UNIVERSITY OF ALBERTA

Wireless Networking in Smart Grid

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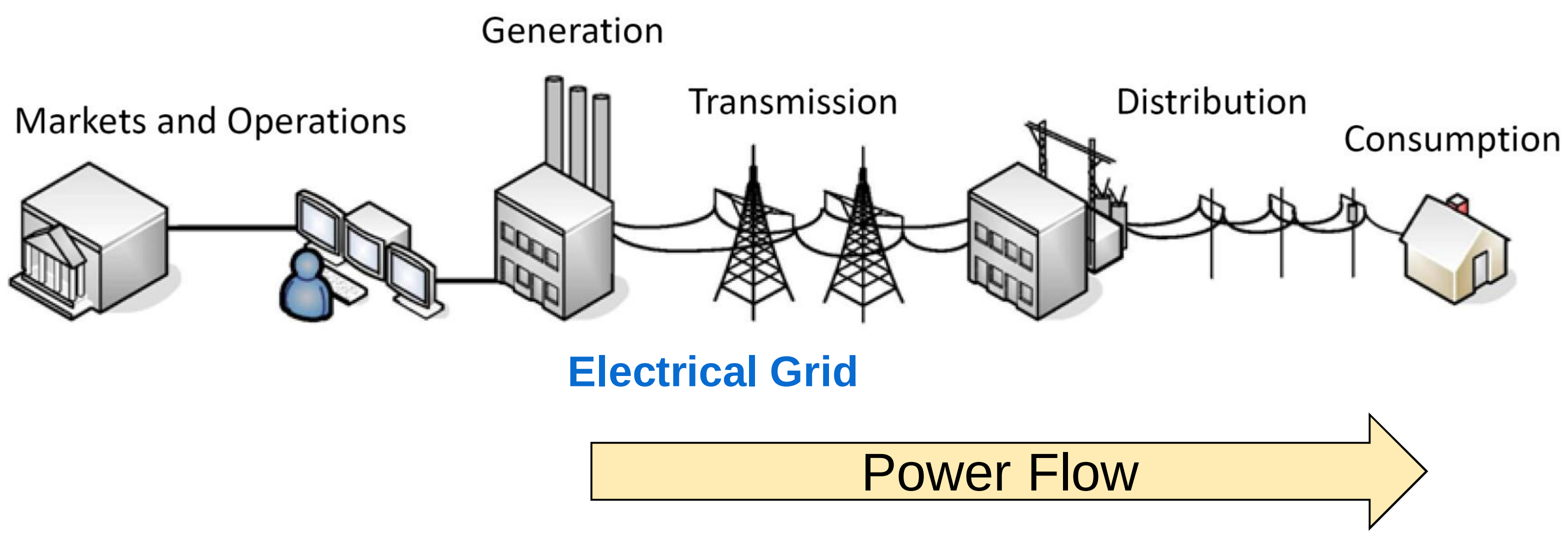
Outline

- What is smart grid?
- Why smart grid?
- Wireless networking for decentralized microgrid
  - What is microgrid?
  - Fault recovery
  - Economic dispatch
  - Droop control
- Conclusions
- Future research topics

Traditional Electrical Grid

- **Electricity is an essential part of our daily lives**
  - Electrification was called “the greatest engineering achievement of the 20th Century” by the US National Academy of Engineering (NAE)



- **Four main domains of electrical grid**
  - Power generation / production
  - Power transmission
  - Power distribution
  - Power consumption / load

Issues of Traditional Electrical Grid

- Vertically integrated, hierarchical, unidirectional power flow
  - Customers (e.g. hospitals, industries, residential communities) play a passive role, and their operations heavily depend on the electrical grid

  Requirement: power supply = power demand
  Imbalance between supply and demand leads to blackouts
  - **August 14, 2003 Northeast America blackout**
  - **July 2012 India blackout**

- Limited and centralized command-and-control functions, no control beyond distribution network to end customers
  - Significant power is lost during transmission and distribution
  - Customers are not equipped for efficient use of power

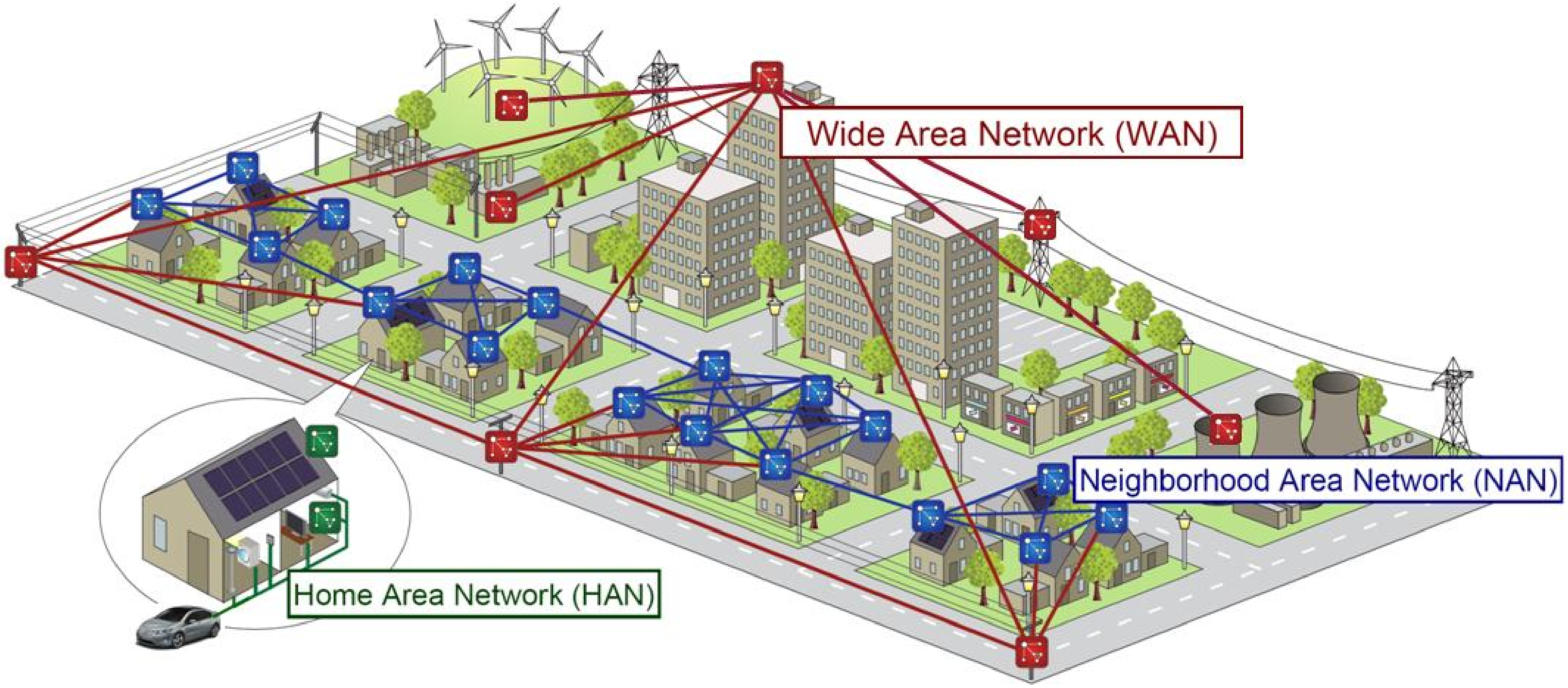
- Lack of renewable energy: generation dominated by fossil fuels

What is Smart Grid

US Department of Energy (DOE) definition – “An automated, widely distributed **energy delivery network characterized by a two-way flow of electricity and information**, capable of monitoring and responding to changes in everything from power plants to customer preferences to individual appliances”

Other definitions by – Alberta Federation of Rural Electrification Associations (AFREA), Ontario Independent Electricity System Operator (IESO), UK Department of Energy and Climate Change (DECC), etc.

Smart Grid – Physical Architecture



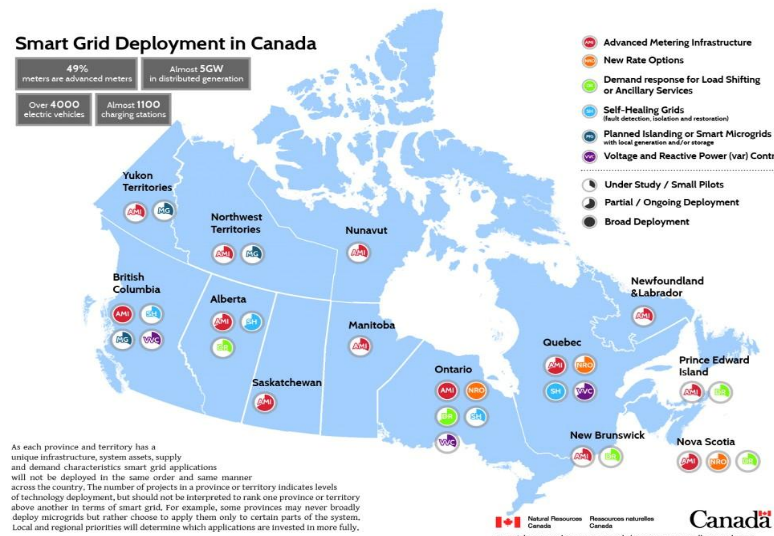
http://www.fluidmesh.com

- HAN: <u>ZigBee</u>, WiFi, power line communications (PLC)
- NAN: ZigBee, <u>WiFi</u>, <u>WiMax</u>, cellular (e.g., GPRS, 3G, and LTE)
- WAN: <u>Fiber optics</u>, microwave, cellular

Why Smart Grid

- **Benefits of smart grid (the US case, source: IEEE Smart Grid)**
  - The cost of nationwide smart grid ranges around \$20 to \$25 billion per year, over a 20-year period
  - Right off the bat, the benefits are \$70 billion per year, including:
    - Reducing the costs of outages by about \$49 billion per year
    - Increasing system efficiency by at least 4 percent (\$20.4 billion per year)
    - Reducing CO_2 emissions by 12-18% by 2030

http://www.sgiclearinghouse.org/



http://www.globalsmartgridfederation.org/

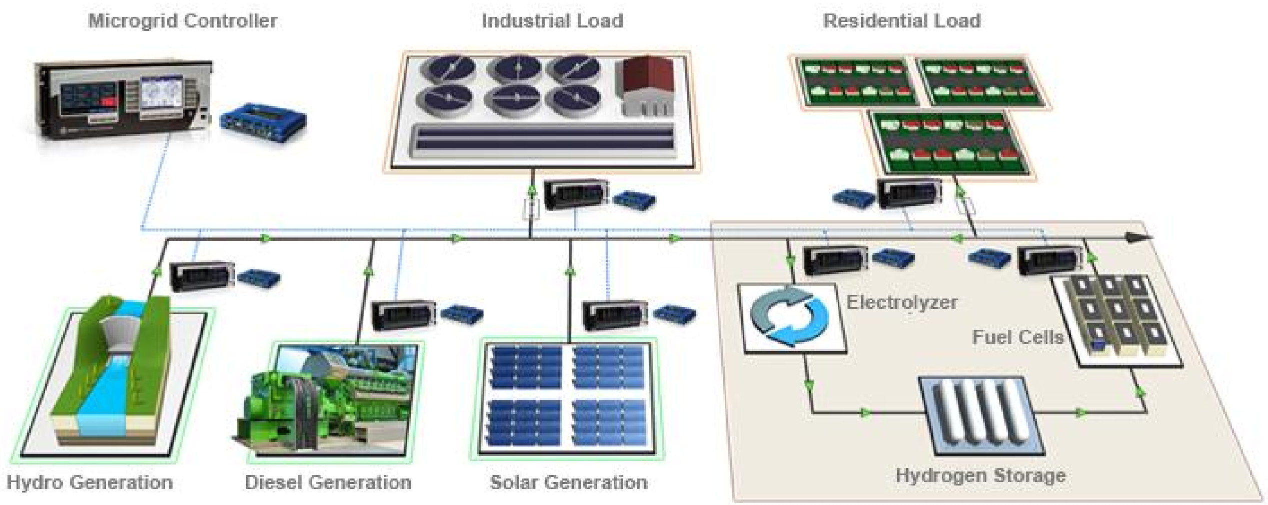
Wireless Networking for Decentralized Microgrid

- What is microgrid?
- Fault recovery
- Economic dispatch
- Droop control

What is Microgrid?

Definition by Electric Power Research Institute (EPRI)

- A microgrid is a small power system composed of one or more DG units that can be operated independently from the bulk power system



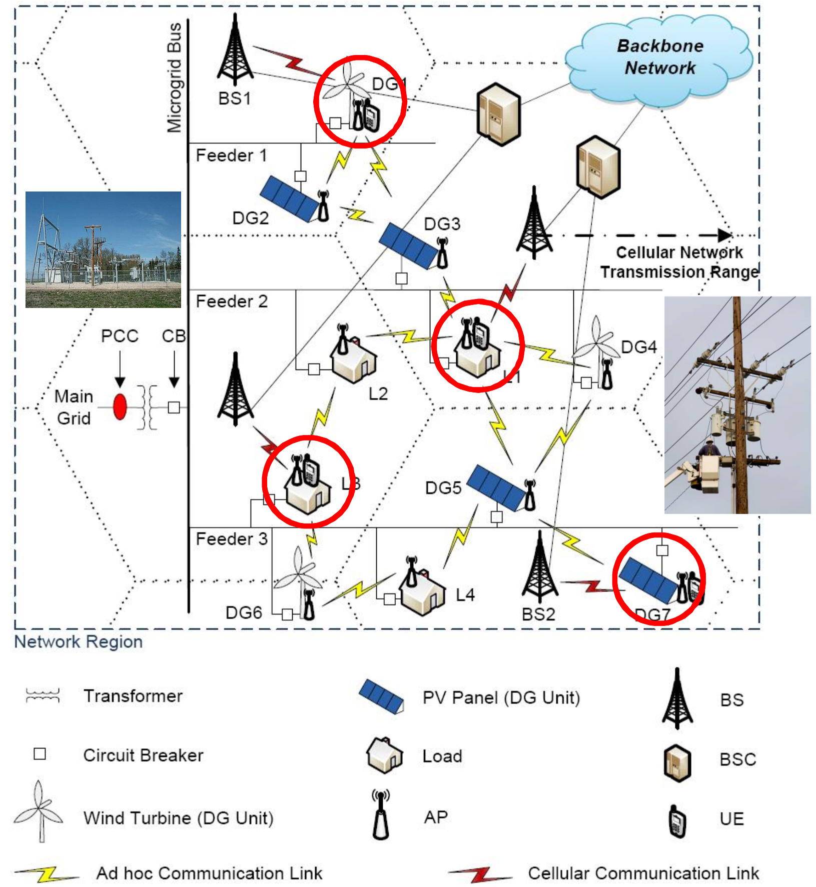
- Number of customers served: up to 50,000 (industrial, residential, and/or commercial)
- Peak load: up to 100 MW
- Area covered: up to 10 square kilometers

A Historical Perspective

- 1880-1910: Early power systems were predominately “simple” microgrids (a single generation plant serves a small area)
- 1910-1950: Early microgrids were phased-out due to the performance advantages of bulk power system
- Today: New technologies, reliability issues, and environmental issues make microgrid viable again
  - Challenge I: The renewable DG output is intermittent in nature, so that the microgrid requires an efficient communication and control strategy
  - Challenge II: The size/scale of DG unit is small, so that the microgrid requires a low-cost (in terms of low deployment and operation costs) communication network solution

Cooperative Wireless Networking for Microgrid

- A low-cost and short-range wireless ad hoc network (e.g., ZigBee or WiFi network) is used as a basic network infrastructure
- A cellular network is used as an auxiliary network infrastructure, but with additional monetary cost
- Some nodes are **dual-mode** (highlighted by red circles in the figure)
- The two kinds of networks can **operate in a coordinated way**, depending on the performance requirements of microgrid operation, control, and protection



Wireless Networking for Decentralized Microgrid

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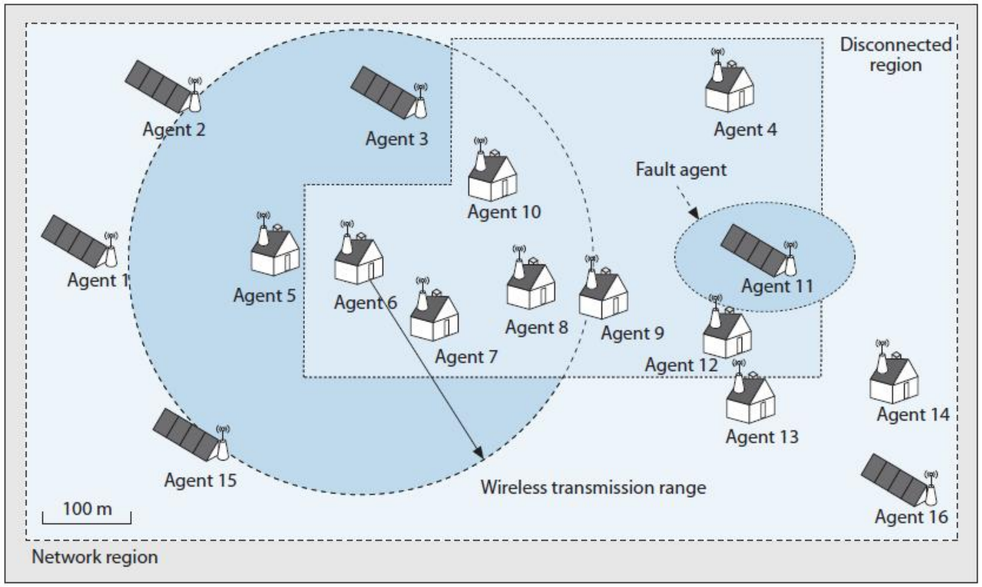
Microgrid Fault Recovery

- Denote each microgrid bus (i.e., DG unit, distributed storage (DS) unit, and/or load connection point) as an agent
- Whenever a fault occurs, the microgrid enters the **fault recovery** (or **self-healing** if the recovery is automatic) mode
- The protection system immediately opens a few circuit breakers to disconnect (or isolate) a few agents close to the fault while keeping the other agents in normal operation



Example:

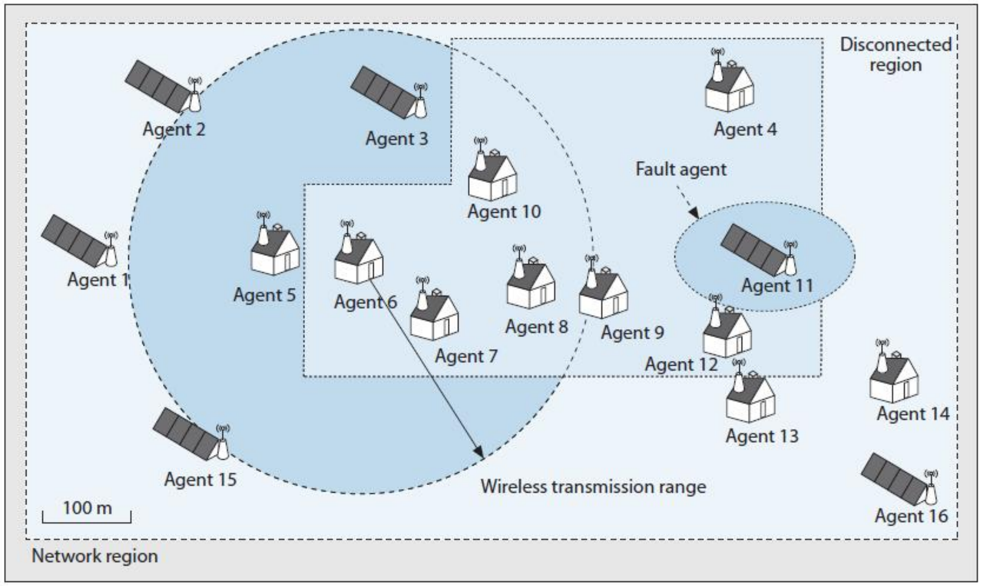
Number of agents: 16

Fault agent: 11

Disconnected agents: 4, 6, 7, 8, 9, 10, 11, 12

Microgrid Fault Recovery (Cont'd)

- An information discovery process is performed to discover the **excessive generation** (i.e., the redundant power not used by the loads) in the unfaulted region and the **loads which are ready-for-recovery** in the disconnected region
- If the excessive generation **exceeds** the ready-for-recovery loads, the loads can be **restored** by closing the opened circuit breakers



Example (Cont'd):

Net power (MW) of agent 1-16: 40 40 50 -25 -35 -20 -15 -25 -5 -30 40 -45 -10 -40 30 50

Excessive generation (MW): 40 + 40 + 50 - 35 - 10 - 40 + 30 + 50 = 125

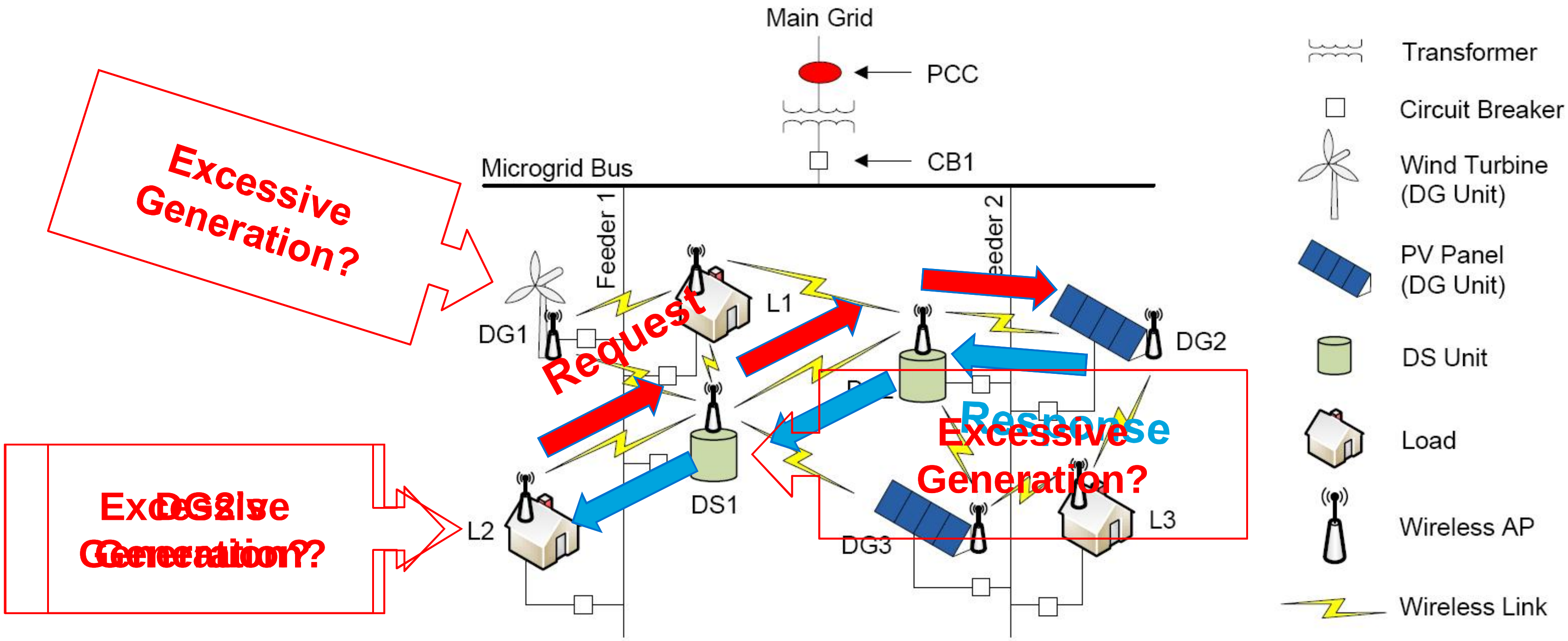
Ready-for-recovery agents: 6, 8, 9

Loads ready-for-recovery (MW):
20 + 25 + 5 = 50 (the loads can be restored)

(Note: Priority can be assigned if more loads are ready-for-recovery.)

Decentralized Microgrid Fault Recovery

- **Motivation and Challenge**
  - Use low-cost, short-range wireless communication (e.g., WiFi and ZigBee) devices for microgrid fault recovery.
  - NO central controller to reduce cost and avoid a single point of failure
  - Challenge: Each agent needs some information for decision making



Multiagent Coordination

Objective: To discover global information, e.g., excessive generation. (The ready-for-recovery loads can be discovered in a similar way)

Key features:

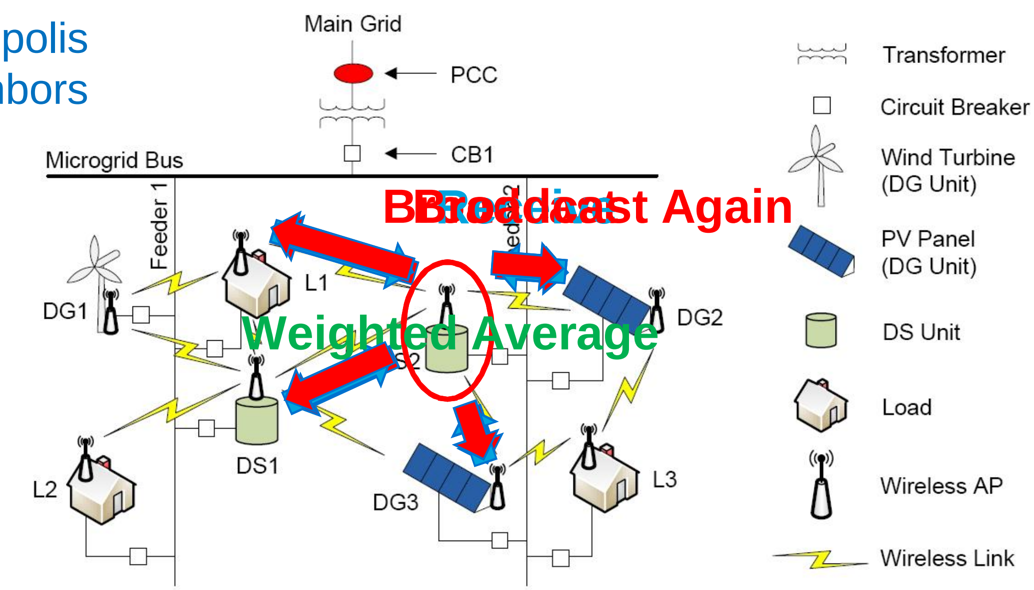
1) Fully decentralized. Communications only need to be established among the neighboring agents;
2) Guaranteed convergence based on average consensus theory. Initial value: local generation of each agent, 0 for agents in disconnected region. Converged value: excessive generation divided by the number of agents (known in advance)

The weight is calculated based on the Metropolis method, which exploits the number of neighbors of each agent to provide a fast convergence

$$\boxed{X(v,t_k)} = \sum_{n\in\mathcal{V}} \boxed{\omega_{\mathcal{V}}(v,n)}\,\boxed{X(n,t_{k-1})}$$

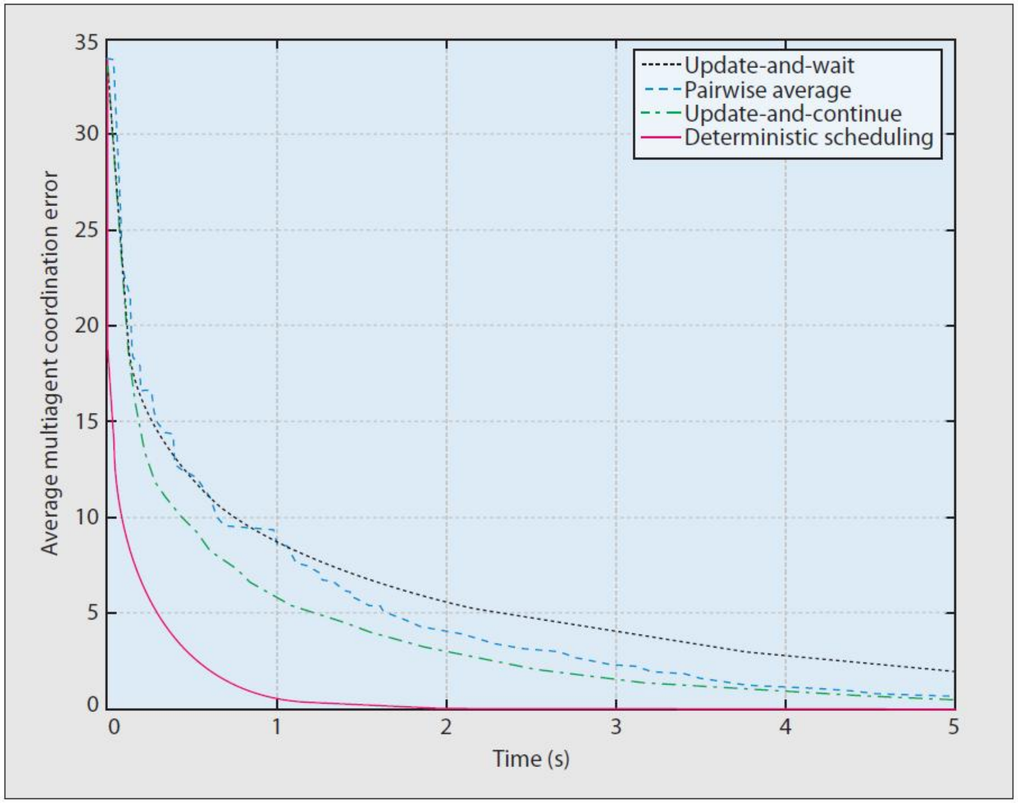
Excessive generation value kept by agent v in the kth iteration

Excessive generation value kept by agent n in the $(k\text{-}1)$th iteration



A Case Study

- The simulator is developed based on the ns-2 IEEE 802.11 MAC implementation. Each net power value is represented by 16 bits



Average multiagent coordination error (root-mean-square error) versus time.

- Update-and-wait: After each broadcast, an agent waits until the next iteration begins (straightforward application of IEEE 802.11 MAC)
- Pairwise average: Each iteration of multiagent coordination only involves one neighbor (instead of all neighbors), but the waiting time is reduced in comparison with update-and-wait
- Update-and-continue: Each agent starts to transmit the updated information to its neighbors whenever a local update is completed (instead of waiting)
- Deterministic scheduling: Utilize network topology information to design optimal TDMA schedule

Wireless Networking for Decentralized Microgrid

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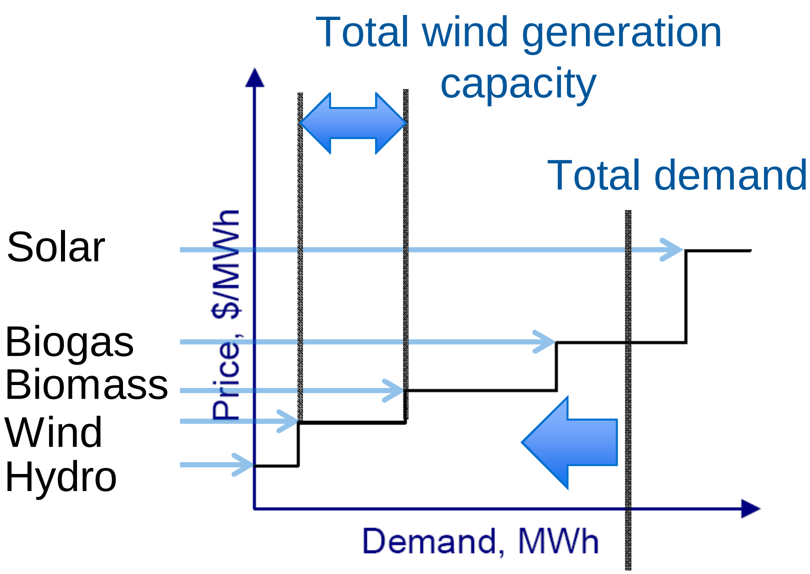
- Fault recovery
- Economic dispatch
- Droop control

Decentralized Economic Dispatch

Objective: To schedule the power generation of DG units in a decentralized manner such that the electrical loads are served at the minimum cost

Assumptions: 1) Self-sustained (islanded) microgrid; 2) Dispatchable DG units

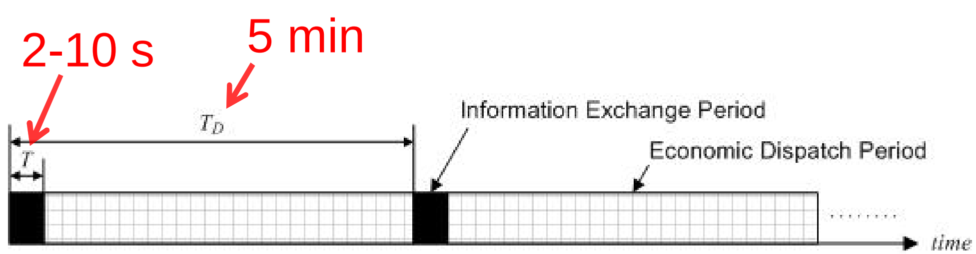
Theorem: The economic dispatch problem can be solved based on multiagent coordination (given generation costs, total generation capacity of each type of generators, and total demand)



Economic dispatch

Challenges: Slow convergence for a large network

- Less accurate information for economic dispatch
- More expenditure on ancillary services

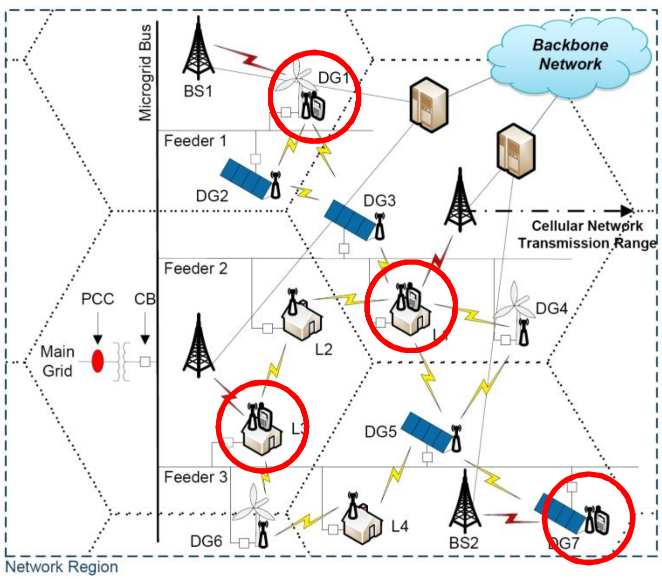


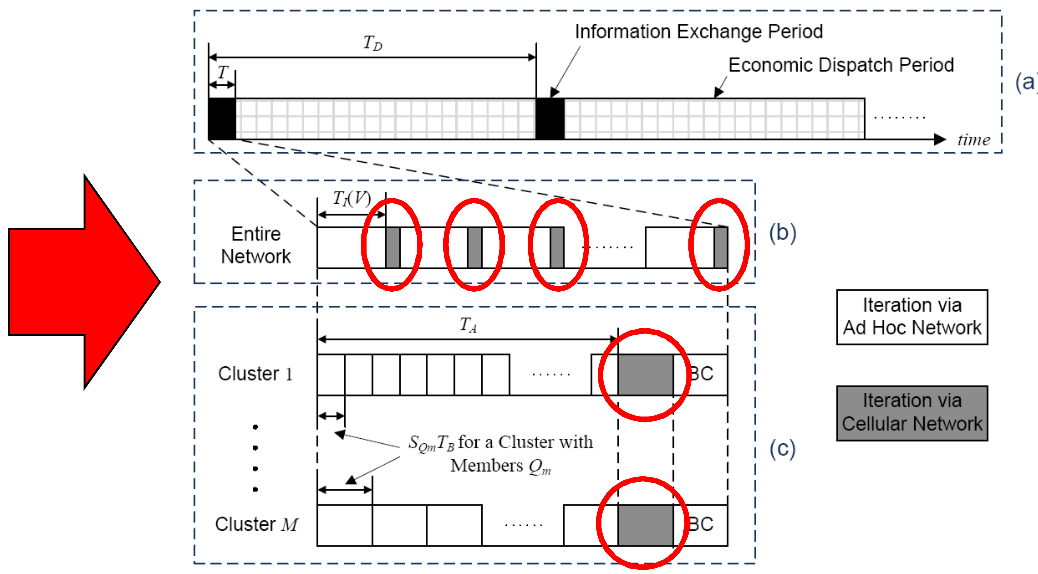
Economic dispatch with wind/solar integration (Source: CAISO)

Decentralized Economic Dispatch (Cont'd)

Key feature: Cellular communication devises are optionally activated to improve the convergence speed (within 2-10s for information exchange)

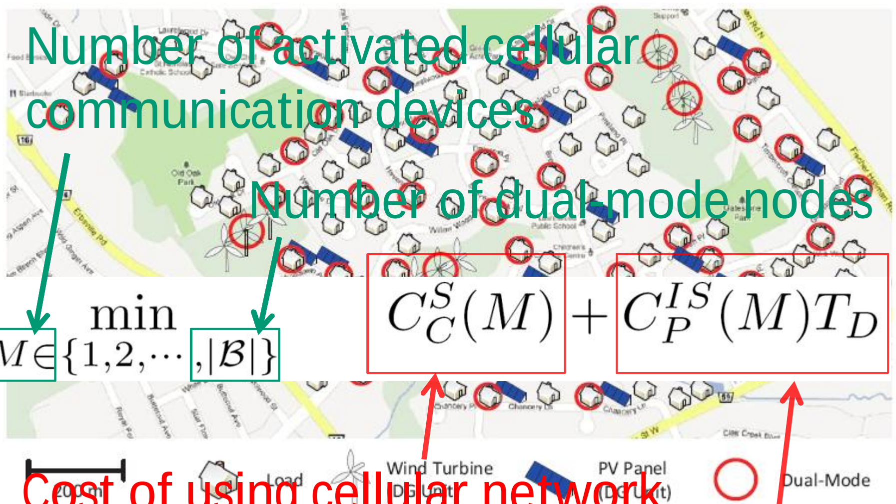
Two schemes: Single-stage multiagent coordination (Subfigure (b)) and hierarchical multiagent coordination (Subfigure (c))





A Case Study

- A case study based on Laurelwood neighborhood in Waterloo Region
- Demand: Smart meter readings
- Wind generation: Canadian wind energy Atlas; Solar generation: NREL
- Pricing: Ontario FIT program
- Communication network: WiFi + 3G with Rogers Canada basic plan



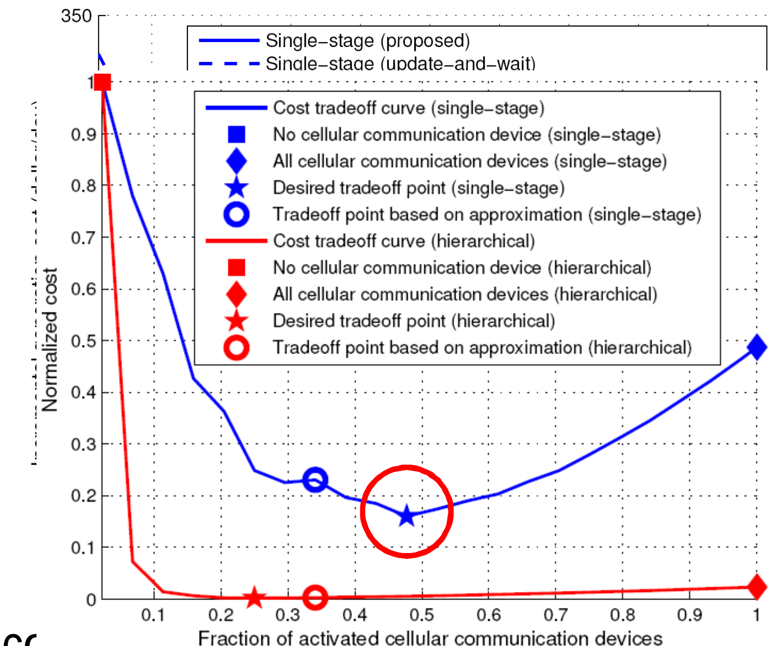
Number of activated cellular communication devices

Number of dual-mode nodes

$$\min_{\boxed{M}\in\{1,2,\cdots,\boxed{|\mathcal{B}|}\}} \boxed{C_C^S(M)} + \boxed{C_P^{IS}(M)T_D}$$

Cost of using cellular network

Incremental generation cost



Incremental generation cost = Actual generation cost (via wireless networks)

– Minimum generation cost (with perfect information)

Wireless Networking for Decentralized Microgrid

– What is microgrid?

– Fault recovery

– Economic dispatch

– Droop control

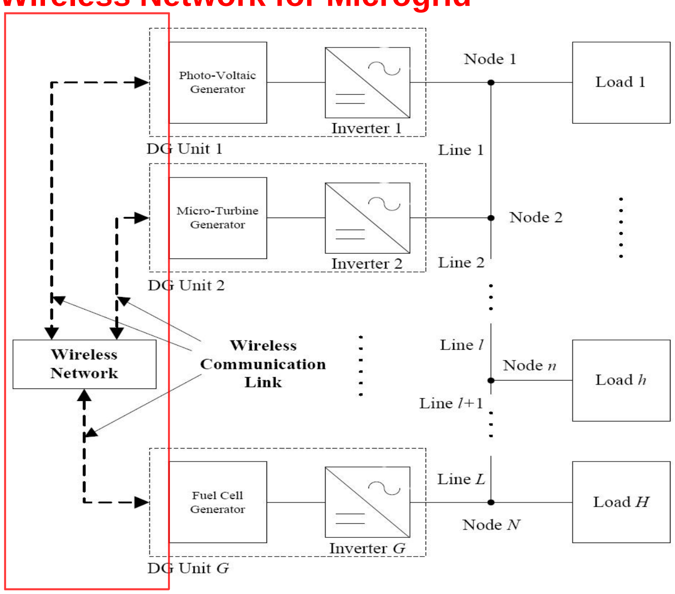
Decentralized Droop Control

Objective: To achieve power sharing in a decentralized manner while maintaining the microgrid stability (given the economic dispatch decision)

Multiagent coordination: 1) To discover the total power generation in microgrid; 2) Compatible with the decentralized economic dispatch approach

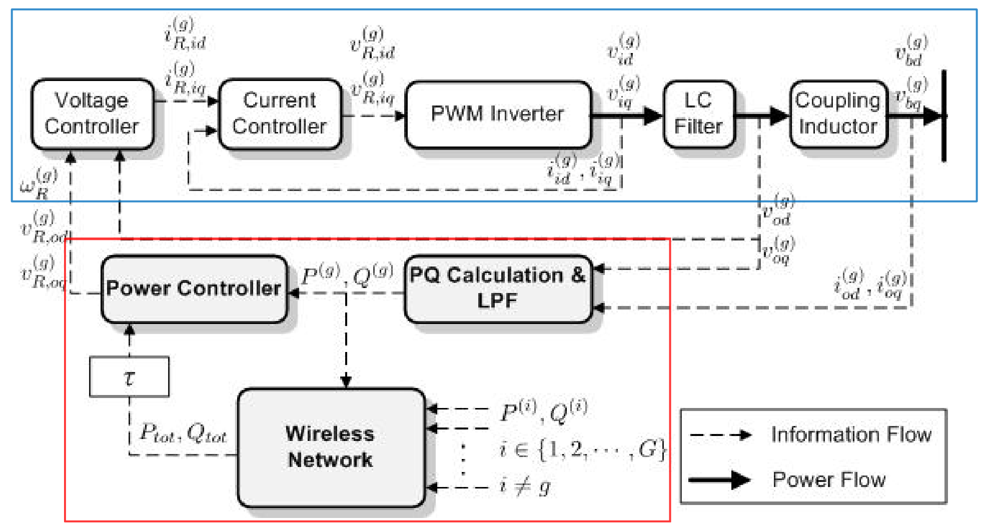
Key feature: 1) Take advantage of the low-cost short-range wireless network to improve microgrid stability; 2) Delay tolerant

Wireless Network for Microgrid



Network Configuration

Blocks of Traditional Inverter Controller



New Blocks based on Wireless Network

Inverter Controller

Additional Information

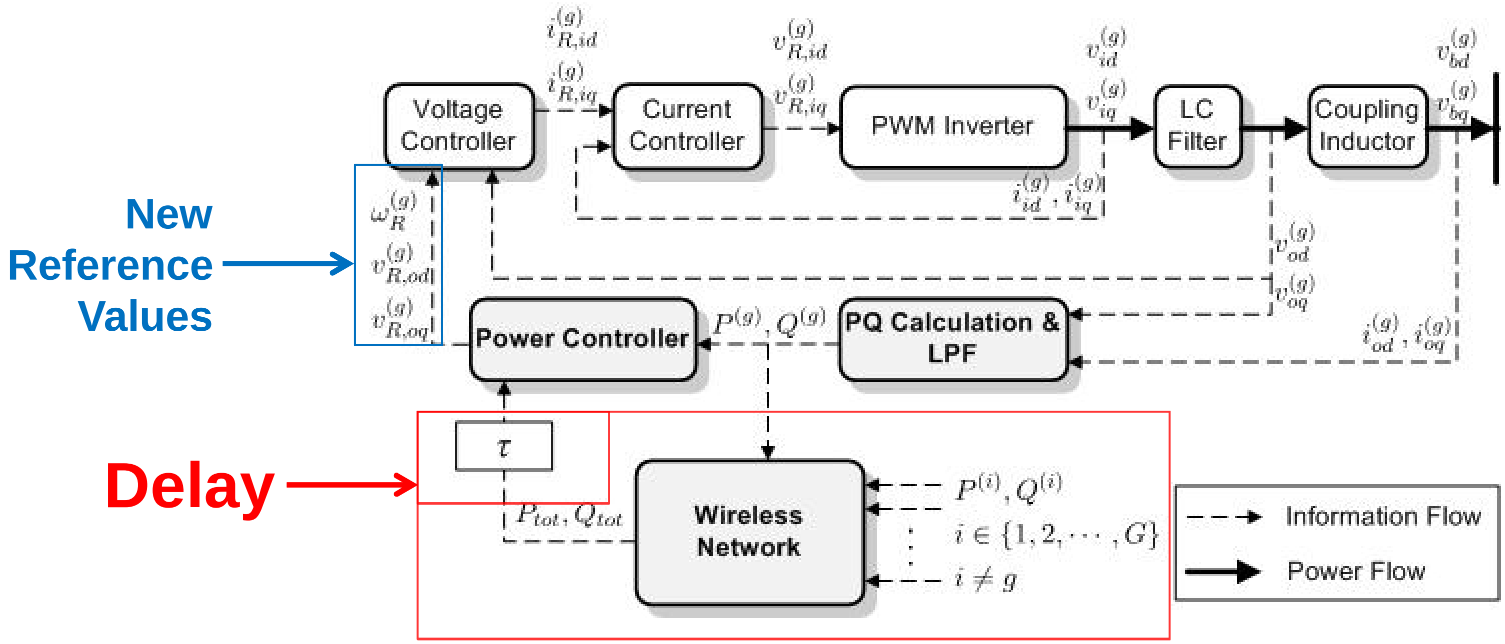
- The multiagent coordination based control strategy utilizes the information with respect to the total active and reactive power generation of all DG units

$$P_{tot} = \sum_{i=1}^{G} P^{(i)} \qquad Q_{tot} = \sum_{i=1}^{G} Q^{(i)}$$

- The desired sharing of active and reactive power by DG unit *g* (pre-configured based on economic dispatch)

$$\alpha_P^{(g)} \quad \alpha_Q^{(g)} \qquad \sum_{g=1}^{G} \alpha_P^{(g)} = 1 \quad \sum_{g=1}^{G} \alpha_Q^{(g)} = 1$$

Power Sharing Based Control Strategy



- The **new reference frequency and voltages** of inverter g are, respectively, given by

Real Power Sharing Gain

$$\omega_R^{(g)} = \omega_{R-dr}^{(g)} + \boxed{K_{P-sh}^{(g)}}[\alpha_P^{(g)} P_{tot} - P^{(g)}]$$

$$v_{R,od}^{(g)} = v_{R-dr,od}^{(g)} + \boxed{K_{Q-sh}^{(g)}}\int[\alpha_Q^{(g)} Q_{tot} - Q^{(g)}]dt$$

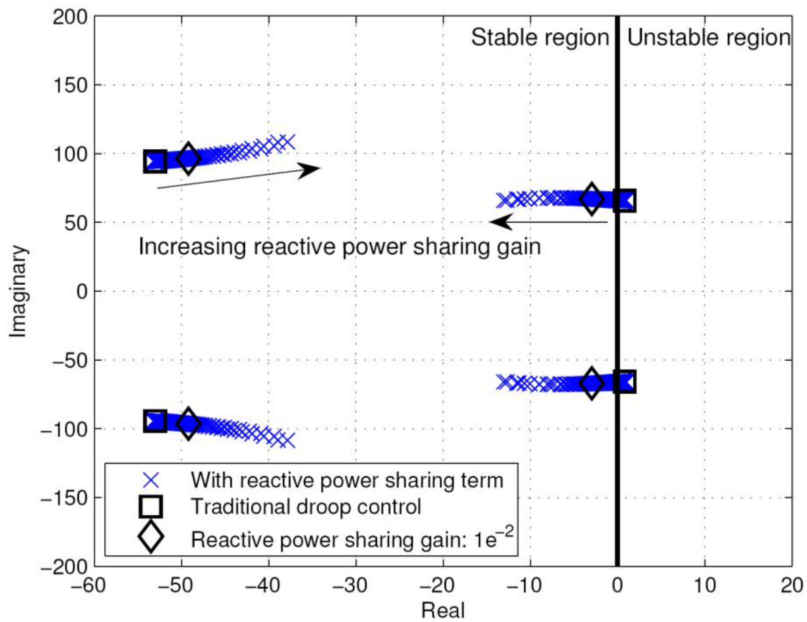
$$v_{R,oq}^{(g)} = 0$$

Reactive Power Sharing Gain

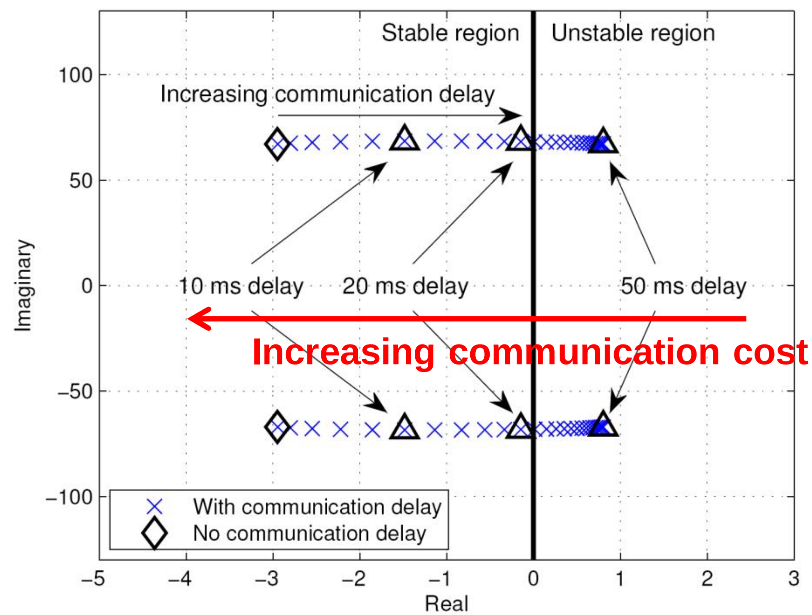
The advantage of using the information of total active and reactive power generation?

A Case Study

- A case study based on a small-scale test microgrid with three generators, two lines, and two loads
- Eigenvalue analysis (for small-signal stability)



No communication delay



With communication delay

Potential delay reduction based on cooperative wireless networking!

There is a tradeoff between microgrid stability and communication cost.

Conclusions

- Wireless networking creates a more affordable/cost-effective path for smart grid deployment, in comparison with the wireline (e.g., fiber-optic) counterparts

- For isolated remote communities without a communication network infrastructure, wireless networking is a main choice

- Benefits and significance of cooperative wireless networking for decentralized fault recovery, economic dispatch, and droop control in microgrid
  - Utility: Microgrid operation can be achieved based on wireless communication devices at a low deployment cost and the minimum operation cost
  - Environment: The use of traditional thermal energy power generators can be reduced via a better utilization of the renewable energy sources
  - Customers: Enjoy reduced electricity bills and higher system reliability which, in turn, promote the use of the renewable energy sources

Future Research Topics

- Cooperative wireless networking
  - Distribution automation - network reliability improvement
  - Transportation electrification - network coverage expansion
  - Wide-area situational awareness - communication delay reduction
- Cyber security and electricity customer privacy
  - False/bad data detection for cyber-physical security
  - Fine-grained access control for customer privacy preserving
- Stochastic information management
  - Randomness in renewable power generation
  - Buffering effect of energy storage devices
  - High mobility of electric vehicles

References

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