation TimeAware systems: • residence time • pdelay turnaround time • Error in rate ratio (or frequency offset) measurement	TC timeInaccuracy limit +-50 nsecs
Grandmaster	Frequency accuracy		Grandmaster timeInaccuracy limit

White Rabbit

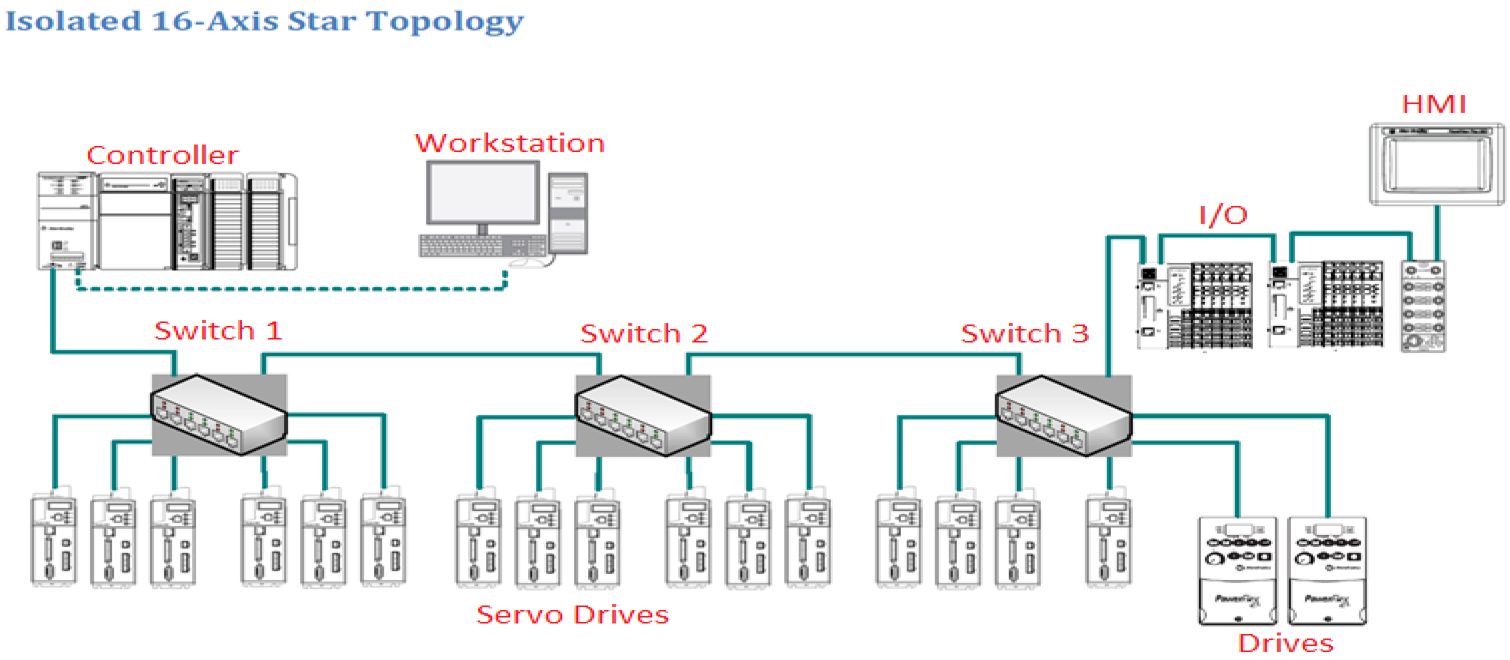


Sub-nanosecond synchronization!

Real World Impact

PTP Errors Translated to Machine Error

Using Multiple Unmanaged Switches in a Large System…

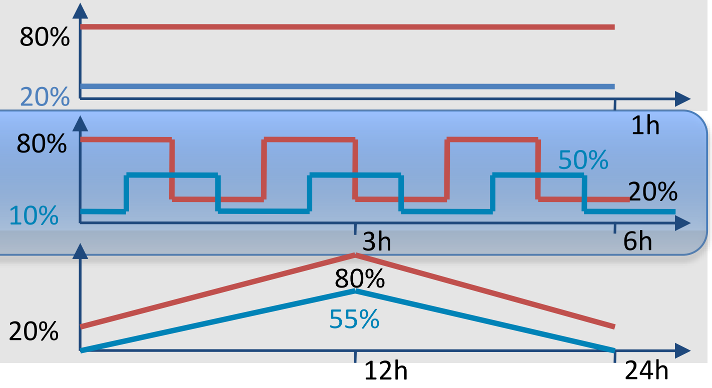


Simulated Network Load – ITU Telecom Profiles

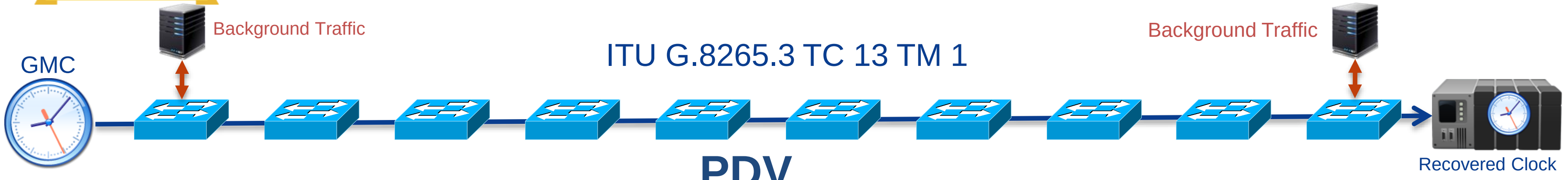
ITU-T G.8261 – Timing & Sync Aspects in PSNs

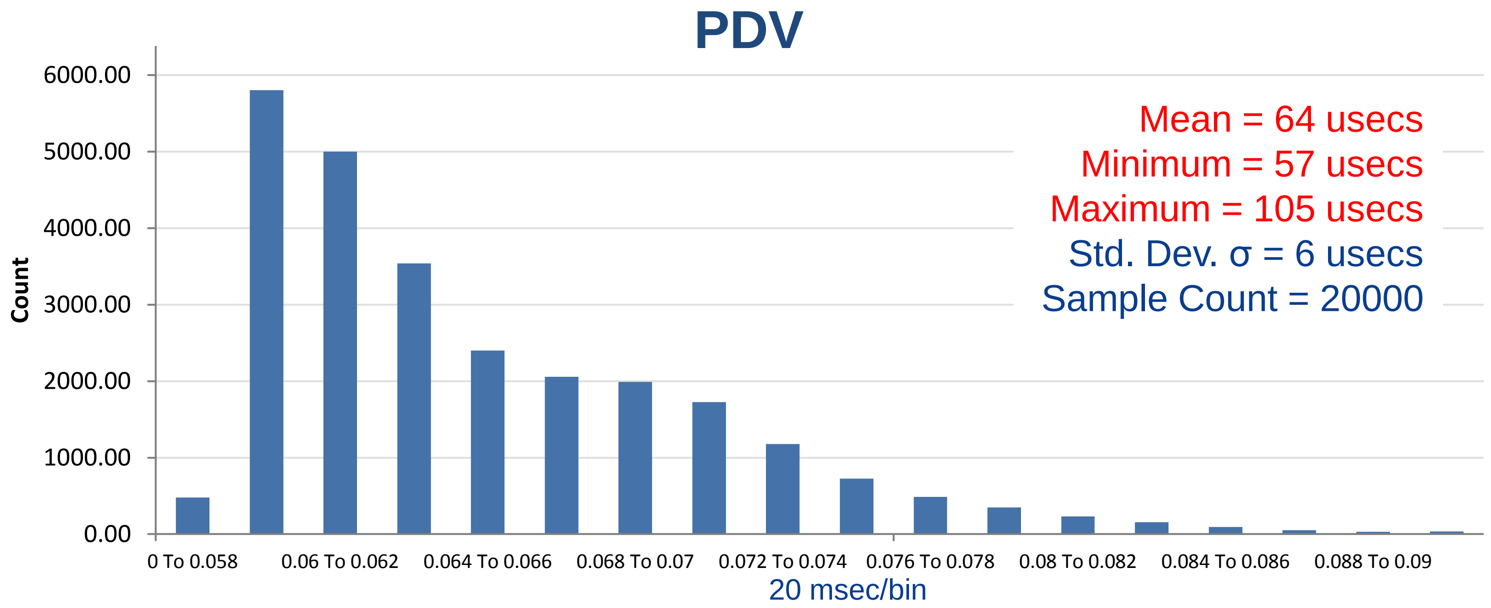
- Appendix VI.5 – Test for Two Way Protocols
- Baseline Test (no Network → Master/Slave back to back)
- Performance Tests (Network & Load)

Test Case	Description	Network Load
12	Static Packet Load	
13	Sudden large and persistent Load Changes	
14	Slow Load Change over extremely long Time	
15	Temporary Network Outage	
16	Temporary Congestion	
17	Routing Changes caused by failures	



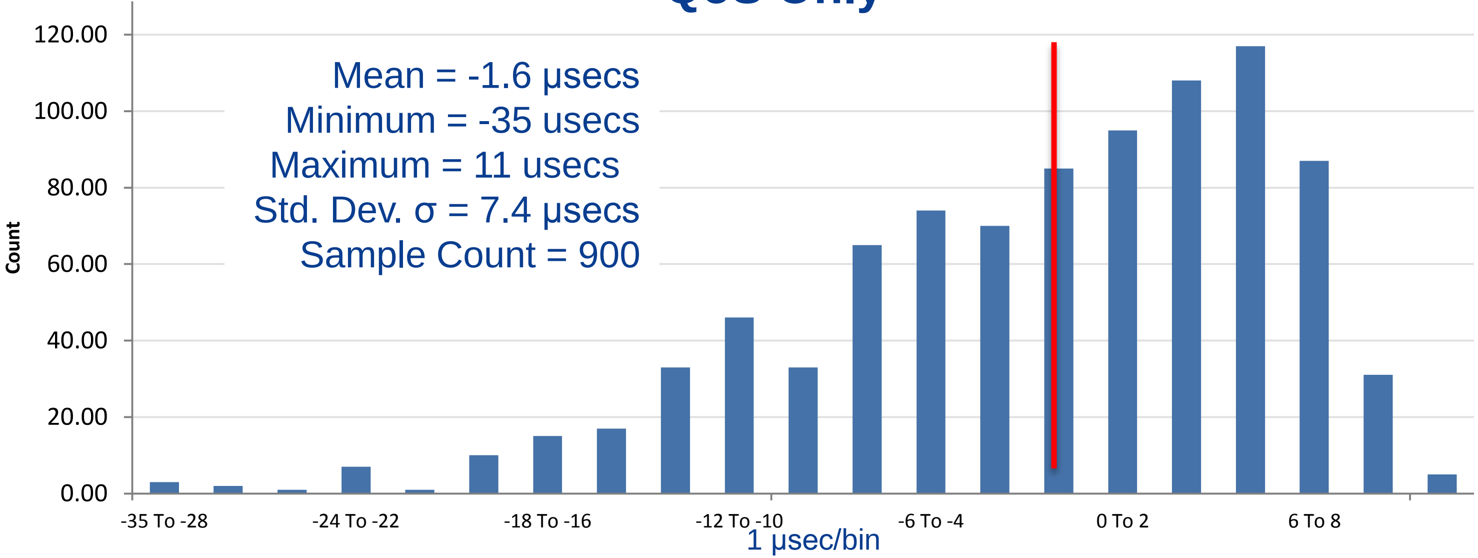
Simulated Network Load – ITU Telecom Profiles



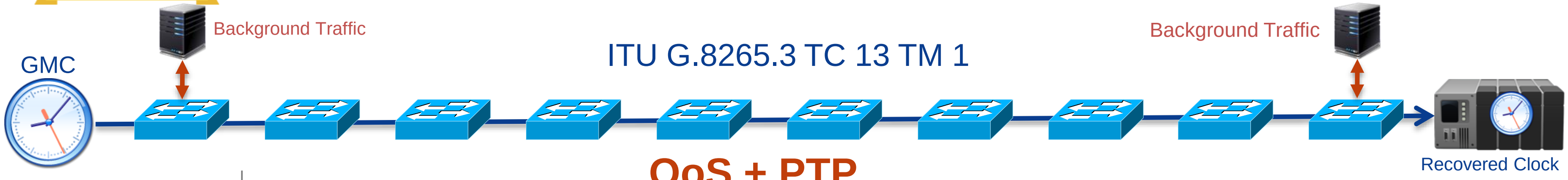


Simulated Network Load – ITU Telecom Profiles

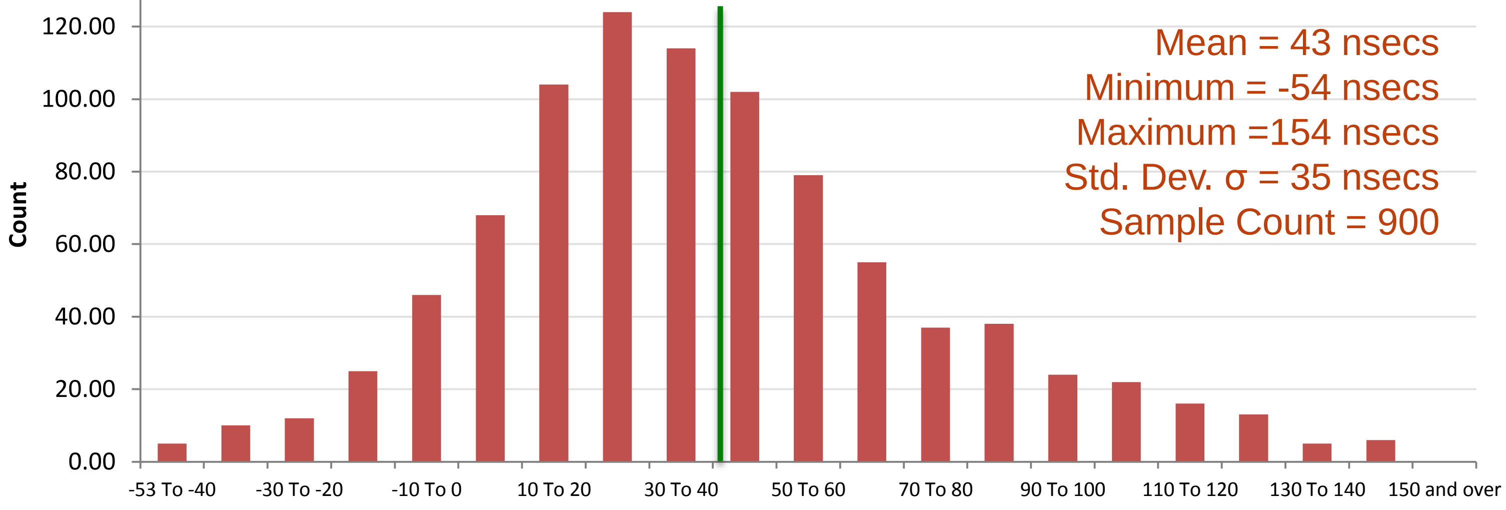
QoS Only



Simulated Network Load – ITU Telecom Profiles

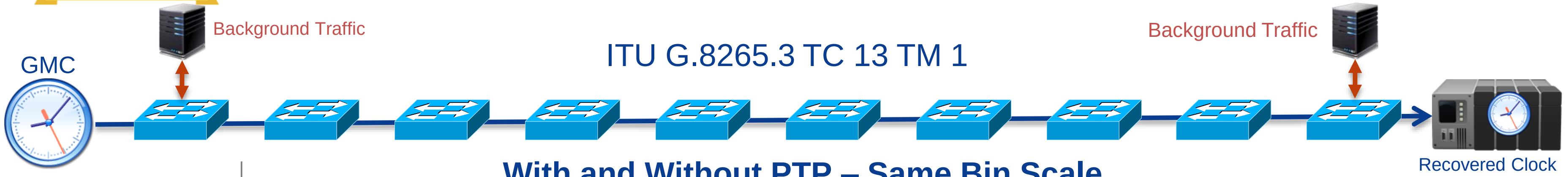


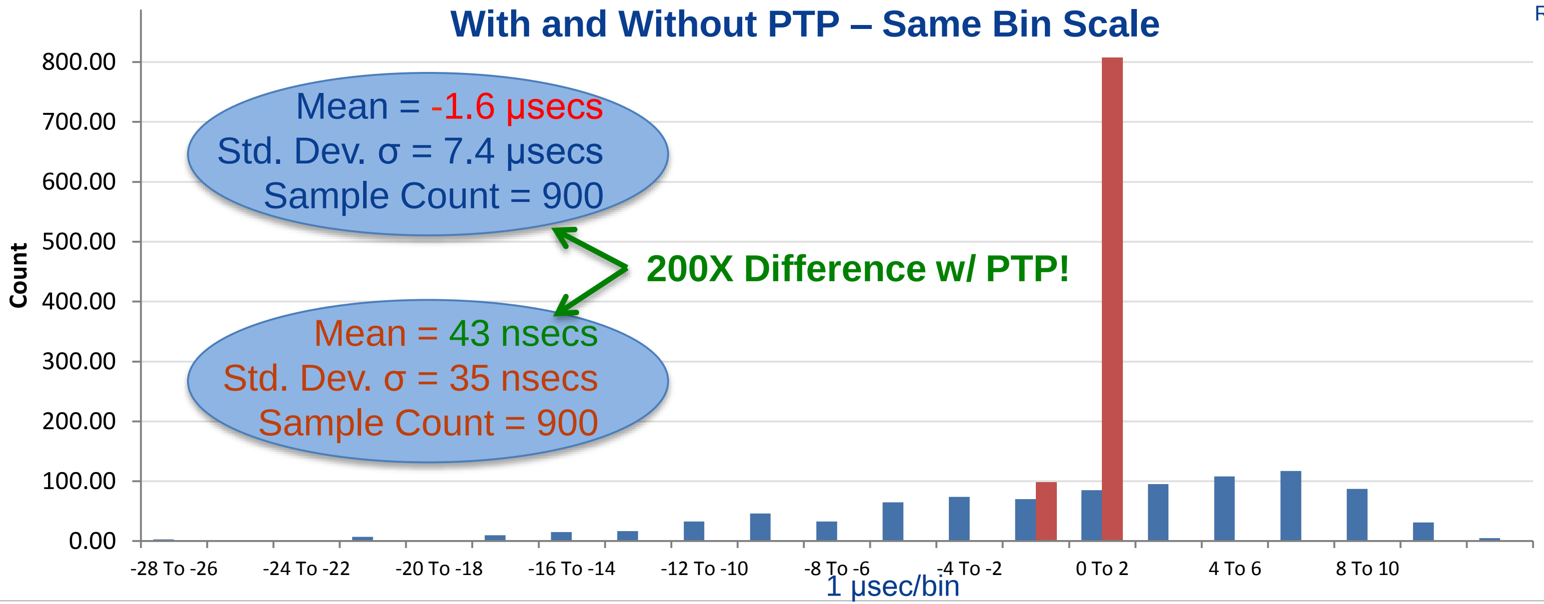
QoS + PTP



10 nsec/bin

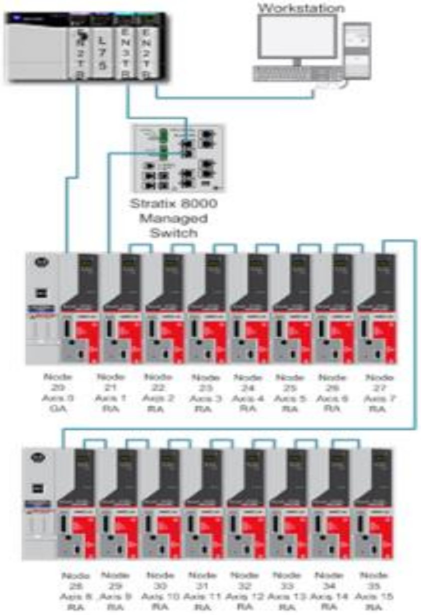
Simulated Network Load – ITU Telecom Profiles





So what do these numbers really mean?

16 Axis Star, Linear K6500, Stratix 8000 Switch

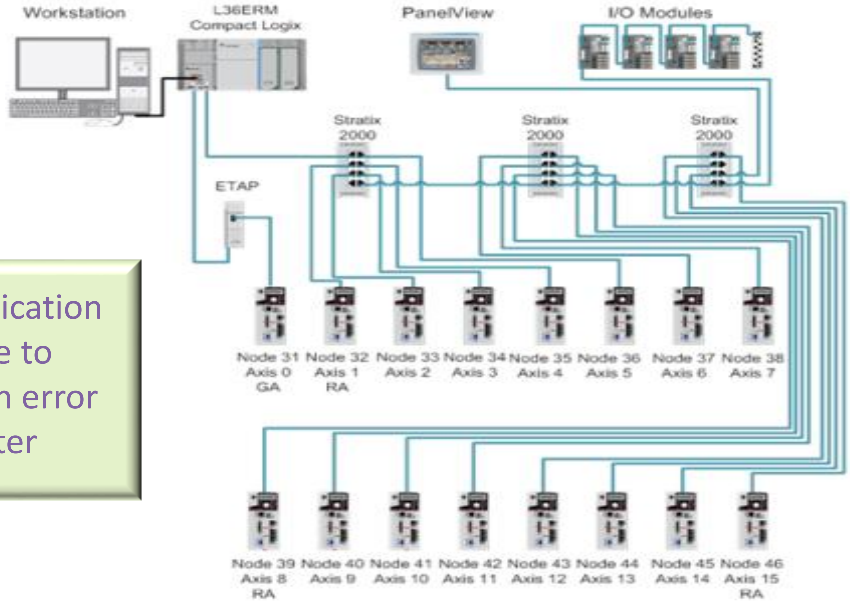


Average System Clock Jitter (Max) ~ 35 nanoseconds

0.000000035s x 6000 RPM/ 60s/min = 0.0000035 Revs

Note: Sample from Axis 2

16 Axis Star, K350, Stratix 2000 Switch



Average System Clock Jitter (Max) ~ 7.4 microseconds

0.0000018s x 6000 RPM/ 60s/min = 0.00074Revs

Note: Sample from Axis 1, off switch 1

Multiply your application speed by this value to determine position error due to network jitter

THANK YOU