Coalitional Game Theory for Micro-Gird Distribution Networks

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Smart Grid

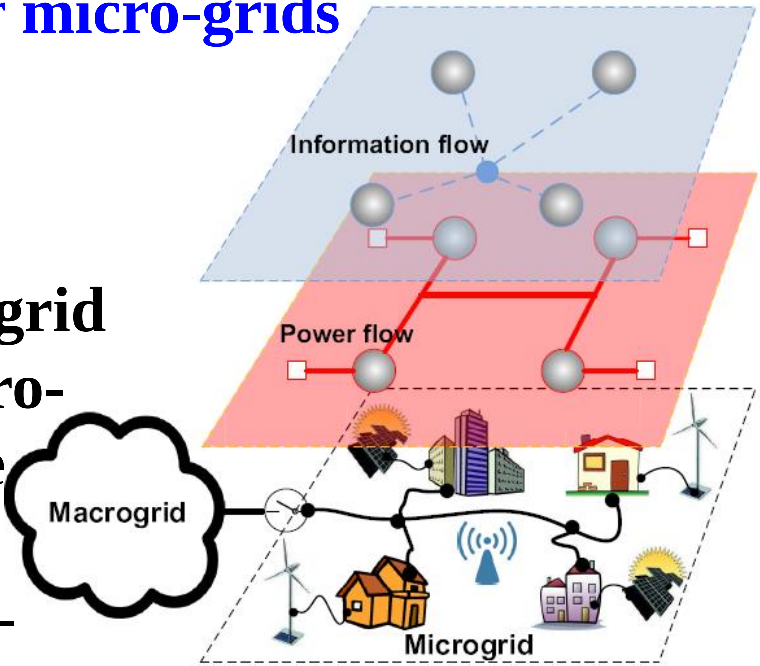
- Key features:
  - Integration of microgrids, diverse generation and storage resources
  - Incorporating "smart" demand-side management,
  - The three "s": self-healing, self-optimizing, self-configuring
  - Communications: **handling** large amounts of data and **securing** this data (e.g., PMU data)

- Many definitions found: IEEE, DOE, Wiki, FERC
- **We are continuously defining the smart grid through research!**

Micro-grid Distribution Networks

- Components
  - Electrical substations that link to the high voltage **transmission network**
    - Composed of transformers and serving an area or city
  - Distribution wiring
    - Distributed energy sources or **micro-grids**

    E.g., Solar or Wind farms
- Role of micro-grids
- Can act autonomously and/or in coordination with the main **macro-grid**
- Serve as a backup to the main **macro-grid** whenever there is an extensive demand
- Can request energy from the macro-grid, if needed to service small areas

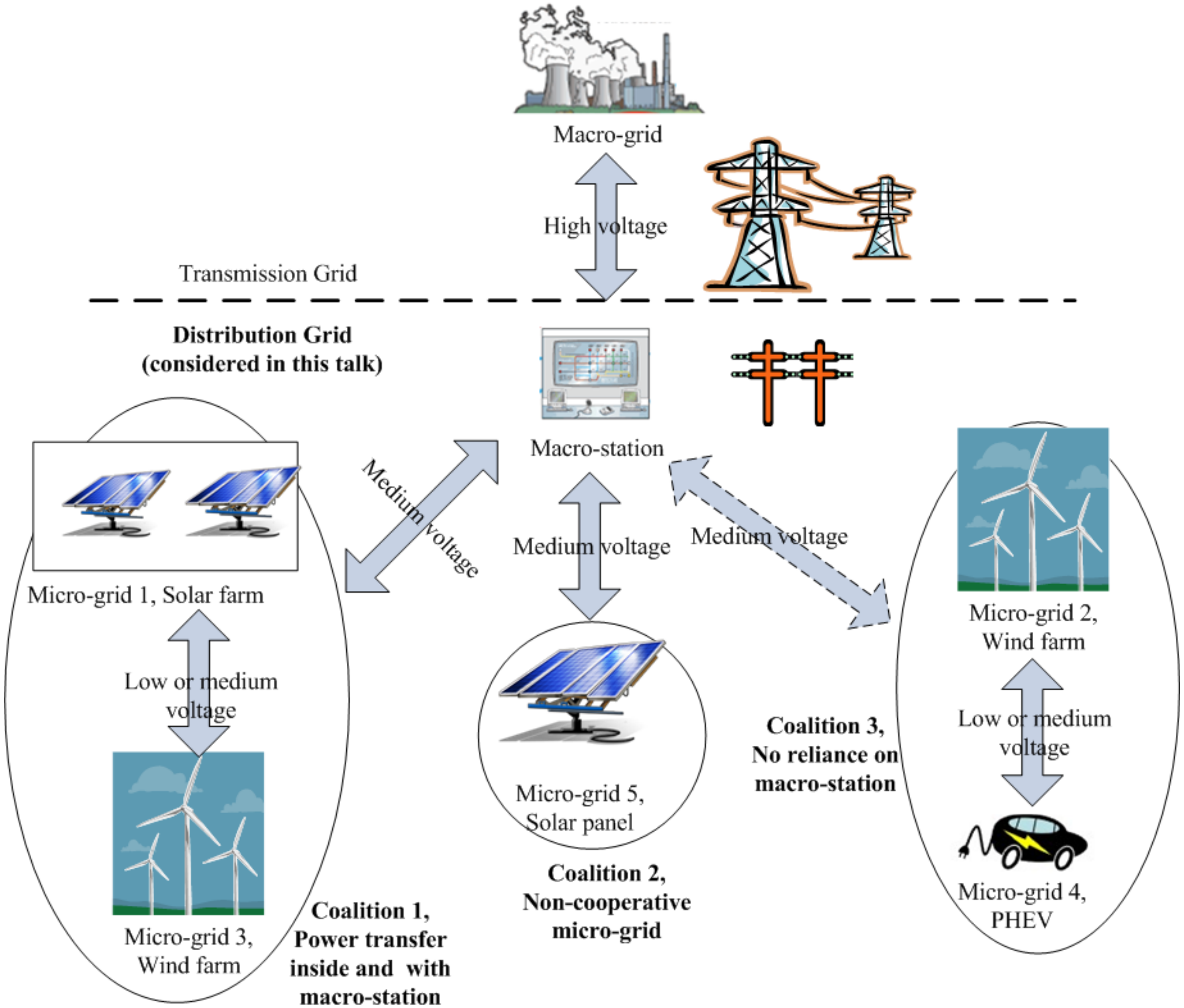


Micro-grid networks: Challenges

- When should the micro-grid energy sources act on their own or coordinate with the grid?
  - Control theory is useful to study distributed decisions of the micro-grids
- Which areas should the micro-grids service?
  - Depends on demand and supply as well as the possible use of storage
- **How can the micro-grids interact to trade energy within a local exchange market?**
  - If micro-grids are "smart" and equipped with communication capabilities, they can interact and possibly trade energy

System model

- Energy trading at the distribution network
- Cooperation needed to:
  - **Exchange energy:** sell surplus and overcome deficiency
  - **Save wasted power** over the transmission lines in the micro-grid
- Coalitional games!



Motivation for Game Approach

- What is Game Theory?
  - The formal study of conflict or cooperation
  - How to make an adversarial decision
  - Modeling mutual interaction among players that are rational decision makers

- Components of a “game”
  - **Rational Players** with conflicting interests or mutual benefit
  - **Strategies** or Actions
  - **Solution** or Outcome

- Nobel prizes
  - Nobel prize in Economic Sciences 1994 awarded to **Nash**, **Harsanyi** (Bayesian games) and **Selten** (subgame perfect equilibrium)
  - 2005, **Auman** and **Schelling,** 2007 **Leonid Hurwicz, Eric Maskin and Roger Myerson** ….

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Coalitional Games Preliminaries

- Coalitional game (*N*,*v*)
  - A set of players ***N*, *a coalition*** S is a group of cooperating players
  - Value (utility) of a coalition ***v***
  - User payoff x_i : the portion received by a player ***i*** in a coalition S
- Transferable utility (TU)
  - The worth ***v(S)*** of a coalition *S* can be distributed arbitrarily among the players in a coalition hence,
  - ***v(S)*** is a function over the real line
- Non-transferable utility (NTU)
  - The payoff that a user receives in a coalition is pre-determined, and hence the value of a coalition cannot be described by a function
  - ***v(S)*** is a set of payoff vectors that the players in *S* can achieve

$$v(S) \subseteq \mathbb{R}^{|S|}$$

Cooperative Eavesdropping: Gains

- Consider a coalition *S* of micro-grids
  - The micro-grids are divided into **sellers and buyers**
  - Consider an ordering π over the buyers in *S*
  - Inside *S*, each buyer attempts to buy from the seller that yields the **smallest power loss**
- For a given π, the losses over the distribution lines due to *S* can be given by (S_s subset of sellers, S_b subset of buyers):

$$u(S,\Pi) = -\left(\sum_{i\in S_s, j\in S_b} P_{ij}^{\text{loss}} + \sum_{i\in S_s} P_{i0}^{\text{loss}} + \sum_{j\in S_b} P_{j0}^{\text{loss}} \right)$$

Losses for power exchange between seller *i* and buyer *j* which depends mainly on the demand, the resistance and the voltage for distribution

Power loss between seller i and the macro-grid (depends on transformer losses, surplus, and resistance)

Power loss between buyer *j* and the macro-grid (depends on transformer losses, energy need, and resistance)

Coalitional game formulation: Value function

- Given these power losses, for any coalition S, we define the value function as

$$v(S) = \max_{\Pi \in \mathfrak{T}_S} u(S, \Pi)$$

  - The maximum is over all orderings of buyers
- The utility represents a **cost paid** per unit of **power loss**, hence, it can be considered as transferable utility
- To divide the utility between the players, we adopt a fair division proportional to the non-cooperative utility of each user:

$$\phi_i = \alpha_i \left(v(S) - \sum_{j \in S} v(\{j\}) \right) + v(\{i\}),$$

Weight chosen according to micro-grid *i*'s non-cooperative utility

Coalition Formation: Merge and Split

- Define the Pareto order preference relation between two collections of coalitions *R* and *S*

$$\mathcal{R} \triangleright \mathcal{S} \Longleftrightarrow \{\phi_j(\mathcal{R}) \geq \phi_j(\mathcal{S})\ \forall\ j \in \mathcal{R}, \mathcal{S}\},$$

with *at least one strict inequality* $(>)$ for a player k.

- **Merge rule:** merge any group of coalitions where

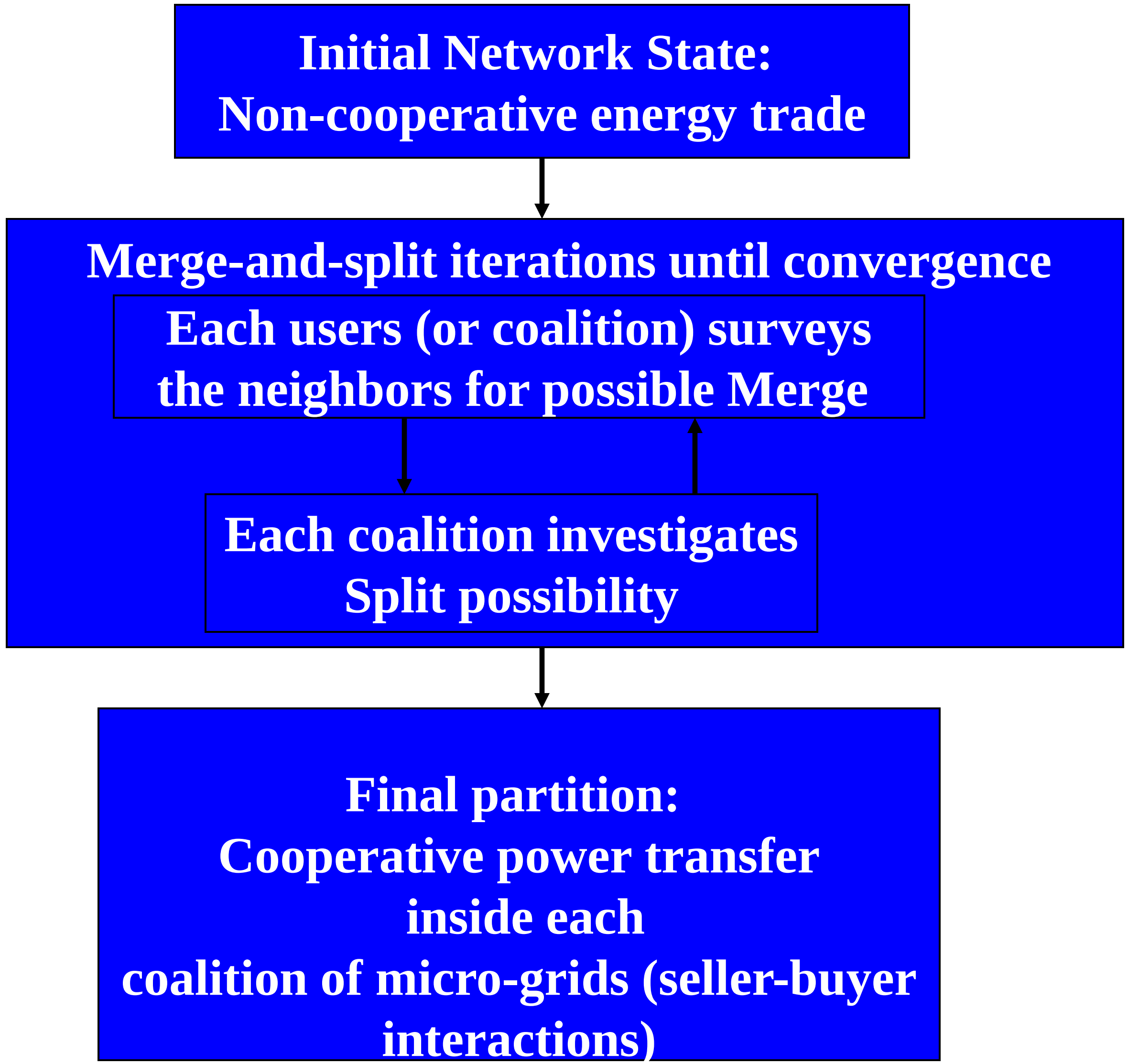
$$\{\cup_{j=1}^{l} S_j\} \triangleright \{S_1, \ldots, S_l\}$$

- **Split rule:** split any group of coalitions where

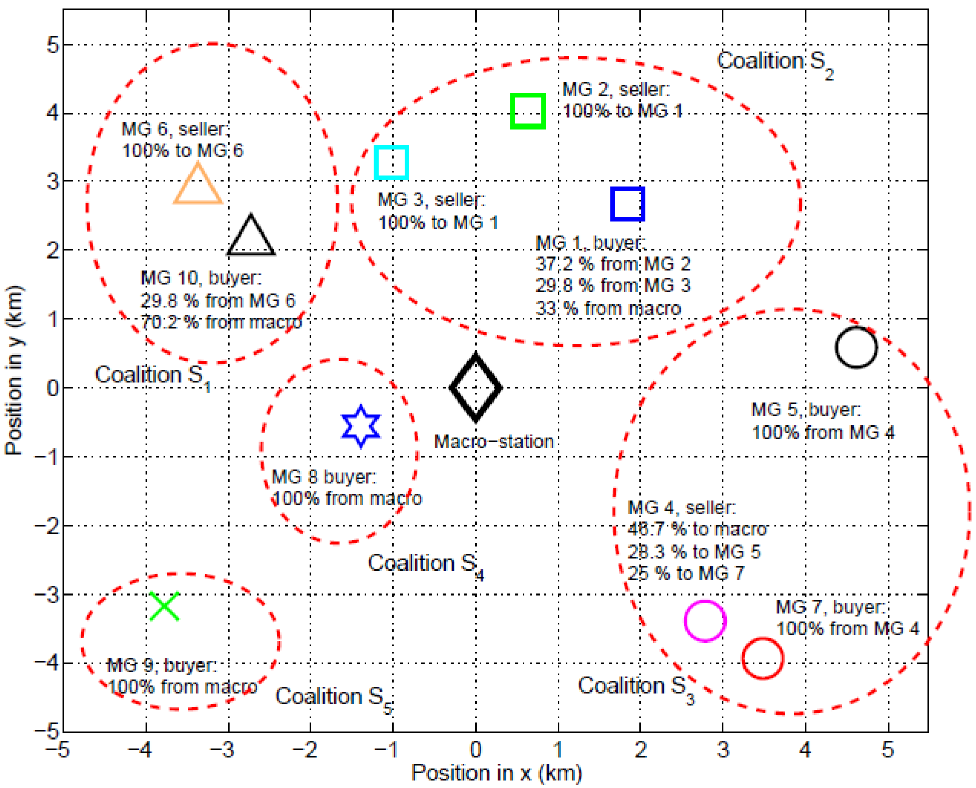
$$\{S_1, \ldots, S_l\} \triangleright \{\cup_{j=1}^{l} S_j\}$$

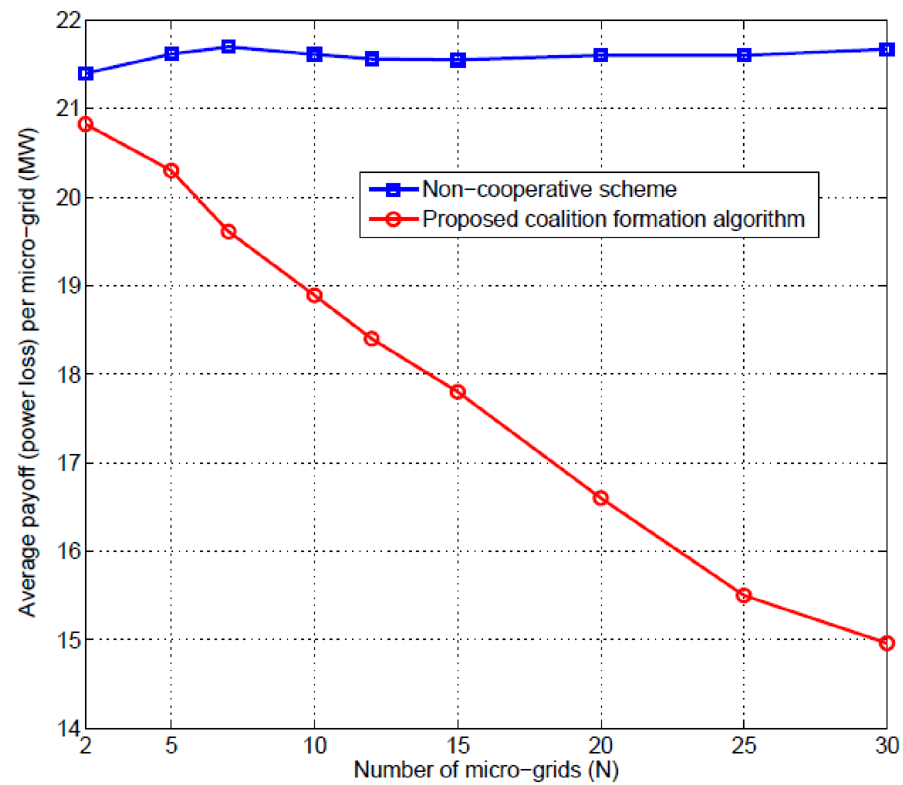
- A decision to merge (split) is an agreement between all players to form (break) a new coalition

Coalition formation algorithm



Simulation results





Summary

- Cooperative energy trading in micro-grid networks can be enabled using **coalitional games**
- Coalition formation for cooperative energy trading
  - Reduce the power losses over distribution lines and/or transformers
  - Create a local energy exchange market between micro-grids
  - Enable the micro-grids to better serve their consumers
- Future work
  - Capturing the seller-buyer interactions using auctions
  - Other types of games
  - Studying pricing schemes

Finally….

Thank You