CROWNCOM 2011 - 6th International ICST Conference on
Cognitive Radio Oriented Wireless Networks and Communications

Game Theoretical Modelling for Dynamic Spectrum Access in TV Whitespace

Ligia Cremene, D. Dumitrescu, Reka Nagy, M.Cremene

Technical University of Cluj-Napoca

Babes-Bolyai University of Cluj-Napoca

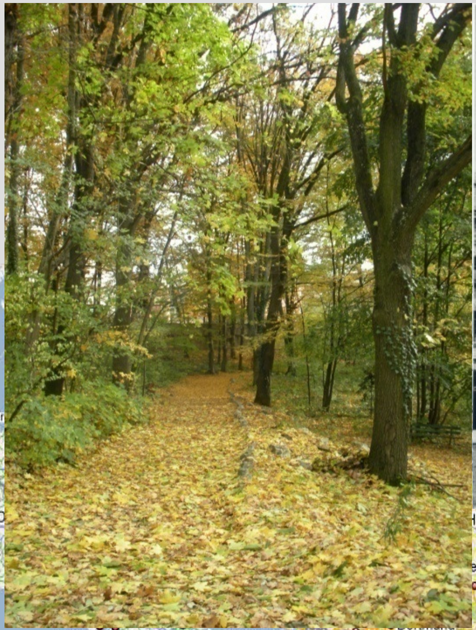
Adaptive Systems Laboratory

http://asl.utcluj.ro

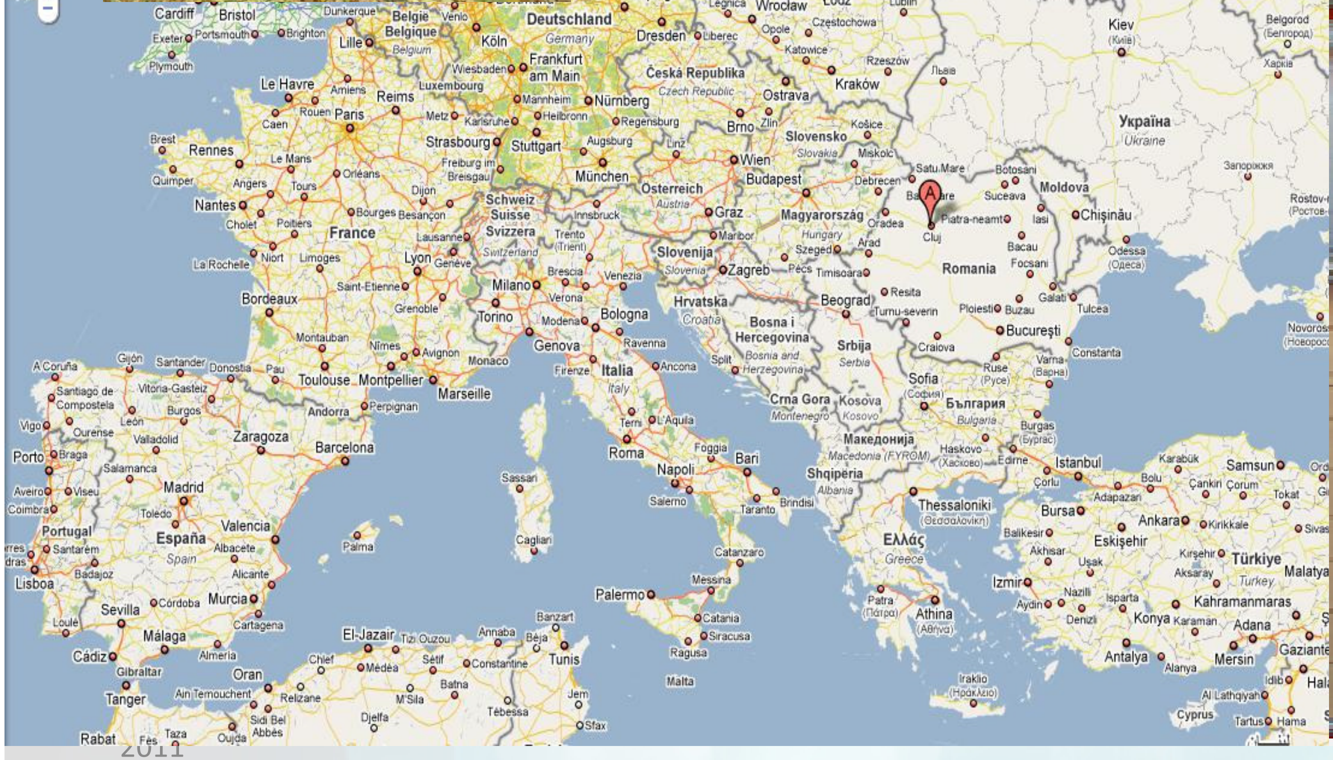
http://users.utcluj.ro/~cligia

Centre for the Study of Complexity

http://csc.centre.ubbcluj.ro



Cluj-Napoca, Romania

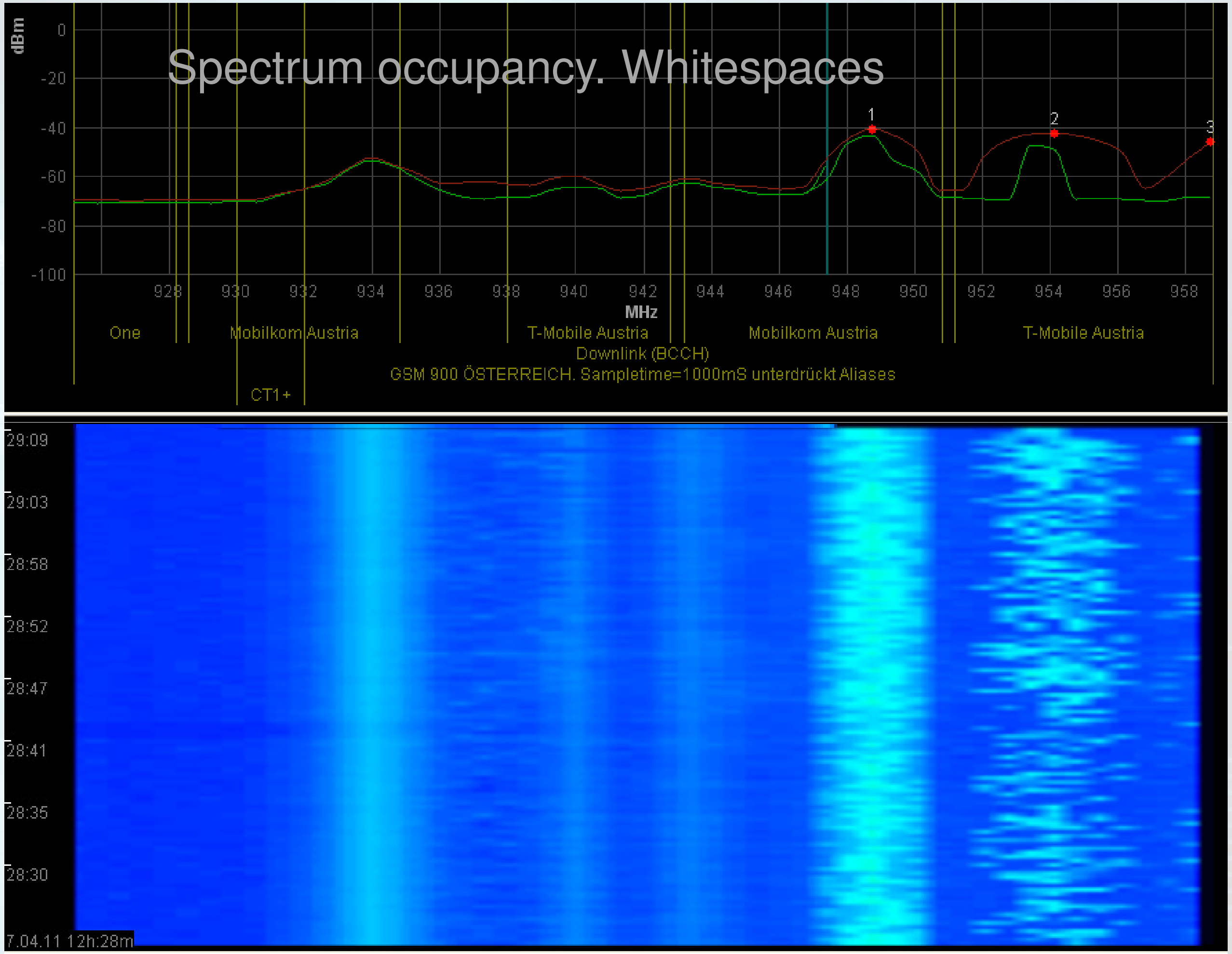


Outline

- Introduction – context, problem, approach
  - Spectrum occupancy. Spectrum management
  - Dynamic spectrum access. Cognitive radios
- Game theoretical modelling of spectrum access
  - Oligopoly game models, relevance of new GT equilibrium concepts
- Numerical experiments
  - ‘commons regimes’, ‘licensed vs. unlicensed’, ‘very crowded’
- Conclusions
  - hopefully some answers for the ’autonomy vs. regulation’ issue.

Introduction

Up to 90% of the radio spectrum remains idle in any one geographical location - TV whitespaces.



DTV whitespaces can provide significantly higher data rates compared to the 2.4 GHz ISM band.

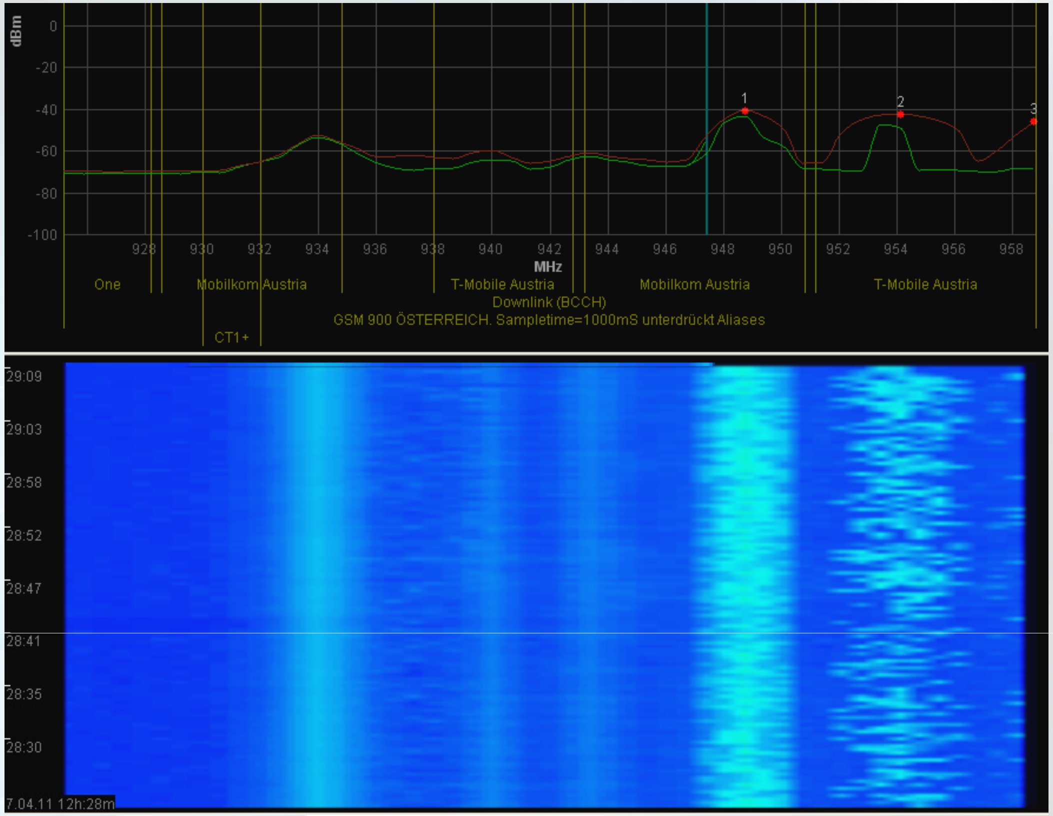
Introduction

- Current spectrum regimes are based on
  - a highly prescriptive approach,
  - centralized control and decisions.

- Traditional spectrum planning
  - only valid for a certain generation of technology,
  - slow process that cannot keep up with new innovations and technologies.

New spectrum bands are being released around the world :

e.g. 2.6 GHz in Europe,
the 800 MHz digital dividend,
700 MHz and AWS –
1700/2100 MHz in the U.S.



- Existing spectrum bands are being deregulated to allow coexistence of 2G, 3G, and 4G technologies.
- Technology neutral spectrum, in the context of infrastructure sharing by operators becomes more and more prevalent.

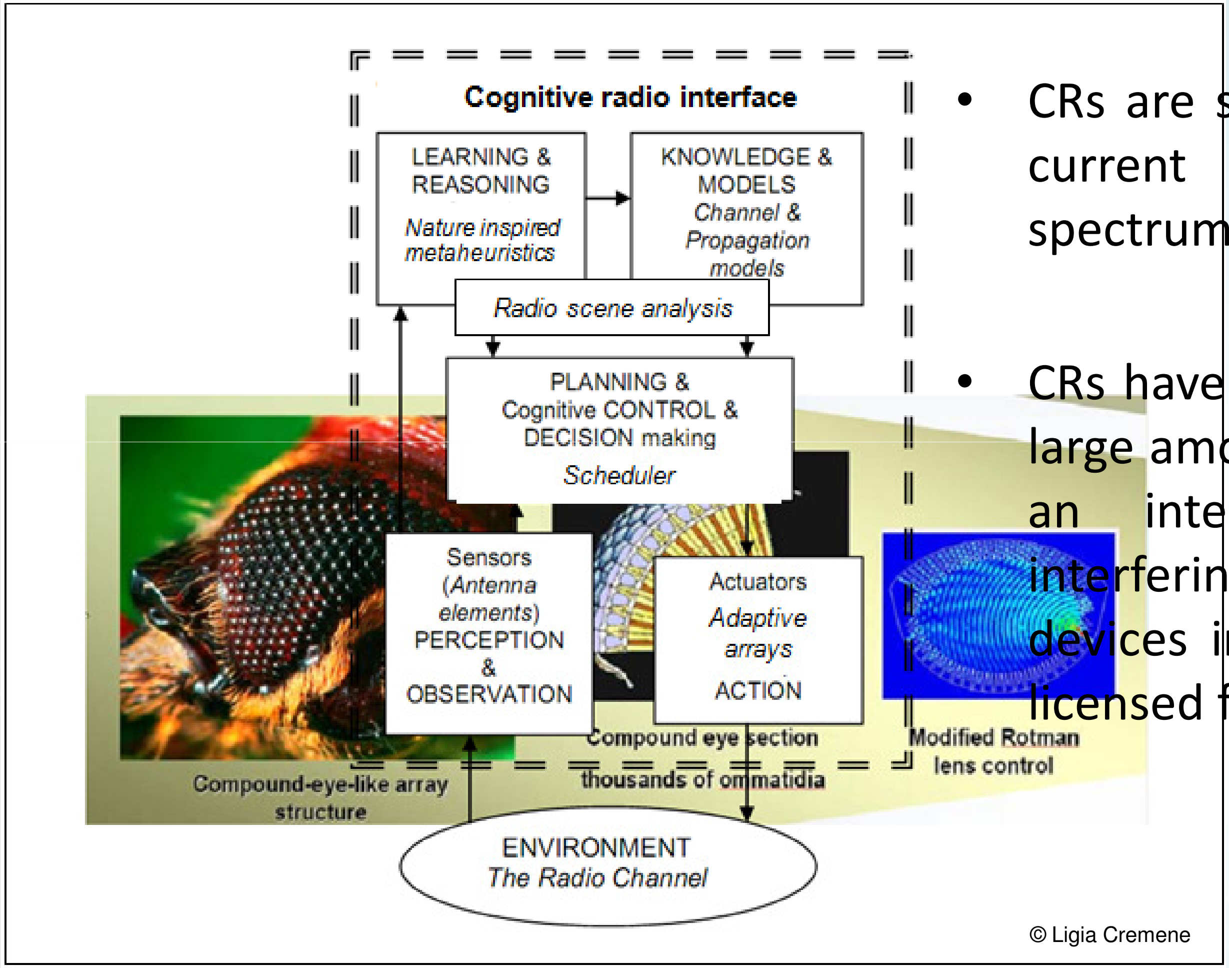
Spectrum management

- Spectrum allocation - static
- Spectrum assignment mechanisms
  - Market driven: spectrum trading, auctioning
  - Commons regimes: spectrum sharing
- Dynamic spectrum access
  - A means of managing spectrum enabled through cognitive radio
  - A generic technique used as a means of interference mitigation.

Dynamic spectrum access

- Spectrum sharing between licensed and unlicensed users
- No static assignment of frequencies is made
- Users with static and non-static frequency assignments can coexist
- Tends to be synonyms with Cognitive Radio (CR).

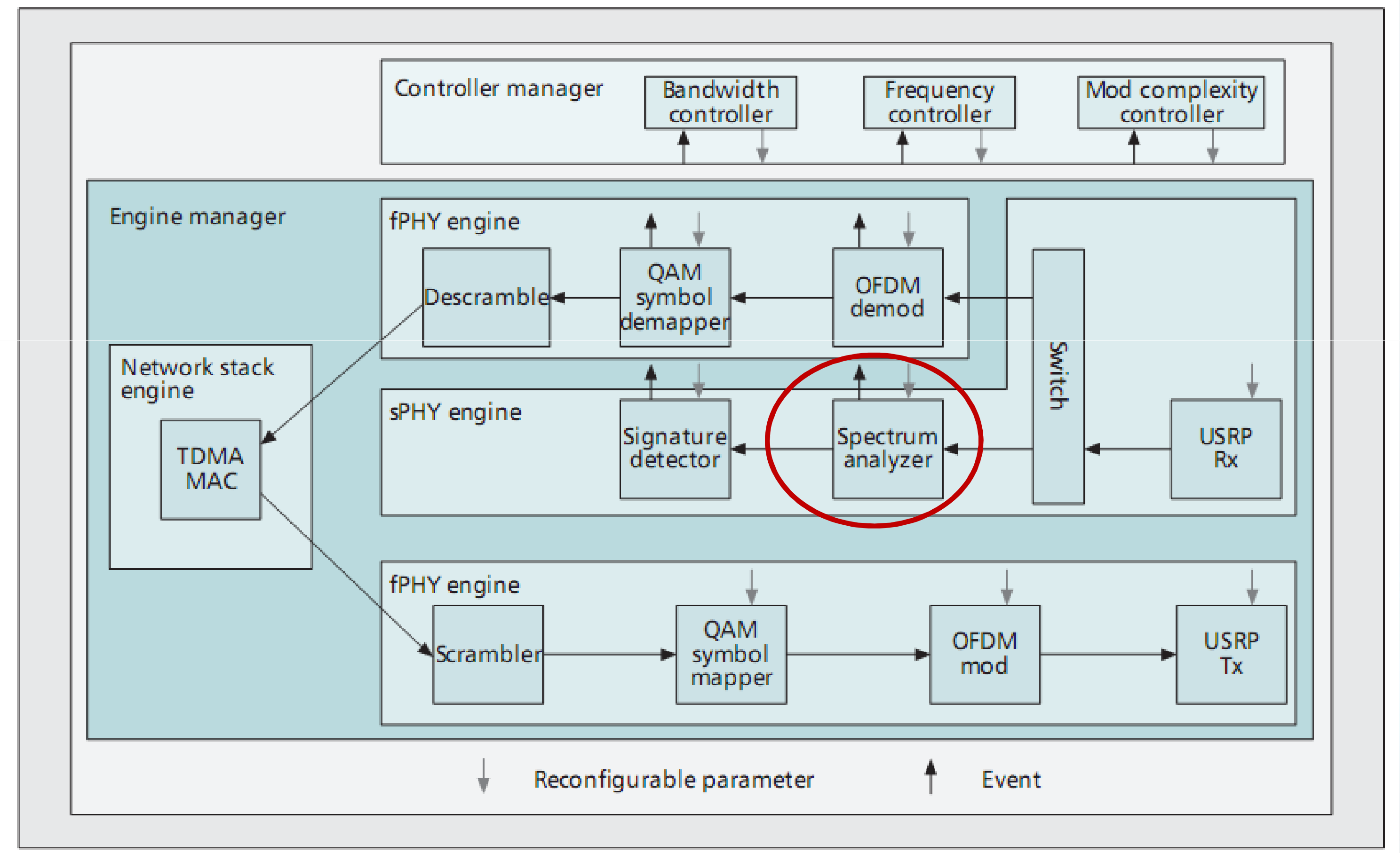
Cognitive Radios



- CRs are seen as the solution to the current low usage of the radio spectrum
- CRs have the potential to utilize the large amount of unused spectrum in an intelligent way while not interfering with other incumbent devices in frequency bands already licensed for specific uses.

CR node - example

Designed at CTVR Trinity College Dublin



USRP – Universal Software Radio Peripheral

Game Theory and Cognitive Radio Environments

- GT has recently emerged as an effective framework for the design of wireless networks (Neel, Reed, Gilles 2004, Maskery, Krishnamurthy, Zhao 2007, Niyato, Hossain 2007). (e.g. steady state analysis).

- Promising approach for analyzing the interactions of adaptive and cognitive radios.

Game Theory and Cognitive Radio Environments

- GT - a powerful tool in developing adaptive strategies in multiagent environments - multiple agents interact trying to achieve their own (conflicting) goals.
- CR environments are such environments (an agent = a CR) – where dynamic spectrum access, spectrum sharing, and issues of planning and decision-making have to be addressed.
- Eventually, adaptive strategies enable system components to learn a satisfactory policy for action through repeated interaction with their environment (equilibria detection) .

Game Theoretical Modelling of Spectrum Access

- Goal – to propose efficient models for harmonized spectrum access in dynamic radio environments (e.g. TV whitespaces).

- Approach – Cognitive Radio + Computational Game Theory
  - DSA ⇔ CR. A CR has to manage a dynamic interaction profile -> task suitable for GT analysis.
  - Radio resource allocation (RRA) and dynamic spectrum access (DSA) may be described as games between CRs.
  - Modelling strategic interactions (each player payoff depends on the actions of all players).
  - Chosen models: Oligopoly game models, relevance of new GT equilibrium concepts.

Oligopoly game modeling of CR environments

- Three oligopoly game models – Cournot, Stackelberg, and Bertrand – reformulated in terms of radio access.
- Aim: to investigate the relevance of certain GT equilibrium concepts for DSA – Nash, Pareto, and the joint Nash-Pareto equilibria.
- The commodity of this oligopoly market is the frequency spectrum.

GT equilibria. Nash equilibrium

- The most frequently used steady-state concept
- A strategy profile is a Nash equilibrium (NE) if no player can improve her payoff by unilateral deviation (no incentive to deviate).
- A strategy profile, *x* is an NE if and only if

$$u_i(x) \ge u_i(y_i, x_{-i}), \forall i \in N, y_i \in S_i$$

where *N* represents the set of *n* players, *N* = {1,…, *n*}.

for each player $i \in N$, S_i is the set of actions, and

u_i :*S* → *is* the payoff function.

By (s_i, s_{-i}^*) we denote the strategy profile obtained from s^* by replacing the strategy of player *i* with s_i, i.e. $(s_i, s_{-i}^*) = (s_1^*, s_2^*, \ldots, s_{i-1}^*, s_i, s_{i+1}^*, \ldots, s_1^*)$.

GT equilibria. Pareto equilibria

- The strategy profile *x* is said to Pareto dominate the strategy profile *y* if the payoff of each player using strategy *x* is greater or equal to the payoff associated to strategy *y* and at least one payoff is strictly greater.

  $(x < P\, y)$ iff

  $u_i(x) \geq u_i(y)$, for each $i = 1, \ldots, n$,

  and there is some *j* for which

  $u_j(x) > u_j(y)$.

- The set of all non-dominated strategies (Pareto frontier) represents the set of Pareto equilibria of the game.

The joint Nash-Pareto equilibrium

- Standard Game Theory deals with the study of strategic interactions between rational agents.

- For a more realistic modeling, a modified rationality paradigm is considered - agents/players may have several approaches and biases towards different equilibrium concepts – Nash or Pareto (Dumitrescu et al., 2009).

The joint Nash-Pareto equilibrium (2)

- In an *n*-player game consider that each player *i* acts based on a certain type of rationality r_i, $i = 1, \ldots, n$.

- We may consider a two-player game where r_1 = Nash (selfish) and r_2 = Pareto (other-regarding).
- Player 1 is biased towards the Nash equilibrium, and player 2 is Pareto-biased.

- An evolutionary eq. detection technique based on generative relations for Nash, Pareto, and NP equilibria is considered (Dumitrescu, et al., 2009).

Spectrum Access Scenario

- n cognitive radios attempting to access the same whitespace W at the same time.

- Each radio i is free to decide the number C_i of simultaneous frequency channels to access.

- How many simultaneous channels should each radio access in order to maximize its operation efficiency?

- Based on this scenario, Cournot, Stackelberg, and Bertrand oligopoly game models are reformulated.

Commons regime access scenario. **Cournot** game modelling

Players	**the CRs attempting to access a certain whitespace *W*;**
Actions	the strategy of each player *i* is the number c_i of simultaneously accessed channels; A strategy profile is a vector $c = (c_1,\ldots,c_n)$.
Payoffs	the difference between a function of goodput and the cost of accessing c_i channels.

Commons regimes – all users are unlicensed;
-- unlicensed does not mean unregulated.

Cournot economic competition model - players simultaneously choose quantities.

Cournot modelling - evolutionary detected **strategies**

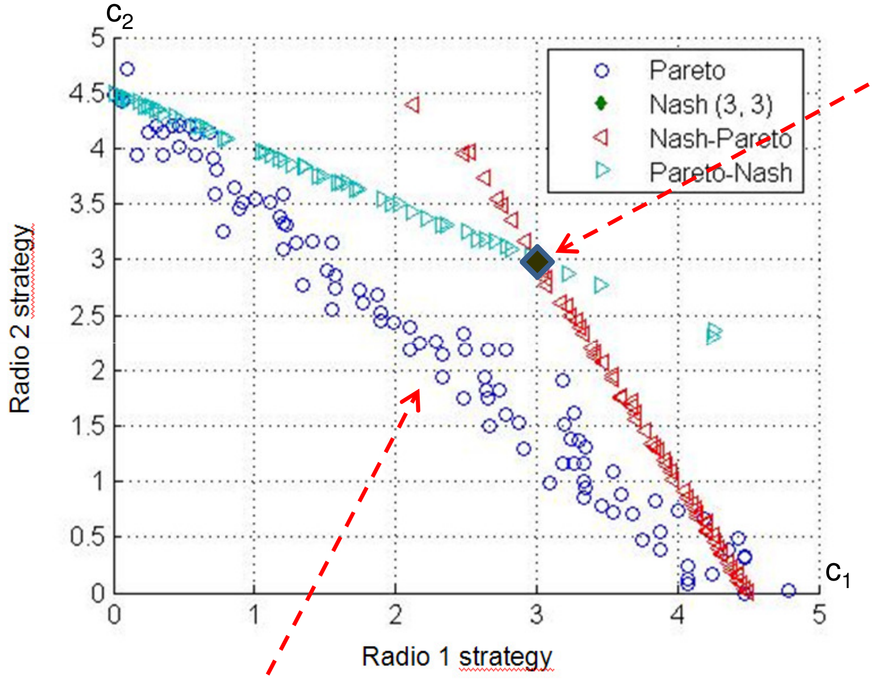


Figure 1. Cournot modelling – two radios (W = 10, K = 1). Evolutionary detected equilibria: Nash (3,3), Pareto, Nash-Pareto, and Pareto-Nash

Nash equilibrium -
each CR activates 3 channels

Although each CR tries to maximize its utility, none of them can access more than half of the available channels.

In some cases, the Nash-Pareto strategy enables the CR to access more channels than for the NE strategy.

None of the NP strategies can reach NE.

Pareto equilibrium (front) – full use of the spectrum resource

Cournot modelling – detected **payoffs**

- For each strategy of the NP equilibrium the Pareto-player has a higher payoff.
- The Nash-player payoff is smaller in a NP situation than in a case where all the players play Nash.
- Even if the NP strategies allow the CRs to access more channels, the payoffs are smaller than for the Pareto strategies (due to interference increasing with the number of accessed channels).

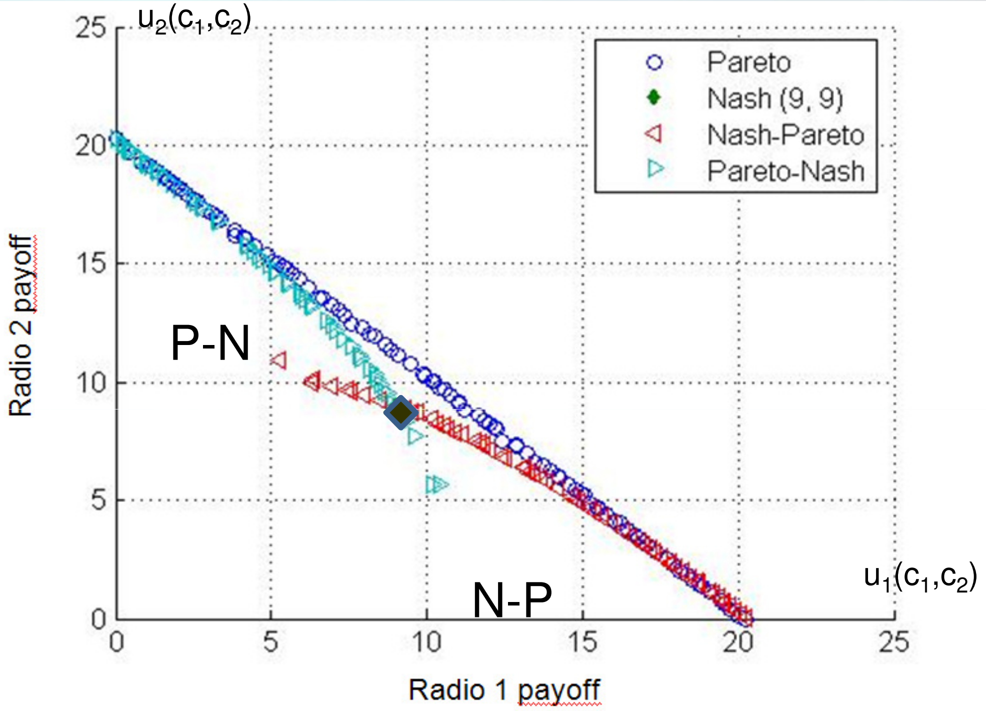


Figure 2. Cournot modelling – two radios (W = 10, K = 1). Payoffs of the evolutionary detected equilibria: Nash (9, 9), Pareto, NP, and PN.

Nash eq. – close to Pareto optimality

Licensed vs. unlicensed access scenario. **Stackelberg** game modeling

Players	**the CRs – licensed and unlicensed (primary and secondary) users attempting to access a given set of channels;**
Actions	the strategy of each player *i* is the number c_i of accessed channels;
Payoffs	the difference between a function of goodput and the cost of accessing c_i channels.

- Stackelberg economic model - players choose quantities sequentially (some have priority) .

- spectrum utilization is improved by detecting unoccupied spectrum holes or whitespaces and assigning them to unlicensed (secondary) users.

- relevant for interference control in dynamic spectrum access scenarios between incumbents and new entrants.

Stackelberg modelling – detected **strategies**

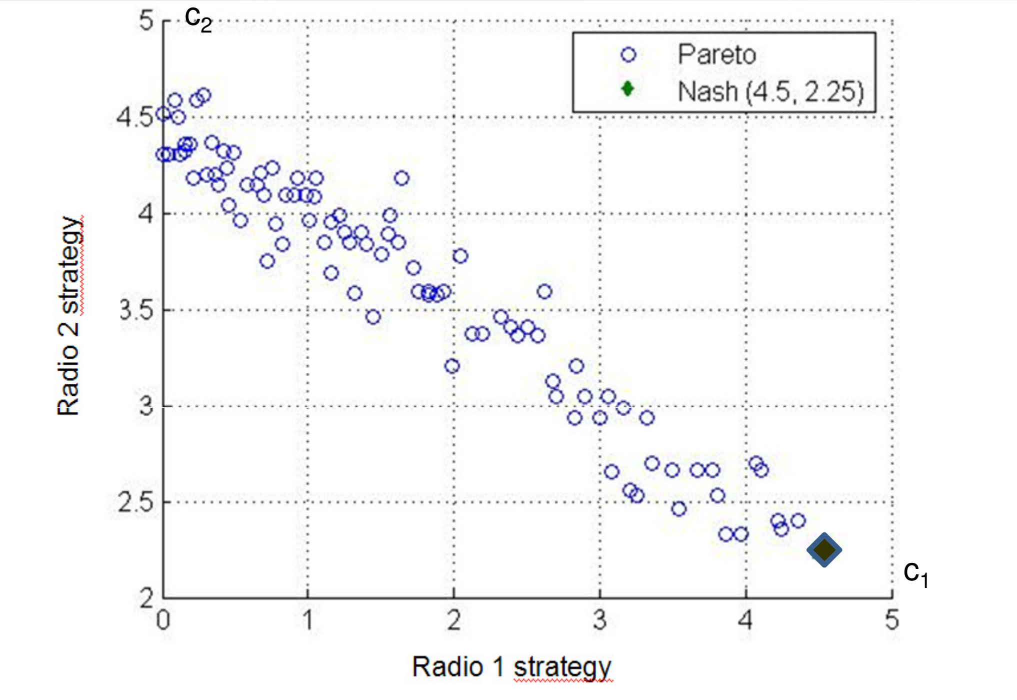


Figure 3. Stackelberg modelling – two radios (W=10, K=1). Evolutionary detected equilibria: Nash (4.25, 2.25), Pareto, Nash-Pareto, and Pareto-Nash.

Any strategy from the Pareto front is also an Nash-Pareto strategy.

The secondary user can access less channels than in the commons regime scenario (Cournot case, c_2 = 2.25 < 3), yet its maximum payoff remains unaffected, 20 (Fig.4).

The primary user's maximum payoff is half, 10, even if it accesses more channels (c_1 = 4.5).

NE lies on the Pareto front –> optimal use of the radio resource.

Stackelberg modelling – detected **payoffs**

- If the primary user plays Nash – the secondary user may maximize its payoff by choosing any strategy.
- If the secondary user plays Nash – the maximum payoff of the primary user is NE (10.13), only slightly highe then in the commons regime scenario (9).

- the NE payoff of the secondary user almost half then in the Cournot case (5 instead of 9).
- the NE payoff of the primary user is slightly increased (10 instead of 9).

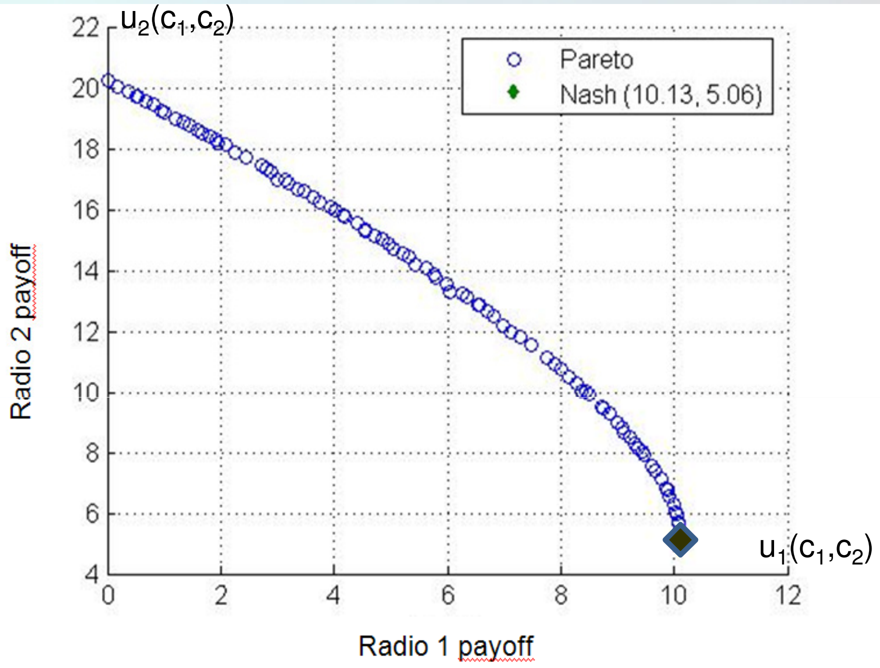


Figure 4. Stackelberg modelling – two radios (W=10, K=1). Payoffs of the evolutionary detected equilibria: Nash (10.13, 5.06), Pareto, NP=Nash, and PN=Pareto.

Primary user's priority guarantees its payoff .

Crowded spectrum access scenario. **Bertrand** game modelling

Players	**The CRs attempting to access the whitespace**
Actions	the strategy of each player *i* is a target number $p_i(c)$ of non-interfered symbols;
Payoffs	the difference between a function of goodput and the cost of accessing c_i simultaneous channels

- Bertrand economic model - players simultaneously choose prices - *P(c)* (target no. of non-interfered symbols).
- The lower this target is, the higher the chances are for the CR to access one or several channels.
- As the number *P(c)* of non-interfered symbols per channel decreases, the need for channels (the demand) increases. Thus, a CR willing to maximize its goodput will attempt to occupy as many low-rate channels as possible.

Bertrand modelling

Qualitative illustration of the winning situations for two CRs trying to access a limited bandwidth *W*

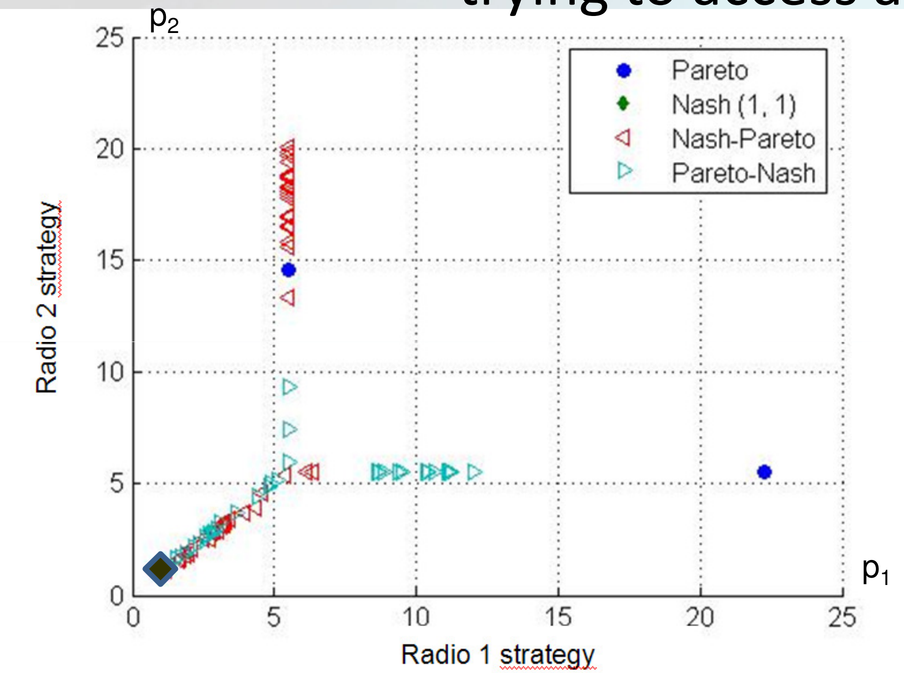


Figure 5. Bertrand modelling – two radios (W=10, K=1). Evolutionary detected equilibria: Nash (1, 1), Pareto, Nash-Pareto, and Pareto-Nash.

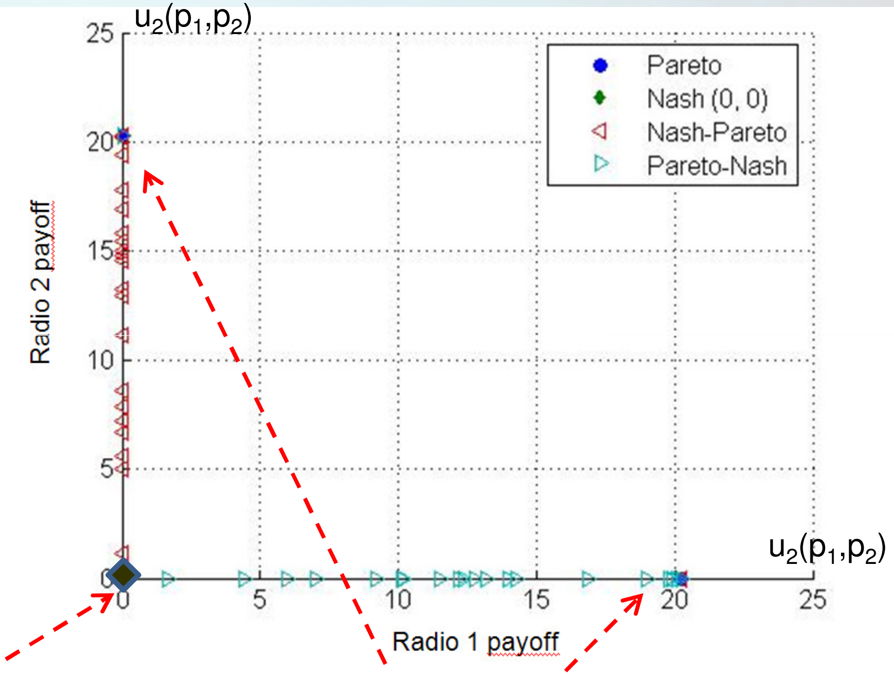


Figure 6. Bertrand modelling – two radios (W=10, K=1). Payoffs of the evolutionary detected equilibria: Nash (0, 0), Pareto, NP, and PN.

Nash Eq - zero payoff for each radio

the Pareto strategy ensures the maximum possible payoff for one radio at a time.

Conclusions

- Three oligopoly game models and new equilibrium concepts are considered in order to investigate DSA scenarios in CR environments: Nash, Pareto, and the joint Nash-Pareto, Pareto-Nash equilibria.

- The experimental observations may be especially relevant for designing new rules of behaviour for cognitive radio environments.

Conclusions (2)

- Cournot modelling (*commons regimes*)– the Nash equilibrium indicates a steady state – the maximum number of channels a CR may access without affecting its payoff.

- Stackelberg modelling (*licensed vs. unlicensed*) – payoffs are maximized for all users if the incumbents are Nash-oriented and the new entrants are Pareto-driven.

- Bertrand modelling (*very crowded*) – valuable in estimating the chances in a win-lose situation, in a very crowded spectrum, and indicates the need for some sort of scheduling or sequential access scheme.

Conclusions (3)

- Extract rules of behavior for an emerging environment, for simultaneous spectrum access of two users
- Identifying suitable GT models for real spectrum access scenario analysis
- Investigate the relevance of the recently proposed joint Nash-Pareto equilibrium
- Deepen the interdisciplinary approach (CR+GT) - metarationality
- Use of evolutionary computing in equilibria detection
- Steps towards an integrative view of the emerging cognitive radio environments.

Future work

- Future experiments include
  - many-player games,
  - investigation of new equilibrium concepts (e.g. Lorenz equilibrium),
  - new game models.

References

- Neel, J.O., Reed, J.H., Gilles, R.P.: Game Models for Cognitive Radio Algorithm Analysis, http://www.mprg.org/people/gametheory/presentations.shtml (2004).
- Dumitrescu, D., Lung, R. I., Mihoc, T. D.: Generative relations for evolutionary equilibria detection, GECCO '09, pp. 1507–1512, (2009).
- Maskery, M., Krishnamurthy, V., Zhao, Q.: GT Learning and Pricing for Dynamic Spectrum Access in Cognitive Radio, Cognitive Wireless Communication Networks, Hossain, E., Bhargava, V.K. (eds.), Springer Science +Business Media., NY, (2007).
- Niyato, D., Hossain, E.: Microeconomic Models for Dynamic Spectrum Management in Cognitive Radio Networks, Cognitive Wireless Communication Networks, Hossain, E., Bhargava, V.K. (eds.), Springer Science+Business Media, NY, (2007).
- Cremene, Ligia C., Dumitrescu, D., Nagy, Réka: Oligopoly Game Modeling for Cognitive Radio Environments, Balandin S., Dunaytsev, R., Koucheryavy, Y., (eds.) Proc. of the Smart Spaces and Next Gen. Wired/Wireless Networking, Springer LNCS, Vol 6294/2010, pp. 219-230, (2010).

Thank you for your attention.

No problem can be solved from the same level of consciousness that created it.

A. Einstein