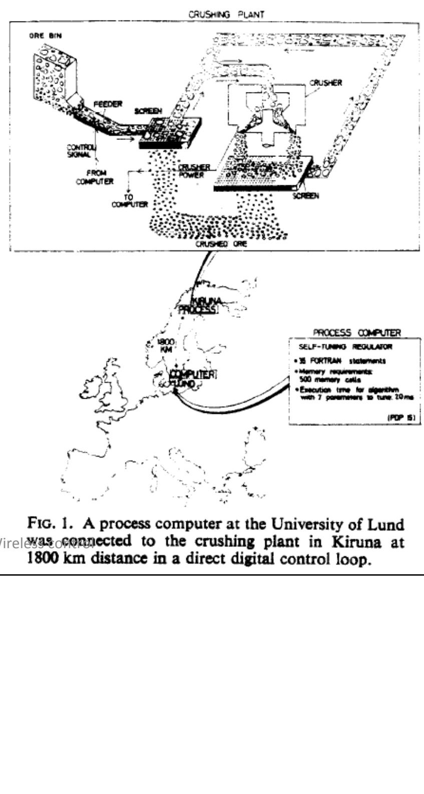
Lecture 13: : Applications

Early example of networked control

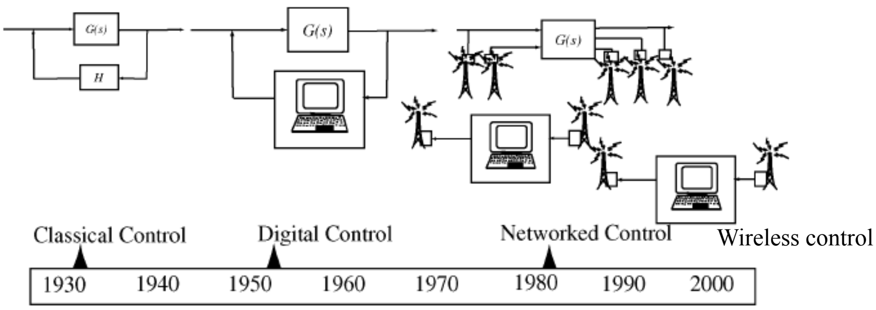
- Adaptive control of an Orecrusher in Kiruna (northern Sweden) in 1973
- Control computer located in Lund (southern Sweden) 1800 km away
- Sensor data and control commands were sent over the public telephone net with sampling interval of 20 s



Borisson and Syding, *Automatica*, 11, 1975

FIG. 1. A process computer at the University of Lund was connected to the crushing plant in Kiruna at 1800 km distance in a direct digital control loop.

A history of control



From dedicated communication links and networks for control systems
To open and ubiquitous wireless networks for control applications

Adopted from [Baillieul & Antsaklis, 2007]

Another history of control

- Internet
- WWW
- Ubiquitous computing

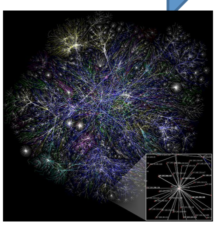
Info Web

- Remote sensing
- Monitoring environments
- Wireless sensor networks

Sensor Web

- Closing the loop
- Critical infrastructures
- Humans in the loop

Action Web

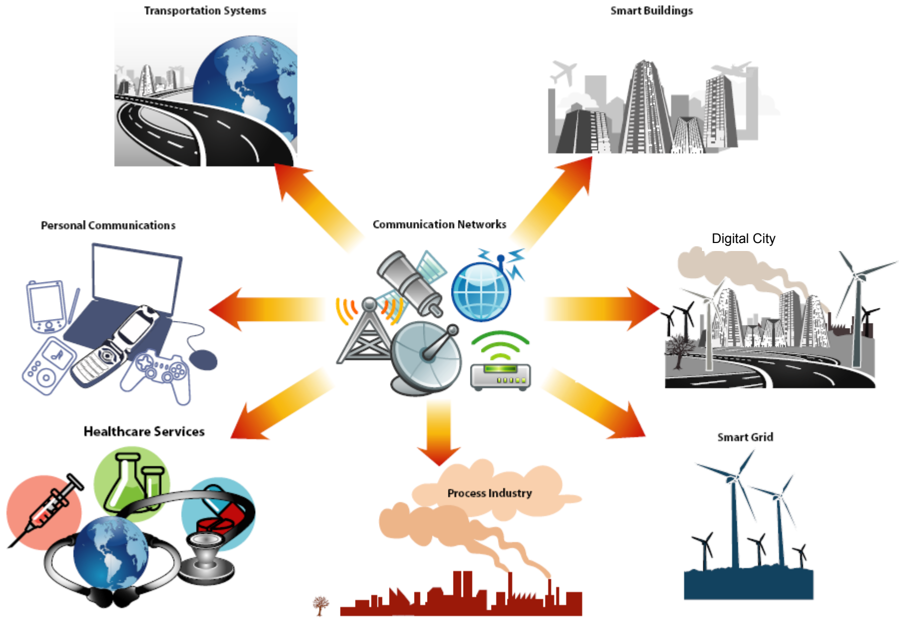


The Internet

Monitoring natural phenomena

Smart infrastructures

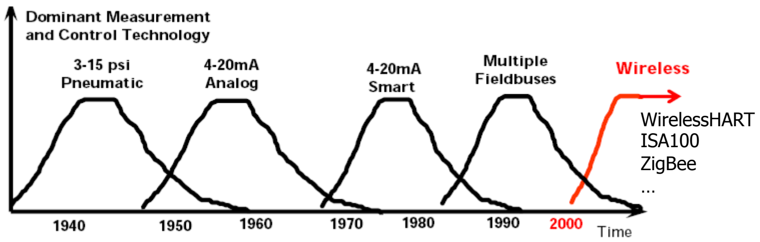
Networked and event-based control systems



Lecture 13 Outline

- Process industry
- Transportation systems
- Smart buildings

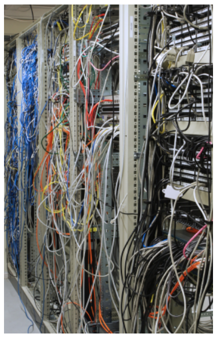
Communication in process industry



[ISA100]

Wireless systems benefit from

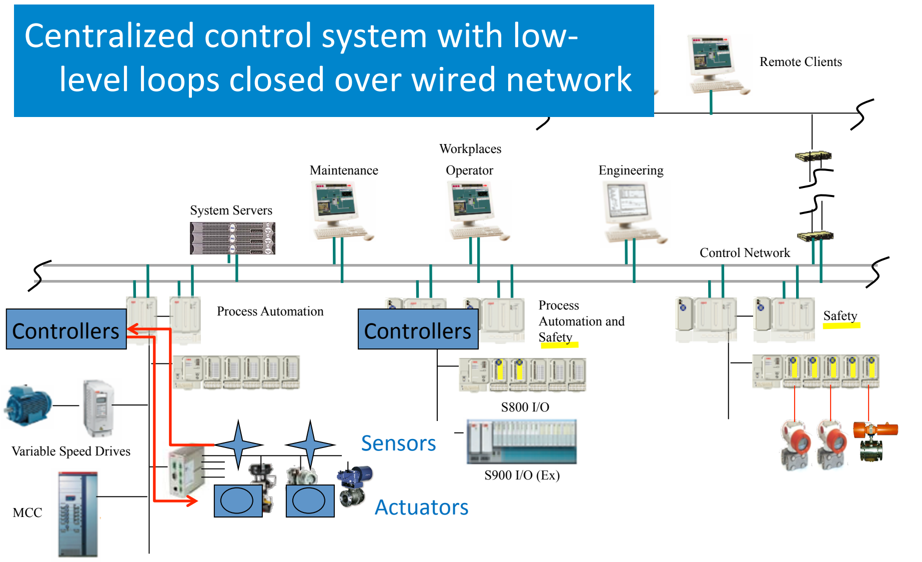
- Lower installation and maintenance costs
- Increased sensing capabilities and flexibility



Major consequence for control system architecture

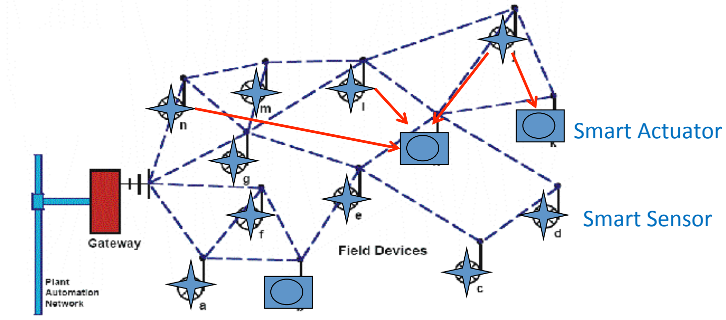
Today's industrial communication architecture

Centralized control system with low-level loops closed over wired network



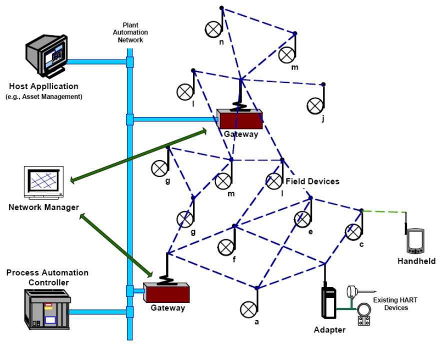
Towards wireless sensor and actuator network architecture

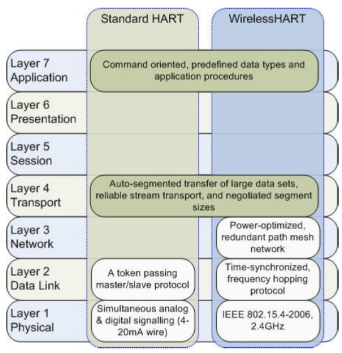
- Local control loops closed over **wireless multi-hop network**
- Potential for a dramatic change:
  - From fixed hierarchical centralized system to flexible distributed
  - From few dedicated computers to many smart sensors/actuators

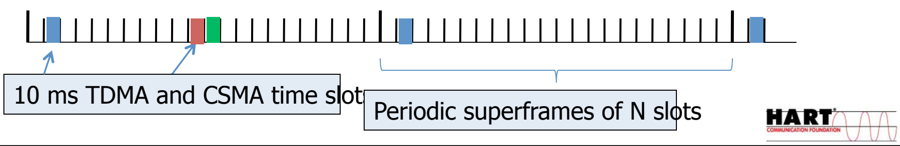


WirelessHART

Wireless networking protocol standard (2007) designed for sensing and control applications

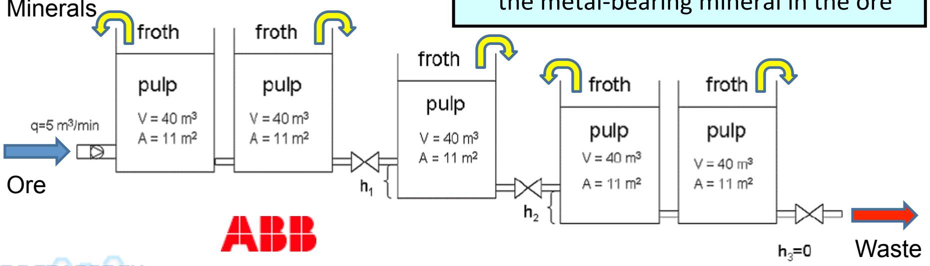






Event-based control of froth flotation process

- Froth flotation process concentrates the metal-bearing mineral in the ore

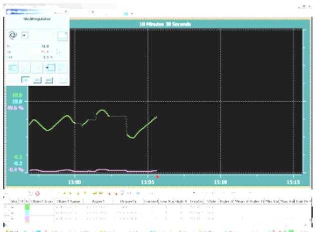


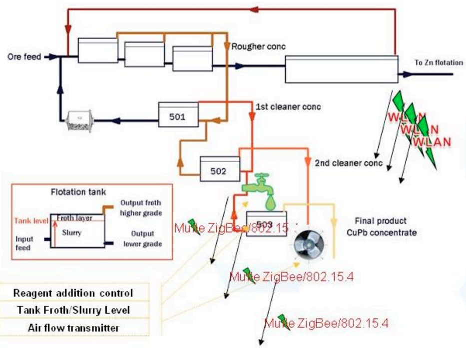
Event-based control of froth flotation process

The Boliden plant

Existing wired communication system

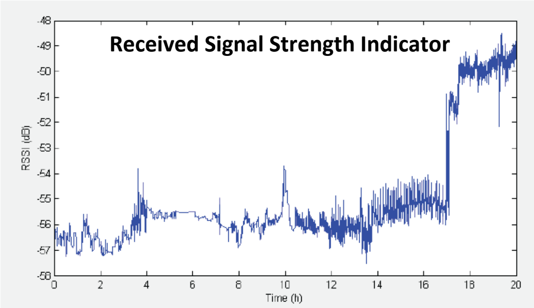
Wireless communication for tank level control





Radio Channel Measurements in Industrial Environment

- Rolling mill at Sandvik in Sweden
- Study of 2.45 GHz radio channel properties
- Slow but substantial RSSI variations due to mobile machines



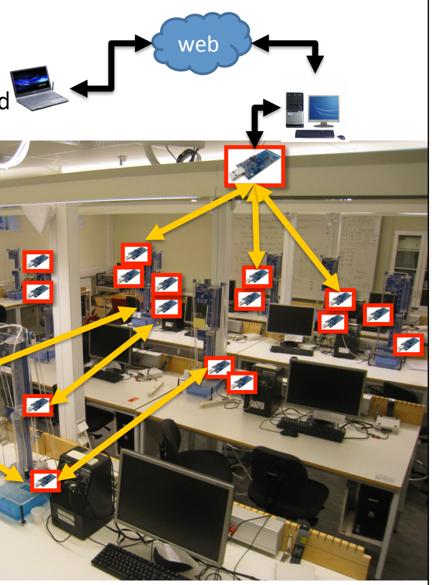
UPPSALA UNIVERSITET ABB KTH

Ahlen et al, 2012

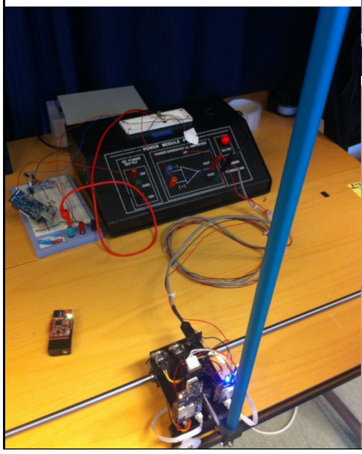
Test-bed for control over IEEE 802.15.4

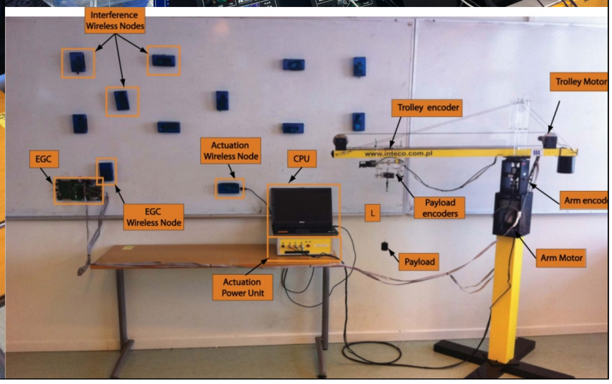
20 coupled water tanks connected over wireless multi-hop network

Test-bed to evaluate new control technology and wireless network protocols



Test-beds for event-based wireless control

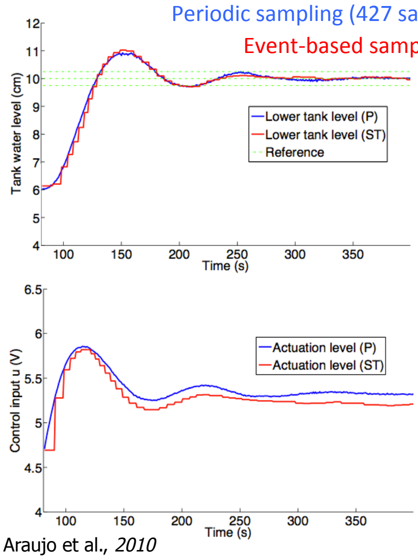


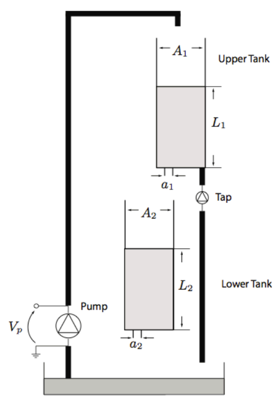


Experimental evaluation of event- and time-based sampling

Periodic sampling (427 samples)

Event-based sampling (62 samples)





Araujo et al., *2010*

Lecture 13 Outline

- Process industry
- **Transportation systems**
- Smart buildings

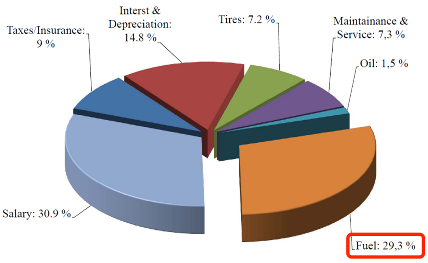
Goods Transportation: Societal Perspective

- Goods transportation accounts for
  30 % of CO_2 emissions
  15 % of greenhouse gas emissions
  of the global fossil fuel combustion
- Goods transport is projected to **increase by 50%** for 2000-2020

International Transport Forum (2010), European Commission (2006)

Goods Transportation: Fleet Owners Perspective

Life cycle cost for a heavy duty vehicle in Europe



Total fuel cost 80 k€/year/vehicle

Schittler (2003)

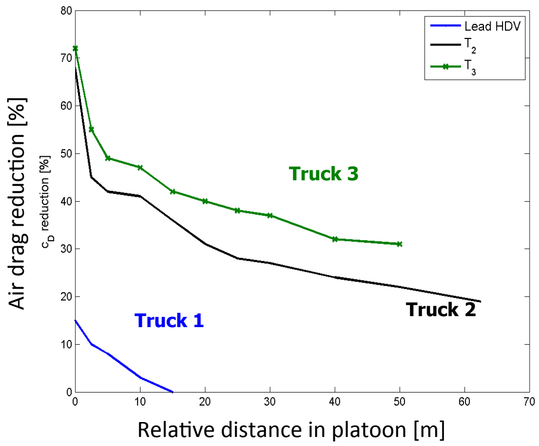
Automated Platooning as a Solution

- May tripple highway throughput
- May reduce fatalities by 10%
- May reduce emissions by 20%

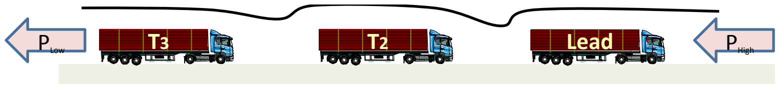
Varaiya et al., PATH project (2010), Robinson et al., (2010)

Air Drag Reduction in Platooning

KTH Electrical Engineering



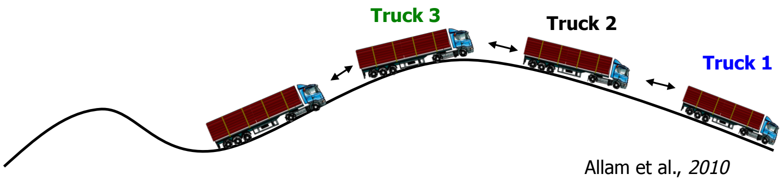
$$F_{\mathrm{air}} = \frac{1}{2} c_D(d) A_a \rho_a v^2$$



Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

Collaborative Driving for Fuel Reduction

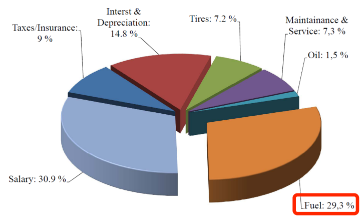
- Drive closer together to **reduce air drag** and prepare vehicles based on road and traffic information
- Enabled by new communication and sensor technologies
- Safety guarantees through automatic control



Allam et al., *2010*

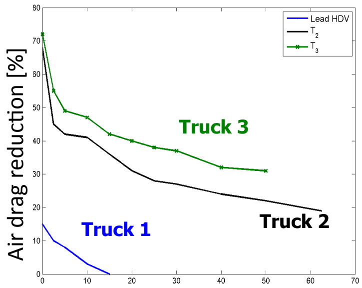
Heavy-Duty Vehicle Fleet Management

Life cycle cost for European heavy-duty vehicles

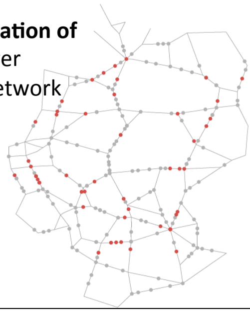


Total fuel cost 80 k€/year/vehicle

Incentives for vehicle platooning

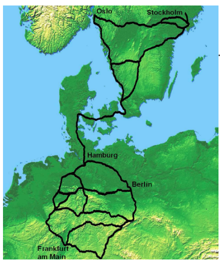


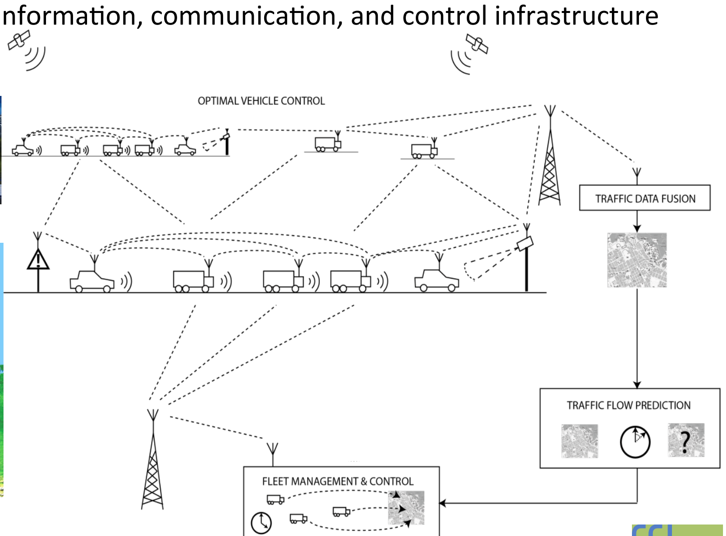
Distributed **coordination of vehicle platoons** over German highway network



Real-Time Fleet Management

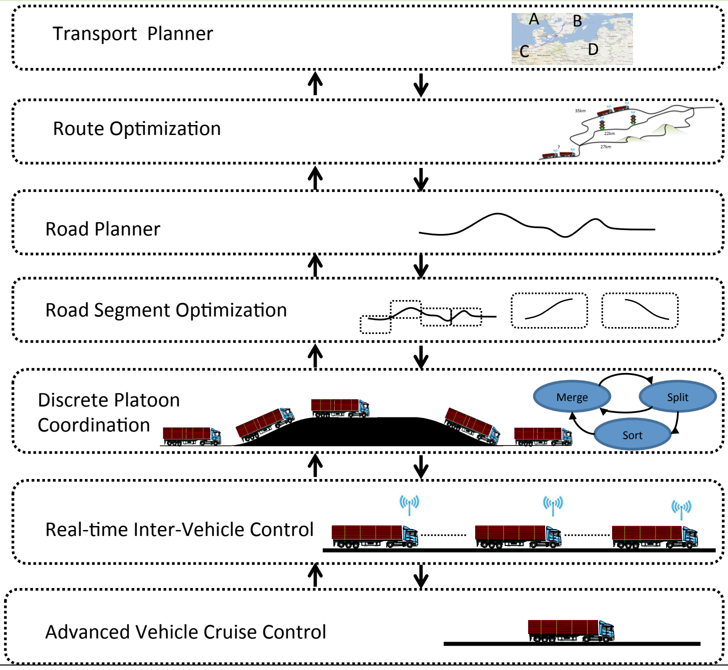
- Global coordination of vehicle platoons for fuel-efficient goods transport
- Large-scale information, communication, and control infrastructure





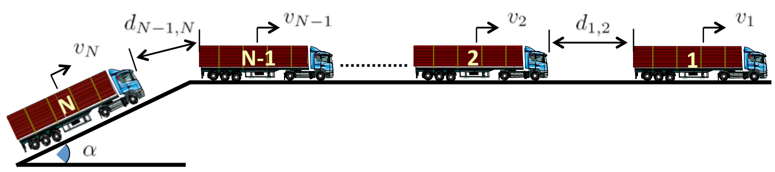
iQFleet

Layered Architecture for Real-time Fleet Management



Alam et al., 2012

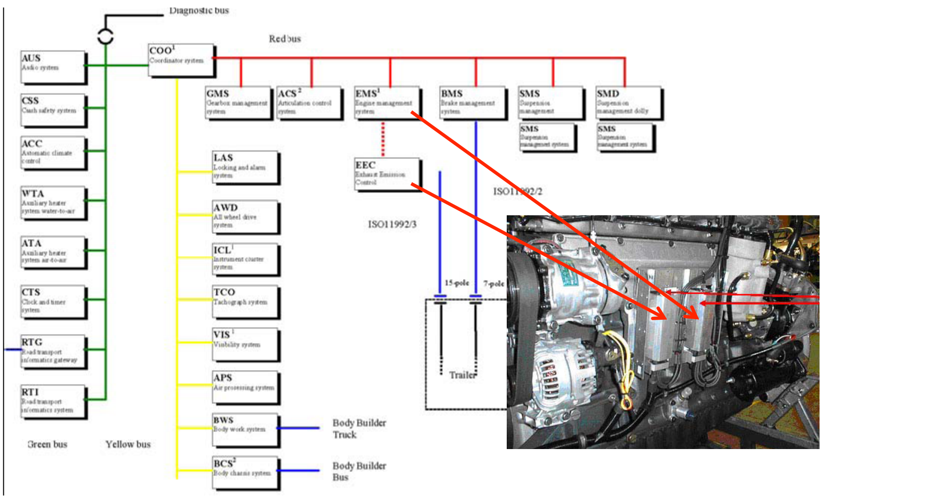
Networked Control in Platooning



- Platooning control applications require **collaborative actions**
  - Fuel-efficient adaptive cruise controllers
  - Collaborative route planning
  - Autonomous safety maneuvers
- Vehicles need **accurate estimates** of neighboring vehicles' states and actions
- Control performance is tightly coupled to how well data (position, velocity, breaking estimates) are communicated across the platoon

- How does the communication influence the system performance?
- What is an efficient communication strategy for specific control tasks?

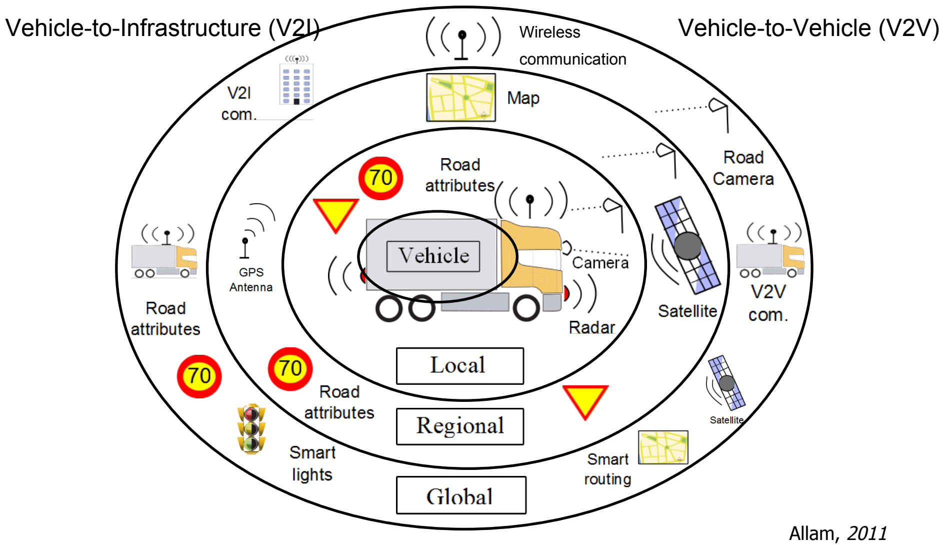
Networked control architecture in a Scania heavy-duty vehicle



Electronic Control Units connected over 3 Controller Area Networks

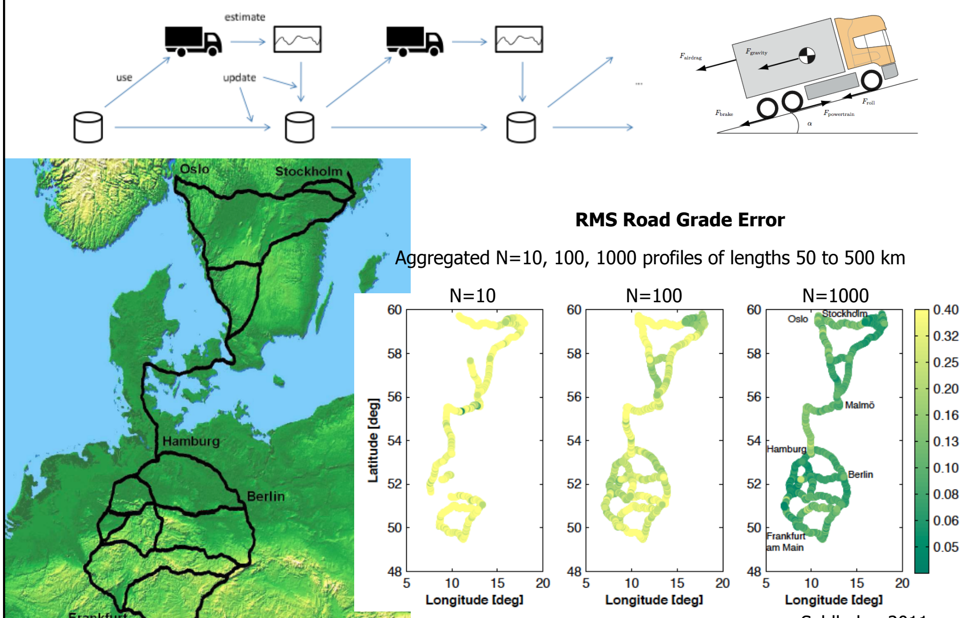
Communication Technology for Cooperating Vehicles

28



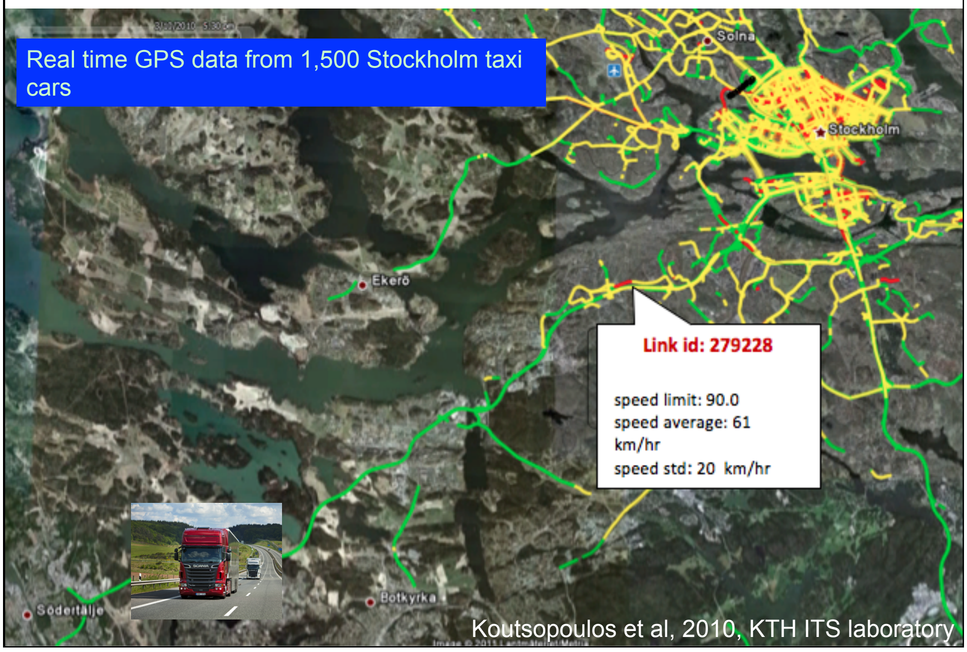
Allam, *2011*

Collaborative Road Grade Estimation



Sahlholm, 2011

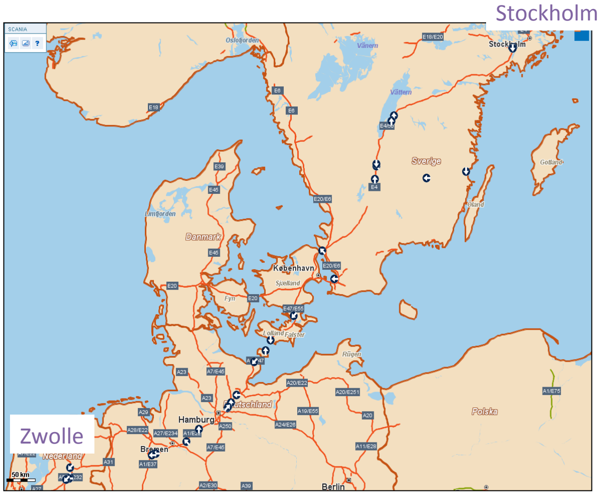
Traffic Control Based on Prediction from Mobile Vehicle Sensor Network



Testsite Stockholm-Zwolle

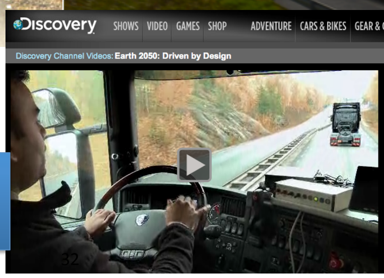
- Real-time fleet management
- Platooning in real traffic
- Fuel reductions and safety
- Driver acceptance
- Public acceptance

Scania Transport Lab
Internal haulage company
20 trucks, 360.000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week



Truck Platooning Demos

Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)

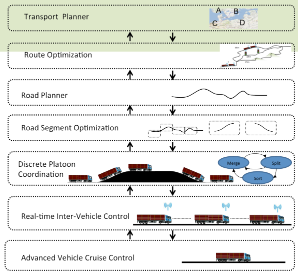


PhD student Assad Alam on *Discovery Channel* (Jan, 2012)

Challenges in Coordinating Heavy-Duty Vehicle Fleets

- **Pricing** of platooning and traffic information services
- **Local vs global** optimization (vehicular vs societal)
- **Integration** with existing infrastructure and management
- **Safety** despite other vehicles and humans in the loop
- V2V and V2I communication and system **security**
- Standardizations

http://www.ee.kth.se/~kallej



Tunnel disaster relief scenario

IoT technology to support rescue operation at tunnel accident

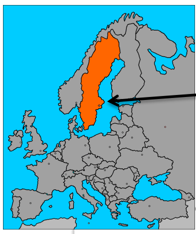
VIDEO

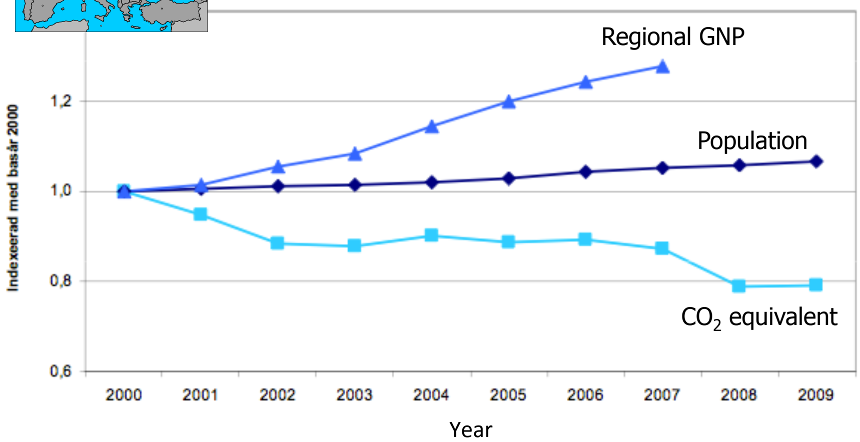
RUNES

Lecture 13 Outline

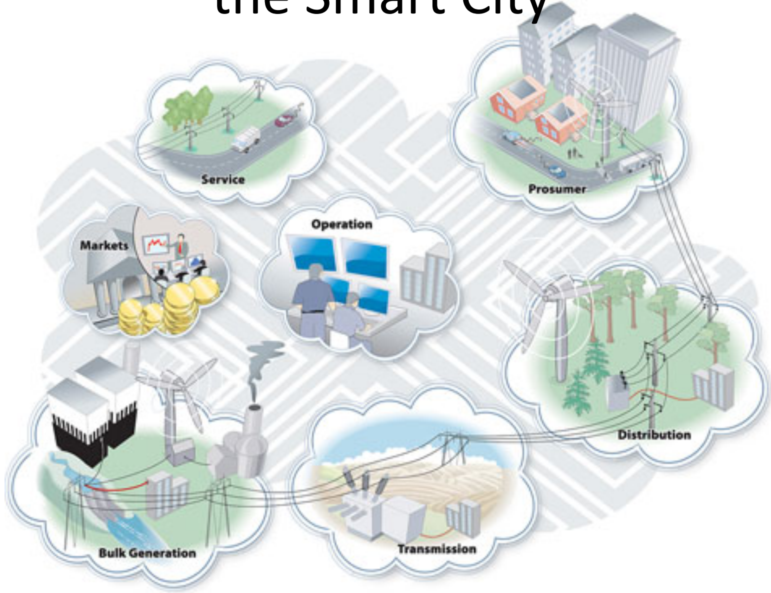
- Process industry
- Transportation systems
- **Smart buildings**

Stockholm Challenge





Integrate Renewable Energy into the Smart City



Stockholm Royal Seaport

2010
- Oil depot
- Container terminal
- Ports
- Gas plant

2030
- 10,000 new homes
- 30,000 new work spaces
- 600,000 m2 commercial space
- Modern port and cruise terminal
- 236 hectares sustainable urban district
- Walking distance to city centre

From a brown field area to a sustainable city district

Stockholm Royal Seaport

2010
- Oil depot
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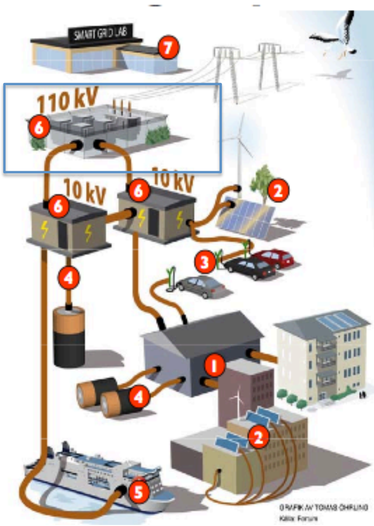
From a brown field area to a sustainable city district

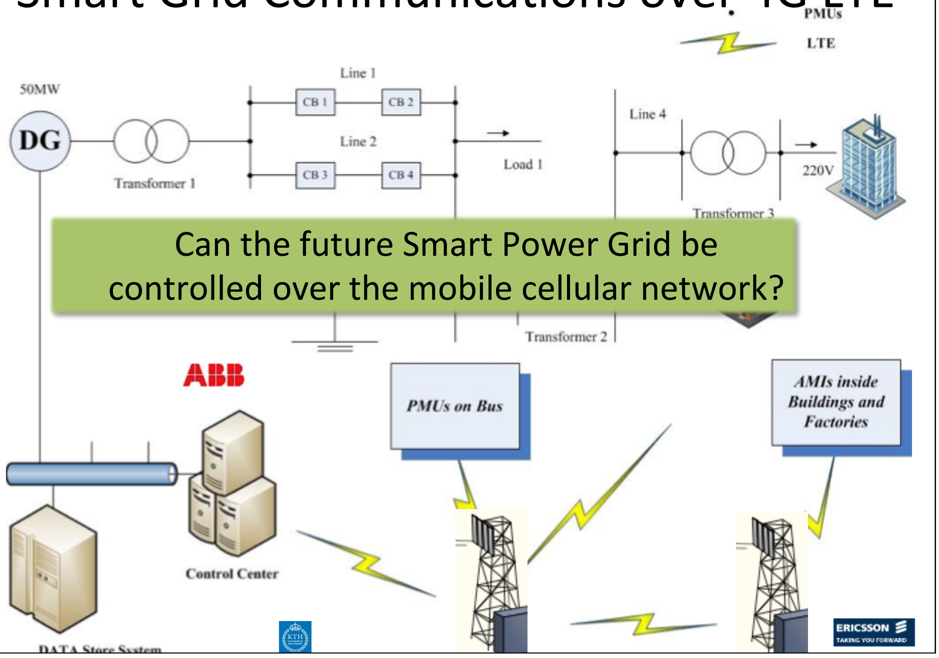
Smart Grid in the Stockholm Royal Seaport



1. Smart homes/Buildings and Demand Response
2. Distributed Energy Systems
3. Integration and Use of electric vehicles
4. Energy Storage for customers and the grid
5. Smart electrified harbour
6. Smart Primary Substations
7. Smart Grid Lab (part of an innovation Center)

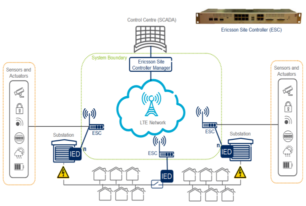
Fortum · Interactive Institute · Ericsson · Electrolux · ABB · NCC · ByggVesta · JM · Stockholms Stad · Stockholm European Green Capital · C40 Cities · Clinton Climate Initiative

Smart Grid Communications over 4G LTE

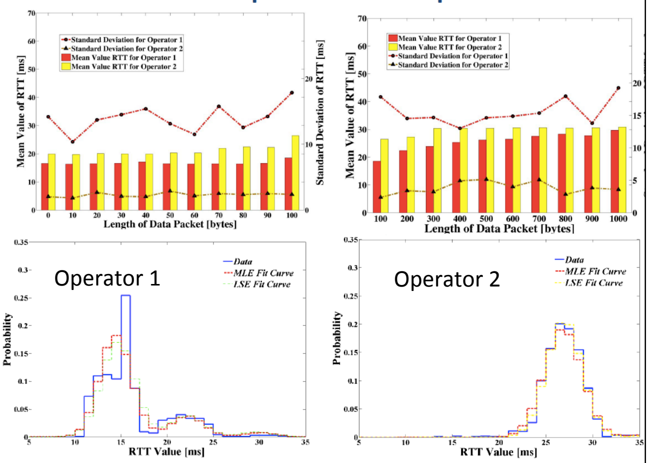


Can the future Smart Power Grid be controlled over the mobile cellular network?

Smart Grid Communications over 4G LTE



Round-trip-times vs. data packet size

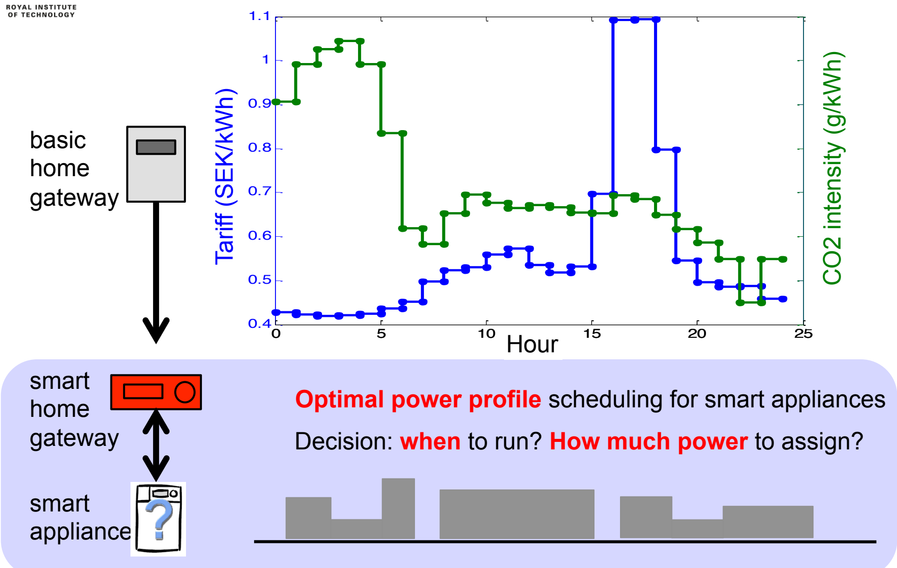


Experiments
- 2 Stockholm LTE services
- Off-the-shelf modems
- ICMP response times

Results
- Meet some requirements
- Comparison to 3GPP
- Further studies needed

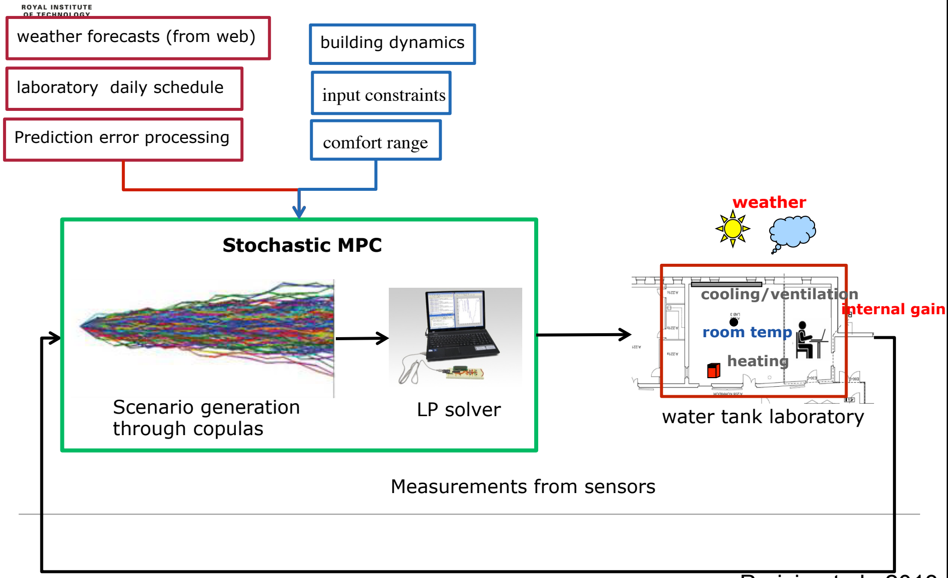
Weimer et al., 2012

Smart Home Appliances Scheduling



Seu et al., 2012

HVAC Control Scheme



Parisio et al., 2013

Control Strategy

Two controllers in cascade:

- SMPCair aims at satisfying the required air quality at a minimum energy use;
- SMPCtemp controls the indoor temperature control.

SMPCair → SMPCtemp →

Minimum mass air flow rate

- Mass air flow rate
- Temperature difference through cooling and heating coils
- Temperature difference through radiators

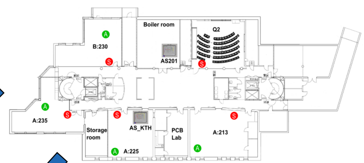
Minimize energy use

subject to:

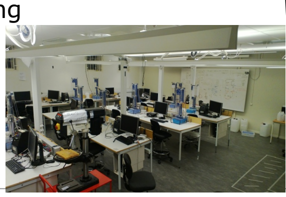
- **room dynamics**
- **input constraints**
- **output constraints (*probabilistic constraints*)**

KTH HVAC Test-bed

Q Building



Second Floor



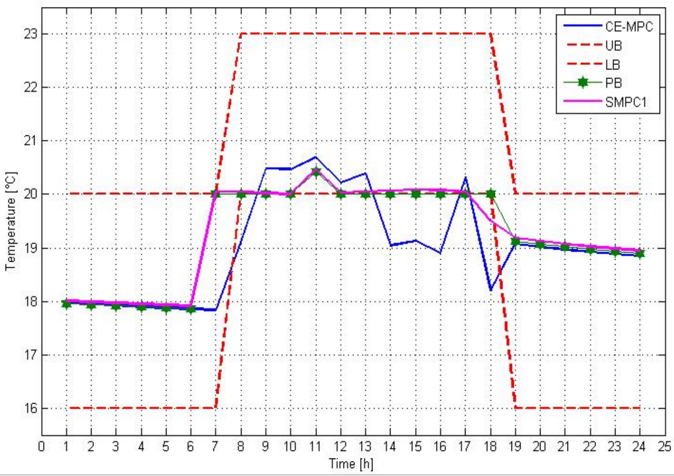
Water tank lab: room considered in simulations

Compared Control Strategies

- **Performance Bound (PB) MPC:**
  an ideal MPC, used as a theoretical benchmark, endowed with error-free forecasts;
- **Certainty Equivalence (CE) MPC:**
  a common practice MPC that simply neglects the uncertainties in the forecasts;
- **Stochastic Model Predictive Control (SMPC):**
  the MPC that uses the copula-based scenarios od random variables (i.e., outside temperature, radiation, occupancy).

We simulate an SMPC with 60 scenarios and a 91% of constraints satisfaction level (SMPC$_1$) and an SMPC with 120 scenarios and a 94% of constraints satisfaction level (SMPC$_2$).

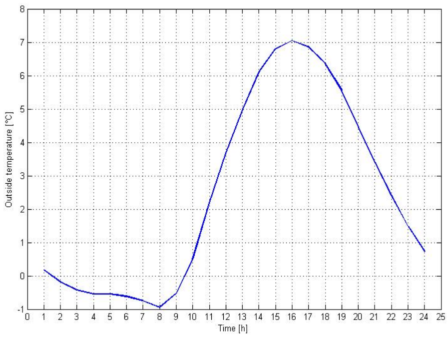
Comparison of the room temperature obtained by the control strategies



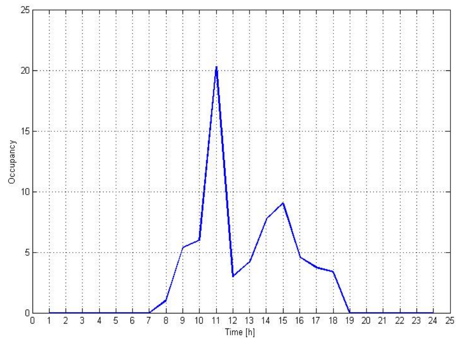
For the SMPC$_1$ the resulting room temperature is significantly close to the theoretical benchmark PB

KTH VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

Outside temperature



Occupancy



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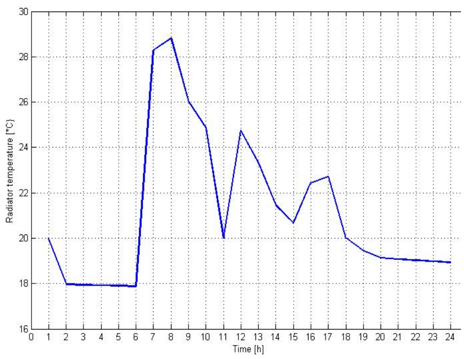
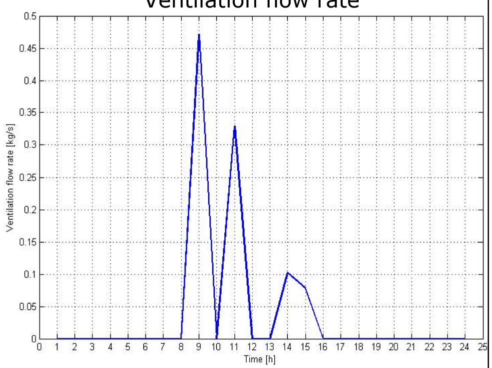
Control inputs

Radiator temperature

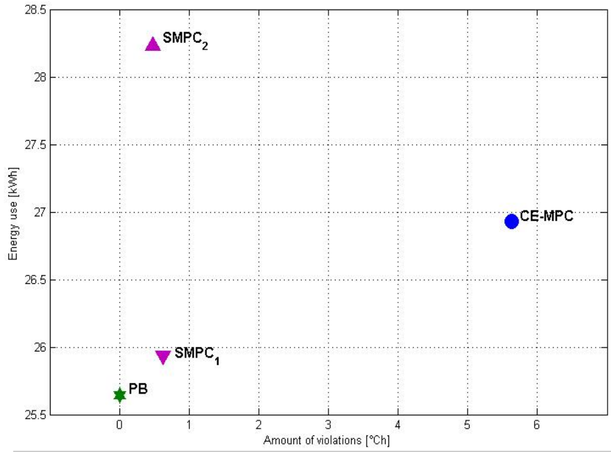


Ventilation flow rate



Assessment of control performance

Energy use vs Amount of constraint violations

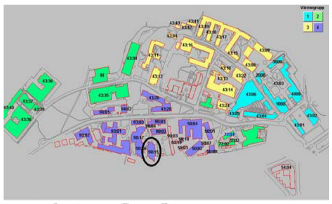


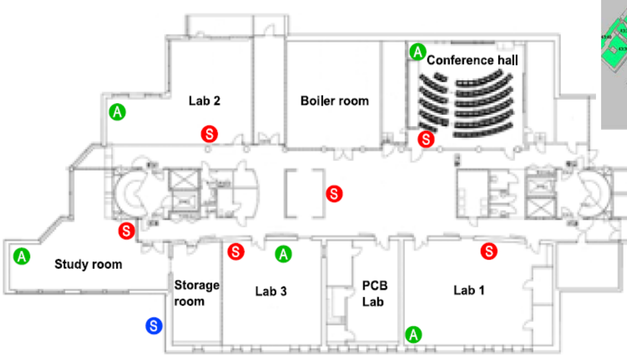
Using a higher constraint satisfaction probability and the number of scenarios (SMPC$_2$):

- provides less violations
- significantly increases the energy use
- does not lead to meaningful improvements in the quality of the solution.

Actuator fault detection in HVAC system

ACCESS the future





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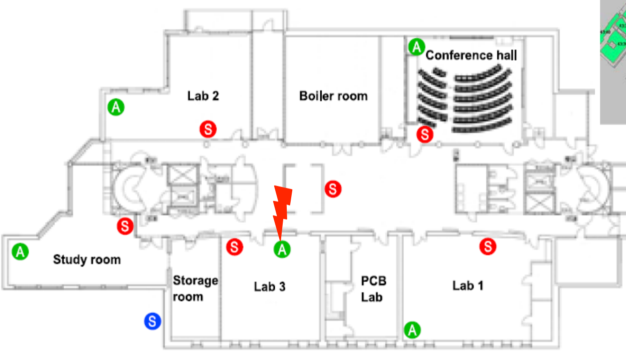
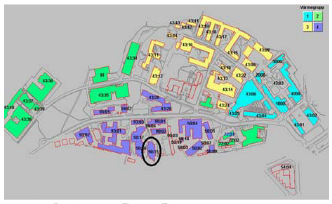
Weimer et al., 2013

Problem Overview





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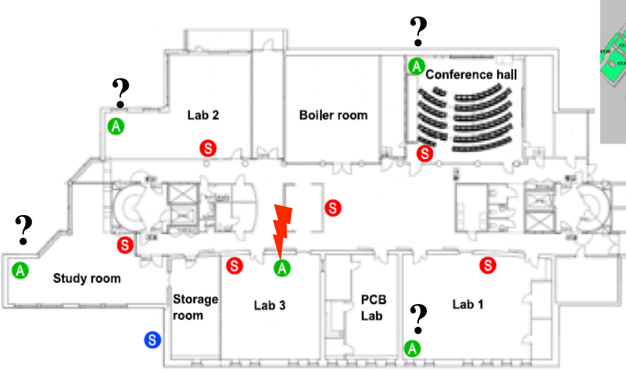
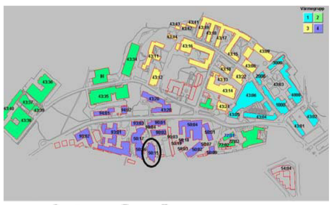
Problem Overview





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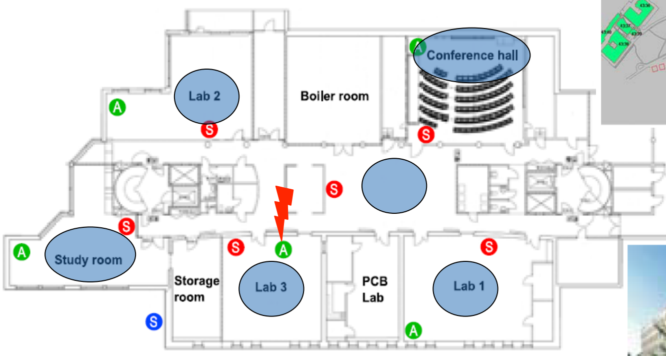
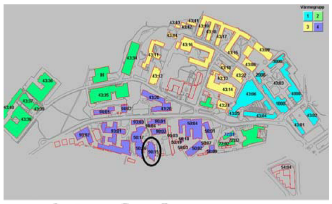
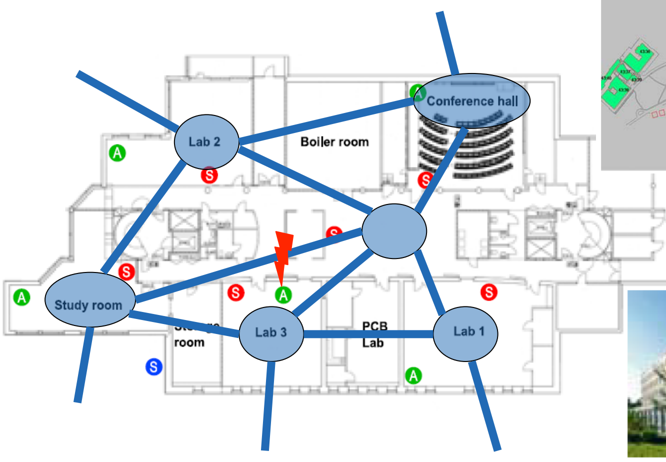
Problem Overview

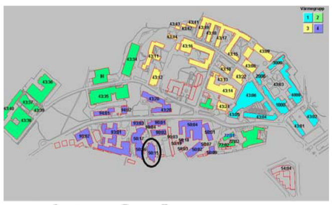




55

Problem Overview





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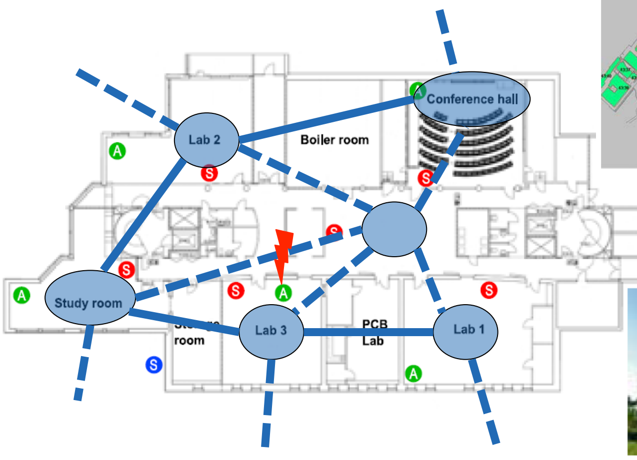
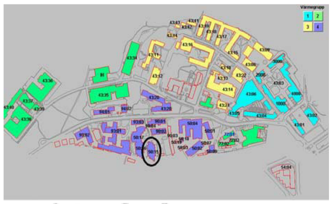
Problem Overview





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Problem Formulation

$$x_j(k+1) = x_j(k) + m_j \sum_{i \in \mathcal{N}_j} a_{ji}\Big(x_i(k) - x_j(k)\Big) + b_j d_j(k) + w_j(k)$$

$$y_j(k) = x_j(k) + v_j(k)$$

(first-principles model)

- x = zone temperature
- y = temperature measurement
- w, v = Gaussian noises
- m = zone mass
- a = inter-zone gain
- b = actuator gain
- d = actuator input

$$\boldsymbol{y}_j := [y_j(0), \ldots, y_j(T)]^\top$$
$$\boldsymbol{d}_j := [d_j(0), \ldots, d_j(T)]^\top$$

(time-series)

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actuator input structure
$$\boldsymbol{d}_\ell = \theta_\ell \mathbf{1} + \mu_\ell \boldsymbol{u}_\ell$$

$$\boldsymbol{y}_j := [y_j(0), \ldots, y_j(T)]^\top$$
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(time-series)

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actuator input structure
$$\boldsymbol{d}_\ell = \theta_\ell \mathbf{1} + \mu_\ell \boldsymbol{u}_\ell$$

hypothesis test

H0 : $\mu_\ell = 1$

H1 : $\mu_\ell = 0$

$$\boldsymbol{y}_j := [y_j(0), \ldots, y_j(T)]^\top$$
$$\boldsymbol{d}_j := [d_j(0), \ldots, d_j(T)]^\top$$

(time-series)

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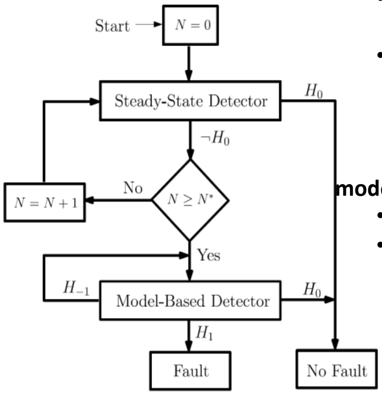
Parameter-Based Actuator FDD

ACCESS the future

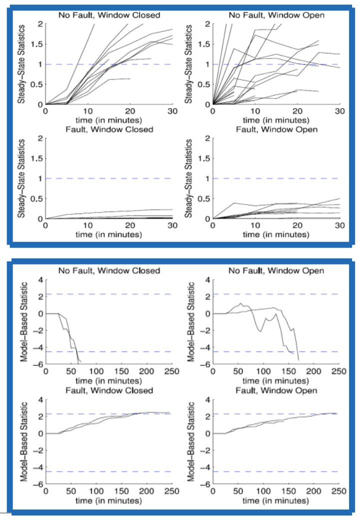


steady-state detector
- **inaccurate (no fault)**
- **fast**

model-based detector
- **accurate**
- **slow**

1) performance varies with parameters

2) biased parameters estimates



J. Weimer, A. Ahamadi, J. Araujo, F. Mele, D. Papale, I. Shames, H. Sandberg, K. Johansson, Active Actuator Fault Detection and Diagnostics in HVAC Systems. *In 4th ACM Workshop on Embedded Sensing Systems for Energy-Efficiency In Buildings (Build Sys 2012)*

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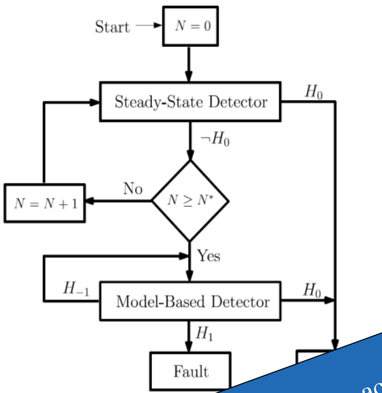
Parameter-Based Actuator FDD

ACCESS the future

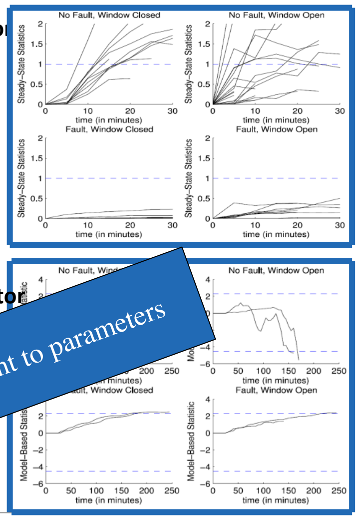


steady-state detector
- **inaccurate (no fault)**
- **fast**

model-based detector
- **accurate**

perform actuator FDD invariant to parameters

2) biased parameters estimates



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- b = actuator gain
- d = actuator input

(Unknown)

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$$\boldsymbol{d}_j := [d_j(0), \ldots, d_j(T)]^\top$$

(time-series)

actuator input structure

$$\boldsymbol{d}_\ell = \theta_\ell \mathbf{1} + \mu_\ell \boldsymbol{u}_\ell$$

hypothesis test

H0 : $\mu_\ell = 1$

H1 : $\mu_\ell = 0$

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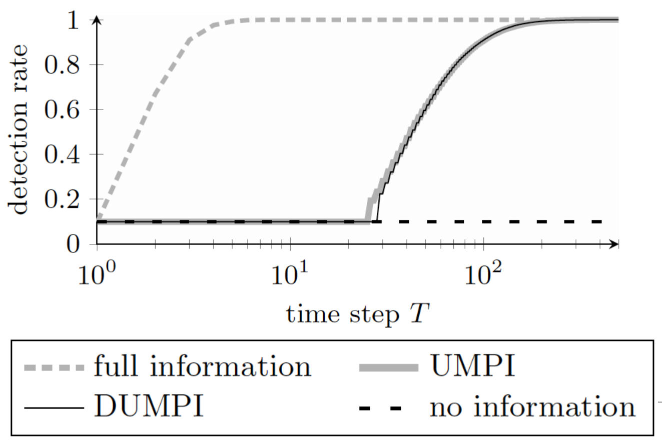
Simulated Results

$\alpha = 0.01$



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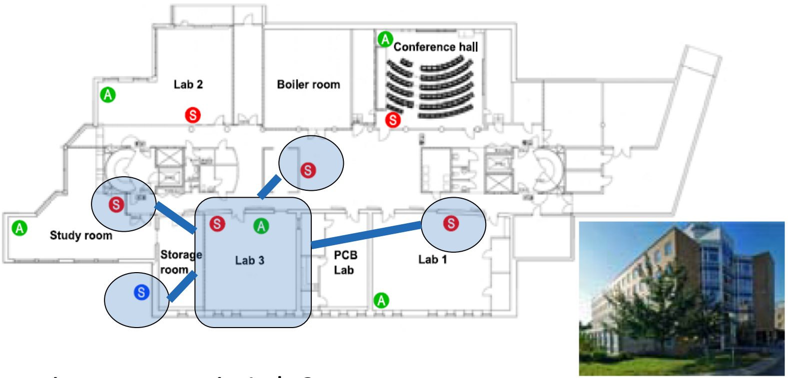
Experimental Setup



- testing actuator in Lab 3
- testing fault/no fault when windows open/closed
- probability of correct detection = 0.90

HVAC data available online at http://hvac.ee.kth.se

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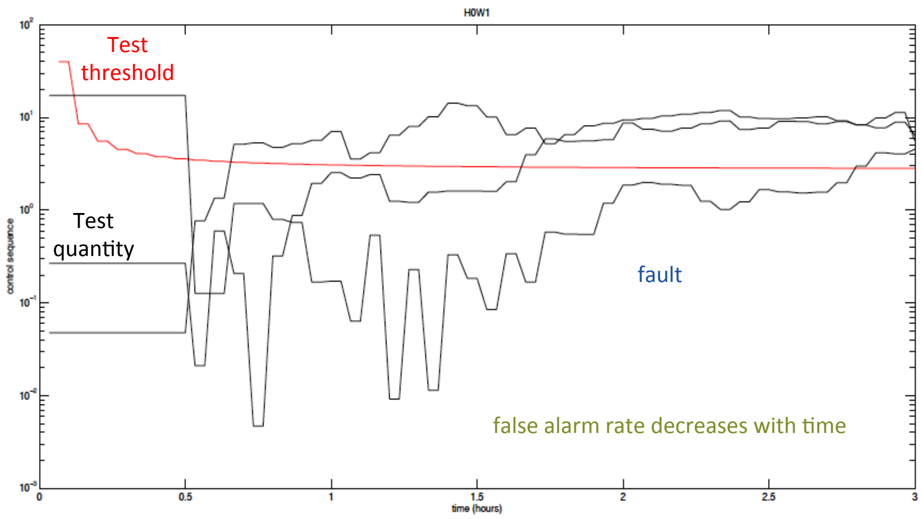
Experimental Results



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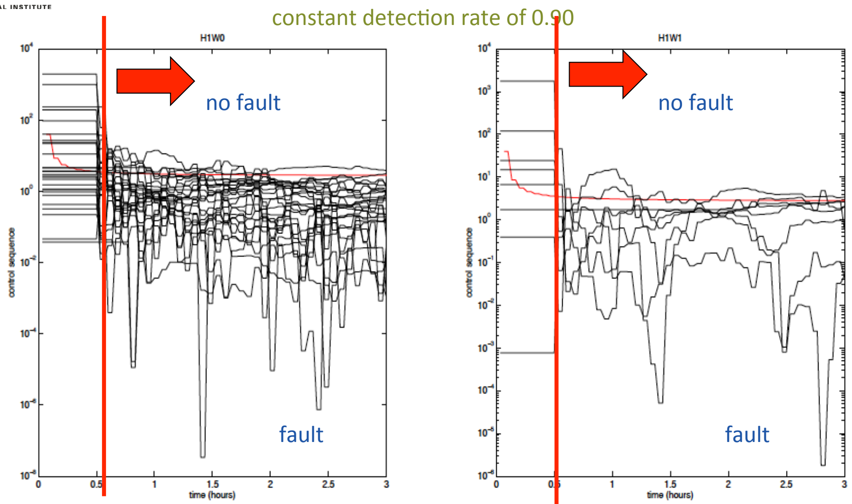
Experimental Results

constant detection rate of 0.90



fault, window closed fault, window open

(3 hours)

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Lecture 13 Outline

- Process industry
- Transportation systems
- Smart buildings