Sundial: Fault-tolerant Clock Synchronization for Datacenters

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Need for synchronized clocks in datacenter

- Simplify or improve existing applications
    - Distributed databases

      Spanner FaRMv2

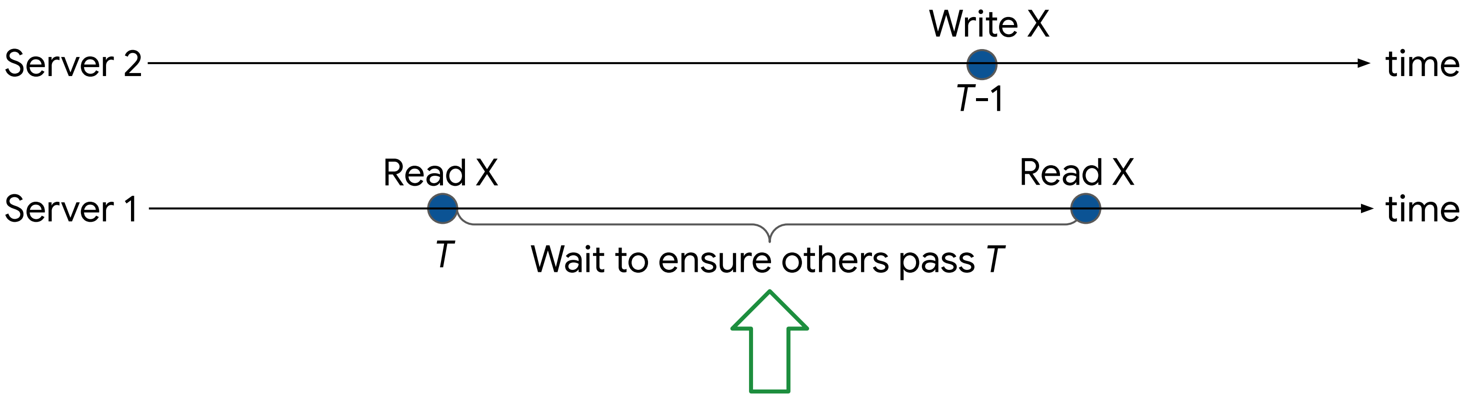
    - Consistent snapshots

- Enable new applications
    - Network telemetry, e.g., per-link loss/latency, network snapshot
    - One-way delay measurement for congestion-control
    - Distributed logging and debugging

- And more, if synchronized clocks with tight bound are available

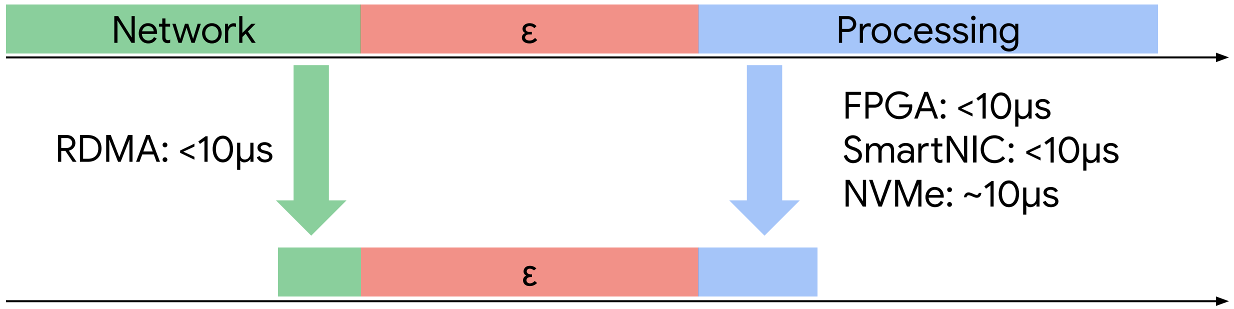
Need for time-uncertainty bound (ε)

Wait: a common op for ordering & consistency



Time-uncertainty bound (ε) decides how much to wait

Need for tighter time-uncertainty bound (ε)



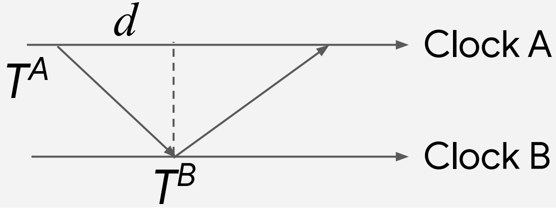
Even 10~20μs ε causes 25% extra median latency*!

Sundial: ~100ns time-uncertainty bound even under failures
2 to 3 orders of magnitude better than existing designs

*FaRMv2 [SIGMOD' 19]

State-of-the-art clock synchronization

Calculate *offset*
Between 2 clocks



$$offset = T^A + \underbrace{d}_{\approx RTT/2} - T^B$$

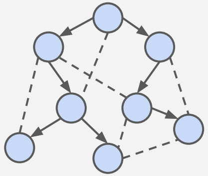
Path of messages

Variable and asymmetric delay ($d \neq RTT/2$):

1. Forward vs. Reverse paths
2. Queuing delay

Sync between neighboring devices
Fixed and symmetric delay ($d = RTT/2$)

Network-wide
synchronization

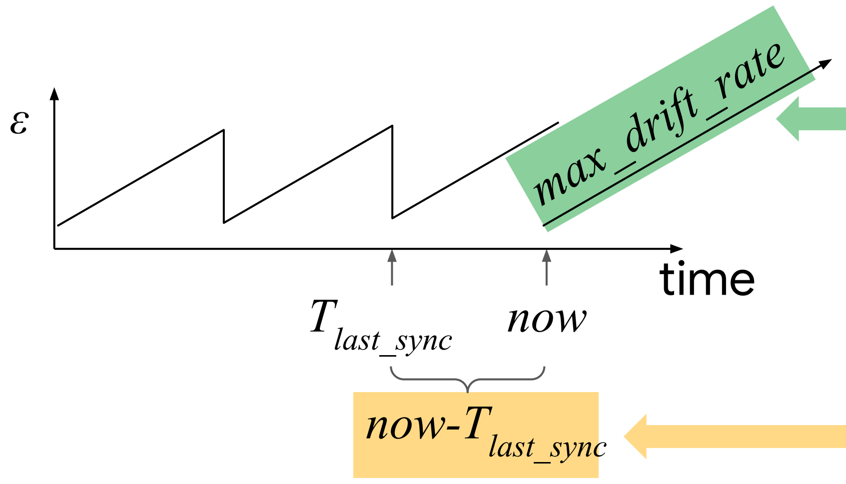


Spanning tree:
Clock values distributed along tree edges

Periodic
synchronization

Clocks can drift apart over time, so periodic synchronization is needed

Calculation of time-uncertainty bound ε



Frequency-related failures:
- Cooling, voltage fluctuations

Connectivity failures:
- link/device failure that break the spanning tree

$$\varepsilon = (now - T_{last\_sync}) \times max\_drift\_rate + c$$

Impact of failures on *max_drift_rate*

- Clocks drift as oscillator frequencies vary with temperature, voltage, etc.
    - E.g., frequency ±100ppm between -40~80 °C from an oscillator specification.
    - Various failures cause frequency variations: cooling failure, fire, voltage fluctuations, etc.
- *max_drift_rate* is set conservatively in production (200ppm in Google TrueTime)
- Reason: must guarantee **correctness**
    - What if we set it more aggressively? A large number of clock-related errors (application consistency etc.) during cooling failures!

< 100ns   **< 500μs**   200ppm

$$\varepsilon = (now - T_{last\_sync}) \times max\_drift\_rate + c$$

1. Need very **frequent synchronization**

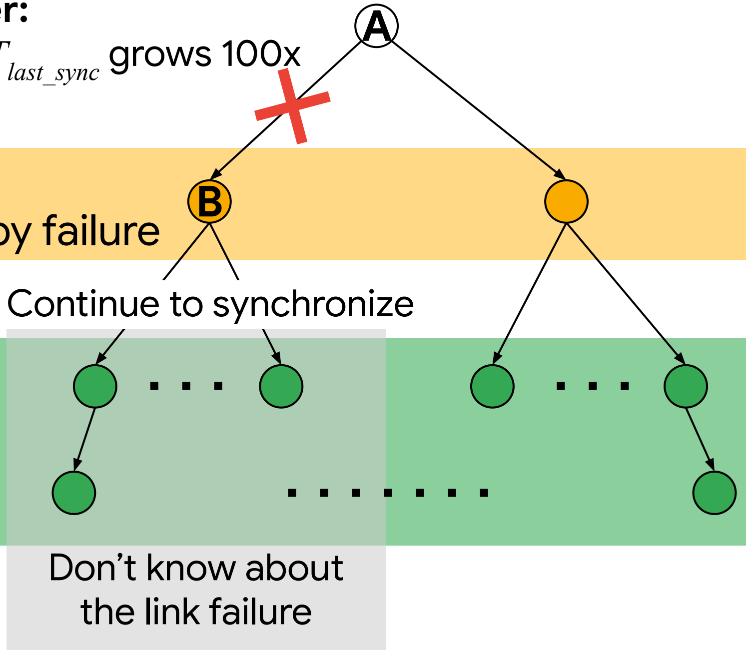
Impact of failures on $now\text{-}T_{last\_sync}$

Needs controller to recover:
If recovery takes 100x, $now\text{-}T_{last\_sync}$ grows 100x

Connectivity recovery time

Root's direct children:
Large ε when affected by failure

Other nodes:
Large ε all the time to prepare for unnoticed failures



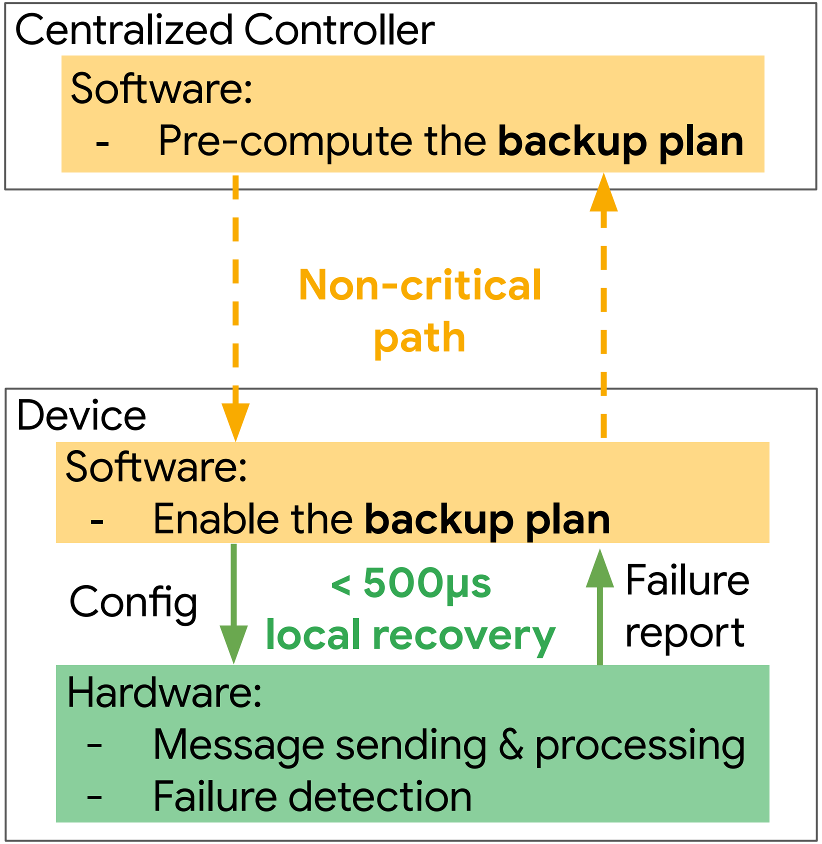
2. Need **fast recovery from connectivity failures**

Sundial design overview

Hardware-software codesign w/ two salient features:

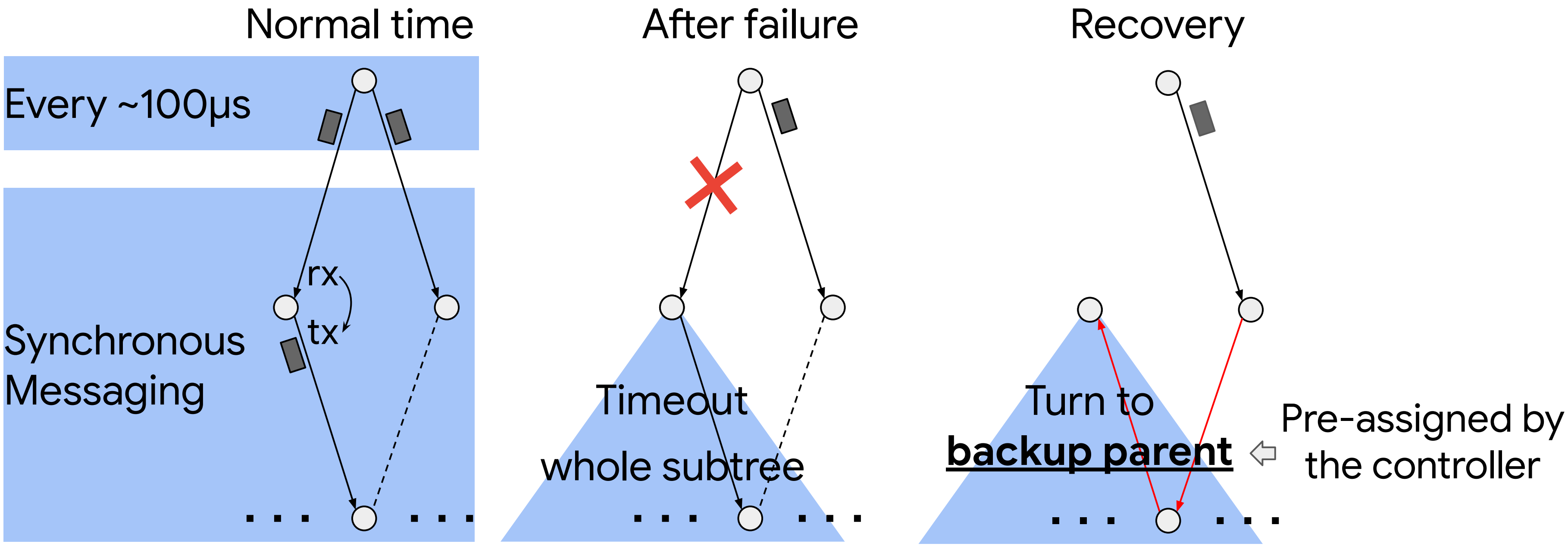
1. Frequent synchronization

2. Fast recovery from connectivity failures

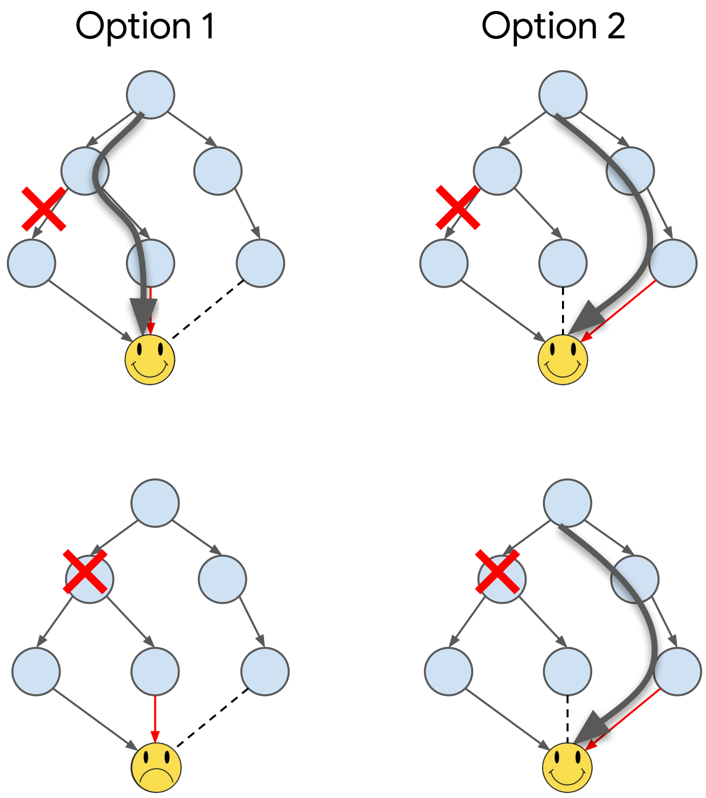


Sundial hardware design

3 key aspects	**Frequent messages** Every ~100μs	**Fast failure detection** Small timeout	**Remote failure detection** Synchronous messaging



Sundial software design
Controller: pre-compute the backup plan



1 backup parent per device

Multiple options for the backup parent

Device can't distinguish different failures

Generic to different failures

Sundial software design
Controller: pre-compute the **generic** backup plan

- Any single link failure
- Any single device failure
- **Root device failure**
- **Any fault-domain (e.g., rack, pod, power) failure: multiple devices/links go down**

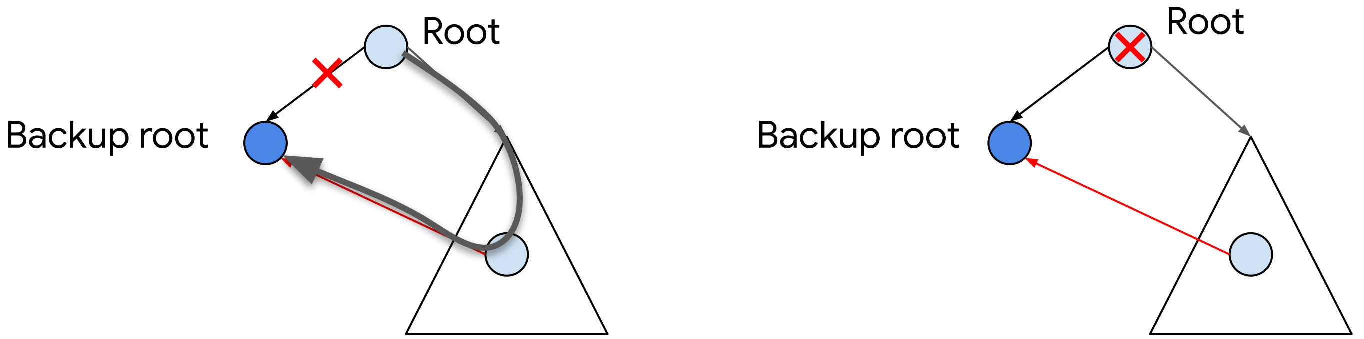
Backup plan
- 1 backup parent per device
- 1 backup root

Backup plan that handles root failure

Backup root: elect itself as the new root when root fails (normal device otherwise)

? How to **distinguish root failure** from other failures?

! Get **independent observation** from other nodes



Non-root failure: continue receiving msg

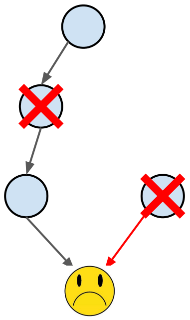
Root failure: no msg

[backup root only] **2nd timeout: elect itself as the new root**

Backup plan that handles fault-domain failures

If one domain failure:

1. Breaks connectivity
2. Takes down backup parent



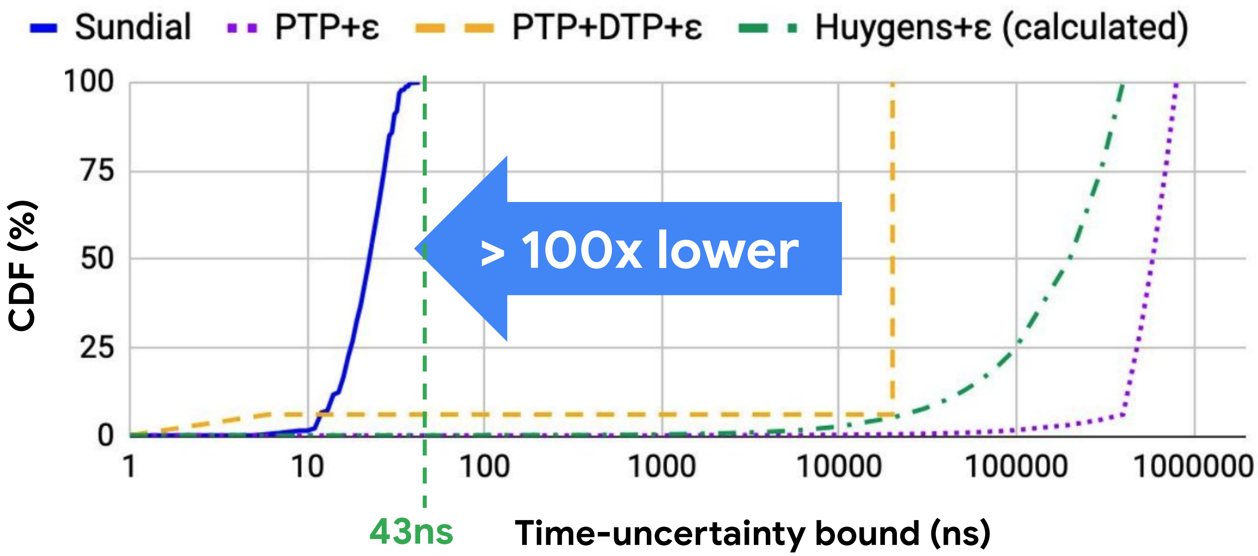
Avoid this case when computing the backup plan

Evaluation

- Testbed: 552 servers, 276 switches
- Compare with state-of-the-art **plus ε**
    - PTP+ε, PTP+DTP+ε, Huygens+ε
- Metrics: **ε**
- Scenarios:
    - Normal time (no failure)
    - Inject failure: link, device, domain

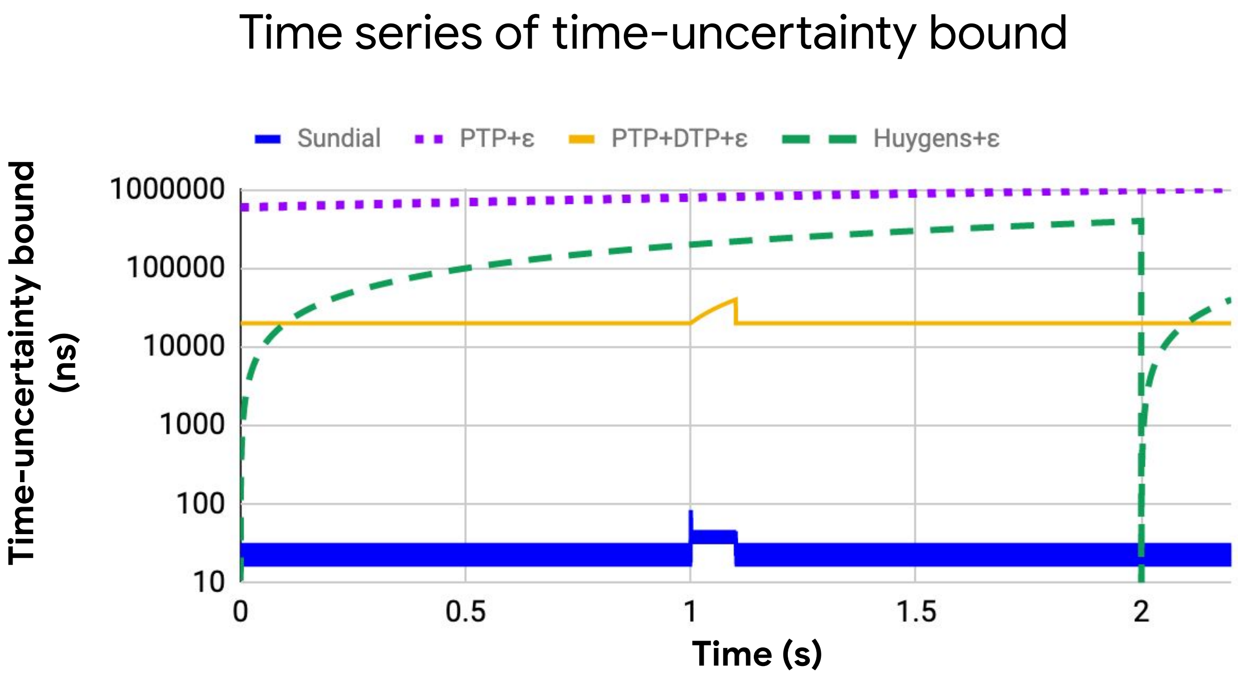
During normal time (w/o failures)

Time-uncertainty bound distribution over all devices



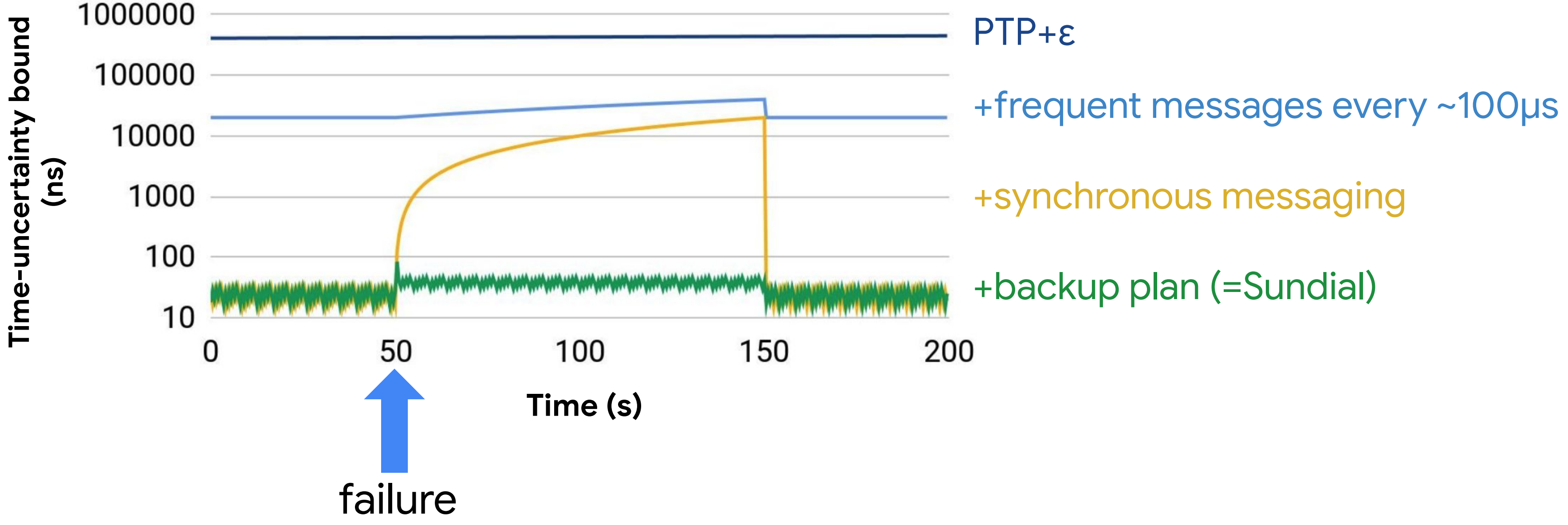
>2 orders of magnitudes lower during normal time

During failures



>2 orders of magnitudes lower during failures

How Sundial’s different techniques help



Sundial improves application performance

- Spanner: **3-4x** lower commit-wait latency
- Swift congestion control: with use of one-way-delays, **60%** higher throughput under reverse-path congestion
- Working on more applications using Sundial

Conclusion

- Time-uncertainty bound is the key metric
  - Existing sub-μs solutions fall short because of failures
- Sundial: hardware-software codesign
  - Device hardware: frequent message, synchronous messaging, fast failure detection
  - Device software: fast local recovery based on the backup plan
  - Controller: pre-compute the backup plan generic to different failures

First system: ~100ns time-uncertainty bound

Improvements on real applications