Dynamic Wireless Network Reconfiguration for Control System Applied to a Nuclear Reactor Case Study

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Pittsburgh and Pitt

• 400,000 → 750,000 inhabitants
• Still affordable (even after Google, Apple, ArgoAI, etc moved in)
• Bikeable!!! (not autonomous, yet)
• 34,750 students, 13,500 faculty and staff
• New School of Computing and Information (SCI): hiring 10+ faculty, lots of students
Wired vs. Wireless Control System (WCS)

Wired Control System
- Actuator
- Remote Controller
- Sensors
- Plant

Wireless Control System (WCS)
- Actuator
- Remote Controller
- Wireless Network
- Plant
- Sensors

Control sampling period
Not easy to do deployment and maintenance
Wired vs. Wireless Control System (WCS)

Wired Control System
- Actuator
- Sensors
- Remote Controller
  - control signal
  - measurements

Wireless Control System (WCS)
- Actuator
- Plant
- Sensors
  - Delay and Message Loss

Not easy to do deployment and maintenance
Major Challenges of WCS

• Instability
  • When the physical system is unstable, the plant or the device can be damaged and leads to serious safety issues and financial loss.

• Performance Degradation
  • Induce additional error, \textit{network-induced error}
Major Challenges of WCS

• Instability
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• Performance Degradation
  • Induce additional error, *network-induced error*

![Diagram showing wired and wireless control system outputs, with network-induced error highlighted.](attachment://diagram.png)
Problem Statement

• Trade-off between delivery ratio and delay
  • Higher delivery ratio -> more redundant nodes -> more delay
  • Need: Optimal network configuration

• Time-correlated link failures [Baccour TOSN’12]
  • Need: Network reconfiguration

• Objective: network-induced error reduction for wireless control system

• Solution
  • Network reconfiguration framework
Network Reconfiguration Framework

• Input: network configuration set
  • The network node placement set

• Offline
  • Optimal network configuration table indexed by LSR values.

• Online
  • LSR estimation at run time
  • Centralized network reconfiguration
Offline Computation

• Network imperfection model
  • Define total induced delay to the control system $D_{estimation}$ as

\[
D = \left[ \frac{D_{\text{network}} + n_{\text{loss}} \Delta_{\text{ssp}}}{\Delta_{\text{csp}}} \right] \Delta_{\text{csp}}
\]

• $n_{\text{loss}} \sim dr$
Offline Computation

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\]

• $n_{\text{loss}} \sim dr$

• Estimate $\Delta$ for each network placement

• Optimal network placement
  • Given LSR, placement with minimum $\Delta$ estimation

• Optimal network placement table indexed by LSR values
Online Reconfiguration

Remote Controller

<table>
<thead>
<tr>
<th>LSR</th>
<th>Estimate node placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>Placement 1</td>
</tr>
<tr>
<td>0.5</td>
<td>Placement 8</td>
</tr>
<tr>
<td>0.2</td>
<td>Placement 20</td>
</tr>
</tbody>
</table>

Network

LSR estimation

Estimated LSR

New node placement

Estimated LSR

Online reconfiguration algorithm
# Online Reconfiguration

**Remote Controller**

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Optimal estimated placement

**Online reconfiguration algorithm**

**Network**

- LSR estimation
- New node placement
- Estimated LSR

**Remote Controller**

- LSR estimation
- Optimal estimated placement
- New node placement
Online Reconfiguration

• LSR Estimation
  • During LSR interval (LSRI), each node will record its own $n_{\text{should}}$ and $n_{\text{rec}}$ over all its receiving links
  • Every LSRI, each node sends out its own $n_{\text{should}}$ and $n_{\text{rec}}$. Parent node will sum up all its children’s $n_{\text{should}}^i$ and $n_{\text{rec}}^i$ and its own $n_{\text{should}}$ and $n_{\text{rec}}$
  • Remote controller estimates average LSR over all the links.

\[
\text{LSRI} = 20s \quad \Delta T = [0s, 19s] \quad \text{LSRI} = 20s \quad \Delta T = 20s
\]

\[
\text{LSR} = \frac{n_{\text{rec}}^1 + n_{\text{rec}}^2 + n_{\text{rec}}^3}{n_{\text{should}}^1 + n_{\text{should}}^2 + n_{\text{should}}^3}
\]
Online Reconfiguration

• Current estimate LSR -> estimate optimal number of nodes

• Centralized Reconfiguration algorithms
  1. Direct Jump to Optimal (DO)
  2. Multiplicative Increase Conservative Decrease (MICD)
  3. Adaptive Control (AC): \( \text{curr}_{node} = \alpha \times \text{curr}_{node} + (1 - \alpha) \times \text{est}_{node} \)
Online Reconfiguration

• Centralized Reconfiguration algorithms
  1. Direct Jump to Optimal (DO)
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• Considering consecutive losses (CL)
  • Add \( k \) more nodes, whenever there are \( m \) consecutive losses
  • CL-DO, CL-MICD and CL-AC
Evaluation

• Case study: one PHX
• Simulator: WCPS [Li ICCPS’15]

• Offline simulation
  • Static RSSI
• Online simulation
  • Dynamic RSSI: dynamic LSR over time
  • LSRI

• Metrics
  • IAE, MAE and RMSE: network-induced error (comparing with wired control system)
  • Network lifetime (days)
Offline Table

• Number of optimal nodes increases, as the LSR decreases

\[ D = \left[ \frac{D_{\text{network}} + n_{\text{loss}} \Delta_{\text{ssp}}}{\Delta_{\text{csp}}} \right] \Delta_{\text{csp}} \]
Network Imperfection Model vs. Offline Simulation Results

- Network imperfection model is accurate
  - Network induced delay is statistically correlated with the power output RMSE (Pearson correlation $r = 0.993, p < 0.001$)
Online Results: sensitivity analysis of RSSI values

Online schemes considering consecutive message losses performs better than those not considering consecutive message losses

- 13.5% error reduction
- 3% power saving

Mossé Pitt—CS RTNS 2018
Online Results: sensitivity analysis of LSRI

LSRI value affects the performance of schemes without considering CL
Online Results: sensitivity analysis of LSRI

Schemes considering CL are not affected by the LSRI values
Sensitivity of $\alpha$ values

$$curr = \alpha \times curr + (1 - \alpha) \times estimate$$

More $\alpha$, slower the # nodes is adjusted to the # estimated nodes
Conclusion

• Our network imperfection model is accurate
  • Pearson Correlation $r = 0.993$, $p < 0.001$

• Online reconfiguration schemes perform better than static scheme
  • 20% error reduction
  • 17% power saving

• Online schemes considering consecutive message losses performs better than those not considering consecutive message losses
  • 13.5% error reduction
  • 3% power saving

• Fine tuning is needed:
  • LSRI value affects the WCS performance
  • $\alpha$ values in the AC scheme also affects the WCS performance
Questions?

1. Nuclear? With wireless? Really?
2. Is it useful for anything else? What’s next?
3. There were 2 Claires scheduled for Session Chairs...