Preventing (Network) Time Travel with Chronos

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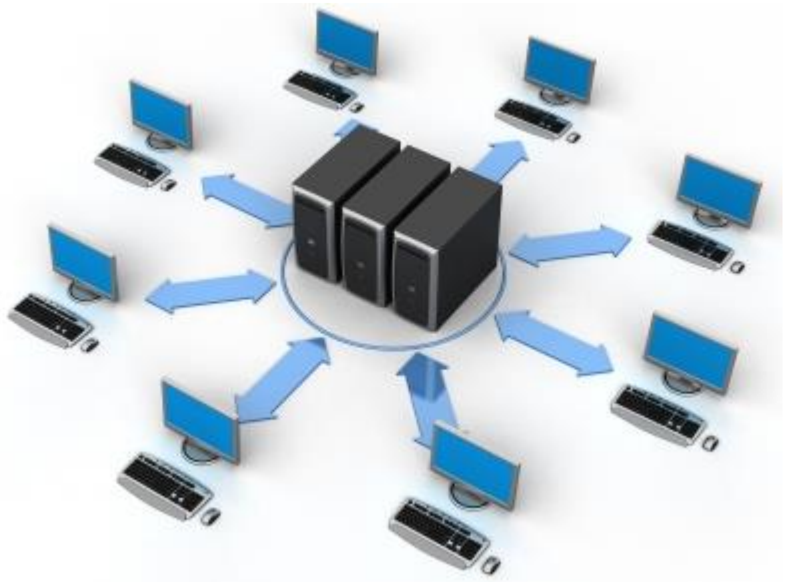
Network Time Protocol (NTP)

- NTP synchronizes time across computer systems over the Internet.

- Many applications rely on NTP for correctness and safety:
  - TLS certificates
  - DNS (and DNSSEC)
  - HTTPS
  - Kerberos
  - Financial applications



Time is Important for Certification

https://www.nanog.org/

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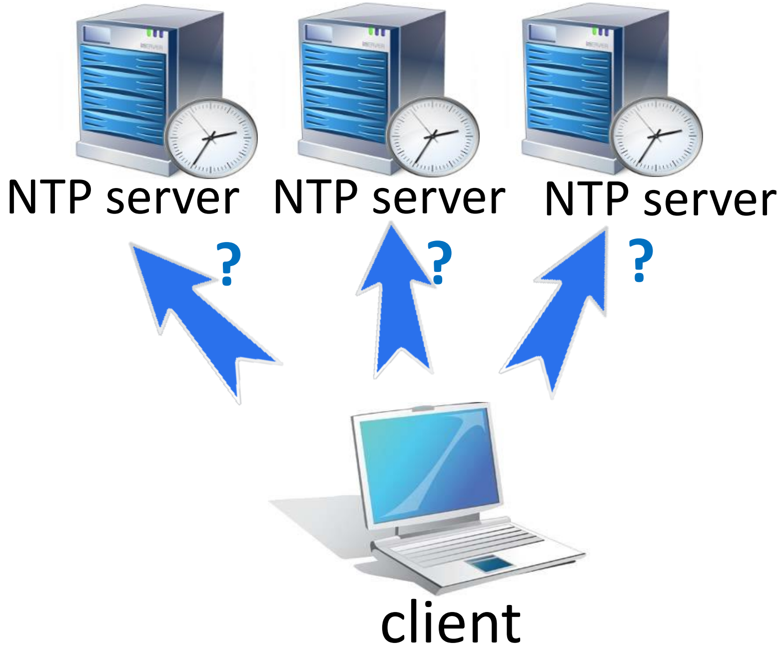
Validating the certificate requires knowing the current time

NTP Architecture

- NTP's client-server architecture consists of two main steps:

1. **<u>Poll process</u>**:
   The NTP client gathers time samples from NTP servers

Poll process: **NTP queries**



NTP Architecture

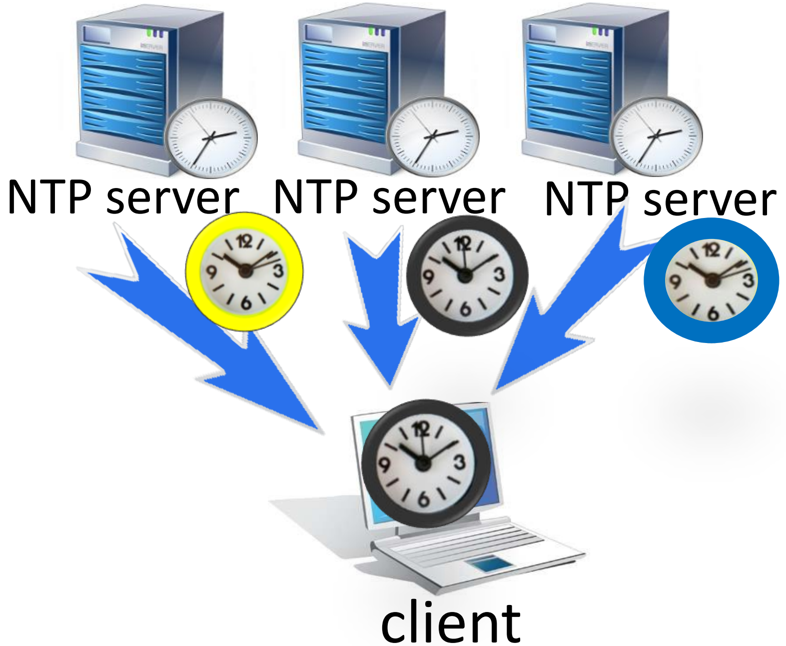
- NTP's client-server architecture consists of two main steps:

  1. **<u>Poll process</u>**:
     The NTP client gathers time samples from NTP servers

  2. **<u>Selection process</u>**:
     The "best" time samples are selected
     and are used to update the local clock

Poll process: **NTP responses:**

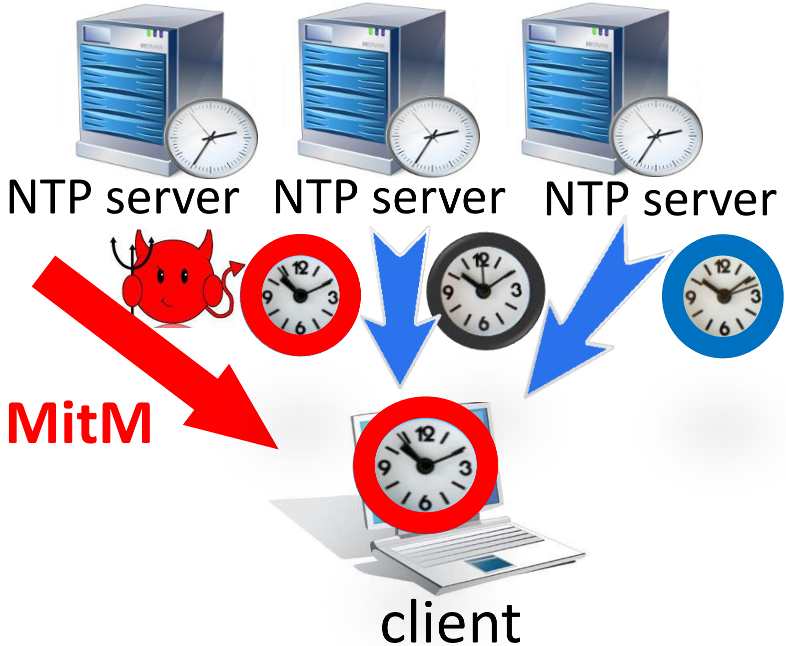
Selection process:



NTP Man-in-the-Middle (MitM) Attack

- NTP is highly vulnerable to time shifting attacks, especially by a MitM attacker
  - Can tamper with NTP responses
  - Can impact local time at client simply by dropping and delaying packets to/from servers **(encryption and authentication are insufficient)**

- Previous studies consider MitM as "too strong for NTP"



Why is NTP so Vulnerable to MitM?

- **NTP's poll process** relies on a small set of NTP servers (e.g., from pool.ntp.org), and this set is often DNS-cached.

Attacker only needs MitM capabilities with respect to few NTP servers

- **NTP's selection process** assumes that inaccurate sources are rare and fairly well-distributed around the UTC (the correct time)

Powerful and sophisticated MitM attackers are beyond the scope of **traditional** threat models

Chronos to the Rescue

The **Chronos NTP client** is designed to achieve the following:

- **Provable security** in the face of fairly powerful MitM attacks
    - negligible probability for successful timeshifting attacks
- **Backwards-compatibility**
    - no changes to NTP servers
    - limited software changes to client
- **Low computational and communication overhead**
    - query few NTP servers

Threat Model

The attacker:

- Controls a large fraction of the NTP servers in the pool (say, ¼)
- Capable of both deciding the content of NTP responses **and** timing when responses arrive at the client
- Malicious

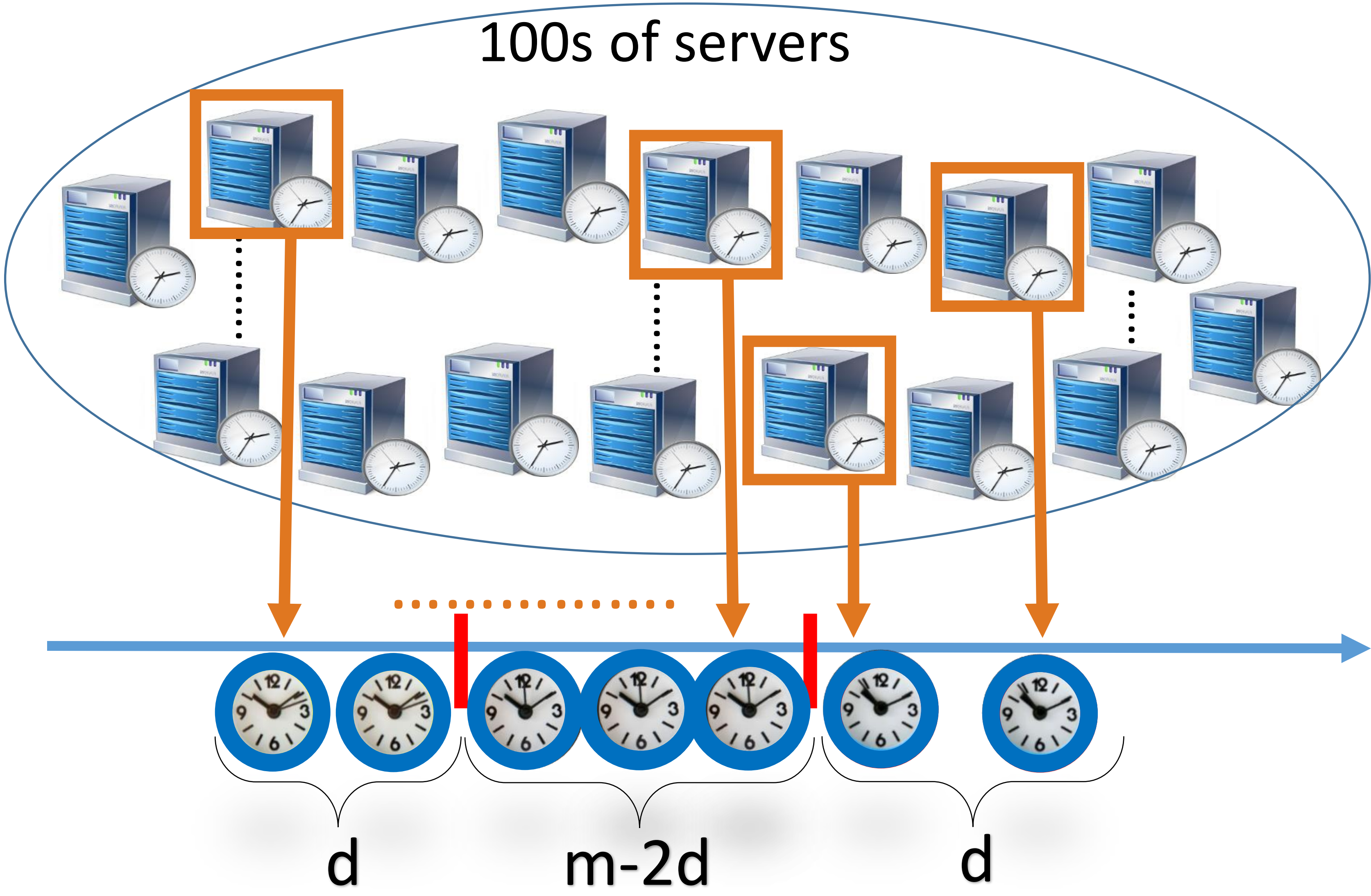
Chronos Architecture

Chronos' design combines several ingredients:

- **Rely on many NTP servers**
  - ➢ Generate a large server pool (hundreds) per client
    - ➢ E.g., by repeatedly resolving NTP pool hostnames and storing returned IPs
  - ➢ Sets a very high threshold for a MitM attacker
- **Query few servers**
  - ➢ Randomly query a small fraction of the servers in the pool (e.g., 10-20)
  - ➢ Avoids overloading NTP servers
- **Smart filtering**
  - ➢ Remove outliers via a technique used in approximate agreement algorithms
  - ➢ Limit the MitM attacker's ability to contaminate the chosen time samples

Chronos' Time-Update Algorithm: Informal

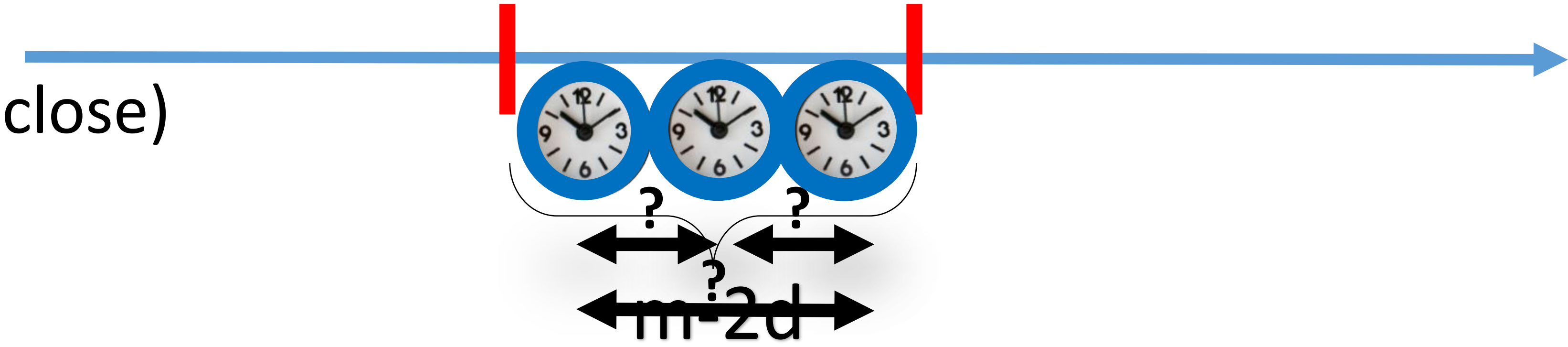
- Query m (10s of) servers **<u>at random</u>**
- Order time samples from low to high
- Remove the d lowest and highest time samples



Chronos' Time-Update Algorithm: Informal

Check:

If (the remaining samples are close)

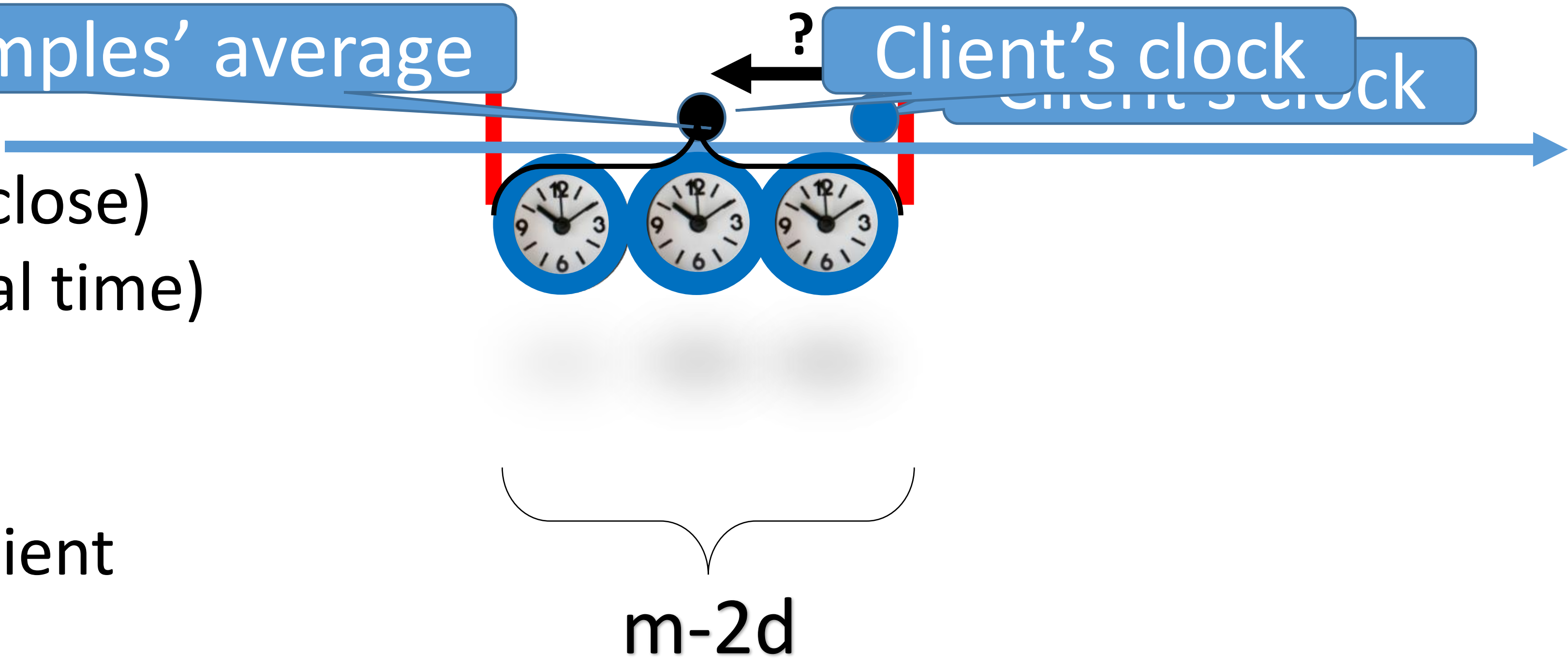


Chronos' Time-Update Algorithm: Informal

Check:

If (the remaining samples are close)

and (average time close to local time)



- **Then:**
  - Use average as the new client time
- **Else**
  - Resample

Chronos' Time-Update Algorithm: Informal

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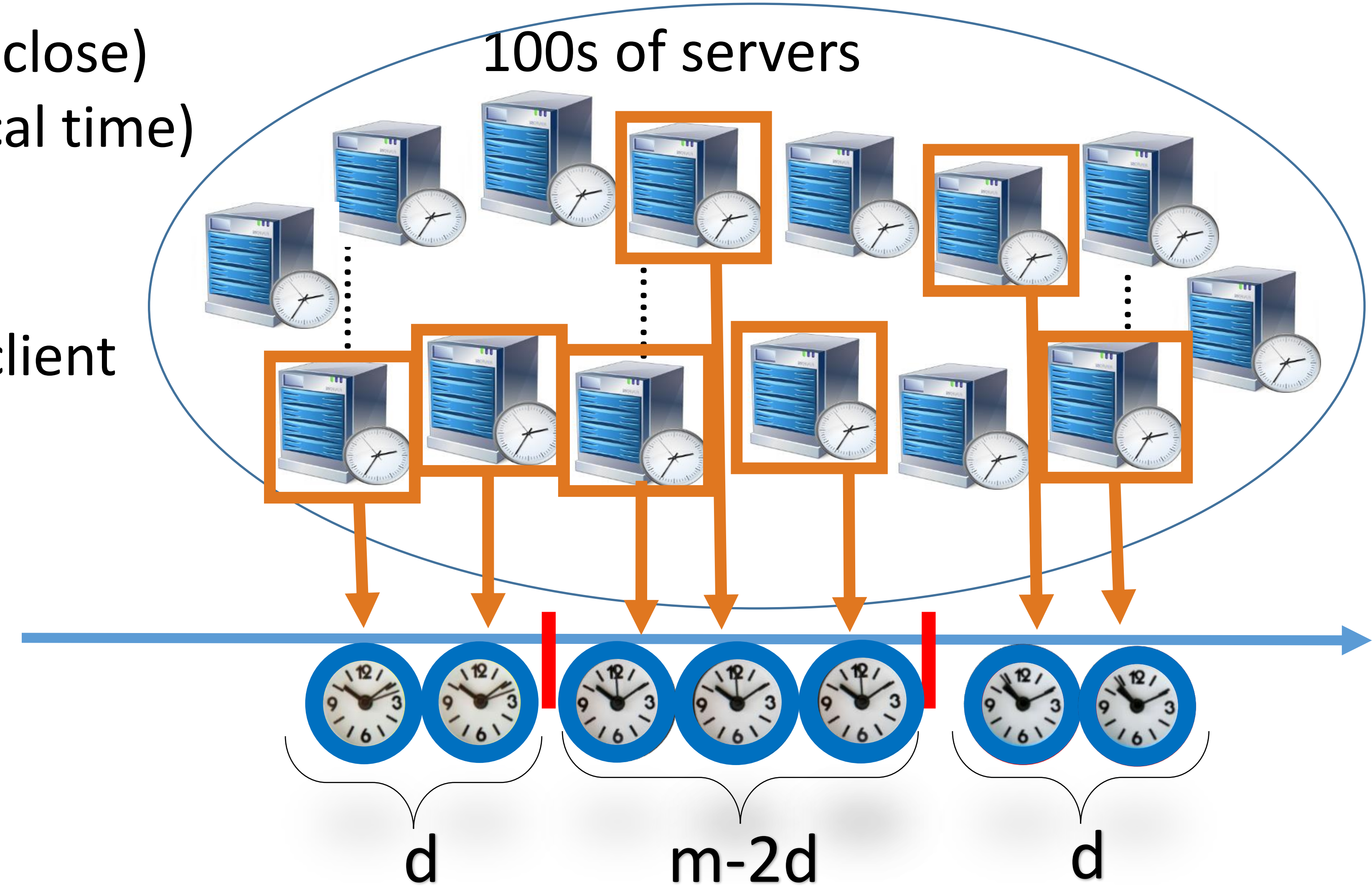
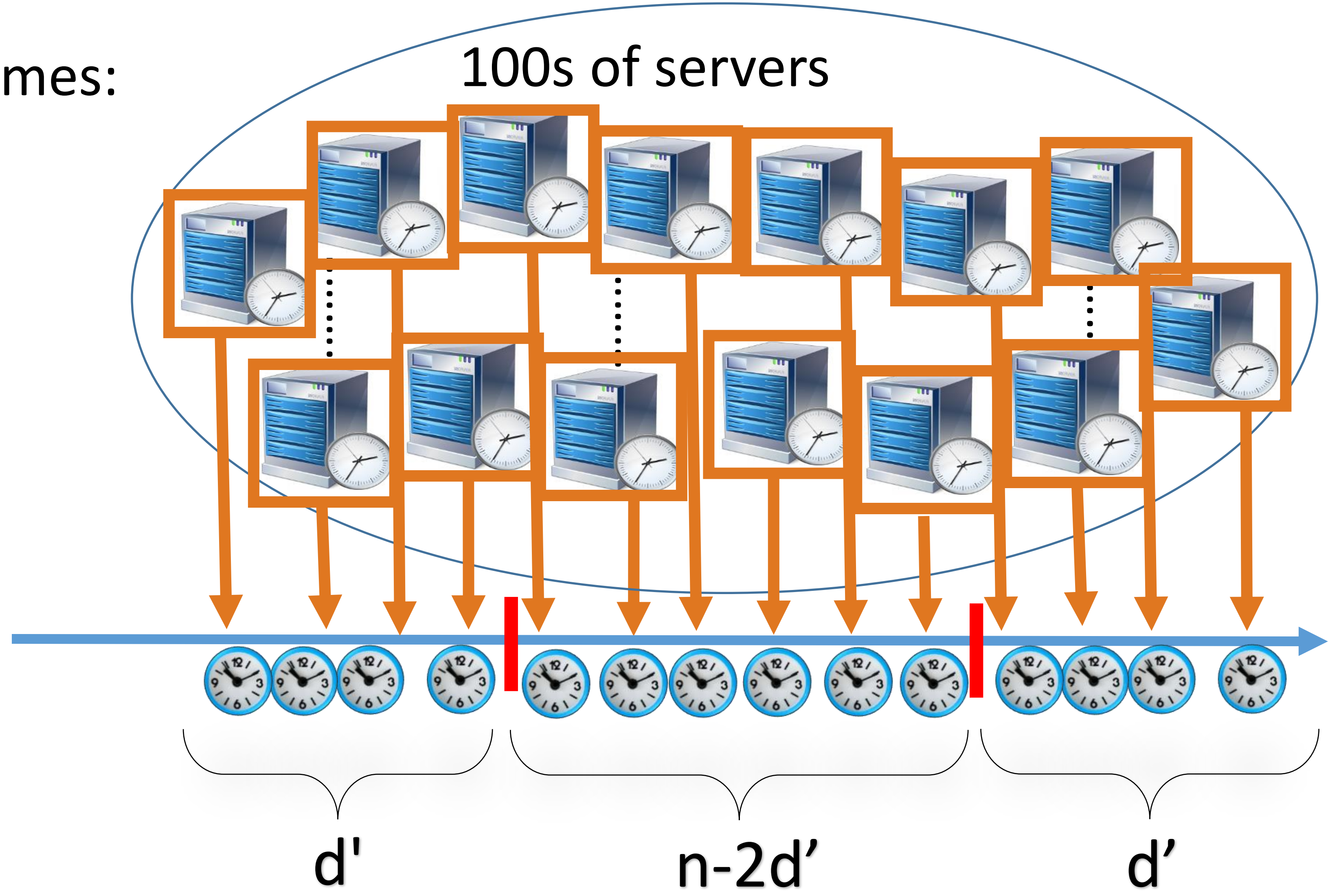


Chronos' Time-Update Algorithm: Informal

if check & resample failed k times:

\\ **panic mode**

- Sample all servers
- Drop outliers
- Use average as new client time



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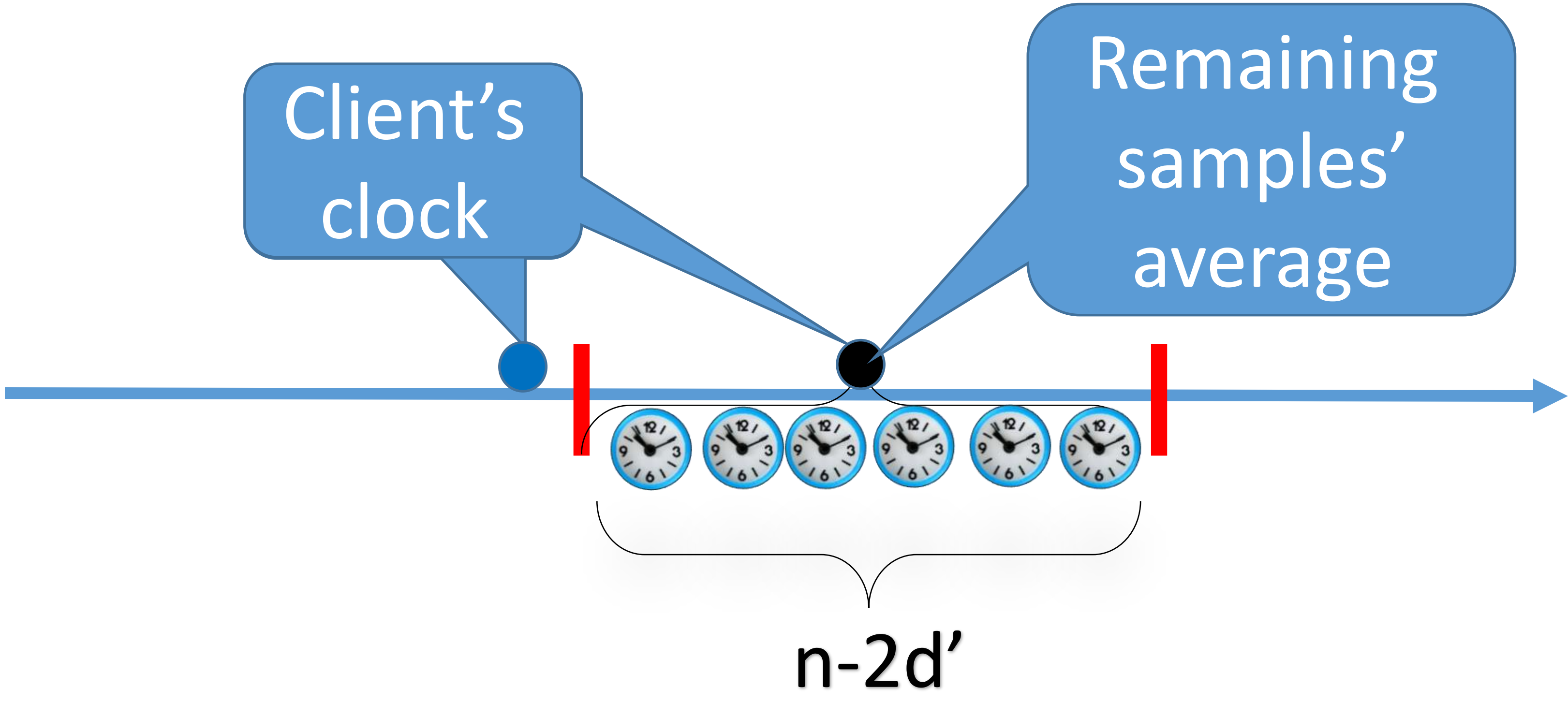


Security Guarantees

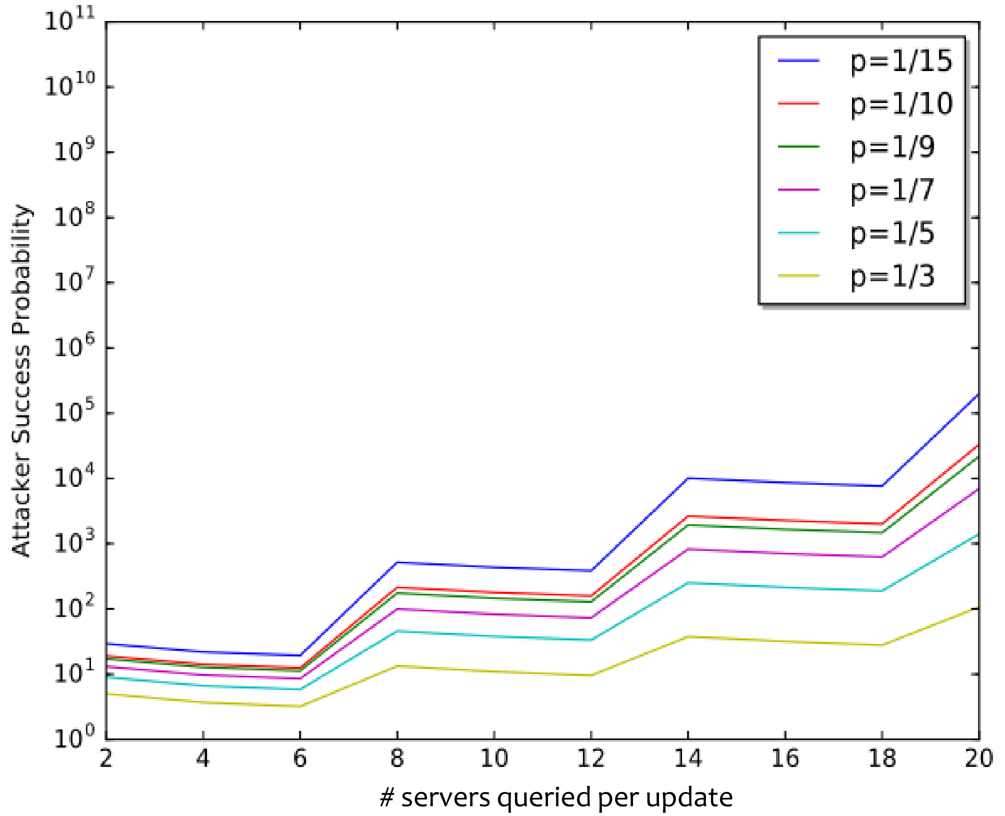
Shifting time at a Chronos client by at least **100ms** from the UTC will take the attacker at least **22 years** in expectation

- … when considering the following parameters:
  - Server pool of 500 servers, of whom 1/7 are controlled by an attacker
  - 15 servers queried once an hour
  - Good samples are within 25ms from UTC (ω=25)

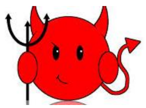
- These parameters are derived from experiments we performed on AWS servers in Europe and the US

Chronos vs. Current NTP Clients

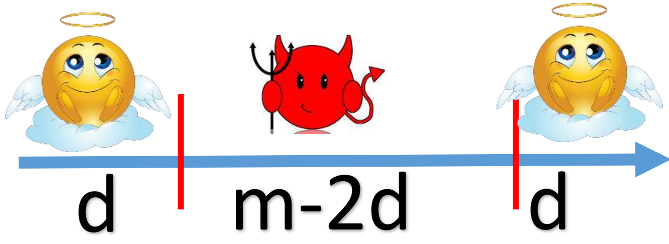
- Consider a pool of 500 servers, a p-fraction of which is controlled by an attacker.
- We compute the attacker's probability of successfully shifting the client's clock
  - ➢ for traditional NTP client
  - ➢ for Chronos NTP client
- We plot the ratio between these probabilities



Security Guarantees: Intuition

Scenario 1: #() > d #() < m-d

- **<u>Option I</u>**: Only malicious samples remain
  - ➢ <u>Assumption</u>: every good sample at most ω-far from UTC
  - ➢ At least one good sample on each side
    - → All remaining samples are between two good samples
    - → All remaining samples are at most ω-away from UTC

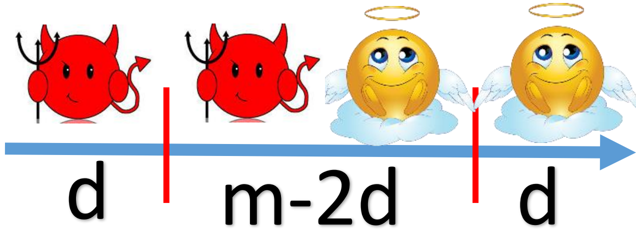


- **<u>Option II</u>**: At least one good sample remains

➢ <u>Enforced</u>: Remaining samples within the same 2ω-interval

➢ Remaining malicious samples are within 2ω from a good sample

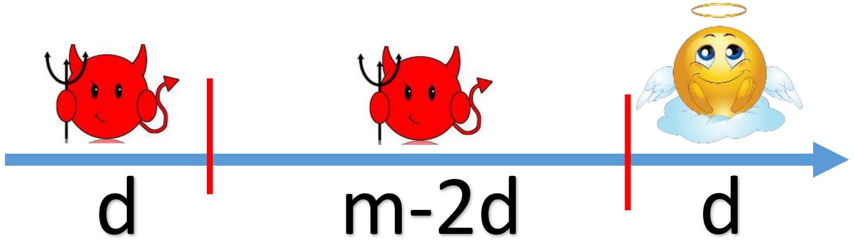
→ Remaining malicious samples are at most 3ω-away from UTC



Hence, these attack strategies are ineffective

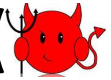
Security Guarantees: Intuition

Scenario 2: #() ≤ d   #() ≥ m-d



- <u>Optimal attack strategy</u>:
  All malicious samples are lower than all good samples
  (Or, all malicious samples are higher than all good samples)

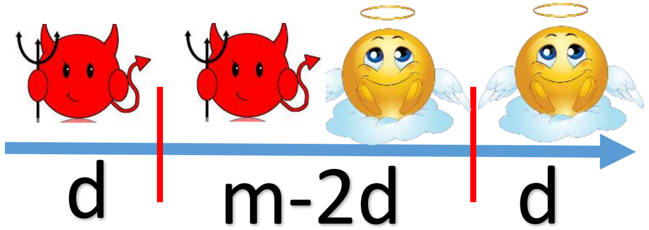
- **Chronos enforces an upper bound of 4ω on the permissible shift from the local clock** (otherwise the server pool is re-sampled)

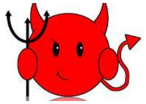
- **The probability that #()≥m-d is extremely low** (see paper for detailed analysis)
  The probability of repeated shift is negligible.

Consequently, a significant time shift is practically infeasible

Can Chronos be exploited for DoS attacks?

- Chronos repeatedly enters Panic Mode.



- Optimal attack strategy requires that attacker repeatedly succeed in accomplishing #() > d #() < m-d
  - At least one malicious sample remains
  - Malicious sample violates condition that all remaining samples be clustered
  - This leads to resampling (until Panic Threshold is exceeded).

Even for low Panic Threshold (k=3), probability of success is negligible (will take attacker decades to force Panic Mode)

Observations and Extensions

- When the pool of available servers is small (say, 3), using Chronos's sampling scheme on the entire server pool (n=m), yields meaningful <u>deterministic</u> security guarantees.

- Important implications for PTP security

Conclusion

- NTP is very vulnerable to time-shifting attacks by MitM attackers
  - ➢ Not designed to protect against **strategic** man-in-the-middle attacks
  - ➢ Attacker who controls a few servers/sessions can shift client's time
- We presented the **Chronos NTP client**
  - ➢ Provable security in the face of powerful and sophisticated MitM attackers
  - ➢ Backwards-compatibility with legacy NTP (software changes to client only)
  - ➢ Low computational and communication overhead

Future Research

- Tighter security bounds?
- Weighing servers according to reputation?
- Benefits of server-side changes?
- Extensions to other time-synchronization protocols (e.g., PTP)?

Thank You

See full paper (@NDSS’18):

http://wp.internetsociety.org/ndss/wp-content/uploads/sites/25/2018/02/ndss2018_02A-2_Deutsch_paper.pdf