Game Theoretical Modelling of Power Allocation Game in ISM-A concept

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ISM band (2.4 GHz and 5 GHz)

- Unlicensed (does not mean unregulated)
- Open spectrum access – treated as free-for-all
- Prone to ‘tragedy of the (unmanaged) commons’
- Uncoordinated deployment
- High-density, increasing
- Dynamic environment (difficult to analyze and to provide sound spectrum management schemes)
- Opportunistic behaviour
- Autonomy <-> regulation?

ISM – Advanced (ISM-A)

- Proposes novel spectrum access rules for unlicensed frequency bands
- Based on CR capabilities $\rightarrow$ improved spectrum usage, QoS
- May lead to elimination of some critical operational restrictions (e.g. the rigid EIRP limit)
• Co-existence in ISM bands, (e.g. 2.4 GHz used for Wi-Fi and many other SRDs) relies nowadays heavily on setting a low ceiling for Effective Isotropically Radiated Power (EIRP) – in Europe now limited to 100 mW.

• We posit that, with appropriately designed rules, the CR-enabled devices should be perfectly capable of choosing most appropriate transmit power while seeking the optimum compromise between link range/quality, ambient interference level, and its own energy consumption.

• Conceptual and computational framework to solve this → Game Theory (GT).
• Multiple nodes making individual radio parameter decisions that impact the performance of every node in the area.

• An interactive decision problem of the type that is well modelled by GT.

• CR interactions are strategic interactions: each player’s payoff depends on the other players’ actions. (basis of GT)
• Radios (e.g. WiFi) are already playing a game but they don’t know it; and they don’t know the game also.

GAME definition:
Players: CRs
Actions/strategies: power levels, channels, etc.
Payoffs: utility (throughput, etc.)

Game Theory for Cognitive Radio

• CR spectrum sharing problem may be seen as a game.
• Game Theory answers questions like:
  – what stable states (equilibria) appear on CR scenes?
  – are these stable states efficient, desirable?
  – which (self-enforcing) rules will lead to desirable stable states/solutions?

• Distributed algorithms may be redesigned to:
  – embed the derived rules (from GT simulations)
  – introduce protocols to start from stable states (reduce convergence time)
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GT place in the CR world

- Open resource access
- CR interactions
- Emerging environment

Regulation?

Game Theoretical simulations of CR interactions
- Stable states

Equilibrium detection
- Interpretation/characterization

- Extract rules of behavior
- Derive norms

- A type of commons regulated from the inside out

- Internalized norms (even values)
- The alternative to external enforcement of rules

- Embed rules/norms into CRs

8th COST-TERRA meeting, Biel, November, 26-27, 2013

Studied equilibria

- Standard eq. (in discrete games - new):
  - Nash, Pareto

- New:
  - Joint Nash-Pareto (capturing heterogeneity of players, different rationality; e.g. standard WiFis vs. CRs)
  - Lorenz (fairness and efficiency, selection criterion when multiple NE are present; e.g. many-player discrete games)
  - Berge-Zhukovskii (borderline situations).
GT equilibria. Nash equilibrium

- No player can improve her payoff by unilateral deviation
- (operating at NE, there is no incentive to deviate)

- Importance of NE:
  - Self-enforcing: no need for external authority intervention.
  - Self-sustainable: players would want to stay in NE

- Key problem: to design spectrum access rules which lead to Nash equilibrium that is fair and efficient (Pareto optimal).

GT equilibria. Pareto equilibrium (efficiency/optimality)

- No player can improve her payoff without decreasing another player’s payoff.
Lorenz equilibrium
(Fairness)

• A small set of Pareto efficient solutions that are equitable for all players
• A selection criterion when multiple NE are present; e.g. many-player, discrete games

• Nash eq and Pareto eq have some limitations when applied to real world problems.
  — Nash equilibrium rarely ensures maximal payoff and is rarely Pareto efficient
  — The Pareto equilibrium is a set of solutions that is often too hard to process and choose from.

Let us consider the payoffs ordered in an ascending order
\[ u_{(1)}(a) \leq u_{(2)}(a) \leq \ldots \leq u_{(n)}(a), a \in A \]  
(1)

and define the quantities:
\[ l_i(a) = u_{(i)}(a), \ldots \]

\[ l_n(a) = \sum_{i=1}^{n} u_{(i)}(a). \]  
(2)

• Strategy \( x \) is said to Lorenz dominate strategy \( y \) (and we write \( >_L \)) if and only if:
\[ l_i(x) \geq l_i(y), i = 1, \ldots, n, \]

\[ \exists j : l_j(x) > l_j(y). \]  
(3)

• **Lorenz equilibrium** of the game is the set of non-dominated strategies with respect to relation \( >_L \), that is considered the generative relation for the Lorenz equilibrium.
INTER-NETWORK INTERFERENCE

PROBLEM DEFINITION [1]

We consider an ad-hoc wireless network formed by N users, where a user is defined as a single transmitter-receiver pair \((Tx_i \rightarrow Rx_i)\).

The Signal to Interference plus Noise Ratio for each user is: \(SINR_i = \frac{h_{ij}p_j}{\sigma^2 + \sum_{k \neq i} h_{jk}p_j}\).

The utility function or the transmission rate for user \(i\) is: \(u_i = \log(1 + SINR_i)\).

The problem we consider is to find:

- Users’ transmission power \(\mathbf{p} = [p_1, p_2, \ldots, p_N]\) such that:
  - The overall utility function is maximum (1)
  - The cumulated power levels are kept to a minimum (2)

The problem can be written as:

\[
\begin{align*}
\text{(1)} & \quad \max \sum_i u_i, \\
\text{(2)} & \quad \min \sum_i p_i, p_i \in [0, P_{\text{max}}]
\end{align*}
\]

\( p = [p_1, p_2] = ? \)

\( \max(u_1 + u_2) \)

\( \min(p_1 + p_2) \)
POWER CONTROL GAME DEFINITION

- To solve this problem, the following non-cooperative power control game is defined:
  - Players: $N$ players, player $i \in \{1,2,\ldots,N\}$
  - Actions: $p_i \in [0,P_{\text{max}}]$ representing player $i$'s transmission power
  - Payoff function: $\pi_i(p_i, p_{-i}) = u_i - c_i p_i$ \hspace{0.5cm} (3)
where $c_i$ is player $i$'s power price that decides the trade-off between network utility and power efficiency.

GT notation:
- $p_i$ - power profile for player $i$
- $p_{-i}$ - power profile for all other players

GT BASED SOLUTION

- A group of players are in Nash equilibrium if each player is making the best decisions that he can taking into account other players decisions.
- In power control game $p_i^*$ is a NE only if:
  \[ p_i^* = \arg \max_{p_i} \pi_i(p_i, p_{-i}) \] \hspace{0.5cm} (4)
- It has been proven that in the power control game there is a unique NE.
- The best response of player $i$ that calculates NE is defined as:
  \[ b_i(p_{-i}) = \frac{1}{c_i} \sum_{j=1}^{N} h_{ij} p_j + n_0 \] \hspace{0.5cm} (5)
**GT BASED SOLUTION** [1]

- **ProActive Power Updating (PAPU) algorithm** uses best response to reach NE
  
  **Definition:**
  - User $i$’s transmission power is updated after best response formula everytime a predefined event happens.
  - Events:
    - other users’ power updating $p_j^t \neq p_j^{t-1}, \forall j \neq i$
    - $|\text{SINR}_i^t - \text{SINR}_i^{t-1}| < P_{th}$

  In order for PAPU algorithm to converge the following convergence condition has to be satisfied:

  \[
  \left| \frac{b_{ij}}{b_{ij}} \right| < \frac{1}{N} \tag{6}
  \]

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**Total system capacity as function of number of users in a 100x100m area.**

Simulation results of a distributed interference-aware power control game with the 100mW limit removed

Given certain rules, the system converges / no excessive over-exploitation of power

Additional power margin used to increase SNR / link quality
Further analysis

- Accurate/ relevant cost modelling (as part of the payoff function)
- Topology → convergence, embedded rules
- Capacity dynamics, limits
• First set of experiments conducted on real infrastructure by mixed team UTCN – JSI/ Ljubljana

• LOG-a-TEC testbed (VESNA platforms).

Some conclusions

• a new set of rules, ISM-Advanced, → an evolutionary improvement to Wi-Fi and open the ISM band to other spectrum efficient and intelligent radio technologies.

• with intelligent radio systems and/or the use of directive antenna systems, higher EIRP scenarios can operate in a stable and controlled manner and will not exacerbate the current ISM interference environment.
How will the radio spectrum look like in 10 or 20 years from now on?
http://videosift.com/video/German-town-removed-all-traffic-signs-lights-and-crosswalks

Thank you for your attention.

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

A. Einstein
List of publications on the topic


Papers under review and work in progress


