WASP WALLENBERG AI, AUTONOMOUS SYSTEMS AND SOFTWARE PROGRAM

ERICSSON

Control over the Edge Cloud
An MPC Example

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The Cloud

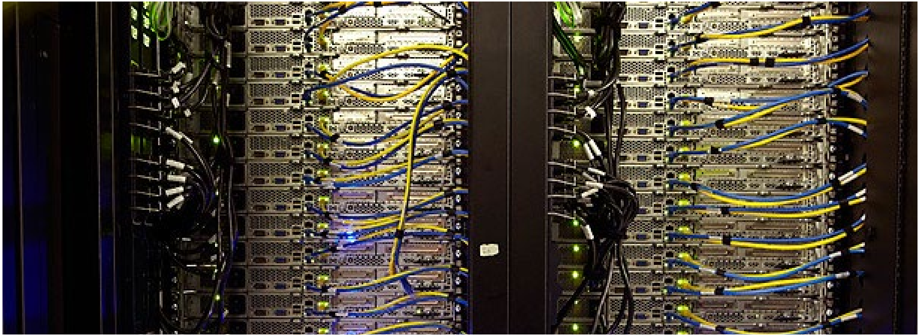
- As soon as you use any networked computing unit (laptop, smart phone, sensor device, …) the likelihood that the computations will be performed in a data center somewhere in the cloud, rather than locally, is very large
- News, mail, photos, tickets, books, clothes, maps, social media, television, music, banking, administrative systems, technical software, …….

The Datacenter

What's inside?

Server racks

What's inside?



Networking

What's inside?

Power supplies

What's inside?

Cooling

Mission-Critical Applications??

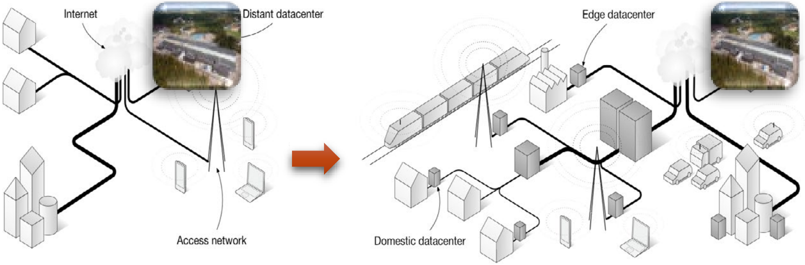
- What about mission-critical applications
    - Robotics and automation, ...
    - Low latency, performance guarantees
    - Wireless connectivity
- Not deployed in the cloud today
- Why?
    - 4G/LTE → too long radio latency
    - Too long communication delay from base station to datacenter
    - No performance guarantees

Mission-Critical Applications??

- 4G/LTE → too long radio latency
    - 5G promises around 1-5 ms radio latency
- Too long communication delay from base station to datacenter
    - Data centers closer to the base stations (closer to the edge)
- No performance guarantees
    - ~~Better resource management techniques~~

Distributed Edge/Fog Cloud

- Low End-2-End latency requires new types of clouds

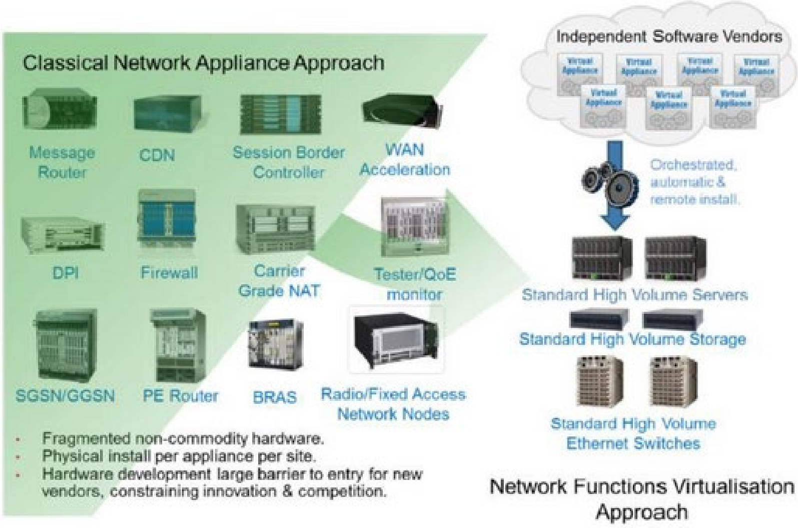


Today

Future

- Local ”edge datacenters”
  - Datacenter-type servers connected to base stations, office buildings, production plants, ...
- Network Function Virtualization (NFV)

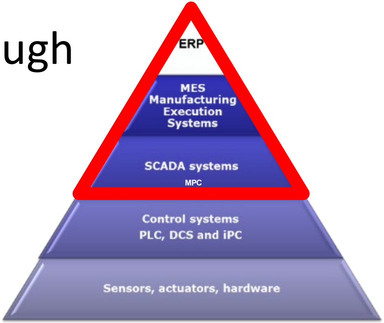
Network Function Virtualization



- Fragmented non-commodity hardware.
- Physical install per appliance per site.
- Hardware development large barrier to entry for new vendors, constraining innovation & competition.

Control over the Cloud

- Closing a control loop over the cloud
  - Not control of the cloud (although related)
- Some part of the control loop executes in the cloud
- What should be in the cloud?
  - A lot of computations, not the PID control
  - Here supervisory Model-Predictive Control (MPC)



Fog/Edge Cloud Characteristics

The further up in the sky

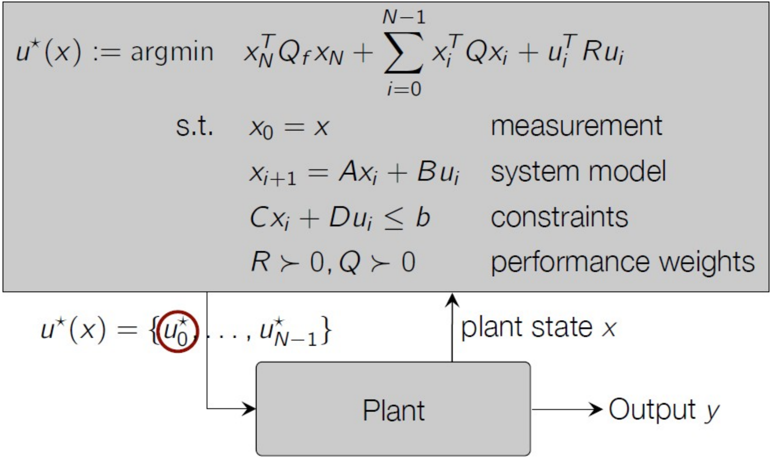
- Longer communication delay
- Sh
- La
- Ac
  models, and sensor data

Drawbacks:

- Potential points of failure increases
- Contention and lost connectivity may require migration and or fall-back

Tradeoff between communication delay and computation delay

Model Predictive Control

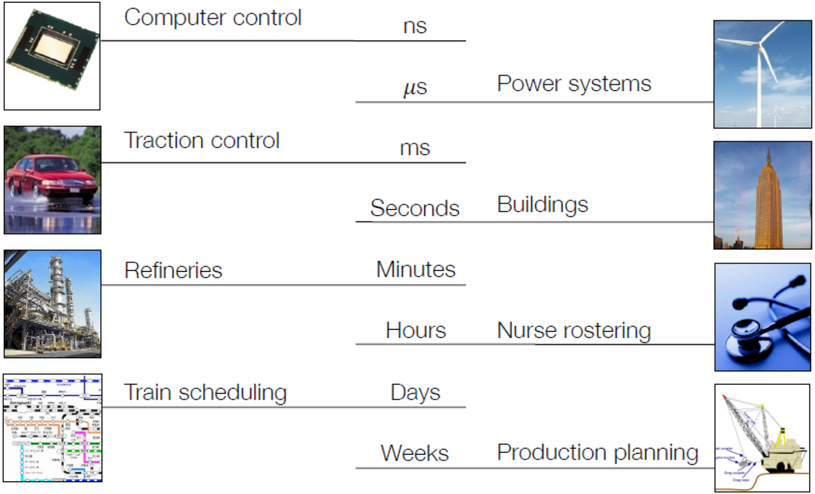


$$
\begin{aligned}
u^\star(x) := \operatorname{argmin} \quad & x_N^T Q_f x_N + \sum_{i=0}^{N-1} x_i^T Q x_i + u_i^T R u_i \\
\text{s.t.} \quad & x_0 = x && \text{measurement} \\
& x_{i+1} = A x_i + B u_i && \text{system model} \\
& C x_i + D u_i \leq b && \text{constraints} \\
& R \succ 0, Q \succ 0 && \text{performance weights}
\end{aligned}
$$

$$u^\star(x) = \{\boxed{u_0^\star}, \ldots, u_{N-1}^\star\}$$

- MIMO controller
- Can handle constraints
- Can be used as a direct level controller or as a supervisory level controller
    - Outputs are setpoints to lower level direct, e.g., PID, controllers

MPC Applications



Computer control ns

μs Power systems

Traction control ms

Seconds Buildings

Refineries Minutes

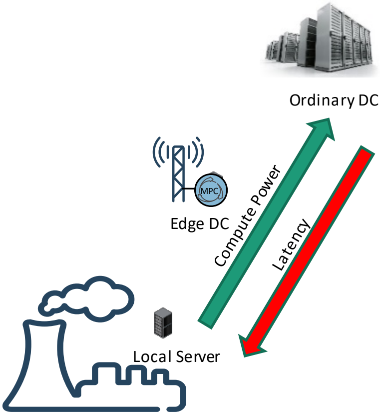
Hours Nurse rostering

Train scheduling Days

Weeks Production planning

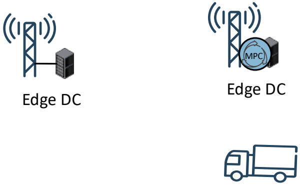
Use Case: Production Plant

- MPC normally in Edge DC
- In case of network failure
    - Migration to local server
    - ”Vertical handover”
- In case of capacity shortage in Edge DC
    - Migration to remote DC
    - Migration to local server



Use Case: Fuel Optimization for Heavy Trucks

- On-line optimization to calculate optimal velocity in order to minimize fuel consumption
  - Geographical info
  - Traffic info
- MPC normally in closest Edge DC
- Mobility causes migration
  - ’Horizontal handover’
- Poor network coverage causes vertical handover



More Use Cases

- City Traffic/Transport Management
  - MPC for traffic control

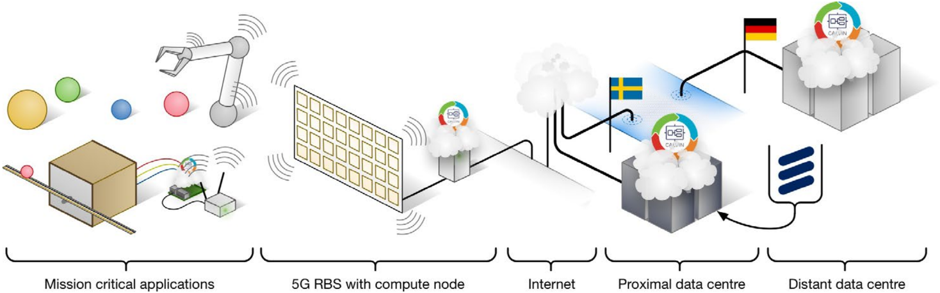
- Robot Cells

An Edge/Fog/Distributed Cloud Testbench

We have built a prototype edge/fog compute testbench

- Next generation (5G) mobile broadband
- A rich application environment through an IoT platform-as-a-service (Calvin)
- Able to control a physical system with short sampling intervals
- While migrating application components (on-the-fly) over geographical disperse and heterogeneous environments

A Platform for Control Over the Cloud



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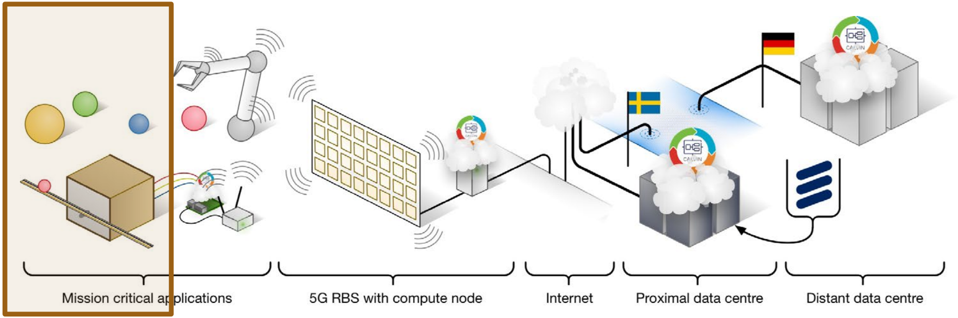
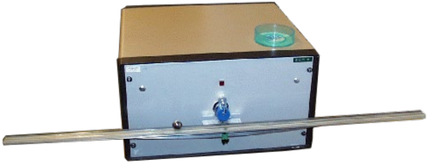
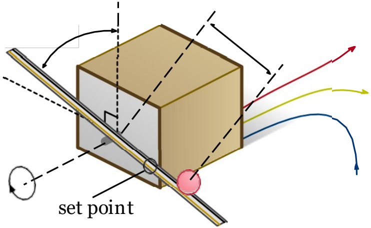


Plant: Ball and Beam





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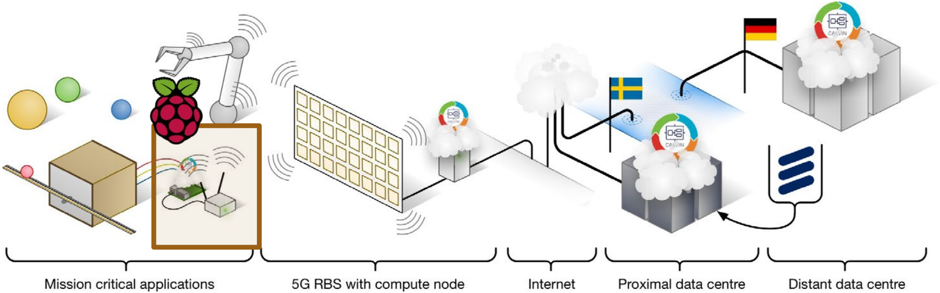

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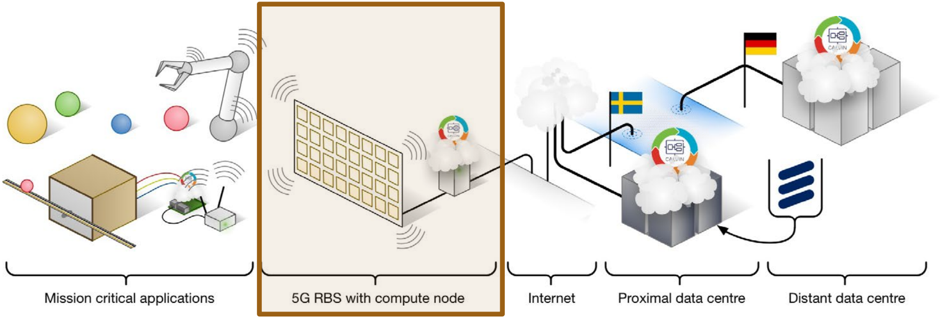
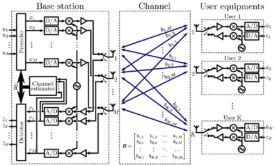


A 5G Massive MIMO Base Station Prototype



S. Malkowsky et al.: The World's First Real-Time Testbed for Massive MIMO

Lund University Massive MIMO (LuMaMi)

M-MIMO is candidate RAT for 5G

Many devices simultaneously (150 antennas)

High reliability wireless

Low latency*

Medium Access Control break-out

*W. Tärneberg et al.: *Utilizing Massive MIMO for the Tactile Internet: Advantages and Trade-offs*, IEEE SECON Workshops

A 5G Base Station Prototype

12 May 2016 | 21:00 GMT

5G Researchers Set New World Record For Spectrum Efficiency

They showed a 22-fold increase over existing 4G networks

By **Amy Nordrum**

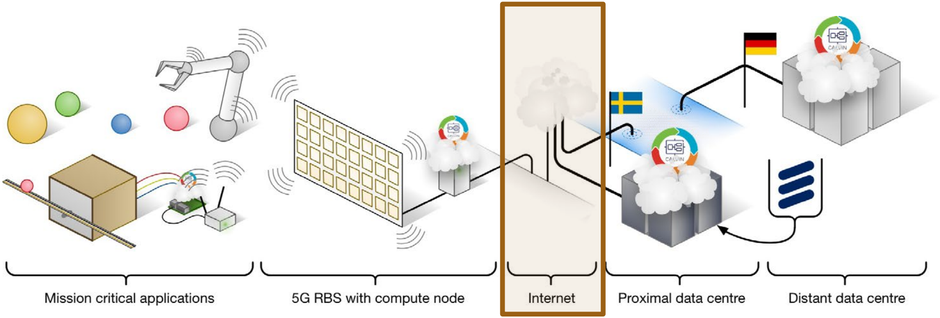
Photo: University of Bristol

Lund University Massive MIMO (LuMaMi)

Set the world record in spectral efficiency in 2016 while delivering an aggregated speed of 3.2 Gbit/sec.

Demonstrated simultaneous transfer and mobility with data rates an order of magnitude that of LTE-like channels.

A Platform for Control Over the Cloud



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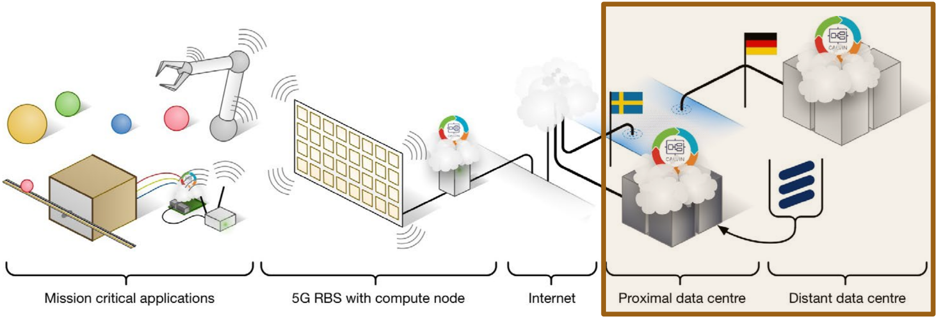


Calvin: IoT Platform-as-a-Service

Open Source

Python runtime and C [+μPython] micro runtime

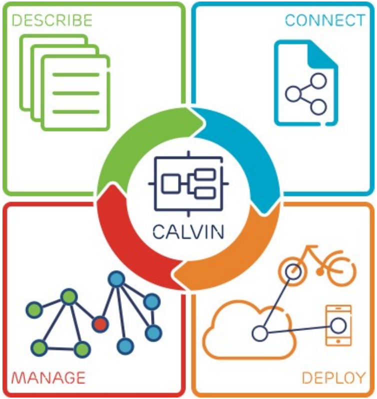
Flow programing with stateful actors

Deployment

Network communication

Application state

Application component migration



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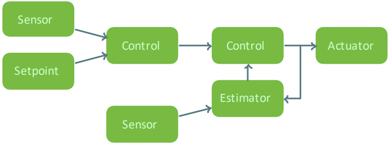

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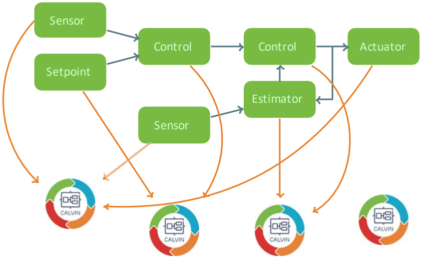

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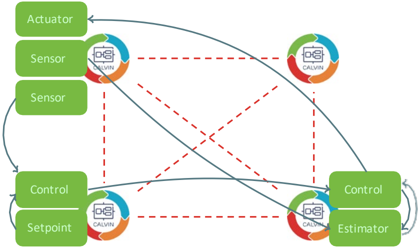

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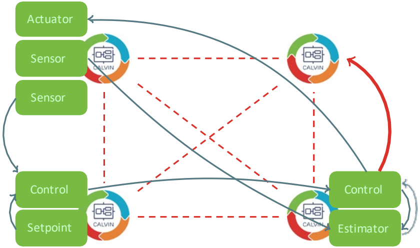

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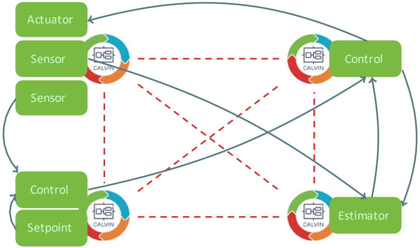
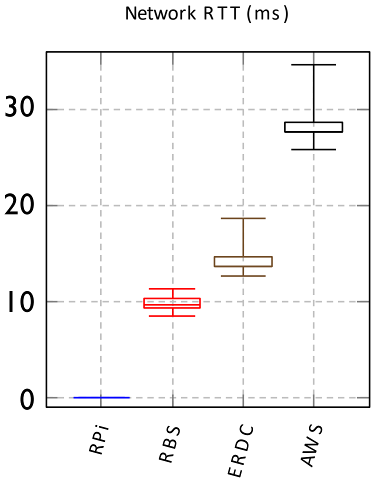


System latencies



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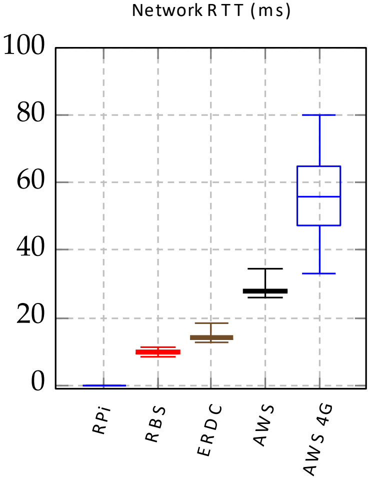

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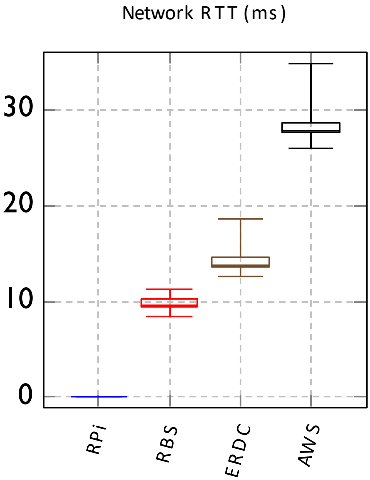

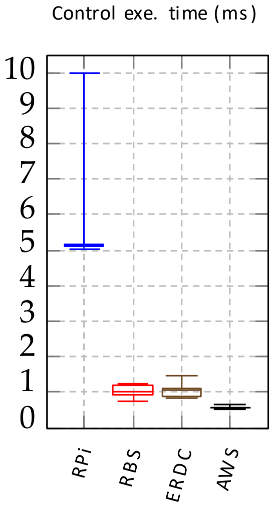

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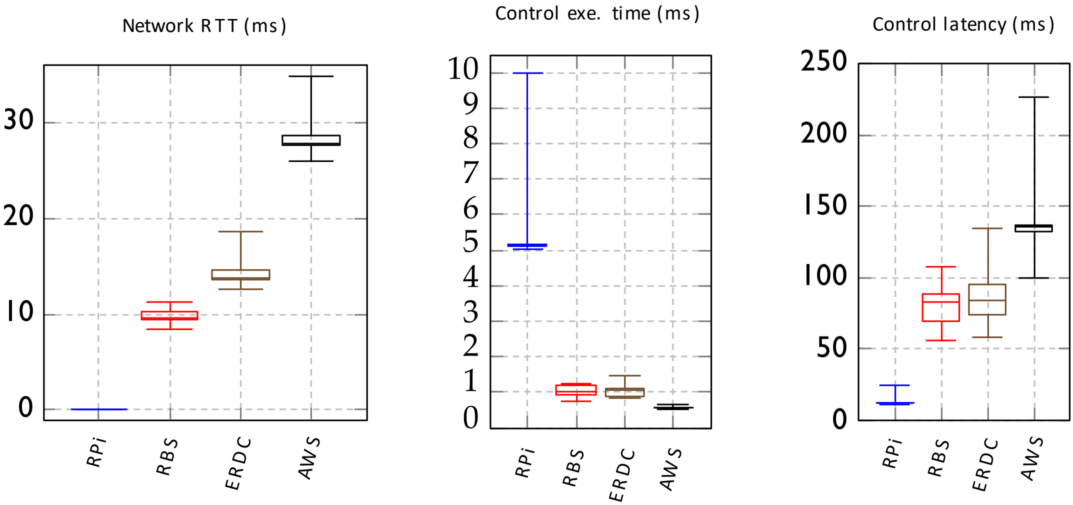
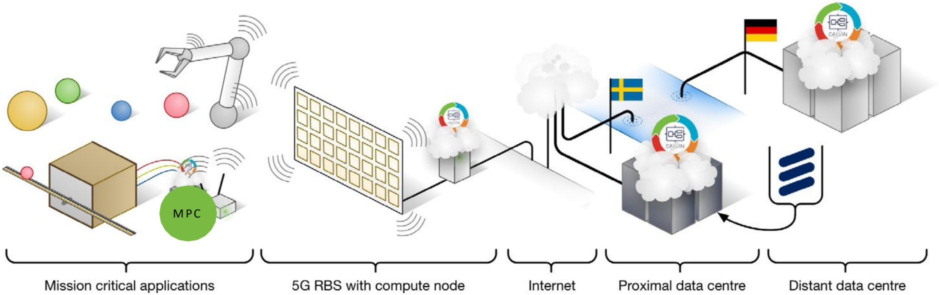


Migration of MPC while Executing



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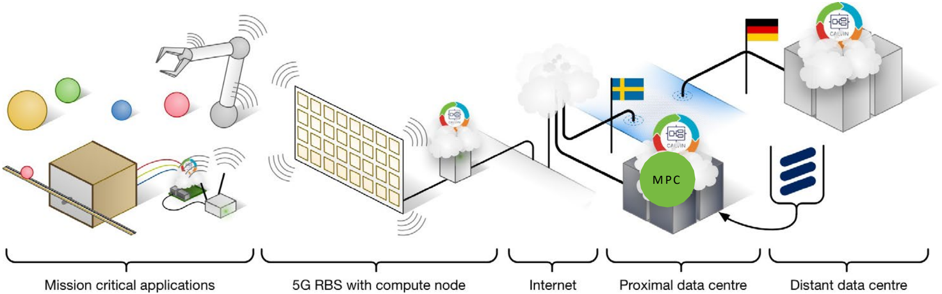

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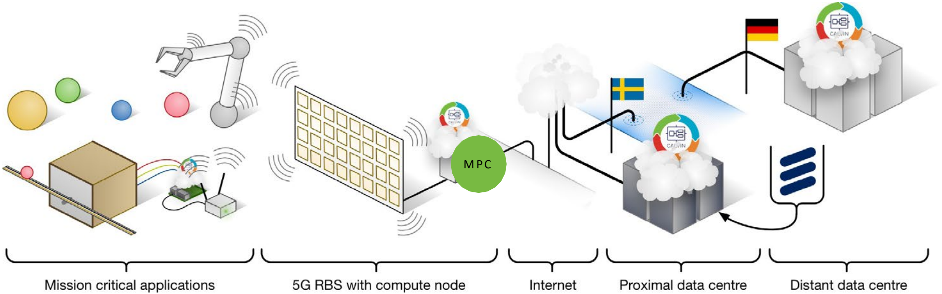

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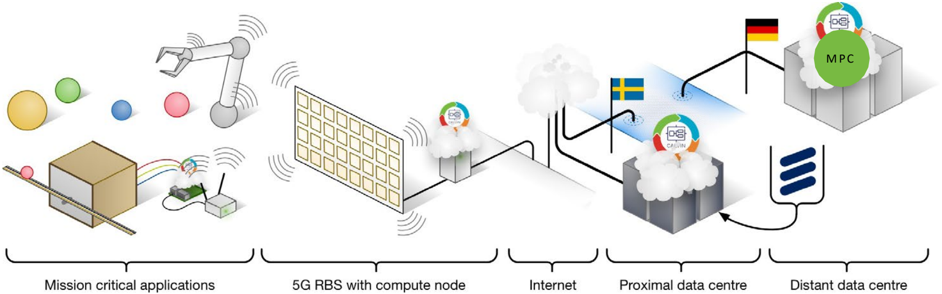

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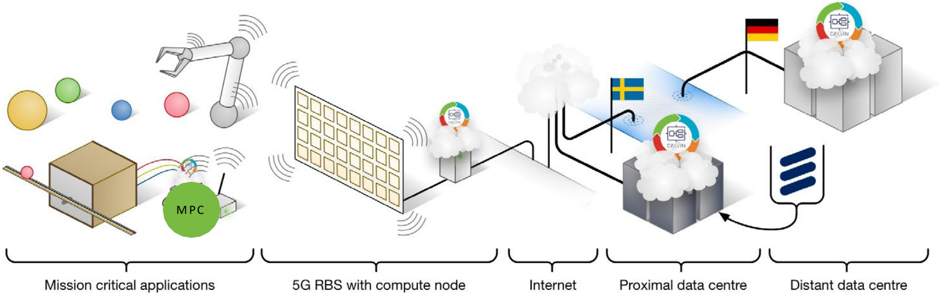

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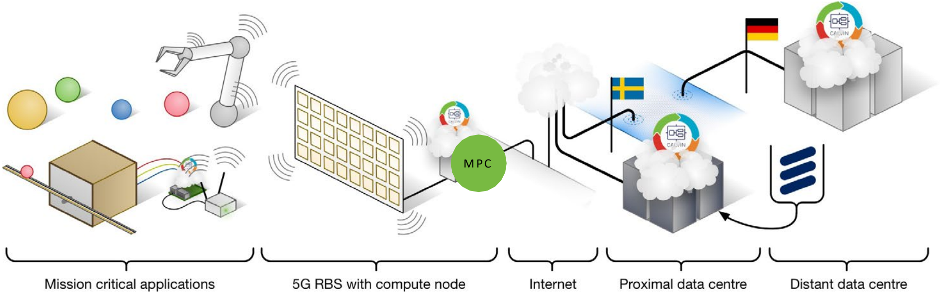
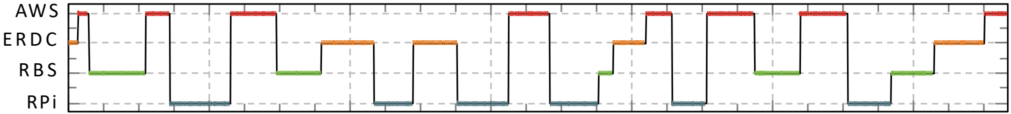


Software migration



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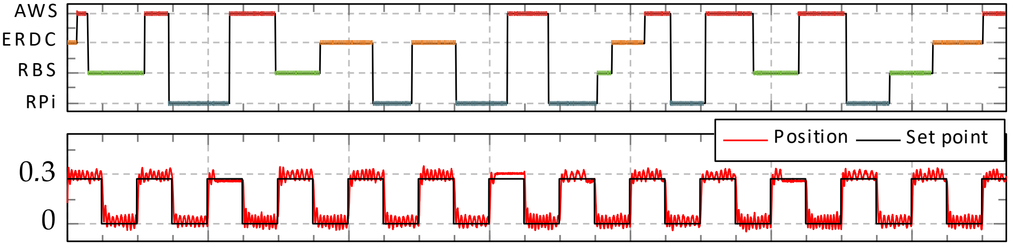
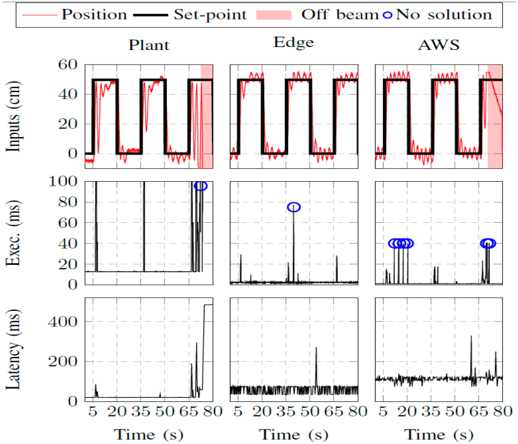


Increased computational demand



Executing in the edge datacenter the only possibility

Timing Issues

In the example the long and varying delay was ignored

- Sampling period = 20ms, round-trip delay up to 200ms

Currently we are working on how to take the time-varying delay into account

- Make sure that the delay is always a multiple of the sampling period by buffering
- Include the pure time delays in the MPC model, or
- Predict what the state will be at a future time correspondiing to the delay

Timing Issues

In the example it was assume that the MPC could be executed in the local device

What if that is not possible?

- Execute the same MPC controller less often and resample the plant model
- Use a less compute-intensive controller in the local device
  - MPC for a smaller problem + conventional PID or LQG control
  - Only PID or LQG

Timing Issues

The need to be able to migrate the computations due to lost connectivity or contention may create situations where a control signal is not available at a time when it should be

Approach:

- Use the fact that a MPC controller not also provides the $u(k)$ but also $u(k+1), u(k+2), \ldots..$
- Corresponds to running the system in open loop during the switches

Timing Issues

Jitter in delays and lost samples or control signals is the focus of the area of ***Networked Control Systems***

- Wifi or LTE

In Control over the (5G) Cloud these issues will probably be less dominant

- 5G promises to be more robust

Instead discrete mode changes in delays due to migration will be the major challenge

Conclusion

Functional 5G edge/fog platform

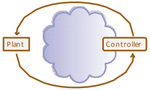
- Mobility support through 5G Massive MIMO wireless (LuMaMi)
- Platform-as-a-Service for application development (Calvin)

Shown that

- We can control time sensitive physical systems using the fog
- We can relocate software in the fog while keeping the control operational
- The controller can benefit from the fog

A lot remain to be done

Thank you for your attention

	Calvin	https://github.com/EricssonResearch/calvin-base
	LuMaMi	https://www.eit.lth.se/mamitheme
	Control Over the Cloud	https://github.com/pskarin/CotC

IoTFog

Workshop on Fog Computing and the IoT

April 15, 2019, Montreal, Canada
Co-located with CPS-IoT Week

Organizing committee

Co-chairs:
Prof. Paul Pop, Technical Univ. of Denmark
Prof. Karl-Erik Årzén, Lund University, Sweden

Website chair: Dr. Bahram Zarrin, TU Denmark
Publicity chair: Prof. Stefan Schulte, TU Wien, AT

Important dates
Jan. 15, 2019: paper submission (firm)
Feb. 11, 2019: notifications
Feb. 15, 2019: camera ready
Apr. 15, 2019: workshop day

Technical Program Committee

Prof. Paul Pop, TU Denmark, DK
Prof. Karl-Erik Årzén, Lund University, SE
Dr. Wilfried Steiner, TTTech Computertechnik, AT
Prof. Stefan Schulte, TU Wien, AT
Prof. Nicola Dragoni, TU Denmark, DK
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Dr. Johan Eker, Ericsson Research, SE
Prof. Yang Yang, ShanghaiTech University, CN
Prof. Tarek Abdelzaher, Univ. of Illinois at Urbana-Champaign, US
Joe M. Butler, Intel Labs, IE

When cyber-physical systems become interconnected with each other and with the internet, they are called the Internet of Things (IoT), forming "the infrastructure of the information society." Fog Computing is a "system-level architecture that distributes resources and services of computing, storage, control and net-working anywhere along the continuum from Cloud to Things" and is about to tremendously impact the IoT. The objective of this workshop is to be a forum for presenting and discussing recent developments and trends in Fog/Edge Computing that represent challenges and opportunities for CPS and IoT researchers and practitioners.

Topics include but are not limited to:

- Fog Computing Architectures and Frameworks
- Virtualization and Hypervisors for Fog Computing
- Middleware for Fog Computing
- Real-Time and Schedulability Aspects of Fog Computing
- Formal Methods for Fog Computing Systems
- CPS and Fog Computing
- Multi-tiered, Novel Resource Management Solutions Involving the Edge/Fog/Cloud
- Software-Defined Solutions in Fog Computing
- Mobile Fog Computing
- Data Centers and Infrastructures for Fog Computing
- Programming Models and Runtime Systems for Fog Computing
- Fog Resource Management for Guaranteed Quality-of-Service
- Control-as-a-service and Virtualization of Control, Guaranteeing Quality-of-Control
- Fog Computing Modeling and Analysis
- Performance Analysis of Fog Computing Systems
- Fog and Cloud Integration
- Data Analytics and AI/ML at the Edge
- Use Cases for / and Applications of Fog Computing
- Emerging Fog Communication Technologies and Protocols (IEEE Time-Sensitive Networking, 5G)
- Fog Computing Security, Data Privacy and Trust
- Fog Computing Dependability and Safety
- Standardization Efforts and Standards Relevant for Fog Computing
- Interoperability Standards and Solutions, Including OPC UA and DDS

Control Over the Cloud