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

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Pittsburgh and Pitt

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

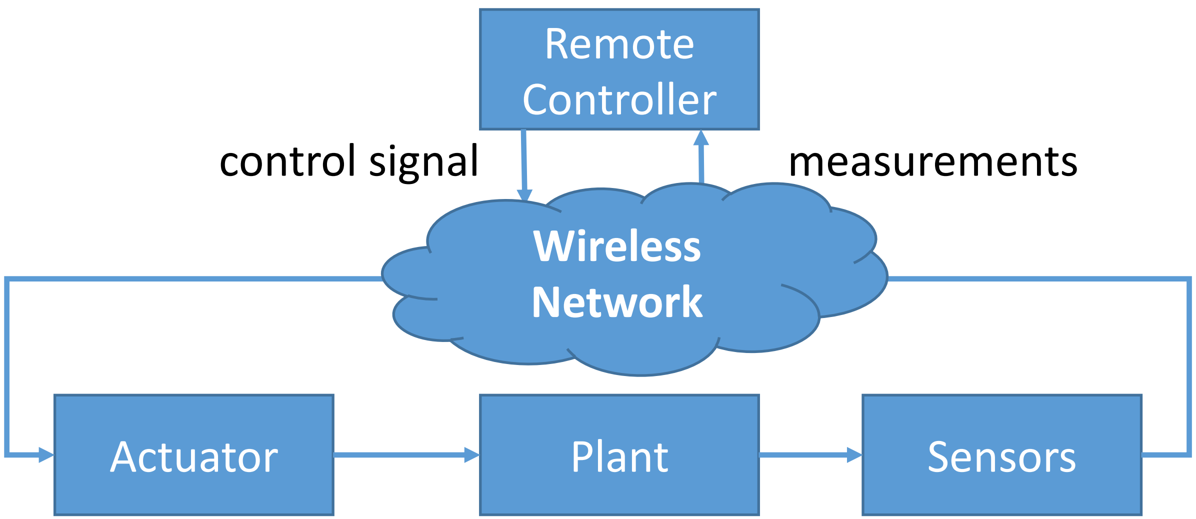
Wired vs. Wireless Control System (WCS)

Wired Control System

Control sampling period

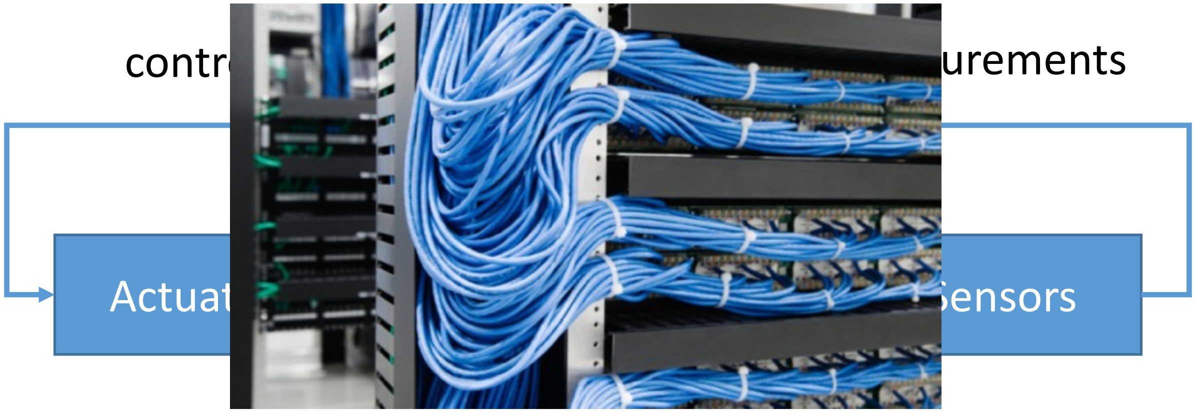
Not easy to do deployment and maintenance

Wireless Control System (WCS)



Wired vs. Wireless Control System (WCS)

Wired Control System



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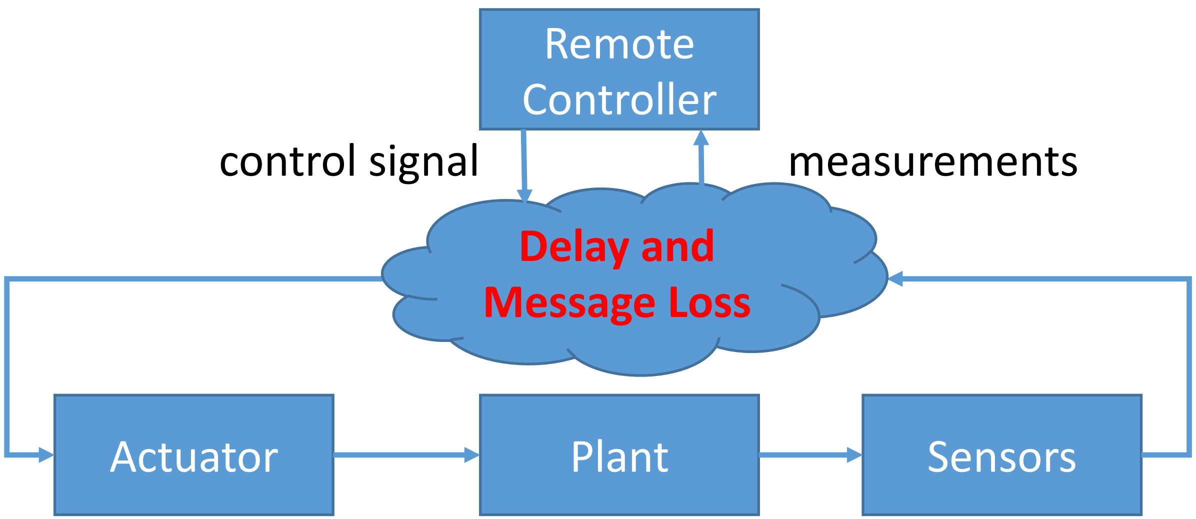
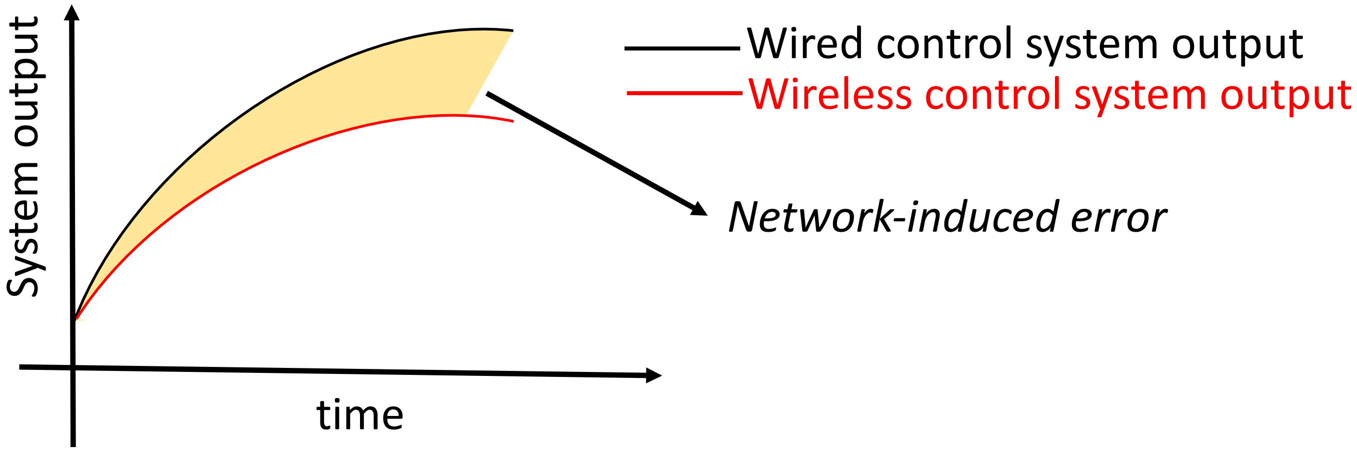
Wireless Control System (WCS)



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, *network-induced error*



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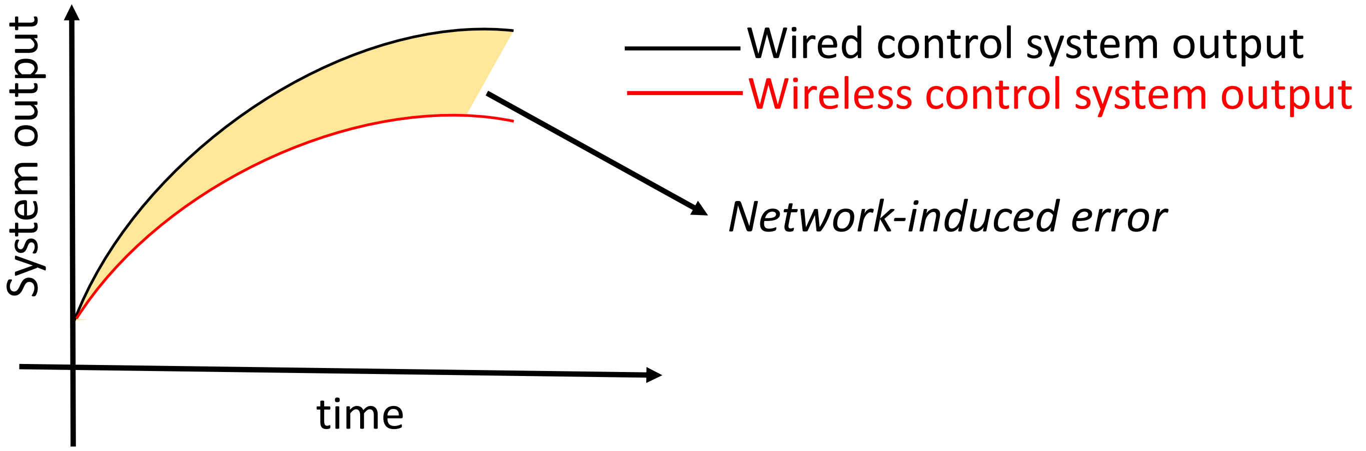
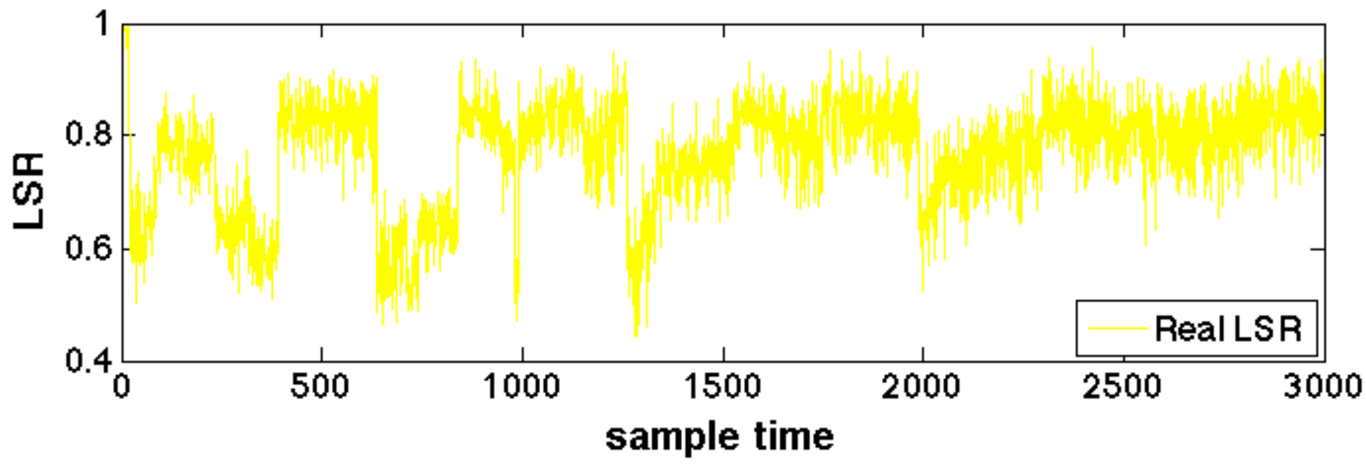


Problem Statement

- 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



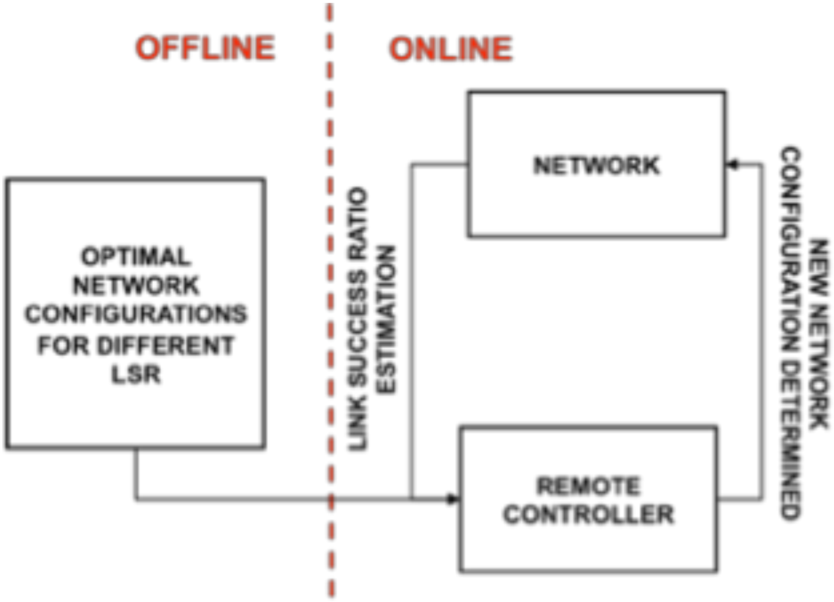
- Objective: network-induced error reduction for wireless control system
- Solution
  - Network reconfiguration framework

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

consecutive message losses　　　　sensing sampling period

$$D = \left\lceil \frac{D_{network} + \boxed{n_{loss}}\boxed{\Delta_{ssp}}}{\boxed{\Delta_{csp}}} \right\rceil \Delta_{csp}$$

Control sampling period

  - $n_{loss} \sim dr$

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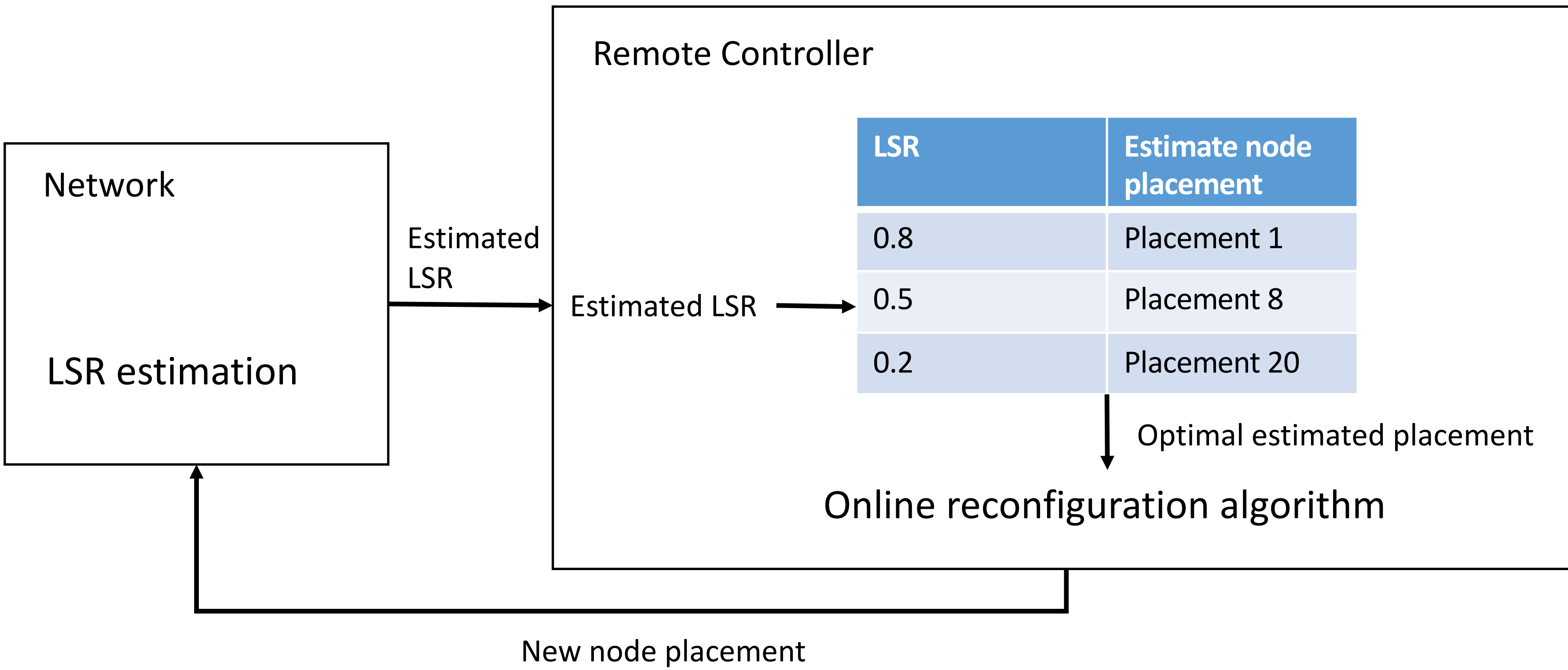
Control sampling period

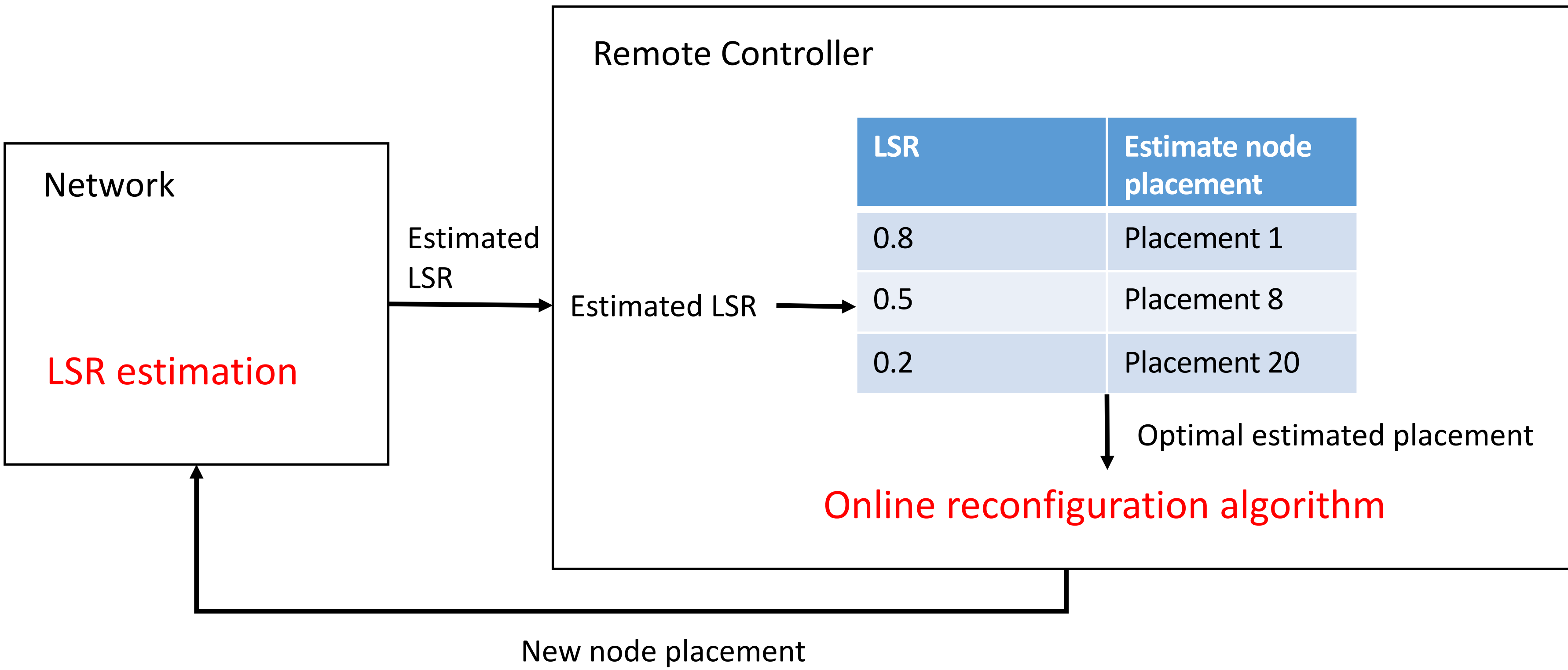
  - $n_{loss} \sim dr$
- Estimate Δ for each network placement
- Optimal network placement
  - Given LSR, placement with minimum Δ estimation
- Optimal network placement table indexed by LSR values

Online Reconfiguration



LSR	Estimate node placement
0.8	Placement 1
0.5	Placement 8
0.2	Placement 20

Online Reconfiguration

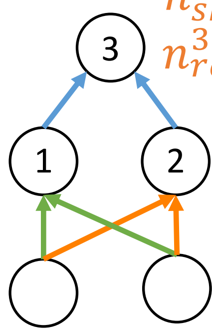


LSR	Estimate node placement
0.8	Placement 1
0.5	Placement 8
0.2	Placement 20

Online Reconfiguration

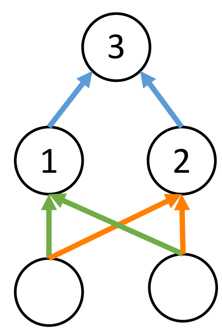
- LSR Estimation
  - During LSR interval (LSRI), each node will record its own n_{should} and n_{rec} over all its receiving links
  - Every LSRI, each node sends out its own n_{should} and n_{rec}. Parent node will sum up all its children's n_{should}^{i} and n_{rec}^{i} and its own n_{should} and n_{rec}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

$LSRI = 20s \quad \Delta T = [0s, 19s]$



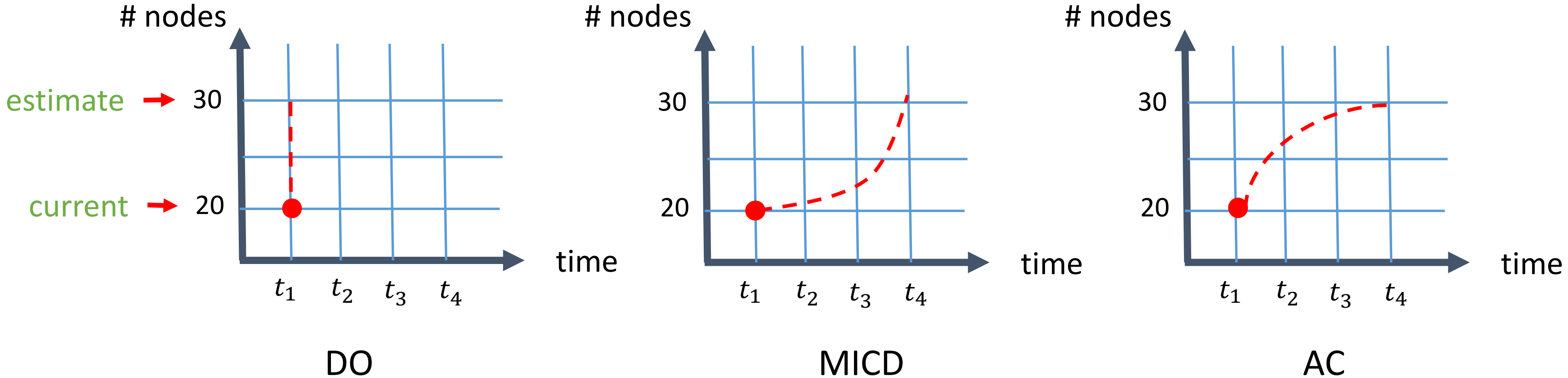
$LSRI = 20s \quad \Delta T = 20s$

$$LSR = \frac{n_{rec}^{1} + n_{rec}^{2} + n_{rec}^{3}}{n_{should}^{1} + n_{should}^{2} + n_{should}^{3}}$$



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): $curr_{node} = \alpha \times curr_{node} + (1 - \alpha) \times est_{node}$



Online Reconfiguration

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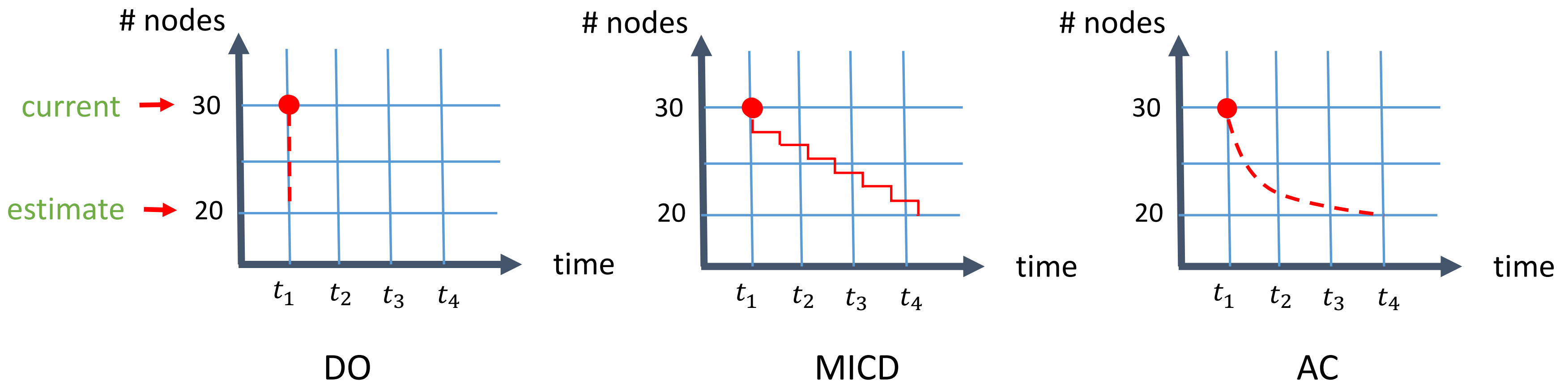
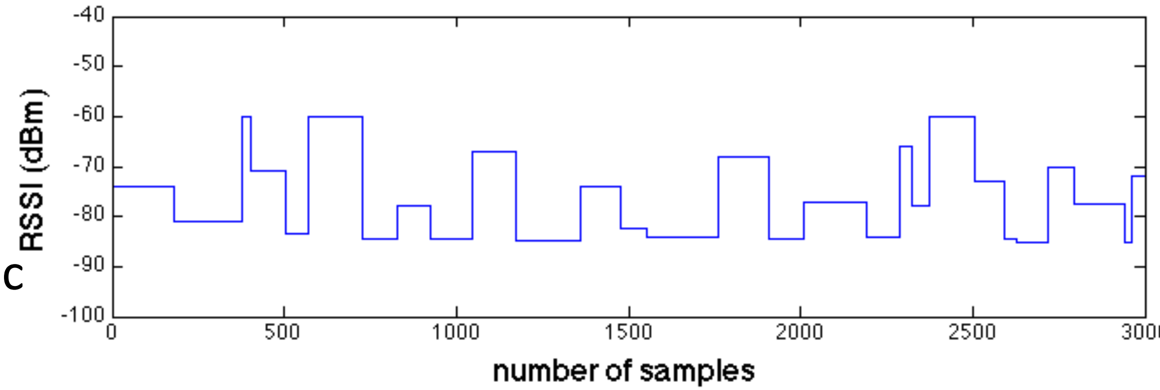


- Considering consecutive losses (CL)
  - Add k more nodes, whenever there are m consecutive losses
  - CL-DO, CL-MICD and CL-AC

Evaluation

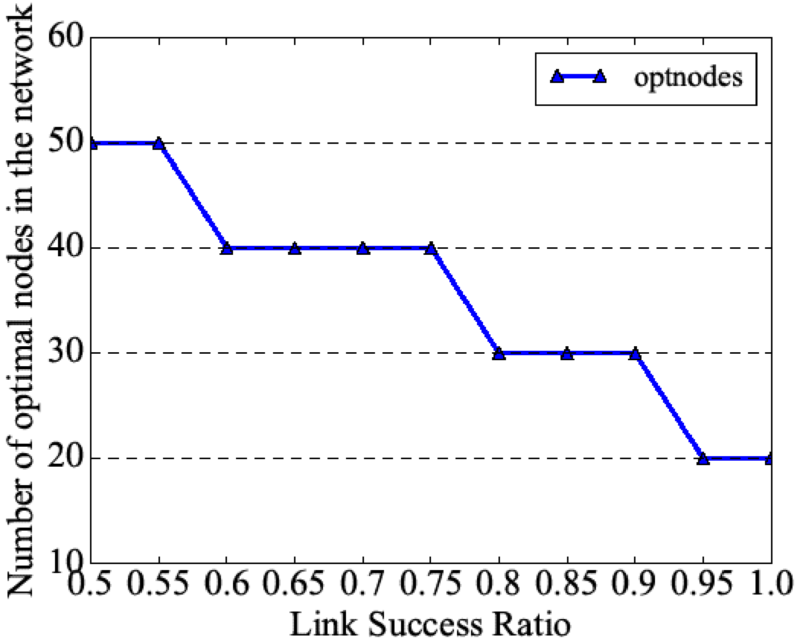
- Case study: one PHX
- Simulator: WCPS [Li ICCPS'15]

- 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)

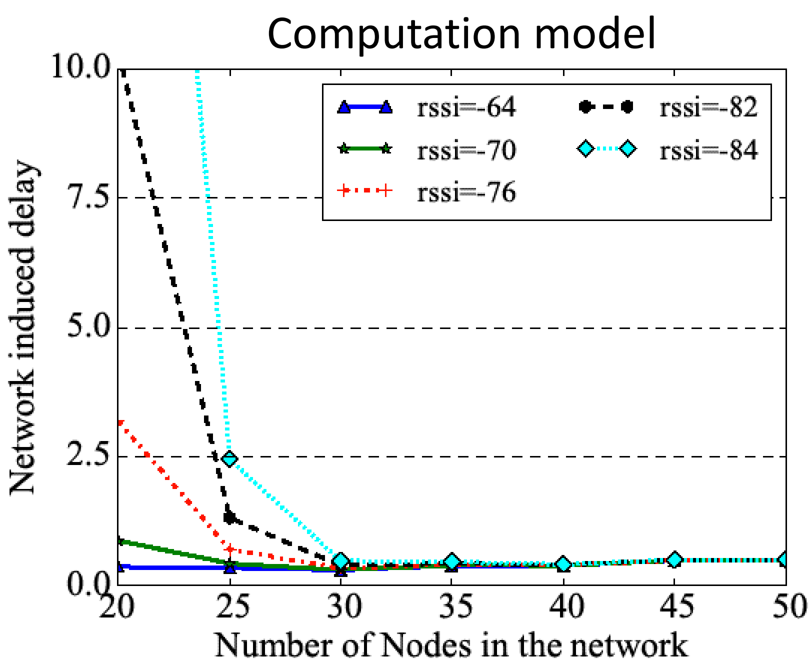
Offline Table

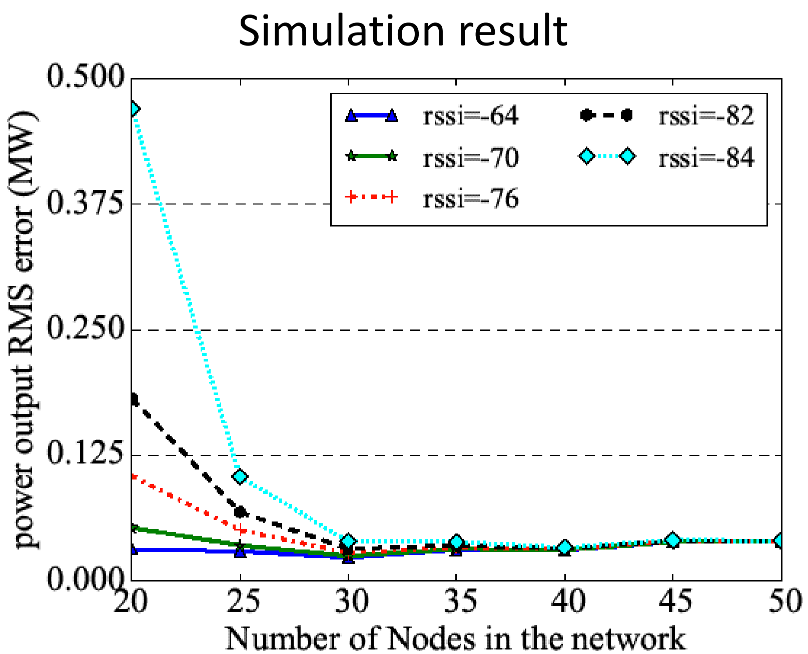


- Number of optimal nodes increases, as the LSR decreases

$$D = \left\lceil \frac{D_{network} + n_{loss}\Delta_{ssp}}{\Delta_{csp}} \right\rceil \Delta_{csp}$$

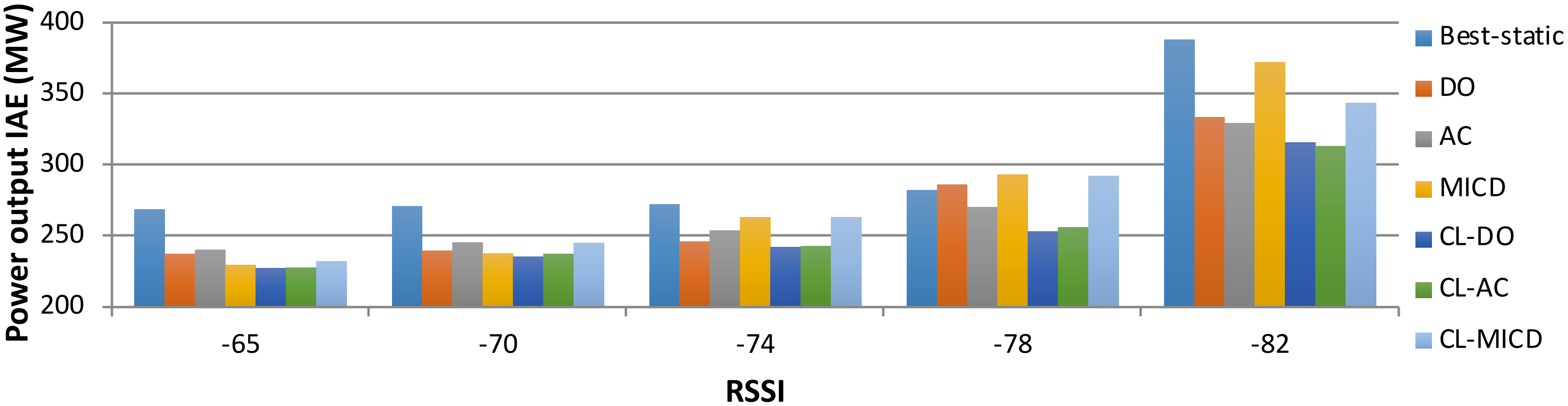
Network Imperfection Model vs. Offline Simulation Results

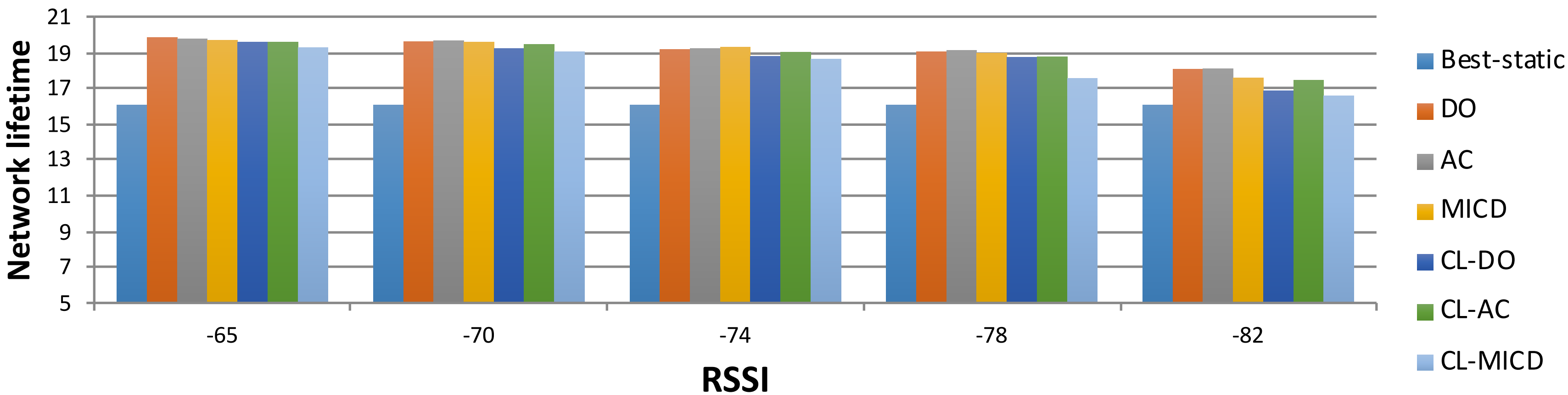




- Network imperfection model is accurate
  - Network induced delay is statistically correlated with the power output RMSE (Pearson correlation $r = 0.993, p < 0.001$)

Online Results: sensitivity analysis of RSSI values

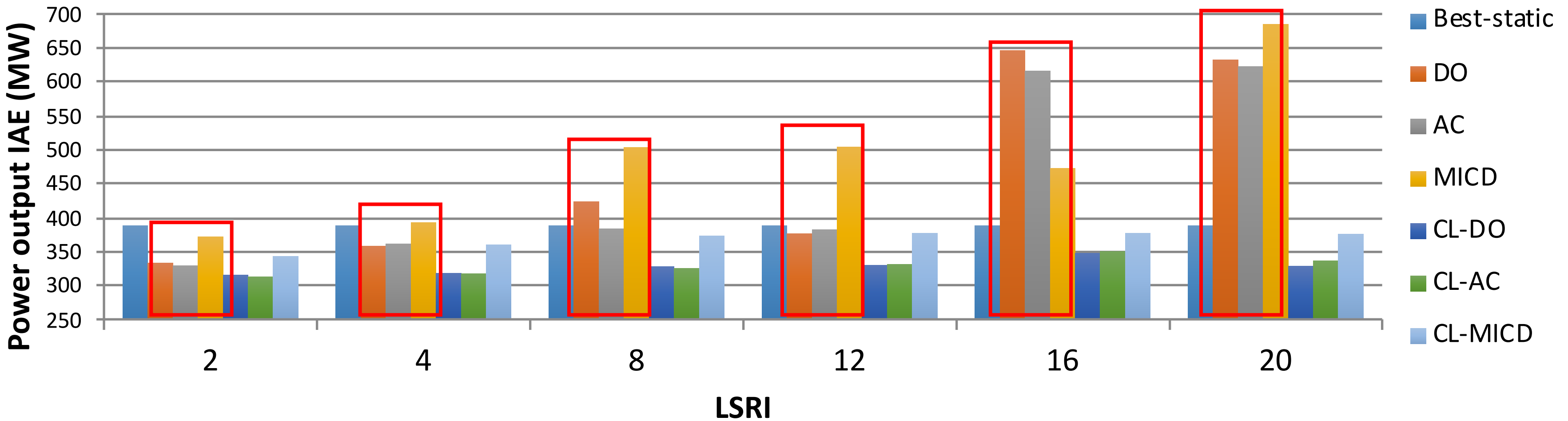


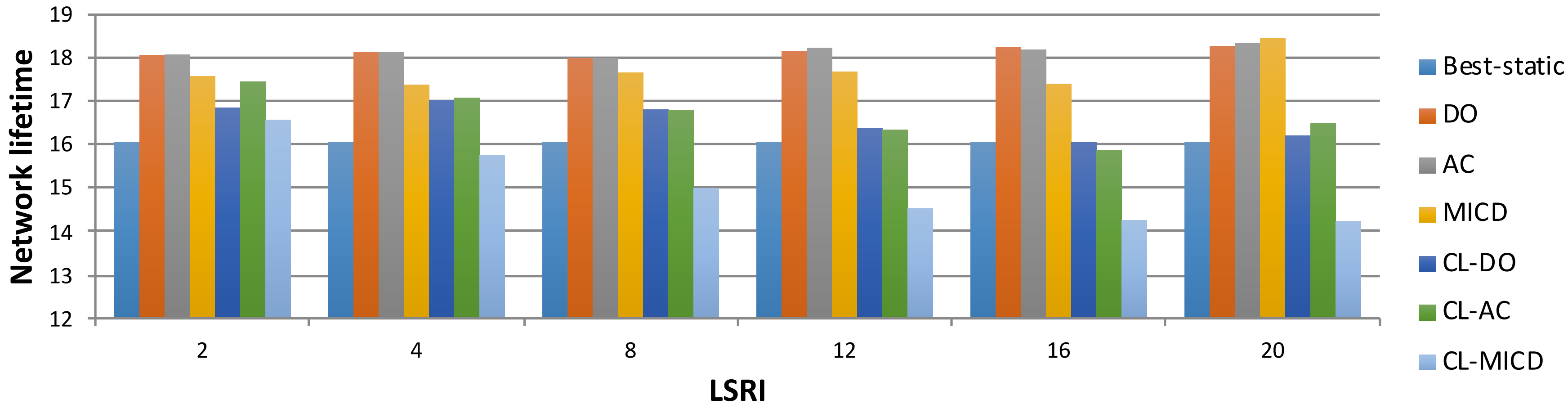


Online schemes considering consecutive message losses performs better than those not considering consecutive message losses

- 13.5% error reduction
- 3% power saving

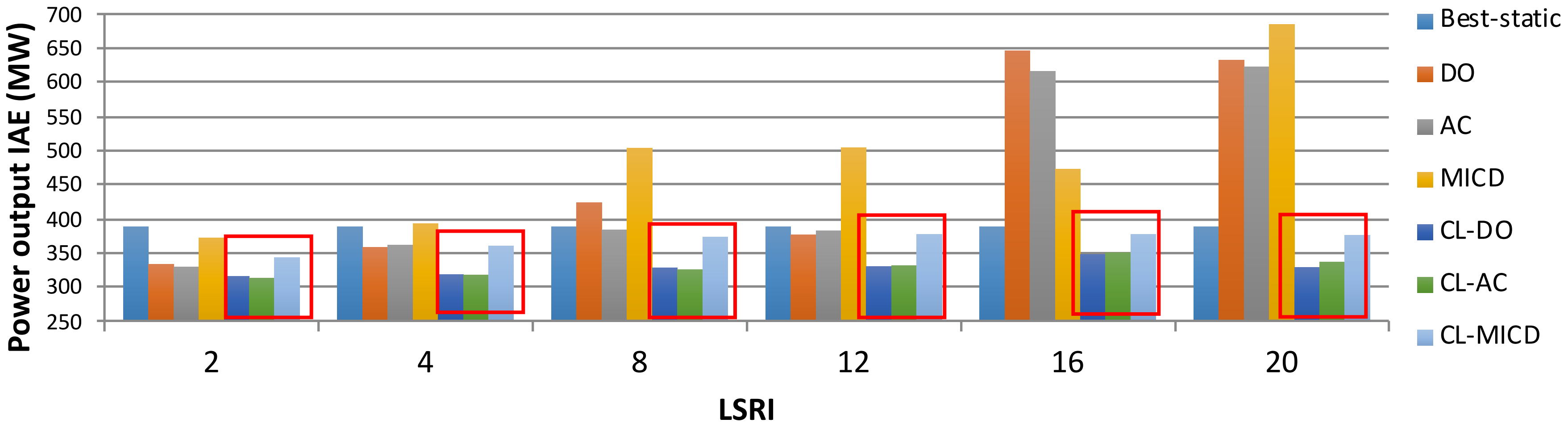
Online Results: sensitivity analysis of LSRI

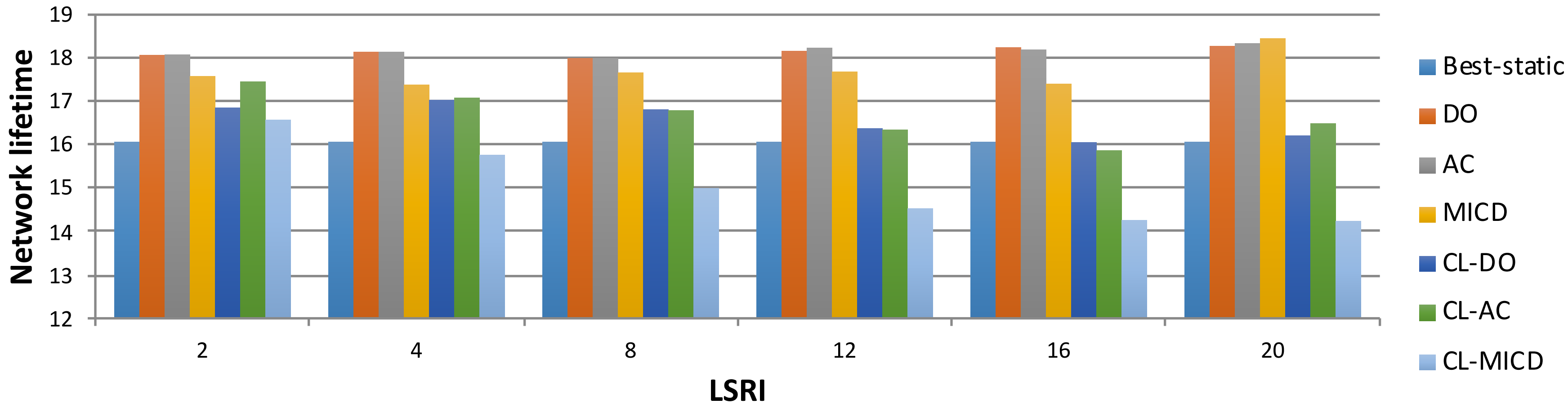




LSRI value affects the performance of schemes without considering CL

Online Results: sensitivity analysis of LSRI



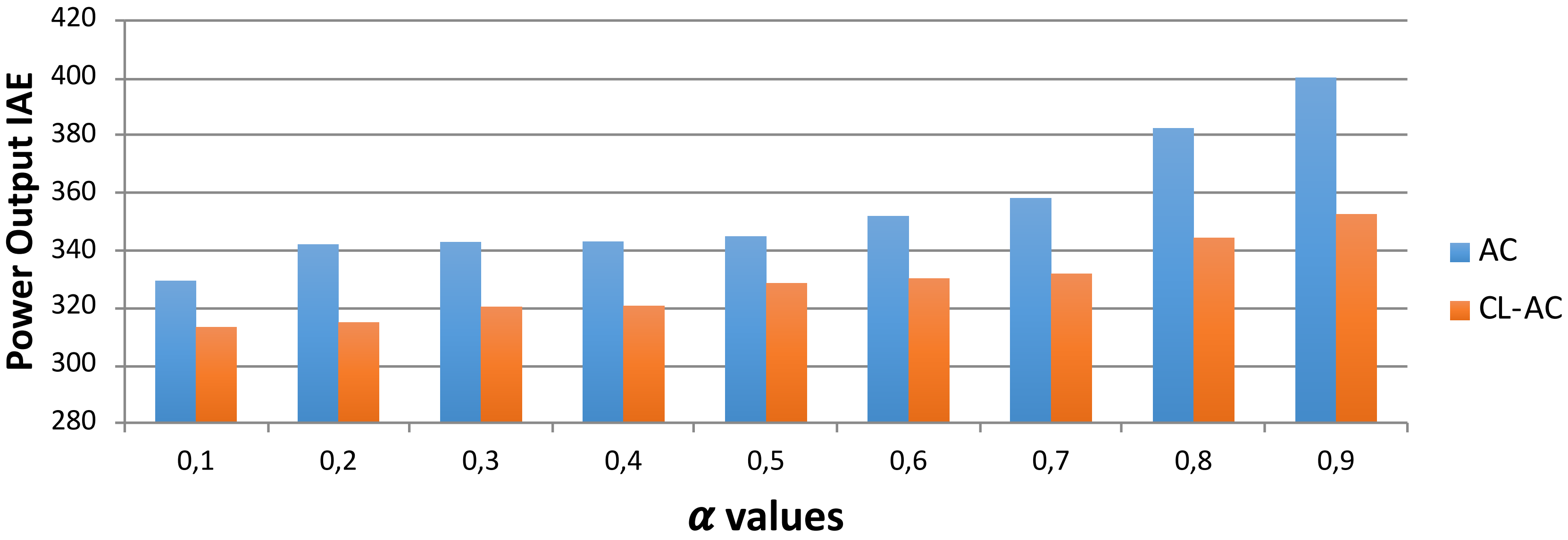


Schemes considering CL are not affected by the LSRI values

Sensitivity of α values

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

More α, 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
  - α 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…