Time-based Coordination in Geo-Distributed Cyber-Physical Systems

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A Shared Notion of Time

- *Coordinated* Actions
- *Ordering* of Events

A Shared Notion of Time is *useful*
→ Replace *Communication* with *Local Computation**

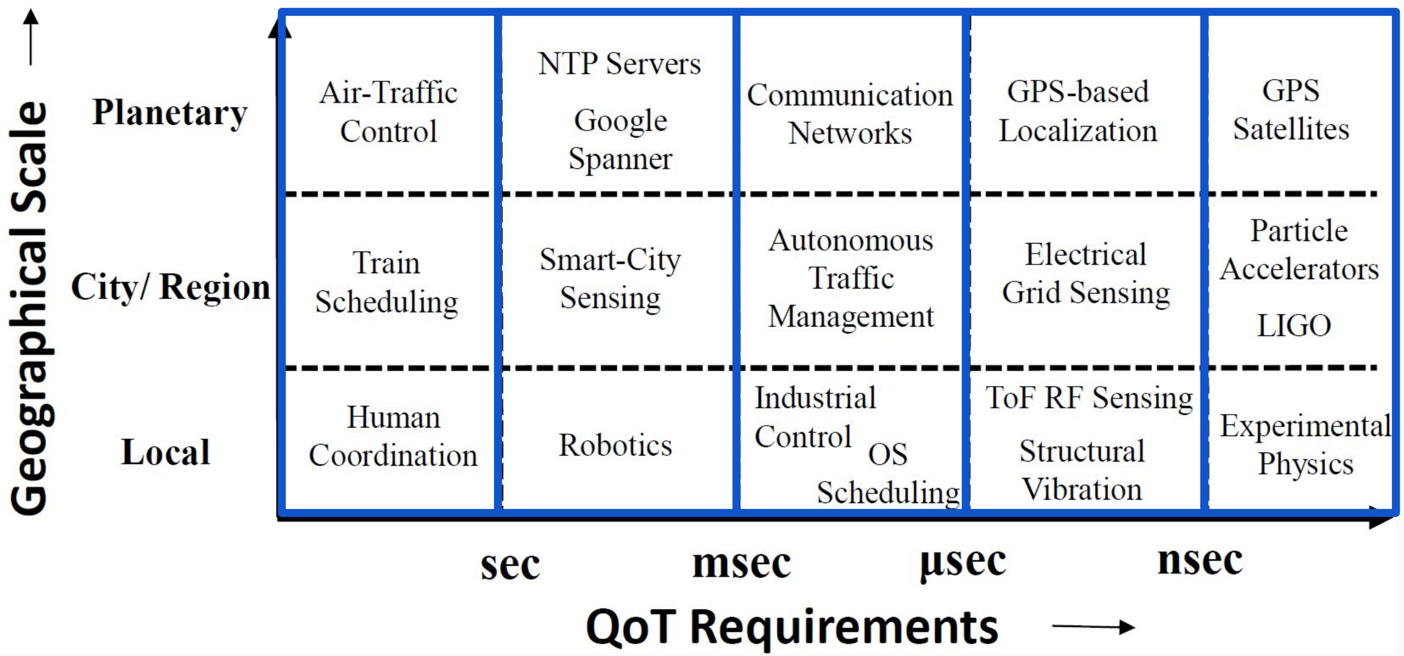
*Liskov, *Distributed Computing ‘93*

Geo-Distributed Cyber-Physical Systems

- **Distributed computation, sensing and actuation**
  - *coordination* at scale (*local* to ***planetary***)
- **Emerging CPS characterized by:**
  - *different* applications, *same* infrastructure
  - *heterogeneous* computation and networking

A shared notion of time is useful to enable *coordinated action* in geo-distributed CPS

Coordination in Space and Time

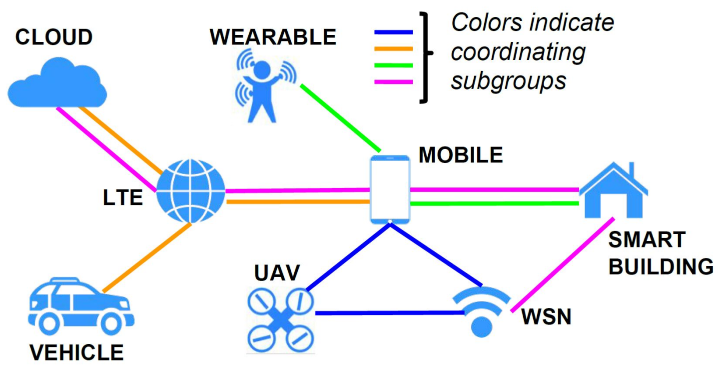


The cloud is *key* to achieve scale

→ Time-aware cloud for geo-distributed coordination

CPS and the Cloud

- **The cloud is *key* to enable geographical scaling**
  - data ***storage***
  - host the ***intelligence*** behind CPS
  - enable ***coordination*** between smaller entities
- **Low-latency requirements of CPS**
  - ***Safety-critical*** + ***real-time*** performance
  - A ***hierarchy*** of cloudlet and cloud deployments



Existing Research: ***Reduce*** Network Latency* and ***Efficient*** Data Storage#

Required: ***Time-based*** coordination in CPS

*Satyanarayanan, *PerComm '15*
#Zhang, *HotCloud '15*

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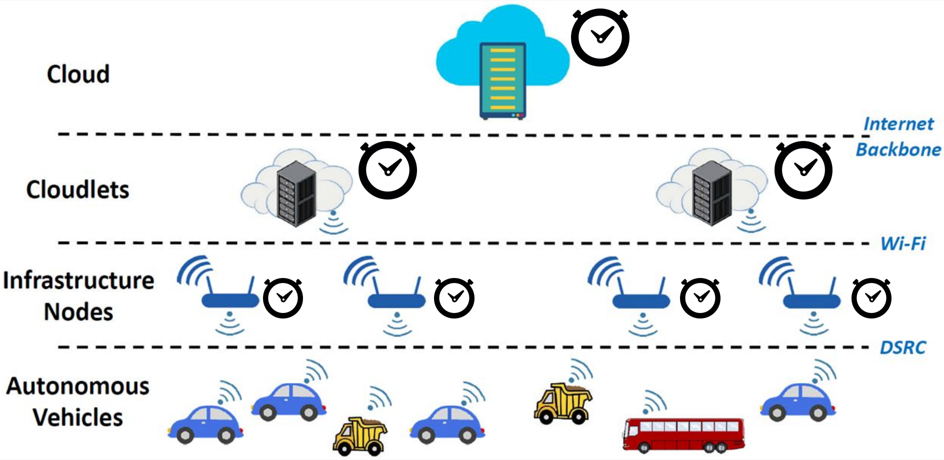
Coordinated Vehicles using *TimeNet*

- ***TimeNet*: Cyber-Physical Internet**
  - *ideal* timesource, ***no uncertainty***
  - *perfect* timestamping
- **Dynamic Traffic Management**
  - *city-scale* vehicular coordination
  - *time-based* hierarchical system
    - timestamps→ event ordering
    - event ordering → policy



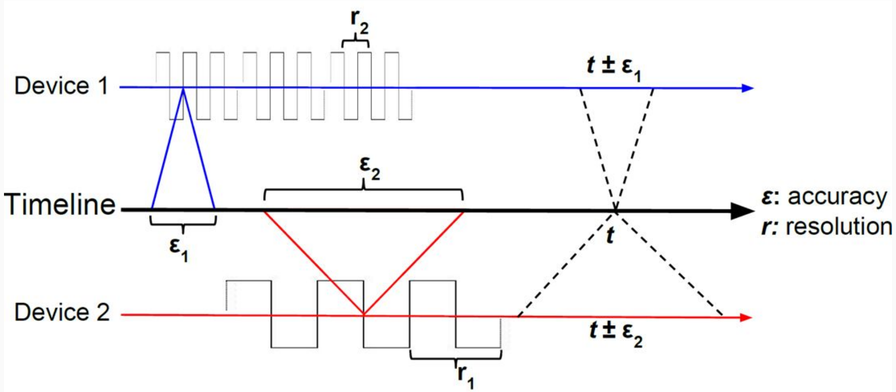
Inherent uncertainties with synchronized clocks

Outline

- Motivation
- **Background**
  - Quality of Time (QoT)
  - QoT Architecture
- **The Case for Shared Time and QoT**
- **QoT-based Cloud CPS Architecture**
- **Conclusion**

Quality of Time (QoT)*

- **Quantified**
  - using ***clock parameters***:
    - accuracy, precision, drift….
  - w.r.t a ***reference clock*** (time)
- **Each timestamp has bounds**
  - Timestamp $\epsilon \{t-\varepsilon_l, t+\varepsilon_h\}$

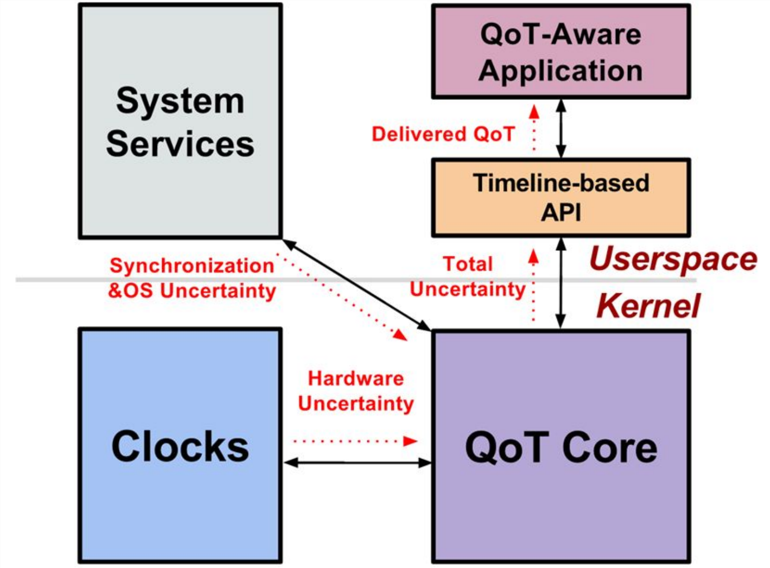


The *end-to-end* uncertainty in the notion of time delivered to an application by the system

*Anwar et al., *RTSS '16*

QoT Architecture*

- **Caters to application timing demands**
  - Applications ***specify*** QoT requirements
- **Provides guarantees on the received QoT**
  - ***Tunable*** clock synchronization
- **Exposes the obtained timing accuracy**
  - ***QoT-estimation*** mechanisms
- **Easy-to-use, secure and scalable**
  - ***Robust*** implementation



Applications *specify* QoT requirements, the QoT Architecture *orchestrates* the system and *returns* the delivered QoT → *closing the time loop*

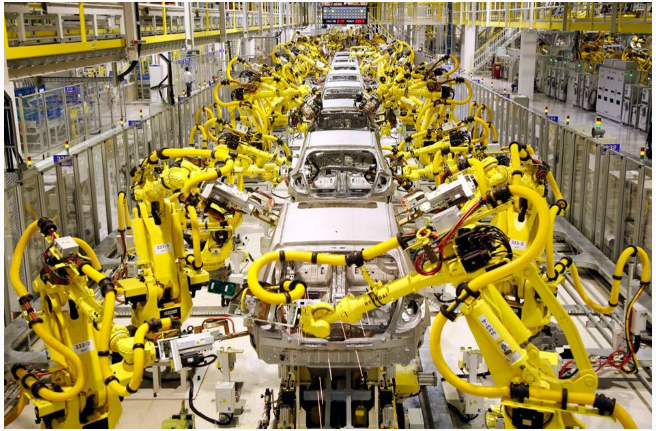
*Anwar et al., *RTSS '16*

Outline

- Motivation
- Background
- **The Case for Shared Time and QoT**
    - Coordination in CPS
    - Shared Time and QoT
- **QoT-based CPS-Cloud Architecture**
- **Conclusion**

Coordination in CPS

- **Scalability**
  - Both ***numerical*** and ***geographical***
- **Fault Tolerance and Reliability**
  - Both ***analytical*** and ***physical*** redundancy
- **Ease of Programmability**
  - ***coordination framework*** with APIs
- **Security**



Need for a QoT-based coordination framework for CPS

Uncertainty: Software Systems **vs** CPS

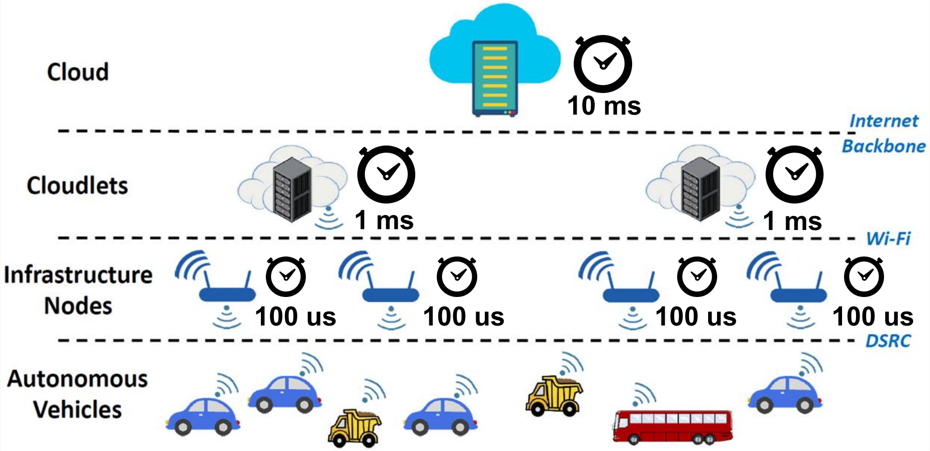
- **Software Systems**
  - *lower* timing uncertainty, *better* QoT, *better* performance
    - **Spanner[#]:** ***lower*** uncertainty, ***smaller*** commit wait
- **Cyber-Physical Systems**
  - if timing uncertainty exceeds specification (***degraded QoT***)
  - **system cannot operate safely**

Application should be *notified* if QoT degrades
→ graceful degradation to satisfy safety requirements

[#]Corbett et al., *OSDI '12*

QoT-based Connected Vehicles

- **Tolerable QoT Requirements based on**
  - timestamps→ event ordering
  - event ordering → policy
- **If uncertainty *exceeds* tolerable limit**
  - coordination policy can ***adapt***
  - **Graceful Degradation:**
    - Increase vehicular spacing
  - **Safe Halt:**
    - Instruct vehicles to stop



Synchronized Clocks → *Scalable Coordination*   Quality of Time → *Fault Tolerance*

→ Need for a QoT-based CPS-Cloud Framework

Outline

- Motivation
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- The Case for Shared Time and QoT
- **QoT-based CPS-Cloud Architecture**
  - Architectural Challenges
  - QoT Stack for Linux
- **Conclusion**

Architectural Challenges

- **Fault-Tolerance Support**
  - ***Robust*** QoT-estimation mechanisms
- **Global Coordination Service**
  - ***Distributed*** apps, ***heterogeneous*** infrastructure
- **Scalable Synchronization Service**
  - ***Tunable*** clock synchronization, ***heterogeneous*** communication
- **Virtualization Support**
  - Adding ***QoT awareness*** to virtualized units of computing
- **QoT-Aware Cloud Scheduling**
  - VM/container ***placement*** based on application QoT requirements

QoT-based platform-independent coordination API needed

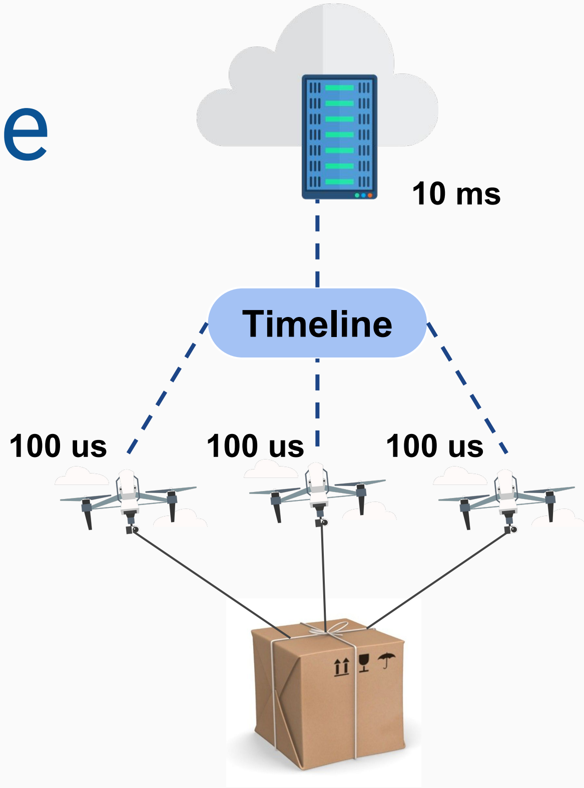
Fault Tolerance

- **Failure Scenario:**
  - *Clock Synchronization* degrades
  - *Reported QoT* must degrade
- **Application-specific *failover* mechanisms**
  - *Physical* and *Analytical* Redundancy

QoT can enable fault-tolerant coordination in CPS

Enabling Coordination at Scale

- **Timeline*:** ***Virtual reference*** **time base**
- ***Coordinated actions*****, distributed components**
  - all components ***bind*** to a timeline
  - each ***specifying*** its required QoT
- **Required:** ***Global-scale Timelines***
  - ***Time-based*** coordination protocol

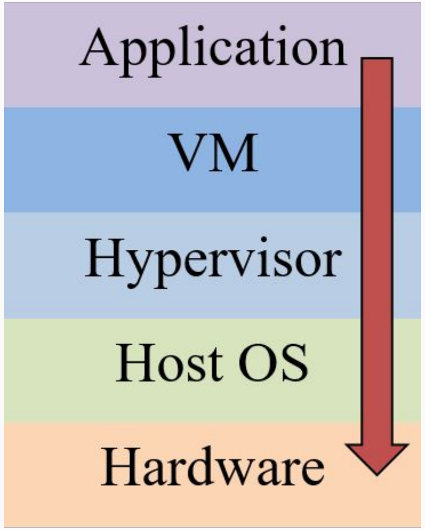


Timelines *abstract* away clock synchronization
→ Applications *specify* QoT requirements, framework *orchestrates* the system

*Anwar et al., *RTSS '16*

Virtualization and QoT

- **Higher clock-read and interrupt latencies***
  - Can we get near-native performance?
- **VM Migration***
  - Clock-related state in the VM or host?
- **Delivering and exposing QoT to applications**
  - Different VMs, different requirements



Virtualization support required for utilizing the cloud

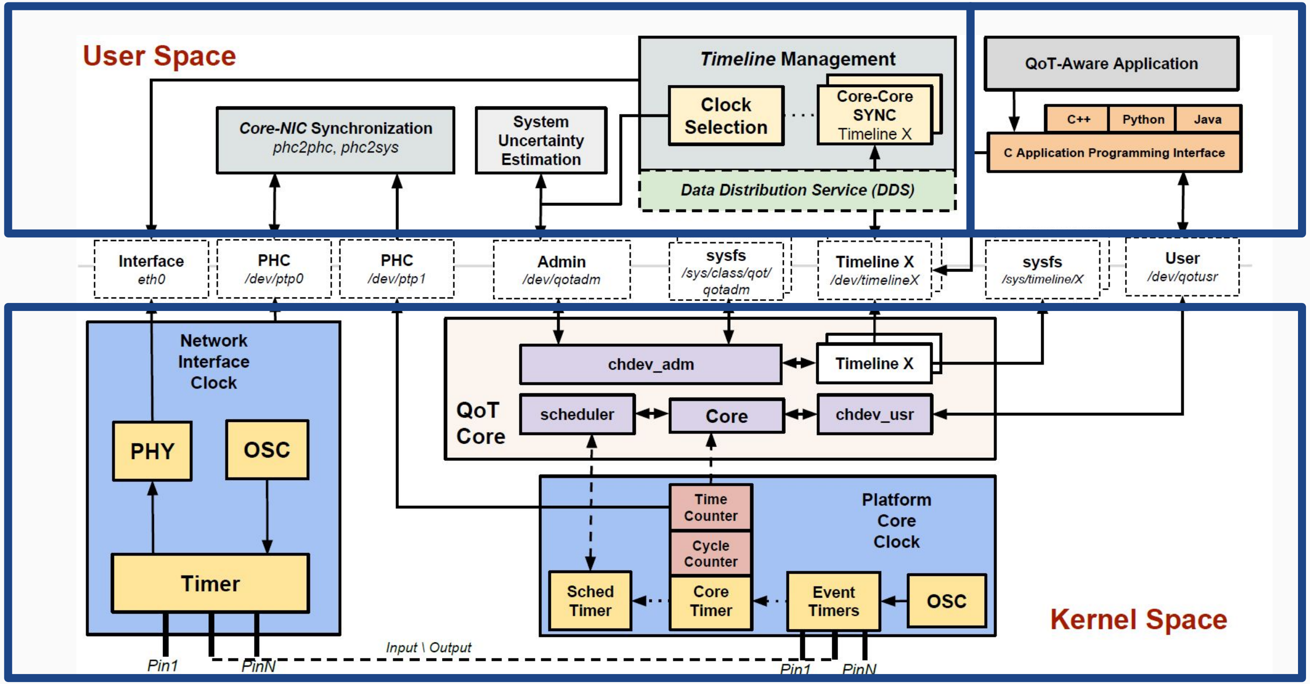
*Broomhead et al., *OSDI '10*

QoT-Aware Cloud Scheduling

- **Multiple virtualized units running applications**
  - *different* QoT requirements
  - *probabilistic* QoT-based Service Level Agreements
- **VM/container placement based on QoT requirements**
  - *dictate* the host to which they are allocated
- **Categorize Servers based on QoT rating**
  - *quality* of on-board clocks
  - *network-proximity* to reference clock source

Make QoT-Aware Cloud Scheduling work with
existing multi-level cloud schedulers

QoT Stack for Linux



Support for ARM and x86 platforms

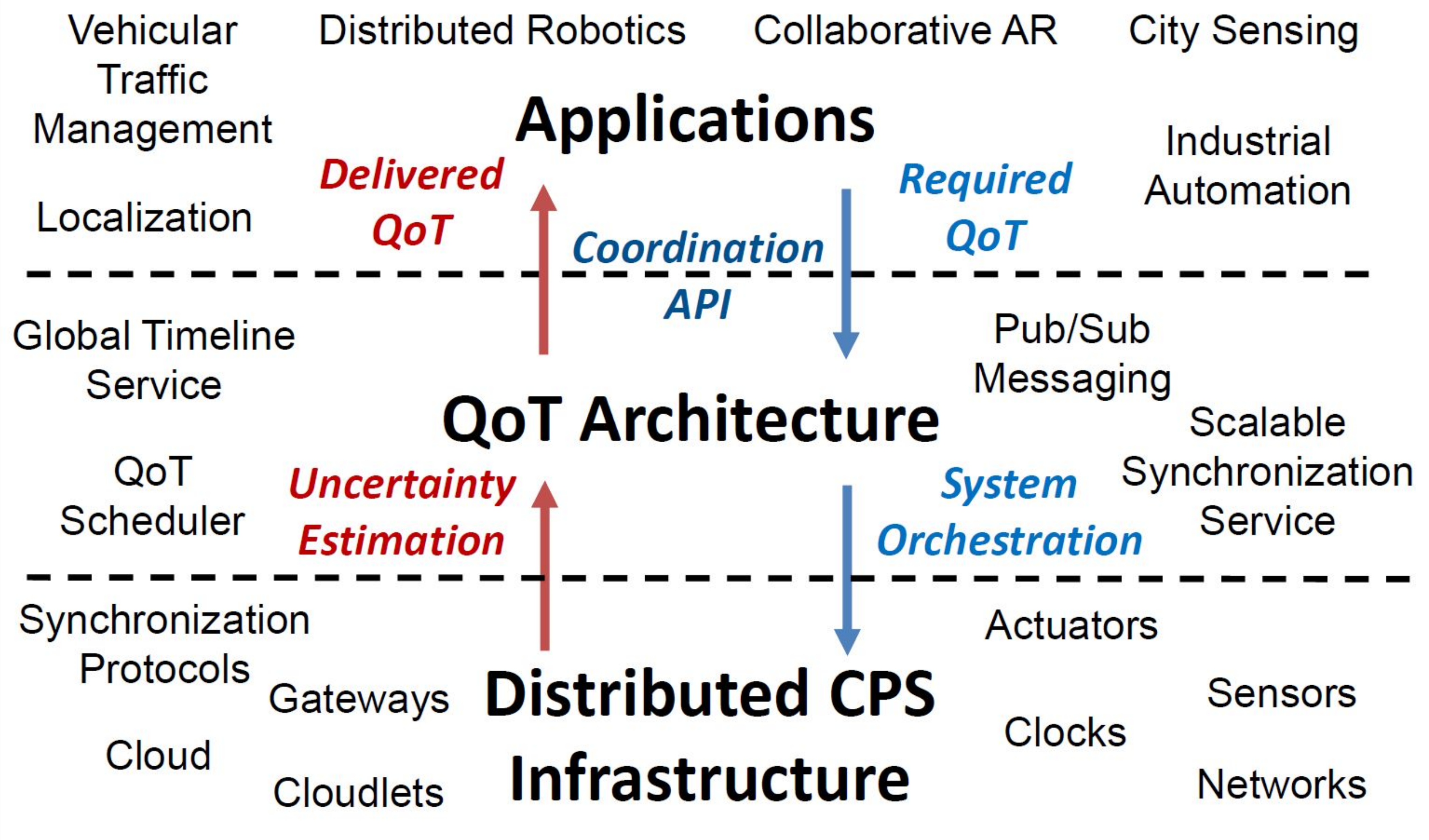
open source, *modular* implementation, *no change to the Linux kernel*

Conclusion and Future Work

- **Geo-Distributed CPS: "*Coordination at scale*"**
- **Using a Shared notion of Time and QoT enables:**
  - *Scalable Coordination* with *Fault Tolerance*
  - *Efficient Management* of Time-related Resources
- **QoT-based CPS-Cloud Architecture**
  - *Scalable Coordination* and *Clock Synchronization*
  - *Quartz-V:* Adding QoT awareness to VMs
  - *QoT-aware* Cloud Scheduling

Synchronized Clocks → *Scalable Coordination*   Quality of Time → *Fault Tolerance*
→ QoT-based CPS-Cloud Coordination Framework

Thank You ! Questions ?


Vehicular Traffic Management
Distributed Robotics
Collaborative AR
City Sensing
Applications
Industrial Automation
Localization
Delivered QoT
Required QoT
Coordination API
Global Timeline Service
Pub/Sub Messaging
QoT Architecture
Scalable Synchronization Service
QoT Scheduler
Uncertainty Estimation
System Orchestration
Synchronization Protocols
Actuators
Gateways
Distributed CPS Infrastructure
Sensors
Clocks
Cloud
Cloudlets
Networks

Discussion

- **Adding QoT awareness to VMs**
  - Paravitualization
  - Security
- **QoT-aware Cloud Scheduling**
  - Challenges?
- **Utility of QoT in Software Systems**
  - Tracing, Databases ….
- ….