

Clock Synchronization, IEEE 1588 and Cyber-Physical Systems

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Outline

- CPS background
- Timing, clocks, and IEEE 1588
- Sources of synchronization error
- Uses of IEEE 1588 in CPS
- Future

Controlling a CPS, e.g. industrial automation Learning about a CPS, e.g. test & measurement

Cyber-Physical System (CPS)

Cyber World (computers and networks) Computation, Control, Communication (CONTROL: based on a model of the physical world) (LEARNING: building a model of the physical world)

Physical World Natural world: physics, chemistry, ecology, biology · · · Man-made world: airplane, power grid, internet, printing press, automobile, $iPod, \cdots ad$ infinitum

Both timing and value are important in a CPS!

Control



Courtesy of Bosch-Rexroth

Measurement



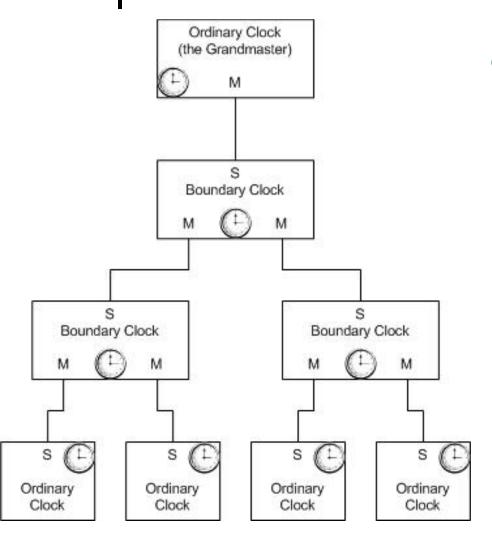
Courtesy of Brüel & Kjær

 Trend: More transducers, distributed systems => synchronized clocks



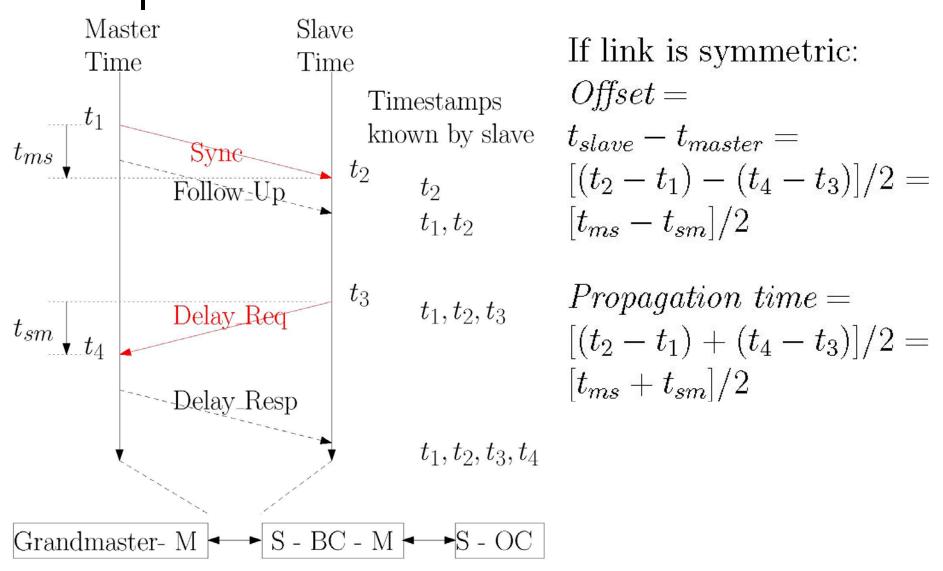
- IEEE 1588 exists due to industry's:
 - Increasing requirement for <u>distributed systems</u>
 - Customer demand for <u>standards based</u> solutions
 - Move to Ethernet from proprietary networks for perceived cost reasons
 - Need for timing <u>accuracy better than 1 µs</u>
- Nothing profound or magical about 1588 just the right thing at the right time
- But it did help focus the discussion on timing in distributed Ethernet-based systems!

Master-slave hierarchy of ordinary and boundary clocks



- Hierarchy based on pair-wise comparison of:
 - 1. priority-1
 - class (UTC traceability)
 - accuracy (with respect to UTC)
 - 4. variance
 - 5. priority-2
 - 6. UUID (tiebreaker)

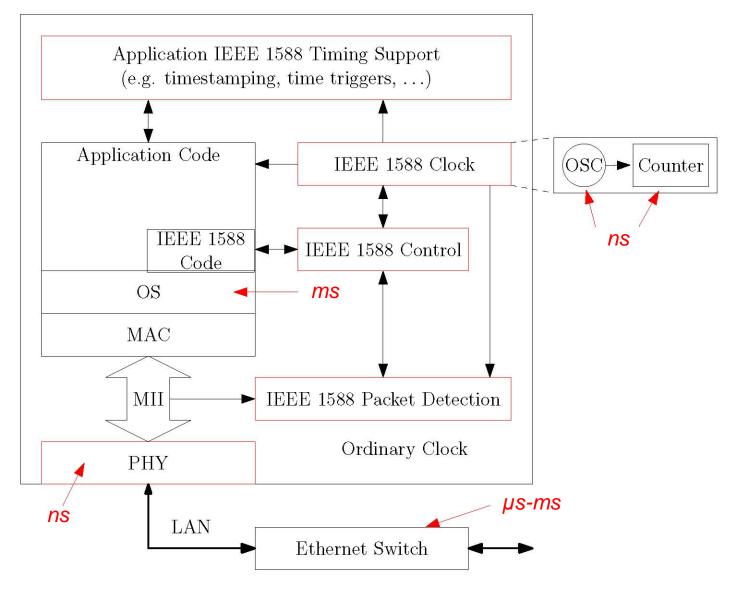
Synchronization: delay request-response mechanism

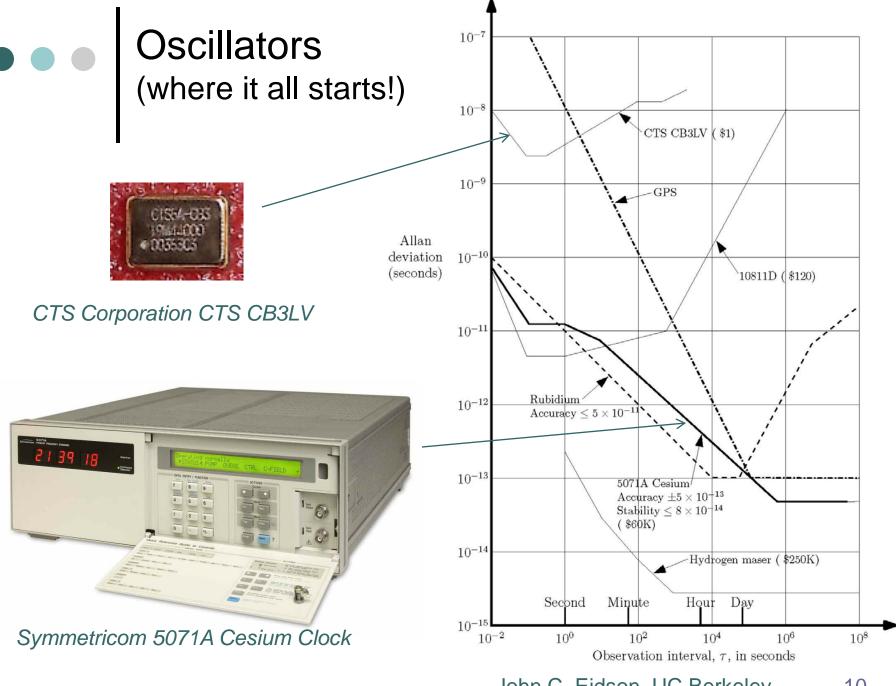




- If the link is not symmetric
 - The propagation time is the mean of the master-to-slave and slave-to-master propagation times
 - The offset is in error by the difference between the actual master-to-slave and mean propagation times
 - IF you know the asymmetry, the standard specifies how to correct for it
- Correcting asymmetry is a major concern in high accuracy synchronization. This is true for all twoway synchronization protocols and is not unique to 1588.

Sources of synchronization error

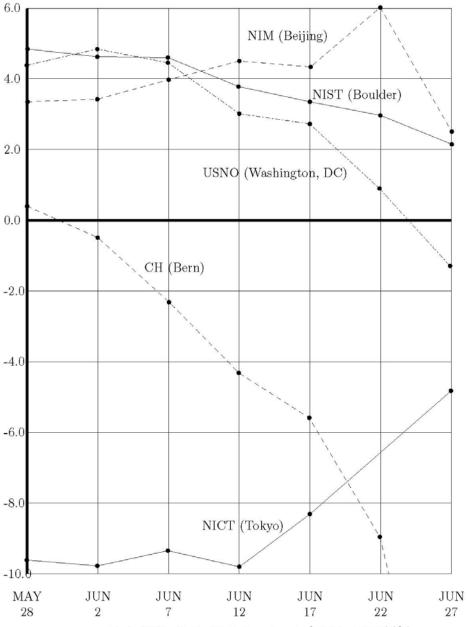




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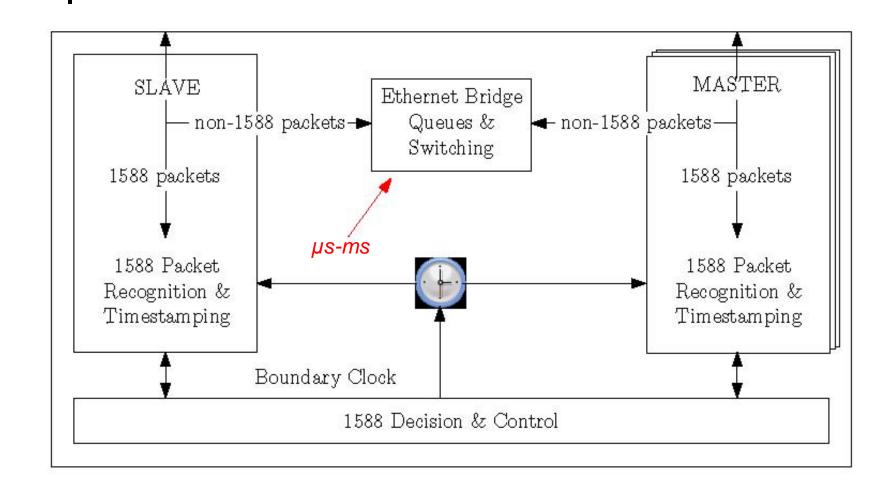
UTC_i vs. UTC

Even atomic clocks drift! Keeping precise and accurate time is very difficult.

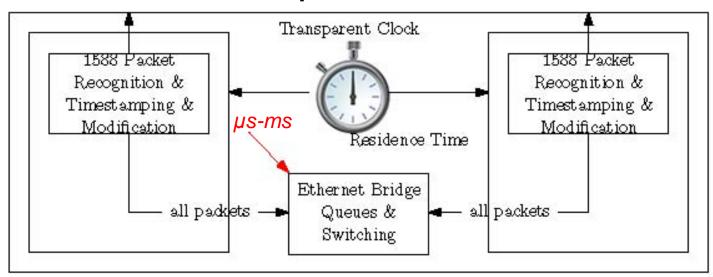


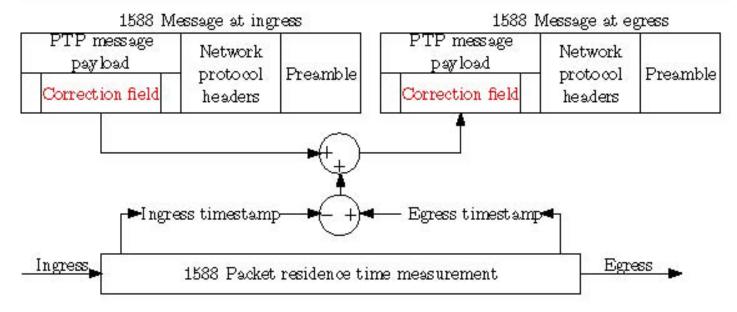
Date 2011, 0h UTC: Laboratory k [UTC - UTC(k)]/ns BUREAU INTERNATIONAL DES POIDS ET MESURES CIRCULAR T 282 2011 JULY 07, 09h UTC

IEEE1588 Boundary Clock

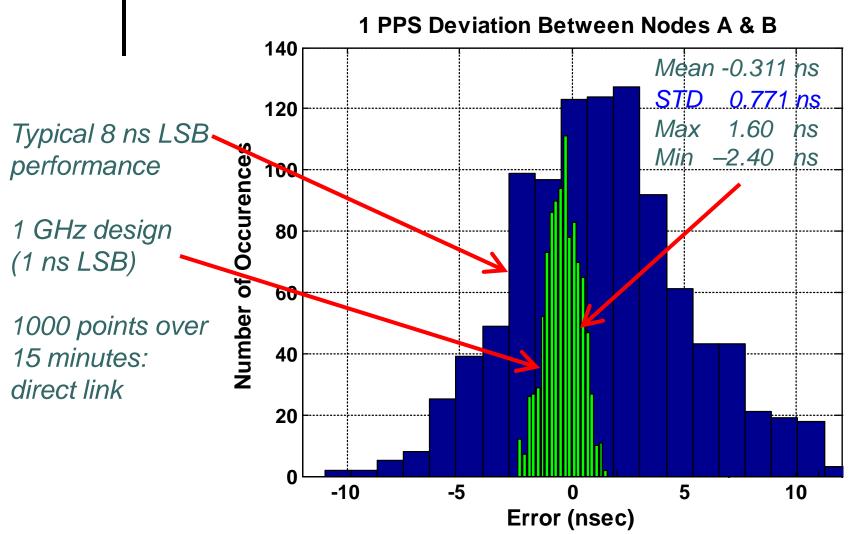


IEEE 1588 Transparent Clock



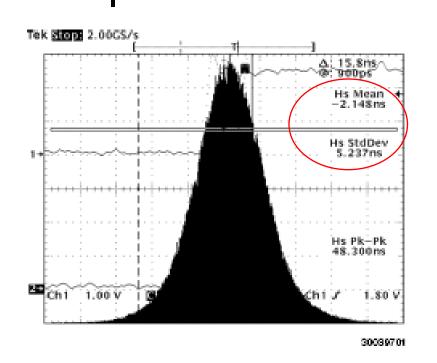


How well can you synchronize?



From: Update on High Precision Time Synchronization, Vook, et.al., IEEE-1588 Conference, Zurich, October 2005

IEEE 1588v2/PTP and SyncE/ITU-T G.8261



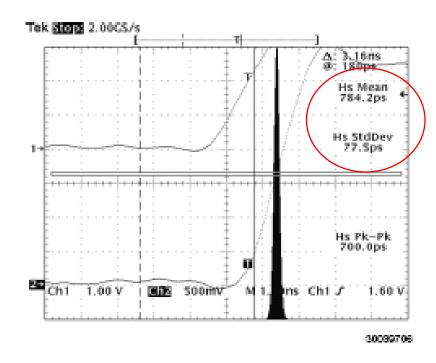
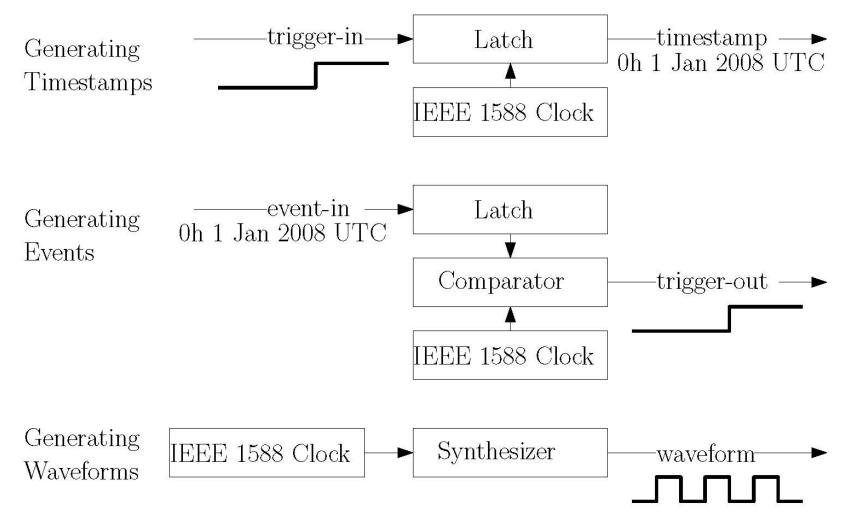


FIGURE 7. Master to Slave 10 MHz CLK_OUT FIGURE 10. Master to Slave 10 MHz CLK_OUT
Synchronization with Synchronous Ethernet Mode Synchronization with Synchronous Mode Enabled and
Disabled Crystal Slave Reference Clock

From: "DP83640 Synchronous Ethernet Mode: Achieving Sub-nanosecond Accuracy in PTP Applications, National Semiconductor Application Note 1730, David Miller, September 2007

How do you use a synchronized clock?

(all 3 forms supported in DP83640 PHY chip)



IEEE 1588 Commercial products (partial listing)

- Boundary and transparent clocks: Hirschmann, RuggedCom, Cisco, Siemens, Huawei,...
- PHY chips: National Semiconductor, Intel, Zarlink, Vitesse, Broadcom, Marvell,...
- Microprocessors: Intel, Conemtech AB, Analog Devices, Freescale,...
- Protocol stacks: IXXAT, RTS, Flexibilis,...
- FPGA IP Blocks: System-on-chip Engineering, MoreThanIP, Xilinx, Altera,...
- Ordinary clocks: Symmetricom, Meinberg, ...
- Debug help: Wireshark, Ixia, Symmetricom,...
- ISPCS- IEEE International Symposium on Precision Clock Synchronization

Power system applications

GE uses 1588 in the Mark[™]VIe control system for large generators, turbines, wind farms, and other DCS applications. (>50K I/O Packs with 1588 shipped to date)











Courtesy of General Electric

Power system synchrophasor application

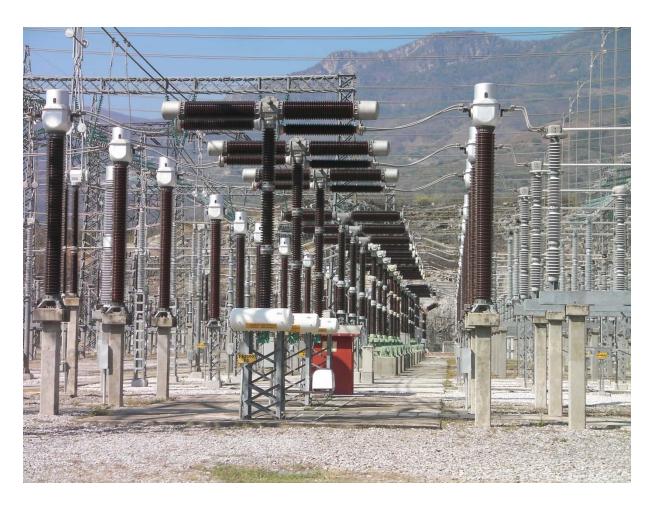
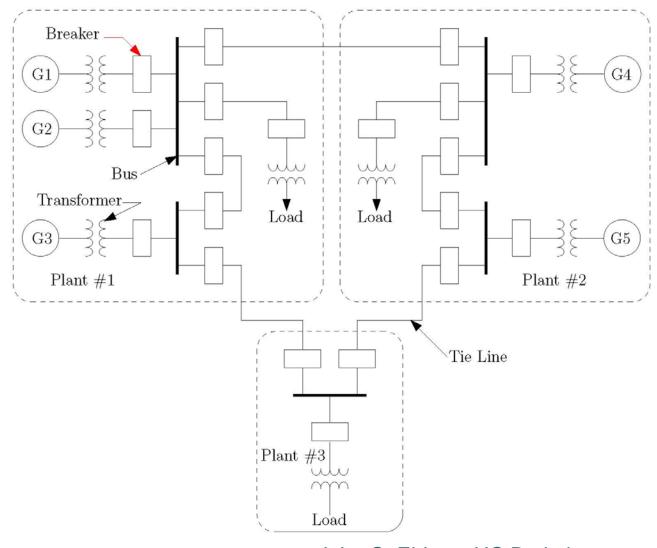


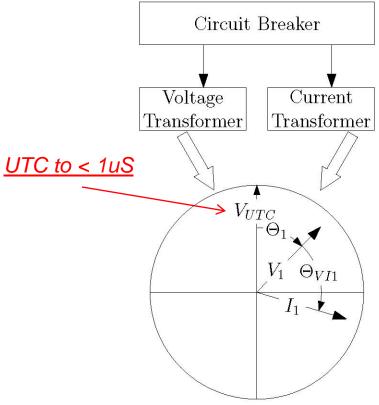
Photo courtesy of Veselin Skendzic

Power system synchrophasor application

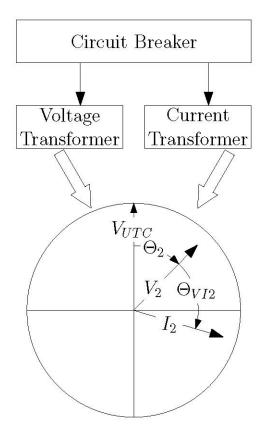


Power system synchrophasors

IEEE 1588 referenced in C37.238, C38.118.1 and C37.118.2



Synchrophasor data: Θ_1 , V_1 , I_1 , Θ_{VI1} Power factor: $\cos(\Theta_{VI1})$



Synchrophasor data: Θ_2 , V_2 , I_2 , Θ_{VI2} Power factor: $\cos(\Theta_{VI2})$

Telecommunications applications

- Cellular backhaul, pico and femto cells are the first major telecommunications applications
- Femto cell access points: ~4M in 2011 to 48M in 2014 (from 'Femtocell Market Status' – Informa, a white paper of the femtoforum)
- IEEE 1588 enabled PHY chips appearing, e.g. Broadcom BCM54682E — octal-port QSGMII 10/100/1000BASE-T GbE transceiver

Standardization activity for packet-based time and frequency transfer in telecommunications

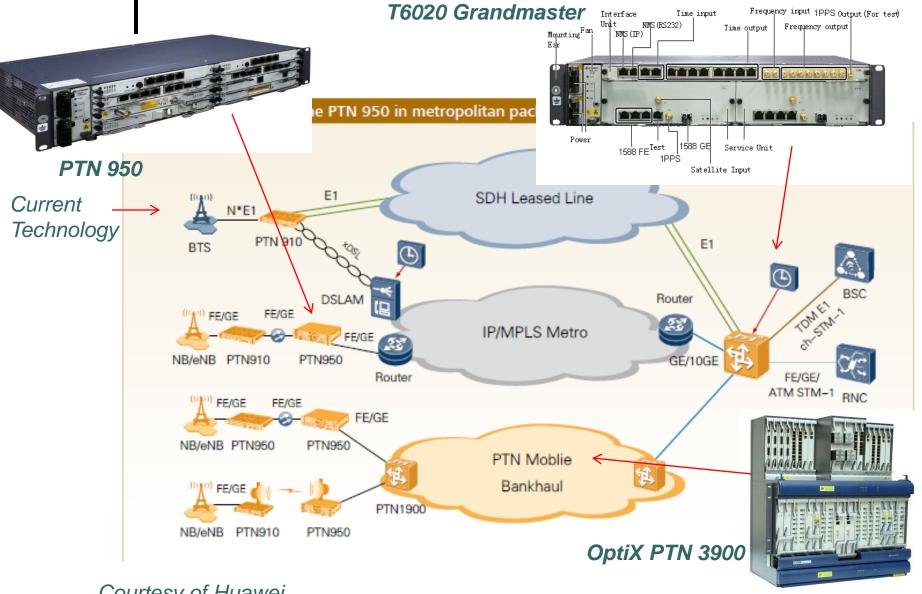
- ITU-T SG15 Q13
 - ITU-T Recommendation G.8265.1 (10/2010), Precision Time Protocol Profile for Frequency Synchronization
 - Starting G.8275 and G.8275.1 for time/phase transfer using IEEE 1588
- o IETF: 'Tic-Tock'
- ICAP- IEEE 1588 Conformity Alliance (testing & certification)

Synchronization requirements for wireless air interface technologies

Technology	Frequency Accuracy	Phase Accuracy
GSM (2G)	±50 ppb	Not required
UMTS	±50 ppb	Not required
CDMA 2000	±50 ppb	±3.0 µs
WCDMA	±50 ppb	±1.25 μs reference to BTS ±2.55 μs between base stations
Pico RBS (WCDMA and GSM)	±100 ppb	±3.0 µs

Based on a Juniper Networks white paper- 'Synchronization Deployment Considerations for IP RAN Backhaul Operators'

Typical cellular backhaul architecture



Telecom time transfer field trial in China

 Each chain had 15 boundary clocks

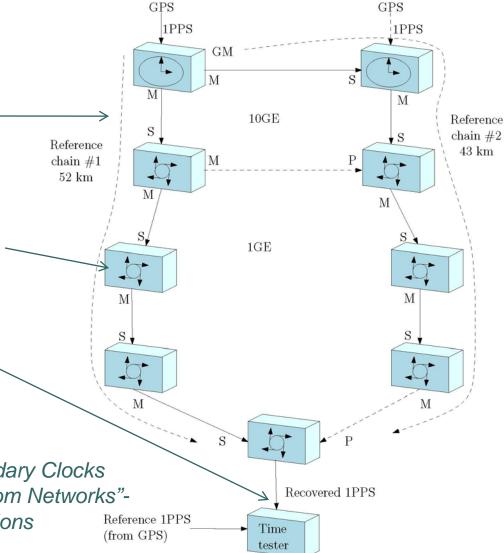
 BCs used SyncE for frequency and 1588 for time transfer

Accumulated error

< 3 µs requirement for TD-SCDMA

From "Using IEEE 1588 and Boundary Clocks for Clock Synchronization in Telecom Networks"-Ouellette, et.al. IEEE Communications

Refer (from Magazine • February 2011

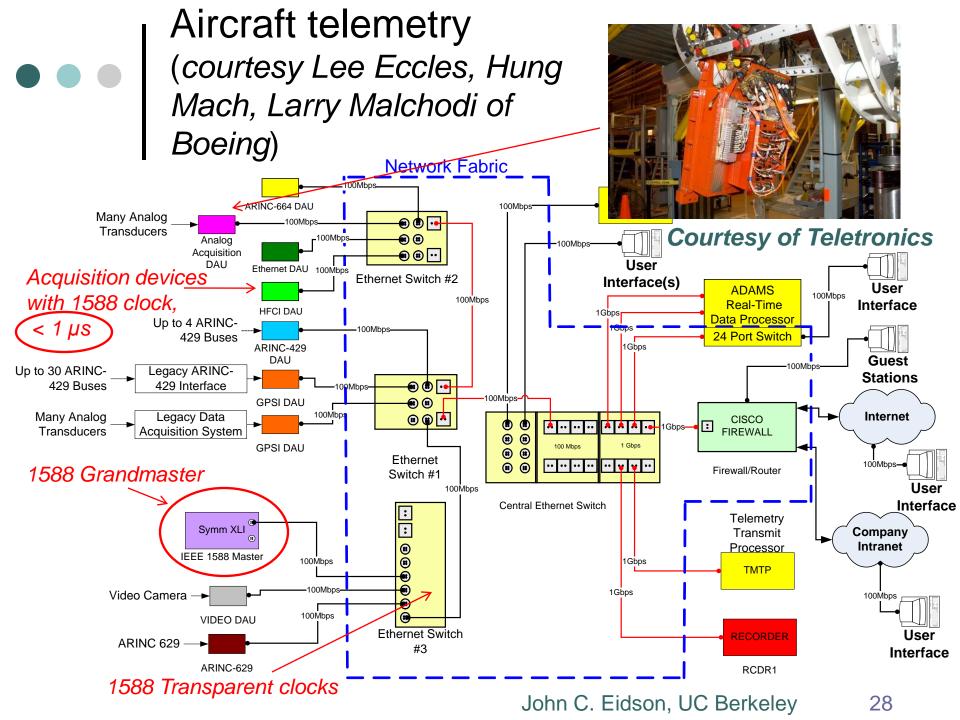


Industrial automation example

- Rockwell Ethernet/IPtm
 Time-based control over
 Ethernet
- Commands and sensor readings are locally timestamped
- Has been installed on 130 axis packaging machines







Sound, vibration,..., machine condition monitoring

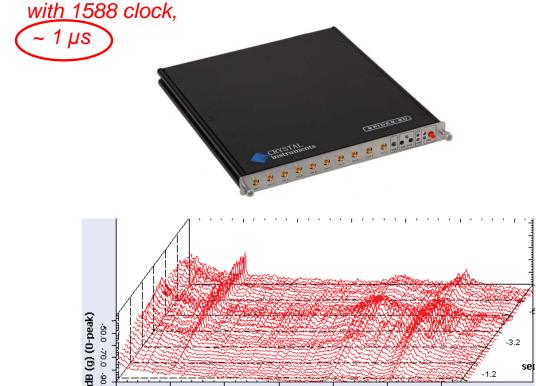
Acquisition devices



Courtesy Brüel & Kjaer



Photograph by Alan D. Monyelle, USN, 5/23/02



Courtesy Crystal Instruments

Frequency (Hz)

26000.0

31000.0

6000.0

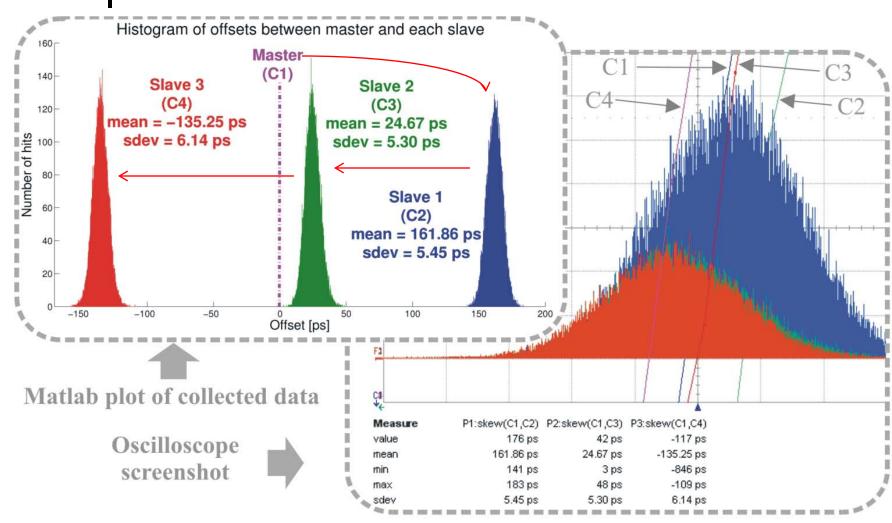
11000.0

CERN's White Rabbit Project

(based on "White Rabbit: a PTP Application for Robust Sub-nanosecond Synchronization"- Maciej Lipinski, et.al., ISPCS 2011 Munich)

- Goal: Develop an alternate timing and control system for the General Machine Timing at CERN
- Synchronization of up to 2000 nodes with subnanosecond accuracy, an upper bound on frame delivery and a very low data loss rate
- Based on and compatible with Ethernet (IEEE 802.3), Synchronous Ethernet (ITU-T Std. G.8262, 2007) and IEEE 1588-2008.
- For sub-nanosecond EVERYTHING matters: oscillators; media, PHY, board asymmetry, temperature, ...

White Rabbit Performance: Sub-nanosecond synchronization error over three 5km fiber optic links!

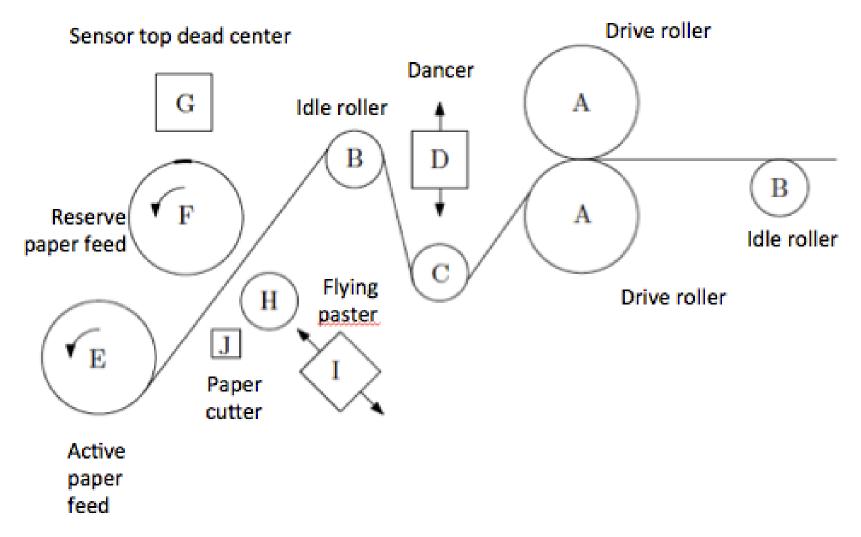


What does the future hold for timing and CPS?

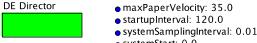
Advances in clock physics

- Symmetricom SA.45s CSAC
- Innovations in time and synchronization in CPS applications, e.g. IA, telecom
- Evolution of applicable standards
- IEEE 802 community takes timing seriously
- Advances in time specific programming languages and development environments: example- the <u>UC Berkeley Ptides Project</u>

Using clocks- UC Berkeley Ptides Project (Patricia Derler, John Eidson, Slobodan Matic, Prof. Edward Lee, Michael Zimmer)

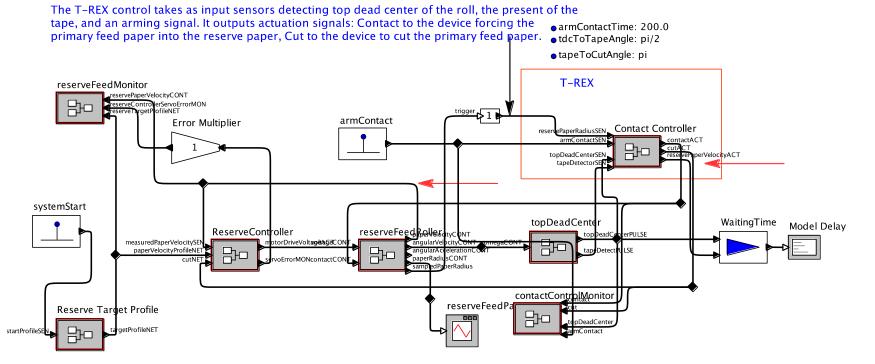


System model

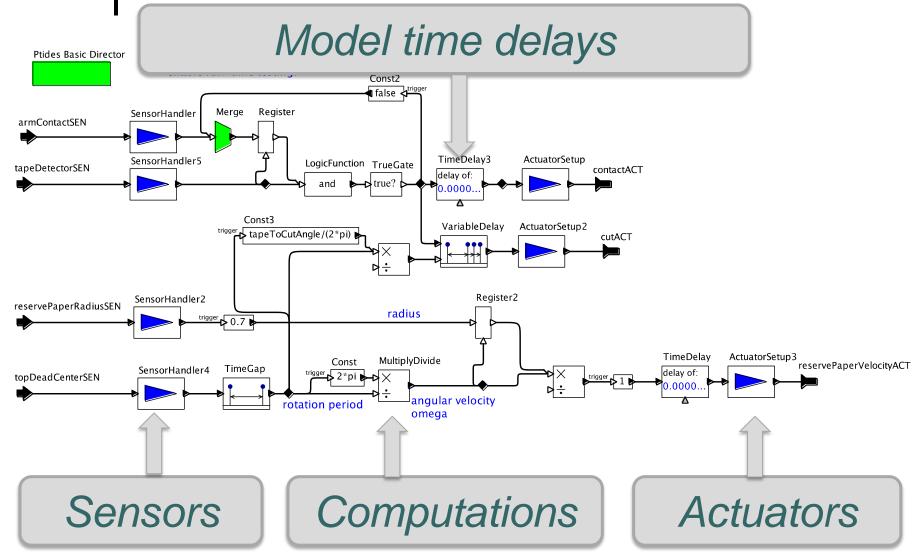


- coreRadius: 0.07 o fullRollRadius: 0.7
- paperThickness: 0.000075 systemStart: 0.0

This design consists of a model of a controler (T-REX) and a plant mode (the rest of the design. The plant models the dynamics of a DC motors driving a feed roller and a controler to cause the resulting paper velocity to track the input profile. All of this is a subset of the larger printing press model.



T-REX Controller



Renesas vs. XMOS: Measured I/O timing

Simulation

Renesas

XMOS

