Cooperative Game Theory for Cognitive Radio

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Gamecomm, 5/16/11

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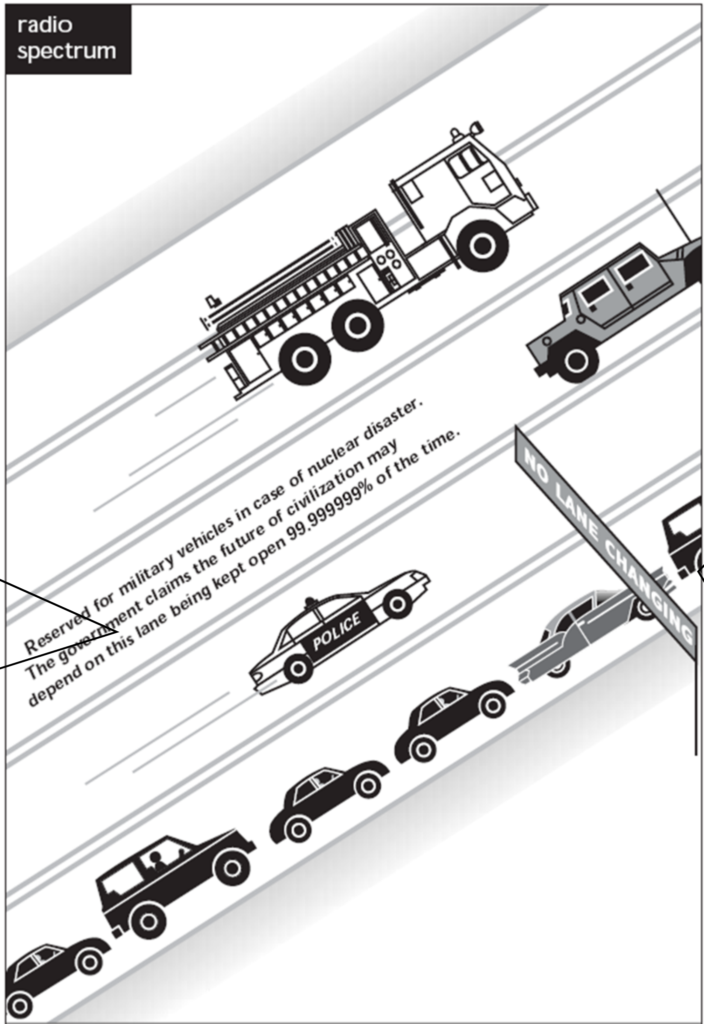
Outline

- Cognitive Radio Networks
  - Spectrum Sensing
  - Dynamic Spectrum Access
  - Exploration and Exploitation
- Overview of Game Theory
- Coalitional Games
  - Class I: Canonical Coalitional Games
  - Class II: Coalition Formation Games
  - Class III: Coalition Graph Games
- Conclusions

Cognitive Radio Overview

Lane: spectrum
Car: mobile user

Lane seldom used but reserved for **Licensed Spectrum Or Primary Users**

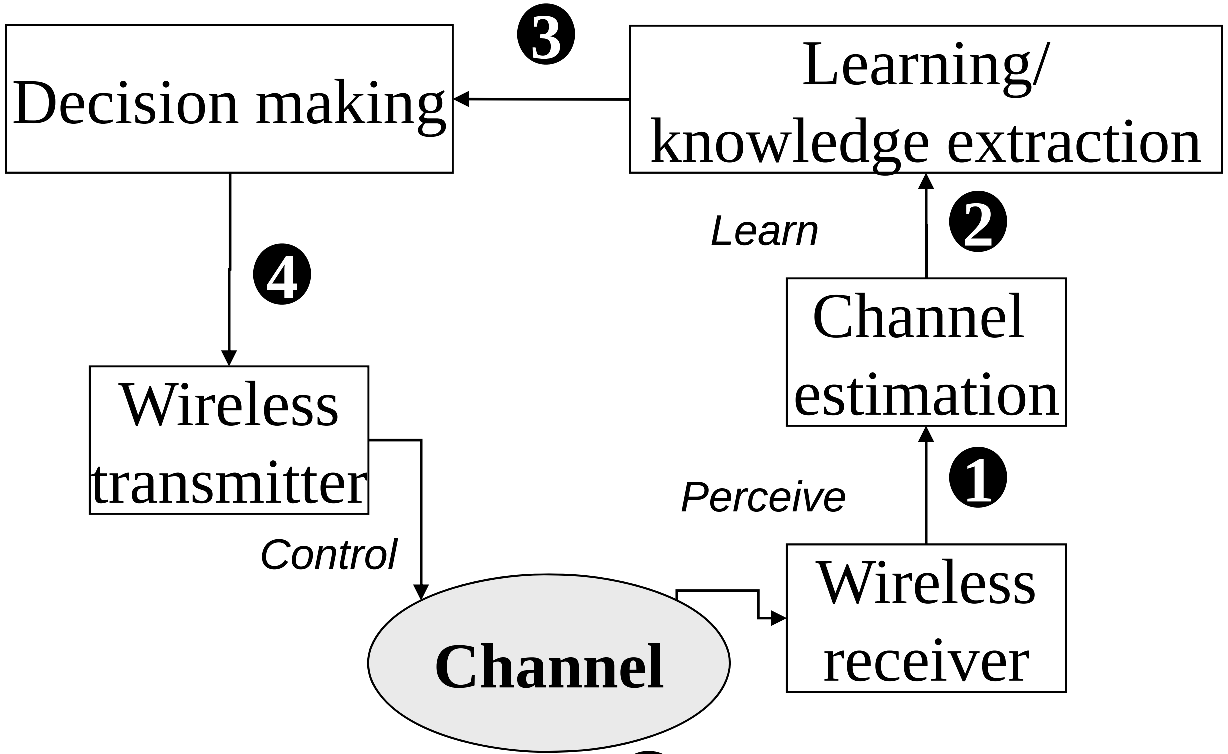


The government forces all public traffic into one lane, and reserves the other lanes for exclusive government use.

Public Traffic Lane congested for **Unlicensed Spectrum Or Secondary Users**

Cognitive Radio Block Diagram

- A cognitive radio is a radio that is able to sense, adapt and learn from its operating environment



❶ *Noisy channel information*

❷ *Noise-removed channel status*

❸ *Knowledge of transmission environment*

❹ *Decision on transmission parameters*

Problem 1: Spectrum Sensing

- Secondary users must sense the spectrum to
  - Detect the presence of the primary user for reducing interference on primary user
  - Detect spectrum holes to be used for dynamic spectrum access
- Spectrum sensing is to make a decision between two hypotheses
  - The primary user is present, hypothesis H_1
  - The primary user is absent, hypothesis H_0

$$x(t) = \begin{cases} n(t), & H_0 \\ h\ s(t) + n(t), & H_1 \end{cases}$$

Channel gain

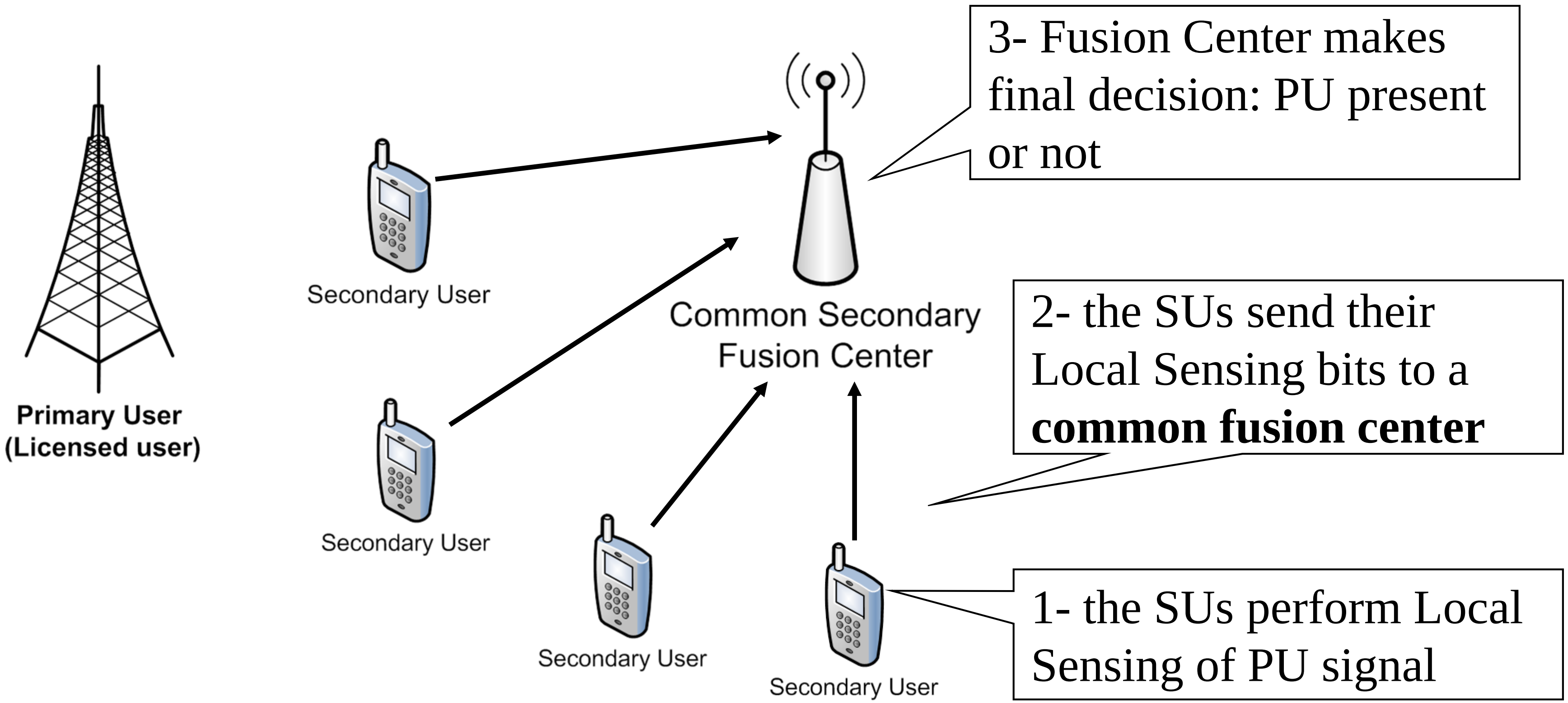
Primary User Signal

Noise

- Possible approaches
  - Matched Filter Detectors
  - Energy Detectors
  - Cyclostationary Detectors

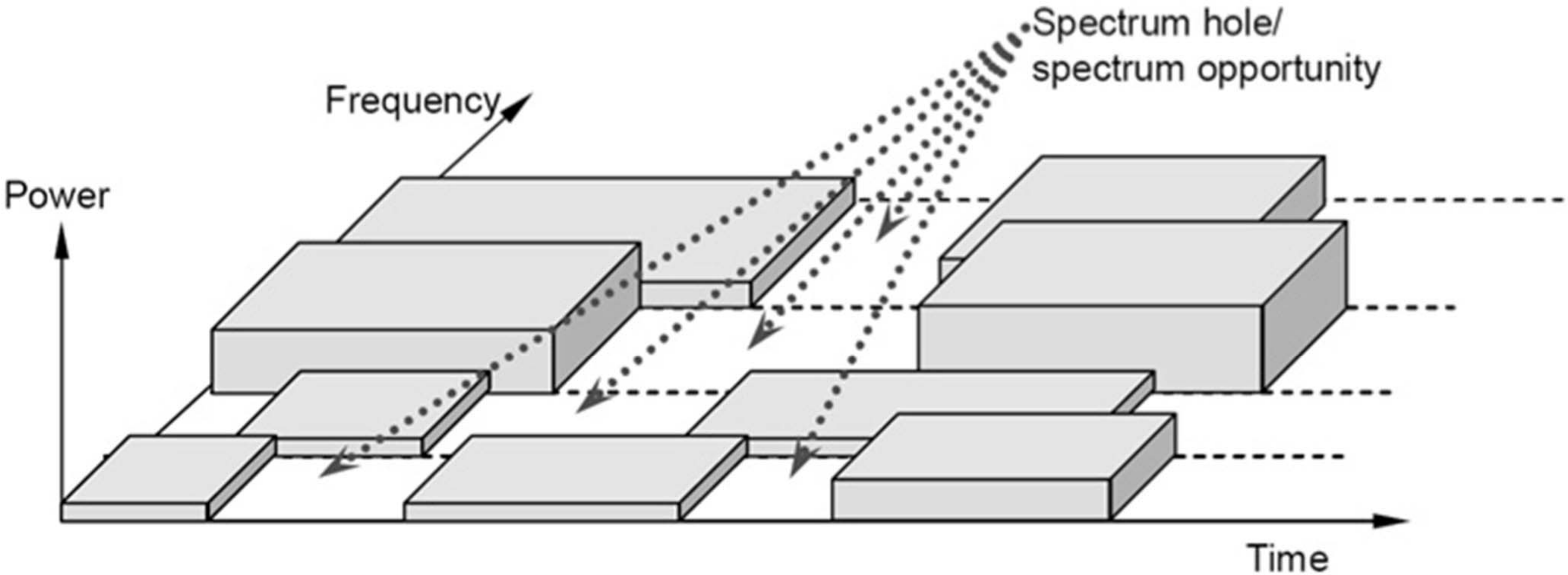
Collaborative Spectrum Sensing

- Overcome hidden terminal problem
- Multiple cognitive radio observe together



Problem 2: Dynamic Spectrum Access

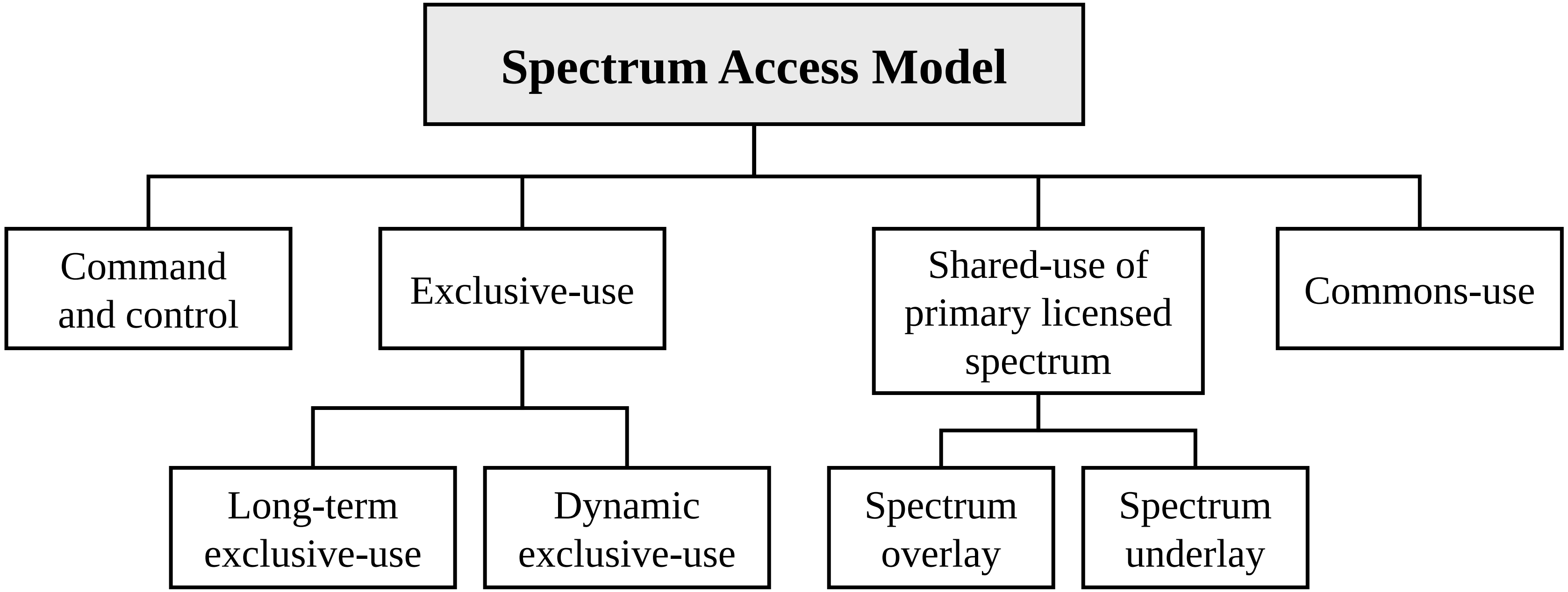
- Adjust spectrum resource usage in the near-real-time manner in response to changes in the users' objectives, changes of radio states, and changes in the environment and external constraints.



Access channels by multiple secondary users: Random vs. Coordinate; non-cooperative vs. cooperative; social optimum vs. fairness, ….

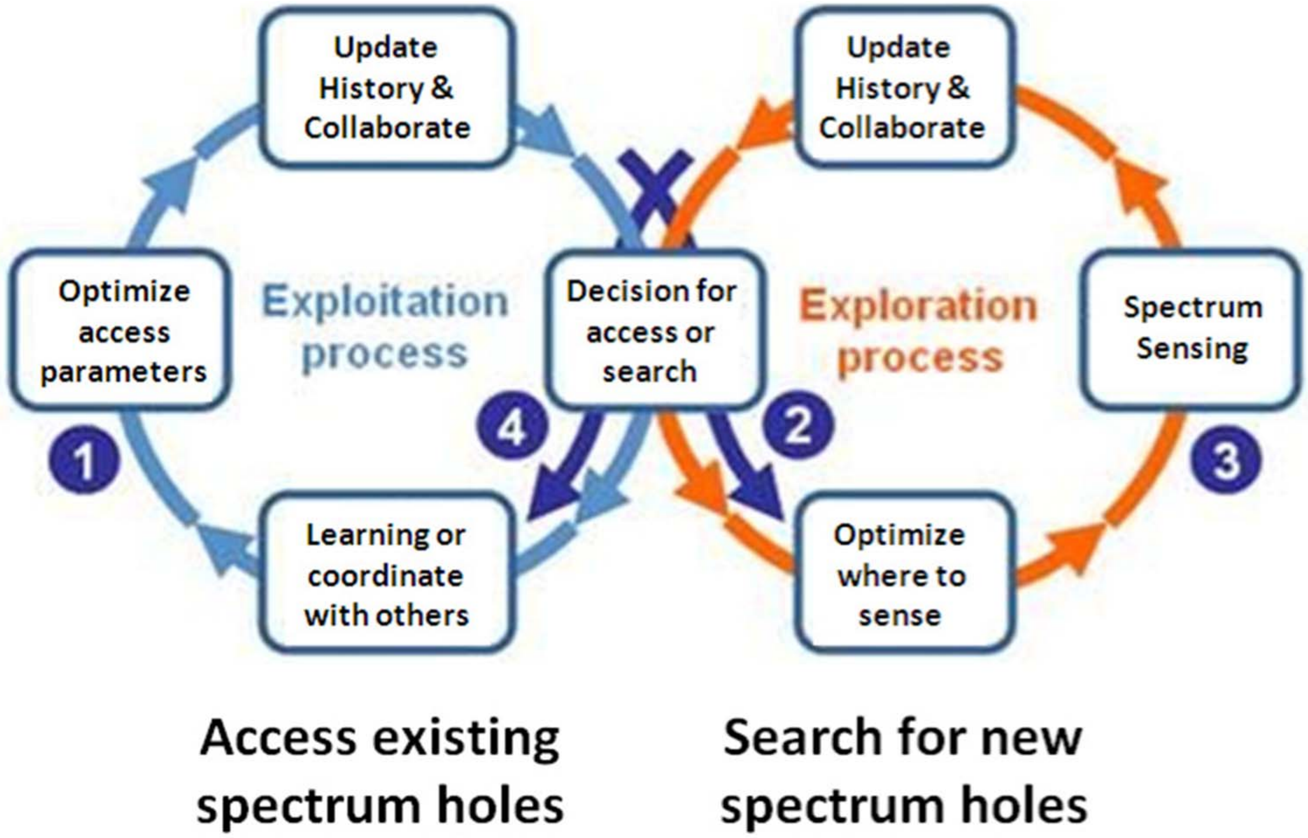
Dynamic Spectrum Access (DSA)

- Dynamic spectrum access allows different wireless users and different types of services to utilize radio spectrum



Problem 3: Exploration and Exploitation

- Exploitation: the immediate benefit gained from accessing the channel with the estimated highest reward
- Exploration is the process by which the cognitive users tend to probe more channels to discover better channel opportunities.
- Example: should find new topics or study the current topics



Game Theory Overview

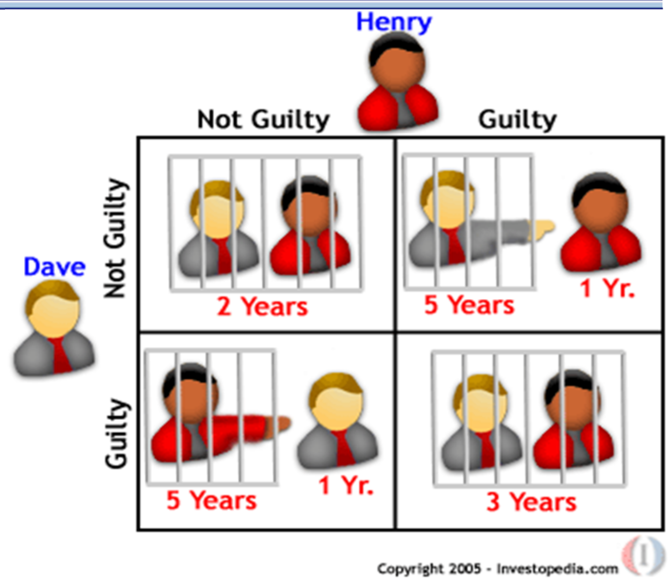
- What is game theory?
  - The formal study of conflict or cooperation
  - Modeling mutual interaction among rational decision makers
  - Widely used in economics
- Components of a “game”
  - **Rational players** with conflicting interests or mutual benefit
  - **Strategies** or actions
  - **Utility** as a payoff of player’s and other players’ actions
  - **Outcome**
- Many types
  - Non-cooperative game theory
  - Cooperative game theory
  - Dynamic game theory
  - Stochastic game
  - Auction theory

Rich Game Theoretical Approaches

- Non-cooperative static

game: play once

Prisoner Dilemma
Payoff: (user1, user2)



  - Mandayam and Goodman (2001)
  - Virginia tech
- Repeated game: play multiple times
  - **Threat of punishment** by repeated game. MAD: Nobel prize 2005.
  - Tit-for-Tat (infocom 2003):
- Dynamic game: (Basar's book)
  - ODE for state
  - Optimization utility over time
  - HJB and dynamic programming
  - Evolutional game (Hossain and Dusit's work)
- Stochastic game (Altman's work)

Auction Theory

Book of Myerson (Nobel Prize 2007), J. Huang, H. Zheng, X. Li

Cooperative Game Theory

- Players have mutual benefit to cooperate
  - Startup company: everybody wants IPO, while competing for more stock shares.
  - Coalition in Parlement
- Namely two types
  - Nash bargaining problems
  - Coalitional game
- We will focus on coalitional game theory
  - Definition and key concepts
  - New classification
  - Applications in wireless networks

Walid Saad, Zhu Han, Merouane Debbah, Are Hjorungnes, and Tamer Basar, ``Coalitional Game Theory for Communication Networks", IEEE Signal Processing Magazine, Special Issue on Game Theory, p.p. 77-97, September 2009.

Coalitional Games: Preliminaries

- **Definition** of a coalitional game (N,v)
  - A set of players ***N*****,** **a *coalition*** S is a group of cooperating players (subset of N)
  - Worth (utility) of a coalition ***v***
    - *In general,* ***payoff v(S)*** *is a real number that represents the gain resulting from a coalition S in the game (N,v)*
    - ***v(N)*** *is the worth of forming the coalition of all users, known as the* ***grand coalition***
  - User payoff $\boldsymbol{x_i}$: the portion of ***v(S)*** received by a player ***i*** in coalition S

Coalitional Games: Utility

- 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** from the power set of N 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

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

  - Developed by Auman and Peleg (1960) using a non-cooperative game in strategic form as a basis

Payoff division

- Equal fair
  - Each user guarantees its non-cooperative utility
  - The extra worth is divided equally among coalition users
- Proportional fair
  - Each user guarantees its non-cooperative utility
  - A proportional fair division, based on the non-cooperative worth, is done on the extra utility available through cooperation
- Other fairness
  - Shapley value
  - Nucleolus
  - Market Fairness

An example coalitional game

- Example of a coalition game: Majority Vote

$$v(S) = \begin{cases} 1, & \text{if } |S| > |N|/2; \\ 0, & \text{otherwise.} \end{cases}$$

  - President is elected by majority vote
  - A coalition consisting of a majority of players has a worth of 1 since it is a decision maker
  - Value of a coalition does not depend on the external strategies of the users
    - *This game is in characteristic function form*
  - If the voters divide the value as money
    - *Transferable utility*

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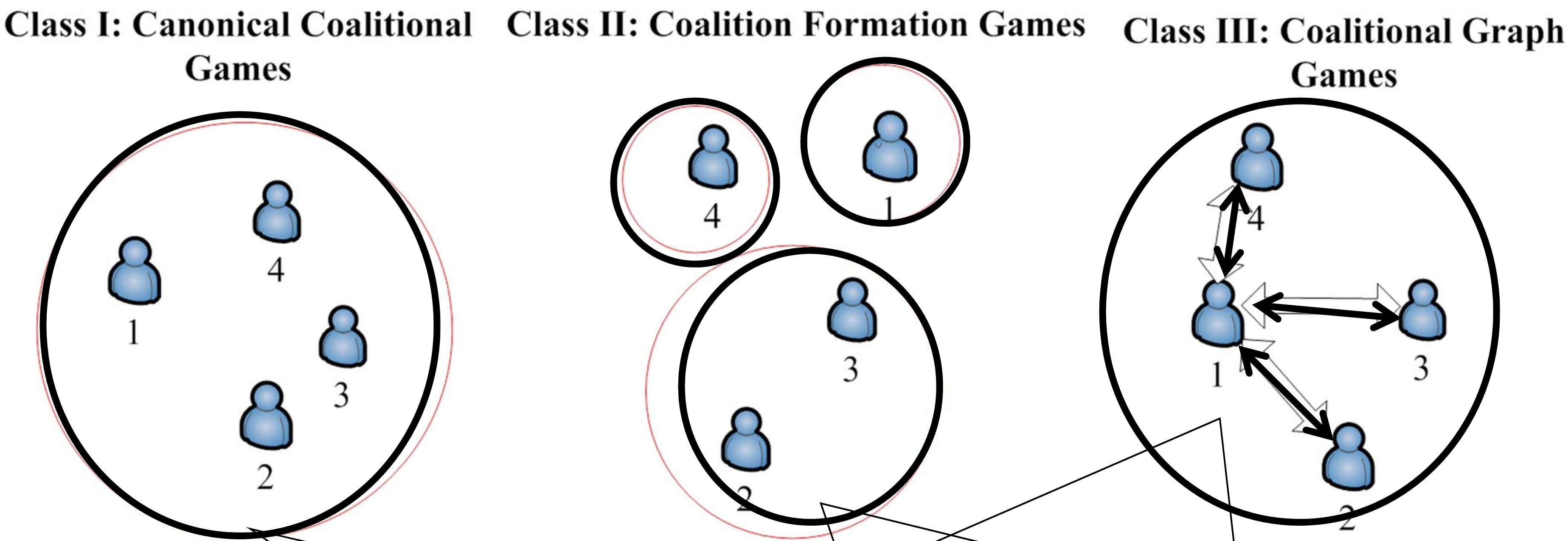
A new classification



- Players' interactions are governed by a communication graph structure.
-Key question "How to stabilize the grand coalition or form a network structure taking into account the communication graph?"
- Solutions are complex, combine concepts from coalitions, and non-cooperative games

- The network structure that forms depends on gains and costs from cooperation.
-Key question "How to form an appropriate coalitional structure (topology) and how to study its properties?"
- More complex than Class I, with no formal solution concepts.

- The **grand** coalition of all users is an optimal structure.
-Key question "How to stabilize the grand coalition?"
- Several well-defined solution concepts exist.

Class I: Canonical Coalitional Games

- Main properties
  - Cooperation is **always** beneficial
    - *The **grand coalition** is guaranteed to form*
  - The game is **superadditive**

$$v(S_1 \bigcup S_2) \geq v(S_1) + v(S_2)\ \forall S_1, S_2 \subset N \text{ with } S_1 \bigcap S_2 = \emptyset$$

  - **The most famous type of coalitional games!**

- Main Objectives
  - Study the properties and **stability** of the grand coalition
    - *How can we stabilize the grand coalition?*
  - How to divide the utility and gains in a fair manner ?
    - *Improper payoff division => incentive for players to leave coalition*

Canonical games: Solution concepts

- The Core: the most **renowned** concept
  - For a TU game, the core is a set of payoff allocation ***(x_1, . . ., x_N)*** satisfying two conditions

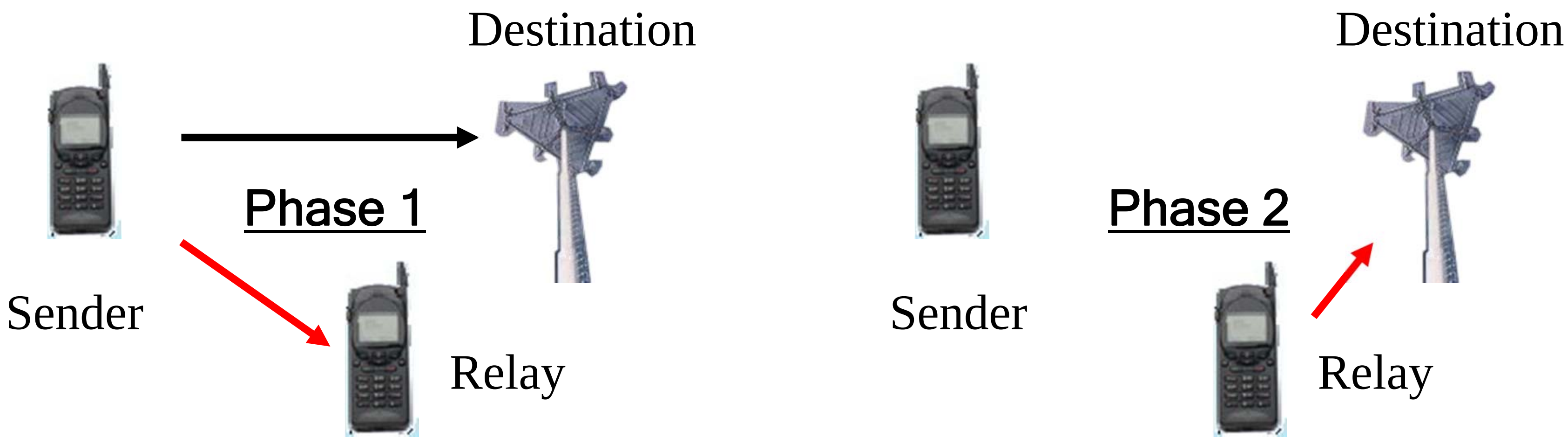
    1. $\sum_{i \in N} x_i = v(N)$

    2. $\sum_{i \in S} x_i \geq v(S), \forall S \in N$

  - The core can be empty
    - ***A non-empty core in a superadditive game => stable grand coalition***
- The drawbacks of the core
  - The core is often empty.
  - When the core is non-empty it is often a large set.
  - The allocations that lie in the core are often unfair.

Ex: Cooperative Transmission

- New communication paradigm
  - Exploring broadcast nature of wireless channel
  - Relays can be served as virtual antenna of the source
  - MIMO system
  - Multi-user and multi-route diversity



  - Most popular research in current wireless communication
  - Industrial standard: IEEE WiMAX 802.16J

Cooperative Transmission Model

- No cooperation (direct transmission), primary user needs power P_d.
- Cooperative transmission
  - Stage one: direct transmission. s, source; r, relay; d, destination
    $$y_{s,d} = \sqrt{P_0} h_{s,d} x + n_{s,d},$$
    and $y_{s,r_i} = \sqrt{P_0} h_{s,r_i} x + n_{s,r_i}, \forall i \in \{1, \ldots, N\}$
  - Stage two: relay retransmission using orthogonal channels, amplified-and-forward
    $$y_{r_i,d} = \frac{\sqrt{P_i}}{\sqrt{P_0 |h_{s,r_i}|^2 + \sigma^2}} h_{r_i,d} y_{s,r_i} + n_{r_i,d}.$$
  - Maximal ration combining at the receiver of backbone node
    $$\Gamma = \Gamma_0 + \sum_{i=1}^{N} \Gamma_i \quad \Gamma_0 = \frac{P_0 |h_{s,d}|^2}{\sigma^2} \quad \Gamma_i = \frac{P_0 P_i |h_{s,r_i}|^2 |h_{r_i,d}|^2}{\sigma^2 (P_0 |h_{s,r_i}|^2 + P_i |h_{r_i,d}|^2 + \sigma^2)}$$
  - To achieve same SNR, power saving for primary user $P_0 < P_d$

Main Idea

To get a good position, try to volunteer first

CR users PR transmission

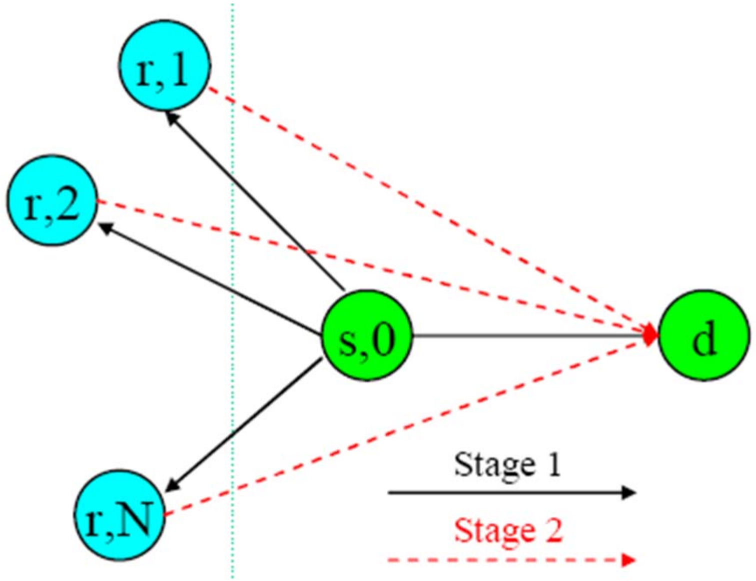


Fig. 2: Coalition Game with Cooperative Transmission

- CR nodes help the PU node reduce transmission power using cooperative transmission, for future rewards of transmission.
- The idea can be formulated by a coalition game.

Other applications of canonical games

- Zhu Han and H. Vincent Poor, ``Coalition Games with Cooperative Transmission: A Cure for the Curse of Boundary Nodes in Selfish Packet-Forwarding Wireless Networks", IEEE Transactions on Communications. vol. 57, No. 1, P.P. 203-213, January 2009.
- Rate allocation in a Gaussian multiple access channel (La and Anantharam, 2003)
  - The grand coalition maximizes the channel capacity
  - How to allocate the capacity in a fair way that stabilizes the grand coalition?
    - *The Core, Envy-free fairness (a variation on the Shapley value)*
- Vitual MIMO (W. Saad, Z. Han, M. Debbah, A. Hjorungnes, 2008)
- Allocation of channels in a cognitive radio network when service providers cooperate in a grand coalition (Aram et al., INFOCOM, 2009)
- Any application where
  - The grand coalition forms (no cost for cooperation)
  - Stability and fairness are key issues

Class II: Coalition Formation Games

- Main Properties
  - The game is NOT **superadditive**
  - Cooperation gains are limited by a cost
    - *The **grand coalition** is NOT guaranteed to form*
  - Cluster the network into partitions
  - **New issues:** network topology, coalition formation process, environmental changes, etc
- Key Questions
  - How can the users form coalitions?
  - What is the network structure that will form?
  - How can the users adapt to environmental changes such as mobility, the deployment of new users, or others?
  - Can we say anything on the stability of the network structure?

Coalition Formation: Merge and Split

- **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
  - Socialist (social well fare improved by the decision)
  - Capitalist (individual benefit improved)

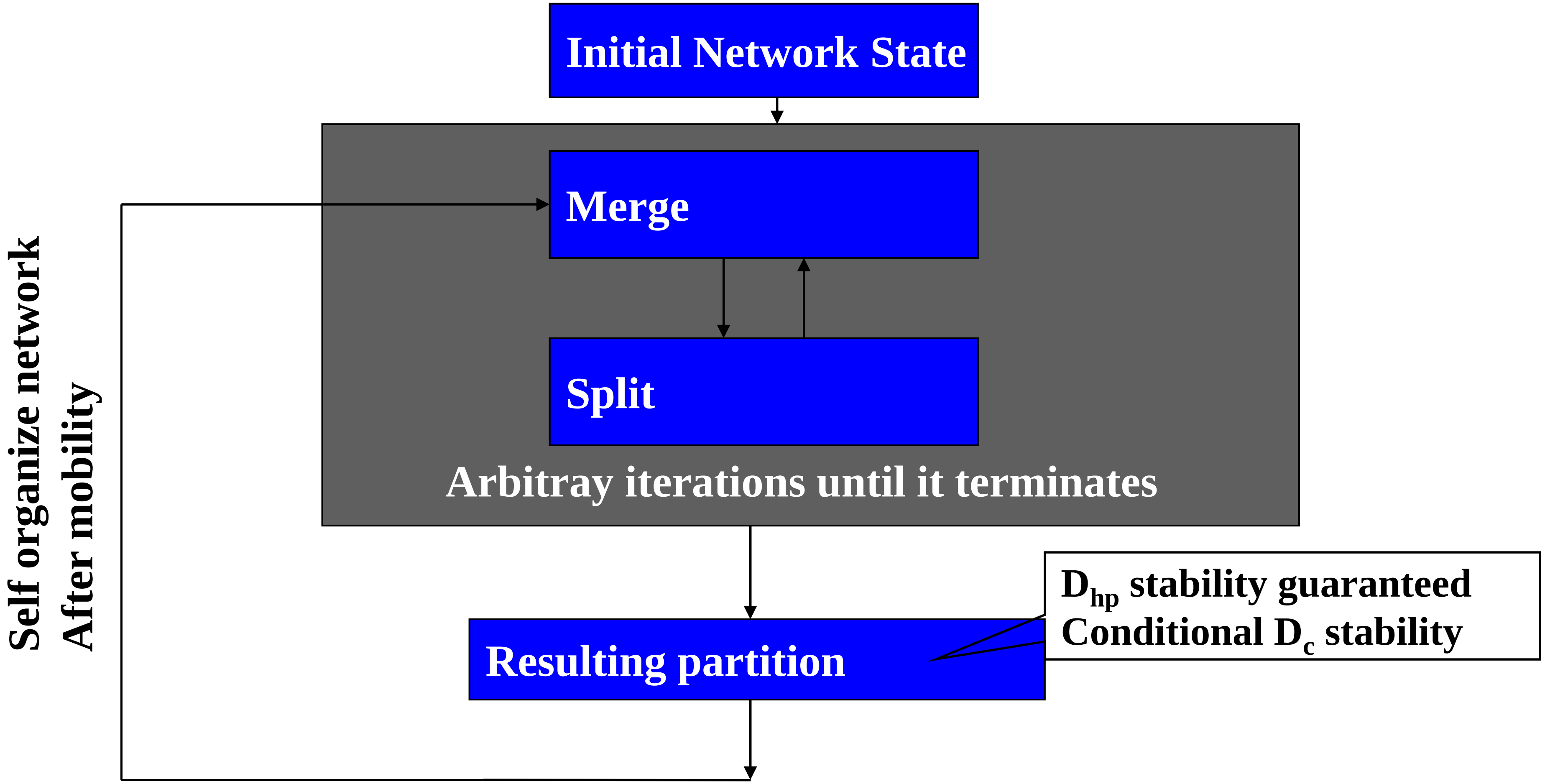
Merge and Split: Properties

- Any merge and split iteration converges and results in a final partition.
- Merge and split decision
  - Individual decision
  - Coalition decision
  - Can be implemented in a distributed manner with no reliance on any centralized entity
- Using the Pareto order ensures that no player is worse off through merge or split
  - Other orders or preference relations can be used

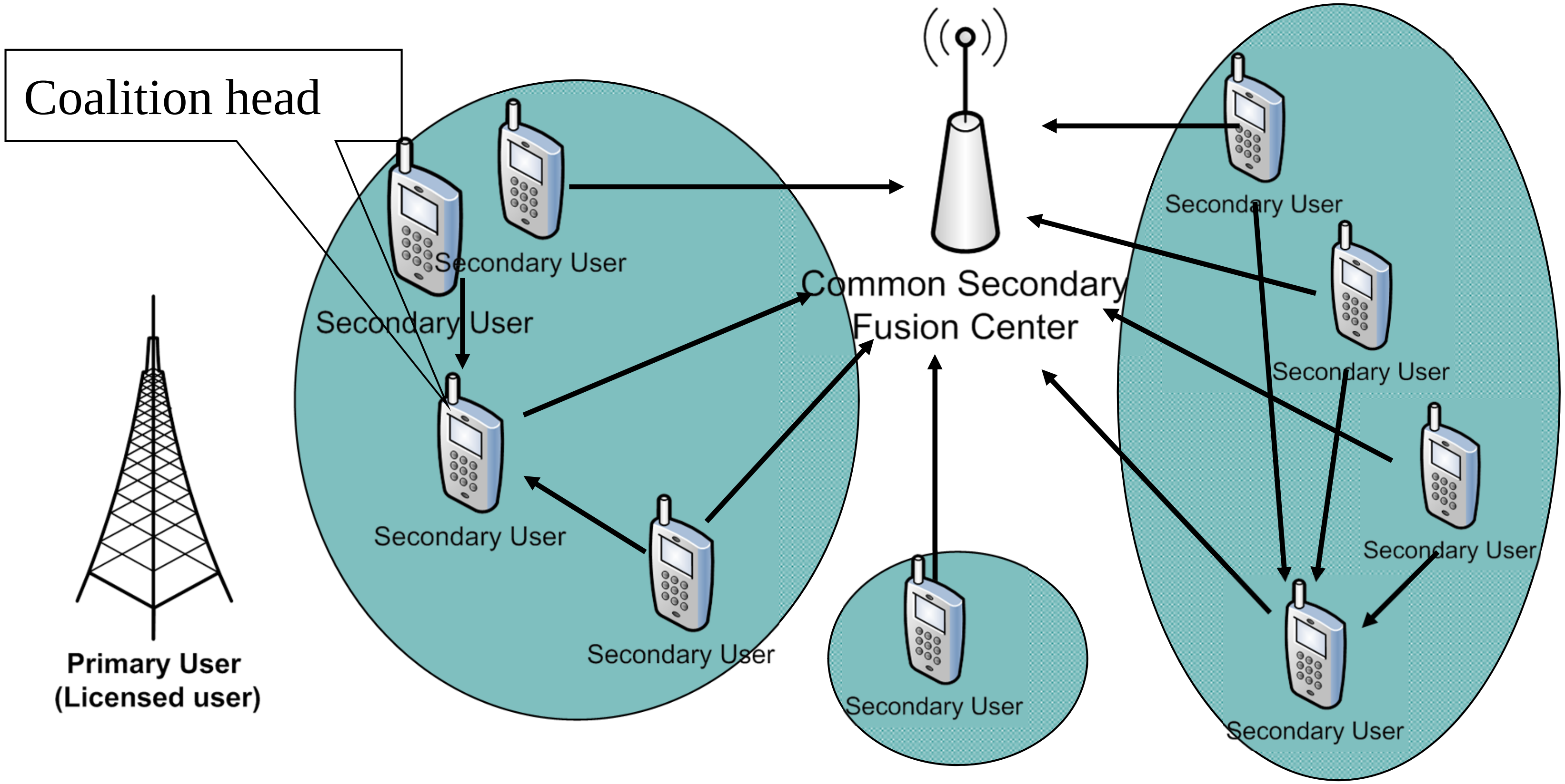
Stability Notions

- D_{hp} stable
  - No users can defect via merge/split
  - Partition resulting from merge and split is D_{hp} stable
- D_c stable
  - No users can defect to form a new collection in N
  - A D_c stable partition is **socially optimal**
  - When it exists, it is the **unique** outcome of any merge and split iteration
  - Strongest type of stability

Merge and Split algorithm



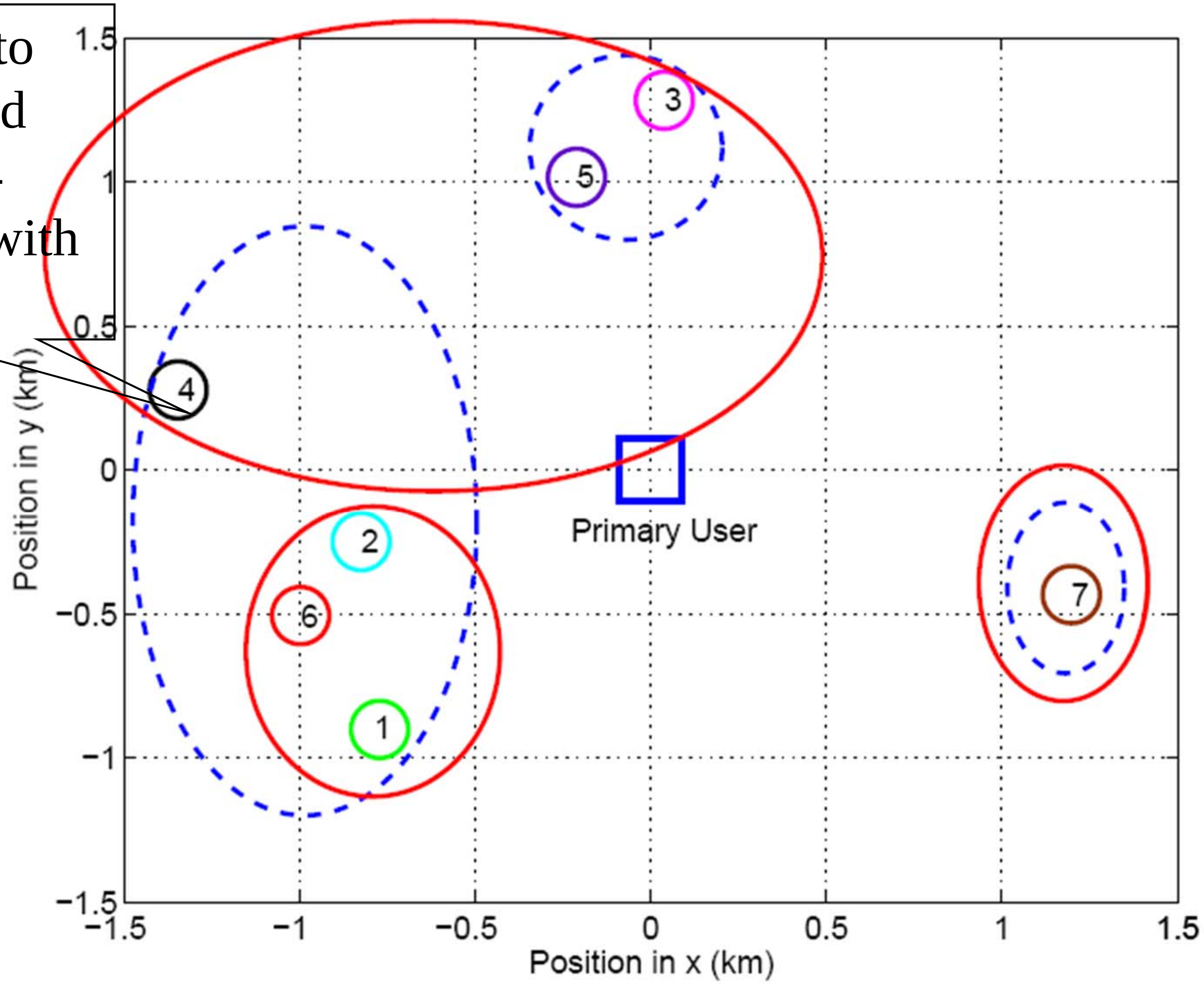
Distributed Collaborative Sensing



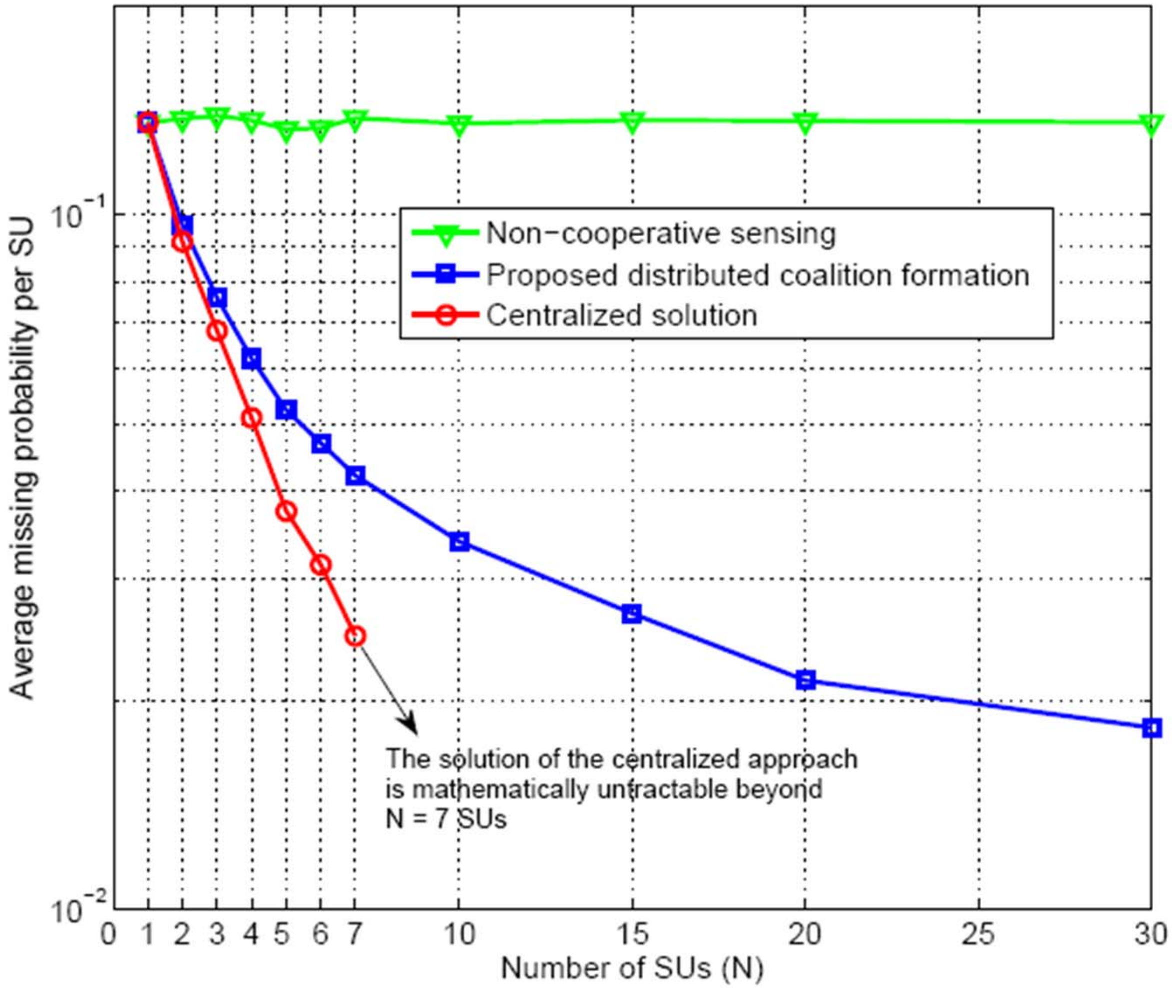
- Distributed collaborative sensing between the users with **no centralized** fusion center
- Which groups will form?
  - **Coalitional games!**

Simulation Results

When allowed to make distributed decisions, SU 4 prefers to stay with {2,1,6}

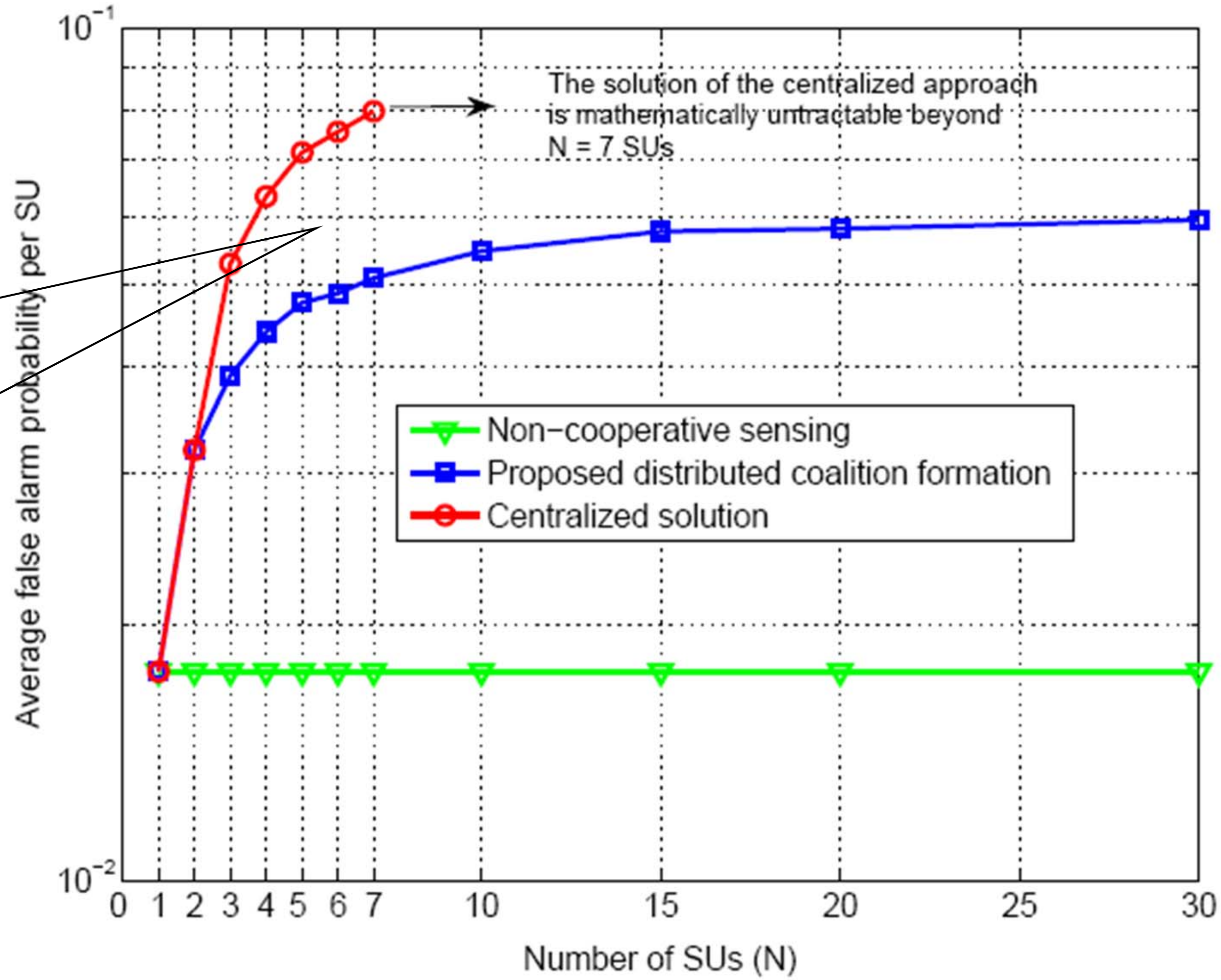


Simulation Results (1)



Simulation Results (2)

The gap with the optimal solution in probability of miss performance is compensated by a lower false alarm

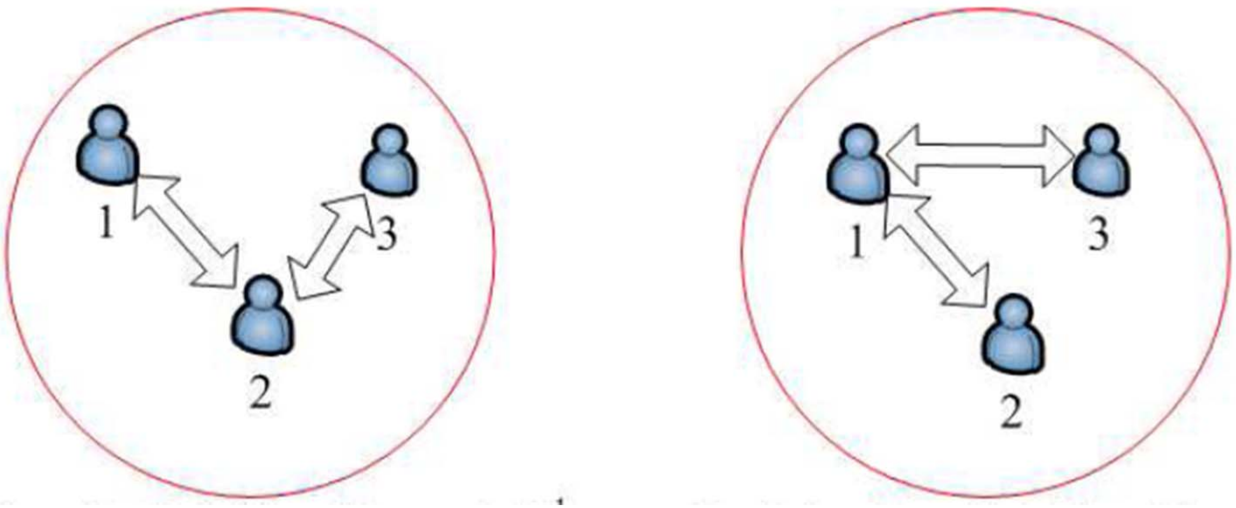


Other applications of coalition formation

- Coalitional games for topology design in wireless networks
  - **Physical layer security**
    - *Merge-and-split for improving secrecy capacity*
    - ***W. Saad, Z. Han, T. Basar, M. Debbah and A. Hjørungnes, "Physical layer security: coalitional games for distributed cooperation," WiOpt, 2009***
  - **Task allocation among UAVs in wireless networks**
    - *Hedonic coalition formation*
    - ***W. Saad, Z. Han, T. Basar, M. Debbah and A. Hjørungnes, "A selfish approach to coalition formation in wireless networks," GameNets, 2009***
  - **Vehicular Network**
    - *``Coalition Formation Games for Distributed Roadside Units Cooperation in Vehicular Networks", JSAC Jan. 2011*
  - **Endless possibilities**
    - *Study of cooperation when there is cooperation with cost*
    - *Topology design in wireless networks*
    - *Beyond wireless: smart grid*

Class III: Coalition Graph Games

- Main properties
  - The game is in **graph form**
    - *May depend on externalities also*
  - There is a **graph** that connects the players of every coalition
  - Cooperation with or without cost
  - **A Hybrid type of games:** concepts from classes I and II, as well as non-cooperative games



Coalition Graph Games

- First thought of by Myerson, 1977, called "Coalitional games with communication structure"
  - Axiomatic approach to find a Shapley-like value for a coalitional game with an underlying graph structure
  - Coalition value depends on the graph
  - The dependence is only based on **connections**
- Key Questions
  - How can the users form the **graph** structure that will result in the network?
  - If all players form a single graph (grand coalition with a graph), can it be stabilized?
  - How can the users adapt to environmental changes such as mobility, the deployment of new users, or others?
  - What is the effect of the graph on the game?

Applications of Coalitional Graph Games

- Coalitional graph games for network formation
  - **WiMAX IEEE 802.16j/LTE**
    - *Network formation game for uplink tree structure formation*
    - ***W. Saad, Z. Han, M. Debbah, and A. Hjørungnes, "Network formation games for distributed uplink tree construction in IEEE 802.16j," in proc. GLOBECOM 2008***
    - ***W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, "A game-based self-organizing uplink tree for VoIP services in IEEE 802.16j," ICC 2009***
  - **Routing in communication networks**
    - *See the work by Johari (Stanford)*
  - **Many future possibilities**
    - *The formation of graphs is ubiquitous in the context of communication networks*

Summary of coalitional game

- Cognitive radio network and its basic problems
- Coalitional games are a strong tool for different models in
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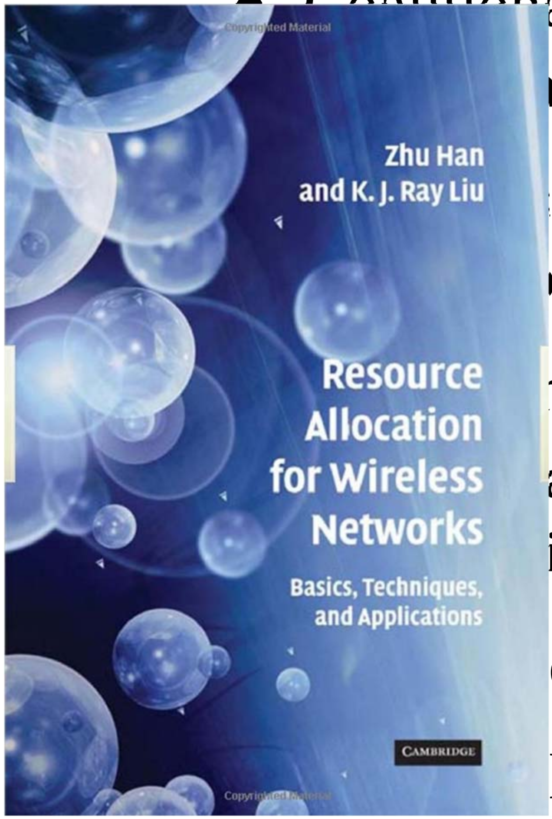

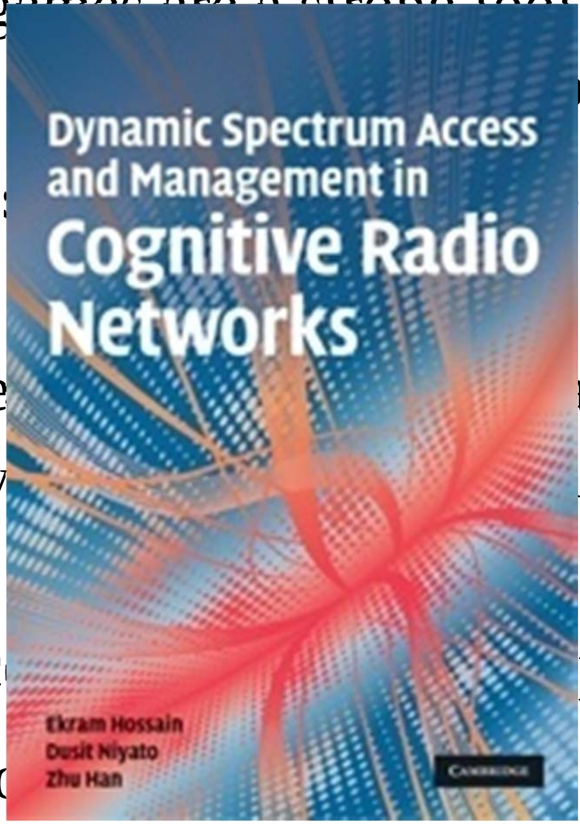

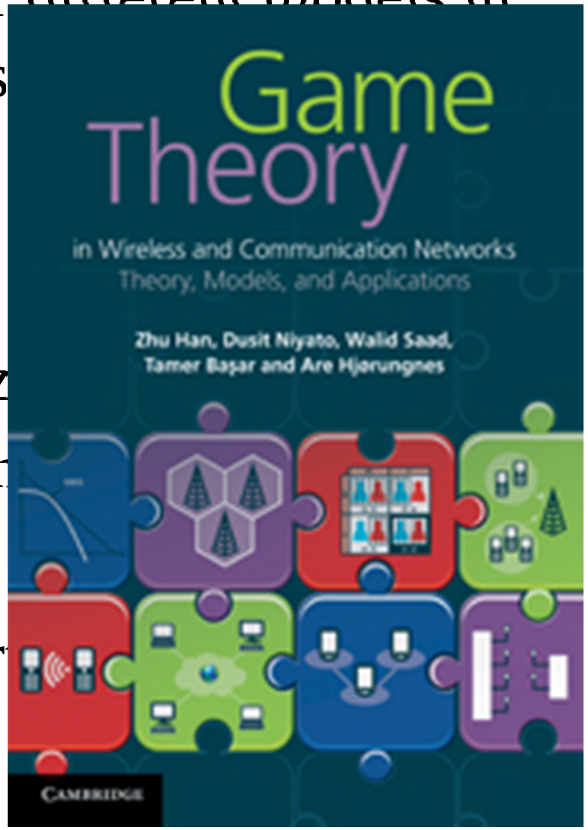

Questions?

Thank you very much