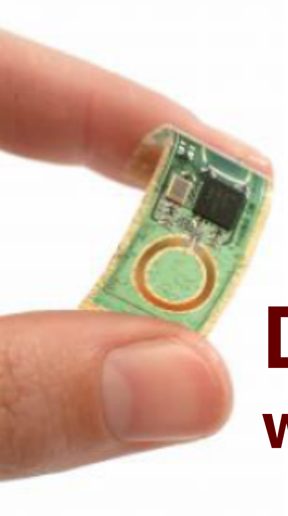

Distributed Control-as-a-Service
with Wireless Swarm Systems

Prof. Rahul Mangharam
Director, Real-Time & Embedded Systems Lab
Dept. Electrical & Systems Engineering
Dept. Computer & Information Science
University of Pennsylvania
rahulm@seas.upenn.edu

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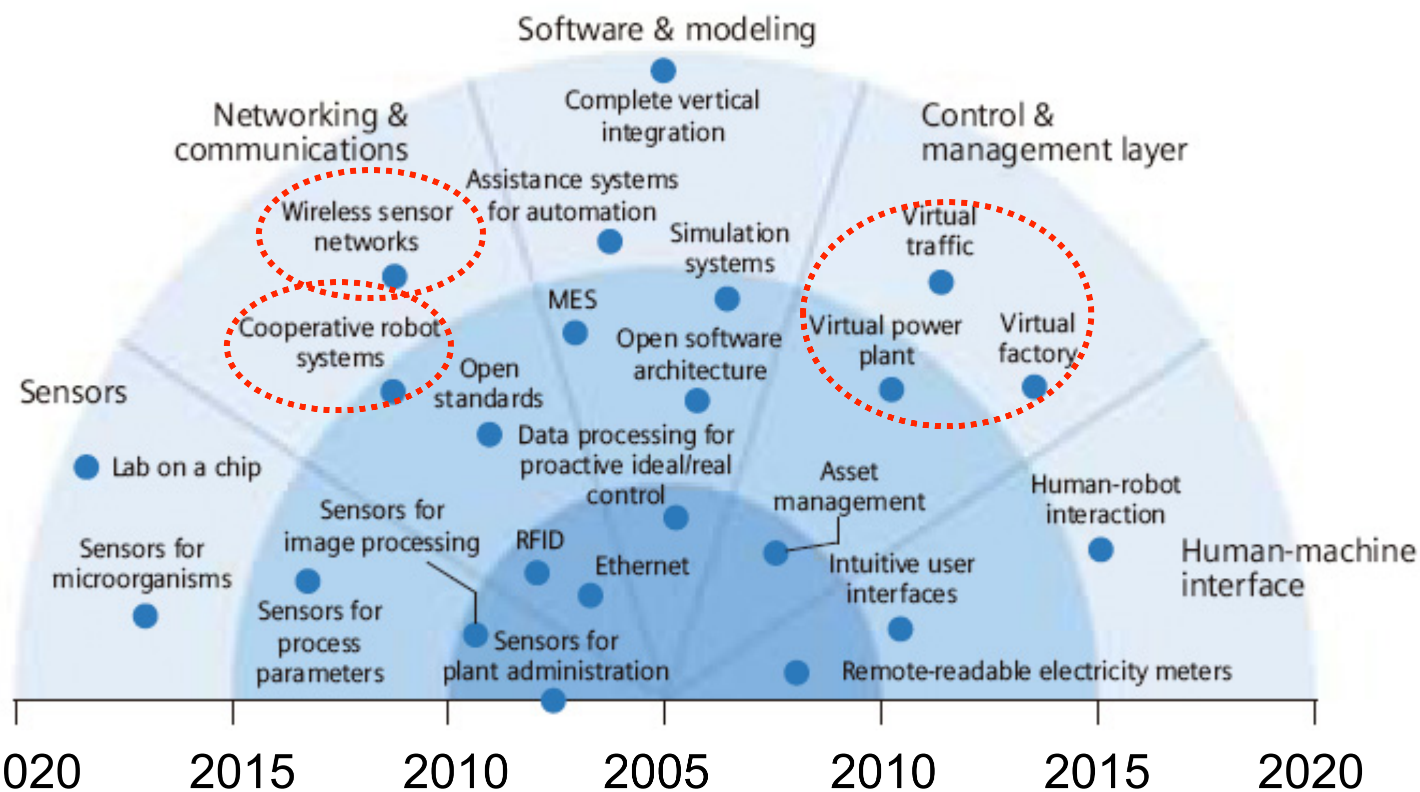
Discrete and Process Wireless Control



Wireless Control/Actuation ← Wireless Monitoring **→ Wireless Control/Actuation**

Roadmap from Siemens

Our Focus: Industrial Control Systems

Natural gas processing plants

Oil-refineries

Paper pulp manufacturing

$120 Billion/Year market

PLC Architectures and Software are from the mid-1980s to early-1990

Software Issues with Industrial Automation

- **Automotive assembly lines lose over $22,000/minute downtime**
- **Systems are rigid, difficult to maintain, operate and diagnose**

Goal: Plug-n-Play Wireless Automation Control Systems

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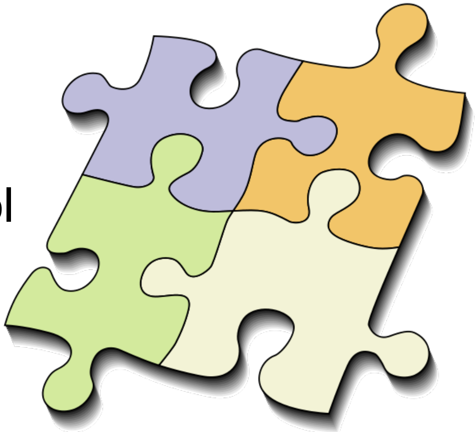
Advantages of wireless control system architectures

1) Plug-n-Play capabilities:

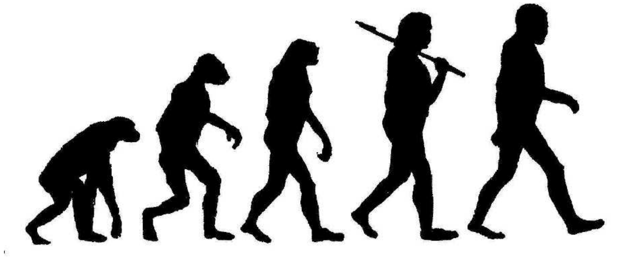
Minimizes downtime with efficient recovery from controller faults as re-connecting the logical I/O lines of a wireless backup controllers is seamless.

2) Compositionality:



Enables system evolution through logical expansion/ contraction of plants and controllers with composable control systems. Suitable for emerging markets.

3) Runtime adaptation:



Control stability and performance are maintained in the presence of node, link and topological changes.

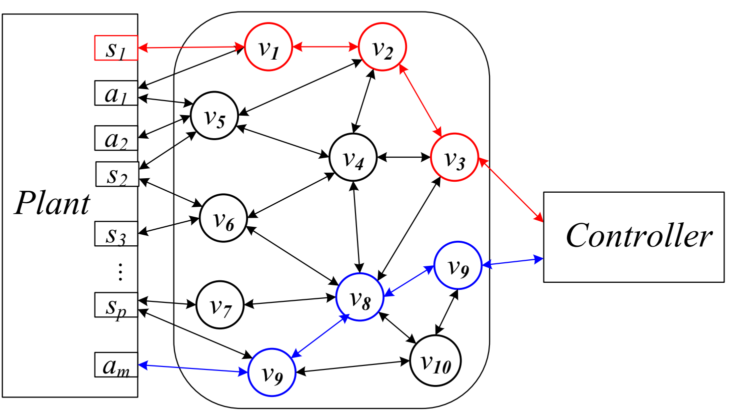
Two Disruptive Approaches for Wireless Control

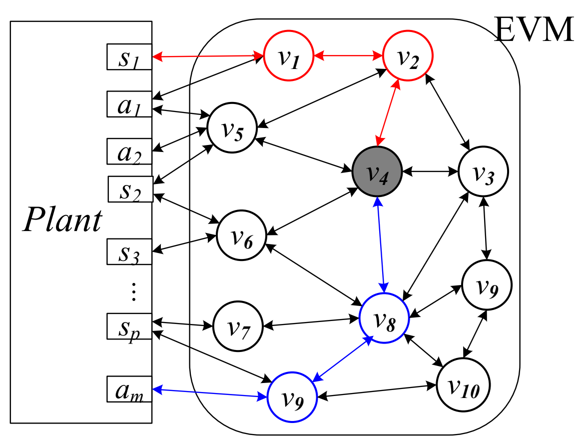
A Embedded Virtual Machines

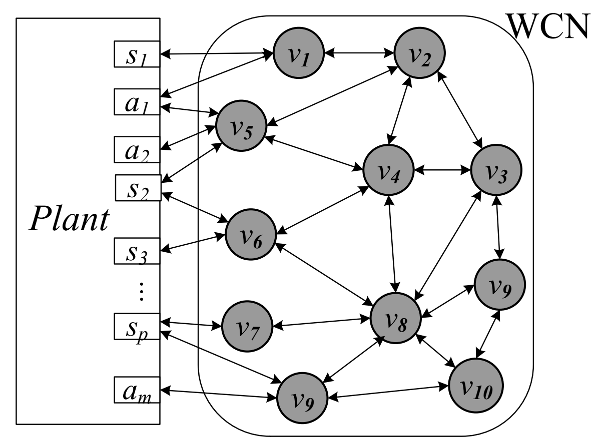
- Runtime abstraction of wireless control
- Controller tasks migrate across physical nodes
- Robust to topological changes

B Wireless Control Network

- Fully distributed in-network approach
- Low computational overhead and simple, static scheduling
- Enables plant & controller composition







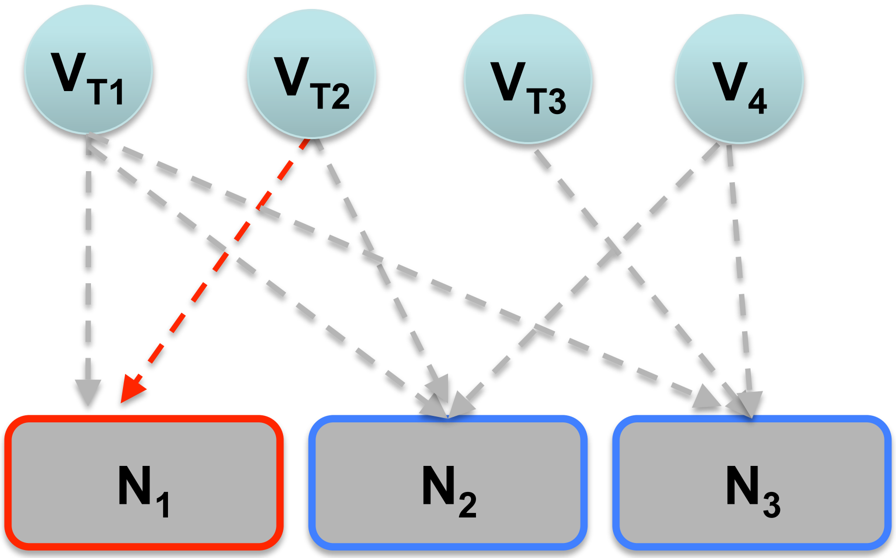
Published in: IEEE WCPS 2009, RTAS'10, CDC_1'10, CDC_2'10, ACM TECS'11, IEEE TAC'11, CDC'11, ACC'11, CDC'12, IPSN'12, JSAC'12, IISc'13…

Embedded Virtual Machines

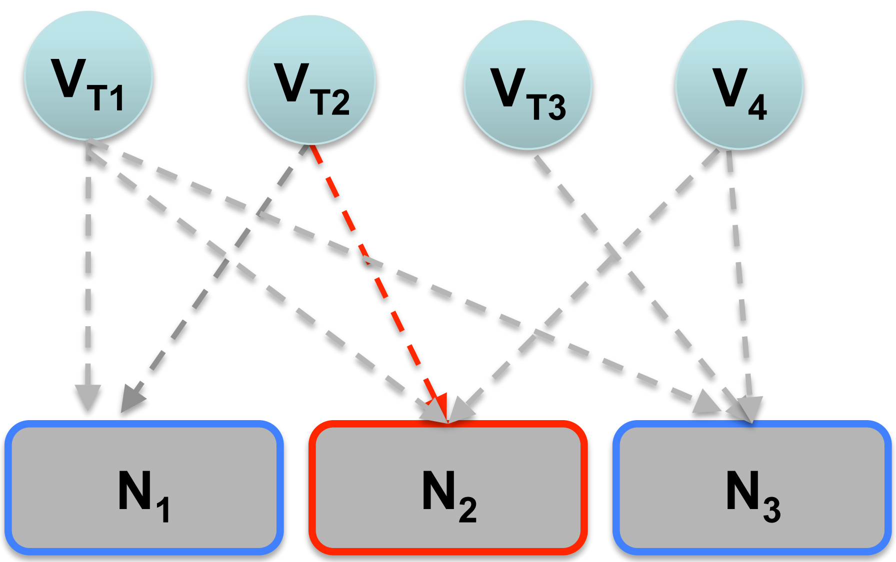
For Robust Wireless Control

The Core Idea

Virtual Task to Physical Resource Mapping



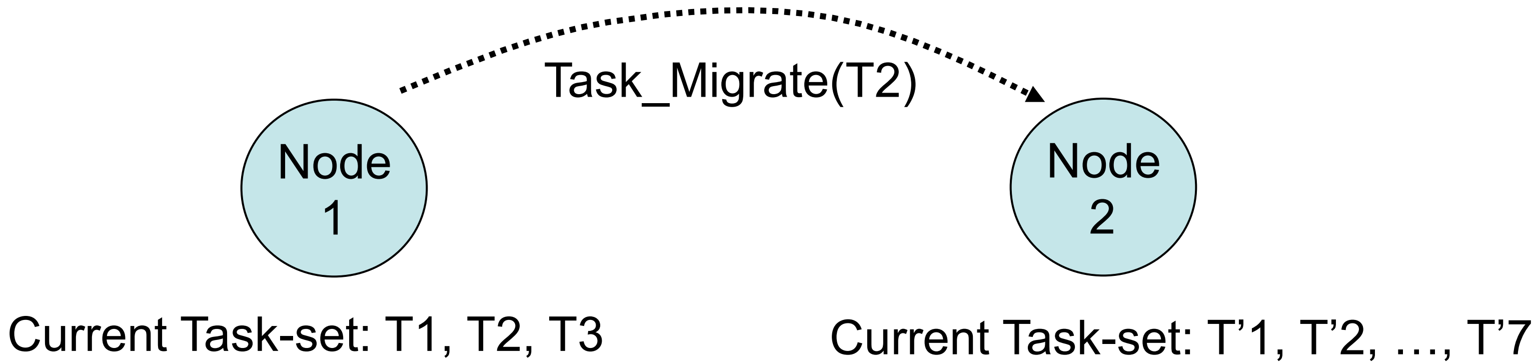
V1	1	N1	active	1s	100ms
V1	1	N3	backup	1s	50ms
V1	1	N2	dormant	1s	100ms
V2	0	N2	active	0.5s	50ms
V2	1	N1	backup	0.5s	50ms
V3	1	N3	active	0.5s	200ms
V4	1	N2	active	0.25s	200ms
V4	1	N3	backup	0.25s	100ms



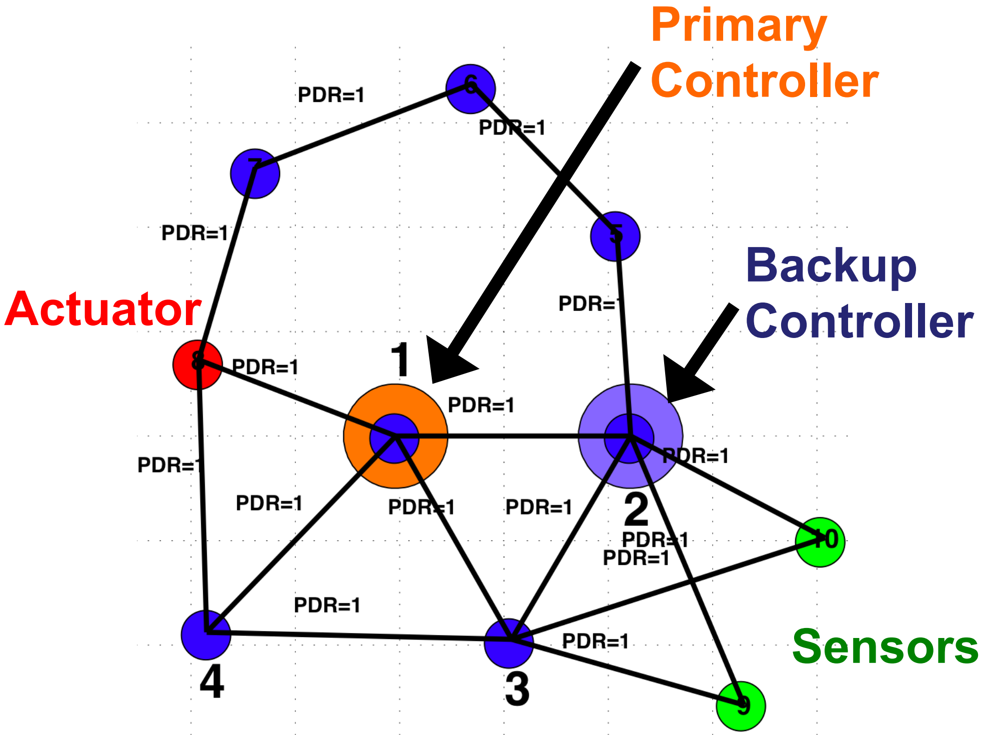
V1	1	N1	active	1s	100ms
V1	1	N3	backup	1s	50ms
V1	1	N2	dormant	1s	100ms
V2	1	N1	active	0.5s	50ms
V3	1	N3	active	0.5s	200ms
V4	1	N2	active	0.25s	200ms
V4	1	N3	backup	0.25s	100ms

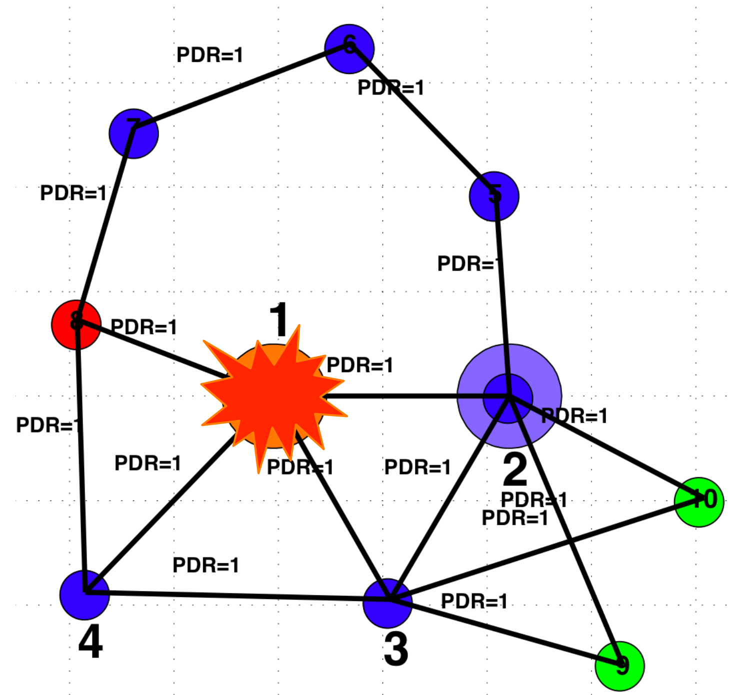
Runtime Task Management

- Task Migrate
  - Task instructions
  - Stack
  - Data
  - Associate libraries
  - Control/Schedule/Resource meta data



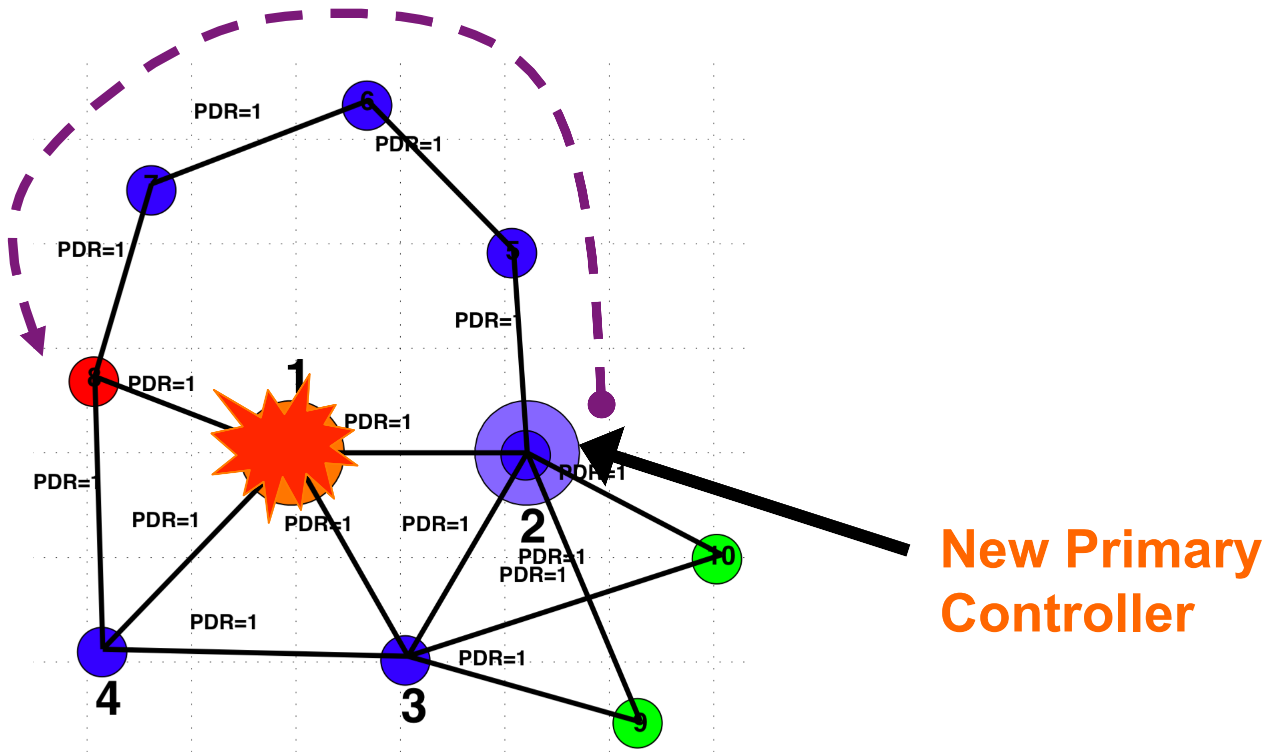
Example: When Routing Fails → Migrate





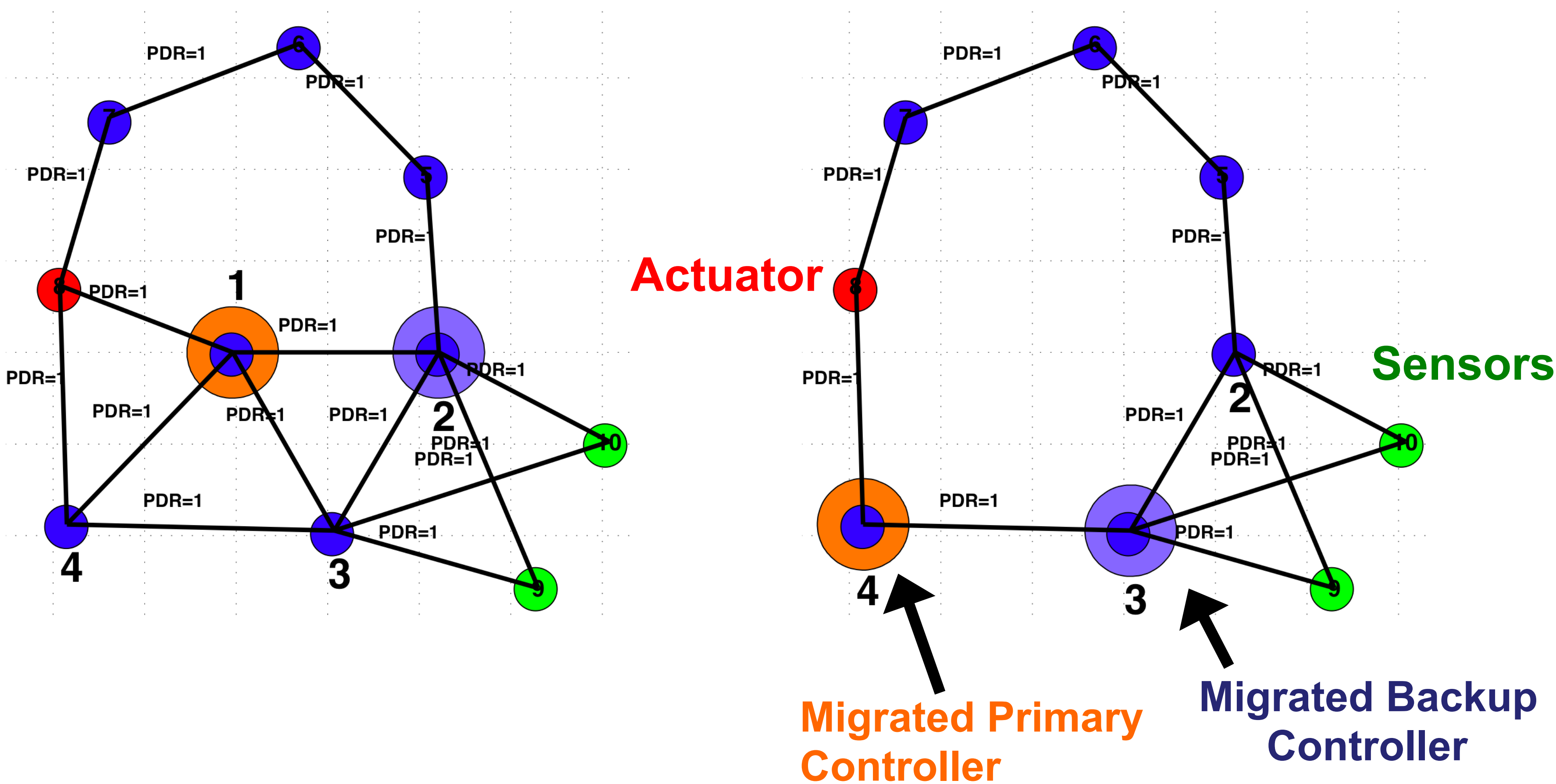
Example: When Routing Fails → Migrate

What if we just used the backup and re-routed the control path?



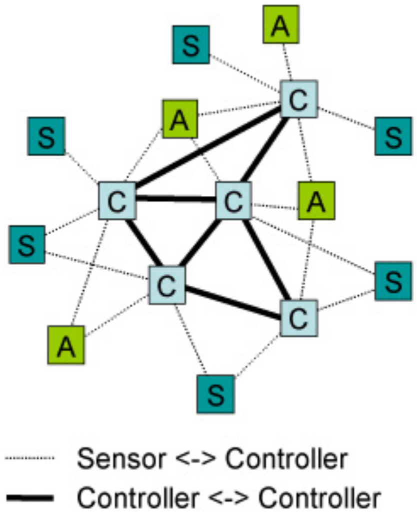
Routing from Backup Controller to Actuator fails to meet Stability Constraint

Example: When Routing Fails → Migrate



Embedded Virtual Machines

- **Distributed runtime system** that dynamically selects primary-backup sets of controllers to guarantee QoS given spatial and temporal constraints of the underlying wireless network.



(a)

- **Algorithms** to program virtual components and ***maintain functional and para-functional invariants*** across the system.

Focus on controller reliability and fault tolerance

The Goal

- **Maintain Functional Invariant**
  - Control Law

Control Stability

- **Maintain Para-Functional Invariants**
  - Timeliness, reliability, fault-tolerance
- **Predictable outcomes** in presence of controller / link failures
  - For planned changes
- **Graceful degradation without violating safety**
  - For unplanned changes

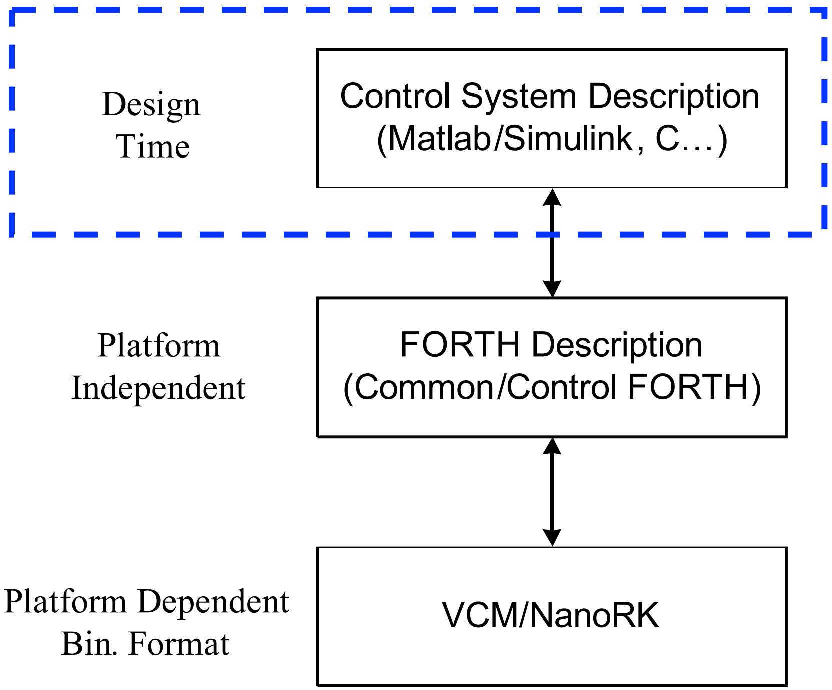
Reliability

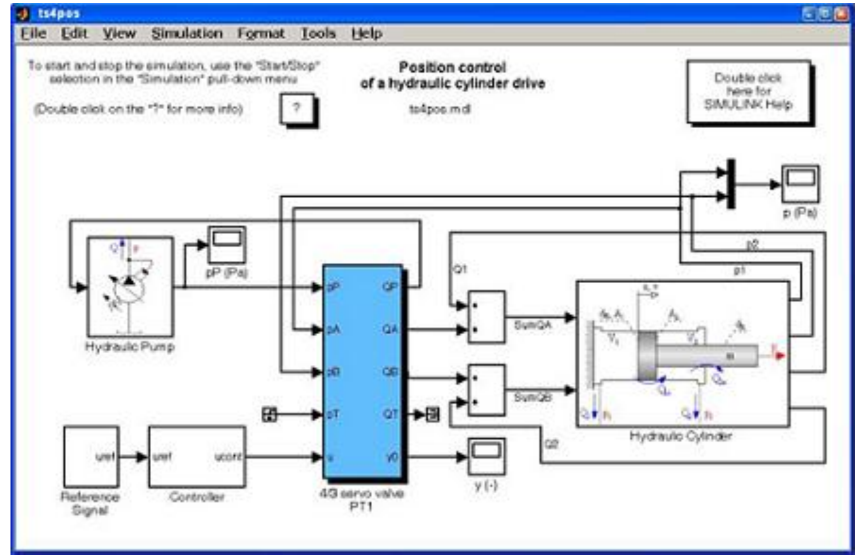
- **Composability: for multiple plants at runtime**
  - Increase functionality or respond failure

Composition

- **Adaptive Runtime Resource Re-appropriation**
  - Optimization for Dynamic changes in service/throughput

EVM Design Flow
Design Time with Simulink





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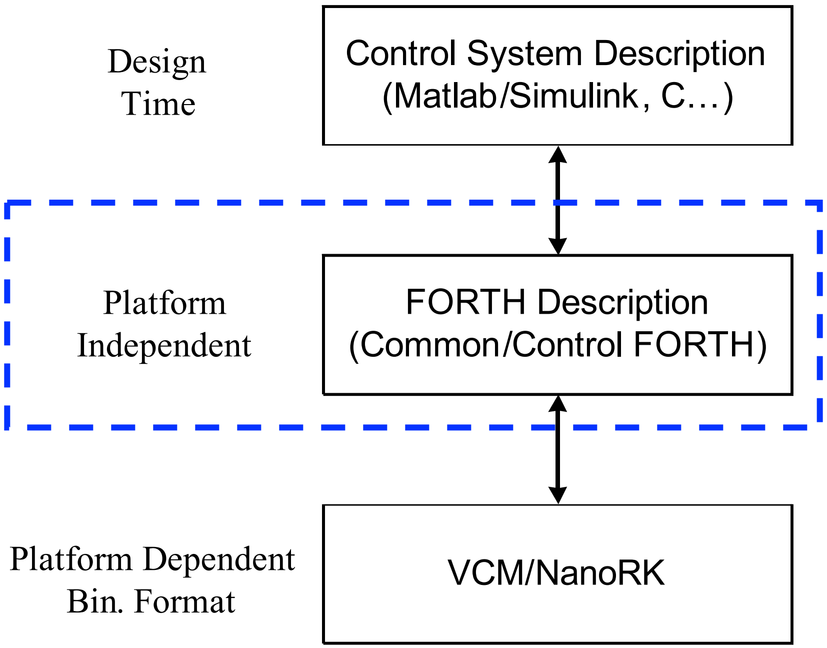
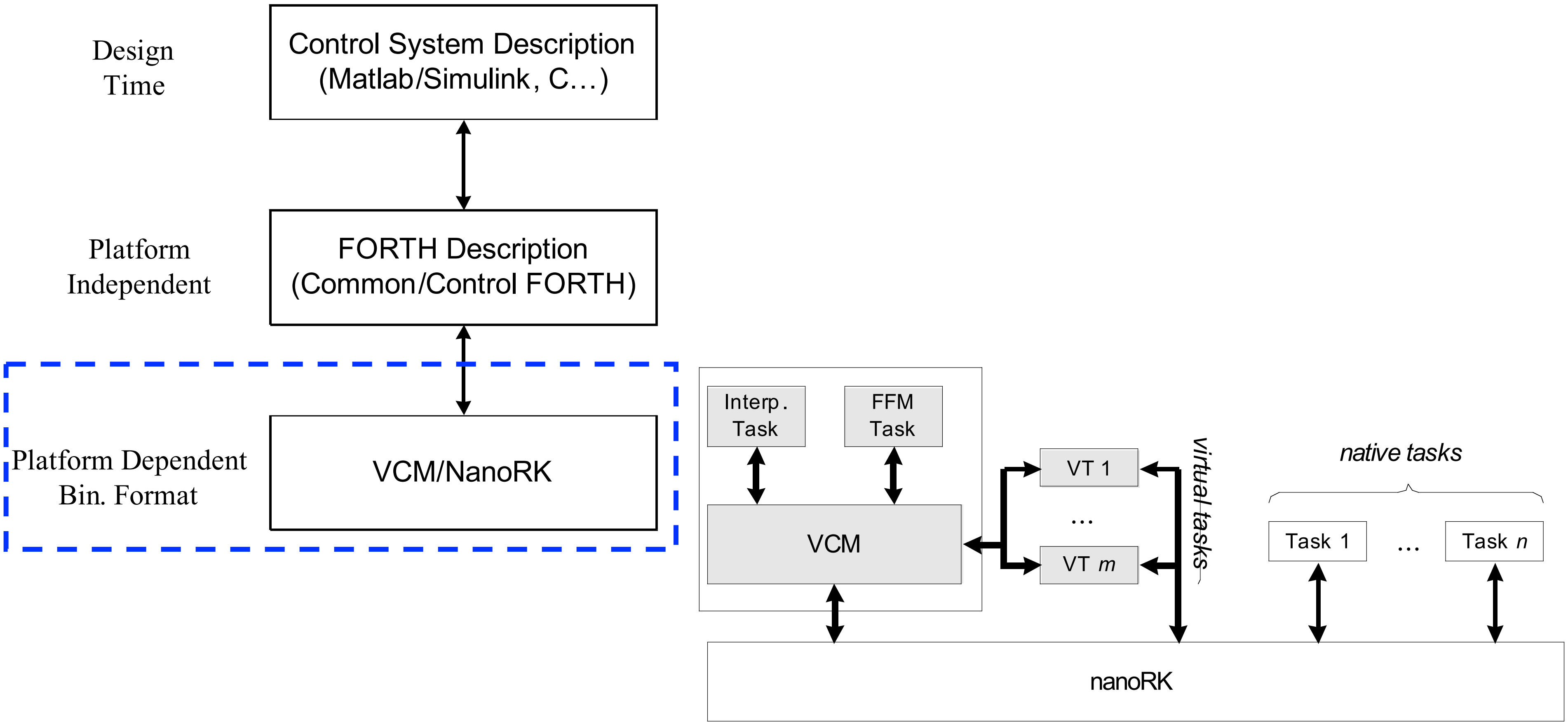
EVM Design Flow
Domain Specific Language Interpreter



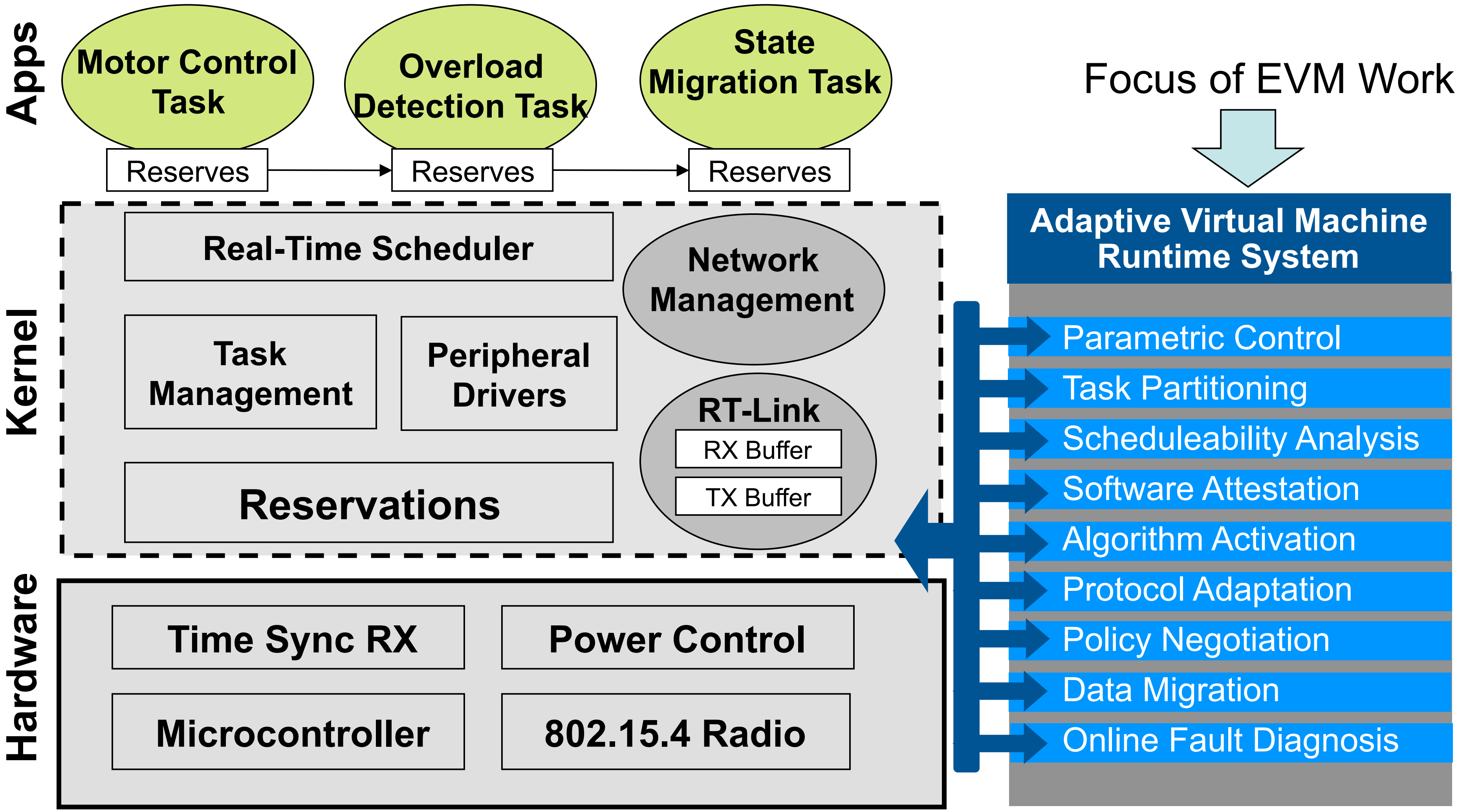

```
 01 CONSTANT  PORT                                        \ Port assignments
/bit-mask      name    bit-mask            name
1 CONSTANT MOTOR            8 CONSTANT    FAUCET
2 CONSTANT CLUTCH           16 CONSTANT   DETERGENT
4 CONSTANT PUMP    32 CONSTANT   LEVEL
                                                          \ Device control
: ON ( mask -- ) PORT C@ OR PORT C! ;
: OFF ( mask -- ) INVERT PORT C@ AND PORT C! ;
                                                          \ Timing functions
: SECONDS ( n -- ) 0 ?DO 1000 MS LOOP ;
: MINUTES ( n -- ) 60 * SECONDS ;
: TILL-FULL ( -- ) BEGIN PORT C@ LEVEL AND UNTIL ; \ Wait till level switch is on
                                                          \ Washing machine
: ADD ( mask -- ) DUP ON 10 SECONDS OFF ;
: DRAIN ( -- ) PUMP ON 3 MINUTES ;
: AGITATE ( -- ) MOTOR ON 10 MINUTES MOTOR OFF ;
: SPIN ( -- ) CLUTCH ON MOTOR ON 5 MINUTES MOTOR OFF CLUTCH OFF
        PUMP OFF ;
: FILL-TUB ( -- ) FAUCET ON TILL-FULL FAUCET OFF ;
                                                          \ Wash cycles
: WASH ( -- ) FILL-TUB DETERGENT ADD AGITATE DRAIN ;
: RINSE ( -- ) FILL-TUB AGITATE DRAIN ;

: WASHER ( -- ) WASH SPIN RINSE SPIN ;                    \ Top-level control
```

EVM Design Flow
Platform Dependent Binary



Embedded Virtual Machine
Architecture



Runtime Parametric and Programmatic Control

Wireless Control Network

A Simple Distributed Method for Control over Wireless Networks

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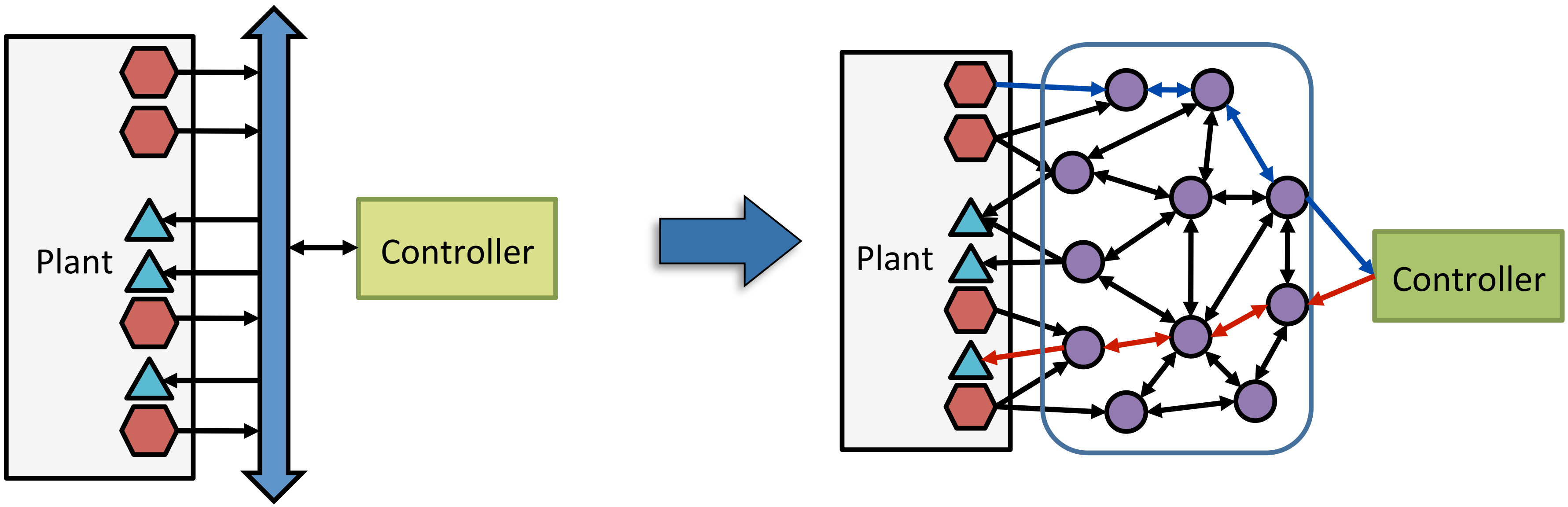
Goal: Use multi-hop wireless networks for closed-loop control
Move from open-loop monitoring to distributed control!

For the past 40 years control architectures have been based on wired networks

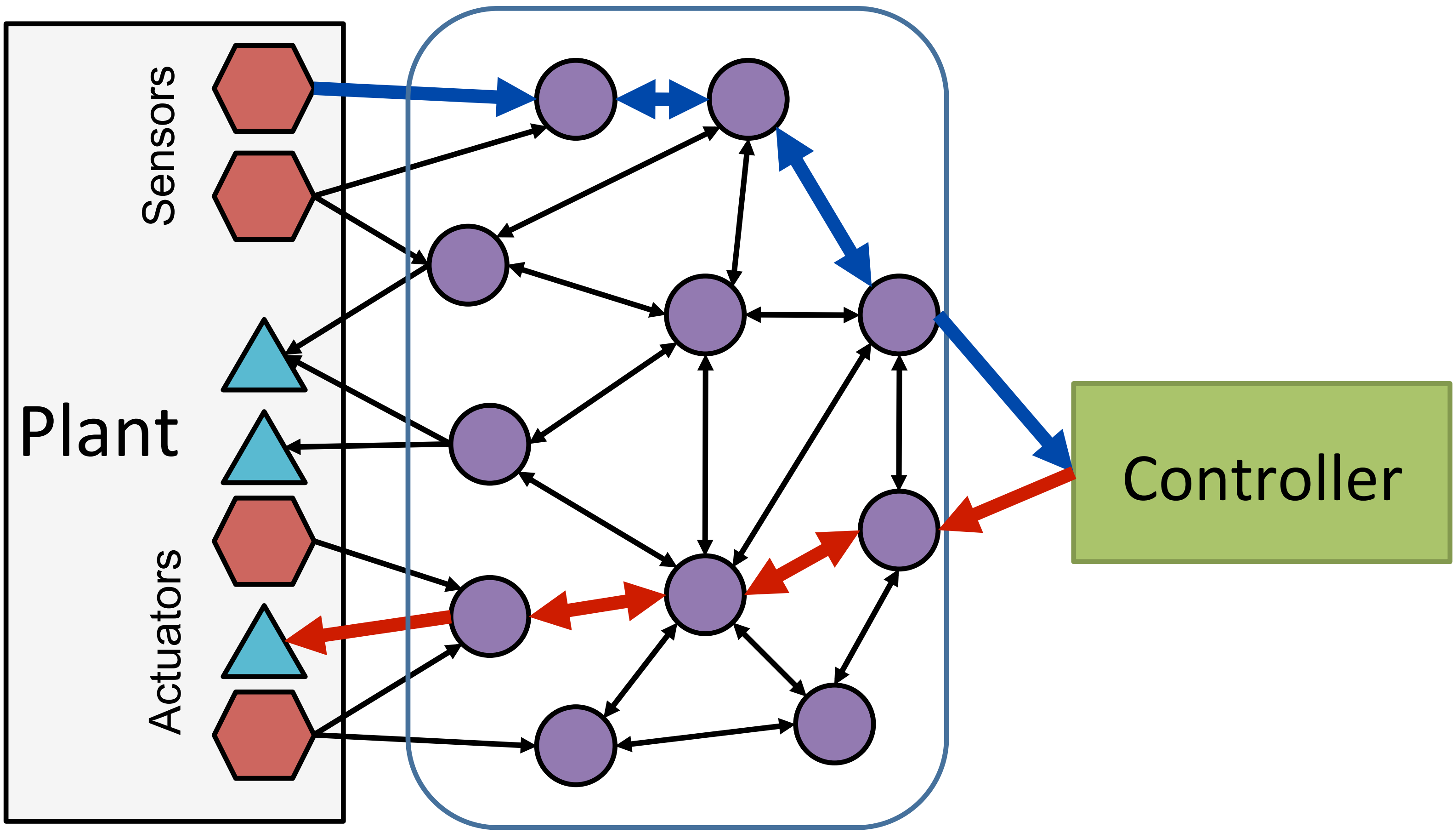
- Sensors ( ) and Actuators ( ) are installed on a plant
- Communicate with controller ( ) over a wired network



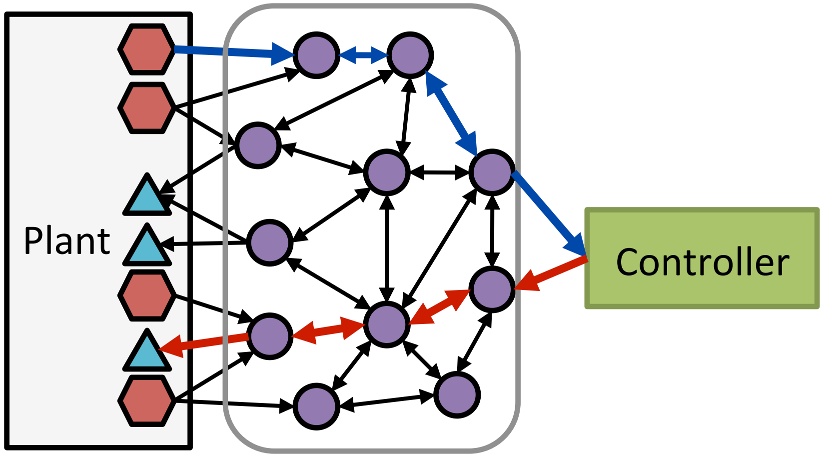
Wired Control System

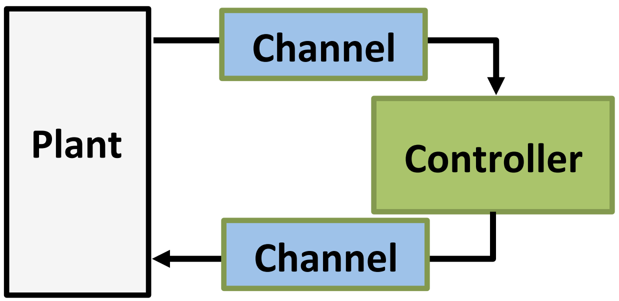
Wireless Control System

Route assignment is static



Control System's view of the Network



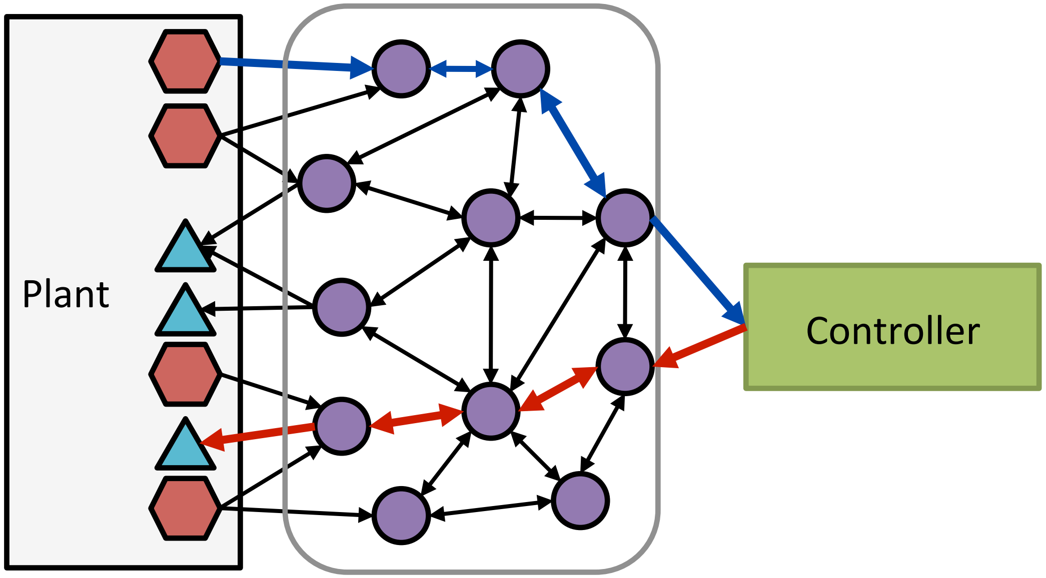


Abstracts away system design to an ideal network

Route assignment is static

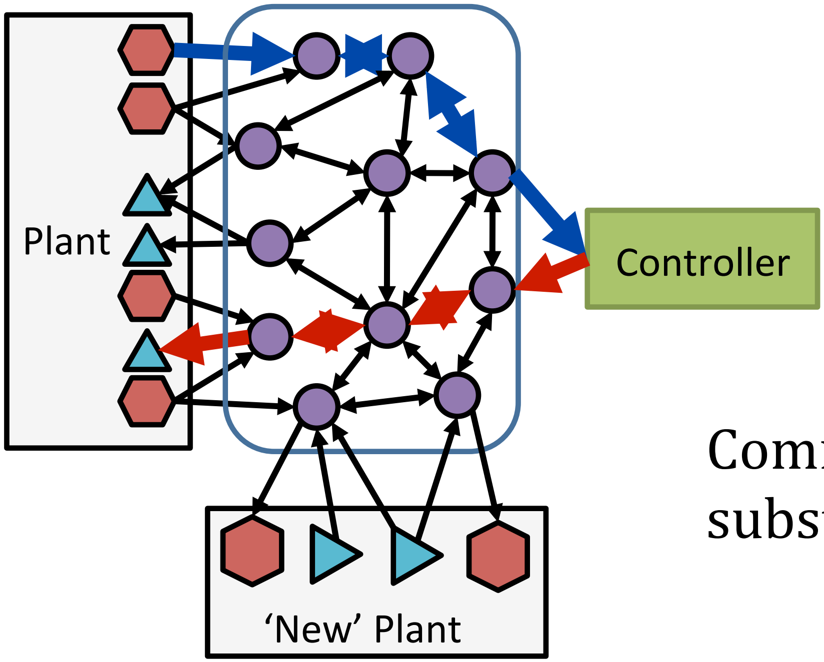
- Control problems impose strict delay requirements

Why we need Distributed Control ?



- Problem I: Changes involve global reorganization
  - Requires significant software support (e.g., EVM, Etherware)

Networks for industrial automation systems are usually shared among several control loops!



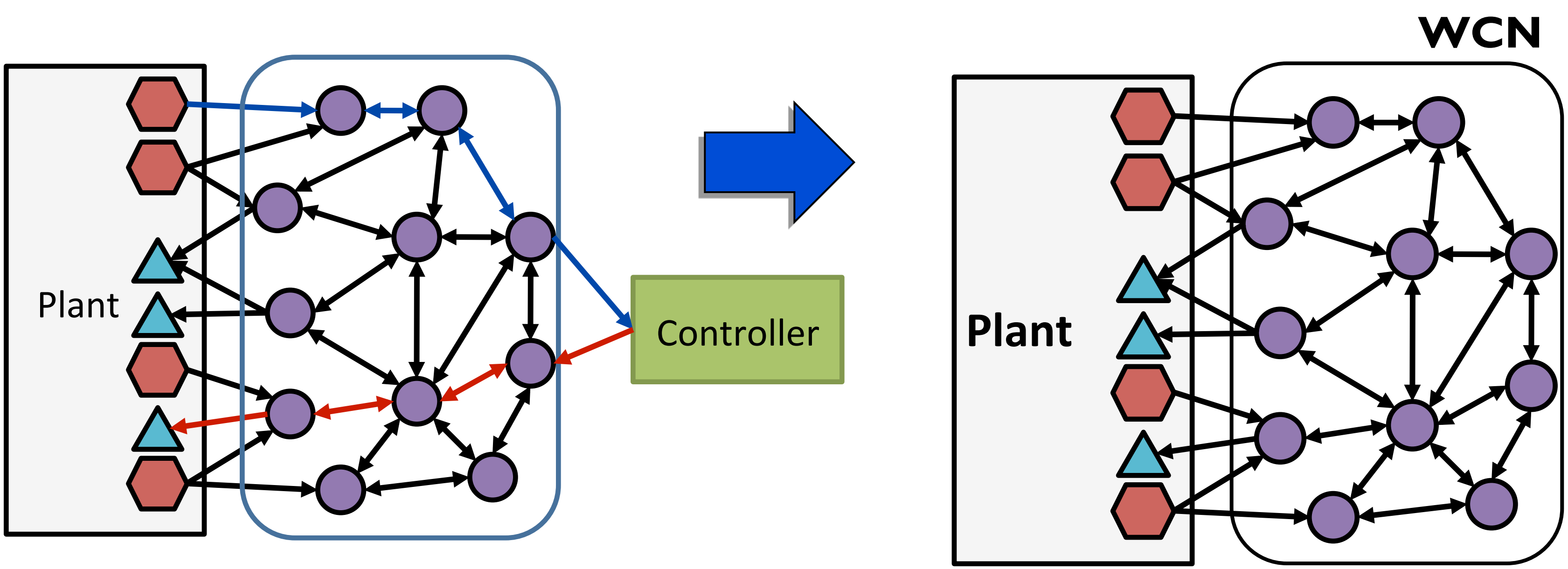
Communication substrate is shared!

- **Problem II**: New feedback loops might affect the existing loops
  - requires full schedule recalculation (problem at runtime)

It is necessary to provide a composable control scheme!

Multi-hop Control Networks: Architectures

- Sensors ( ) and Actuators ( ) are installed on a *plant*
- Communicate with controllers ( ) over a wireless network



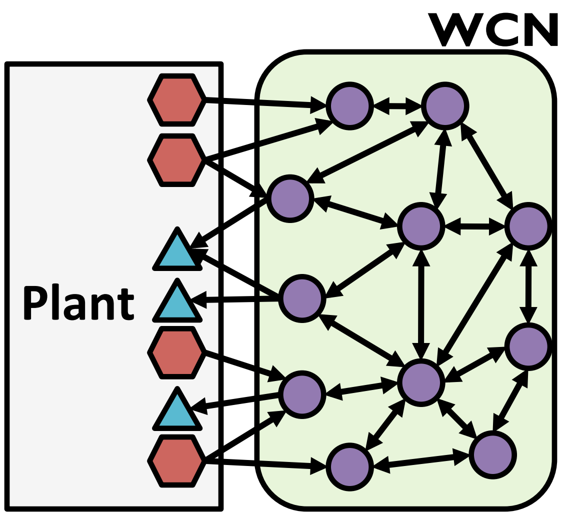
Out-of-network computation

Distributed In-network computation

Outline: Control-as-a-Service

A simple distributed method for control over wireless networks

1. Wireless Control Networks (WCNs)
2. Modeling
3. Synthesis of Optimal WCNs
4. Robustness
5. Case Study



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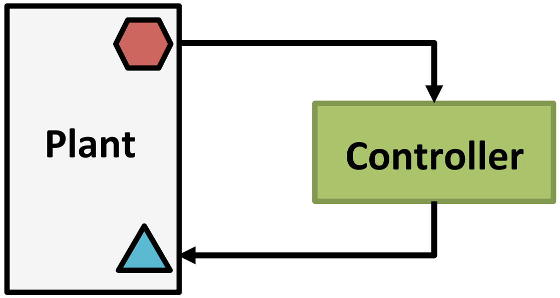
Standard Feedback Control Schemes

Linear-Time Invariant model of the plant:

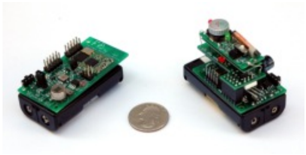
$$\mathbf{x}[k+1] = \mathbf{A}\mathbf{x}[k] + \mathbf{B}\mathbf{u}[k] + \mathbf{B_w}\mathbf{u}_w[k]$$
$$\mathbf{y}[k] = \mathbf{C}\mathbf{x}[k],$$



Linear dynamic feedback controllers:

$$\mathbf{x_c}[k+1] = \mathbf{A_c}\mathbf{x}_c[k] + \mathbf{B_c}\mathbf{y}[k]$$
$$\mathbf{u}[k] = \mathbf{C_c}\mathbf{x}_c[k] + \mathbf{D_c}\mathbf{y}[k]$$

- **Goal**: Leverage the computational capability *in the network*
- Each node acts as a **local** linear dynamical controller
  - Resource constrained nodes → Small states
  - States of the nodes' neighbors are considered as inputs!



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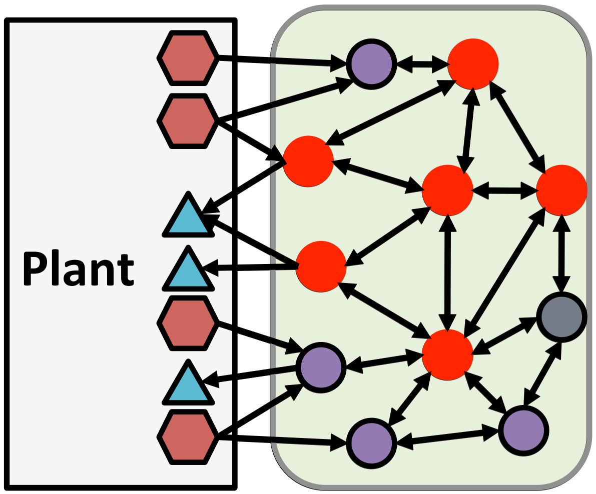
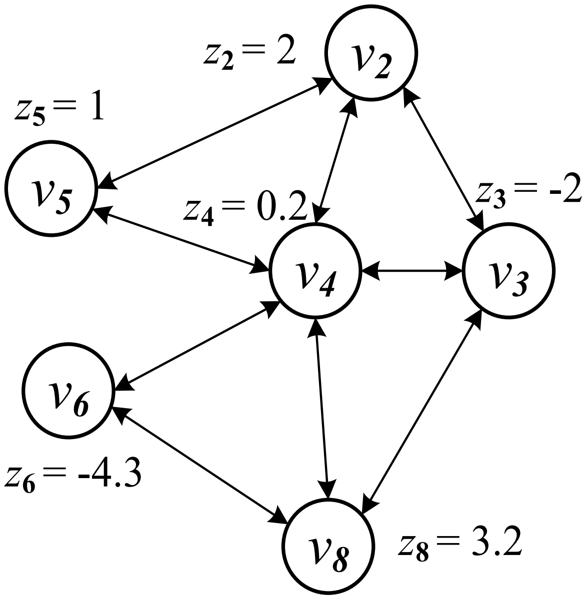
Linear Iterative Scheme

- Each node maintains its (*possibly vector*) state
  - Transmits state exactly once in each step (per frame)
  - Updates state using linear iterative strategy

- Example:



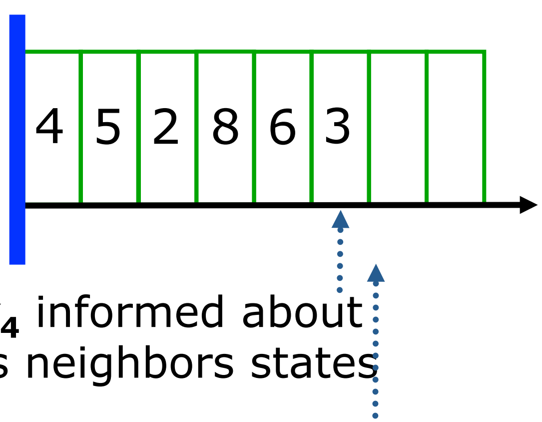


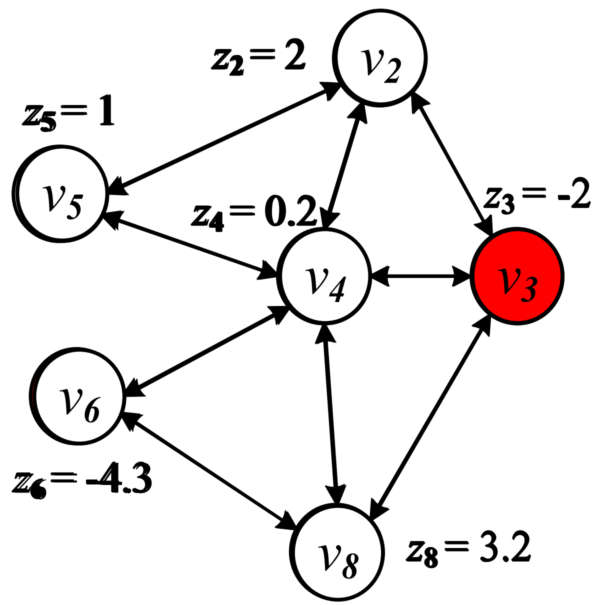
Initial state

Linear Iterative Scheme

- Each node maintains its (*possibly vector*) state
  - Transmits state exactly once in each step (per frame)
  - Updates state using linear iterative strategy

- Example:





WCN Modeling

- Each node maintains state $z_i[k]$

- Node state update procedure:

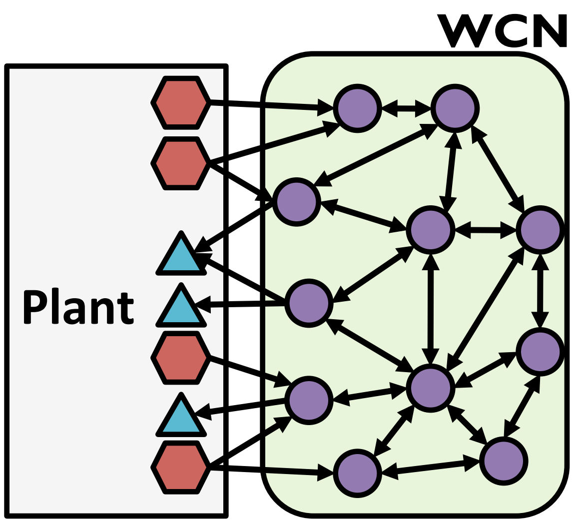
$$z_i[k+1] = w_{ii} z_i[k] + \sum_{v_j \in \mathcal{N}_{v_i}} w_{ij} z_j[k] + \sum_{s_j \in \mathcal{N}_{v_i}} h_{ij} y_j[k]$$

From neighbors **From sensors**

- Actuator update procedure:

$$u_i[k] = \sum_{j \in \mathcal{N}_{a_i}} g_{ij} z_j[k]$$

From actuator's neighbors



Each node acts as part of a dynamical compensator

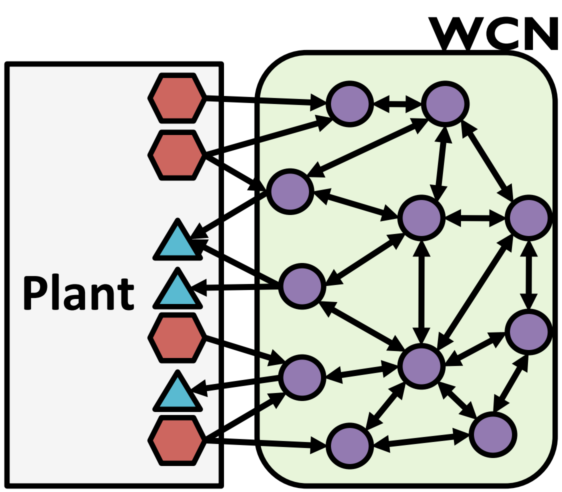
WCN Modeling

Network acts as a linear dynamical compensator

$$\mathbf{z}[k+1] = \underbrace{\begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1N} \\ w_{21} & w_{22} & \cdots & w_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ w_{N1} & w_{N2} & \cdots & w_{NN} \end{bmatrix}}_{\mathbf{W}} \mathbf{z}[k] + \underbrace{\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1p} \\ h_{21} & h_{22} & \cdots & h_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1} & h_{N2} & \cdots & h_{Np} \end{bmatrix}}_{\mathbf{H}} \mathbf{y}[k]$$

$$\mathbf{u}[k] = \underbrace{\begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1N} \\ g_{21} & g_{22} & \cdots & g_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{m2} & \cdots & g_{mN} \end{bmatrix}}_{\mathbf{G}} \mathbf{z}[k]$$

Structural constraints: Only elements corresponding to existing links (link weights) are allowed to be non-zero



WCN modeling: Closing the loop

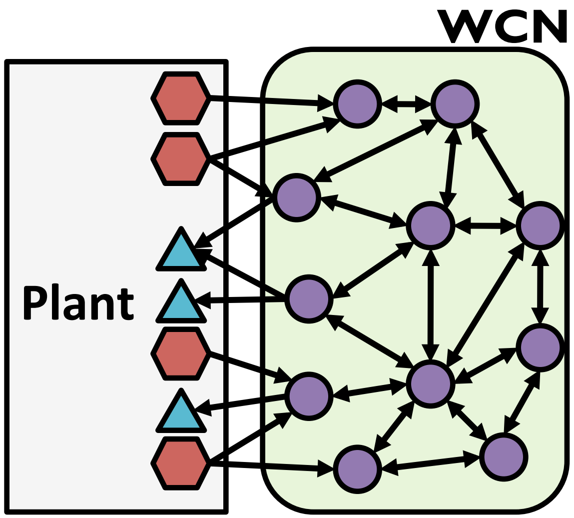
- Overall system state:

$$\hat{\mathbf{x}}[k] = \begin{bmatrix} \mathbf{x}[k] \\ \mathbf{z}[k] \end{bmatrix} \begin{matrix} \leftarrow \text{plant} \\ \leftarrow \text{network} \end{matrix}$$

- Closed-loop system:

$$\hat{\mathbf{x}}[k+1] = \underbrace{\begin{bmatrix} \mathbf{A} & \mathbf{BG} \\ \mathbf{HC} & \mathbf{W} \end{bmatrix}}_{\hat{\mathbf{A}}} \underbrace{\begin{bmatrix} \mathbf{x}[k] \\ \mathbf{z}[k] \end{bmatrix}}_{\hat{\mathbf{x}}[k]} + \underbrace{\begin{bmatrix} \mathbf{B}_w \\ \mathbf{0} \end{bmatrix}}_{\hat{\mathbf{B}}} \mathbf{u}_w$$

- Matrices W, G, H are structured
- Sparsity constraints imposed by topology!



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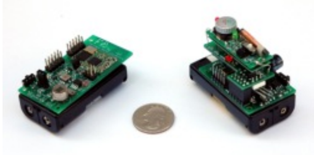
Advantages: **Simple & Powerful**



- **Low overhead**
  - Easily incorporated into existing wireless networks
    (e.g., ISA100.11a or wirelessHART)
- **Simple scheduling**
  - Each node needs to transmit only once per frame
  - Static (conflict-free) schedule
- **No routing!**
  - Easily deals with multiple sensing/actuation points

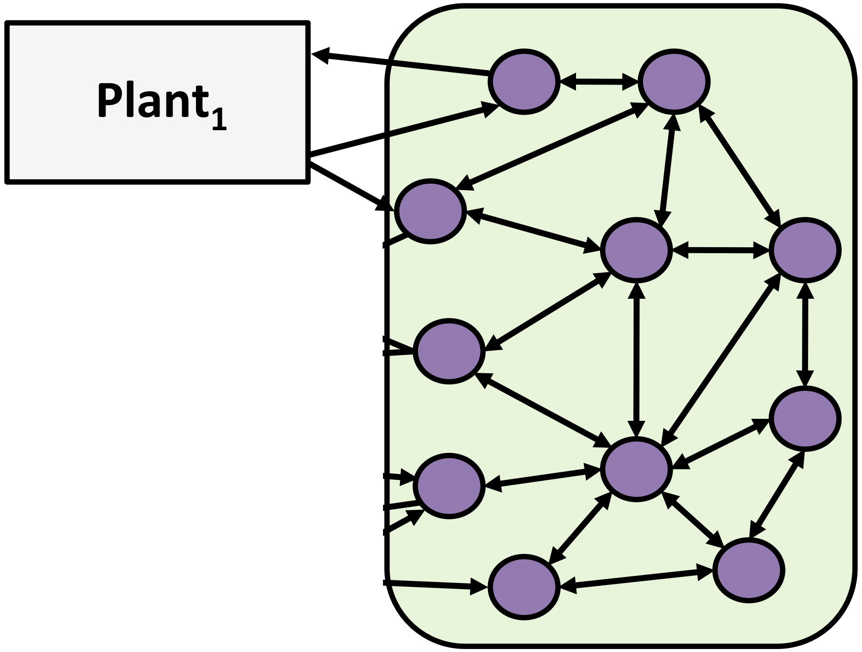
Advantages: **Compositionality**

- Adding new control loops is easy!
  - Does not require any communication schedule recalculation

- WCN configurations can be combined

Stable configuration

$$(\mathbf{W}_1, \mathbf{H}_1, \mathbf{G}_1) \in \Psi$$

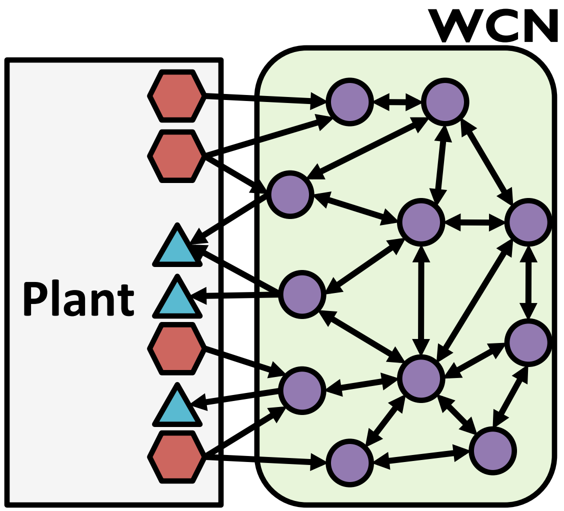


Outline

A simple distributed method for control over wireless networks

1. Wireless Control Networks (WCNs)
2. Modeling
3. **Synthesis of Optimal WCNs**
4. **Robustness**
5. Case Study

$$\hat{\mathbf{x}}[k+1] = \underbrace{\begin{bmatrix} \mathbf{A} & \mathbf{BG} \\ \mathbf{HC} & \mathbf{W} \end{bmatrix}}_{\hat{\mathbf{A}}} \underbrace{\begin{bmatrix} \mathbf{x}[k] \\ \mathbf{z}[k] \end{bmatrix}}_{\hat{\mathbf{x}}[k]} + \underbrace{\begin{bmatrix} \mathbf{B}_w \\ \mathbf{0} \end{bmatrix}}_{\hat{\mathbf{B}}} \mathbf{u}_w$$



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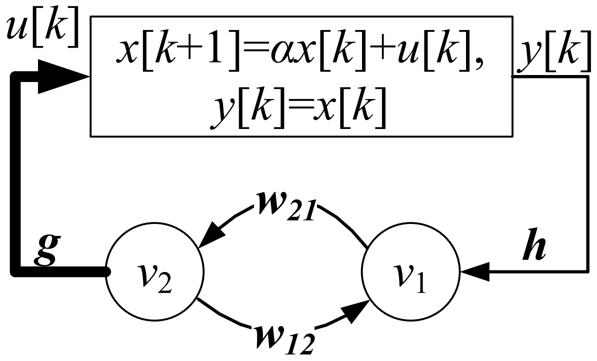
Robustness to Link Failures

- Example

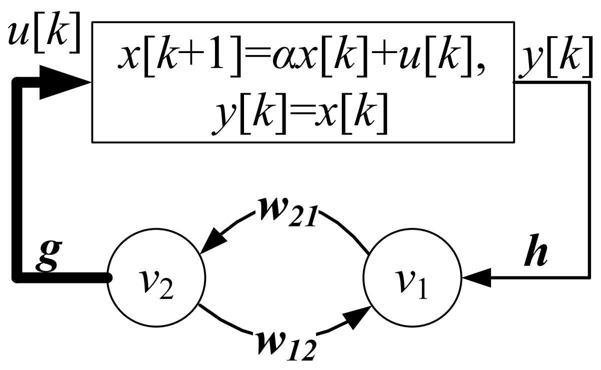


- Maximal message drop probability which guarantees MSS, α=2

	WCN (scalar state)	WCN ($\mathbb{R}^2$ state)	$oWCN$ (scalar state)	$oWCN$ ($\mathbb{R}^2$ state)
$N=2$	$p_m = 1.18\%$	$p_m = 1.30\%$	$p_m = 10.46\%$	$p_m = 17.82\%$
$N=3$	$p_m = 1.32\%$	$p_m = 1.46\%$	$p_m = 11.24\%$	$p_m = 17.88\%$
$N=4$	$p_m = 1.41\%$	$p_m = 1.54\%$	$p_m = 11.46\%$	$p_m = 17.88\%$
		$oWCN$ ($\mathbb{R}^3$ state)	$oWCN$ ($\mathbb{R}^4$ state)	$oWCN$ ($\mathbb{R}^5$ state)
$N=2$		$p_m = 20.40\%$	$p_m = 20.48\%$	$p_m = 20.64\%$

Robustness to Link Failures

- Example – WCN with observer style updates



For α=2, maximal message drop probability which guarantees MSS

$$p_{max} \approx 21\% < 25\%$$

Approaching theoretical limit for robustness with centralized controllers!

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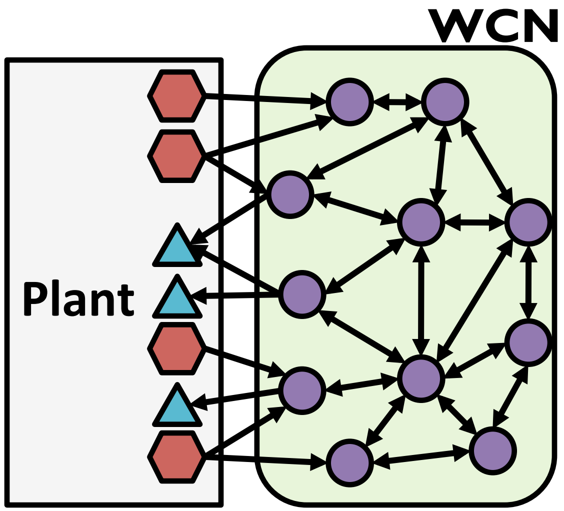
Outline

A simple distributed method for control over wireless networks

1. Wireless Control Networks (WCNs)
2. Modeling
3. Synthesis of Optimal WCNs
4. Robustness
5. **Case Study**



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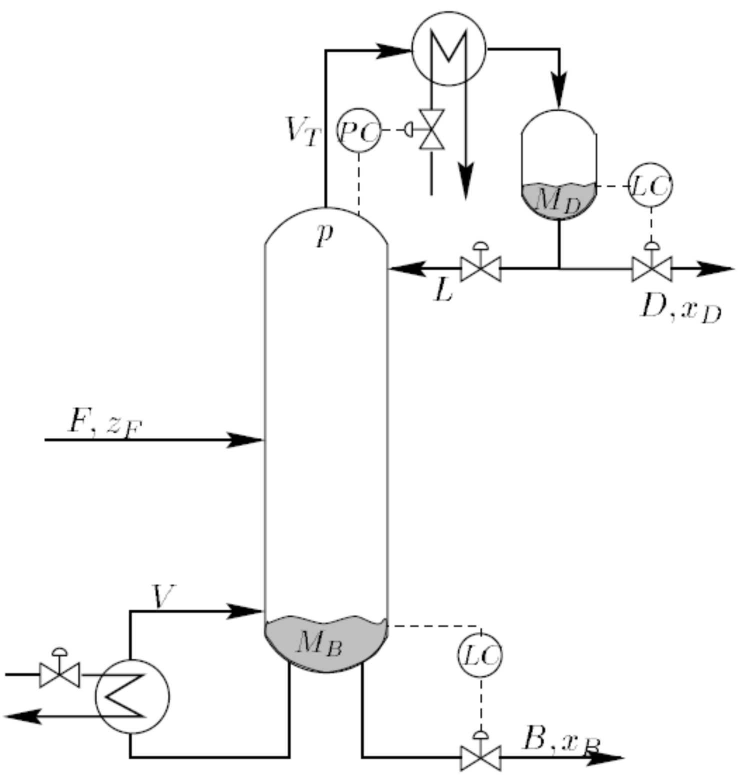
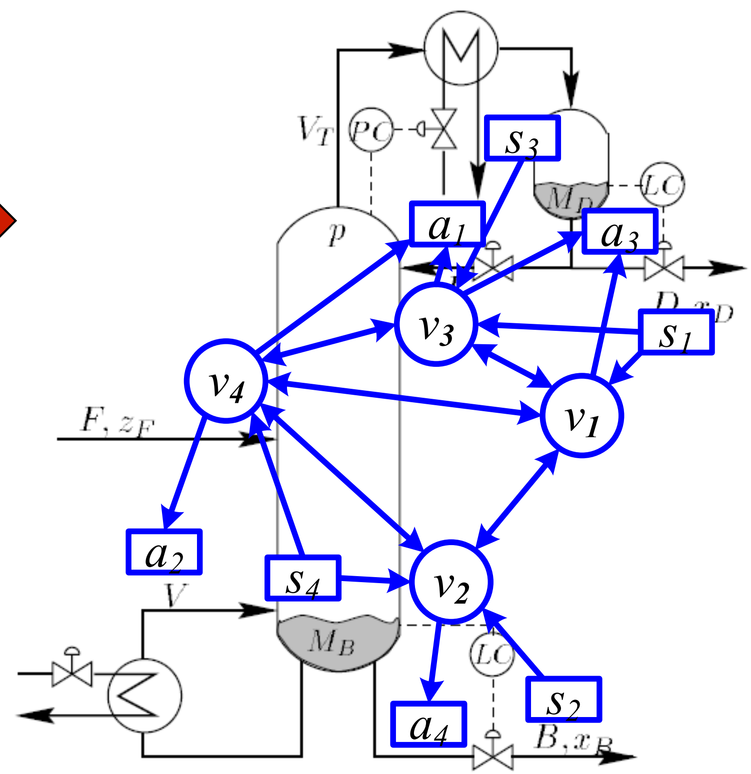
WCN demo: Distillation column process control

- Distillation column control
  - Plant **continuous-time** model contains 8 states, 4 inputs, 4 outputs

- Distillation column structure





System configuration

WCN demo: Distillation column process control

- Distillation column control
  - Plant model contains 8 states, 4 inputs, 4 outputs
- WCN contains 4 nodes

Stable configuration (obtained after plant discretization):

node→node

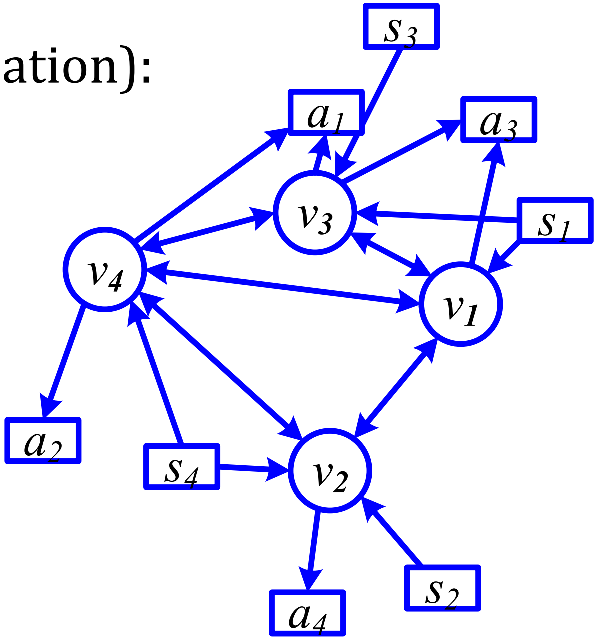
$$\mathbf{W} = \begin{bmatrix} -0.470 & 0.339 & -0.260 & -0.390 \\ -1.117 & -0.145 & 0 & -0.269 \\ 0.0514 & 0 & -0.703 & 0.600 \\ 0.854 & 0.277 & -0.086 & -0.112 \end{bmatrix}$$

sensor→node

$$\mathbf{H} = \begin{bmatrix} 1.260 & 0 & 0 & 0 \\ 0 & 0.104 & 0 & 0.075 \\ 0 & 0 & 0.421 & 0 \\ 0 & 0 & 0 & -0.034 \end{bmatrix}$$

node→actuator

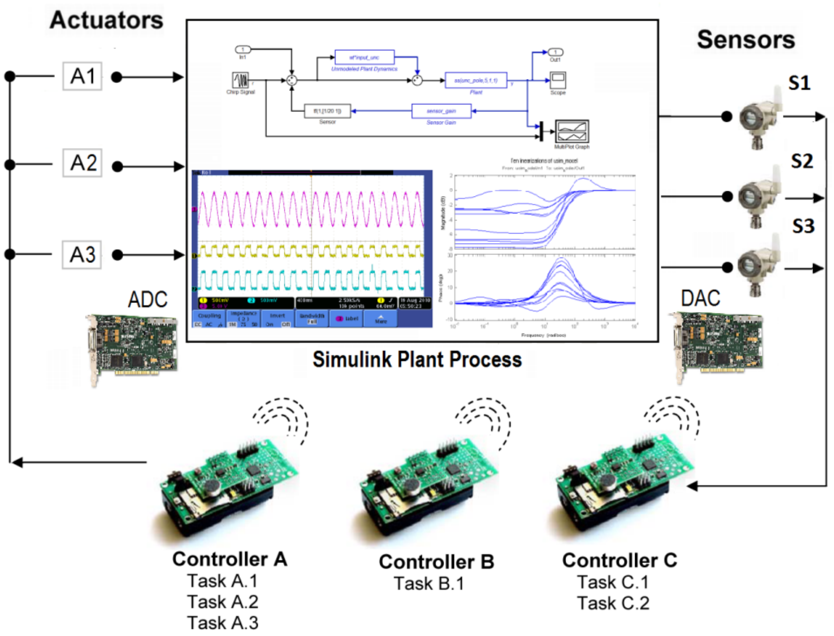
$$\mathbf{G} = \begin{bmatrix} 0 & 0 & -0.226 & -0.459 \\ 0 & 0 & 0 & 0.102 \\ 0.120 & 0 & 1.072 & 0 \\ 0 & 2.549 & 0 & 0 \end{bmatrix}$$



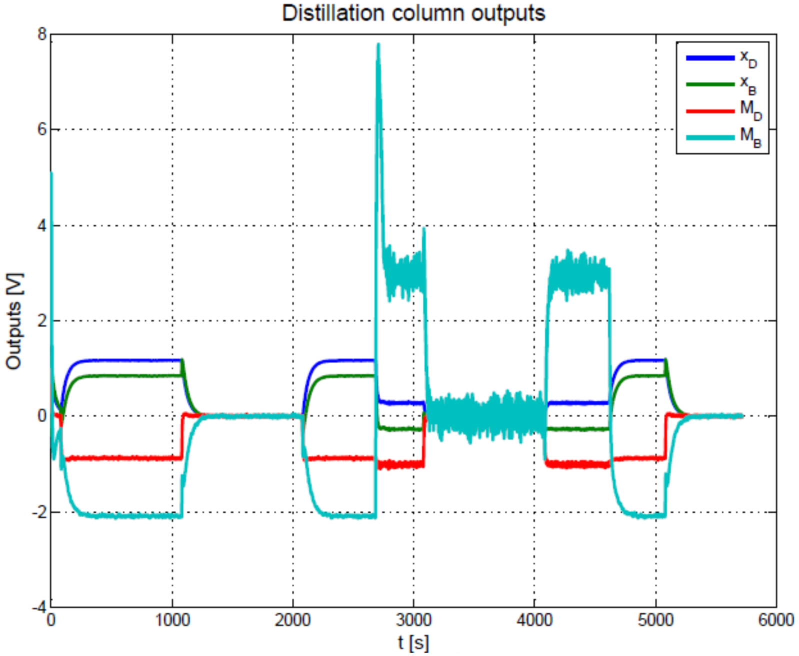
Network topology

WCN demo: Distillation column process control

Process-in-the-loop test-bed



Scenario I: v_1 turned OFF/ON



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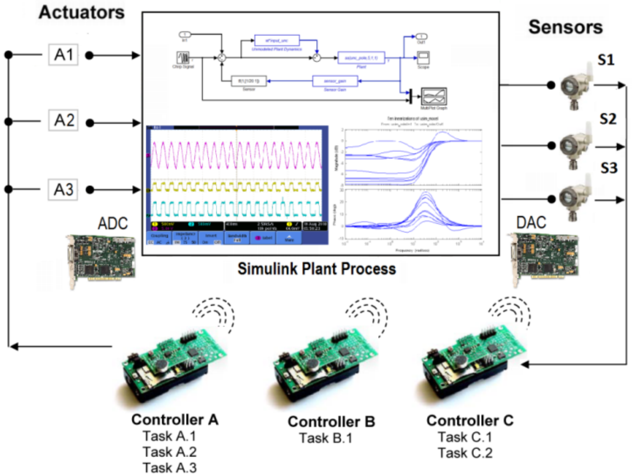
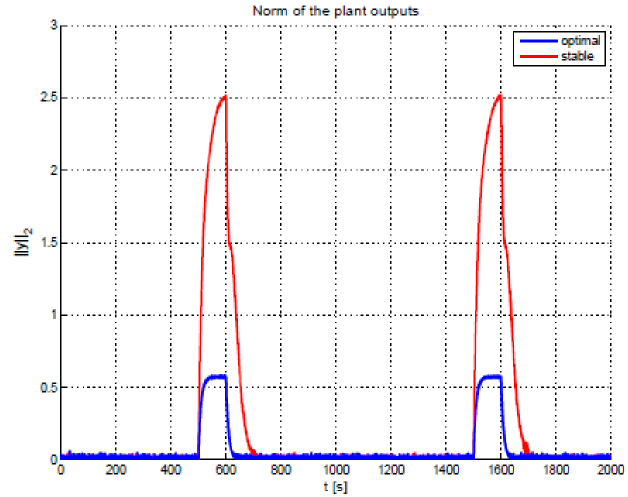
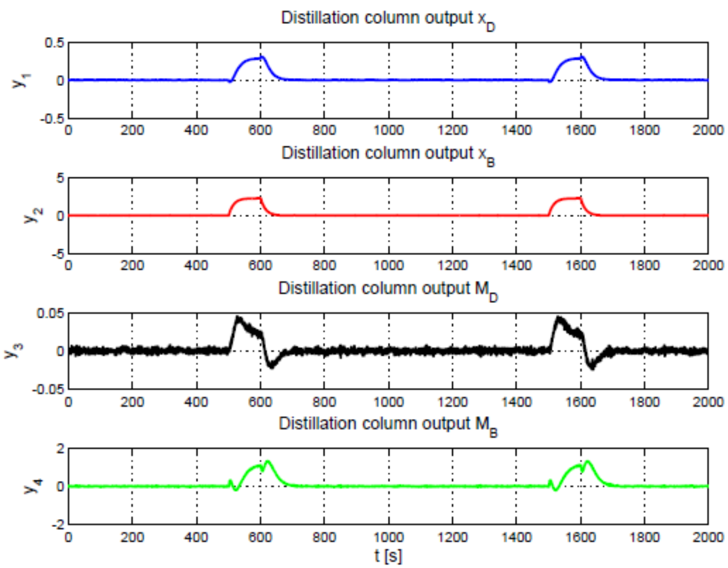
WCN demo: Distillation column process control

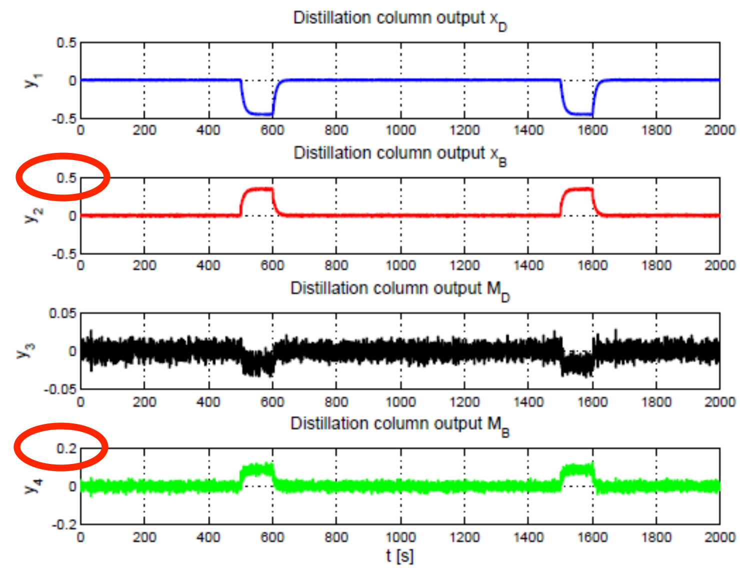
Process-in-the-loop test-bed



Scenario II: Optimal control







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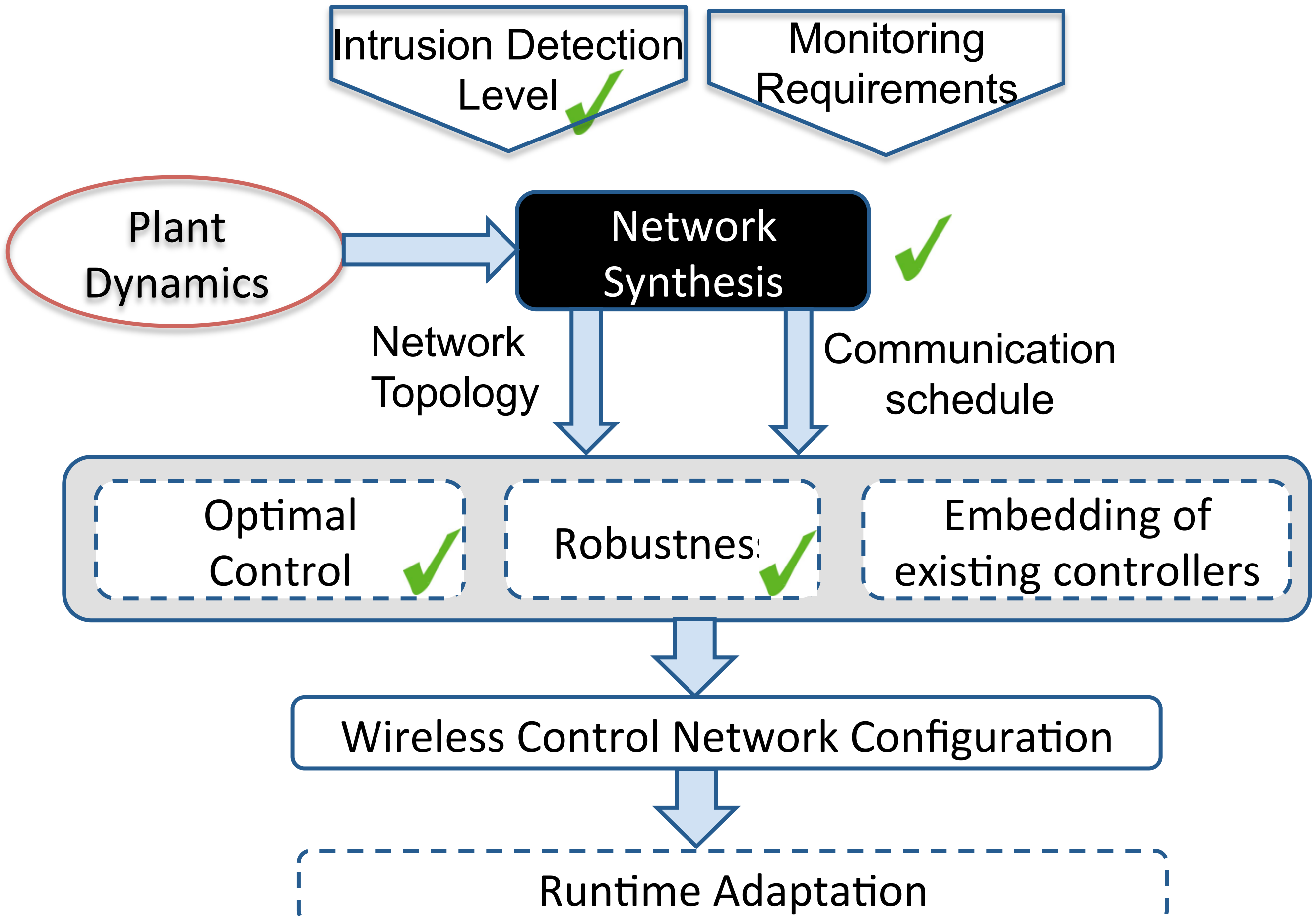
Winners of the Honeywell Users Group 2011 Industrial Wireless Competition

PRECISE Ph.D. Student: Miroslav Pajic. **Embedded Sys MS Student:** Harsh Jain

Controller-as-a-Service with Wireless Control Networks



Thank You

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Demo