Energy Efficiency and Fairness in Cognitive Radio Networks: a Game Theoretic Algorithm

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Outline

• Introduction

• Resource allocation methods:
  ✓ Simulated annealing
  ✓ Iterative Water-Filling

• Game theoretic model

• Simulation results

• Conclusions
Created on 1 June 2011 by the merger of SELEX Communications with Elsag Datamat, an operation also involving SELEX Service Management and Seicos, SELEX Elsag is the Finmeccanica Group company specialised in the design and development of hi-tech systems, products, solutions and services for the following business areas:
Integrated communication solutions for strategic and tactical, naval and satellite applications

**Land Electronic Warfare**
Electronic Warfare solutions for the Electronic Attack, Support and Protection components, integrated with communication systems based on the “Connect and Protect” paradigm to guarantee the connectivity of friendly forces and protect them from the threat posed by improvised explosive devices (IEDs).

**Digital Legionary**
Modular soldier digitalisation systems that improve operating flexibility and effectiveness, as well as delivering superior mobility and survival capacity.

**Network Enabled Capabilities**
New generation communication systems for sea and land platforms, with advanced networking capabilities to allow coalition forces to achieve information superiority in the NEC framework.

**Tactical communications**
Programmable or software-defined radio and satellite systems, with multi-role and multi-mission capabilities, for the digitalisation of modern armed forces in both interforce and coalition scenarios.
Possible update of SDR Platforms to COGNITIVE architectures

- Policy Database (Security, QoS, Power, etc)
- Knowledge Database (Awareness, routing, past experience, etc)

COGNITIVE MANAGER

- Interface
  - Geolocation, Voice, Video, etc
  - CR TRANSPORT PROTOCOL
  - CR MAC PROTOCOL
  - Networking
  - Radio
  - Sensing

SWave SDR Platform
SELEX Elsag SDR Platforms and Waveform

HANDHELD

Vehicular Mono-Channel

SWave HANDHELD

SELFNET™ Soldier Broadband Waveform

WIDEBAND QoS MANET

MULTIHOP VOICE/DATA SERVICES

Resource Allocation (RA) Methods

- Distributed (Non-Cooperative) based on Game Theory
  - Potential games
    - Common (shared) utility function
    - Super-modular games (w pricing)
      - Individual (private) utility function
- Centralized (Non-Cooperative) based on Heuristics Methods
  - Simulated annealing
  - Tabu search
  - Genetic algorithms
- Centralized (Non-Cooperative)
  - Water Filling
  - Game Theory
Main features:
• Stochastic heuristic method
• Escaping local optima
• High flexibility
• At each step solution may be worst than previous solution
• Optimal solution is guaranteed for infinite decision time

Temperature is a control parameter that decreases at each step. When temperature is low, the probability of acceptance of a solution is small.

In a power allocation scenario:
• Complexity depends on users’ number
• Algorithm is not oriented to energy efficiency
Main features:
• Halfway between modern heuristics and Game Theory
• High flexibility
• Quasi-Optimal solution

In a power allocation scenario:
• excellent performance only in weak interference environments
• in strong interference environments only the user with best conditions channel should be active.
• Algorithm is not oriented to energy efficiency
The scenario

- 1 primary system
- N secondary users (completely independent positions)
- 1 radio resource.
- Discrete-time model
- No "direct" cooperation among primary and secondary users → “Interference Cap”

REMARK
Proposed scheme can be extended to include:
- more than one primary user
- M available radio resources (i.e. different channels or subcarriers of the same multi-carrier channel)
The Game

- **Players**: N users (completely independent positions)
- **Strategies**: transmission power levels
- **Utility function**:

\[ u_i(p(t), p(t - 1)) = W \frac{R_i f(y_i)}{p_i(t)} - \Omega_i(p(t), p(t - 1)) \cdot p_i \]

Where:

- \( p \) is the complete set of strategies of all secondary users,
- \( W \) is the ratio between the number of information bits per packet and the number of bits per packet,
- \( R_i \) is the transmission rate of the \( i \)th user in bits/sec,
- \( f(y_i) \) is the efficiency function, that represents a stochastic modelling of the number of bits that are successfully received for each unit of energy drained from the battery for the transmission.
- \( \Omega_i(p) \) is the pricing function that generates pricing values basing on the interference generated by network users.
The pricing function is defined as follows:

\[ \Omega_i = \beta - \delta \exp \left( -\mu \frac{p_i(t-1) \sum_{k \neq i}^N g_{k,i}}{I_i^r(p_{-i}(t-1), P)} \right) \]

where:

- \( \beta > 1 \) is the maximum pricing value,
- \( \delta > 1 \) is the price weight of the generated interference,
- \( \mu > 1 \) is the sensitivity of the users to interference.
Speed of Convergence

Thanks to the pricing parameters \((\beta, \delta, \mu)\), simulations are easily tunable in terms of:

- Time for convergence
- Sensibility of users to interference

Utility convergence for \(\delta = 10^{-4}\)

Utility convergence for \(\delta = 9 \cdot 10^{-3}\)
Simulation Results

- Convergence of the proposed system is quasi-independent from the number of users in the networks.

Convergence of the utility for a 10 users cognitive network.

Convergence of the SINR values for a 25 users cognitive network.
Simulation Results – SINR values

- Proposed game converges to similar SINR values obtained from Simulated Annealing, generally is better than Iterative Water-Filling.

*Trends of SINR mean values for increasing number of secondary users in the network; SA in red, Game in blue, IWF in green.*
Simulation Results – Energy Efficiency and Fairness

- Proposed game is much more energy efficient than Simulated Annealing and Iterative Water-Filling, also for a large number of considered users.

Allocated power for a 15-user simulation;
Game in (purple), SA in (purple+yellow), IWF in (purple+yellow+blue).
Simulation Results – Functional Q

Functional Q: the mean value of the ratio between the SINR level received and allocated power of the transmitter, calculated for each user.

\[ Q = \text{Mean} \left( \frac{\text{SINR}_i}{p_i} \right) \]

*Trends of SINR mean values for increasing number of secondary users in the network; Game in blue, SA in green, IWF in red.*
Conclusions

- Totally distributed (no central billing system)
- Throughput fairness among autonomous users
- Misbehavior avoidance
- Fast converging
- Easy tunable

**Objective function:**
- Total transmission rate maximization
- Total throughput maximization
- Total transmit power minimization
Let’s *play* more!

Thanks for your attention!

*Questions?*