Research on Communication and Control in Smart Grid

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Outline

• Introduction

• Sensing-Delay Tradeoff for Communication in Cognitive Radio enabled Smart Grid

• Sensing-Performance Tradeoff in Cognitive Radio enabled Smart Grid
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Introduction

• Power grid challenges
  – rising demand
  – aging infrastructure
  – increasing greenhouse gas emission

• Smart grid
  – renewable & distributed energy resources
  – two-way communication
  – demand response
  – agile, reliable, efficient, secure, economy, and environmental friendly
Introduction (cont’d)

- big pictures of smart grid
Outline

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Sensing-Delay Delay Tradeoff
- Introduction

- A closed-loop system
  - input, feedback, controller, actuator and output

- Two-way communication
  - HAN: WiFi/ZigBee; NAN: Wifi; WAN: 3G/satellite/WiMAX
Sensing-Delay Tradeoff
- Introduction (cont’d)

• **Cognitive radio**
  – licensed/Primary User (PU)
  – unlicensed/Secondary User (SU)
  – SU can use “spectrum hole” when PU is absent
  – but vacate it instantly when PU is in operation
Sensing-Delay Tradeoff
- Introduction (cont’d)

• **Motivation**
  – data from smart meters will be up to tens of thousands of terabytes
  – conflict between spectrum scarcity and under-utilization

• **Cognitive radio enabled smart grid**
  – spectrum sensing/channel switching
  – to improve communication reliability/timeliness
  – home area network with cognitive radio (CogHAN)

• **Contribution**
  – cognitive radio to improve smart grid communication
  – optimal sensing time to reduce packet loss rate/delay
  – sensing-delay tradeoff through theorem/simulation
Sensing-Delay Tradeoff - System Model

- **Channel model**
  - In CogHAN, smart meters periodically transmit data to gateway
  - Two wireless channels:
    - One from unlicensed spectrum - original channel $Ch_1$
    - The other from licensed spectrum - cognitive channel $Ch_2$

- **Spectrum sensing/channel switching**
  - Assume $Ch_2$ is better than $Ch_1$, and smart meter can switch data transmission to $Ch_2$
  - $Ch_2$ is randomly occupied by PU
    - Spectrum sensing to detect the state of $Ch_2$ for opportunistic utilization
    - Detection probability $P_d$: the probability of detecting PU when it is in operation
Sensing-Delay Tradeoff - Theoretic Analysis

- Theorem 1
  - spectrum sensing before channel switching reduces collision probability on $\text{Ch}_2$, compared to that without sensing

- Framework of spectrum sensing before channel switching for CogHAN communication
Sensing-Delay Tradeoff
- Theoretic Analysis (cont’d)

- Probability of channel switching
  - $P_{sw}$ increases with sensing time $\tau$

- Packet loss rate/delay of CogHAN communication

$$\begin{align*}
L &= -(L_1 - L_2)P_{sw} + L_1 \\
D &= \tau - (D_1 - D_2)P_{sw} + D_1
\end{align*}$$

- where $L_1, D_1/L_2, D_2$ are packet loss rate/delay of $Ch_1/Ch_2$
  respectively

- Packet loss rate
  - $L$ decreases with sensing time $\tau$
Sensing-Delay Tradeoff
- Theoretic Analysis (cont’d)

• Delay

\[ D = \tau - (D_1 - D_2)P_{sw} + D_1 \]

– \( D \) decreases when \( \tau \) is small and increases when \( \tau \) is large
– tradeoff between sensing capacity and delay
– objective: to find optimal sensing time such that delay is minimized while PU is sufficiently protected

\[
\min_{\tau} D(\tau) \quad \text{s.t. } P_d(\tau) \geq \overline{P_d}
\]

– where \( \overline{P_d} \) is target probability to sufficiently protect PU

• Theorem 2

– for any target detection probability \( \overline{P_d} > 0.5 \), there exists unique optimal sensing time \( \tau^* \in [\tau_{min}, +\infty) \) which yields minimum delay of CogHAN communication
Sensing-Delay Tradeoff
- Numerical Results

- **Simulation setup**
  - $Ch_2$ is assumed to have bandwidth 6 Mhz. Noise is AWGN. We are interested in a low SNR = -15 dB

- probability of channel switching increases with sensing time
- packet loss rate decreases with sensing time
Sensing-Delay Tradeoff
- Numerical Results (cont’d)

- Sensing-delay tradeoff
  - delay first decrease and then increase with sensing time
  - there exists unique optimal sensing time with minimum delay
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Sensing-Performance Tradeoff
- Demand Response Management

- Smart distribution grid with one power provider, \( N \) power consumers and control unit
  - provider cost function \( C(s) \): increasing and convex
  - consumer utility function \( G_i(d_i) \): non-decreasing and concave
Sensing-Performance Tradeoff
- Demand Response Management (cont’d)

- Problem formulation
  - provider profit:
    \[ \max_s [ps - C(s)] \]
  - consumer profit:
    \[ \max_{d_i} [G_i(d_i) - pd_i] \]
  - social welfare:
    \[ \max_{s,\{d_i\}} [\sum_{i=1}^N G_i(d_i) - C(s)] \]
    s.t. \[ s \geq \sum_{i=1}^N d_i \]
  - distributed & iterative @
  - optimal: \[ s^* = \sum_{i=1}^N d_i^* \]

Sensing-Performance Tradeoff
- Communication Affects Control

- Communication outage $\zeta$
  - iteration: $p_{k+1} = [p_k - \gamma(s_k^* - (1 - \zeta)\sum_{i=1}^{N}d_{i,k}^*)]^+$
  - suboptimal: $\tilde{s} = (1 - \zeta)\sum_{i=1}^{N}\tilde{d}_i$

- price: $\tilde{p} = f^{-1}(1 - \zeta)$ where $f \triangleq \frac{(C')^{-1}}{\sum_{i=1}^{N}(G_i')^{-1}}$

- supply: $\tilde{s} = (C')^{-1}(\tilde{p})$
- demand: $\tilde{d}_i = (G_i')^{-1}(\tilde{p})$
- $(C')^{-1}$, $f^{-1}$ increasing, and $(G_i')^{-1}$ decreasing
- $\tilde{p} < p^*$, $\tilde{s} < s^*$, $\tilde{d}_i > d_i^*$

how outage affects provider/consumer profit/social welfare?
• **Two stages**
  - unit commitment: forward price $p_f = \tilde{p}$
  - economic dispatch: option price $p_o > \tilde{p}$

• **Communication affects control**
  - provider profit: $\tilde{P}_p = \tilde{p}\tilde{s} - C(\tilde{s}), \frac{\partial \tilde{P}_p}{\partial \zeta} < 0$
  - consumer profit: $\tilde{P}_c = \sum_{i=1}^{N} G_i(\tilde{d}_i) - \tilde{p}\tilde{s} - p_o (\sum_{i=1}^{N} \tilde{d}_i - \tilde{s}), \lim_{\zeta \to 0} \frac{\partial \tilde{P}_c}{\partial \zeta} > 0, \lim_{\zeta \to 1} \frac{\partial \tilde{P}_c}{\partial \zeta} < 0$
  - social welfare (control performance): $\Phi = \tilde{P}_p + \tilde{P}_c, \frac{\partial \Phi}{\partial \zeta} < 0$

Sensing-Performance Tradeoff
- Tradeoff

- Spectrum sensing reduces communication outage
  - energy cost by spectrum sensing $\varphi(\tau)$: increasing and convex
  - control performance $\bar{\Phi}(\tau)$: degradation incurred by communication outage

- Net revenue
  \[ R(\tau) = \bar{\Phi}(\tau) - \kappa \varphi(\tau) \]

- Sensing-performance tradeoff problem
  \[ \max_{\tau} R(\tau) \]
  \[ \text{s.t. } P_d \geq \bar{P}_d \]
  - tradeoff between control performance and communication cost
  - towards green smart grid
Sensing-Performance Tradeoff
- Tradeoff (cont'd)

- Theorem 1
  - there exists unique optimal sensing time $\tau^*$ with the maximum revenue

- Proof

\[
\lim_{\tau \to 0} \frac{\partial R}{\partial \tau} > 0, \quad \lim_{\tau \to +\infty} \frac{\partial R}{\partial \tau} < 0
\]
\[
\frac{\partial^2 R}{\partial \tau^2} < 0
\]

- Solution

\[
\mathcal{L}(\tau, P_d, \lambda) = \Phi(\tau) - \varphi(\tau) + \lambda(P_d - \bar{P}_d)
\]
\[
\frac{\partial \mathcal{L}}{\partial \tau} = \frac{\partial \mathcal{L}}{\partial P_d} = \frac{\partial \mathcal{L}}{\partial \lambda} = 0
\]
Sensing-Performance Tradeoff
- Numerical Results

- Cognitive radio improves communication quality
Sensing-Performance Tradeoff
- Numerical Results (cont’d)

- Communication quality affects control performance

\[ s^* = d^* \]
Sensing-Performance Tradeoff
- Numerical Results (cont’d)

- Sensing-performance tradeoff

![Graph showing sensing-performance tradeoff](image)
Sensing-Performance Tradeoff
- Conclusion & Future Work

• **Conclusion**
  - cognitive radio improves communication
  - communication quality affects control performance
    • communication outage reduces provider profit and social welfare
    • however, it may not always decrease consumer profit
  - unique optimal sensing time tradeoff between control performance and communication cost

• **Future work**
  - impact of supply uncertainty on demand response management
  - impact of supply uncertainty and communication unreliability
Thank you!