UNISI Team

- Control
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  - Daniele Bernardini (PhD student)
  - Marta Capiluppi (postdoc)
  - Giulio Ripaccioli (PhD student)
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- Communications
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  - Marco Belleschi (PhD student)
  - Cesare Carretti (PhD student)
- Operations research
  - Alessandro Agnetis (prof.)
  - Marco Pranzo (prof.)
- Project manager
  - Ilaria Sbragi

UNISI Team - Expertise

- Model Predictive Control (MPC): theory, algorithms, tools
- Hybrid systems: modeling, analysis, control, optimization, tools
- Resource allocation for wireless networks (ad-hoc & sensor networks)
- Combinatorial optimization for planning and scheduling problems
- Experimental activities on data processing using WSNs

MPC of Large-Scale Constrained Linear Systems

Cost function: full matrices Q,R,P

$$\sum_{k=0}^{N-1} \left[x_k' Q x_k + u_k' R u_k\right] + x_N' P x_N$$

Centralized approach

Process model: coupled dynamics

$$x_{k+1} = Ax_k + Bu_k, \ x \in \mathbb{R}^n, \ u \in \mathbb{R}^m$$

Constraints: $u_{\text{min}} \leq u_k \leq u_{\text{max}}$

Drawback

All the n components of $x(t)$ must be transmitted to a central unit to solve a (large) QP, and m signals must be transmitted back to the corresponding actuators

Idea: replace a centralized MPC algorithm with m simpler decentralized MPC algorithms, one for each actuator

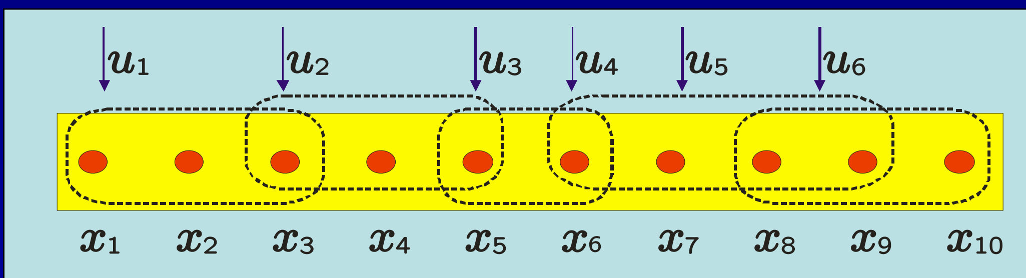
(Alessio, Bemporad, ECC 2007) (Alessio, Bemporad, ACC'08)

Decentralized Model

- Assume matrices A,B have certain number of negligible components (dynamical sub-systems are partially decoupled)

$$A = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & a_{1j} & a_{1n} & \\ a_{21} & a_{22} & 0 & a_{2k} & 0 & 0 & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots \\ 0 & a_{k2} & 0 & a_{kk} & 0 & a_{kn} & \\ a_{j1} & a_{j2} & 0 & 0 & a_{jj} & 0 & \\ a_{n1} & 0 & 0 & a_{nk} & 0 & a_{nn} & \end{bmatrix} \qquad B = \begin{bmatrix} b_{11} & 0 & 0 & b_{1k} & b_{1j} & 0 \\ b_{21} & b_{22} & 0 & 0 & 0 & b_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & b_{k2} & 0 & b_{kk} & 0 & b_{km} \\ b_{j1} & 0 & 0 & b_{jk} & b_{jj} & b_{jm} \\ 0 & b_{n2} & 0 & b_{nk} & 0 & b_{nm} \end{bmatrix}$$

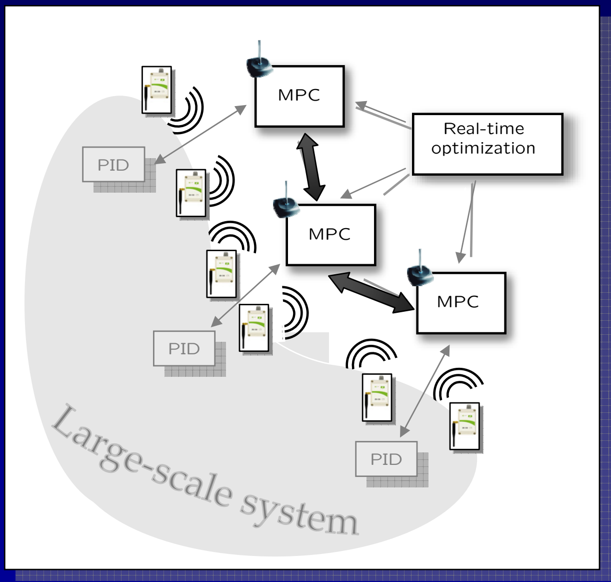
- Let m be the number of decentralized control actions we want to design
- Define m (possibly "*overlapping*") submodels



$$A_1 = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad B_1 = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \end{bmatrix}, \quad A_2 = \begin{bmatrix} a_{33} & a_{34} & a_{35} \\ a_{43} & a_{44} & a_{45} \\ a_{53} & a_{54} & a_{55} \end{bmatrix} \quad B_2 = \begin{bmatrix} b_{32} & b_{33} \\ b_{42} & b_{43} \\ b_{52} & b_{53} \end{bmatrix}, \quad \text{etc.}$$

Control over Networks: Pros

Decentralized MPC requires architectures where different components of the control system communicate over (possibly wireless) network links

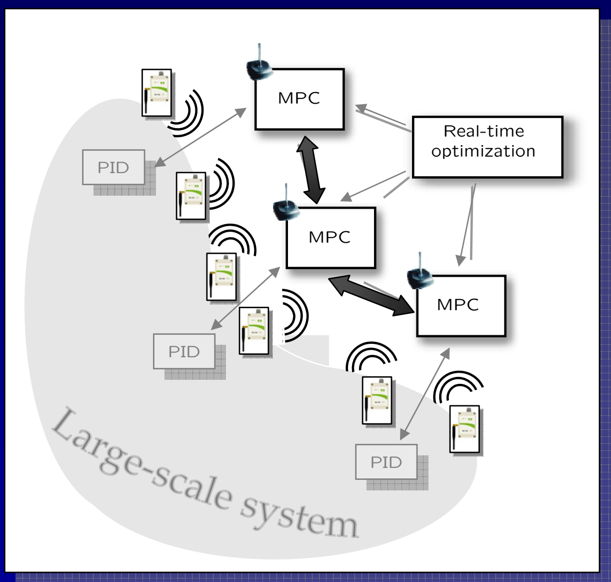


Pros:

- delocalization of the controllers
- often reduced installation and maintenance costs
- flexible and easily reconfigurable

Control over Networks: Cons

Closing the loop over wireless communication networks introduces additional problems:



Cons:

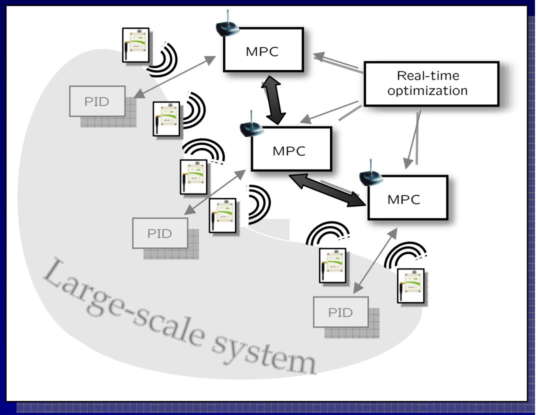
- Data loss (packet drop)
- Data loss (total loss of connectivity)
- Communication delays
- Jitter
- Wireless sensors are usually powered by batteries, so energy consumption must be minimized

New challenges in decentralized control over networks !

Energy-Aware Control over WSNs

(Bernardini, Bemporad, CDC'08)

- Problem: **battery consumption**
- **Radio chip** is the dominant power hog. Control strategy should keep the radio off (both TX & RX) as much as possible !



- Tradeoff: closed-loop **performance** vs. **transmission rate**
- Idea: transmit measurements *only when necessary*, according to the threshold logic:

$$\text{Measurement } y(k) \text{ is transmitted } \Leftrightarrow |y(k) - \hat{y}(k)| > \varepsilon$$

where $\hat{y}(k)$ is a *prediction* of $y(k)$ computed by the controller and received by the sensor node

Energy-aware control – Intuitive sketch

Note: a non-measurement is also a "measurement" ! (assuming all packets are received)

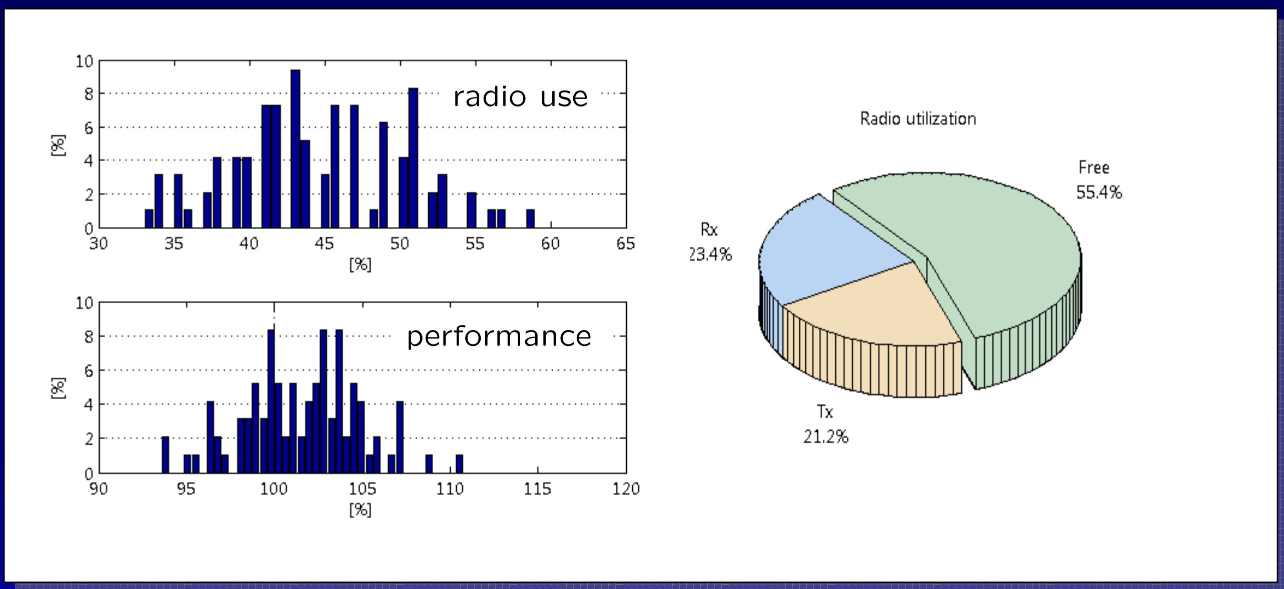
Energy-Aware Control over WSNs

- Note: Wireless communication protocols require a *minimum frame size* (e.g. 248 bits in ZigBee)

→ Transmitting a (small) *set* of measurements costs (almost) as much as transmitting a *single* measurement

- When the controller receives the measurement, it computes a new set of M predictions and transmits them to the node
- In the ideal case of no disturbances, i.e. $y(k) = \hat{y}(k)\ \forall k$,
  → the overall transmission rate is $1/M$
- Compute control action via explicit Model Predictive Control:
  - can handle *constraints*,
  - *closed-loop* predictions easily computed and transmitted
  - can be formulated to achieve robust control by explicitly taking into account the error induced by the threshold logic

Energy-Aware Control over WSNs



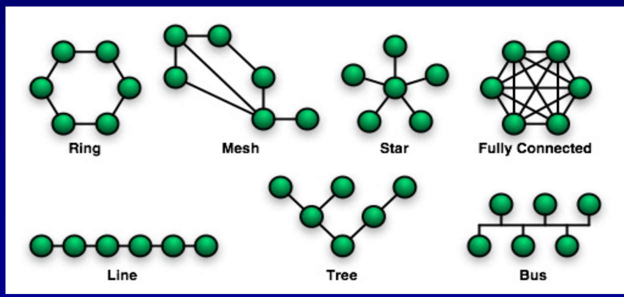
Controller	performance	Tx. Rate
Standard MPC	30.39	100%
Energy-Aware MPC	30.87	44.6%

Radio savings: -55.4%
Performance loss: +1.58%

Sensor placement and network topology design

(Abrardo et al.)

- Maximize the network lifetime
- Minimize the application-specific total cost, given a fixed number of sensor nodes in a region with a certain coverage requirement
- Optimize routing
- Optimize nodes redundancy



Protocols and distributed processing for state estimation and monitoring

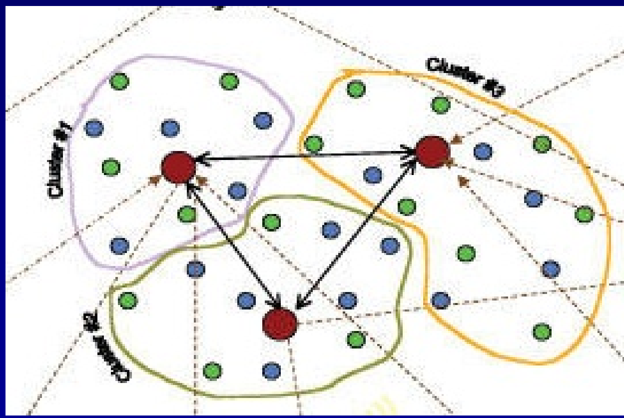
(Abrardo et al.)

- Distributed optimization algorithms over IEEE 802.15.4 (*in collaboration with KTH*)
- Communication only between neighbors or with routing
- Distributed approach vs. centralized approach
- Use of network synchronization techniques for battery saving

Protocols and distributed processing for state estimation and monitoring

(Abrardo et al.)

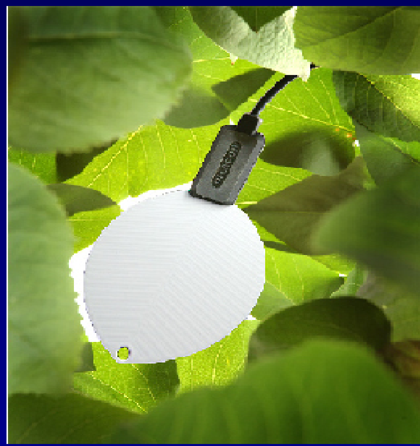
- Use of optimized clustering to improve network efficiency and data sampling following real values distribution
- Trade-off between values precision and energy efficiency
- Network self-configuration and self-healing
- Synchronization inter-cluster and intra-cluster



Experimental activities at UNISI on WSNs

WSNs for agriculture

- Humidity
- Temperature
- Light
- Soil Moisture
- Leaf wetness
- Wind



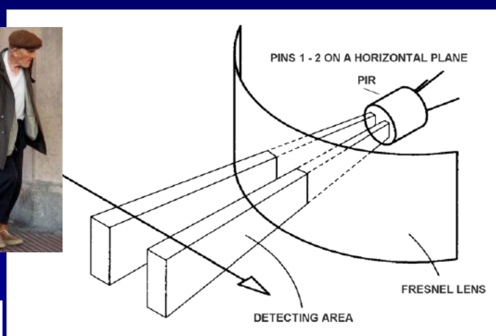
GOALS:

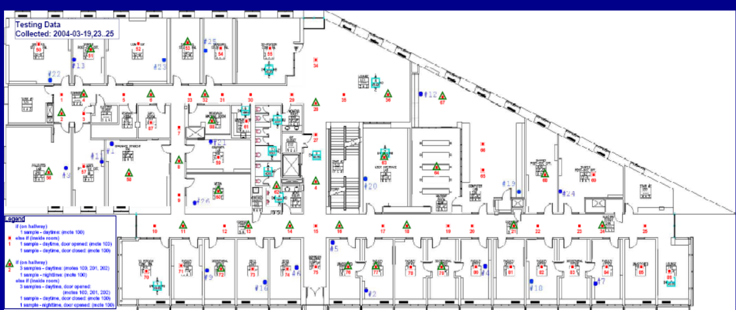
- Prevent presence of fungi and parasites
- Automate irrigation process

WSNs for localization and tracking

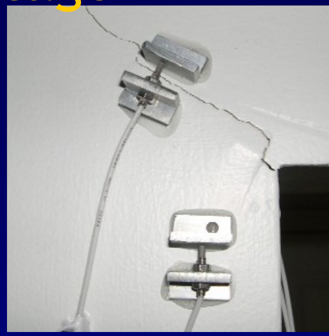
Accelerometers and pyro-electric (PIR) sensors used to detect position of humans (indoor)

- Monitoring movements in the house
- Detect patient falling down and send alarms





WSN for architectural heritage

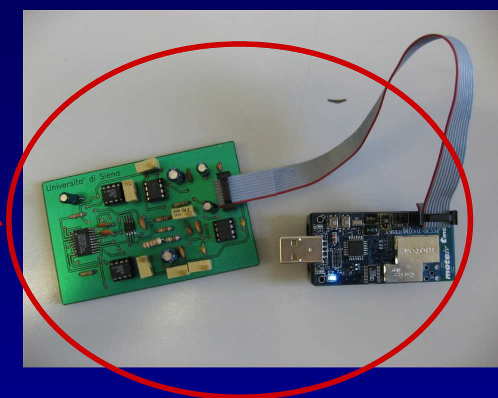


- Sensor fusion of humidity, temperature, vibration measurements
- Send alarm messages in case of danger

- Surveillance and touristic informations
- Report generation (e.g. while monitoring cracks)
- Data gathering to decide intervention priorities

WSNs for vehicle detection

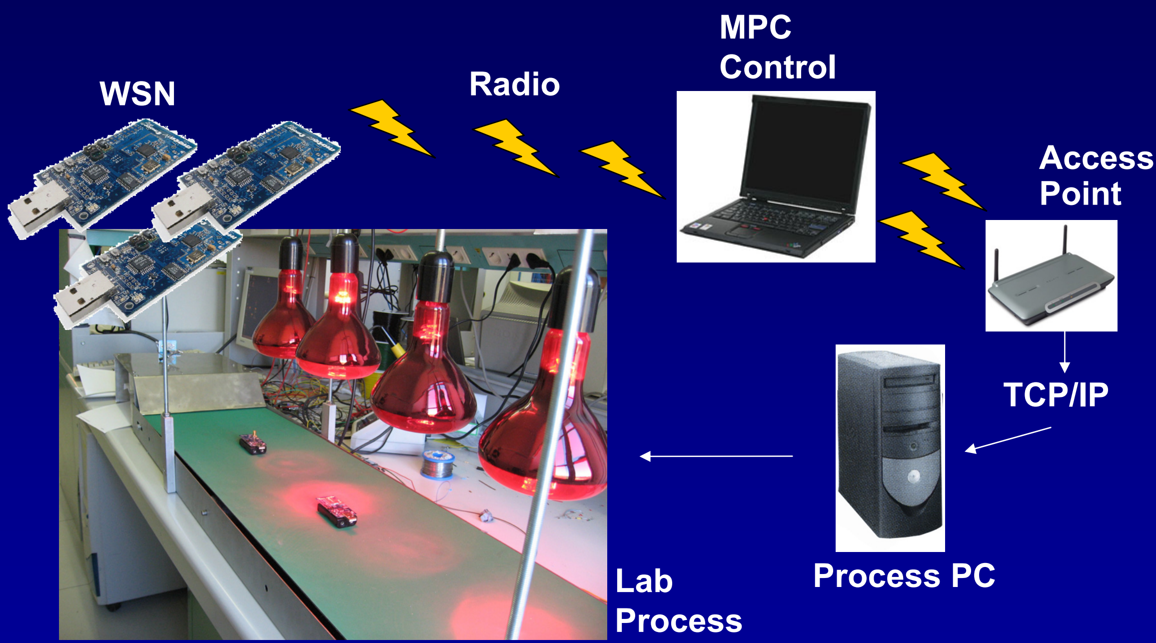
Telos + sensor board



- Magnetic field sampled at 64Hz
- Packets received in Matlab through Java interface
- Sensor board developed at the Automatic Control Lab (Siena) based on Honeywell magnetoresistive sensors

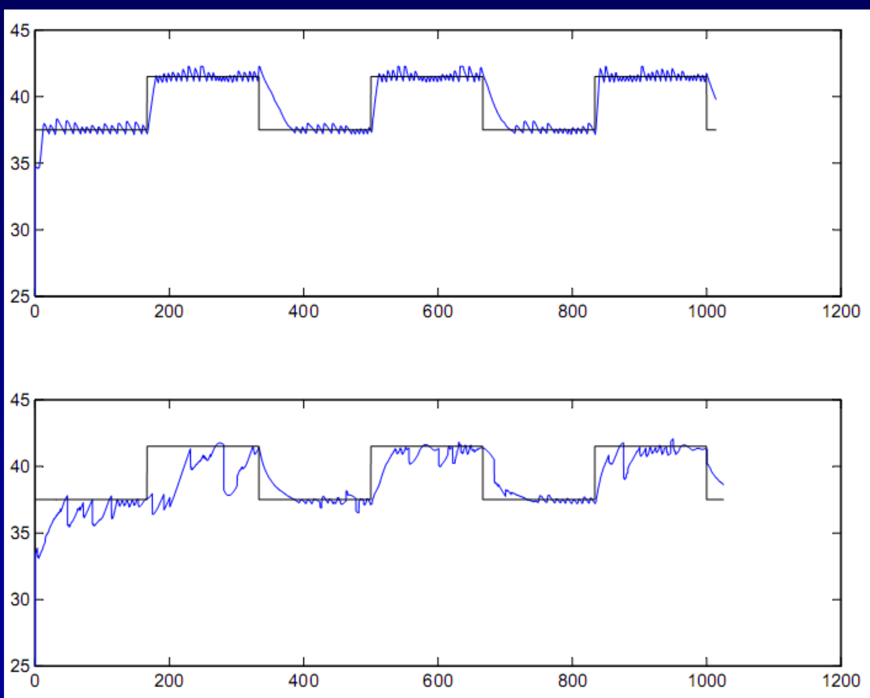
- Estimation algorithm provide vehicle detection and vehicle velocity

Wireless Automation Experiments



Robustness w.r.t. packet drop

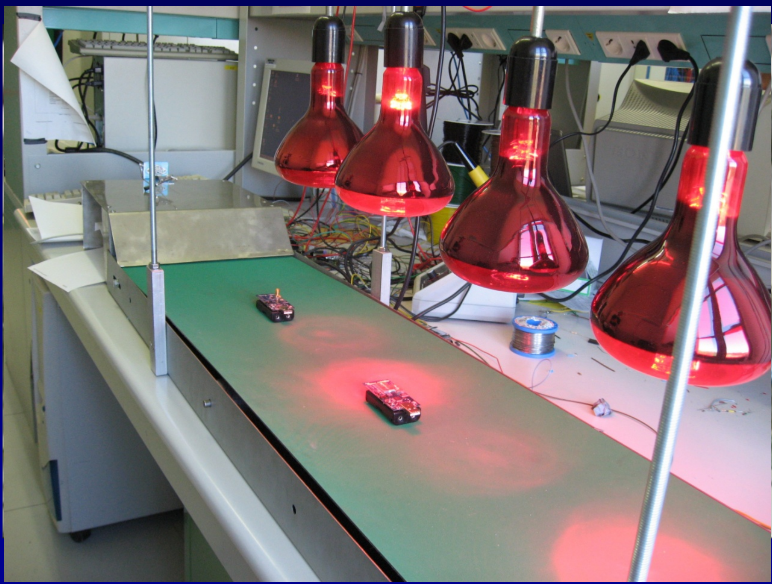
Experimental results:

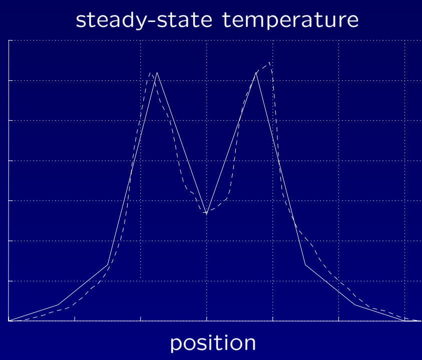


Reliable WSN
(3.7% max loss)

Unreliable WSN
(69.7% loss)

Demo Application in Wireless Automation





Hybrid MPC problem:

- 2 binary inputs (lamps)
- 1 continuous input (speed)
- PWL state function heating=f(position)
- Outputs: temp, position
- Sampling = 4Hz

Objective: track **position** and **temperature** references while enforcing safety constraints