Real-Time Wireless Sensor-Actuator Networks

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Roadmap

- Real-time transmission scheduling theory for WSAN
  - Dynamic priority
  - Fixed priority
    - End-to-end delay analysis
    - Priority assignment
- Scheduling-control co-design for WSAN
- CapNet: real-time WSAN for data center power capping
- WSAN over TV White Spaces
Wireless Data Center Power Management

Power infrastructure in an enterprise data center costs hundreds of millions USD.

**Power capping**: regulate the power consumption of a cluster of servers.
Wireless Data Center Power Management

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Management using low-cost wireless

- **Reduced cost**: for 100,000 servers, only 5.4%-8% of the wire solution cost
- Simple, flexible, easily manageable
**Power Capping**

- **Cap**: circuit breaker’s capacity for a cluster of servers
- **Using nameplate power rating**: less servers per cluster

**Oversubscription**: put more servers on a circuit

**Aggregate power**: rarely exceeds the cap

**Power capping**: brings the aggregate power consumption back to cap
Power Capping Real-Time Requirement

- **Trip time**: allowed time duration above the cap
- If oversubscription duration > trip time → circuit breaker trips
  - Server shutdowns
  - Power outage

**Power capping** must be done within trip time (deadline)
Designing Wireless Capping Protocol

- A naive protocol will repeatedly
  - Collect power consumption data from each server
  - Determine aggregate consumption; do capping if it exceeds cap
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- Collect power consumption data from each server
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![Graph showing power consumption over time](image)

Power capping is a rare event!

Interferes with wireless in other clusters/applications!

We design a distributed event-driven protocol
- Global cap to local cap $\rightarrow$ local detection $\rightarrow$ servers generate alarms
- Aggregation is done only upon detection of a potential event
CapNet Design and Implementation

- **CapNet**: Wireless Sensor Network for Power Capping
  - Employs conflict-free, event driven protocol

- Operates in 3 phases
  - Local detection → alarm
  - Aggregation upon k alarms: increase k to suppress false alarms
  - Triggers capping, if the alarms are true

![Flowchart](image-url)
CapNet Design and Implementation

- **CapNet**: Wireless Sensor Network for Power Capping
  - Employs conflict-free, event driven protocol

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  - Local detection $\rightarrow$ alarm
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implemented in TinyOS on TelosB platform.
Power Consumption in a Data Center

180×180 matrix

\[ [i,j] : \text{correlation between i-th and j-th server} \]

Microsoft Data Center clusters running Web-Search, Email, Map-Reduce, cloud apps

- Strong synchrony among the servers in the same cluster
  - Cluster exceeds cap → many servers exceed local cap → fast alarm
  - CapNet benefits from correlation → a practical approach!
Experiment

- Deployed in Microsoft data center experimental facility
- TelosB to Server through serial
Real-Time Performance (480 servers)

\[ \text{Capping latency} = \text{Network latency} + \text{OS latency} + \text{Hardware latency} \]

\[ 110-350 \text{ms} \]

\[ \text{Slack} = \text{Trip time-capping latency} \]

94% transmission suppression compared to the naive protocol!

CapNet meets the real-time requirements in capping.
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WSAN over TV White Space

- WSAN scalability challenge
  - Smart city $\rightarrow$ hundreds of thousands of nodes
  - Clinical monitoring in large medical systems

- Approach: WSAN over white spaces
Sensor Networking over White Space

White Spaces: unused UHF/VHF band between 50-698 MHz

Advantage
- Long transmission range
- Wall penetration

Challenge
- Energy, real-time requirements
- Exploit bandwidth and data rate

Spectrum inside a data center
Sensor Networking over White Space

White Spaces: unused UHF/VHF band between 50-698 MHz

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More than 60% spectra are white spaces

$<$

-85dBm
Sensor Networking over White Space

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![Bar chart showing spectrum availability](image)

Spectrum availability based on counties in USA
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For sensor network applications that involve
- Wide-area sensing: Large civil infrastructure, oil field
- Wall/obstacle penetration: Hospital, industry sensor network
Conclusion

- **Real-time wireless sensor-actuator network is a reality.**
  - Enables cyber-physical systems in industry, home, hospital

- **Our contributions and research impacts**
  - Real-time wireless scheduling theory for WSAN
  - Scheduling-control co-design for wireless control
  - CapNet: the first real-time WSAN for data center power capping

- **Vision: large-scale wireless cyber-physical systems**
  - Scalable real-time network architecture and protocols
  - Wide-area sensor networking over White Spaces