Wireless Sensor and Actuator Networks for Measurement and Control
Phase II

TKK Department of Communications and Networking
TKK Control Engineering Group
KTH Radio Communication Systems Group
KTH Automatic Control Group
State of Art in Wireless Automation

ISA SP100 process classification

<table>
<thead>
<tr>
<th>Category</th>
<th>Class</th>
<th>Application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>0</td>
<td>Emergency action</td>
<td>(always critical)</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>Closed loop regulatory control</td>
<td>(often critical)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed loop supervisory control</td>
<td>(usually non-critical)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Open loop control</td>
<td>(human in the loop)</td>
</tr>
<tr>
<td>Monitoring</td>
<td>4</td>
<td>Alerting</td>
<td>Short-term operational consequence</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Logging and downloading/uploading</td>
<td>No immediate operational consequence</td>
</tr>
</tbody>
</table>

![Figure 2 - ISA SP100 Classification of Wireless Automation Applications](image)

Today, industry solutions start to appear for 5-3(2)
Pushing the performance envelope:

- **our focus is feedback control over wireless (class 1)**
### Major Barriers for Wireless Automation

#### User study

<table>
<thead>
<tr>
<th>Reason</th>
<th>% of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data security concerns</td>
<td>45.8%</td>
</tr>
<tr>
<td>Reliability concerns</td>
<td>43.0%</td>
</tr>
<tr>
<td>Too little knowledge</td>
<td>27.5%</td>
</tr>
<tr>
<td>Too few industrial products</td>
<td>19.7%</td>
</tr>
<tr>
<td>Too expensive</td>
<td>14.8%</td>
</tr>
<tr>
<td>Technologies may not be available in the future</td>
<td>13.4%</td>
</tr>
<tr>
<td>Data transmission too slow</td>
<td>12.0%</td>
</tr>
<tr>
<td>Communication distance too short</td>
<td>12.0%</td>
</tr>
<tr>
<td>Too few frequency channels</td>
<td>7.0%</td>
</tr>
<tr>
<td>Other reasons</td>
<td>9.2%</td>
</tr>
<tr>
<td>There are no barriers</td>
<td>16.9%</td>
</tr>
<tr>
<td>We have no requirement</td>
<td>24.6%</td>
</tr>
</tbody>
</table>

#### Challenges for the academia

- New control theory
- New control schemes
- New communication solutions
- New design and verification tools

Knowledge transfer between academy and industry

Nordite WISA Project

Requirements for current control algorithms

- Increase jitter margin and tolerance to errors
- PID Controller tuning
- New control algorithms

Performance of current wireless networks

- Increase robustness
- Degrease jitter

Quality of service

Data fusion

Coexistence protocols

Multi-path routing (mesh)

Synchronization

Wireless automation systems
WISA Phase I & II

WISA Phase I

Control, data fusion and networking algorithms, testbeds and simulation tools

WISA Phase II

Control and data fusion, Wireless networking, Design tools

Cross-layer design

Tool chain
Project organization

- Strategic framework (Shankar Sastry, University of California Berkeley, 2006).

WISA-II

Workpackages

WP1: Reliable and secure communication protocols for wireless automation

WP2: Communication constrained reliable control

WP3: Implementation of WiSA

WP4: Project management

Algorithms, Protocols, Theory, Tools, Schemes, Testbed
WP 1: Reliable and secure communication

• Security and reliability requirements often coincide
• Security aspects to be addressed in the project
  – Accessibility: Mitigating denial of service attacks and jamming
  – Data integrity: Handling out of sequence delivery of packets, timing
  – Data confidentiality on the link level
• Tasks
  – T1.1. Interference avoidance and dynamic spectrum management
  – T1.2. Reliable networking
  – T1.3. Sensor and network monitoring, fault detection, and fault recovery
WP 1/T1.1: Results

- Objective: wireless sensor nodes should be able to communicate in a reliable fashion despite bad channel conditions (interference, fading).
- We aim at improving reliability by means of:
  - Interference Avoidance through Dynamic Spectrum Access
  - Frequency Hopping
  - Channel Coding
WP 1/T1.1 : Results

- Dynamic Spectrum Access solutions for WSNs:
  - Energy Efficient Detection of Interference/Jamming (Es: WLAN interference in 2.4 GHz ISM band)
  - Algorithms for Multi-Channel Coordination in Frequency Agile Networks
  - Algorithms for Efficient Neighbor Discovery in Multi-Channel Networks

- Frequency Hopping:
  - Developed an adaptive algorithm for Interference Aware FH

- Channel Coding:
  - Coding solutions meeting energy and complexity constraints of Wireless Sensor Networks
WP 1/T1.1: Result

- An Example: Interference Detection in the 2.4 GHz ISM band.

Experimental Results (TMote Sky):
Probability of Detection vs Interference Level

Channels with high interference levels are unsuitable for sensor communications and must be avoided.

We developed a simple and energy efficient algorithm for interference detection.

Channels with low Interference Level are classified as Clear.

Channel with Dangerous Interference Levels are Identified and Avoided.
Sink initiated Routing Protocol (SIRP):

- Establishes Multiple Paths to the Destination
- Significantly reduced routing overhead compared to reactive routing protocol, thus saving valuable battery power.
- Tunable Refresh Rate for challenging wireless environment

Simulation Results for Factory Warehouse:
Nodes are static: Two Gateway and 30 sensors (Max hops 3)
Link breaks occur due to fading (channel: Shadowing Model)

<table>
<thead>
<tr>
<th></th>
<th>PDR (%)</th>
<th>Normalized routing overhead (%)</th>
<th>Average E2E .delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIRP</td>
<td>98,47</td>
<td>0,227</td>
<td>32</td>
</tr>
<tr>
<td>AODV</td>
<td>82,13</td>
<td>1,01</td>
<td>38,5</td>
</tr>
<tr>
<td>LMNR</td>
<td>87,29</td>
<td>2,16</td>
<td>35</td>
</tr>
</tbody>
</table>
WP 1/T1.2: Skeleton of the Network Monitoring, Configuration and Online Testing Management Solution

Node-view:

- RSSI
- HOPS
- MAC ID
- Sensors
- Temperature
- Illuminance
WP2: Communication constrained reliable control

• Wireless communications is unreliable. Hence, there is need for data fusion and control methods that are robust against jitter and occasional faults.
• Control schemes should be simple enough to be accepted by the practitioners (PID control and MPC)
• Tasks
  – T2.1. Communication-aware data fusion and control
  – T2.2. Control structures, architectures and scalability
  – T2.3. Adaptive and robust control
WP 2: Results

- Objective: the controller parameters could be easily set based on the application requirements, such as the network maximum delay or packet loss probability
  - The controller would adapt to the requirements set by the network
  - Ultimately: adaptive, distributed, self-* control schemes
WP 2: Results

• Tuning *methods* and *rules-of-thumb* for the widely applied control algorithm, the PID controller, have been developed for wireless networked control systems, aiming at:
  – Performance optimization
  – Robustness to delays, delay variations, and packet loss
  – Robustness in the traditional sense, to noise and disturbances

• The methods have been developed in close cooperation between TKK and KTH
An example: Extended plant approach

- One of the proposed PID tuning methods for NCS

\[ G(s) \] → \[ G_f(s) = \frac{1}{(1+sT_f)^n} \] → Extended plant response

Filter design
\[ 0 \leq \delta(t) \leq \delta_{\text{max}} \] → \[ T_f = f(\delta_{\text{max}}, n) \]

AMIGO design on extended plant, tuning rules

- Measurement filter design based on the network delays

\[
T_f = \begin{cases} 
\frac{1}{3} \delta_{\text{max}}, & n = 1 \\
\frac{1}{3\sqrt{n}} \left( \frac{n}{n-1} \right)^{(1-n)/2} \delta_{\text{max}}, & n > 1.
\end{cases}
\]
Some simulation results

- Improved delay tolerance and comparable performance with respect to the state-of-the-art PID tuning rules (AMIGO tuning)

\[ G_{\text{exp,2'}} \quad \text{ITAE: AMIGO: } \infty, \text{ Jitter-aware: } 2.76, n = 1: 1.62, n = 2: 1.50, n = 3: 1.64 \]
WP 2: Results Novel algorithms for distributed MPC

Classical (wired, centralized) MPC

\[
\begin{align*}
\text{minimize} & \quad \sum_t x_t^T Q x_t + u_t^T R u_t \\
\text{subject to} & \quad x_{t+1} = A x_t + B u_t \\
& \quad x_t \in X, \quad u_t \in U
\end{align*}
\]

Optimal control via optimization.
- Powerful but demanding

Decentralized wireless MPC

Decentralized MPC:
- Many small controllers take “local responsibilities” (optimize subset of control actions, accounting for subset of states)

Issues:
- Coordination under uncertainty
WP 2: Results Novel algorithms for distributed MPC

A prototypical problem

\[ f_1(u_1, \theta) \quad f_2(u_2, \theta) \quad f_3(u_3, \theta) \]

\[
\text{minimize} \quad \sum_{v \in V} f_v(u_v, \theta) \\
\text{subject to} \quad u_v \in U_v, \ \theta \in \Theta
\]

Each controller has individual objective (cost of operating local loop), local and global variables (to be coordinated to minimize "total cost")

Contributions:
- Application to robot coordination
- Novel optimization algorithms
  - Incremental subgradients
  - Consensus and subgradients
- Evaluation in WSN testbed
WP 3: WISA Toolchain

• A co-simulation platform for (wireless) networked control systems
  – Enabling automatic implementation of the algorithms on real hardware
  – Based on the PiccSIM platform developed in WISA project

• Based on the integration of two most common design tools
  – NS2 for Network Simulation
  – Matlab/Simulink/XPC Target for control design, system dynamics simulation and algorithm implementation
WP 3: PiccSIM platform

PiccSIM Architecture

Local User Interface
PiccSIM Toolchain

Simulink or xPC Target
Controller
Sensors
I/O Board
Process

Simulation

Hardware in the loop
Configuration and management

Server, DB

Internet

Remote User Interface
MoCoNet GUI

Ns-2 Network Simulator
WP 3: Results

- **WiSA Toolchain**
  - Hardware-in-the-loop simulation (Sensinode nodes)
  - Automatic code generation, and code reusability
  - Graphical user interfaces for network design
  - Data-based modeling tools, controller design and tuning

- **Modeling, design, simulation and implementation of wireless networked control systems, all in ONE tool**
WP 3: Results

- Network design
  - Number of nodes
  - Node positions
  - Networking and communications protocols
  - TCL script generation for Ns-2

- Radio environment modeling from the blueprint of an office
WP 3: Automatic code generation

Algorithm implementation
- A/D and D/A settings (sensors and actuators)
- Radio: send and receive
- Triggering (time)
- Definitions of the data types in packets
Implementation

Code generation

Compilable code for Sensinodes
WP 3: A complete demo

- Demonstration of the toolchain during lunch and coffee!
Project management

• Steering group
  – Swedish partners
    • VINNOVA
    • Åkerströms, Jan Forsgren (jan.forsgren@akerstroms.se)
    • ABB, Tiberiu Seceleanu (tiberiu.seceleanu@se.abb.com)
    • connectBlue, Mats Andersson (mats.andersson@connectblue.se)
  – Finnish partners
    • TEKES
    • Honeywell, Keijo Manninen* (keijo.manninen@honeywell.com)
    • Konecranes Oyj, Timo Sorsa (timo.sorsa@konecranes.com)

• Interest group
  – Most relevant industry stake holders will be invited to the project interest group which is to serve as a tool for information dissemination between the academy and industry
Collaboration between research groups

- WiSA workshop on Standards and research challenges for industrial wireless control, KTH, March 2008
- Researcher visits: Lasse Eriksson @ KTH, 5/2006 and 6/2007
- Joint publications:
  - Several joint publications between the groups at TKK
Collaboration with industry

• Delay estimation and Kalman filtering for an asynchronic measurement case study provided by Konecranes

• Preliminary discussions on wireless monitoring of a bridge crane system with wireless sensor networks (Konecranes)

• Active participation of the industry in the steering board meetings (e.g. simulation testbed demo attracted Åkerströms to travel to Helsinki)

• Joint workshop on ”Standards and research challenges for industrial wireless control” with industrial partners in Stockholm, Sweden 4th of March 2008
Publications (2008)

- **Thesis**

- **Journal paper**

- **Conference paper**
Publications (2008)

- Mikael Johansson, On the source-channel coding trade-off in networked control, IFAC World Congress, Seoul, South Korea, July 2008.
- Maben Rabi, Luca Stabellini, Peter Almström and Mikael Johansson, Analysis of networked estimation under contention-based medium access, IFAC World Congress, Seoul, South Korea, July 2008.
Maben Rabi, Luca Stabellini, Peter Almström and Mikael Johansson, Analysis of networked estimation under contention-based medium access, IFAC World Congress, Seoul, South Korea, July 2008.

Other

Information dissemination

Seminar presentations and invited talks:

• DoD/TEKES workshop in Washington 11 - 12 March 2008

• Rutgers/HiIT Workshop on Spontaneous Networks in Rutgers 5-9 May, 2008

• Third International Summer School on Applications of WSN and Wireless Sensing in the Future Internet (SenZations) in Slovenia 1 - 5 September 2008

• 8th Scandinavian Workshop on Wireless Adhoc Networks (Adhoc’08) May 7-8, 2008 Johannesberg Estate

• Sensinode research seminar, Vuokatti, Finland, 16th of September