

Middleware and Distributed Systems

Time

Peter Tröger

Time In Distributed Systems

- Time is important
 - Timestamp of electronic commerce transactions
 - Some distributed algorithms depend on global time (consistency, authenticity checking, duplicate elimination)
- Time is problematic in distributed systems
 - Absence of global physical time
 - Local physical clock deviation
 - Order of event pairs from different nodes
 - E.g. distributed garbage collection

Time In Distributed Systems

- Collection of N processes $p_i = p_1, p_2, \dots, p_N$
 - Each *process* on a single processor, no shared memory, own state s_i
 - Only message communication - send and receive *actions* change state
- *Event* as communication or state change action
 - Single total ordering of events in one process: $\text{history}(p_i) = e_i^0, e_i^1, e_i^2, \dots$
- Timestamp for event
 - Physical computer clock: Counting of crystal oscillations, divide count and storage in register as hardware clock value $H_i(t)$
 - *Clock drift*: time is counted in different rates in the hardware clock
 - *Drift rate*: Offset to perfect clock value (10^{-6} to 10^{-8} , atom clock 10^{-13})

Drift Rates

Time	Quartz Clock
1 second	0,000001 seconds
1 minute	0,00006 seconds
1 hour	0,0036 seconds
1 day	0,0864 seconds
1 week	0,6048 seconds
~11.6 days	1 second

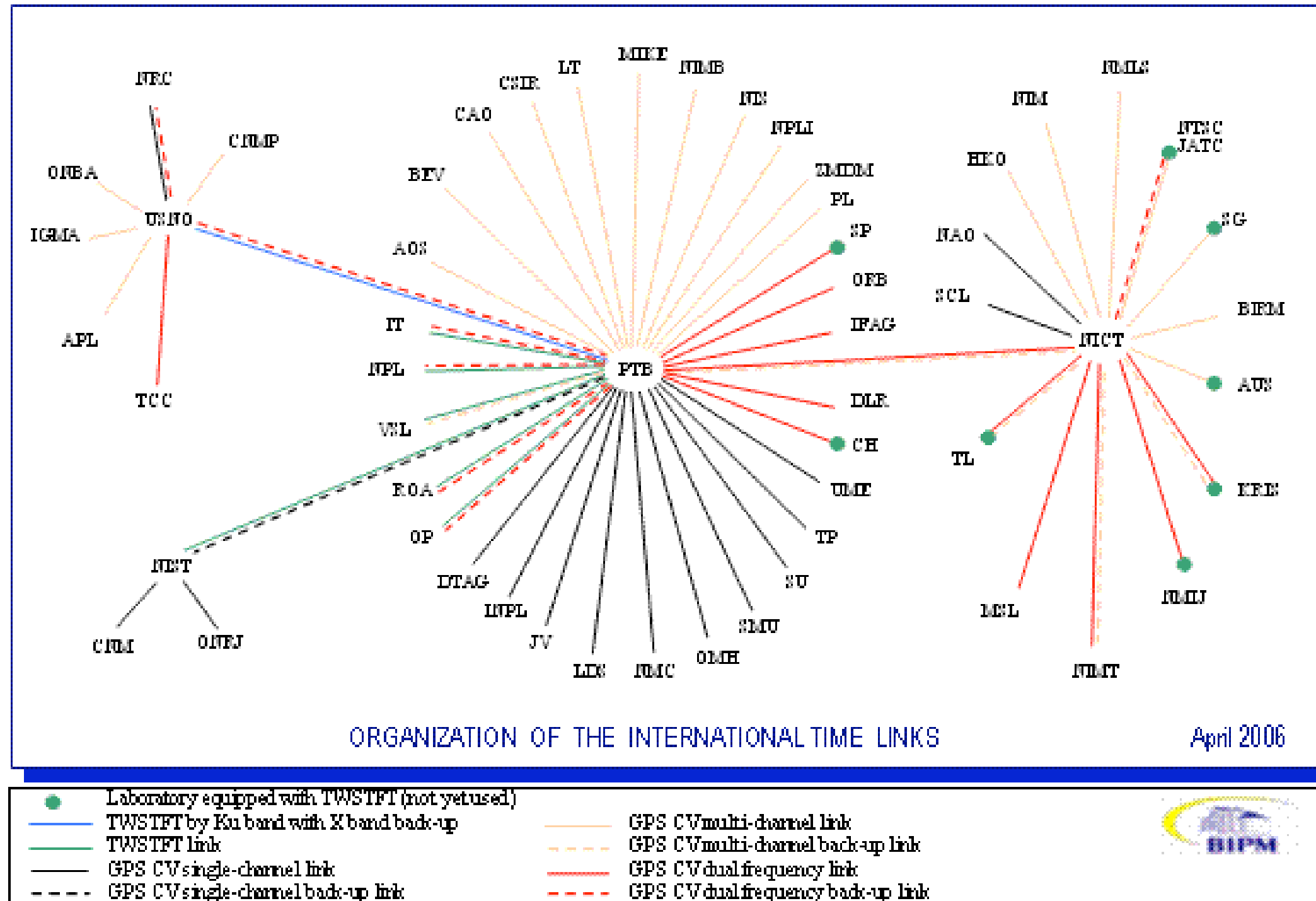
Clock Correctness

- *Correct* clock: Error in measured time interval is bounded
 - No jumps in time larger than pre-defined drift rate bound
- *Monotonous* clock: Clock only ever advances
 - Typical assumption for software clocks (make utility)
- Hybrid correctness approach: Monotonicity condition, but bounded drift rate only between synchronization points
- Faulty clock: crash fault (no more ticking) or arbitrary fault
 - Y2K clock: monotonicity condition broken
 - Large drift rate

Global Time

- A mean solar second is $1/86400$ of a mean solar day
 - Solar day is interval between two consecutive transits (max height) of the sun
 - Solar day has gradually become 1.7 ms longer every century (moon acceleration)
 - 300 million years ago, a year had 400 days
- Invention of atomic clock in 1948
 - Counting of transitions of cesium 133 atom, since 1.1.1958
 - Increasing delay between mean solar time (UT1) and measured atomic time (TAI)
- International atomic time (TAI - Temps Atomique International)
 - Weighted average of the ticks of around 300 atomic clocks worldwide, e.g. TA(PTB)
 - Publication of latest TA(n) drift to TAI in Circular T publication
 - Managed by Bureau International des Poids et Mesures (BIPM)

TAI Computation by Pair-Wise Atomic Clock Drift



TAI Correction Factors

- Ionospheric Maps
- Operational satellite positioning from International GPS Service (IGS)
- 1970's: Different tick rates due to gravitational time dilation
 - Corrections to correspond to proper time at mean sea level
 - TAI slowed down by about 10^{-12}
- 1990's: Periodic variations due to blackbody radiation, which varies with ambient temperature
 - Corrections factors to correspond to caesium atom at rest and at absolute zero temperature
 - TAI speed up by $10^{-14.3}$

UTC

- Coordinated Universal Time (CUT) or Temps Universel Coordonné (TUC)
 - Compromise abbreviation UTC by ITU organization
 - Replaced 'greenwich mean time' (astronomical time) with TAI time
 - Zero-point reference for time zones: 'zulu time'
 - Occasionally insertion of leap second (diff > 0.6s), to keep in step with solar time
 - End of June 30 or December 31, decided by IERS
- Most power companies rely 60Hz / 50Hz timing on UTC clock
 - With leap second, frequency raised to 61Hz or 51Hz for 60 or 50 sec
 - Meanwhile 33 leap seconds in UTC
- UTC time by shortwave radio pulse every second ($\pm 10\text{ms}$) or satellite ($\pm 0.5\text{ ms}$)

Synchronizing physical clocks

- Synchronized clocks needed for global total ordering of events
- *External synchronization*
 - Process clocks must be synchronized with authoritative external source
 - Clocks C_i are accurate to within a given bound D
- *Internal synchronization*
 - Synchronization of process clocks with each other, without external reference
 - Clocks C_i agree within a given bound D
- Externally synchronized system with bound D is internally synchronized with bound $2D$

Interaction Models

- Synchronous distributed system
 - Lower and upper bound for each process execution step
 - Upper bound for message transmission time
 - Local clock for each process, upper bound for clock drift rate
 - Mostly for theoretical models, hard to build in reality
- Asynchronous distributed systems
 - Different process execution step times, each with arbitrary length
 - Different message transmission delays
 - Different clock drift rates on each node

Clock Synchronization In Synchronous System

- Known bounds for drift rate and transmission delay
- P_1 sends t_1 of local clock to P_2 , which theoretically sets $t_2 = t_1 + T_{\text{trans}}$
 - T_{trans} is unknown
 - Uncertainty $U(T_{\text{trans}}) = T_{\text{max}} - T_{\text{min}}$
 - Receiver can set his clock: $t_2 = t_1 + T_{\text{max}}$ or $t_2 = t_1 + T_{\text{min}}$
-> clock skew may be as much as U in both cases
 - Receiver can set $t_2 = t_1 + (T_{\text{max}} - T_{\text{min}})/2$ -> clock skew is at most $U/2$
 - [Lundelius and Lynch 84] Optimum bound on clock skew for N clocks in a synchronous system is $U \cdot (1 - 1/N)$
- Asynchronous system:
 - Unbounded message delays and execution step time

Task: Server time synchronization algorithm

Old Approaches

- First protocols in 1983
- DAYTIME protocol (RFC 867), port 13
 - Unspecified ASCII string with date and time
 - Example: time.nist.gov
- TIME protocol (RFC 868), port 37
 - 32-bit number, number of seconds since 00:00 1 January, 1900 GMT.

Clock Synchronization (Cristian 89)

- Central time server with time t_s , synchronized with UTC source
- Estimate roundtrip time between two nodes, since it remains constant
 - Exact local measurement of roundtrip time t_{round} is possible, because of relatively small clock drift rate (1 - 10 ms LAN, 10^{-5} ms drift rate)
 - $t_p = t_s + t_{\text{round}}/2$ (same time for request / reply)
- With minimum transmission time t_{min}
 - t_s was obtained earliest t_{min} after sending, and t_{min} before receiving
 - Accuracy of computed server time is $\pm(t_{\text{round}}/2 - t_{\text{min}})$
 - Time when reply arrives is in range width $t_{\text{round}} - 2t_{\text{min}}$
 - Minimal roundtrip time (as known value) brings most accuracy

Problems with Cristian Algorithm

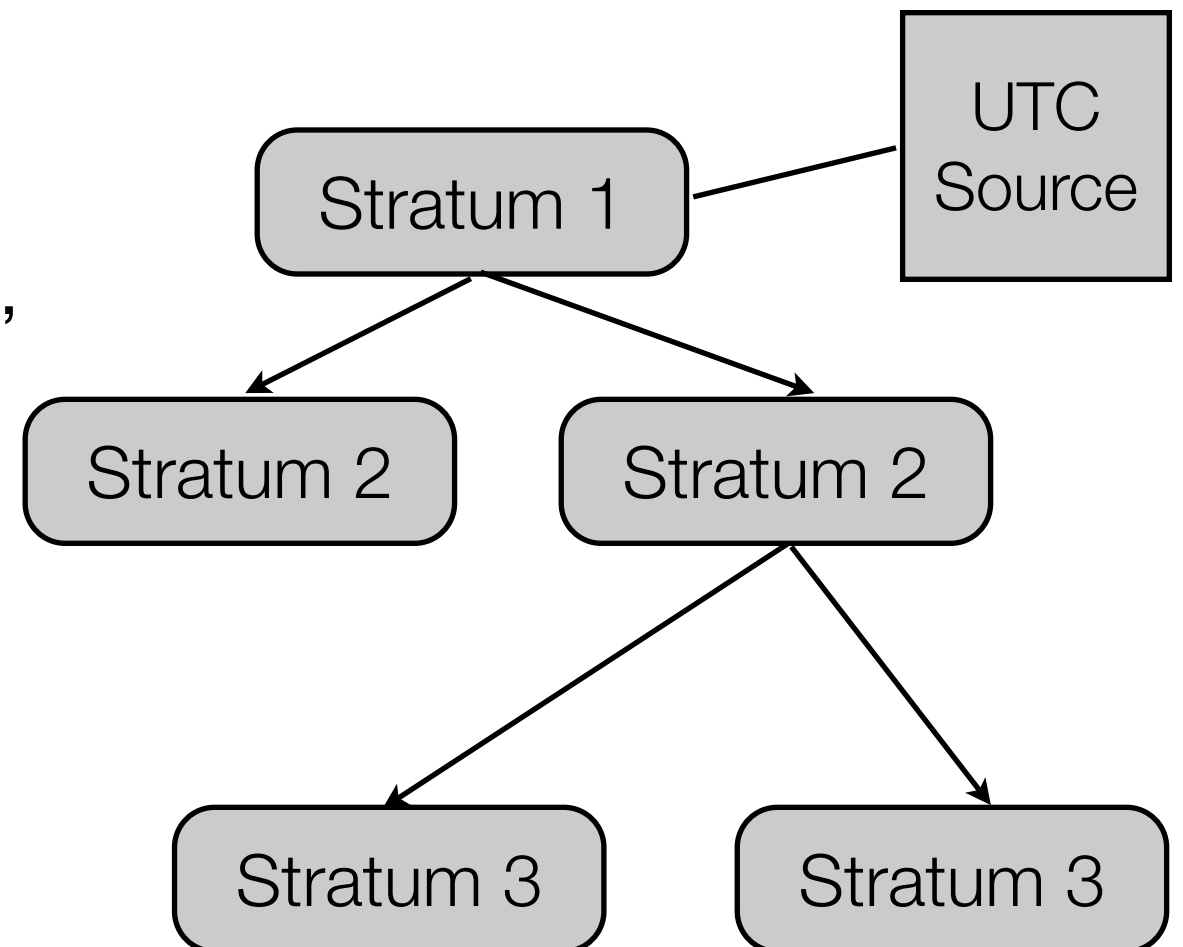
- No consideration of faulty clocks
 - Cristian suggested group of synchronized time servers
 - [Dolev 86]: f faulty clocks out of N demands $N > 3f$ for agreement
- Possibly time jumps on large skews
- Single roundtrip is possibly inexact
 - multiple measurements with average forming
 - discard runaways

Clock Synchronization (Gusella and Zatti 89)

- Berkeley (Unix) algorithm for internal synchronization
 - Master node polls slave nodes, slaves send clock values back
 - Master estimates each roundtrip time, and averages all values
 - Accuracy depends on maximum roundtrip time - longer reads are not considered in the average computation
 - Master sends back adjustment for each slave clock
 - Sending master time would introduce another transmission uncertainty
 - Failed master demands election protocol
 - Faulty slave nodes detected by fault-tolerant average
 - Average for sub-group should not differ too much from other sub-group

Network Time Protocol (Mills 95)

- Time synchronization over the Internet
 - Large and variable message delays - statistical techniques for data filtering, different time quality for different servers
 - Redundant servers and paths
 - Scalability for large numbers of periodically synchronizing clients
 - Protection with authentication techniques
 - Leaf servers executed in users workstation
 - External synchronization



NTP Terminology

- Clock stability: How well it can maintain a constant frequency
- Clock accuracy: How well frequency and time compare to national standard
- Clock precision: Precision of time quantities
- Clock offset: Time difference between two clocks
- Clock skew: Frequency difference between two clocks
- Clock skew variation: clock drift (assumed zero in NTP)
- NTP produces clock offset, roundtrip delay and dispersion
 - Clock offset is amount to adjust local clock to reference clock
 - Roundtrip delay allows to launch a message to arrive at specific time
 - Dispersion means the maximum clock offset to reference time

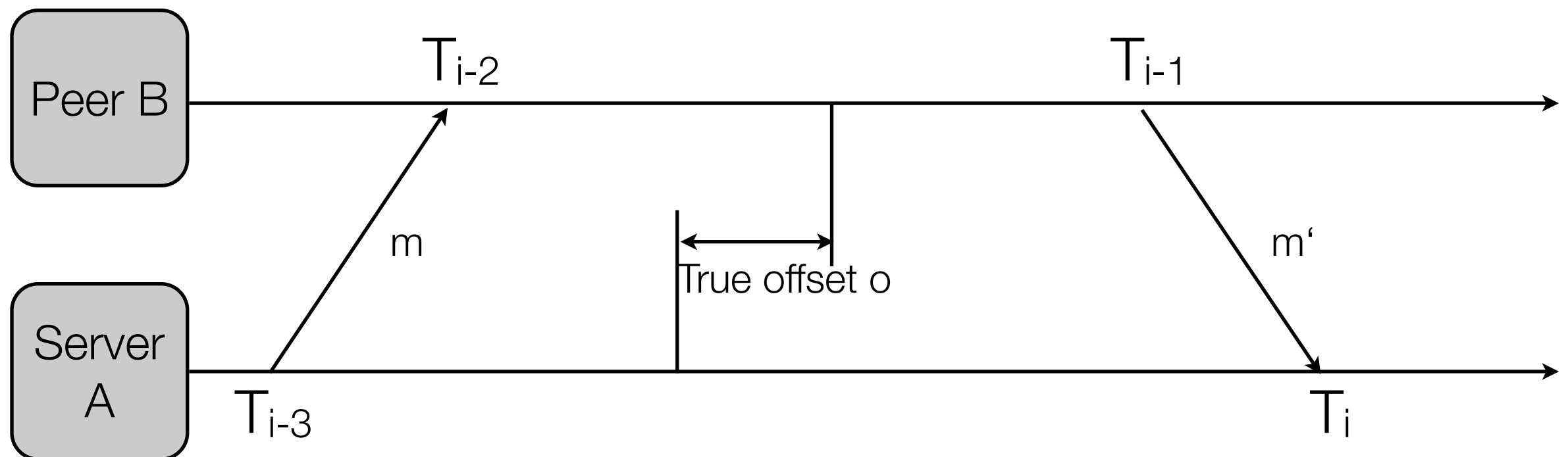
Demo

Network Time Protocol

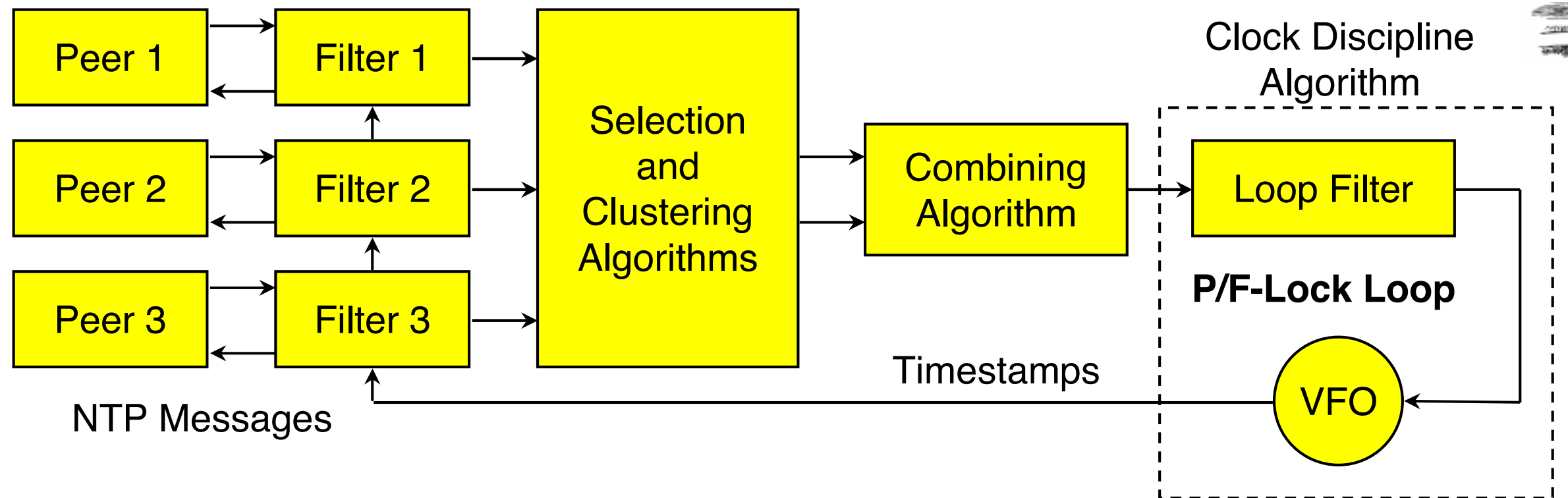
- UDP transport, port 123; oldest protocol in today's internet
 - Own duplicate detection, single message format
- Over 230 primary servers, estimated 10-20 million NTP servers
- NTPv3 in RFC 1305, NTPv4 finished
- Long periods and multiple comparisons (with low network load) needed
- Accuracy in order of tens of milliseconds (Internet) or one millisecond (LAN)
- Operating system kernel adjusts microseconds / clock tick, based on measured clock drift
 - Consideration of *time_adj* value in each call of `update_wall_time_one_tick()` (Linux *timer.c*)

NTP Algorithm

- Exchange of timestamps to estimate offset o_i between the clocks at T_i and roundtrip delay $d_i = m + m'$; Errors due network delays dominate
- $T_{i-2} = T_{i-3} + m + o_i$ and $T_i = T_{i-1} + m' - o_i$, therefore $d_i = T_{i-2} - T_{i-3} + T_i - T_{i-1}$
- Estimated offset $o_i = (T_{i-2} - T_{i-3} + T_i - T_{i-1}) / 2$
- $o \leq T_{i-2} - T_{i-3}$ and $o \geq T_i - T_{i-1}$ since $m, m' > 0$, leads to **$o_i - d_i/2 \leq o \leq o_i + d_i/2$**



NTP Algorithm



(C) David Mills 2004

- Computed delay and offset pairs $\langle o_i, d_i \rangle$ are filtered
- Statistical quantity expresses the measurement quality (filter dispersion)
- Similar to Cristian, the o_j for the smallest d_j is taken (from 8 samples)
- Clock frequency adjustment according to drift rate, runs in interval of a second

Synchronization Modes

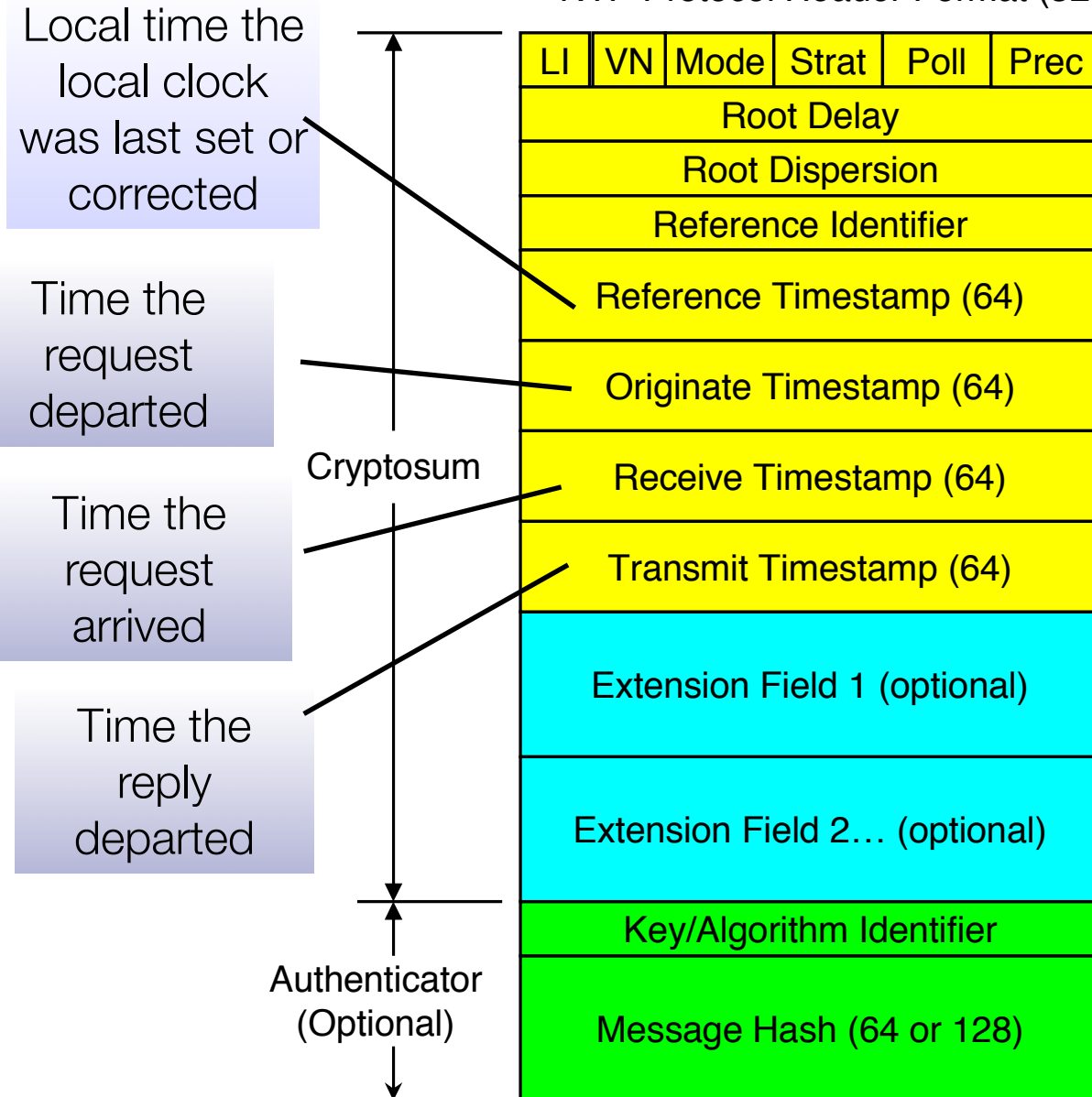
- Multicast
 - For high-speed LAN, receiving servers assume small delay of a few milliseconds
 - Server announces time, but does not accept NTP messages
- Procedure call
 - Server in client mode is willing to be synchronized, but offers no service
 - For LAN's without multicast or demand for higher accuracy
- Symmetric
 - Active mode for high-stratum servers, with pre-configured peers
 - Passive mode for low-stratum servers and large number of peers

Data Formats in NTP

- NTP timestamp: 64bit unsigned fixed-point number
 - Number of standard seconds since 1.1.1900, relative to UTC
 - Precision of 232 picoseconds
 - 1968, the most significant bit has been set - overflow in 2036
- Leap indicator: 00 no warning, 01 last minute has 61 seconds, 10 last minute has 59 seconds
- Precision of the local clock, roundtrip delay to primary reference source, maximum error to primary reference source
- Reference clock identifier
 - Stratum 2 or greater - IP address of reference clock; otherwise special tag (e.g. ATOM or GPS)

NTP Protocol

NTP Protocol Header Format (32 bits)



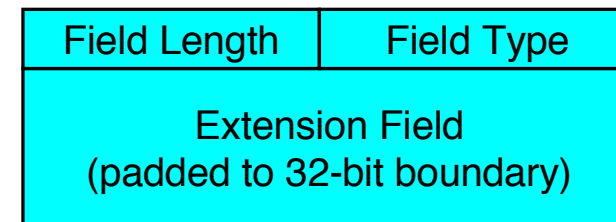
LI leap warning indicator
 VN version number (4)
 Strat stratum (0-15)
 Poll poll interval (log2)
 Prec precision (log2)

NTP Timestamp Format (64 bits)

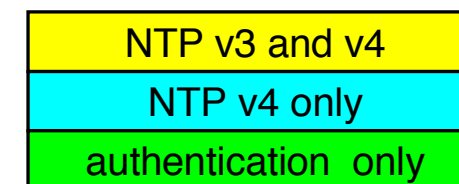


Value is in seconds and fraction since 0^h 1 January 1900

NTPv4 Extension Field



Last field padded to 64-bit boundary



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

(C) David Mills 2004

NTP Robustness

- Peer is considered unreachable if 8 poll intervals fail
- Originate timestamp as one-time pad
 - Should somehow match to transmit timestamp of last message
- Longest poll intervals must be consistent with required accuracy
 - Poll interval is increased from minute to about 17 minutes, as long as filter dispersion is below an experimentally determined threshold
- Consistency algorithm for NTP peer selection (to find most reliable clock from a population)
 - Highest reliability = lowest stratum and lowest synchronization distance (sum of total roundtrip delays to the synchronization root)