CT420

Real-Time Systems

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1 Introduction

1.1 Lecturer Contact Information

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1.2 Assessment

- 2 hours of face-to-face & virtual labs per week from Week 03.
- 30% Continuous Assessment:
  - 2 assignments, 10% each.
  - 2 in-class quizzes between Week 07 & Week 12, worth 5%.

1.3 Introduction to Real-Time Systems

A system is said to be **real-time** if the total correctness of an operation depends not only upon its logical correctness but also upon the time in which it is performed. Contrast functional requirements (logical correctness) versus non-functional requirements (time constraints). There are two main categorisation factors:

- **Criticality:**
  - **Hard RTS:** deadlines (responsiveness) is critical. Failure to meet these have severe to catastrophic consequences (e.g., injury, damage, death).
  - **Soft RTS:** deadlines are less critical, in many cases significant tolerance can be permitted.
- **Speed**
  - **Fast RTS:** responses in microseconds to hundreds of microseconds.
  - **Slow RTS:** responses in the range of seconds to days.

A **safety-critical system (SCS)** or life-critical system is a system whose failure or malfunction may result in death or serious injury to people, loss of equipment / property or severe damage, & environmental harm.

2 The Essence of Time: From Measurement to Navigation & Beyond

Time is the continued sequence of existence & events that occurs in an apparently irreversible succession from past, through the present, into the future. Methods of temporal measurement, or chronometry, take two distinct forms:

- The **calendar**, a mathematical tool for organising intervals of term;
- The **clock**, a physical mechanism that counts the passage of time.

Global (maritime) exploration requires exact maritime navigation, i.e., longitude & latitude calculation. **Latitude** (north-south) orientation is straightforward; **longitude** (east-west orientation) requires a robust (maritime) clock.

Ground-based navigation systems like LORAN (LOng RAnge Navigation) were developed in the 1940s and were in use until recently, and required fixed terrestrial longwave radio transmitters, and receivers on-board of ships & planes. They are also referred to as hyperbolic navigation or multilateration. The principles of ground-based navigation systems is as follows:

1. A **master** with a known location broadcasts a radio pulse.
2. Multiple **slave** stations with a known distance from the master send their own pulse, upon receiving the master pulse.
3. A **receiver** receives master & slave pulses and measures the delay between them.
4. This allows the receiver to deduce the distance to each of the stations, providing a fix.

NEED TO FINISH

3 Time Synchronisation in Distributed Systems

A **distributed system (DS)** is a type of networked system wherein multiple computers (nodes) work together to perform a task. Such systems may or may not be connected to the Internet. Time & synchronisation are important issues here: think of error logs in distributed systems – how can error events recorded in different computers be correlated with each other if there is no common time base? The problem is that GNSS-based time synchronisation may or may not be available, as GPS signals are absorbed or weakened by building structures. There is no other time reference such systems can rely on because in such a distributed system there are just a series of imperfect computer clocks.

In distributed systems, all the different nodes are supposed to have the same notion of time, but quartz oscillators oscillate at slightly different frequencies. Hence, clocks tick at different rates (called *clock skew*), resulting in an increasing gap in perceived time. The difference between two clocks at a given pot is called *clock offset*. The **clock synchronisation problem** aims to minimise the clock skew and subsequently the offset between two or more clocks. A clock can show a positive or negative offset with regard to a reference clock (e.g., UTC), and will need to be resynchronised periodically. One cannot just set the clock to the "correct" time: jumps, particularly backwards, can confuse software and operating systems. Instead, we aim for gradual compensation by correcting the skew: if a clock runs too fast, make it run slower until correct and if a clock runs too slow, make it run faster until correct.

Synchronisation can take place in different forms:

- Based on **physical** clocks: absolute to each other by synchronising to an accurate time source (e.g., UTC), absolute to each other by synchronising to locally agreed time (i.e., no link to a global time reference), where the term *absolute* means that the differences in timestamps are proper time intervals.
- Based on **logical** clocks (i.e., clocks are more like counters): timestamps may be ordered but with no notion of measurable time intervals.

In either case, the DS endpoints synchronise using a shared network. For physical clock synchronisation, network latencies must be considered as packets traverse from a sending node to a receiving node. In a **perfect network**, messages *always* arrive, with a propagation delay of *exactly* d; the sender sends time T in a message, the receiver sets its clock to $T + d$, and synchronisation is exact.

In a **deterministic network**, messages arrive with a propagation delay $0 < d \leq D$; the sender sends time T in a message, the receiver sets its clock to $T + \frac{D}{2}$, and therefore the synchronisation error is at most $\frac{D}{2}$. **Deterministic communication** is the ability of a network to guarantee that a message will be transmitted in a specified, predictable period of time.

3.1 Synchronisation in the Real World

Most off-the-shelf networks are *asynchronous*, that is, data is transmitted intermittently on a best-effort basis. They are designed for flexibility, not determinism, and as a result, propagation delays are arbitrary and sometimes even unsymmetric (i.e., upstream & downstream latencies are different). Therefore, synchronisation algorithms are needed to accommodate these limitations.

3.1.1 Cristian's Algorithm

Cristian's algorithm attempts to compensate for symmetric network delays:

1. The client remembers the local time T_0 just before sending a request.
2. The server receives the request, determines T_S, and sends it as a reply.
3. When the client receives the reply, it notes the local arrival time T_1.
4. The correct time is then approximately $(T_S + \frac{(T_1 - T_0)}{2})$.

The algorithm assumes symmetric network latency. If the server is synced to UTC< all clients will follow UTC. Limitations of Cristian's algorithm include:

- Assumes a symmetric network latency;
- Assumes that timestamps can be taken as the packet hits the wire / arrives at the client;
- Assumes that T_S is right in the middle of the server process; for example, consider the server process being pre-empted just before it sends the response back to the client, which will corrupt the synchronisation of the client.

3.1.2 Berkeley Algorithm

In the **Berkeley algorithm**, there is no accurate time server: instead, a set of client clocks is synchronised to their average time. The assumption is that offsets / skews of all clocks follow some symmetric distribution (e.g., a normal distribution) with some clocks going faster and others slower, and therefore a mean value close to 0.

1. One node is designated to be the **master node** M.
2. The master node periodically queries all other clients for their local time.
3. Each client returns a timestamp or their clock offset to the master.
4. Cristian's algorithm is used to determine and compensate for RTTs, which can be different for each client.
5. Using these, the master computes the average time (thereby ignoring outliers), calculates the difference to all timestamps it has received, and sends an adjustment to each client. Again, each computer gradually adjusts its local clock.

Client clocks are adjusted to run faster or slower, to be synced to an overall agreed system time. The client networks is an intranet, i.e., an isolated system. Therefore, the Berkeley algorithm is an **internal clock synchronisation algorithm**. The Berkeley algorithm was implemented in the TEMPO time synchronisation protocol, which was part of the Berkelely UNIX 4.3BSD system.

3.2 Logical Clocks

Logical clocks are another concept linked to internal clock synchronisation. Logical clocks only care about their internal consistency, but not about absolute (UTC) time; subsequently, they do not need clock synchronisation and take into account the order in which events occur rather than the time at which they occurred. In practice, if clients or processes only care that event a happens before event b, but don't care about the exact time difference, they can make use of a logical clock.

We can define the **happens-before relation** $a \rightarrow b$:

- If events a and b are within the same process, then $a \rightarrow b$ if a occurs with an earlier local timestamp: **process order**.
- If a is the event of a message being sent by one process, and b is the event of the message being received by another process, then $a \rightarrow b$: **causal order**.

- We also have **transitivity:** if $a \to b$ and $b \to c$, then $a \to c$.

Note that this only provides a *partial order*: if two events a and b happen in different processes that do not exchange messages (not even indirectly), then neither $a \to b$ nor $b \to a$ is true. In this situation, we say that a and b are **concurrent** and write $a \sim b$, i.e., nothing can be said about when the events happened or which event happened first.

Happens-before can be implemented using the **Lamport scheme:**

1. Each process P_i has a logical clock L_i, where L_i can be simply an integer variable initialised to 0.
2. L_i is incremented on every local event e; we write $L_i(e)$ or $L(e)$ as the timestamp of e.
3. When P_i sends a message, it increments L_i and copies its content into the packet.
4. When P_i receives a message from P_k, it extracts L_k and sets $L := \max(L_i, L_k)$ and then increments L_i.

This guarantees that if $a \to b$, then $L_i(a) < L_k(b)$, but nothing else.

The primary limitation of Lamport clocks is that they do not capture **causality**. Lamport's logical clocks lead to a situation where all events in a distributed system are ordered, so that if an event a (linked to P_i) "happened before" event b (linked to P_k), i.e., $a \to b$, then $a$will also be positioned in that ordering before b such that $L_i(a) < L_k(b)$ or simply $L(a) < L(b)$; however, nothing can be said about the relationship between two events a & b by merely comparing their time values $L_i(a)$ and $L_k(b.)$: we can't tell if $a \to b$ or $b \to a$ or $a \sim b$ unless they occur in the same process.

3.2.1 Vector Clocks

In practice, causality is captured by means of **vector clocks**:

1. There is an ordered list of logical clocks, with one per process. Each process P_i maintains a vector $\vec{V_i}$, initially containing all zeroes. Each index k of a vector clock $\vec{V_i}[k]$ represents the number of events that process P_i knows have occurred in process P_k. $\vec{V_i}[i]$ is the count of events that have occurred locally at process P_i, while $\vec{V_i}[k]$ (for $k \neq i$) is the count of events in process P_k that P_i is aware of.
2. On a local event e, P_i increments its own clock component $\vec{V_i}[i]$. If the event is "message send", a new $\vec{V_i}$ is copied into the packet, so that on message sends the current vector state is included in the message.
3. If P_i receives a message from P_m, then each index $\vec{V_i}[k]$ where $k \neq i$ is set to $\max(\vec{V_m}[k], \vec{V_i}[k])$, and $\vec{V_i}[i]$ is incremented.

Intuitively, $\vec{V_i}[k]$is the number of events in process P_k that have been observed by P_i.

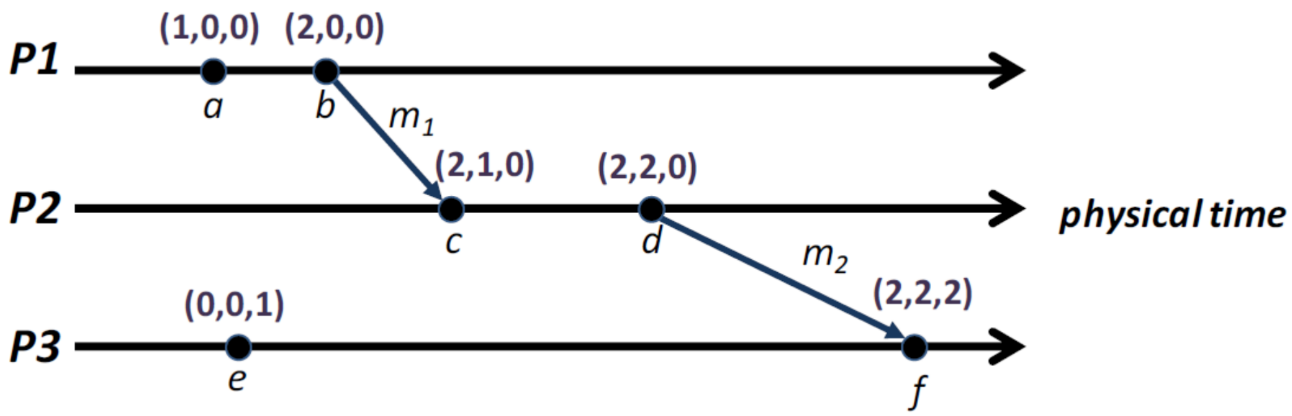

Figure 1: Vector clocks example

In the above example, when process P_2 receives message m_1, it merges the entries from P_1's clock by choosing the maximum value of each position. Similarly, when P_3 receives m_2, it merges in P_2's clock, thus incorporating the changes from P_1 that P_2 already saw. Vector clocks explicitly track the transitive causal order: f's timestamp captures the history of a, b, c, & d.

To use vector clocks for ordering, we can compare them piecewise:

- We say $\vec{V_i} = \vec{V_j}$ if and only if $\vec{V_i}[k] = \vec{V_j}[k] \forall k$.
- We say $\vec{V_i} \leq \vec{V_j}$ if and only if $\vec{V_i}[k] \leq \vec{V_j}[k] \forall k$.
- We say $\vec{V_i} < \vec{V_j}$ if and only if $\vec{V_i} \leq \vec{V_j}$ and $\vec{V_i} \neq \vec{V_j}$.
- We say $\vec{V_i} \sim \vec{V_j}$ otherwise, e.g., $\vec{V_i} = [2, 0, 0]$ and $\vec{V_j} = [0, 0, 1]$.

For any two event timestamps $T(a)$ & $T(b)$:

- if $a \to b$, then $T(a) < T(b)$; **and**
- if $T(a) < T(b)$, then $a \to b$.

Hence, we can use timestamps to determine if there is a causal ordering between any two events.

Lamport Clocks

	a	b	c	d	e	f
P_1	1	2				
P_2			3	4		
P_3					1	5

Is it e → c or e ~ c?

Vector Clocks

	a	b	c	d	e	f
P_1	(1,0,0)	(2,0,0)				
P_2			(2,1,0)	(2,2,0)		
P_3					(2,2,1)	(2,2,2)

It is e ~ c!

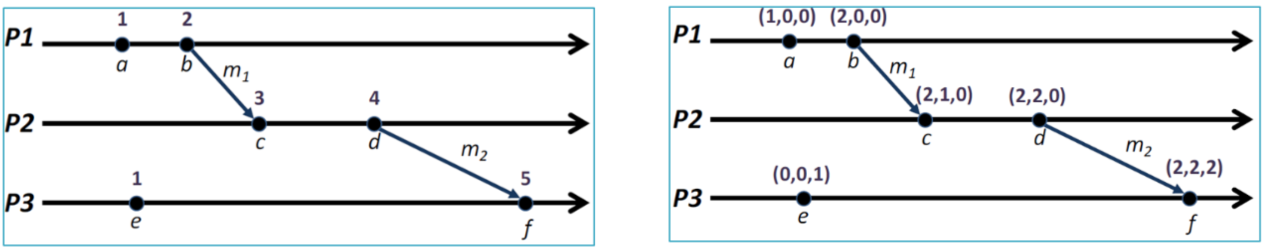

Figure 2: Lamport clocks versus vector clocks

4 The NTP Protocol

The options for computer clocks are essentially as follows:

- **Option A:** stick to crystals.
  - Costly precision manufacturing.
  - Works indoors.
  - Temperature Compensated Crystal Oscillator (TCXO).
  - Oven Controlled Crystal Oscillator (OCXO).

- **Option B:** buy an atomic clock ($50,000 – $100,000) or a GNSS receiver (based on an atomic clock, but doesn't work indoors), or a time signal radio receiver if you are based in central Europe.
- **Option C:** use software-based approaches to discipline cheap crystal clocks. Less quality, but useful for certain applications, and works indoors.

Distributed master clocks provide a time reference to hosts that are inter-connected via a network. The underlying time-synchronisation protocols combine aspects of Cristian's algorithm (i.e., RTD calculation) and Berkeley's algorithm (i.e., combining multiple reference time sources). Good time synchronisation requires:

- Good time references: easily done with GPS, atomic clocks, etc.
- Predictable / symmetric / deterministic network latencies: doable in LAN setups, but not guaranteed in Internet data communication.

There are two main distributed master clock protocols:

- **Network Time Protocol (NTP):** defined in RFC 5905, originally used in the Unix-based NTP daemon, one of the first Internet protocols that ever evolved.
- **Precision Time Protocol (PTP):** designed for managed networks, e.g., LAN.

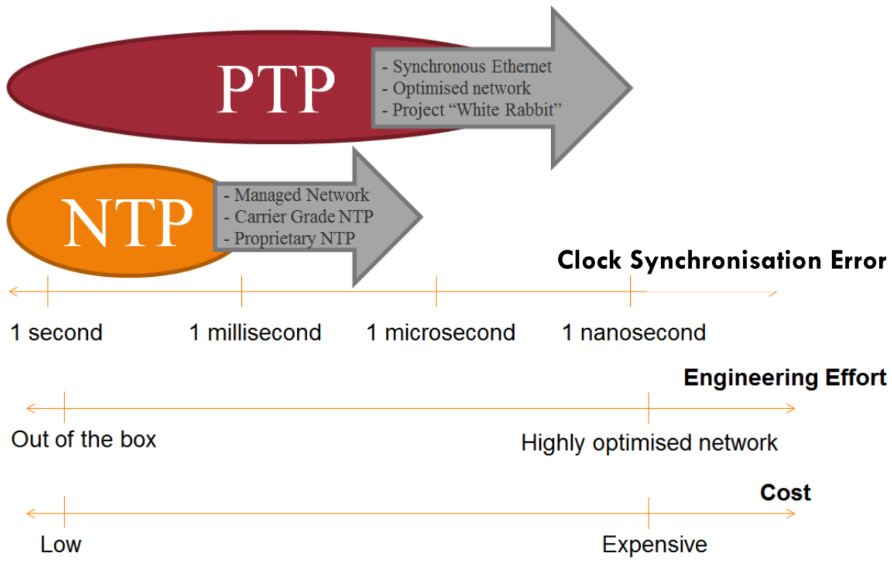

Figure 3: NTP & PTP characteristics

In **uni-directional synchronisation** a reference clock sends a timestamp to a host via a network. The host then uses the timestamp to set its local clock. Useful when message latencies are minor relative to the synchronisation levels required.

In **round-trip synchronisation (RTS)** a host sends a request message, receives a reference clock response message with known (local) submission & arrival times, allowing for the calculation of the round-trip delay (1) and the host clock error (2), i.e., the phase offset. Variations of RTS form the basis for NTP & PTP.

$$\delta = (T_{i+3} - T_i) - (T_{i+2} - T_{i+1}) \tag{1}$$

$$\theta = (T_{i+1} - T_i) + \frac{(T_{i+2} - T_{i+3})}{2} \tag{2}$$

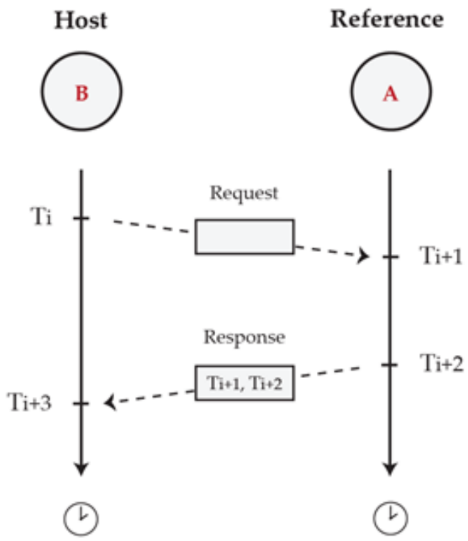

Figure 4: RTS example

4.1 NTP

The NTP architecture, protocol, & algorithms have evolved over the last 40 years to the latest NTP Version 4. NTP is the standard Internet protocol for time synchronisation & co-ordinated UTC time distribution. It is a fault-tolerant protocol, as it automatically selects the best of several available time sources to synchronise with. It is highly scalable, as the nodes form a hierarchical structure with reference clock(s) at the top:

- Stratum 0: Time Reference Source (e.g., GPS, TAI atomic clocks, DCF 77).
- Stratum 1: Primary Time Server.

NTP applies some general aforementioned principles such as avoiding setting clocks backwards and avoiding large step changes; the required change (positive or negative) is amortised over a series of short intervals (e.g., over multiple ticks).

NTP is the longest-running and continuously operating Internet protocol (since around 1979). Government agencies in many other countries and on all continents (including Antarctica) operate public NTP primary servers. National & regional service providers operate public NTP secondary servers synchronised to the primary servers. Many government agencies, private & public institutions including universities, broadcasters, financial institutions, & corporations operate their own NTP networks.

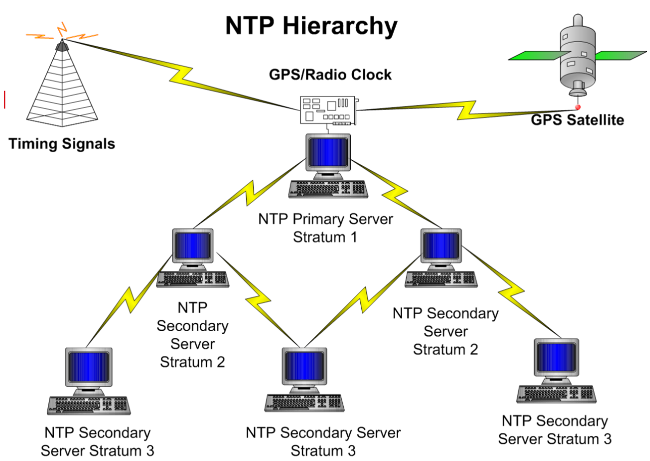

Figure 5: NTP hierarchy

In **client/server mode**, UDP is used for data transfer (no TCP), i.e., NTP over UDP on UDP port 123. There is also the optional use of broadcasting or multicasting (not covered here). Several packet exchanges between the NTP client and the Stratum server take place to determine the client offset:

1. The client sends a packet with **originate timestamp** A.
2. The server receives the packet and returns a response containing the originate timestamp A as well as the **receive timestamp** B and the **transmit timestamp** C.
3. The client receives this packet and processes A, B, C, as well as the packet arrival time D of the received packet; it then determines the offset and the round-trip delay (RTD).

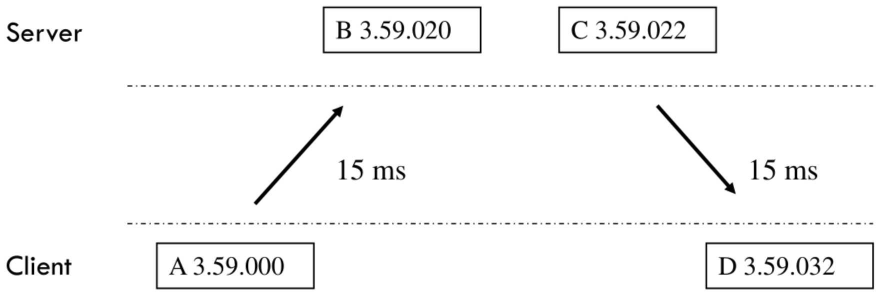

Figure 6: NTP operation

The above example is of a symmetric network with a 15ms delay each way; the client's clock lags 5ms behind the server's clock:

$$\text{RTD} = (D - A) - (C - B) = 32 - 2 = 30\text{ms}$$
$$\text{Offset} = \frac{((B - A) + (C - D))}{2} = \frac{(20 + (-10))}{2} = 5\text{ms}$$

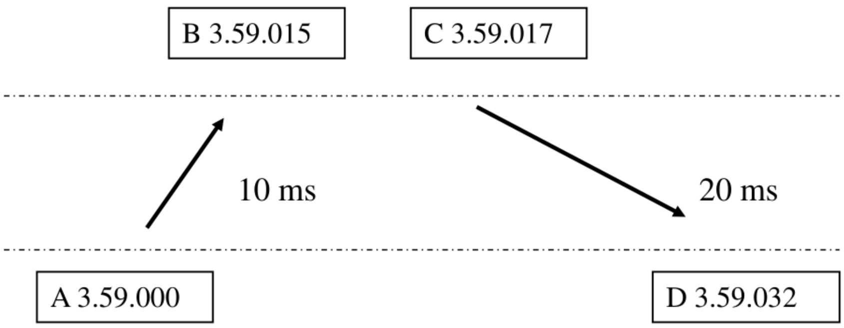

Figure 7: Network delay asymmetry

In the above example, the client's clock still lags 5ms behind the servers clock, but there is an asymmetric network latency: 10ms versus 20ms:

$$\text{RTD} = (D - A) - (C - B) = 32 - 2 = 30\text{ms}$$
$$\text{Offset} = \frac{((B - A) + (C - D))}{2} = \frac{(15 + (-15))}{2} = 0\text{ms}$$

Typical NTP performance for various set-ups is as follows:

- Small LAN: $\sim$10 microseconds best possible case on a 2-node LAN, $\sim$220 microseconds on a real-world small LAN.

- Typical large-building LAN: ~2ms.
- Internet with a few hops: 10–20ms.
- Long distance and/or slow or busy link: 100ms–1s.

Accuracy is further degraded on networks with asymmetric traffic delays.

The **NTP time format** has a reference scale of UTC. Time parameters are 64 bits long:

- Seconds since January 1, 1900 (32 bits, unsigned).
- Fraction of second (32 bits, unsigned).

The NTP time format has a dynamic range of 136+ years, with rollover in 2036. Its resolution is 2^{-32} seconds ~232 picoseconds.

4.1.1 NTP Protocol Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|LI | VN  |Mode |    Stratum     |     Poll      |  Precision   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Root Delay                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Root Dispersion                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Reference ID                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                     Reference Timestamp (64)                  +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                      Origin Timestamp (64)                    +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                      Receive Timestamp (64)                   +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                      Transmit Timestamp (64)                  +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 8: NTP protocol header

- `LI` (**Leap Indicator**) 2-bit:
  - `0`: no warning;
  - `1`: last minute of the day has 61 seconds;
  - `2`: last minute of the day has 59 seconds.
- `VN` (**Version Number**) 2-bit: currently 4.
- `Mode`: 3-bit integer, including:
  - `3`: client;
  - `4`: server.
- `Stratum`: 8-bit integer for Stratum server hierarchy level, including:
  - `1`: primary server (i.e., stratum 1);

  – `2–15`: secondary server.

- `Poll`: 8-bit signed integer representing the maximum interval between successive message, in $\log_2$ seconds. This field indicates the interval at which the client will poll the NTP server for time updates. The client dynamically adjusts this interval based on its clock's stability & the network conditions to balance accuracy & network load.
- `Precision`: 8-bit signed integer representing the resolution of the system clock (the tick increment) in $\log_2$ seconds; e.g., a value of -18 corresponds to a resolution of about one microsecond (2^{-18}) seconds.
- `Root Delay`: round-trip packet delay from a client to a stratum 1 server. It gives a crude estimate of the worst-case time transfer error between a client and a stratum 1 server due to network asymmetry, i.e., if all of the round-trip delay was in one direction and none in the other direction.

For a single client clock, the **dispersion** is a measure of how much the client's clock might drift during a synchronisation cycle:

$$\text{Dispersion} = DR \times (D - A) + TS$$

where $(D - A)$ is the duration of a synchronisation cycle, with A being the first timestamp and D being the last timestamp, DR being the local clock skew (i.e., the deviation of actual clock tick frequency to nominal clock tick frequency), and TS being the timestamping errors due to the finite resolution of the clock and delays in reading the clock when fetching a timestamp.

The **root dispersion** of a client clock is the combined dispersions of all stratum servers along the path to a Stratum 1 server.

The **root distance** is the sum of root dispersion and half the root delay. It provides a comprehensive measure of the maximum error in time synchronisation as the total worst case timing error accumulated between the Stratum 1 server and the client.

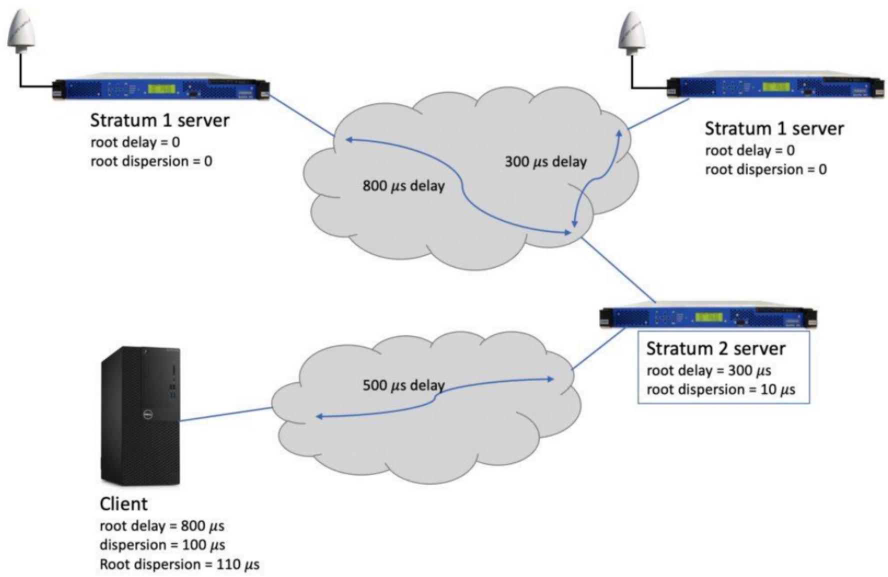

Figure 9: Example root dispersion & root delay

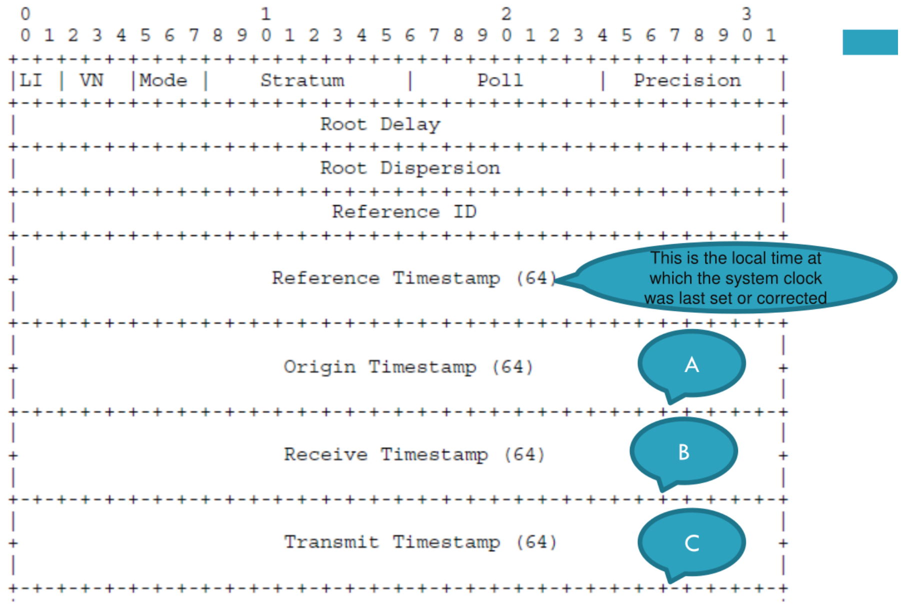

Figure 10: Annotated NTP protocol header

A **reference ID (refid)** is a 32-bit code (4 ASCII bytes) identifying the particular server or reference clock, e.g.,:

- `GPS`: Global Positioning System;
- `GAL`: Galileo Positioning System;
- `PPS`: Generic Pulse-Per-Second;
- `DCF`: LF Radio DCF77 Mainflingen, DE 77.5 kHz;
- `WWV`: HF Radio WWV Fort Collins, Colorado;
- `GOOG`: unofficial Google refid used by Google NTP servers as `time4.google.com`.

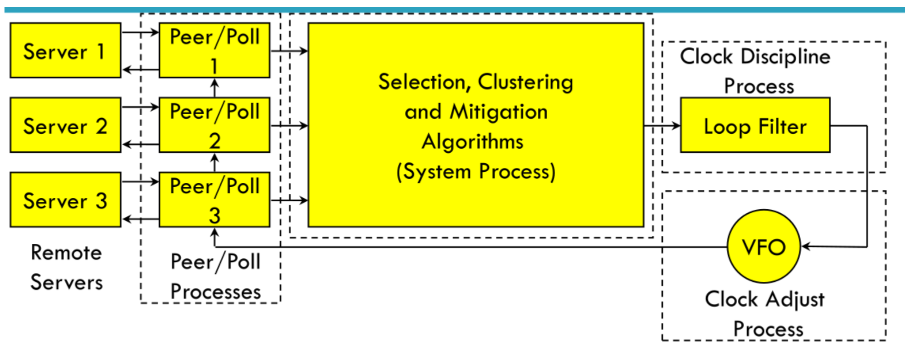

Figure 11: NTP architectural overview

An NTP client synchronises with multiple stratum servers. It uses a range of algorithms to deal with variable & asymmetric non-deterministic network delays and to determine its most likely offset, thereby running a series of processes:

- The peer process runs when a packet is received;
- The poll process sends packets at intervals determined by the clock discipline process & remote server;
- The system process runs when a new update is received;

- The clock discipline process implements clock time adjustments;
- The clock adjust process implements periodic clock frequency (VFO) adjustments.

For each stratum there is a **poll process** that sends NTP packets at intervals ranging from 8 seconds to 36 hours. The corresponding **peer processes** receive NTP packets and, after performing some packet sanity tests, $T1 - T4$ are determined / extracted. The NTP daemon calculates offset & delay as seen before. The time series of offset & delay values calculated by multiple peer processes are processed by a sequence of algorithms, thus eliminating servers with long RTD or servers that show "strange" offsets which, for example, are often the result of network asymmetries.

4.1.2 Mitigation Algorithms

The **clock filter algorithm** uses a sliding window of eight samples for each stratum server and picks out the sample with the least expected error, i.e., it chooses the sample with the minimum RTD. It is effective at removing spikes resulting from intermittent network congestions.

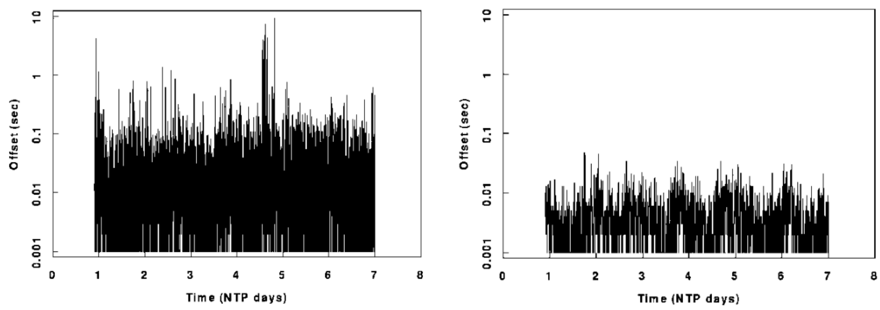

Figure 12: Clock filter algorithm before and after

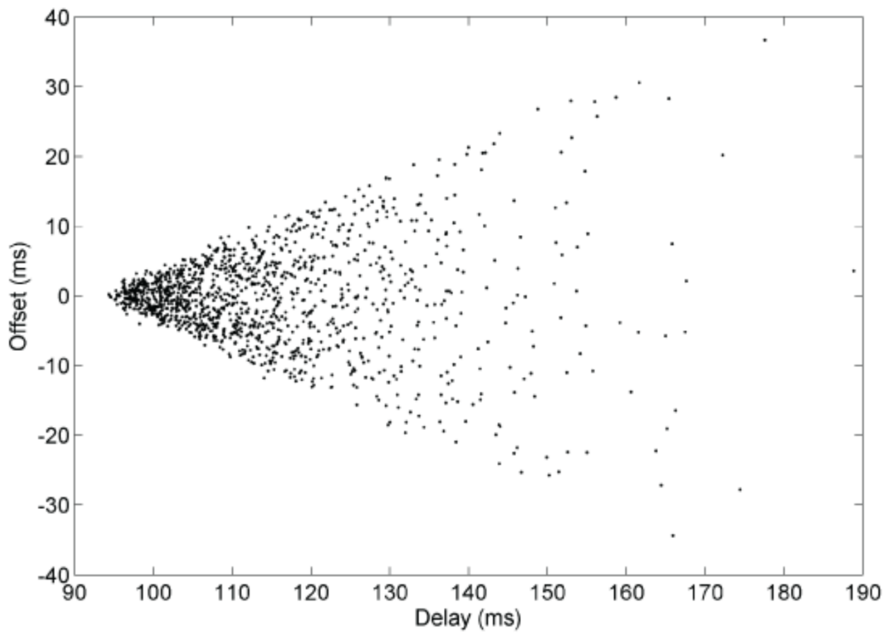

Figure 13: The wedge scattergram plots sample points of offset versus delay (RTD) collected over a 24-hour period by a client clock communicating with a single stratum server. For this experiment, the client clock is externally synced to the stratum server, so the offset should be zero; however, as the (network) round trip delay increases, the offset variability increases, resulting in increasingly larger offset errors. Therefore, the best samples are those at the lowest delay. This is taken into account by the clock filter algorithm.

The **intersection algorithm** selects a subset of peers (i.e., stratum servers) and identifies truechimers & truetickers based on the intersection of confidence (offset) intervals (i.e., min/max offsets of a clock over x readings determines its invterval).

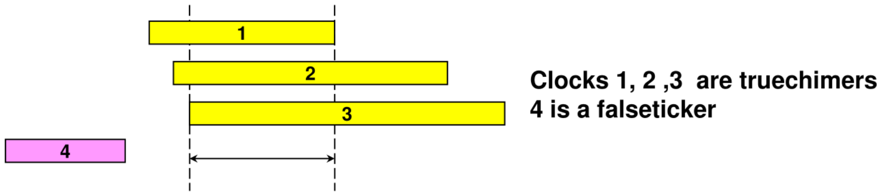

Figure 14: Plot range of offsets calculated by each peer with 1, 2, & 3 overlapping

Marzullo's algorithm is an agreement protocol for estimating accurate time from a number of noisy time sources by intersecting offset intervals; if some intervals don't intersect, it considers the intersection of the majority of intervals. It eliminates false tickers.

The **clock cluster algorithm** processes the truechimers returned by the clock intersection algorithm. It produces a list of survivors by eliminating truechimers that have a comparably large root delay & root dispersion. Finally, the **clock combining algorithm** averages the time offsets of survivors using their root dispersions as a weight, i.e., survivors with a small root dispersion have a higher weight.

The **combining algorithm** provides a final offset, so the client clock can be adjusted. The UNIX Clock Model provides the kernel variable `tickadj` which amortises the required change gradually by making adjustments every tick e.g., every 10 milliseconds.

5 Soft RTS

A **soft RTS** is a RTS in which performance is degraded but not destroyed by failure to meet response time constraints, e.g., multimedia systems.

5.1 Quality of Service (QoS)

Perceived QoS reflects the subjective evaluation of service quality from the end user's perspective and overall satisfaction. It encompasses factors like application responsiveness, ease of use, consistency, reliability, and the overall user interface delay. It is challenging to measure accurately as it involves subjective experiences & user feedback, often gathered through surveys, user studies, or feedback mechanisms.

Intrinsic QoS refers to the technical & measurable characteristics of a network or service that directly affects its performance & reliability. Intrinsic QoS parameters include bandwidth, latency, packet loss rate, jitter, & throughput. Intrinsic QoS measures are typically quantifiable and can be objectively measured using various tools & monitoring techniques.

5.1.1 QoS Metrics

Latency is the time it takes to send a packet from point A (say, the client) to point B (say, the server). It is physically limited by how fast signals can travel in wires or the open air. Latency depends on the physical, real-world distance between A and B. Typical latencies are conceptually small, between roughly 10 and 200 milliseconds. High latency can result in delays between user actions and system responses, leading to sluggish or unresponsive behaviour in real-time applications.

Jitter is the inconsistency or fluctuations in the arrival time of data packets at the receiver. It can be caused by various factors, such as network congestion, packet loss, routing changes, etc. It can have significant implications for real-time communication applications, particularly voice & video sharing. Inconsistent packet arrival times can lead to disruptions, distortion, and out-of-sync audio or video playback.

Bandwidth measures the amount of data that is able to pass through a network at a given time. It is measured in bits per second. Real-time applications with high-bandwidth requirements, such as high-definition video streaming &

VOIP may experience performance issues if the available bandwidth is insufficient to accommodate the data transmission demands.

5.2 Real-Time Multimedia Technologies

5.2.1 Transport Layer for Real-Time Media

TCP provides reliability, ordered delivery, & congestion control. Retransmissions can lead to high delay and cause delay jitter. TCP is not suitable for real-time systems and does not support mulitcast.

UDP has no built-in reliability or congestion control, and no defined technique for synchronising. It has low latency and minimal overhead (no handshake, no retransmissions). A feedback channel must be defined for quality control.

5.2.2 Service Requirements for Real-Time Flows (Voice / Video)

- **Sequencing:** the process of maintaining the correct order of data packets during transmission and ensuring that they are re-assembled correctly at the receiver's end.
- **Synchronisation:** ensures that different types of data streams (such as audio & video) are aligned in time during playback.
- **Payload identification:** different media types (MPEG1, MPEG2, H.261) may require different handling in terms of decoding or processing.
- **Frame indication:** specifying which packets belong to the same frame or video sequence and helps with decoding & rendering video frames accurately.

5.2.3 RTP

Real-time Transport Protocol (RTP) provides end-to-end transport functions suitable for real-time audio/video applications over multicast & unicast network services. It works in user space over UDP. The working model is as follows:

- The multimedia application generates multiple streams (audio, video, etc.) that are fed into the RTP library.
- The library multiplexes the streams & encodes them in RTP packets which are fed to a UDP socket.

Secure RTP (SRTP) is used by applications including WhatsApp, Zoom, Skype, etc. for transporting voice & video streams.

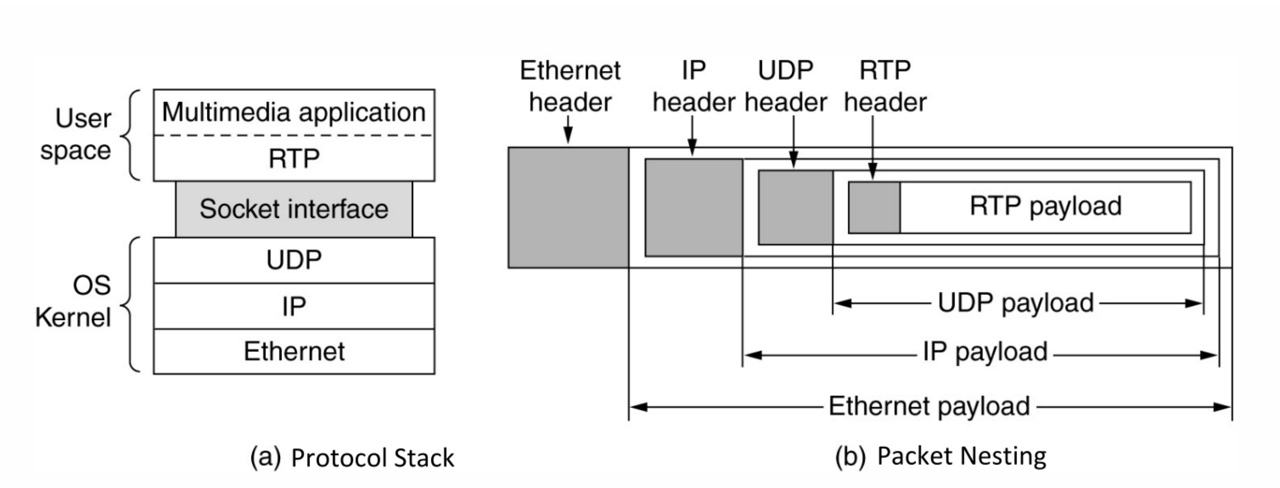

Figure 15: RTP protocol

RTP services include:

- Payload type identification: determination of media encoding.
- Synchronisation source identification: assigned to each distinct media source (such as a microphone or a camera). Enables synchronisation of multiple streams coming from the same source (e.g., lip-syncing audio & video).
- Sequence numbering: a counter is used which is incremented on each RTP packet send and is used to detect lost packets.
- Time-stamping: time monitoring, synchronisation, jitter calculation.
- RTP issues: no QoS guarantees, no guarantee of packet delivery.

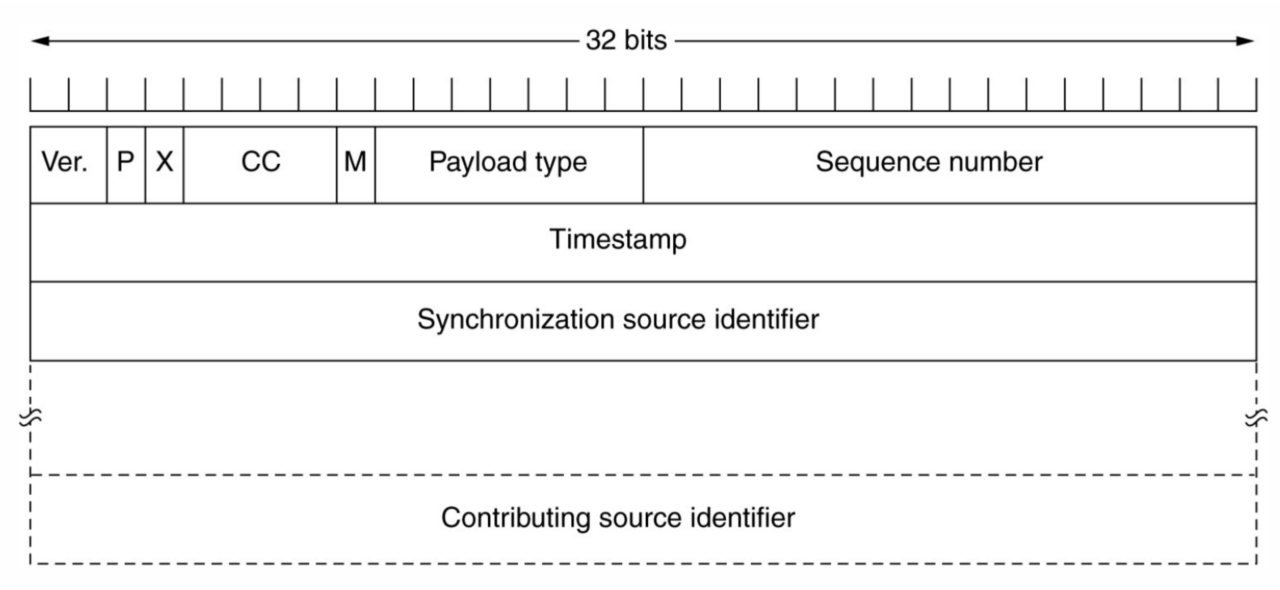

Figure 16: RTP header

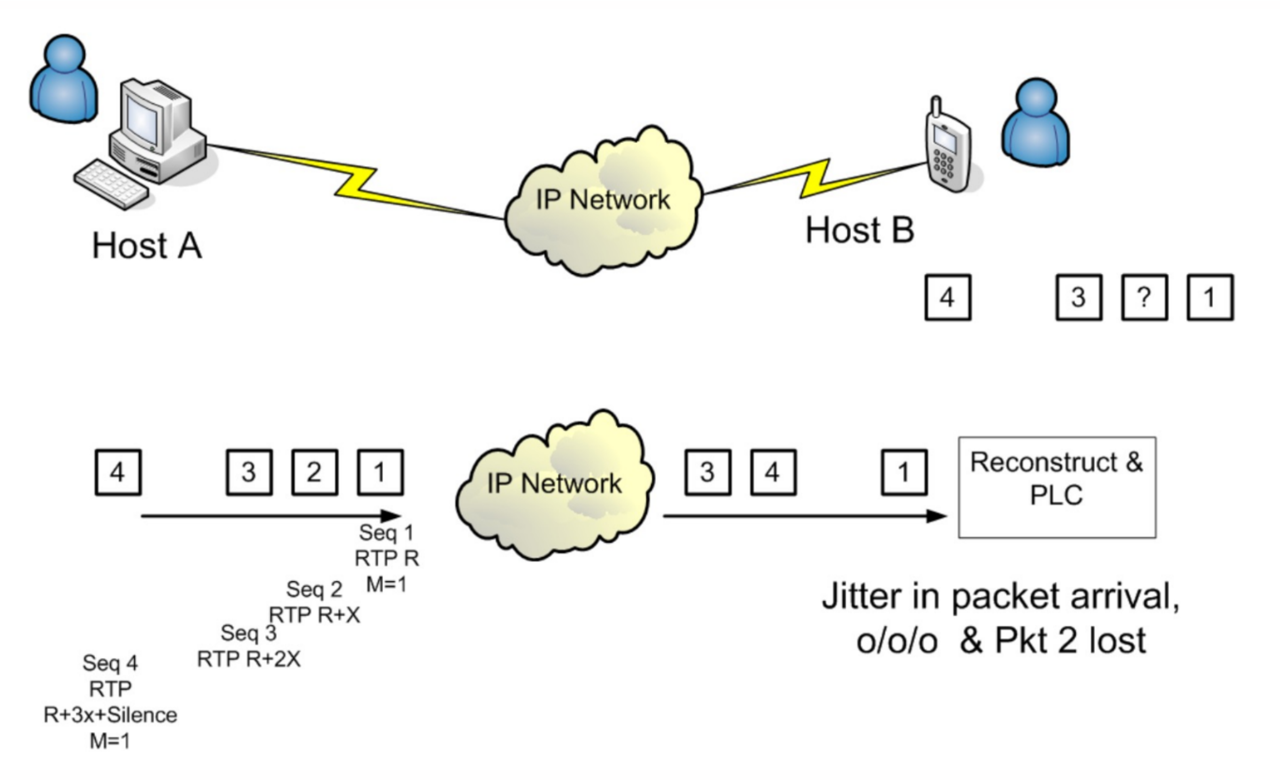

Figure 17: RTP data delivery

RTP Control Protocol (RTCP) is a companion protocol to RTP that is used periodically to transmit control packets to participants in a streaming multimedia session. It gathers statistics on the media connection, including bytes sent, packets sent, lost packets, jitter, feedback, & round-trip delay. It provides feedback on the quality of the service being provided by RTP but does not actually transport any data. The application may use this information to increase the quality of service, perhaps by limiting flow or using a different codec.

5.2.4 Mouth-to-Ear M2E Delay

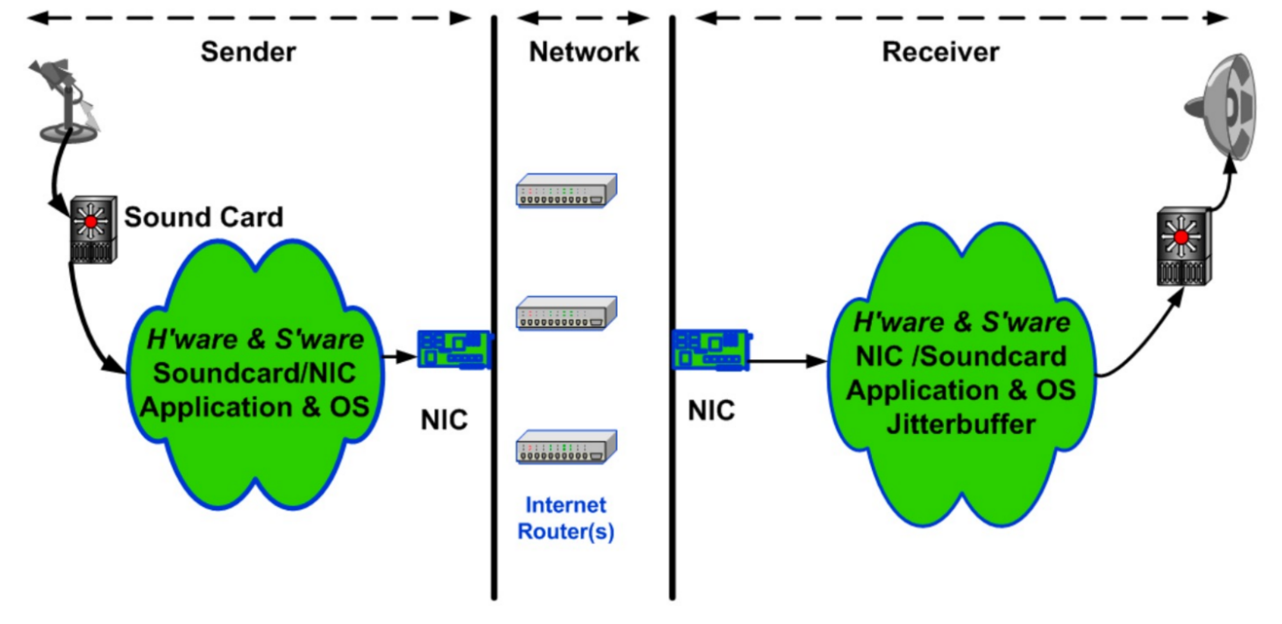

Figure 18: M2E delay

M2E delay consists of:

- Sender:
  - Packetisation delay.
  - Encoding delays.
  - OS/Application/Driver software.
  - MAC delays.
- Network:
  - Propagation delay.
  - Queuing delays.
  - Processing/serialisation delays in routers.
- Receiver:
  - NIC delays.
  - OS/Application/Driver software.
  - Jitter buffer delays.
  - Decoding delays.

VOIP QoS strategies include:

- Sender-based:

  - RTCP feedback with adaptive codeces: if loss/delay excessive, switch to lower-bandwidth code or implement Forward Error Correction (FEC) strategy.

- Network-based:
  - Prioritising delay-sensitive traffic flows.

- Receiver-based:
  - Buffering strategies: the human ear is not sensitive to short-term variations; the buffer "absorbs" variation in network queueing delays and the voice can be reconstructed using RTP timestamps, but this adds to overall M2E delay.
  - Packet Loss Concealment (PLC) and FEC.

5.3 Packet Loss Strategies

The use of UDP limits delays but can lead to packet loss; to mitigate this, compensation strategies can be employed at the sender or receiver:

- Forward Error Correction (FEC): a form of information redundancy.
- Packet Loss Concealment (PLC): silence (simplest), repetition of last packet, or interpolation.

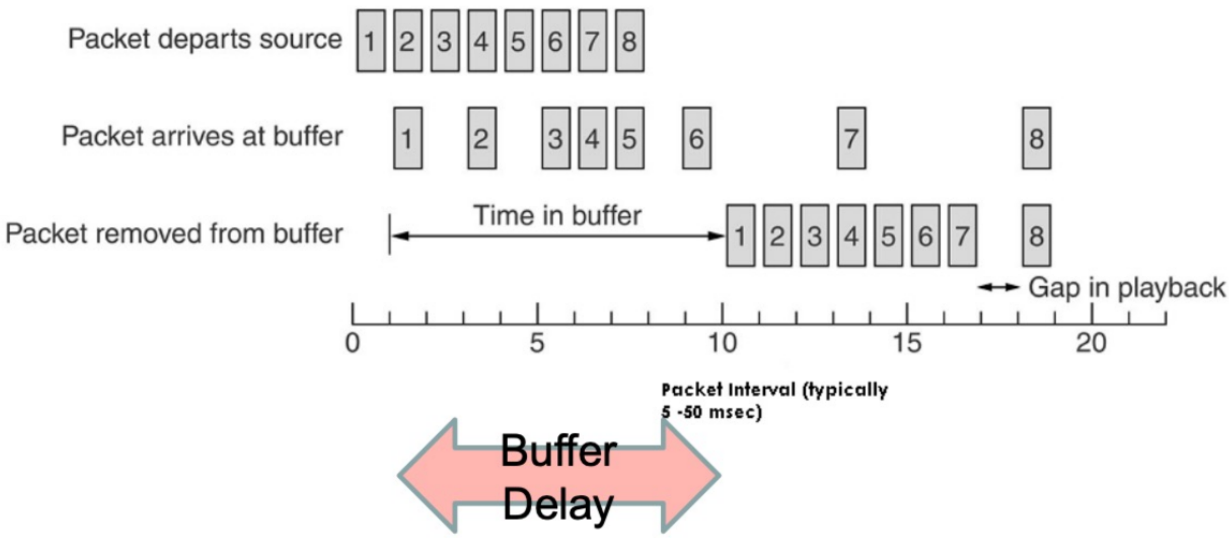

Figure 19: Receiver-based packet loss strategies: jitter buffer strategies

The buffer playout delay adds to the M2E delay. In the above figure, packet 8 arrives too late for the playout; we could drop the packet, or increase the buffer size in response to increasing delays. With a fixed buffer, the limitations are that if it is too large, it extends overall delay, and if it is too small, there will be additional late packet losses due to late arrival. An adaptive buffer size can adapt to network conditions:

- **Per Talkspurt (PT):** operates by elongating/shortening inter talkspurt silence periods; less noticeable.
- **Per Packet Scaling (PPS):** speed up/slow down speech, like in Skype or Zoom.

5.3.1 Network-Based Strategies

In a LAN environment: switched LANs are typically QoS enabled, and fast ethernet links are rarely congested. In a WAN environment, we could increase bandwidth (which is costly and mostly a temporary solution) or employ a reservation policy, traffic categorisation, & prioritisation which requires an admission control policy.

5.4 Cloud Gaming

In **cloud gaming**, the game is installed and executed on a powerful remote server located in the cloud. The game rendering (processing graphics, physics, & game logic) is done on this server. Once the game is rendered on the server, the video frames & audio are compressed and streamed to the player's device via the internet. The player's inputs, such as controller buttons, mouse movements, or keyboard presses are sent back to the could server over the Internet in real-time. It is commonly used in Massively Multiplayer Online Games (MMOG), and the server must deal with multiple players. Cloud gaming solves several issues of the traditional approach:

- Tedious installation & patching process.
- Extensive hardware & GPUs.

It is an RTC application, so we need to minimise delays (lag) and need time synchronisation to measure delays. Simultaneity is also required: all players need to see the same game representation.

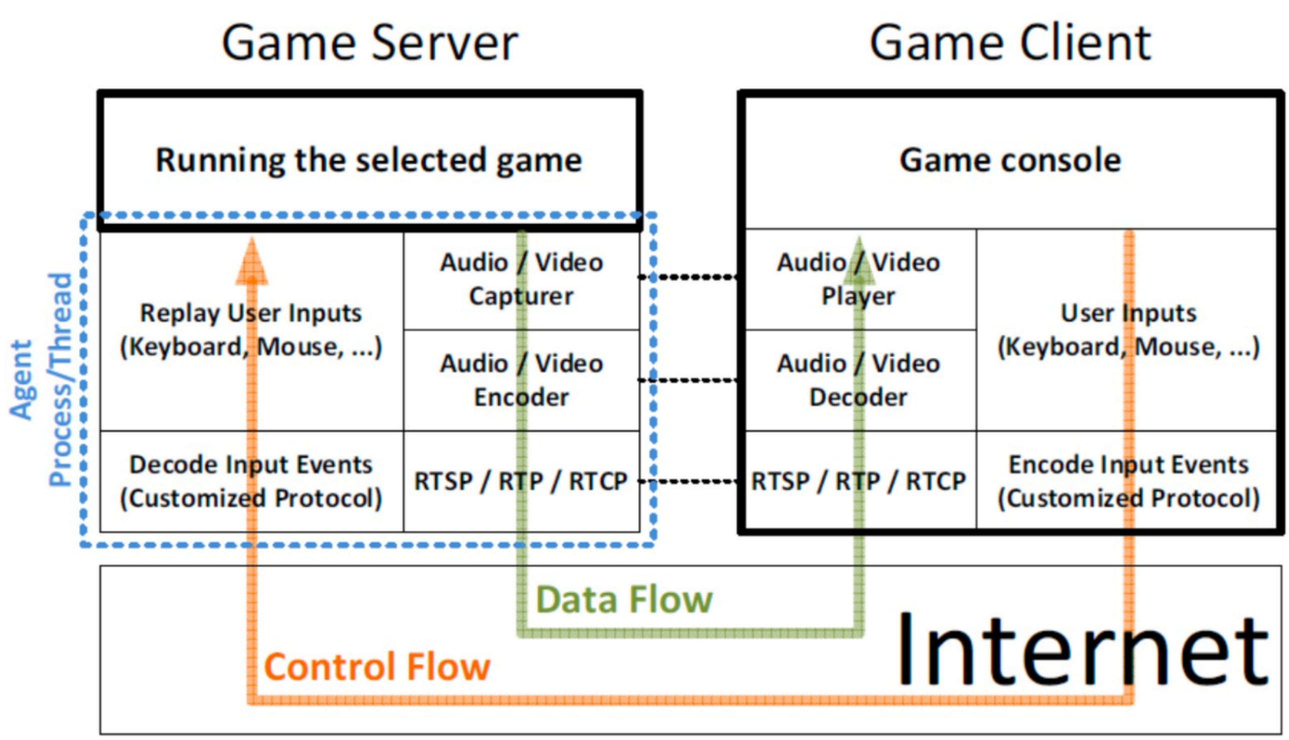

Figure 20: Client/server architecture of GamingAnywhere

5.4.1 Response Delay

- **Response Delay (RD)** is the time difference between a user submitting a command and the corresponding in-game action appearing on the screen.
- **Processing Delay (PD)** is the time required to receive / process a player's command and encode / transmit the corresponding frame.
- **Playout Delay (OD)** is the time required for the client to received, decode, and render a frame on the display.
- **Network Delay (ND)** is the round-trip delay.

$$\text{Response Delay (RD)} = \text{PD} + \text{OD} + \text{ND}$$

5.5 WebRTC

Web Real-Time Communications (WebRTC) is a free, open-source project that provides web browsers & mobile applications with real-time communication (RTC) via simple APIs. It allows audio & video communication to work inside web pages via direct peer-to-peer communication using JavaScript & HTML, that is, eliminating the need to install plugins or download native apps. It uses DTLS for encryption & SRTP for secure media streams. It works on major web browsers (Chrome, Firefox, Safari, Edge) and mobile platforms. Use cases include the web versions of Google Meet, Discord, Facebook Messenger, peer-to-peer file sharing, etc.

5.5.1 WebRTC Working Model

1. **Media capture:** accesses camera & microphone using browser APIs.
2. **Connection management:** exchanges session control messages (via WebSockets, SIP, or custom methods) to set up connections.
3. **Data transmission:** WebRTC uses the Interactive Connectivity Establishment (ICE) techniques to overcome the complexities of real-world networking like NAT:
   - STUN: finds public IP addresses.
   - TURN: relays media if direct connections fail.

   RTP/SRTP streams media, ensuring low-latency delivery.
4. **Peer discovery:** in P2P communication, the peers need to be able to identify or locate each other over the wire. Peer discovery mechanisms are not defined by WebRTC, although the process can be as simple as sharing a URL that peers can use to communicate.
5. **ICE techniques:** ICE will first try to make a connection using the host address obtained from a device's operating system. If the network is unsuccessful, ICE will obtain an external address using the STUN server. If that fails, the traffic is routed via a TURN relay server.

Session Traversal Utilities for NAT (STUN) is a protocol that is used to discover public addresses that determines any restrictions in your router that would prevent a direct connection to a peer. Clients receive their public addresses as requested from STUN servers.

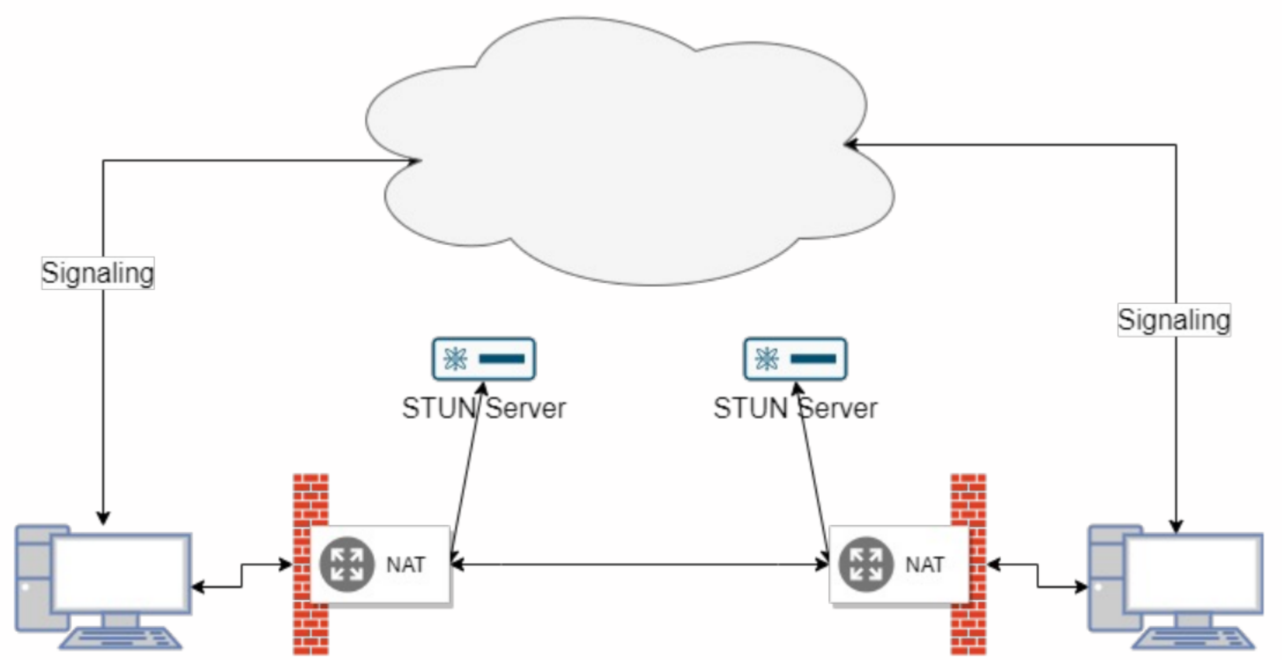

Figure 21: STUN

Traversal Using Relays around NAT (TURN) bypasses the symmetric NAT restriction by opening a connection with a TURN server and relaying all information through that server. A connection is required with a TURN server which will tell all the peers to send packets to the server which will then be forwarded to the requester.

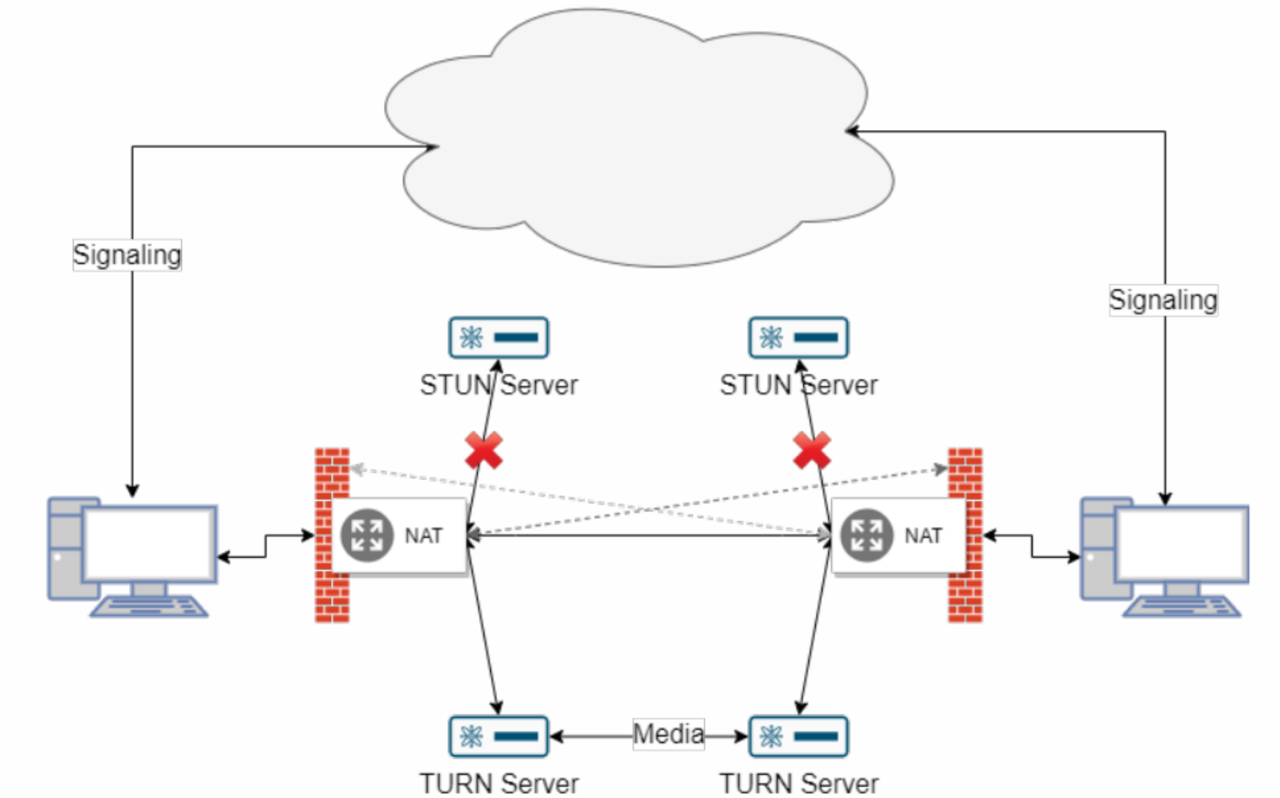

Figure 22: TURN

5.6 DASH

DASH stands for Dynamic Adaptive Streaming over HTTP:

- **Dynamic:** reacts to changing scenarios.
- **Adaptive:** has media represented in different it rates / codecs.
- **Streaming:** not strictly real-time communication, but timelines are still important.
- **HTTP:** web model, HTTP good for firewalls etc.

The DASH working model is as follows:

- **Encoding & Segmentation:** the original video/audio content is divided into small segments (usually 2-10 seconds each). Each segment is encoded at multiple bitrates & resolutions for adaptability. A manifest file is created, containing metadata about segments, their URLs, codecs, & timing.
- **Delivery:** segments and the MPD file are uploaded to HTTP servers or CDNs. The encoded video segments are pushed out to client devices over the Internet.
- **Playback:** the client downloads the MPD file to understand the available content & quality options. It chooses appropriate “representation” based on network conditions, device capabilities, & user preferences, decodes the chunks, and plays back the video.
- **Quality adjustment:** the player continuously downloads & plays segments, adjusting the quality as network conditions change.

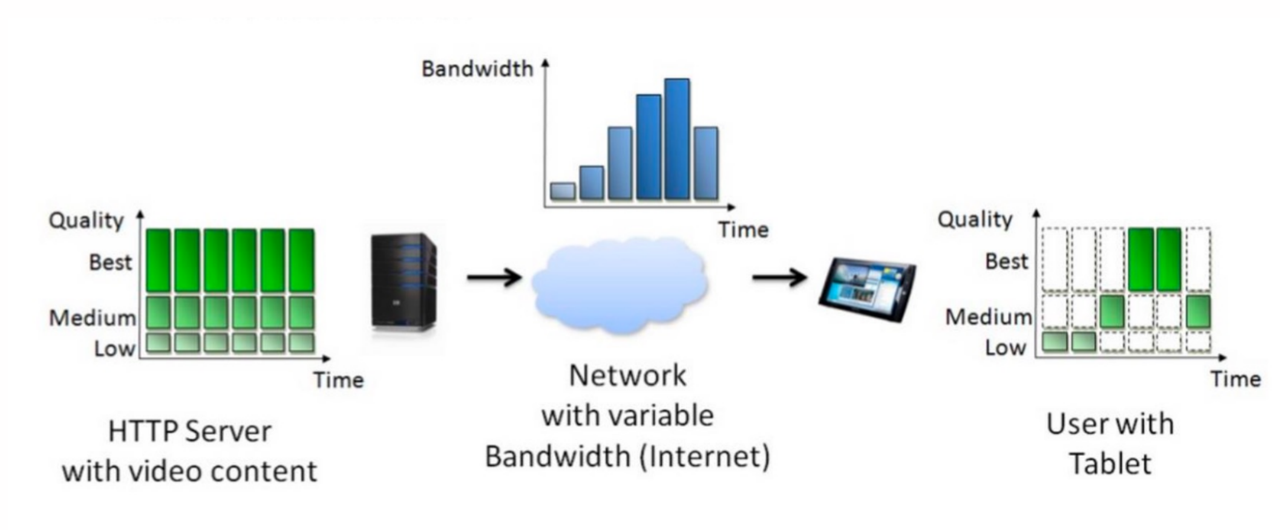

Figure 23: DASH

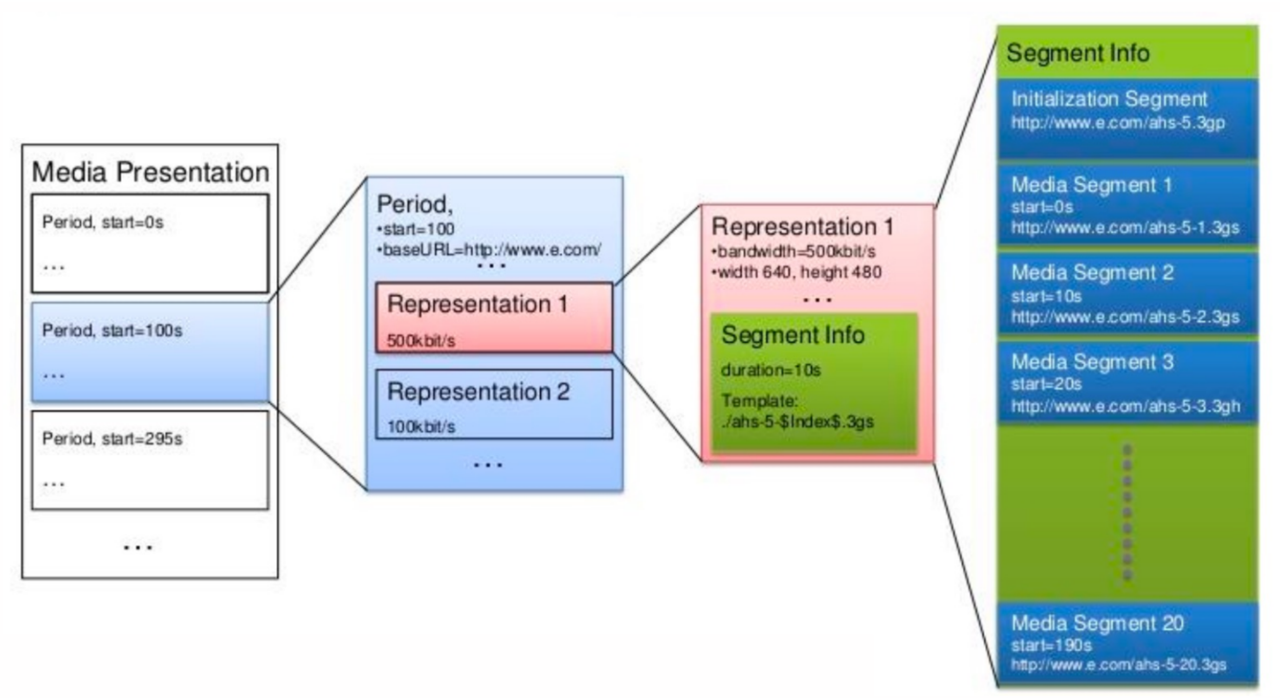

Figure 24: DASH data model