TSCclock: Ten Microseconds Over LAN, for free

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ISPCS, Vienna, Oct 3, 2007

Low Cost, Low Performance?

Aim: A Software Clock Using:

- Commodity local hardware
- Time server access over a commodity network
- Standard operating system (Linux, BSD)

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Result: Need a robust, non-trivial synchronisation algorithm

THE TSCCLOCK

The TSCclock

Design

- Use oscillator driving CPU, accessible via TSC register (commonly available, high resolution, hardware updating)

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  (commonly available, high resolution, hardware updating)
- Feedforward, asynchronous, round-trip Master-Slave, deterministic algo
  - time-scale aware drift model
  - separate and decoupled treatment of rate and absolute time
  - non-linear minima filtering based on RTT

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- Accuracy an order of magnitude higher than *ntpd* (or more)
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Applications:

- Replacement of *ntpd*
- Push envelope of commodity solns. (remove GPS for 10 –1000 μs range)
- Provide precision time difference measurement

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PROVIDES

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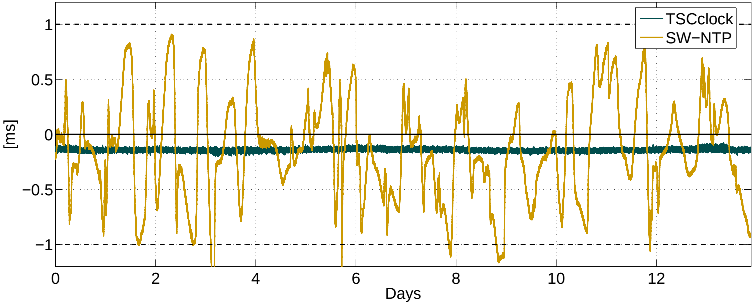
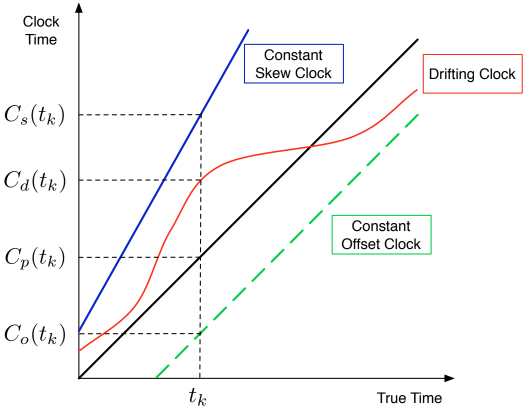
A Quick Comparison with *ntpd*



ntpd: sync'd to stratum-1 NTP server on LAN (broadcast mode)
TSCclock: sync'd to stratum-1 NTP server outside LAN

Offset, Skew and Drift



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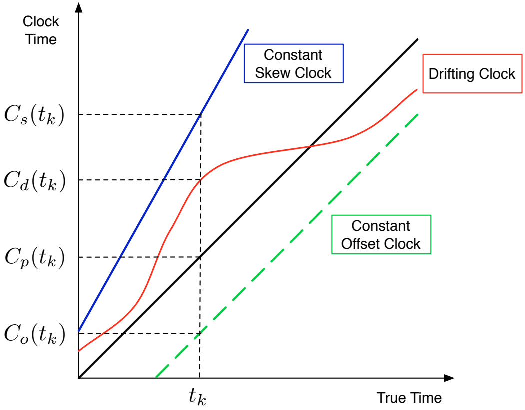


Offset: error $\theta(t) = C(t) - t$ of clock $C(t)$ at time t

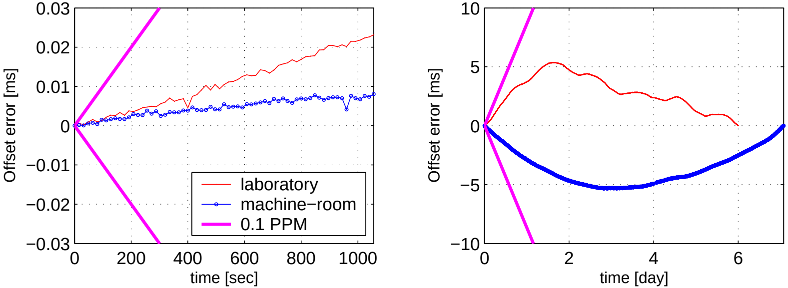
Skew: error in rate. E.g.: $\theta(t) = C + \gamma t$ (*Simple Skew Model* (SKM))

Drift: non-linear evolution of $\theta(t)$

The Role of Time Scale

Laboratory: $\bar{p} = 1.82263812 * 10^{-9}$ (548.65527 Mhz)

Machine Room: $\bar{p} = 1.82263832 * 10^{-9}$ (548.65521 Mhz)



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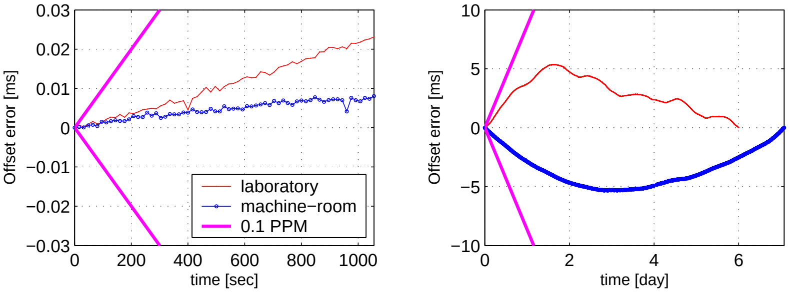
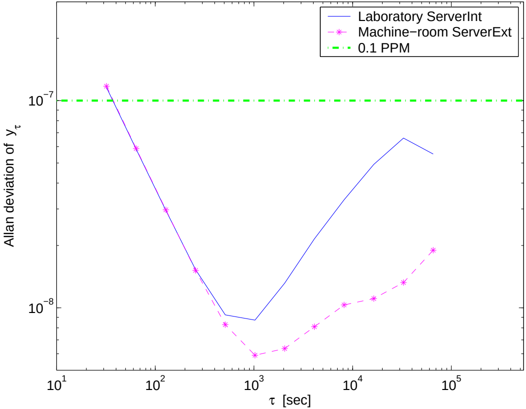


Short timescales: Simple Skew Model applies

Large timescales: unpredictable drift must be tracked

Oscillator Stability

Allan deviation: scale dependent rate errors: $y_\tau(t) = \dfrac{\theta(t+\tau) - \theta(t)}{\tau}$



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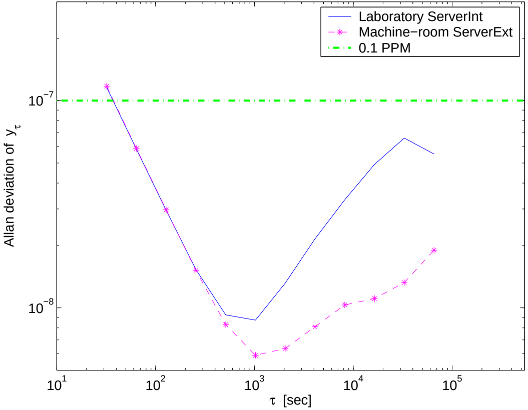

- SKM holds for $\tau^* = 1000$ [sec], (here TSC period p meaningful)
- Average rate error upper bounded by 0.1 PPM no matter the scale

The Need for Difference Clocks

Stable rate (p good to 10^{-7}) implies accurate $\Delta(t)$ measurement:

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- To synchronize $C_a(t)$, could
  - continuously modulate rate (*ntpd* uses $\pm$500 PPM band)
  - regularly add corrective jumps
- Either way, rate is disturbed
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Result: high native stability degraded by unbounded amount!

A Dual Clock Architecture

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- Used for time differences below $\tau^* \sim 1000$ sec
- $C_d(t) = C_u(t)$ Example: $C_d(t_2) - C_d(t_1) = \bar{p} \cdot (\mathrm{TSC}(t_2) - \mathrm{TSC}(t_1))$
- Immune from errors in drift correction
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Absolute Clock

- Absolute timestamps (and time differences above τ^*)
- $C_a(t) = C_u(t) - \hat{\theta}(t)$
- Drift correction estimate $\hat{\theta}(t)$ only applied when clock read
- Use: latency, global event ordering and scheduling ..

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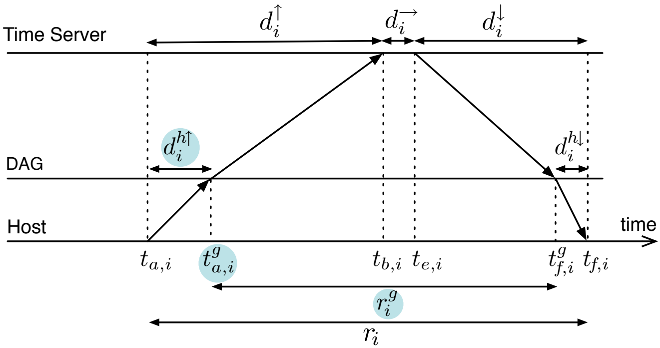
Require robust, accurate algorithms for $\bar{p}$ and $\hat{\theta}$

A CLIENT-SERVER PARADIGM



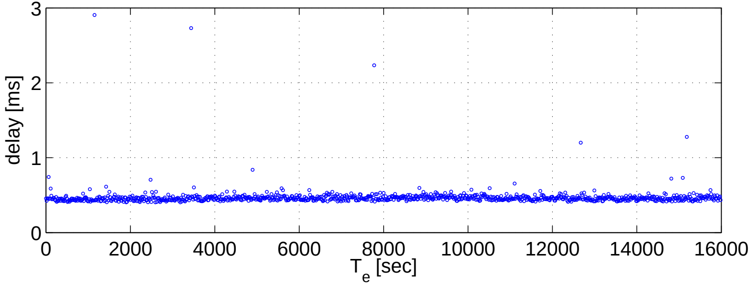
Obtain timestamps $\{T_{a,i}, T_{b,i}, T_{e,i}, T_{f,i}\}$ from i-th exchange

$\{T_{a,i}, T_{f,i}\}$: host timestamps in TSC counter units
$\{T_{b,i}, T_{e,i}\}$: server timestamps in seconds

Filtering Network Delays

Choose RTT based filtering, not one-way (using same clock good!)

Round–Trip Times r_i of packet i



Model for RTT: $r_i = r +$ positive random noise

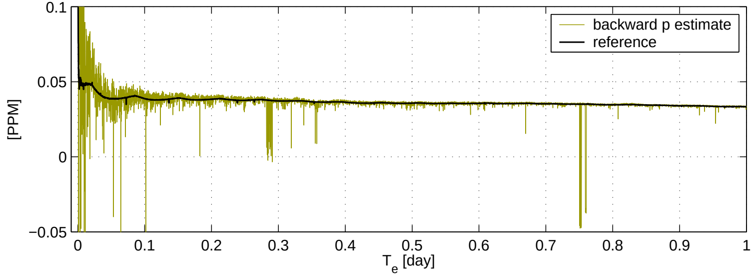
Filter using point error: excess over minimum RTT

Naive Rate Synchronization

Wish to exploit the relation $\Delta(t) = \Delta(\text{TSC}) * \bar{p}$

Naive estimate based on widely separated packets j and i:

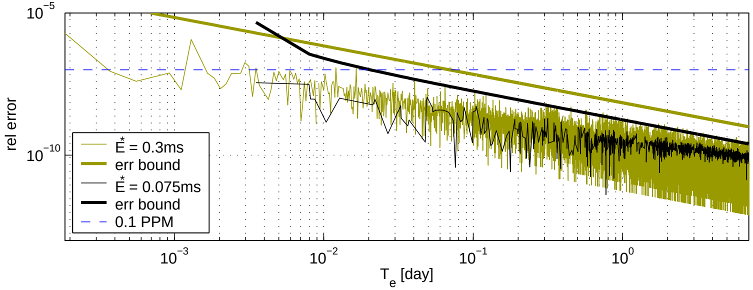
$$\hat{p}^{\uparrow}_{i,j} \equiv \frac{T_{b,i} - T_{b,j}}{T_{a,i} - T_{a,j}}$$



Network delay and timestamping noise $\sim \frac{1}{\Delta(\text{TSC})}$, but errors not bounded.

Rate Synchronization Algorithm

Use selected naive estimates based on point error threshold



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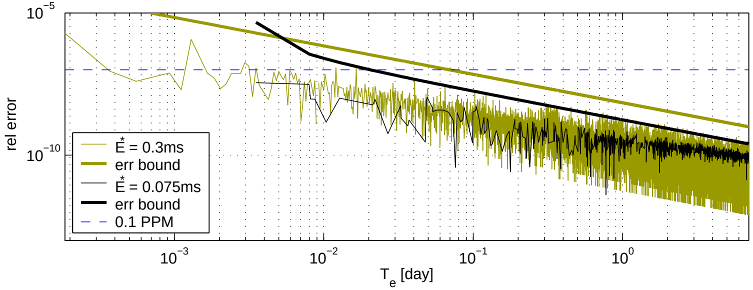


Properties

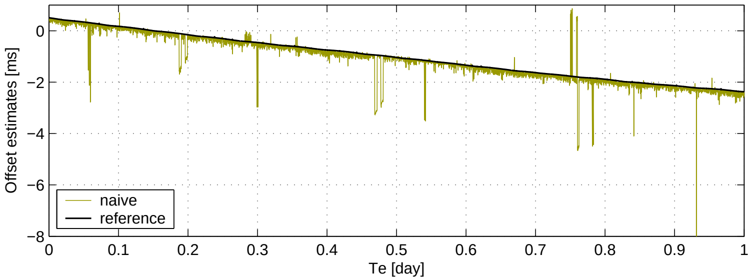
- Error quickly < 0.1 PPM, In 10mins, measure 10ms to better than 1ns!
- Error reduction (in timestamping, latency) guaranteed by $\Delta(t)$
- Inherently robust to packet loss, congestion, loss of server..
- Based on $\bar{p}$, no local rate estimates

Naive Absolute Synchronization

Wish to exploit SKM over small scales to measure $\theta(t)$

Naive estimate again ignores network congestion, exploits steady rate over RTT

$$\hat{\theta}_i = \frac{1}{2}(C(t_{a,i}) + C(t_{f,i})) - \frac{1}{2}(T_{b,i} + T_{e,i})$$

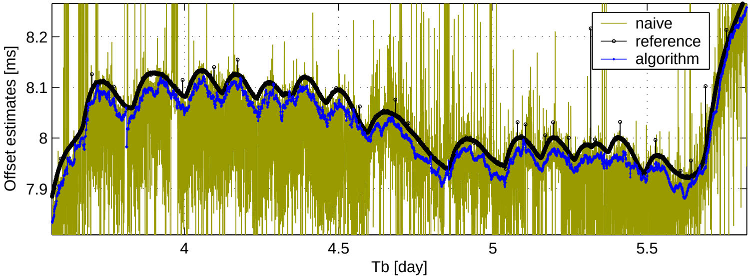


Absolute Synchronization Algorithm

Must track, so use all naive estimates, but carefully

Algorithm for $\hat{\theta}(t)$

- Weighted estimate of naive θ_i's over SKM window
- Weights very strict, based on RTT quality (if quality very bad, freeze)
- Meaningful sanity check: ignore if hardware rate bound exceeded



The Path Asymmetry

Fundamental Ambiguity

Asymmetry $A \equiv d^{\uparrow} - d^{\downarrow}$ and $2\theta(t)$ non-unique up to a constant.

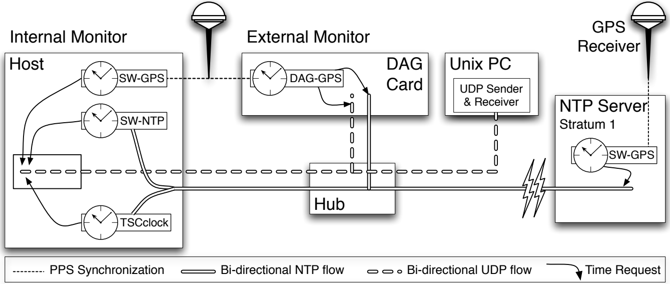
Impact on Absolute Clock

- A unknown: generally forced to assume $A = 0$
- However, bounded by minimum RTT: $A \in (-r, r)$
- Create constant errors from 5μs to 100's ms
- Causes jumps when server changed
- $\rightarrow$ Important to use a single, close, server.

Impact on Difference Clock

- None
- Difference clock can be used to measure r

TESTBED



- GPS synchronized DAG card for *external* validation
- GPS synchronized SW and modified kernels for *internal* validation

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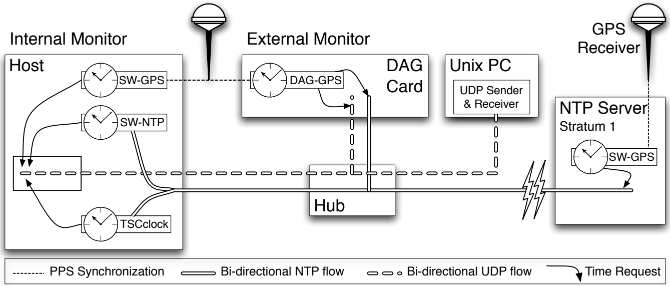
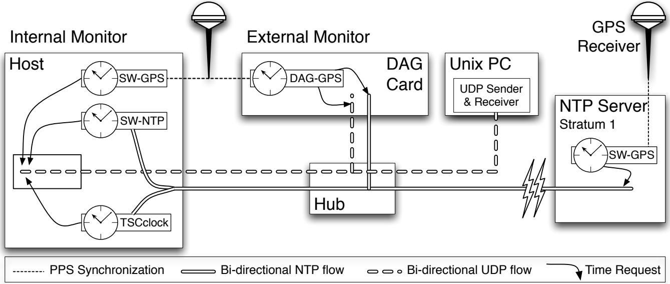


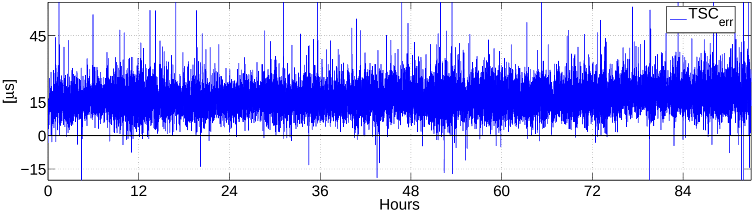
- GPS synchronized DAG card for *external* validation
  - timestamps accurate to 100ns, but
  - comparison polluted by ‘system noise’
  - splits asymmetry: $A = A_n + A_h$
  - allows network component A_n to be measured
  - host component A_h can only be bounded, can be >200μs!
- GPS synchronized SW and modified kernels for *internal* validation

Testbed

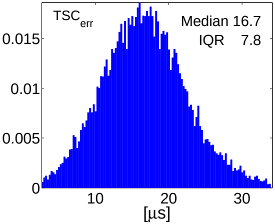


- GPS synchronized DAG card for *external* validation
- GPS synchronized SW and modified kernels for *internal* validation
  - side by side timestamps cancels noise, but
  - only relative performance measurable, not absolute

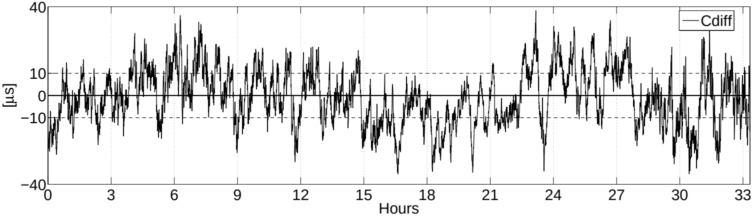
External Validation: TSCclock vs DAG



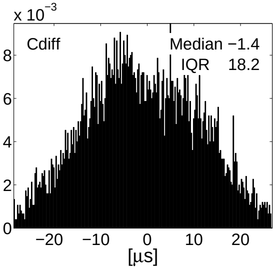
Server:	Stratum-1 NTP on LAN
Polling Period:	256 sec
System Noise:	$\sim 20\mu s$
Asymmetry:	Measured at $36\mu s$ and removed



Internal Validation: TSCclock vs SW-GPS

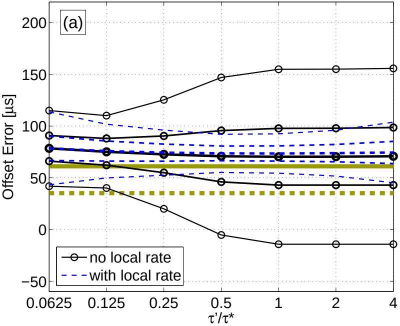


Server:	Stratum-1 outside LAN
Polling Period:	16 sec
System Noise:	$\ll 1\mu$s
Asymmetry:	As before for TSCclock, but SW-GPS component?

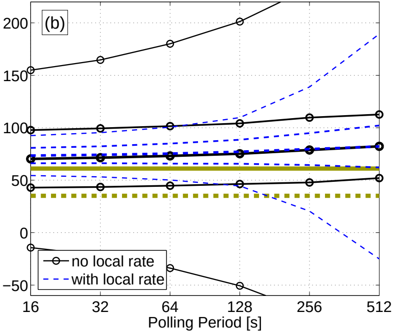


Parameter Dependence

window width



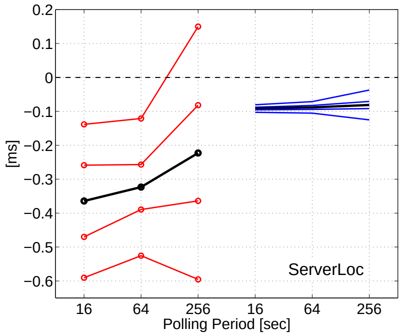
polling period



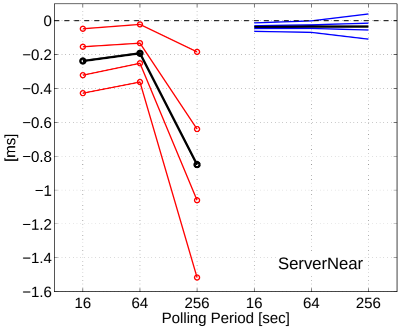
Duration:	32 days
Server:	Stratum-1 NTP, 5 hops away, $r = 0.61$ ms
Poll Period:	16 sec
Asymmetry:	$A_n = 70\ \mu$s
Median IQR:	12μs (corrected for A)
IQR:	15μs (including external validation noise)

COMPARISON WITH *nptd*

Server on LAN

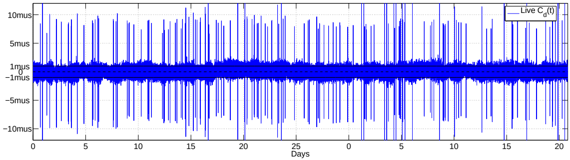


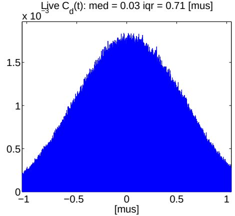
Server outside LAN



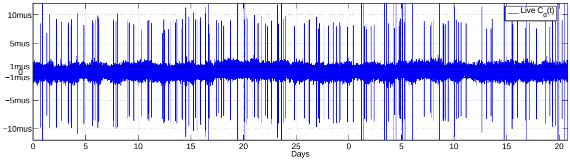
Asymmetry: Same for each clock

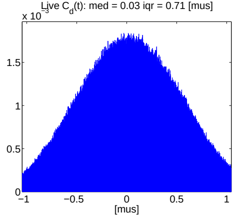
Difference Clock versus GPS





DIFFERENCE CLOCK VERSUS GPS





Now compare if *no connectivity* with server

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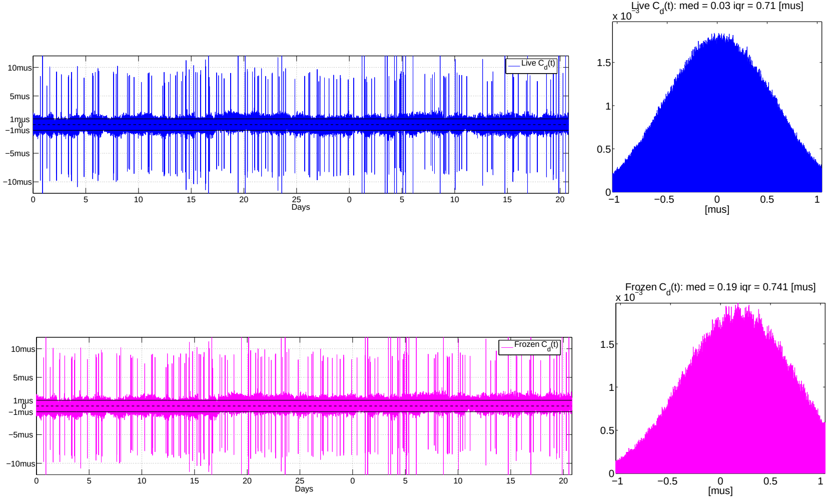

THE SYSTEM

- API
  - absolute and difference clock reading
  - mode setting/reading
  - diagnostics
- Timestamping solution
  - better with kernel support
- Synchronization algorithm:
  - runs as daemon or on command line
  - can store and replay log files
- Server
  - no server side solution, yet
  - client compatible with existing NTP servers
  - designed (and recommended) for use with a single server

Timestamping

Kernel

User

Timestamping

Kernel

- Packet timestamping:
  - Normal mode: TSCclock works in parallel with SW
  - TSCclock mode: SW also returns $C_a(t)$ transparently
- Other timestamping:
  - TSCclock works in parallel with SW

User

- Packet timestamping:
  - Kernel packet timestamps inferred from userland
  - TSCclock works in parallel with SW

PACKAGING

- Ubuntu 6.10 (Edgy)
- Ubuntu 7.04 (Feisty)
- Debian 4.0 (Etch)
- Fedora Core 6
- and soon Fedora Core 7 ...

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Generic design: can handle high jitter, but not tuned for it

LINKS

- Publications:
  http://www.cubinlab.ee.unimelb.edu.au/articles
- TSCclock page:
  http://www.cubinlab.ee.unimelb.edu.au/tscclock
- Homepage:
  http://www.cubinlab.ee.unimelb.edu.au/∼darryl