Wireless Control Systems: Scientific Challenges and Emerging Applications

Karl Henrik Johansson
School of Electrical Engineering
Royal Institute of Technology, Stockholm, Sweden

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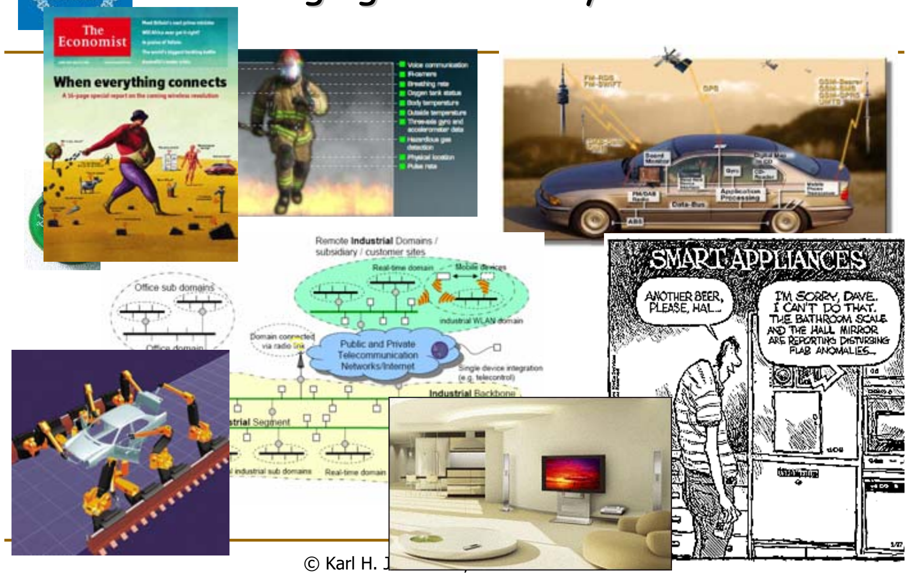
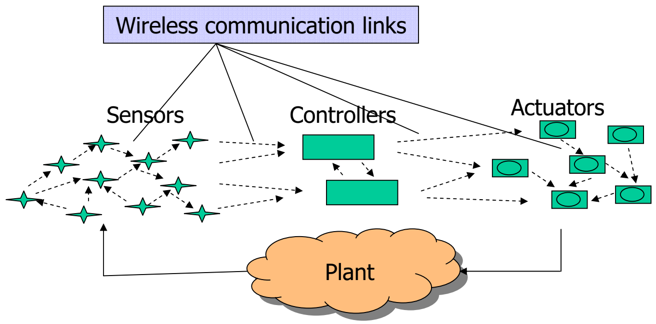
An emerging world of dynamic networks



Wireless control system

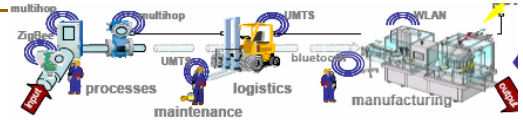
Distributed control system with sensor, actuator and controller communication supported by wireless network



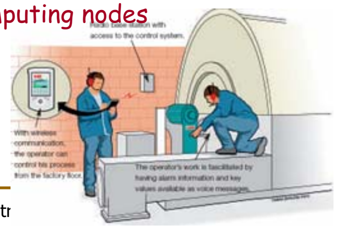
Outline

- Why wireless control
- Aspects of design
  - Layered **models** of abstraction
  - Global objective from local **controls**
  - Component-based **implementation**
- Conclusions

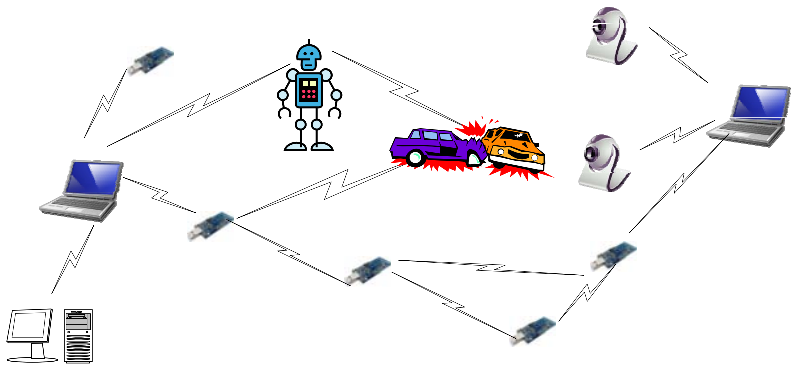
Benefits of wireless networking in industrial control



- Reduced installation and maintenance costs
  - Less cabling
  - Efficient monitoring and diagnosis
  - Fault-resilient connectivity
- Added flexibility
  - Better placed sensor, actuators and computing nodes
  - Enhanced maneuvers and control actions
  - Easier to reconfigure

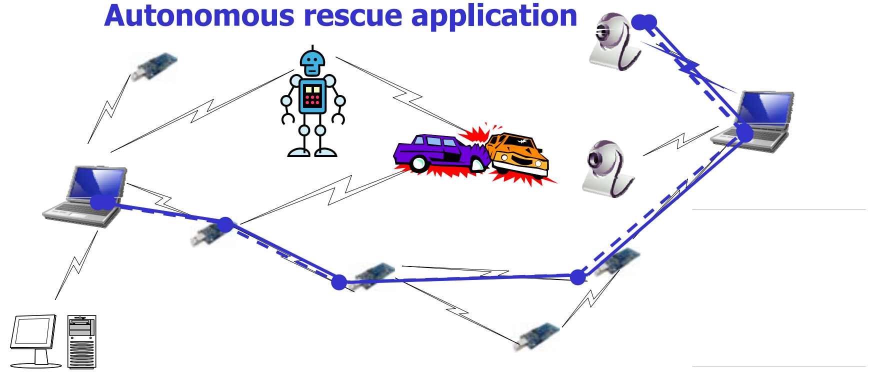


Layered models of abstraction

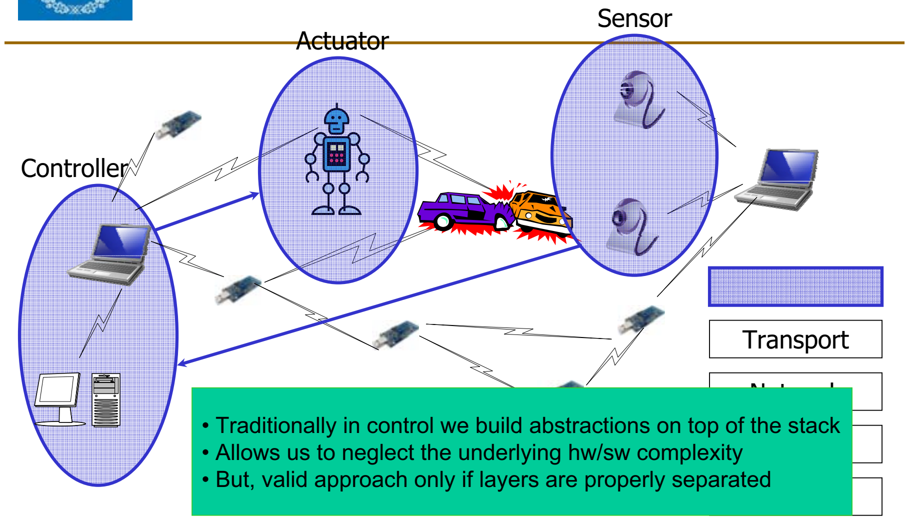


Communication abstractions

Autonomous rescue application



Control abstractions



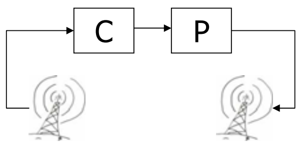
- Traditionally in control we build abstractions on top of the stack
- Allows us to neglect the underlying hw/sw complexity
- But, valid approach only if layers are properly separated

© Karl H. Johansson, Wireless control

What's the difference between wireless and wired control?

Wireless communication is more challenging than **wired**:

- Larger variations in connectivity, bandwidth, delays etc
- More explicit energy constraints
- Potential for mobility
- Less well-developed communication theory



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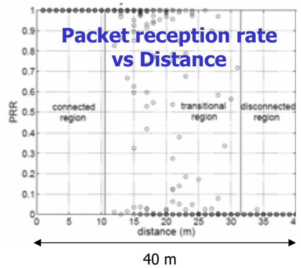
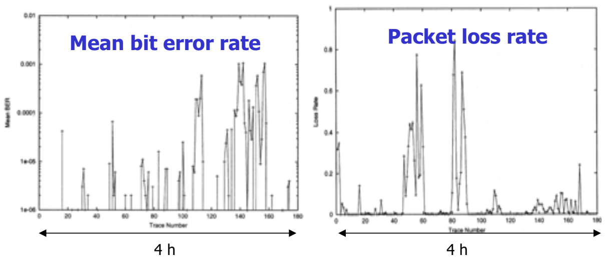
Respect imperfect layer separation in wireless networks



Zuniga & Krishnamachari, *SECON*, 2004

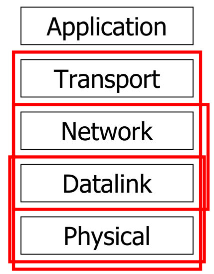


Willig et al., *IEEE Trans. Ind. Electron.*, 49, 6, 2002

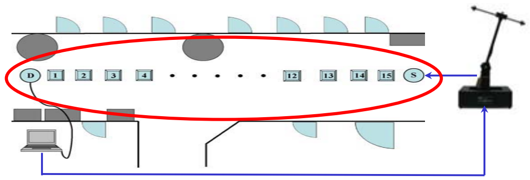
Park et al., KTH, 2007

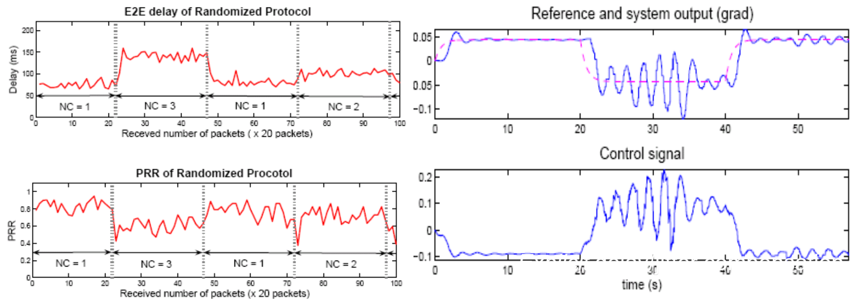
Large variations in

- Connectivity
- Bit and packet delivery
- End-to-end delivery



Influence on control performance



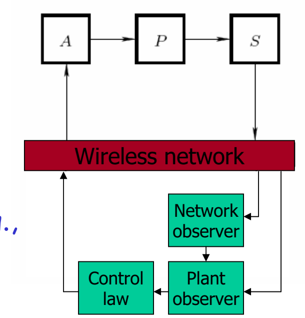


Witrant et al., *IEEE CCA,* 2007

A simple network-aware control architecture

Modify controller to cope with communication imperfections

- Control under varying **network delay**
- Control under varying **data loss**
- Control under **bandwidth limitations**
- Control under **topology variations**



Measure or estimate network state, e.g.,

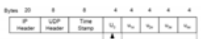
- Network delay
- Data loss probability
- Bandwidth

and adjust controller

A slightly more complex network-aware control architecture

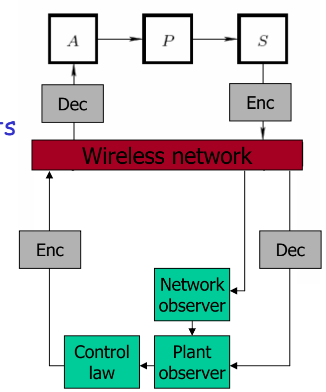
- Coding-control codesign
- Employs communication and control theories

- Large variation of implementation constraints
  - Processing capabilities in nodes
  - Time- or event-triggered nodes
  - Data delivery format



  - Cross-layer signaling

- Major recent progress, but lack of unifying theory

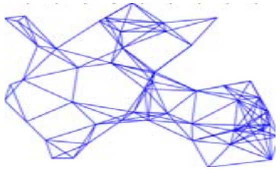


Bushnell, *IEEE CSM,* 21-1, 2001
Antsaklis & Baillieul, *IEEE TAC,* 49-9, 2004
Baillieul & Antsaklis, *Proc. IEEE,* 95-1, 2007

Global objective from local controls

Large-scale wireless control networks

- Wireless control networks are potentially very large
- Need architecture and protocols that scale well
  - Distributed implementation (control, resource allocation etc)
  - Limited information exchange

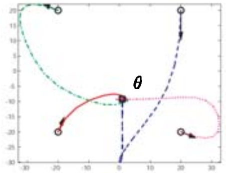


- How obtain a global objective from local actions?
- How is performance affected by network architecture?

A prototype problem on "global objective from local controls"

$$\underset{u\ \ ,\theta}{\text{minimize}} \quad \sum_{i=1}^{N}\sum_{t=1}^{T} \underbrace{(y_i(t)-\theta)^{\mathsf T} Q_i\,(y_i(t)-\theta) + u_i(t)^{\mathsf T} R_i u_i(t)}_{V_i(y_i(t),u_i(t),\theta)}$$

s.t.	$x_i(t+1) = A_i x_i(t) + B_i u_i(t)$	Linear dynamics
	$y_i(t) = C_i x_i(t)$	
	$y_i(T) = \theta$	Finite time consensus
	$\theta \in \Theta$	Consensus point constraint
	$u_i(t) \in \mathcal{U}_i$	Input constraints
	$x_i(0) = x_i^0$	Initial state

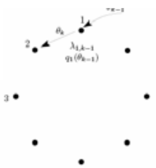


- Decentralized negotiation on Θ among agents
- Based on primal decomposition and incremental subgradient method

Johansson et al., *MTNS*, 2006

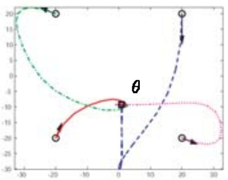
Sequential negotiation and control

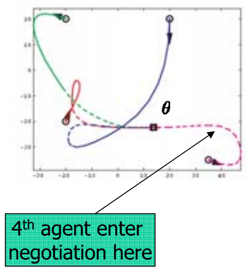
- Negotiation based on subgradient algorithm



1: Initialize θ_0 and α_0
2: $k := 0$
3: **loop**
4: **for** $i := 1$ to N **do**
5: Compute a subgradient, $\lambda_{i,k}$, corresponding to $q_i(\theta_k)$
6: $\theta_{k+1} := \mathcal{P}_\Theta\{\theta_k - \alpha_k \lambda_{i,k}\}$
7: $k := k+1$
8: $\alpha_k := \alpha_0 / k$
9: **end for**
10: **end loop**

- Distributed receding horizon control





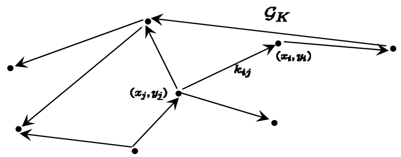
Johansson et al., *MTNS*, 2006

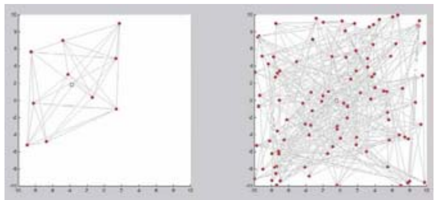
How does network size and connectivity influence performance?

Simplest local control dynamics

- consensus algorithm

$$x_i^+ = x_i + \frac{1}{\operatorname{indeg}(i)} \sum_{\substack{j \neq i \\ (j,i)\in\mathcal{E}}} (x_j - x_i).$$





Here we will discuss scalability and connectivity

Speranzon, PhD Thesis, KTH, 2006
Carli et al., *Automatica*, 2007

Hence, original compared to

Tsitsiklis et al., *IEEE TAC*, 31(9), 1986
Jadbabaie et al., *IEEE TAC*, 48(6), 2003
Olfati-Saber & Murray, *IEEE TAC*, 49(9), 2004
Etc.

Cayley graphs

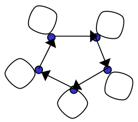
Cayley graph (G, S) is a graph with $G \supset S$ finite Abelian group:

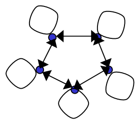
Vertex set G

Edge set $E = \{(x, y) \in G \times G : \ \exists s \in S, y = x + s\}$

Examples

$G = \mathbb{Z}_5,\ S = \{0, 1\}$ $\qquad$ $G = \mathbb{Z}_5,\ S = \{-1, 0, 1\}$





Abelian group $(G, +)$ is a set G with binary operation $+$:

- $a, b \in G \Rightarrow a + b = b + a \in G$
- $a, b, c \in G \Rightarrow (a + b) + c = a + (b + c)$
- $\exists e \in G$: $a \in G \Rightarrow e + a = a + e = a$
- $a \in G \Rightarrow \exists b \in G$: $a + b = b + a = e$

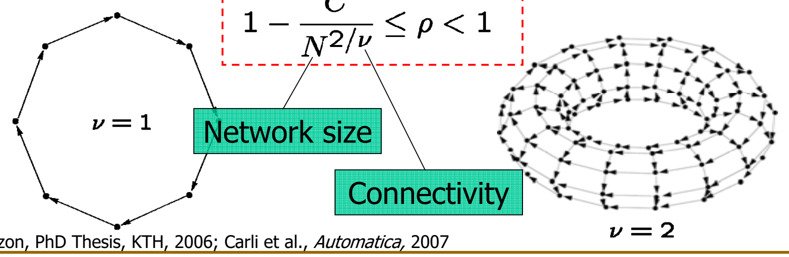
Consensus under symmetries

$$x(t+1) = (I + K)x(t), \qquad I + K \text{ doubly stochastic}$$

$$\rho = \inf_K \max\{|\lambda| : \lambda \in \sigma(I + K), \lambda \neq 1\}$$

If communication network is described by Cayley graph $\mathcal{G}_K$ and $\nu > 0$ is the in-degree of each vertex, then

$$1 - \frac{C}{N^{2/\nu}} \leq \rho < 1$$

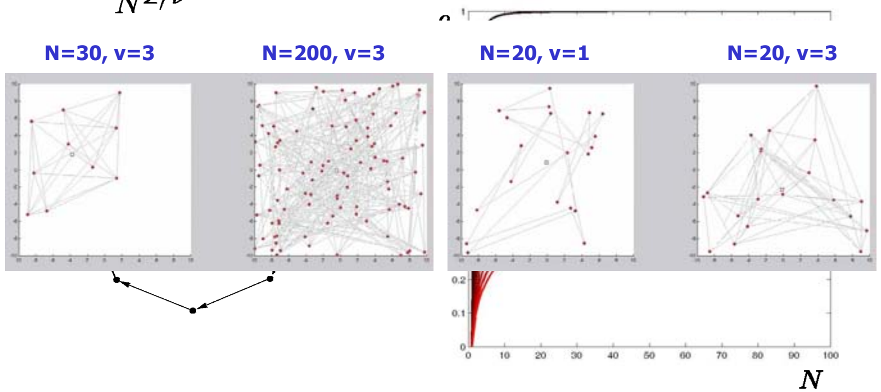


Speranzon, PhD Thesis, KTH, 2006; Carli et al., *Automatica,* 2007

Consensus under symmetries

$$1 - \frac{C}{N^{2/\nu}} \leq \rho < 1$$

If ν is fixed and $N \to +\infty$ then $\rho \to 1$



Speranzon, PhD Thesis, KTH, 2006; Carli et al., *Automatica,* 2007

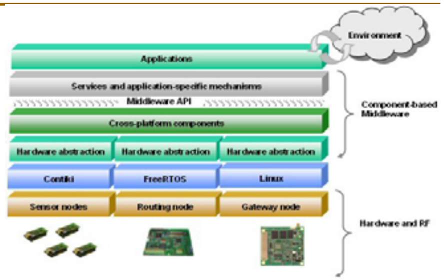
Component-based implementation

RUNES component-based programming model

A component is a reusable software objects offering a service and able to communicate with other components

Shield application level software from details of the hardware and low-level software implementation and vice versa

Component-based approach to networked embedded control problems



- Component model implemented w/ Contiki: lightweight OS for tiny network nodes
- Provides µIP stack for TCP and UDP, µAODV routing protocol
- Components can be replaced during runtime

Zhang et al., *Int. Conf. on Distr. Comp. Systems*, 2002
Heck et al., *IEEE CSM*, 23(1), 2003
Baliga et al., *IEEE Distributed Systems Online*, 5(8), 2004
Baras & Huang, *Army Science Conf.* 2006

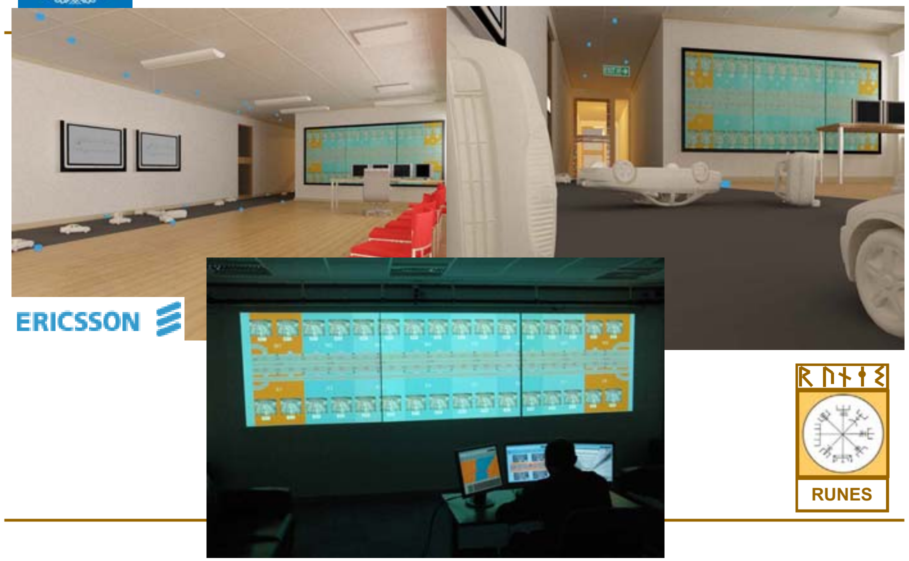
Dunkels et al., *IEEE Workshop Embedded Networked Sensors*, 2004

RUNES tunnel disaster relief scenario

Wireless sensor networks to support rescue operation at tunnel accident

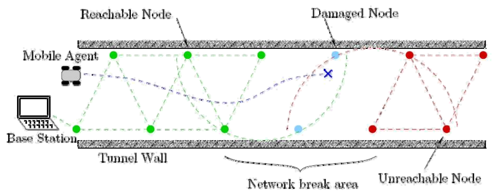
RUNES video

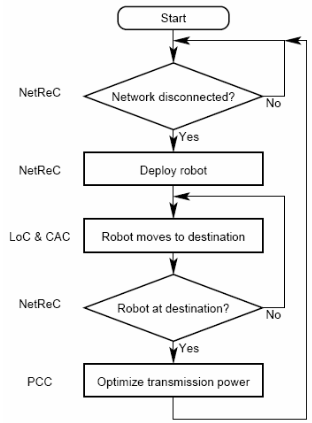
Demonstration in Stockholm 25-27 July 2007



Network reconfiguration scenario and control components

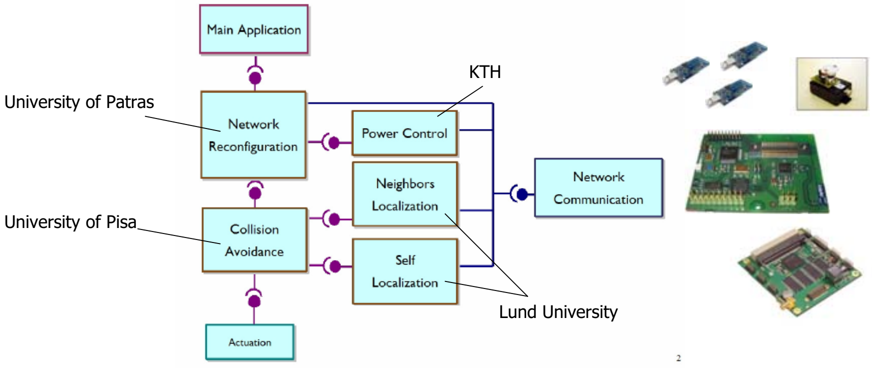
Components on each mobile agent
- Localization Component (LoC)
- Collision Avoidance Component (CAC)
- Power Control Component (PCC)
- Network Reconfiguration Component (NetReC)

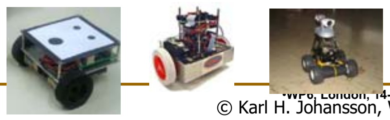




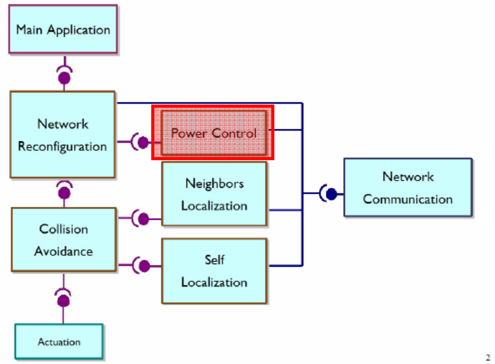
Årzen et al., *EJC*, 2-3, 2007; Johansson & Lygeros, *ECC*, 2007

Software structure

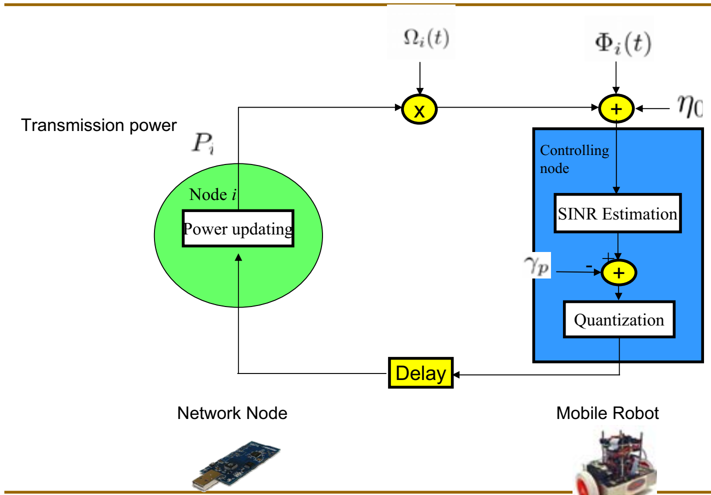




Power control component

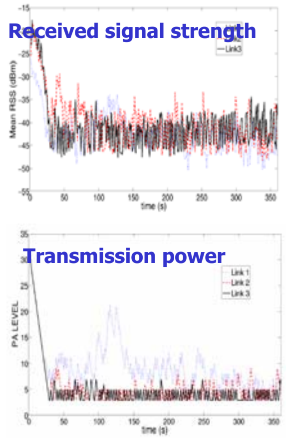


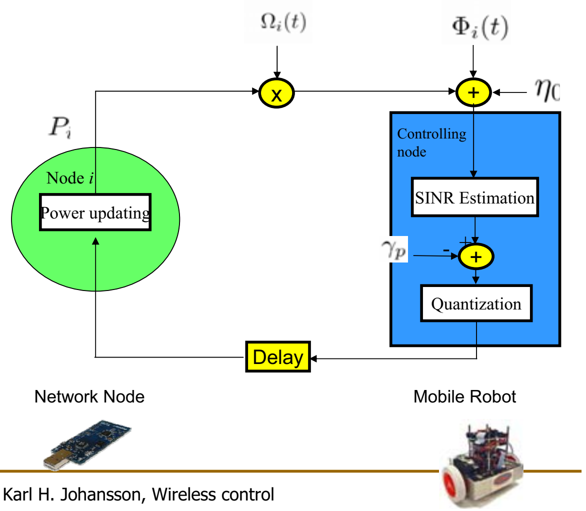
Power control component



Zurita Ares et al., *ECC*, 2007

Power control component

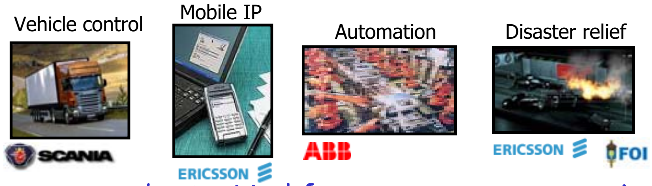




Zurita Ares et al., *ECC*, 2007

Conclusions

- Some emerging wireless control applications



- Challenges can be tackled from common perspectives
  - Layered models of abstraction
  - Global objectives from local controls
  - Component-based implementation
- Lack of theory, not technology

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