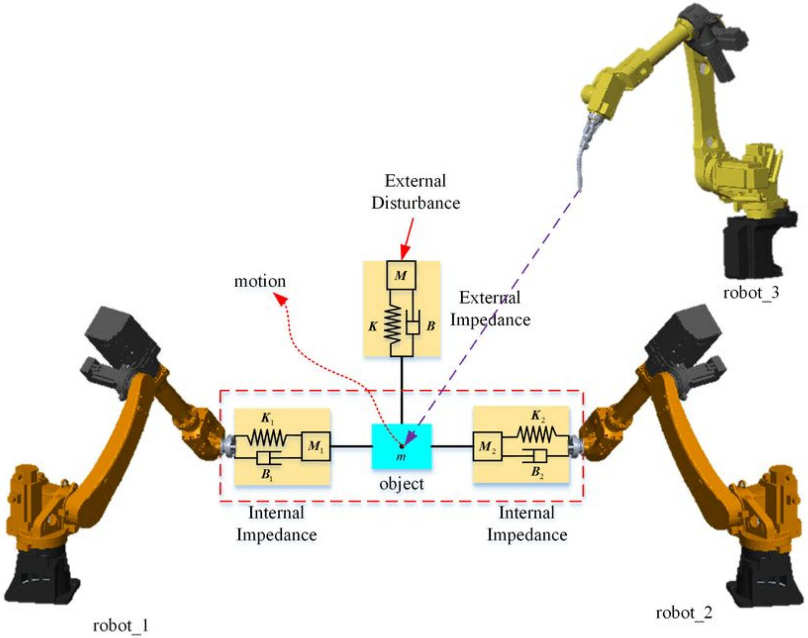
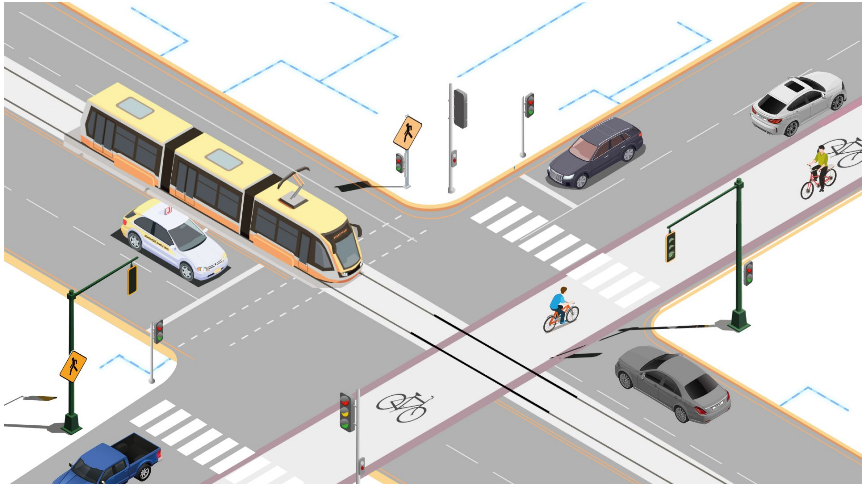
Quartz

Cyber-physical Applications





Coordination is Key

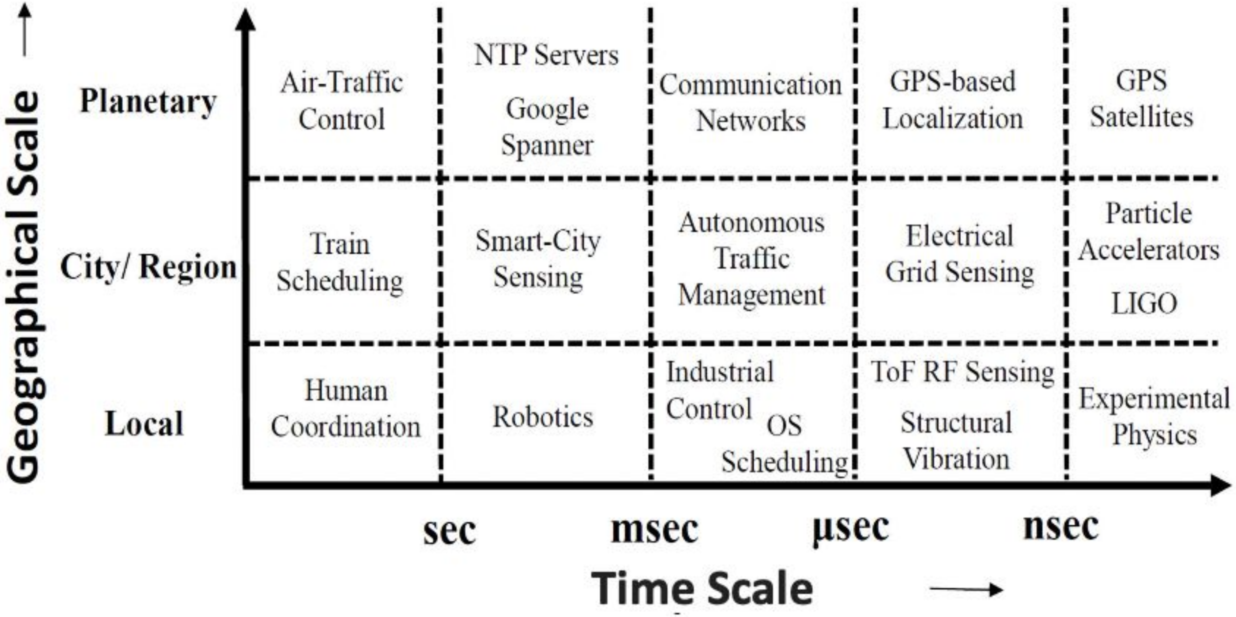


Figure 1: The scale of coordination in time and space

Shared Notion of Time

Clock synchronization systems:

- GPS
- Network Time Protocol
- Precision Time Protocol

Agnostic to application-specific requirements

Clock synchronization is not perfect -> uncertainty

Time-as-a-Service (TaaS)

The ability to provide an application-specific clock tracking time reference, such that the timing uncertainty does not exceed application specified requirements

Quality of Time: end-to-end uncertainty bounds corresponding to a timestamp, with respect to a clock reference

1) Safety constraints
2) Performance requirements
3) Assumptions/tolerances of the controller

Quartz

Features fully user-space implementation that

1) Supports multi-tenancy
2) Operates at geo-distributed (WAN) scale
3) Portable to an array of application domains and platforms
4) Provides API for distributed coordination based on abstracting timeline

DronePorter

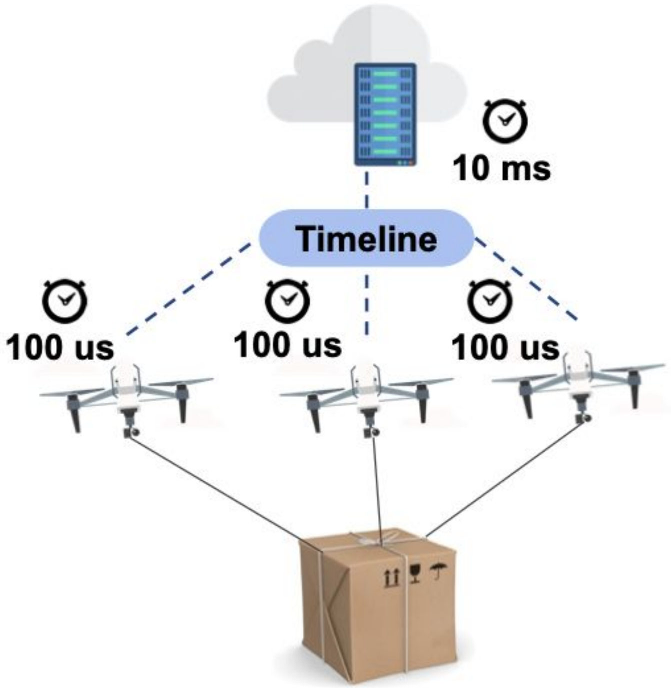


Figure 2: *DronePorter*: Drone coordination

TimeCop

Timeline Abstraction

Abstracts away clock synchronization from applications

A timeline provides a shared virtual clock reference to all distributed components of an application

Provides functionalities

1) Allows application to specify which components coordinate with each other
2) provides visibility into where each application component is deployed, and what its QoT requirements are with respect to the timeline reference

To allow orchestration of clock-synchronization protocols which ensures QoT requirements are met

Quartz API

Table 1: Quartz API Calls

Category	API Call	Return Type	Functionality
Timeline Association	**timeline_bind** (node_name, accuracy, resolution)	timeline	Bind to a timeline
	timeline_unbind (timeline)	status	Unbind from a timeline
	timeline_setaccuracy (timeline, accuracy)	status	Set Binding accuracy
	timeline_setresolution (timeline, resolution)	status	Set Binding resolution
Time Management	**timeline_gettime** (timeline)	timestamp+QoT	Get timeline reference time with uncertainty
	timeline_translate (timestamp, src_timeline, dst_timeline)	timestamp+QoT	Translate a timestamp on one timeline into another
Event Scheduling & Timestamping	**timeline_waituntil** (timeline, absolute_time)	timestamp+QoT	Absolute blocking wait
	timeline_sleep (timeline, interval)	timestamp+QoT	Relative blocking wait
	timeline_set_schedparams (timeline, period, start_offset)	status	Set period and start offset
	timeline_waituntil_nextperiod (timeline)	timestamp+QoT	Absolute blocking wait until next period
	timeline_timer_create (timeline, period, start_offset, count, callback)	timer	Register a periodic callback
	timeline_timestamp_events (timeline, event_type, event_config, enable, callback)	status	Configure events/external timestamping on a pin
Latency	**timeline_reqlatency** (timeline, src_node, dst_node, num_measure, percentile)	duration	Get the latency between two nodes on a timeline

Quartz Code Example

Listing 1: Simple Periodic App using the Quartz API

```
def main_func(timeline_uuid: str, app_name: str):
# Initialize the TimelineBinding class as an app
binding = TimelineBinding("app")
# Bind to the timeline with 1ms accuracy and resolution
ret = binding.timeline_bind(timeline_uuid, app_name, 1ms, 1ms)
if ret != ReturnTypes.QOT_RETURN_TYPE_OK:
print ('Unable to bind to timeline, terminating ....')
exit (1)
# Set the Scheduling Period and Offset (1s and 0ns repectively)
binding.timeline_set_schedparams(1000000000, 0)
while running:
# Wait until the next period
binding.timeline_waituntil_nextperiod()
# Do Something -> Read the time with the uncertainty
tl_time = binding.timeline_gettime()
print('Timeline time is       %f' % tl_time["time_estimate"])
print('Upper Uncertainty is   %f' % tl_time["interval_above"])
print('Lower Uncertainty is   %f' % tl_time["interval_below"])
# Unbind from the timeline
binding.timeline_unbind()
```

Architecture and Implementation

Challenges to overcome:

- Scalability (architecture)
- Autonomy (architecture)
- Portability (implementation)
- Ease of development (api)

Hierarchical Architecture

Node: single computing node/device with an independent clock

Cluster: any administrator-defined set of networked nodes that can communicate each other

- nodes setup over LAN

Global: represents global set of clusters

Types of Timelines

Local: discoverable only on nodes inside cluster in which the timeline is created

Global: discoverable by any node in the global set of clusters.

Architecture

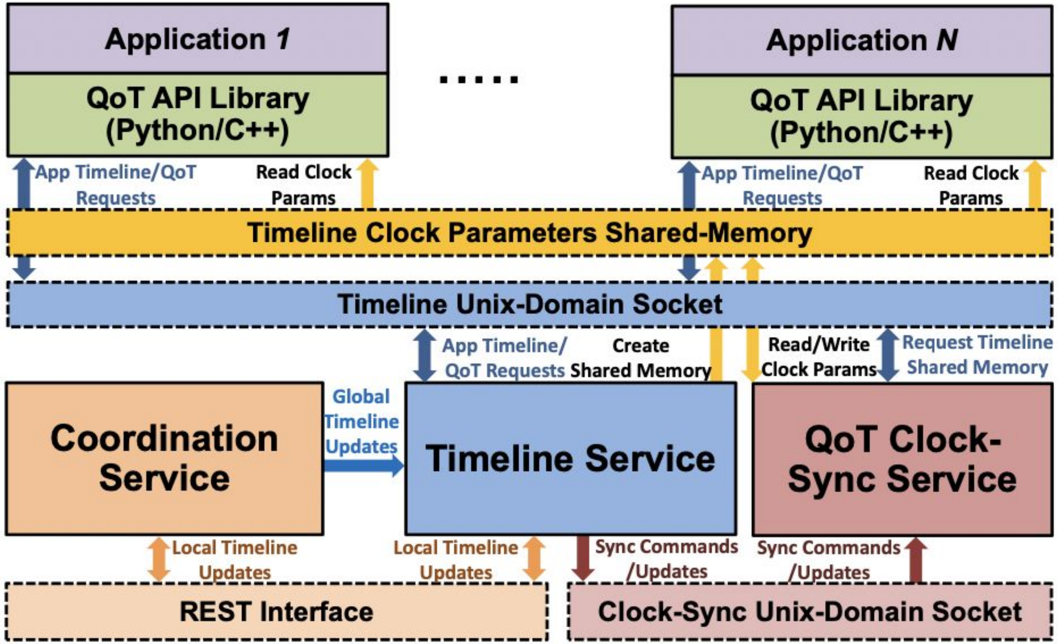
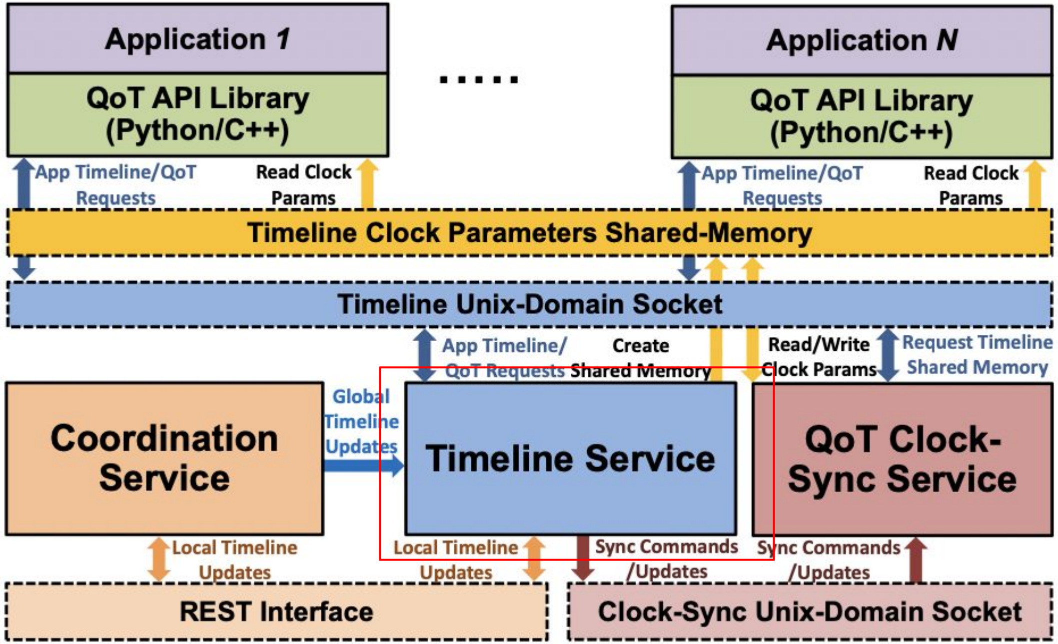


Figure 4: Quartz Time-as-a-Service. Solid boxes indicate components, dashed boxes indicate interfaces.

Timeline Service



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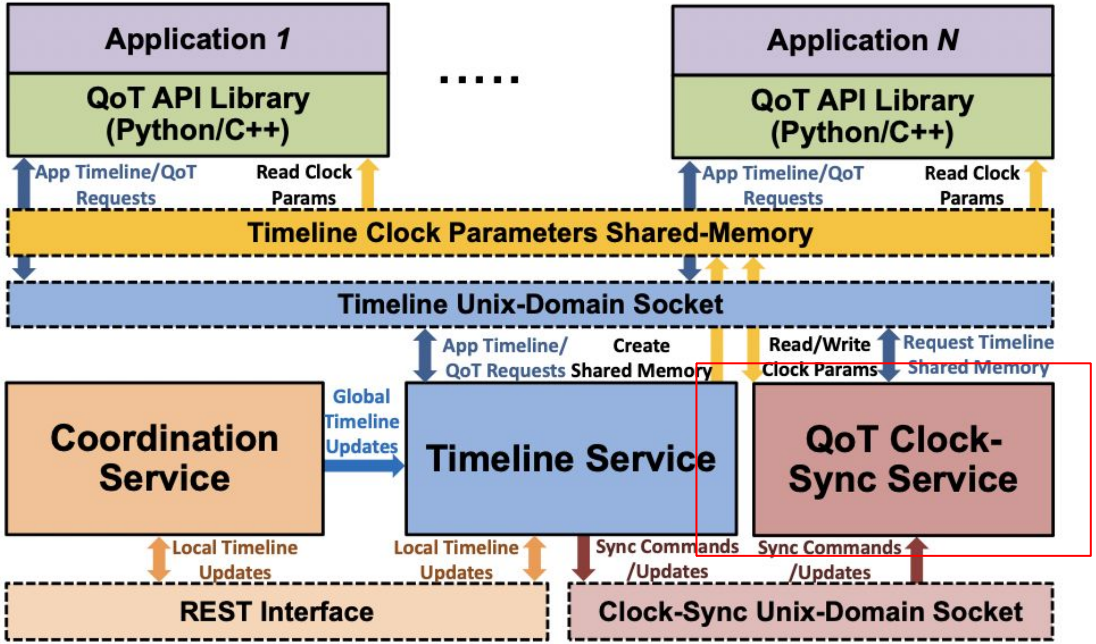
QoT Clock-Synchronization Service



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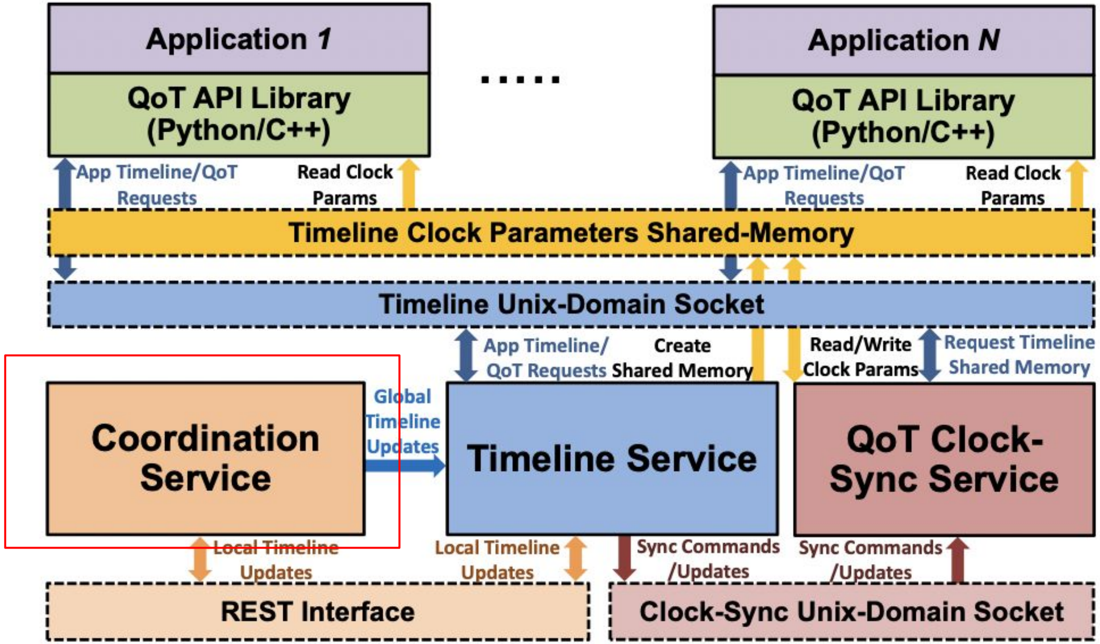
Coordination Service



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Global View

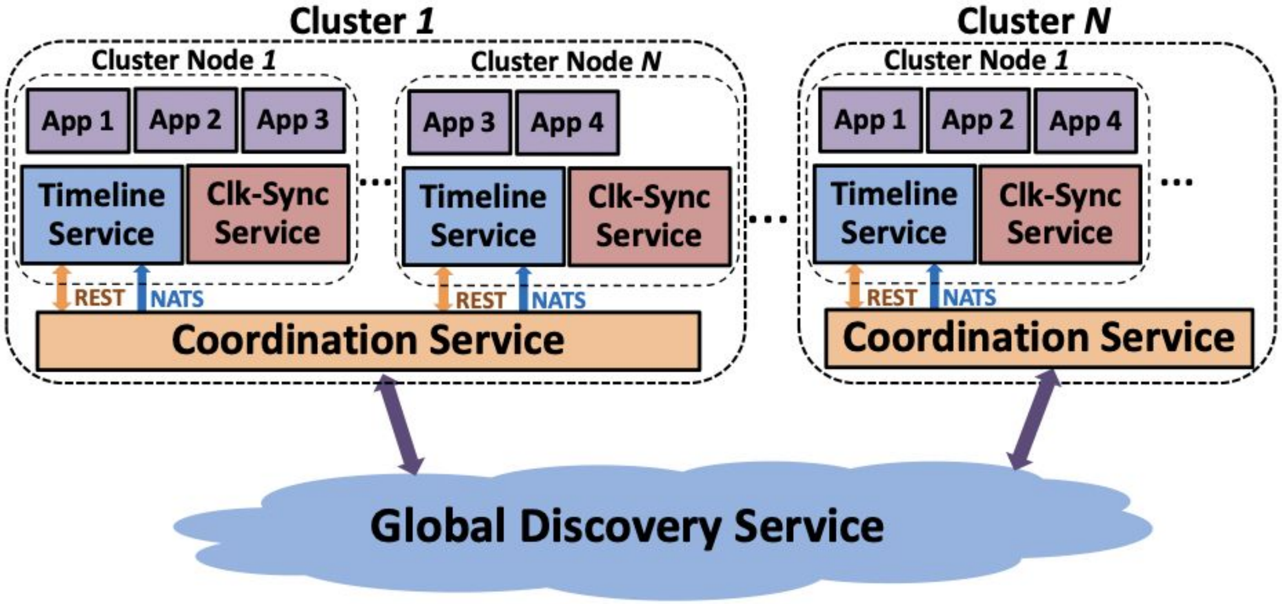

Figure 5: Quartz Time-as-a-Service at global scope

Quartz Clocks

$$tl_{now} = tl_{last} + tl_{drift} * (core_{now} - core_{last}) \tag{1}$$

$$\epsilon = tl_{bound} + tl_{skew} * (core_{now} - core_{last}) \tag{2}$$

Hardware Timestamping

Network interfaces usually have their own clocks and provide ability to timestamp in hardware at physical layer to enable accurate timestamping and clock synchronization

How is it autonomous?

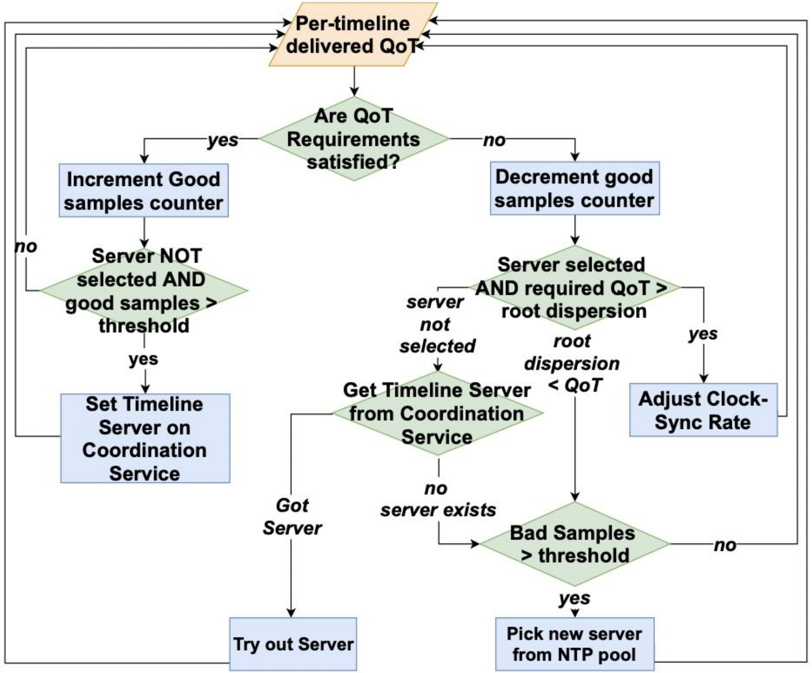

Figure 6: Adaptive NTP: Server Selection & Rate Adaptation

Timeline Clock Synchronization

Global

- NTP to synchronize to Universal Coordinated Time (UTC)

Local (cluster scope)

- PTP Precision Time Protocol
- Huygens - state of the art protocol

TimeCop

Evaluation: Accuracy

Assess accuracy of the clock-synchronization protocols that Quartz supports

NTP, PTP, and Huygens

Two embedded/edge-form-factor platforms:

- Intel NUC and Beaglebone Black (BBB)

How well do they track UTC?

Evaluation: Accuracy

Table 2: NTP [15] Accuracy (μs)

Platform	Timestamps	Cluster	Stratum	Max	Mean	Std. Dev
NUC	HW	Intra	1	4267	**380**	**633**
	HW	Intra	2	12607	2480	3351
BBB	SW	Intra	1	1638	**542**	**245**
	SW	Intra	2	5855	2380	717
	SW	Inter	1	2127	**929**	**553**
	SW	Inter	2	6033	3582	1032

1μs = 1 microsecond = a millionth of a second

Evaluation: Accuracy

Table 3: PTP [16] Accuracy (μs)

Platform	Timestamps	Rate (s)	Max	Mean	Std. Dev
NUC	HW	1	183	31	113
	HW	2	220	24	32
	HW	4	13	**9**	**2**
BBB	HW	1	14	**2**	**3**
	HW	2	39	8	7
	HW	4	39	5	7

Evaluation: Accuracy

Table 4: Huygens [26] Accuracy (μs)

Platform	**Timestamps**	**Rate** (ms)	**Max**	**Mean**	**Std. Dev**
NUC	HW	10	401 (1596)	294 (1099)	21 (501)
	HW	100	405 (382)	**104 (105)**	**64 (75)**
	SW	10	1835 (1205)	294 (252)	242 (163)
	SW	100	1251 (965)	234 (328)	259 (243)
BBB	HW	100	13000000	2000000	3000000
	SW	10	782	**170**	**153**
	SW	100	4593	1091	340

Evaluation: Scalability

Assess ability to provide time- as-a-Service at geo-distributed scale

Continental - 15 VMS -> 3 states (VA, OHIO, OR)

Global - 20 VMS -> 5 continents (NA, EU, AUS, ASIA)

Continental Scalability Results

Specified QoT (Accuracy)	**Worst Delivered QoT**	**Best Delivered QoT**
500μs	442μs	284μs
1ms	994μs	233μs

Global Scalability Results

Table 6: Geo-distributed Scalability: Microsoft Azure

QoT Spec.	Region	Worst QoT	Best QoT	Average QoT	Fraction
500μs	east-us	506μs	200μs	327μs	0.98916
	central-us	504μs	216μs	354μs	0.98844
	west-europe	508μs	249μs	415μs	0.97398
	east-australia	NA	NA	NA	NA
	east-asia	NA	NA	NA	NA
1 ms	east-us	635μs	199μs	365μs	1
	central-us	568μs	140μs	293μs	1
	west-europe	640μs	307μs	476μs	1
	east-australia	1003μs	490μs	758μs	0.99076
	east-asia	1006μs	459μs	645μs	0.97398

Key Contributions

1) Overcoming challenges and architectural decisions in exposing TaaS to maintain timelines and estimate QoT at geo-distributed scale
2) Introduces techniques to make clock-synchronization protocols that are adaptive to application QoT requirements
3) Introduces Quartz