— PhD Thesis Defense —

Dynamic Spectrum Access in Cognitive Radio Networks: A Game Theoretical Approach

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Outline

Outline

Introduction

Background

- Most of the frequency spectrum resource has been allocated. [U.S. FA Chart]
- Most of the frequency spectrum inefficiently utilized. [Berkeley '04] Spectrum utilization depends strongly on time and place. [FCC '02]
- Fixed spectrum allocation results in resources wasting.
- Thought: Improve efficiency by allowing unlicensed users to exploit spectrum whenever it would not cause interference to licensed users.

Introduction

Features of Cognitive Radio

- Cognitive Capability: spectrum sensing, spectrum analysis and spectrum decision.
- Reconfigurability: operating frequency, modulation, transmission power, communication technology, etc.

Objectives of Cognitive Radio

- Achieve highly reliable and highly efficient wireless communications
- Improve the utilization of the frequency spectrum

Introduction

Definitions of Cognitive Radio

- Full Cognitive Radio [Joseph Mitola '99]
- Spectrum Sensing Cognitive Radio [FCC '03, Haykin '05, etc.]

Functions of Cognitive Radio [Akyildiz '06]

- Spectrum Sensing
- Spectrum Management
- Spectrum Sharing
- Spectrum Mobility

Introduction

Dynamic Spectrum Access

- A mechanism to adjust the spectrum resource usage in response to the changing environment and objective.
- Dynamic spectrum access by the unlicensed users is a key approach to achieve cognitive radio.
- Major models of dynamic spectrum access: [ZhaoQing '07]
  - Commons-use model
  - Shared-use model
  - Exclusive-use model

Introduction

Main Contributions

- In this work, we consider the economic theory based dynamic spectrum access in cognitive radio networks, including:
  - Game-based DSA in multi-hop CRN and multi-cell CRN
  - Auction-based spectrum trading in multi-seller CRN
  - Contract-based spectrum trading in monopoly CRN

General Assumptions

- Perfect spectrum sensing ability
- Perfect spectrum mobility

Outline

Related Works

Classifications of Spectrum Access Techniques

- According to access scheme: static, dynamic and hybrid
- According to network architecture: centralized and distributed
- According to collaboration behavior: cooperative and non-cooperative

Spectrum Access in Cognitive Radio Network

- Spectrum access in CRN are usually (but not restricted in) dynamic, distributed, and non-cooperative.
- Related works in dynamic spectrum access:
  - Graph theory based DSA schemes
  - Game theory based DSA schemes
  - Auction theory based DSA schemes

Related Works

Graph Theory Based Dynamic Spectrum Access

- List-coloring model [Xin Liu '05]
- Color-sensitive graph coloring model [Haitao Zheng '05]
- Modified color-sensitive graph coloring model with low complexity [Chulin Liao '06]
- ... ...

Related Works

Game Theory Based Dynamic Spectrum Access

- Stackelberg game model [Ali O. Ercan '08, Igor Stanojev '08]
- Correlated Equilibrium [Zhu Han '07]
- Exact potential game (EPG) model [Nie Nie '06]
- Bertrand game model [Dusit Niyato '08]
- ... ...

Related Works

Auction Theory Based Dynamic Spectrum Access

- Auction-based spectrum sharing [Jianwei Huang '06]
- Truthful and computationally-efficient spectrum auction [Xia Zhou '08]
- Truthful double spectrum auction [Xia Zhou '09]
- Repeated auction [Zhu Han '09]
- ... ...

Outline

Game Theory based DSA - I

Basic Cognitive Radio Network Model

- System description:
  - Channel allocation process is performed by the users distributedly.
  - Each users equips with multiple radio devices.
  - All users resides in a single collision domain.
  - All communication sessions are single-hop.
  - All channels are identical for each user.
  - Channel is shared equally among the radios using that channel.
  - User's utility is defined as the achieved channel capacity.
- Non-cooperative Game Approach [M. Felegyhazi, PhD Thesis '07]

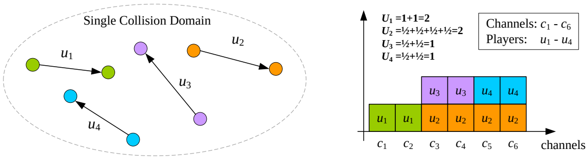


Figure: (a) Single-hop cognitive radio network model, (b) An example of channel allocation

Game Theory based DSA - I

Non-cooperative Game Approach

- Each user make its decision independently.
  - Strategy of user: Selecting a channel for each radio
  - Utility of user: Achieved channel capacity

Nash Equilibrium

- A channel allocation is an NE iff the following conditions hold:

  c.1 $k_i = k$ for any user i, and

  c.2 $\delta_{i,j} \leq 1$ for any channel c_i and c_j.

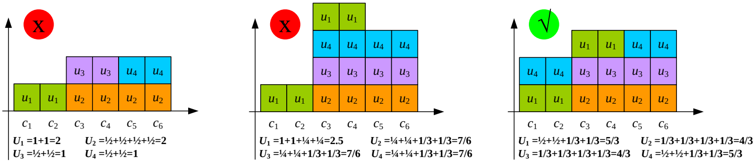


Figure: Illustration of NE and non-NE channel allocations where $k = 4$

Game Theory based DSA - II

Multi-hop Extension

- System modification:
  - Communication sessions may contain multiple hops.
  - The utility is defined as the end-to-end throughput of the session, i.e., the minimal capacity of users in the same session.
- Non-cooperative game and Nash equilibrium are not suitable for multi-hop networks.
- Hybrid game approach [L. Gao, TMC '09]

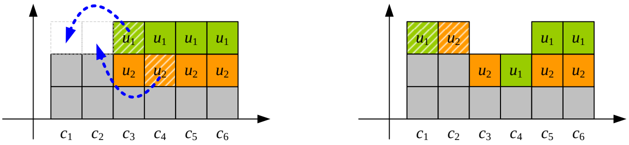


Figure: Assume u_1 and u_2 are within the same session. By simultaneously adjusting the strategies of u_1 and u_2, both utilities increase from 1.33 to 1.5 !

Game Theory based DSA - II

Hybrid Game Approach

- Non-cooperative among communication sessions
- Cooperative within communication session
  - Case I: Relocating the radios to improve the capacity of others
  - Case II: Exchanging the channels with each other

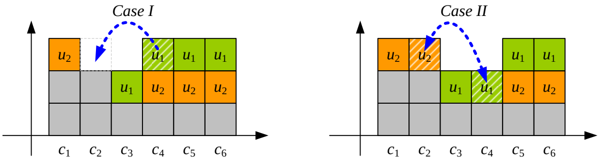


Figure: (a) Relocating the radio of u_1 to improve the capacity of u_2, and (b) Exchanging the channels of u_1 and u_2 to improve the capacity of u_2.

Game Theory based DSA - II

Nash Equilibrium (MMCPNE)

- Definition of MMCPNE
  - MMCPNE is such a channel allocation that none of sessions can improve its utility by changing the strategies of its members.
- Necessary conditions for MMCPNE
  - Theorem 2 [L. Gao, TMC '09]
- Sufficient conditions for MMCPNE
  - Conjecture 1 [L. Gao, TMC '09]

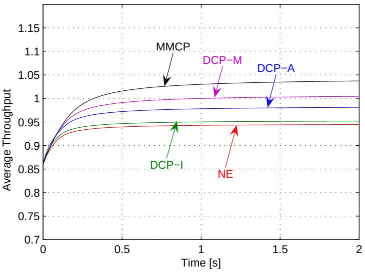
Convergence

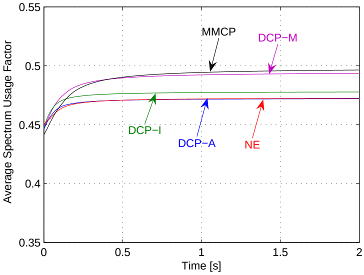
- MMCP Algorithm
  - Distributed algorithm that enables users to converge to MMCPNE.

Game Theory based DSA - II

Simulation Results

- Simulation parameters:
  - 8 channels, 5 communication sessions (1 two-hop session and 4 single-hop sessions), 4 radios in each user
- Performance criterions:
  - Average throughput of multi-hop sessions
  - Average spectrum usage factor of multi-hop sessions





Game Theory based DSA - III

Multi-cell Extension

- System modification:
  - The allocated channels belong to multiple cells.
  - Channels are identical within a cell, but different among cells.
  - Each user can only connect with one cell.
  - Each user decides which cell it should camp on and which channels (of the serving cell) it should occupy.
- Two-tier game approach [L. Gao, CS-RA '09]

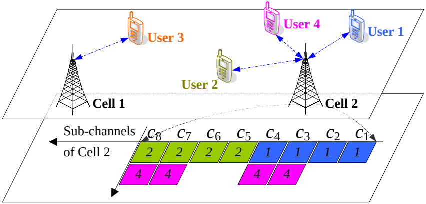


Figure: Multi-cell cognitive radio network model and an example of cell selection and channel allocation.

Game Theory based DSA - III

Two-tier Game Approach

- Inter-cell game:
  - Selecting the optimal cell according to mixed strategy (probabilities) derived from the expected payoff.
- Intra-cell game:
  - Choosing the proper channels in the serving cell.

Nash Equilibrium of Intra-cell Game

- Same as NE of non-cooperative game in the basic model.
- Achieve load balancing over the channels in each cell.
- Expected utility of user i in cell c:
  - $\overline{U_{i,c}} = G_{i,c} \cdot \min\left\{ \frac{|n_c| K_i}{\sum_{t \in U_c} K_t}, K_i \right\}$

Game Theory based DSA - III

Mixed-Strategy Nash Equilibrium of Inter-cell Game

- Mixed-strategy: $z_i = (p_i^1, \ldots, p_i^m)$, s.t. $\sum_{j=1}^m p_i^j = 1$.
- Mixed-Strategy Nash Equilibrium is such a mixed-strategy profile that none of users can improve its expected payoff by unilaterally changing the strategies of itself.
- Best response dynamic: $z_i^{(t)} = B_i\left(\mathbf{z}_{-i}^{(t-1)}\right)$

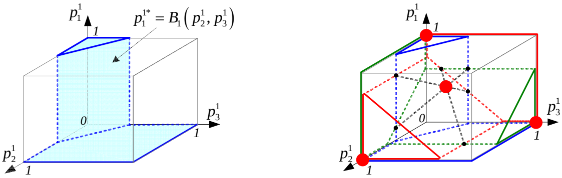


Figure: The best response function and mixed-strategy Nash equilibrium for the network with 2 cells and 3 users.

Game Theory based DSA - III

Convergences

- RA Algorithm: Converging to intra-cell Nash equilibrium.
  - Problem: Unstable channel allocations caused by simultaneously moving of different users.
  - Solution: Backoff mechanism
- CS Algorithm: Converge to inter-cell mixed Nash equilibrium.
  - Problem 1: Mixed strategy of one user can never be observed by other users, which makes best response dynamic unavailable.
  - Solution: Learning the load distribution of cells
  - Problem 2: Mixed strategy z_i will degenerate to pure strategy due to the non-smooth feature of best response functions.
  - Solution: Smoothed best response function

Game Theory based DSA - III

Simulation Results

- Simulation parameters:
  - 3 cells each owning 64 channels, 50 users each equipping 5 radios.

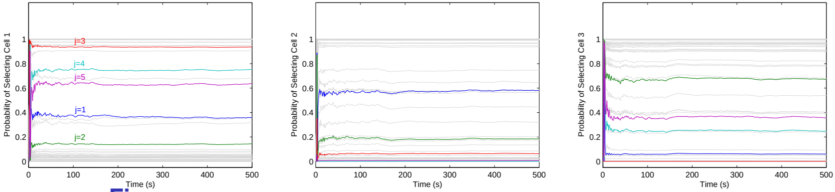


Figure: Dynamic of mixed strategies of all users in the inter-cell game.

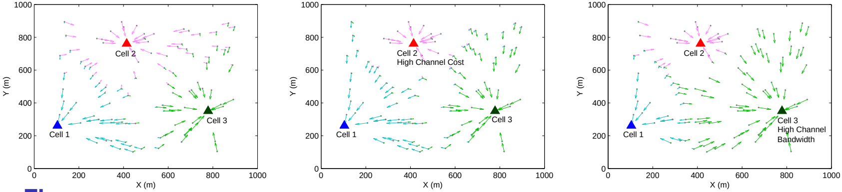


Figure: Impaction of channel's cost and bandwidth on the mixed-strategy Nash equilibrium.

Outline

Dynamic Auction based Spectrum Trading

Multi-seller Spectrum Market Model

- System Description:
  - Multiple POs (sellers) each owning a set of idle channels.
  - Multiple SUs (buyers) each desiring to employ a channel.
  - Channels are identical within a PO, but different among POs.
  - Each channel can only be used by one SU.
  - Each SU has a valuation (e.g., capacity) for each channel.
  - No cooperation among POs and among SUs.
- Objective: Efficiency, Incentive

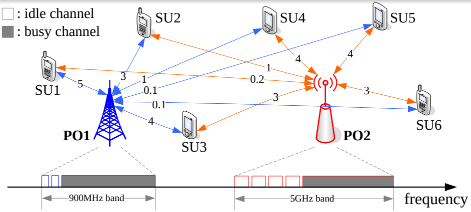


Figure: Multi-seller cognitive radio network model with 2 POs and 6 SUs.

Dynamic Auction based Spectrum Trading

Centralized Spectrum Allocation Approaches

- Solution for Assignment Problem:
  - Linear-programming-based branch-and-bound algorithm
  - Graph-theory-based optimal matching algorithm
- Centralized approaches are not suitable for the distributed and non-cooperative CR network.
  - Difficult to obtain complete information
  - Without considering the incentive of SUs

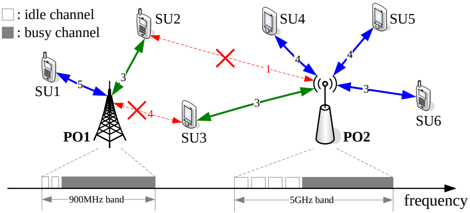


Figure: An example of channel allocation which is social optimal but not optimal for SU3.

Dynamic Auction based Spectrum Trading

Spectrum Auction Basic

- Elements of auction:
  - Auctioneers: all POs (sellers)
  - Bidders: all SUs (buyers)
  - Auctioned Items: the idle channels owned by all POs
- Types of auction:
  - First-price sealed-bid auctions
  - Second-price sealed-bid auctions (Vickrey auctions)
  - Open ascending-bid auctions (English auctions)
  - Open descending-bid auctions (Dutch auctions)

Dynamic Auction based Spectrum Trading

Traditional Spectrum Auction Designs

- One-shot (or static) spectrum auction:
  - Truthful spectrum bidding strategy [Xiang-Yang Li, ’08]
  - Truthful and computationally-efficient spectrum auction [Xia Zhou ’08]
  - Truthful double-auction [Xia Zhou ’09]
- Multi-shot (or dynamic, progressive) spectrum auction:
  - Repeated auction [Zhu Han ’09]
- The above spectrum auctions are restricted within the scenario of single auctioneer, either acted by a PO in single-seller networks or a virtual centralized entity in multi-seller networks.

Dynamic Auction based Spectrum Trading

MAP: Multi-Auctioneer Progressive Auction

- Basic thought [L. Gao, MAP '09]
  - Multi-Auctioneer and Multi-Item Extension of English Auction

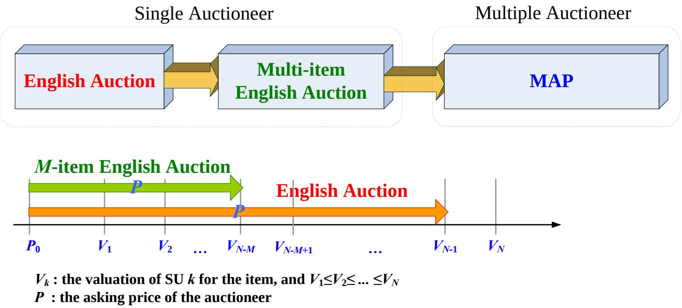


Figure: (a) An illustration of English Auction and MAP, (b) An illustration of the asking price in (Multi-item) English Auction.

Dynamic Auction based Spectrum Trading

MAP: Multi-Auctioneer Progressive Auction

- Structure of MAP:
  - In each auctioneer (PO), there is a multi-item English auction.
  - Each bidder (SU) decides which auction market it is going to join.

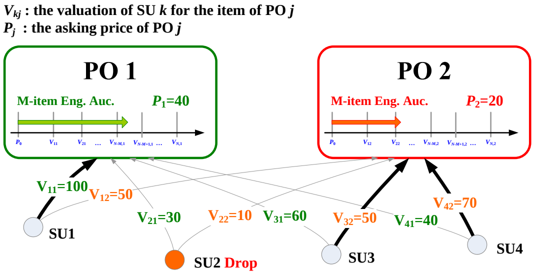


Figure: An illustration of MAP Auction in a cognitive radio network with 2 POs and 4 SUs.

Dynamic Auction based Spectrum Trading

Mechanism of MAP

- Due to the progressive nature of MAP, we define MAP as a round-based distributed process that works as follows:
  - **(i)** Asking: In the first stage of each round, each PO elicits the demands for his channel in previous round and judges whether he is in demanded surplus. If so, the PO raises his price by a step.
    `-- For each PO` i, `if` $d_i > m_i$, `then` $P_i = P_i + \epsilon$
  - **(ii)** Bidding: In the second stage of each round, each SU decides whether to buy a channel, and if so, selects the PO which maximizes his utility for bidding, based on the prices vector of POs.
    `-- For each SU` i, `find` $k = \arg\max_k V_{ik} - P_k$
    `--     if` $V_{ik} - P_k \geq 0$, `then select PO` k `for bidding`
    `--     else, drop out`

Dynamic Auction based Spectrum Trading

Equilibrium of MAP

- Weak Equilibrium (*W.E.*)
  - *W.E.* is defined as a state in which the demand for channels of each PO i does not exceed the supply of PO i, i.e., $d_i \leq m_i$.
- Strong Equilibrium (*S.E.*)
  - *S.E.* is defined as a state in which (i) the demand for channels of each PO i does not exceed the supply of PO i, i.e., $d_i \leq m_i$, and (ii) if the demand for channels of PO i is less than the supply of PO i, then the price of PO i equals his initial price, i.e., $P_i = c_i$ if $d_i < m_i$.

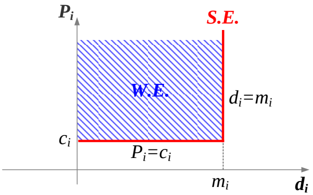


Figure: Illustration of *W.E.* and *S.E.* with different properties.

Dynamic Auction based Spectrum Trading

Efficiency of MAP

- Theorem 1: The channel assignment achieved by MAP is social optimal, if ϵ is small enough.
- We prove this theorem using *duality theory* (specifically the primal-dual method):
  - **L.1** A channel allocation is optimal if it satisfies the complementary slackness conditions in primal-dual method.
  - **L.2** The channel assignment achieved by MAP satisfies the complementary slackness conditions.

Dynamic Auction based Spectrum Trading

Simulation Results

- Simulation parameters:
  - 4 POs each owning 6 idle channels, 100 SUs.
- Performance criterion:
  - Converging Speed

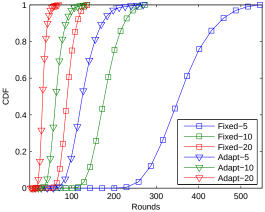


Fig. 13. CDF of converging rounds T, using $M = 4, N = 100, m_i = 6$.

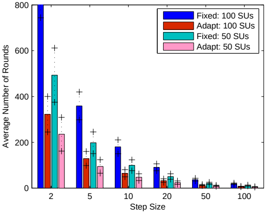


Fig. 14. Expectation of T vs. step ϵ, using $M = 4, m_i = 6, N = \{50, 100\}$.

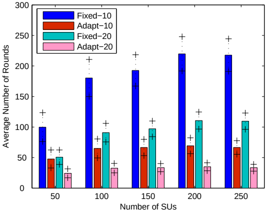


Fig. 15. Expectation of T vs. N, using $M = 4, m_i = 6, \epsilon = \{10, 20\}$.

Dynamic Auction based Spectrum Trading

Simulation Results

- Performance criterion:
  - Convergence and Efficiency

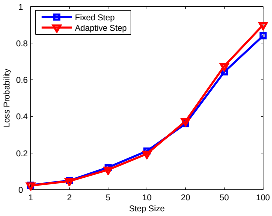


Fig. 16. Loss probability vs. step ϵ, using $M = 4, N = 100, m_i = 6$.

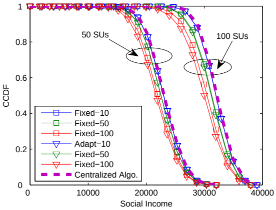


Fig. 17. CCDF of S and S^*, using $M = 4, m_i = 6, N = \{50, 100\}$.

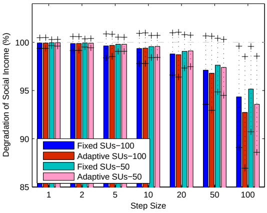


Fig. 18. Ratio of S to S^* vs. step ϵ, using $M = 4, m_i = 6, N = \{50, 100\}$.

Dynamic Auction based Spectrum Trading

Simulation Results

- Performance criterion:
  - Equilibrium Price and Profit Transfer

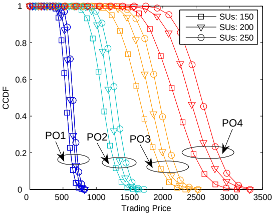


Fig. 19. CCDF of equilibrium prices, using $M = 4, m_i = 6, N = \{150, 200, 250\}$ and fixed step $\epsilon = 10$.

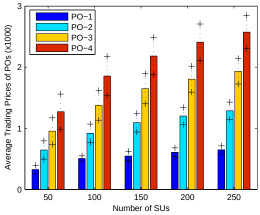


Fig. 20. Expectation of equilibrium prices vs. N, using $M = 4, m_i = 6$ and fixed step $\epsilon = 10$.

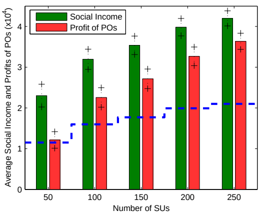


Fig. 21. Expectation of social income and profit of POs vs. N, using $M = 4, m_i = 6$ and fixed step $\epsilon = 10$.

Contract based Spectrum Trading

Monopoly Spectrum Market Model

- System Description:
  - An PO (monopolist) sells his channels to multiple SUs.
  - Each channel is associated with an attribute: quality, and a channel can be traded in different qualities (Quality Discrimination).
  - SUs are classified into multiple categories (types) according to their preference for a given channel quality.
  - The type of a particular SU is private information.
- Objective: Maximizing the revenue of PO

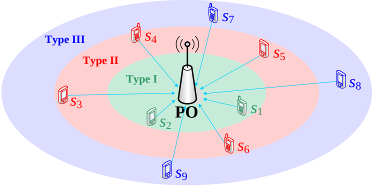


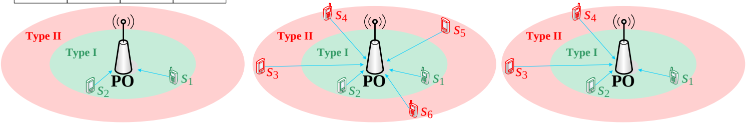
Figure: Monopoly Spectrum Market Model with 3 SU types.

Contract based Spectrum Trading

Quality Discrimination

- Each channel can be traded in different quality q.
  - For PO, the cost $C(q)$ satisfies: $C'(q) > 0$, $C''(q) > 0$.
  - For SUs, the valuation $V(\theta, q)$ satisfies: (i) $V_q(\theta, q) > 0$, $V_{qq}(\theta, q) < 0$, and (ii) $V_\theta(\theta, q) > 0$.
- The monopolist select a set of qualities and a set of associated prices for his products.

q	C(q)	V(I, q)	V(II, q)
L	1	6	3
H	4	10	5



Qualities	{L}	{H}	{L, H}
Prices	{6}	{10}	{6, 10}
Revenue	10	12	10

Qualities	{L}	{H}	{L, H}
Prices	{3}	{10}	{3, 7}
Revenue	12	12	14

Qualities	{L}	{H}	{L, H}
Prices	{6}	{10}	{3, 7}
Revenue	10	12	10

Figure: An illustration of the optimal qualities and prices for PO in different system scenario.

Contract based Spectrum Trading

Quality-Price Contract Formulation [L. Gao, QPCtr '09]

- Since only one quality will be chosen by each SU, effectively the PO will be assigning a quality q_i and a price π_i to each SU type θ_i. Such a set of quality-price combinations is referred to as quality-price contract, denoted by $\mathcal{C} = \{q_i, \pi_i\}$.
- A contract is feasible, iff the IC and IR constraints satisfy:
  - Incentive Compatible (IC): $V(\theta_i, q_i) - \pi_i \geq V(\theta_i, q_k) - \pi_k, \ \forall k \neq i$
  - Individual Rational (IR): $V(\theta_i, q_i) - \pi_i \geq 0$
- An optimal contract is defined as a feasible contract which maximizes the revenue of PO.
  - Revenue of PO: $R = \sum_i N_i(\pi_i - C(q_i))$

Contract based Spectrum Trading

Feasibility of Contract

- Suppose $\theta_1 \leq ... \leq \theta_N$. A feasible contract $\mathcal{C}$ satisfies: $q_1 \leq ... \leq q_N$ and $\pi_1 \leq ... \leq \pi_N$ with $q_i = q_{i+1}$ iff $\pi_i = \pi_{i+1}$.
  - **L.1** $q_i > q_j \Leftrightarrow \pi_i > \pi_j$, and $q_i = q_j \Leftrightarrow \pi_i = \pi_j$.
  - **L.2** $\theta_i > \theta_j \Rightarrow q_i \geq q_j$.
- Given $q_1 \leq ... \leq q_N$. The feasible price range can be obtained:
  - **c.1** $0 \leq \pi_1 \leq V(\theta_1, q_1)$, and
  - **c.2** $\pi_{k-1} + A \leq \pi_k \leq \pi_{k-1} + B$, for all $k = 2, 3, ..., T$, where $A = V(\theta_{k-1}, q_k) - V(\theta_{k-1}, q_{k-1})$ and $B = V(\theta_k, q_k) - V(\theta_k, q_{k-1})$.

Contract based Spectrum Trading

Optimality of Contract

- Given $q_1 \leq ... \leq q_N$. The best price set can be obtained:
  c.1 $\pi_1^* = V(\theta_1, q_1)$, and
  c.2 $\pi_k^* = \pi_{k-1}^* + V(\theta_k, q_k) - V(\theta_k, q_{k-1})$, for all $k = 2, 3, ..., T$.
- Substitute the best prices into revenue R. The best quality set can be obtained:
  - $\vec{q}^* = \arg\max_{\vec{q}} R$, where $\vec{q} = \{q_1, q_2, ..., q_N\}$.

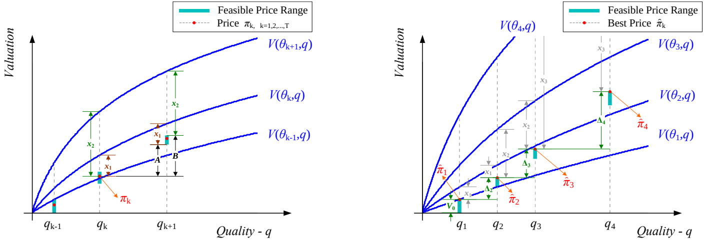


Figure: An illustration of the feasible price range and best price assignment.

Contract based Spectrum Trading

Continuous-SU-Type Model

- System Modification:
  - θ is a continue random variable with PDF $f(\theta)$ and CDF $F(\theta)$.
- Given an increasing function $q(\theta)$. The best price function can be obtained:
  - $\pi(\theta)^* = V(\theta, q(\theta)) - \int_{\theta_s}^{\theta} \frac{q(x)}{1+xq(x)} dx$
- Substitute the best price function $\pi(\theta)^*$ into revenue R. The best quality function $q(\theta)^*$ can be derived.

Contract based Spectrum Trading

Simulation Results

- Simulation parameters:
  - 25 SU types and $\theta_i = 1, 2, ..., 25$, $\forall i = 1, 2, ..., 25$.
  - Case (a): $N_i = i$; Case (b): $N_i = 12$; Case (c): $N_i = 25 - i + 1$;

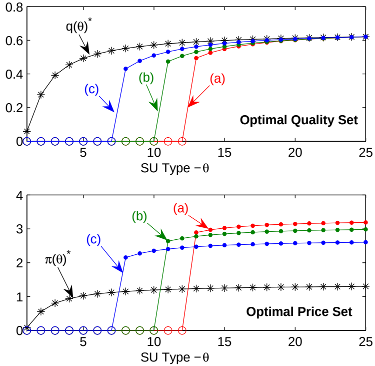


Figure: The best quality set and price set in the optimal contract.

Outline

Summary

Conclusion

- We propose a hybrid game approach for DSA in multi-hop CRN;
- We propose a two-tier game approach for CS-RA in multi-cell CRN;
- We propose a multi-auctioneer progressive auction for spectrum trading in multi-seller CRN;
- We propose a quality-price contract for spectrum trading in monopoly CRN;

Summary

Publications

1. H. Wang, **Lin Gao**, Xiaoying Gan, Xinbing Wang, Ekram Hossain, "Cooperative Spectrum Sharing in Cognitive Radio Networks: A Game-Theoretic Approach," to appear in Proceeding of IEEE ICC 2010.
2. H. Yu, **Lin Gao**, Z. Li, Xinbing Wang, and Ekram Hossain, "Pricing for Uplink Power Control in Cognitive Radio Networks," to appear in IEEE Transactions on Vehicular Technology, 2010.
3. **Lin Gao**, Xinbing Wang, and Youyun Xu, "Multi-radio Channel Allocation in Multi-hop Wireless Networks," IEEE Transactions on Mobile Computing, Vol. 8, 2009.
4. H. Yu, **Lin Gao**, Xinbing Wang, Youyun Xu, etc., "Information Sharing in Spectrum Auction for Dynamic Spectrum Access," in Proceeding of IEEE GlobeCom 09, Hawaii, USA, Nov, 2009.
5. **Lin Gao**, and Xinbing Wang, "A Game Approach for Multi-Channel Allocation in Multi-Hop Wireless Networks," in Proceeding of ACM MobiHoc 08, Hong Kong, May, 2008.
6. **Lin Gao**, Xinbing Wang, and Youyun Xu, "Distributed Multi-radio Channel Allocation in Multi-Hop Ad Hoc Networks," in Proceeding of IEEE ICC 08, Beijing, May, 2008.
7. Y. Xu, **Lin Gao**, "Dynamic Spectrum Allocation in Cognitive Radio Networks Based on Auction," Journal of University of Science and Technology of China (in Chinese), Vol. 10, 2009.
8. **Lin Gao**, Youyun Xu, and Xiaoyin Gan, "Linear Precoding for MIMO System Based on Imperfect CSIT," Journal of Shanghai Jiao Tong University (in Chinese), Vol. 11, 2007.

Summary

Submissions

9. T. Chu, **Lin Gao**, and Xinbing Wang, “An Agent-based Spectrum Trading in Cognitive Radio Networks,” submit to Proceeding of IEEE Globecom 2010.
10. Haobing Wang, **Lin Gao**, Xinbing Wang, “A Game Approach for Cooperative Spectrum Sharing in Cognitive Radio Networks,” submit to IEEE Transactions on Mobile Computing.
11. T. Chu, **Lin Gao**, and Xinbing Wang, “Spectrum Trading in Cognitive Radio Network: An Agent-based Model under Demand Uncertainty,” submit to IEEE Transactions on Communications.
12. **Lin Gao**, Xinbing Wang, and Youyun Xu, “Spectrum Trading in Cognitive Radio Networks: A Contract-Theoretic Modeling Approach,” submit to IEEE Journal on Selected Areas in Communications.
13. **Lin Gao**, Youyun Xu, and Xinbing Wang, “A Game Approach for Cell Selection and Resource Allocation in Heterogeneous Wireless Networks,” submit to IEEE Transactions on Networking (prepare 2nd review).
14. **Lin Gao**, Youyun Xu, Zheng Li, and Xinbing Wang, “MAP: Multi-Auctioneer Progressive Auction in Dynamic Spectrum Access,” submit to IEEE Transactions on Mobile Computing (under 2nd review).

Thank you!

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