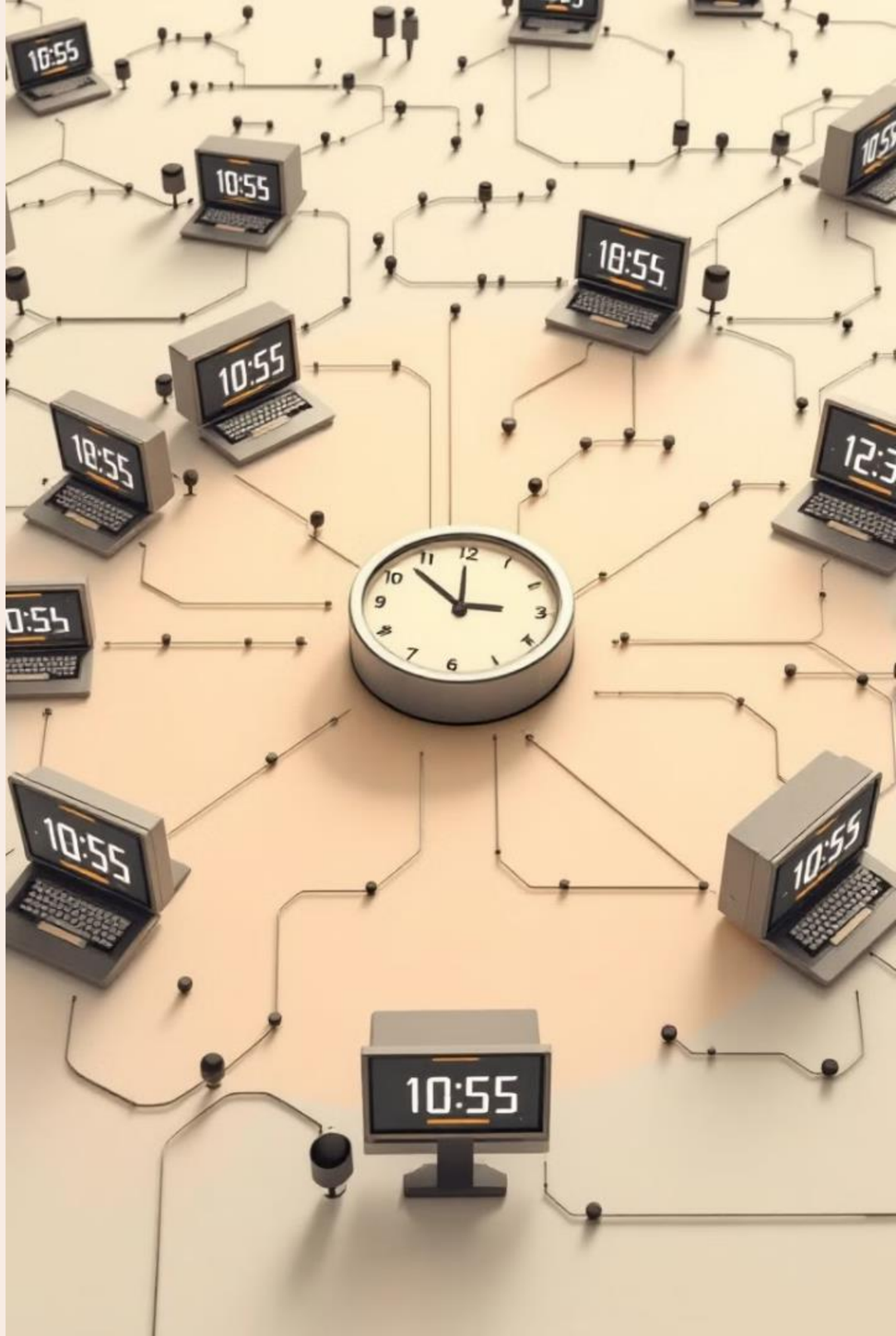
Excuse me, do you have the time ?

Please excuse all the AI images.

This is an "experiemental" set of slides.



Why Time Sync Matters

Log Accuracy

Including causality across distributed systems.

Broadcast Systems

SMPTE / ST2059 built on PTP.

Stock Market / HFT

Banking and stock trading systems require precise timing.

Databases: Optimistic Concurency

Can avoid the need for locking and vastly improve performance.

Goals.

Time synchronization in networks has two distinct goals:

1. Device-to-Device Synchronization

Ensures all devices in a network have the **same time relative to each other**, regardless of whether that time is accurate to the real world.

2. Wall Clock Accuracy

Ensures devices maintain time that is **accurate to the real world standard** (UTC/GMT).

Ideally you want both!

Stepping vs. Slewing the Clock

Stepping the Clock

Instantaneously changes the clock time.

Issues with Stepping:

- Stepping backwards can break causality
  - Effects can come before cause
  - Many applications assume time moves forward monotonically
- Stepping forwards can break durations
  - A customer may get billed for more usage than they actually had
  - You may jump past a timed event and not trigger it

Slewing the Clock

Gradually adjusts the clock time.

Benefits of Slewing:

- Preserves causality of events
- Maintains monotonic time progression

Generally preferred for ongoing time synchronization, but may take too long if clock offset is too high.

Mario Odyssey: Time Manipulation Trick

The Setup

Speedrunners set the Switch clock to 8 minutes before daylight savings time shift occurs.

The Execution

Players spend 8 minutes playing the game, until they get to a part where they throw a seed into a plant pot that normally takes 20 minutes to grow.

The Zone Change

They run around a corner into a building (zone change), then return to find time has jumped forward due to daylight savings.

The Reward

The plant has already sprouted and produces a moon, saving 12 minutes of waiting time!

NTP.

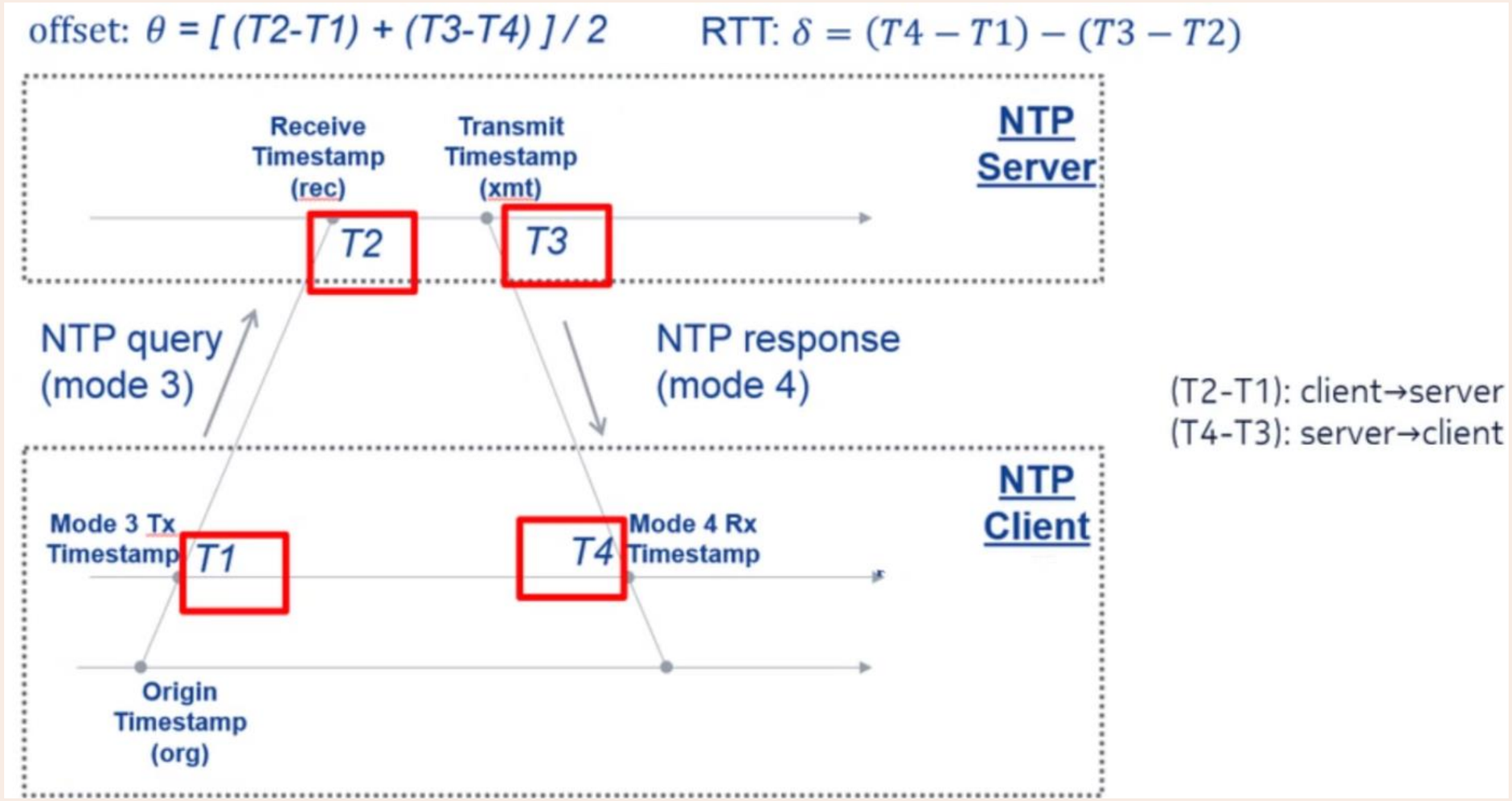
NTP (Network Time Protocol).

Aims for microsecond level precision.

Developed by David Mills in 1985.

Currently at NTPv4, with some NTPv3 legacy.

NTP Timestamp Exchange.
Regular Mode.



NTP (v4) Packet Structure

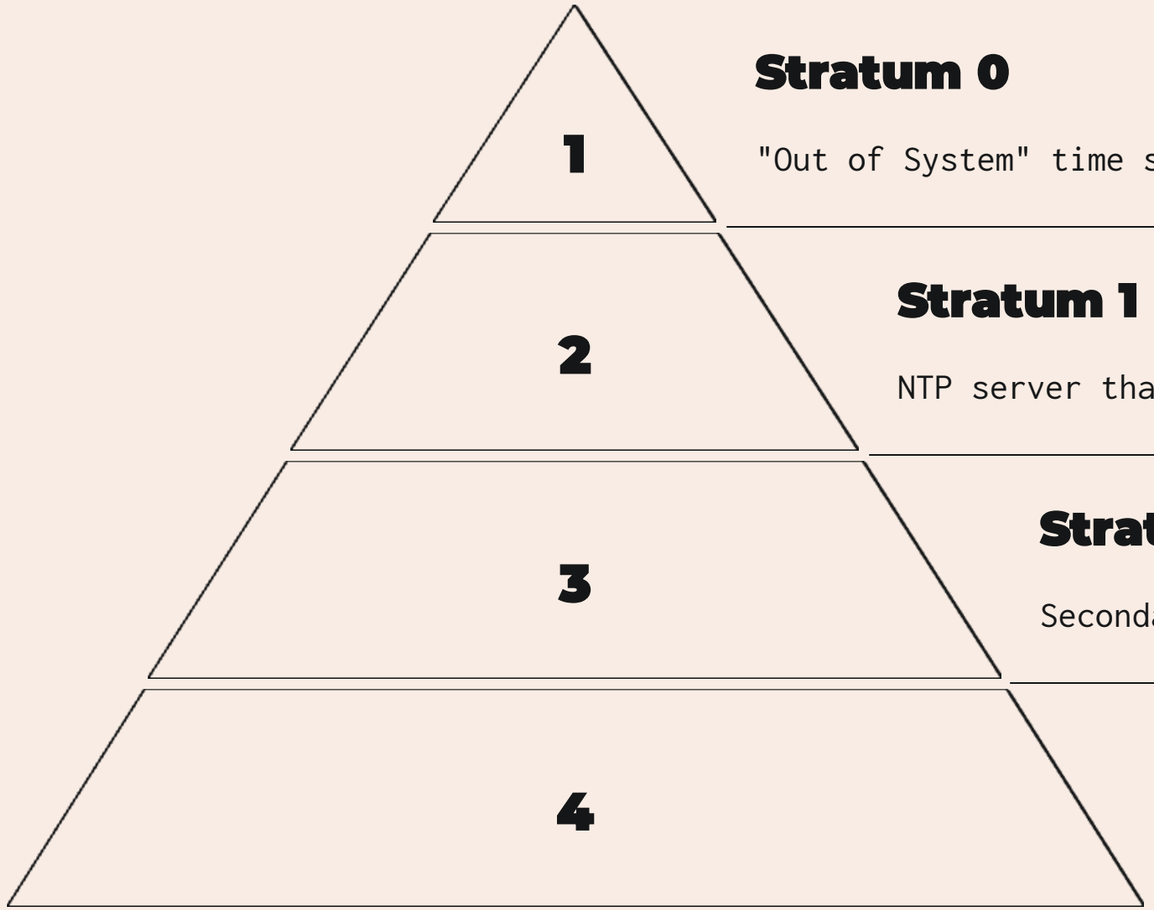
NTP packet header format[5] (section 7.3)

Offset	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	*LI*		*VN*			*Mode*			*Stratum*								*Poll*								*Precision*							
4	32	*Root Delay*																															
8	64	*Root Dispersion*																															
12	96	*Reference ID*																															
16	128	*Reference Timestamp (64-bits)*																															
20	160																																
24	192	*Origin Timestamp (64-bits)*																															
28	224																																
32	256	*Receive Timestamp (64-bits)*																															
36	288																																
40	320	*Transmit Timestamp (64-bits)*																															
44	352																																

NTP Packet Fields

- **2bits: Leap Indicator (LI):** Warns of impending leap second to be inserted/deleted in the last minute of the month.
- **3bits: Version Number (VN):** NTP version number (e.g., 3 for NTPv3, 4 for NTPv4).
- **3bits: Mode:** Indicates the mode (e.g., query/response/peer/broadcast/multicast).
- **8bits: Stratum:** Indicates the clock stratum level.
- **8bits: Poll Interval:** Maximum interval between successive NTP messages.
- **8bits: Precision:** Precision of the local clock.
- **32bits: Root Delay:** Total round-trip delay to the primary reference source.
- **32bits: Root Dispersion:** Maximum error relative to the primary reference source.
- **32bits: Reference ID*:** Identifier of the reference source (complicated !)
- **64bits: Reference Timestamp:** Time at which the system clock was last set or corrected.
- **64bits: Origin Timestamp:** Time at which the client sent the request.
- **64bits: Receive Timestamp:** Time at which the server received the request.
- **64bits: Transmit Timestamp:** Time at which the server sent the response.

NTP Architecture: Stratum Levels



Stratum 0

"Out of System" time source.

Stratum 1

NTP server that gets time from outside system.

Stratum 2-15

Secondary servers.

Stratum 16

Unsynchronized.

Reference ID's.

Reference IDs have different meanings depending on the Stratum level:

0 Stratum 0: "Kiss of Death" Packets

- Kiss of Death.
- The Reference ID contains a 4-letter ASCII code indicating an error, examples :-
  - RATE
  - DENY
  - INIT

1 Stratum 1: Time Source Identifiers

When Stratum is set to 1, the Reference ID contains 0-padded ASCII characters identifying the Stratum 0 source:

- GPS: Global Positioning System time
- MSF: UK radio time signal
- WWVB: US NIST radio time signal

2 Stratum 2-15: Network Identifiers

- May be an IPv4 address (which fits in 32 bits)
- For IPv6 addresses (which don't fit), common practice is to take an MD5 hash and truncate to the first 4 bytes

NTP Timestamp Format.

- NTP uses a 64-bit timestamp format to represent the time.
- The timestamp is split into two 32-bit parts:
  - The first 32 bits represent the number of seconds since the NTP epoch (January 1, 1900, at 00:00:00 UTC).
  - The second 32 bits represent the fraction of a second, providing a resolution of about 200 picoseconds.
- We have an NTP rollover problem 2 years ahead of the UNIX rollover problem !
- NTP uses system date to infer what epoch we are in.

Example: NTP Representation of 11 March 2025 @ 12:34:56.12345

Calculation	Value
Seconds since NTP epoch (Jan 1, 1900)	3,954,264,896
Complete NTP timestamp (binary)	11101011100111010101111110000000 (seconds) 00011111100110101101110100110111 (fraction of second)

NTP Algorithms

Clock Select

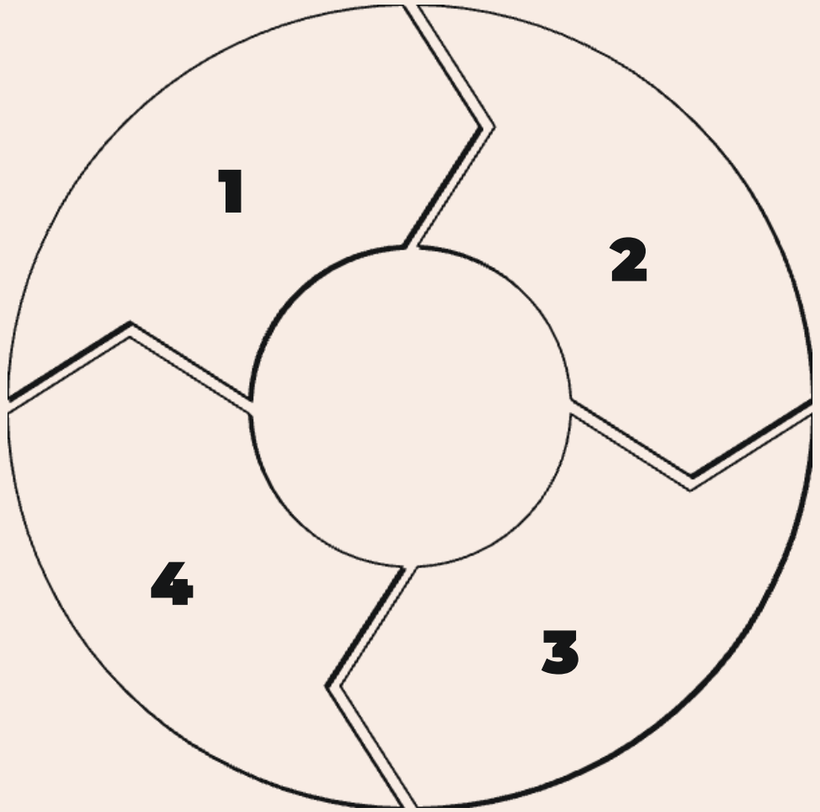
Chooses reliable servers.

Based on latency / jitter / stratum / precision.

Clock Discipline

Nudge local time.

Adjust oscilator correction.



Filter Outliers.

Hard filter outliers.

Sample Weighting

Weights sources closer to mean higher.

NTP TLV Extensions

- **NTP TLV's** (Type-Length-Value) add extensions to the protocol.
- TLV's are added to the end of the standard packet.
- TLV's can send signalling commands like "increase frequency of NTP updates".
- Another important use of TLV extensions is **signing NTP updates**. By adding a TLV field containing a digital signature of the NTP packet, systems can authenticate the update and ensure that it has not been tampered with.
  - **NTP** supports pre-shared-secret signing using SHA-1 or SHA-256.
  - **NTPv4** introduced Autokey. Don't use it, it is broken in multiple ways.
  - **NTS** (Network Time Security) uses an out of band connection secured by TLS to exchange a "session" key to use with NTP.

NTP Sources of Error / Latency

1 2 3

Client

- Userspace program makes packet with timestamp in it.
- Kernel needs to process it.
- Put in NIC TX buffer.
- Be played out NIC.

Network

- Packet spends time in network devices RX and TX buffers.
- Packet spends time in cables.
- Without QoS, these residence times can be variable.

Server

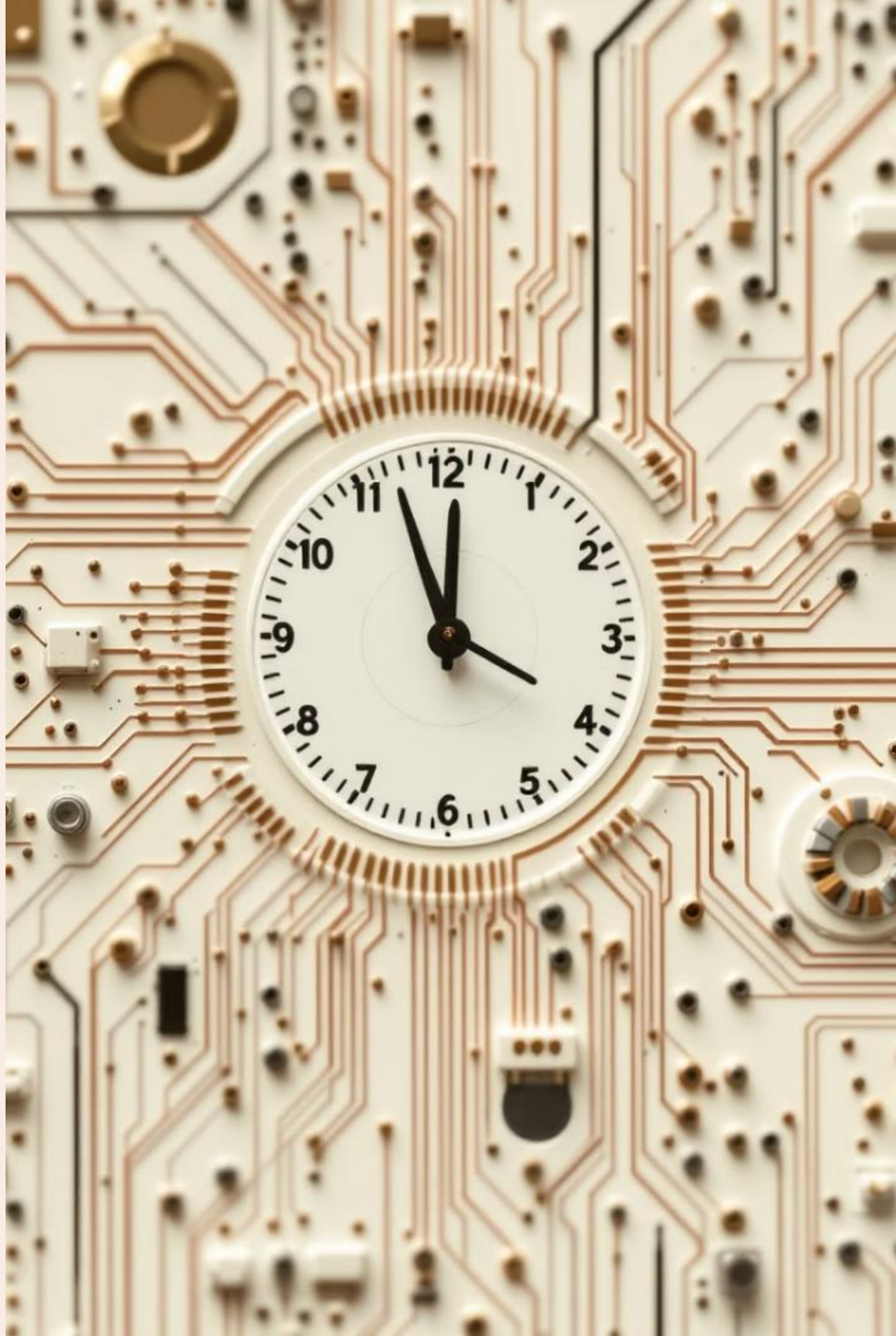
- Packet enters RX buffer on server.
- Kernel needs to give packet to userspace program.
- Kernel needs to schedule userspace program.

- And the same back the other direction.
- This limits NTP's practical accuracy, typically to milliseconds in LAN environments
- and maybe tens of milliseconds across the internet.

Precision Time Protocol (PTP).

An introduction to PTP, a protocol providing precise time synchronization in local area networks.

IEEE 1588 - 2002: PTPv1 (legacy).
IEEE 1588 - 2008: PTPv2 (common).
IEEE 1588 - 2019: PTPv2.1 (new, backwards compatible).



PTP Hardware Requirements

PTP-Specific Hardware Support

Hardware Timestamping

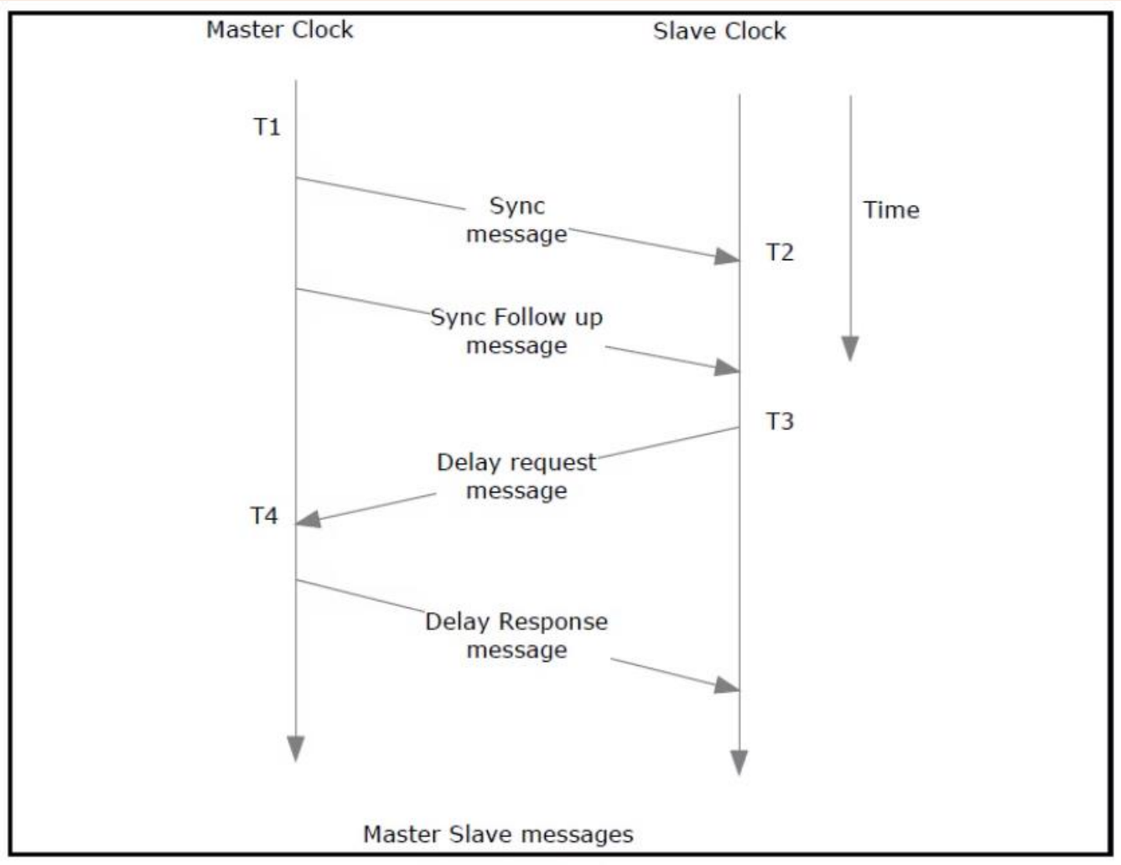
PTP requires specialized Network Interfaces with hardware timestamping capabilities.

Network Infrastructure

PTP needs PTP-aware switches and routers (boundary clocks or transparent clocks) that actively participate in the synchronization process.

- PTP capable hardware used to be rare and expensive.
  - But now a Raspberry PI 5 is capable.
  - More and more "normal" NIC's have support, but not all.
  - Basic Switches/Routers usually still don't have support.

End to End Mode.

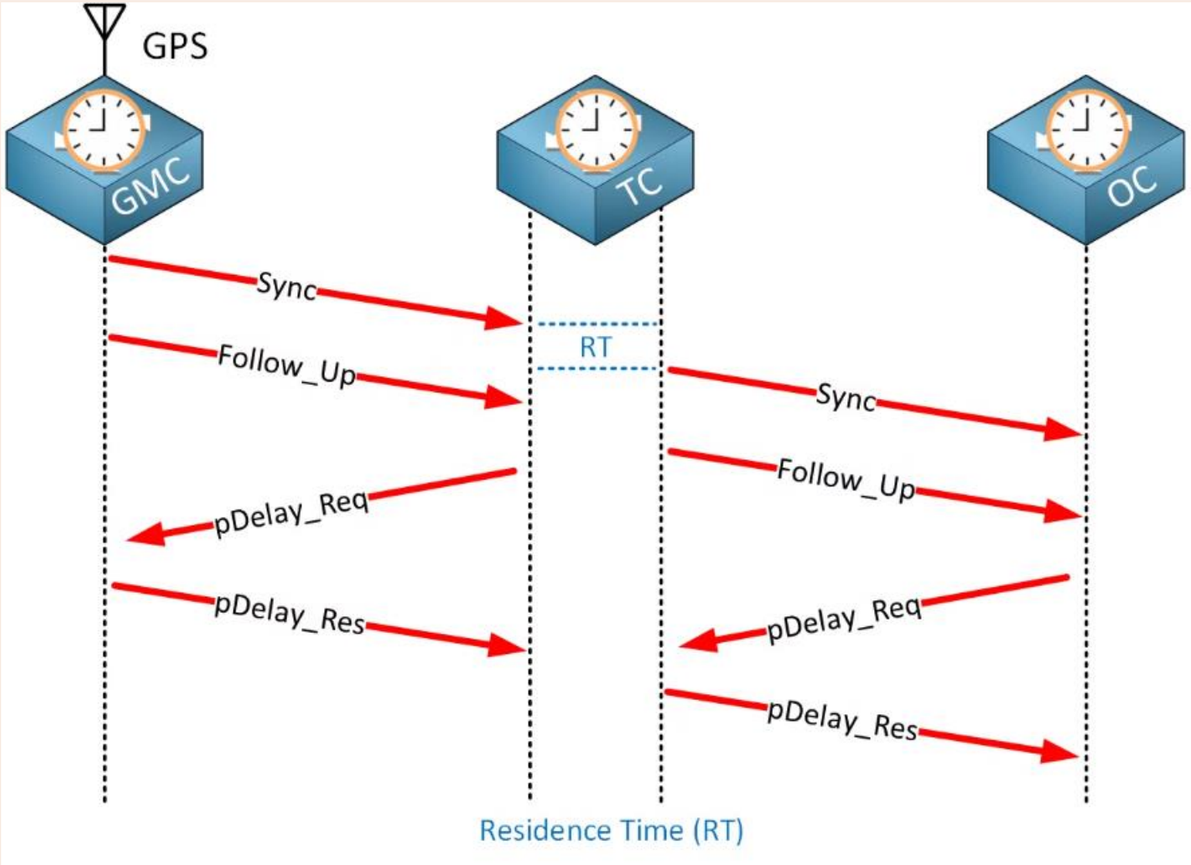


- If One Step, no Follow Up.
- If Two Step, then T1 time is in FollowUp.
- Calculation is then like it was in NTP.

Offset = ((T2 - T1) - (T4 - T3)) / 2

Each switch modifies the packet/frame, adding on the **RESIDENCE TIME**. This is the time from the packet arriving at the device, until it leaves.

Peer to Peer Mode.



In peer to peer mode, additionally.

- Latency is constantly measured between neighbouring network devices and recorded.
    - This is done via pDelay messages.
    - Both serialisation and transmission delay can be measured.
- When a packet arrives on a port, this measured peer delay latency is ADDED to the **residence time**, to account for the link the packet was recieved on.

PTP Clock Modes

- **Grandmaster Clock:** The primary time source in a PTP network. It provides the reference time to which all other clocks synchronize.
- **Ordinary Clock:** Either a Master (timeTransmitter / leader) or Slave (timeReceiver / follower).
- **Transparent Clock:** A clock that measures the delay of PTP packets as they pass through it and compensates for this delay in the PTP timestamps. This improves the accuracy of time synchronization.
- **Boundary Clock:** A clock that acts as both a Slave on one side and a Master clock on the other side.

PTP's Grandmaster Clock

- The Grandmaster Clock is the primary time source in a PTP network.
- It is elected using the BMCA (Best Master Clock Algorithm).

The BMCA uses several factors to determine the best clock, in this order.

- **Priority1**: User-configurable priority (0-255, lower is better).
- **ClockClass**: Quality of the clock (e.g., 6 for GPS-locked).
- **ClockAccuracy**: Precision level (e.g., 0x21 for within 100 ns).
- **OffsetScaledLogVariance**: Stability of the clock.
- **Priority2**: Secondary user-configurable priority (0-255, lower is better).
- **ClockIdentity**: Tiebreaker (usually based on MAC address or IP address).

PTP Transport Mechanisms: UDP vs. Ethernet

PTP over UDP.

- UDP for message transport.
- Port 319 (timekeeping events).
- Port 320 (non-time critical messages).
- Most messages are Multicast 224.0.1.129 / FF0x::181.
- Peer to Peer messages are Multicast 224.0.0.107 / FF02:6B

(More addresses in multi-domain environments).

PTP over Ethernet.

- Raw Ethernet frames.
- EtherType (0x88F7).
- 01-1B-19-00-00-00 for most messages.
- 01-80-C2-00-00-0E peer to peer messages.

Types of PTP messages.

ANNOUNCE (multicast): Announces a master clock and starts an BMCA election.

SYNC (multicast): The main message type. Contains the timing information.

FOLLOW_UP (multicast): Only used if clock doesn't have hardware timestamping.

DELAY_REQ (unicast): Used in End to End mode. Measures delay from Master to Slave.

DELAY_RESP (unicast): Responses to **Delay_Req**.

PDELAY_REQ (unicast): Used in Peer to Peer mode. Measures delay between devices.

PDELAY_RESP (unicast): Responses to **PDelay_Req.**

MANAGEMENT / SIGNALLING (mixed): Control traffic.

IEEE 1588 - 2008 Timestamp Format.

- Note: IEEE 1588 - 2002 (PTPv1) uses an incompatible format.
- Other proprietary formats / quirks exist (Intel 64bit TOD for example).

Bits	Value
0-15 (16 bits)	15.26 femotoseconds (1/65536 of a nanosecond).
16-47 (32 bits)	Nanoseconds.
48-95 (48 bits)	Seconds since 00:00:00 1st Jan 1970 TAI.

- Due to the 48bit counter, PTP won't overflow for for about 9 million years.

PTP Hardware Requirements

PTP-Aware Server Equipment

Servers require NICs with **hardware timestamping** capabilities to achieve microsecond or nanosecond precision.

Essential components include a **high-precision oscillator on the NIC.** Getting time from the CPU has too high latency/jitter.

NIC PHY chips with timestamp registers that capture packet arrival/departure times at the hardware level for two-step-sync.

NIC PHY chips that can modify packet/frame content for one-step-sync.

PTP-Aware Switch Equipment

A central **high precision oscillator** for keeping overall switch time.

A system to sync that oscillator to the **per-port / per-linecard osccciators**.

ASIC's that can **calculate and update residence time** for transparent mode.

ASIC's that can independently **collect peerDelay** for peer to peer mode.

Buy a PTP Grandmaster.

- Microchip TP4100 (top) = $13,000. Common in Mobile Networks.
- Meridian II = $4,000. Dual use NTP / PTP master.

Build your own PTP Grandmaster.

1 Use appropriate server.

- Hardware Timestamping NIC.
  - (or PCIe slot to contain one).
- PCIe slot for OCP timecard.

2 Antenna

Attach the OCP timecard via a cable to an anetnna with good GPS reception.

This likely needs to be on the roof of your building.

3 Sync all clocks.

Use phc2sys to sync.

- Server clock to Timecard.
- NIC clock to Timecard.

(ideally set Timecard + NIC to same PCI-E lane).

4 Configure the PTP daemon

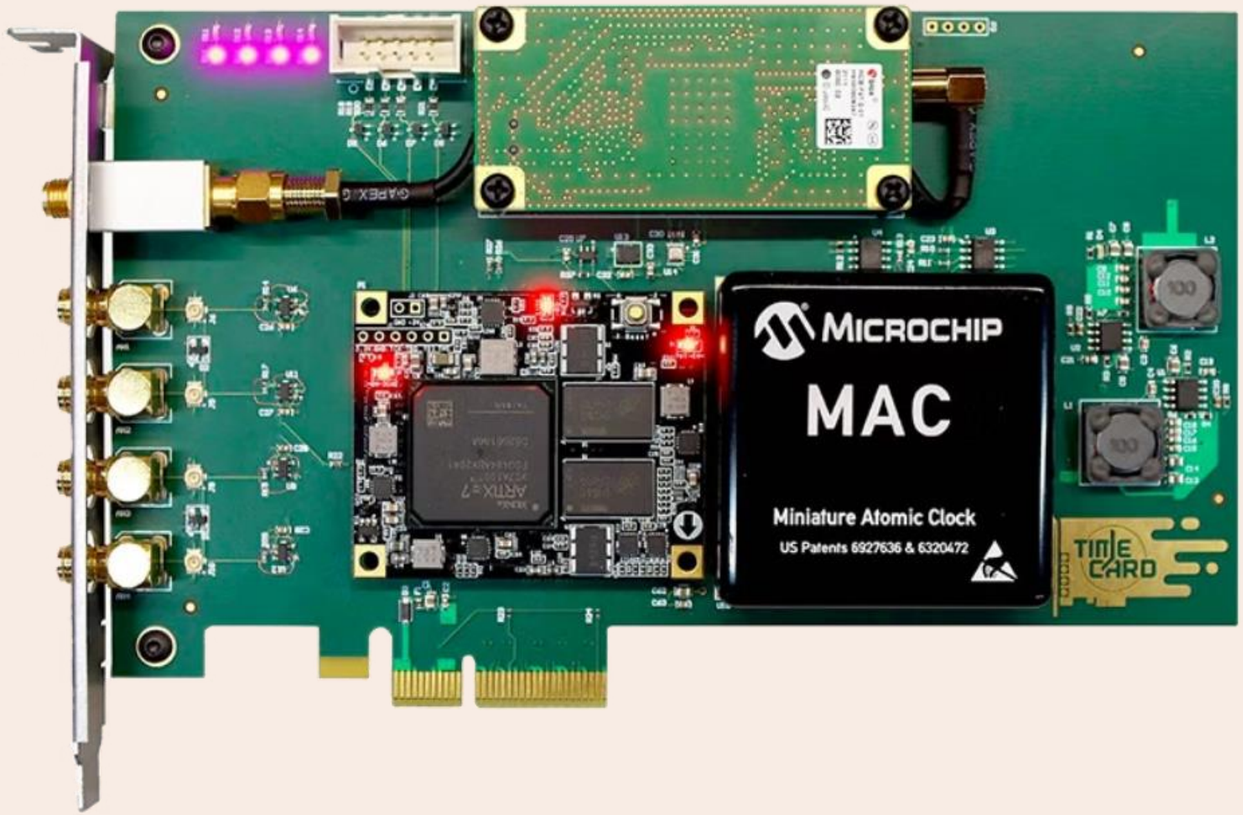
Set up ptp4l.

Configure to use hardware timestamping mode.

Configure to use one-pass if NIC supports it.

Otherwise configure FollowUps.

OCP Timecard from Timebeat.



- GNSS port (top left).
- 4 x External PPS ports.
- Rubidum Atomic clock on right.

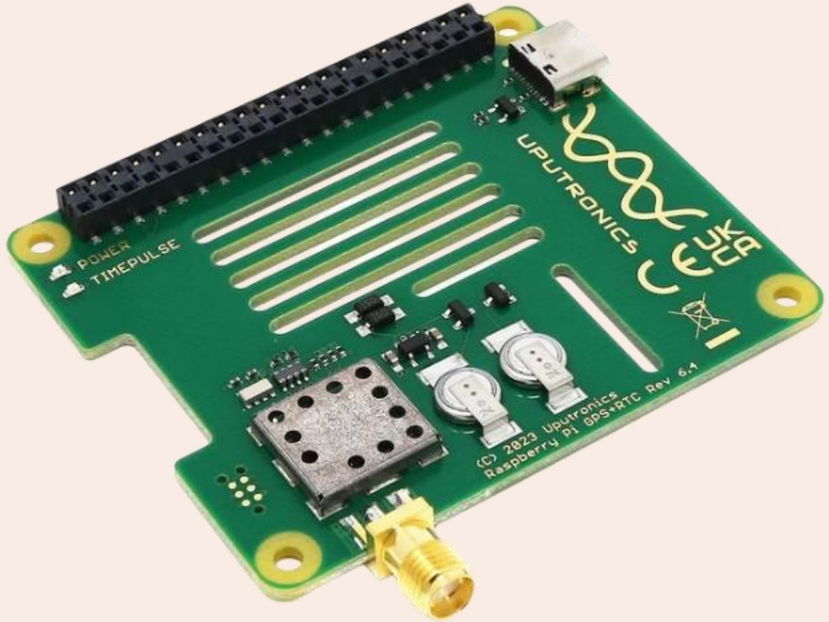
- Measured holdover of MAC
- around ± 30 nanoseconds per day.

Card is around $300.

Atomic Clock Module around $800.

Building a Cheaper One.

Raspberry Pi 5



GNSS Pi-Hat

Pi5 8GB

£80.

GNSS Pi-Hat

£48.

No local high precision osscilator.

SYNC-E.

Ethernet is traditionally asynchronous. Two devices on a link do not need to be in phase with each other.

SYNC-E attempts to change this, and put them in phase, so they both send bits at the exact same time.

ITU G.8262 Standard

Defines the clock characteristics for SyncE equipment, with minumum requirements for Jitter and Drift.

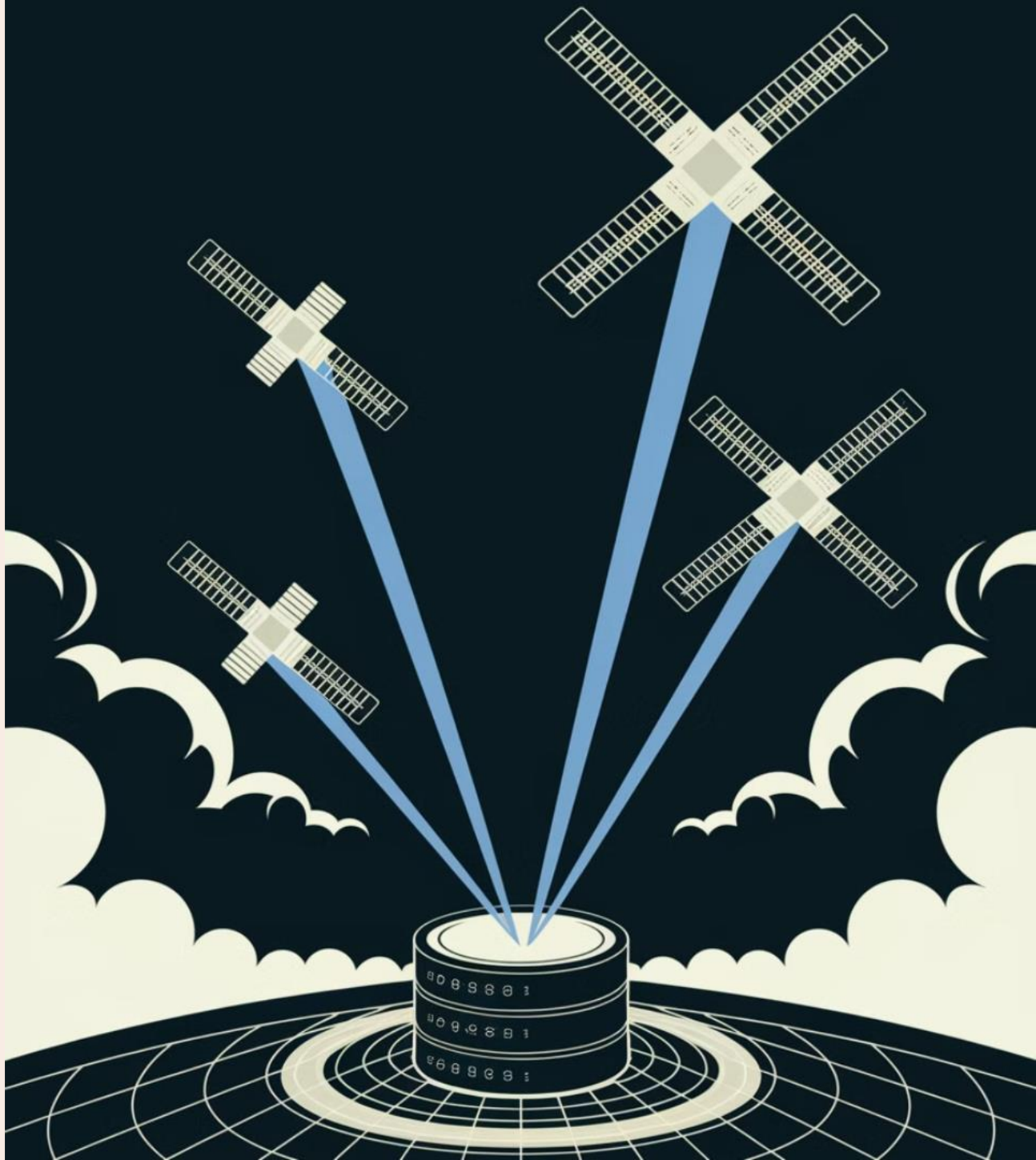
ITU G.8264 Standard

Specifies the Ethernet Synchronization Messaging Channel (ESMC) protocol used to communicate between directly connected elements.

SyncE + PTP Complementary Roles.

Helps make sure Round trip time = 2 x Each One Way Trip.

A Real World Example.



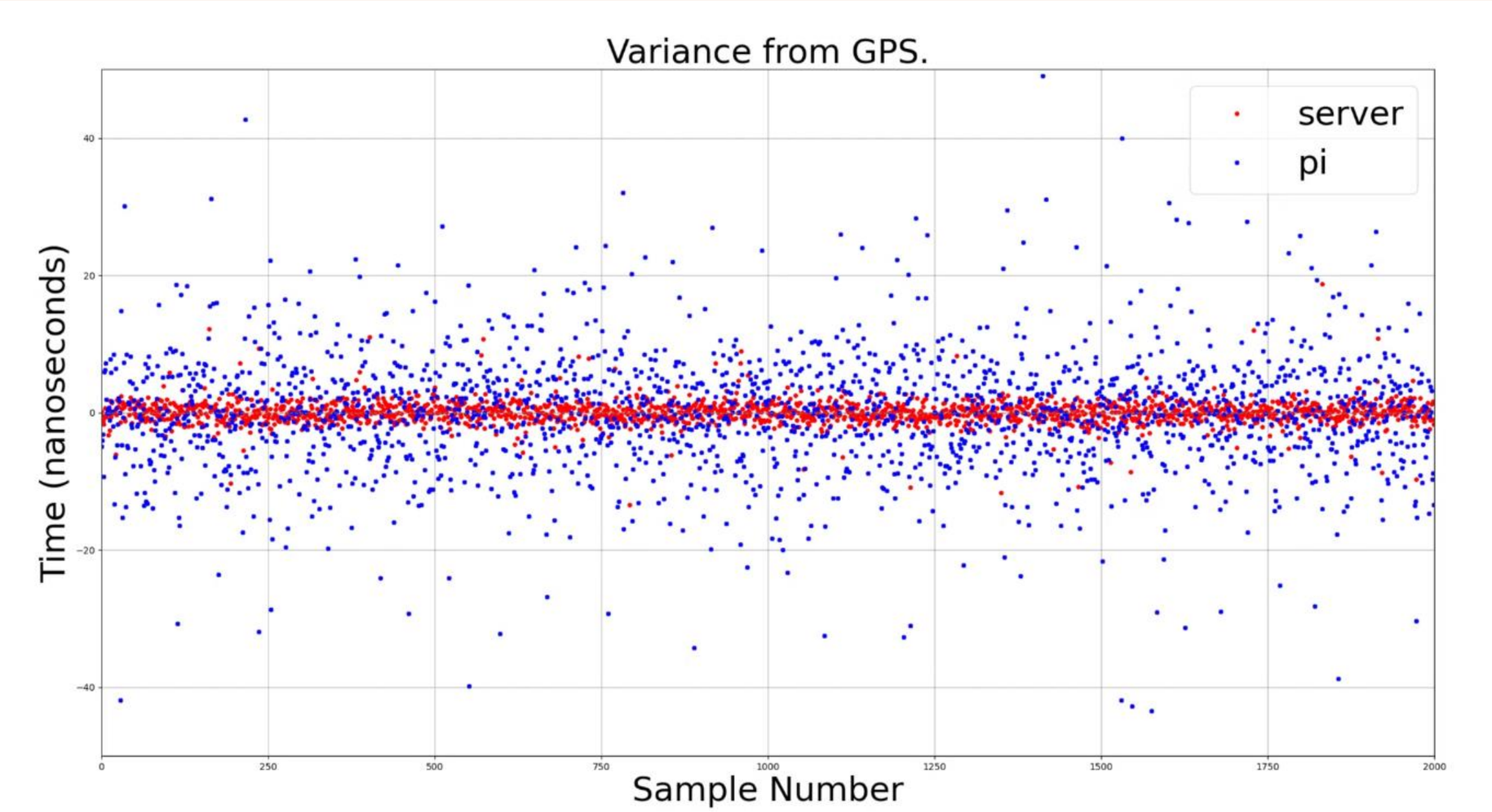
A DC Network.

- 2 x PTP SuperMicro servers.
  - With OCP Timecards + Rubidium Atomic Clocks.
  - Intel XL710-BM2 NIC's (40Gbps).
  - Each connected to independant GPS antenna.
- 4 x Spine Switches (Arista 7280 series).
- 16 x Leaf Switches (Arista 72xx series).
- Each leaf had 13 servers connected to it.
  - 208 servers in total.
- All 40Gbps.
- Every switch was a boundary clock.

Testing.

- Take a test database server getting its time from PTP.
- Also connect a OCP Timecard + GPS reciever to it.
- Use phc2sys / pmc to compare OCP Timecard clock to system sync'd clock.
- Plots results !

Results (OCP Timecard + SYNCE).



What should you do ?

What are my requirements ?

- Do I need accurate walltime, or just sync'd devices ?
- What level of precision do I need under normal conditions ?
- What level of precision do I need with a failed external clock ?
- Do I need accuracy on hosts if the network goes down ?
- Do I have some specific requirement (like A/V SMPTE / ST2059 requires UDP transport).

What is my budget / kit ?

- GPS antenna ?
- Master Clock (bought vs built) ?
- Network switches / routers with PTP ?
  - Transparent vs Boundary Clock ?

Precision Comparison.

Synchronization Method	Expected Precision
NTP over Internet	1-10ms.
NTP over LAN (no QoS).	1-3ms.
NTP over LAN (priority-queue).	~1ms.
PTP End-to-End.	100-500ns.
PTP Peer-to-Peer.	5-50ns.
PTP Peer-to-Peer with SYNC-E.	< 10ns.

Misc Notes.

- Beware of Hypervisors and Time Sync. It can work, but defaults might not.
- If you can make all your network devices boundary clocks, it is LIKELY better than having transparent clocks, but test !
- Beware of Leap Seconds (use Google smear method ?).
  - Remember TAI vs UTC offset (leap seconds).
- Monitor it. The more precise you go, the harder this gets.
- NTP interleaved mode works a bit like FOLLOW_UP messages and can improve NTP accuracy in stable networks.

- I have a wider presentation on time.

What LINX offer.

- 3 NTP servers.
  - ntp0.linx.net + ntp1.linx.net are in Telehouse North.
    - Use GPS + German DCF77 radio as time sources.
  - ntp2.linx.net is in Digital Reality Cloud House.
    - Use GPS + UK MSF radio signal as time sources.
- All three use GPS.
- This is a best effort only service, but has had 99.995% avaliability over the last few years.
- If you think LINX could offer additional time services you would want, please speak to **Tim Preston.**

Questions ? (and URL).