Cognitive Radios Games: Overview and Perspectives

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Summary

Summary

Cognitive Radio Network CRN

Introduction

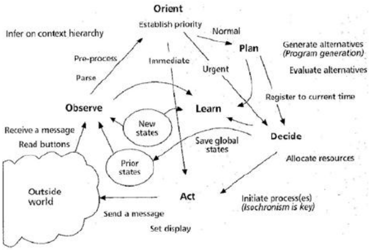
- new way of thinking wireless networks ("smart radio")
- more flexible secondary use of the Radio Spectrum

Definition

A **cognitive radio** is an adaptive radio that is capable of the following:

- awareness of its environment and its own capabilities,
- goal driven autonomous operation,
- understanding or learning how its actions impact its goal, and
- recalling and correlating past actions, environments, and performance.

Cognition Cycle [Mitola'99]



Some standards

1. The IEEE 802.22 working group is pursuing the development of a waveform intended to provide high bandwidth access in rural areas using cognitive techniques (de-allocation from analog TV).
   - spectral efficiencies of up to 3 bits/sec/Hz, peak download rates at coverage edge at 1.5 Mbps
   - achieved 100 km of coverage
   - MAC layer will provide cognition capabilities
   - **problem**: market competition with the WiMAX technology (high data rates for rural areas).
2. The IEEE 802.11h is not formulated as a cognitive radio standard, but can be considered.
3. The IEEE 802.11k supports spectrum agility and defines various measurement requests and reports between AP and mobiles regarding roaming decisions, channel traffic, hidden nodes and so on.

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Spectrum agility in IEEE 802.11h

802.11h

A 802.11h WLAN might be considered a cognitive radio because the protocol 802.11h requires that a WLAN is capable of the followings tasks:

- **Observation**: 802.11h requires WLANs to estimate channel characteristics such as path loss and link margin
- **Orientation**: based on these observations, the WLAN has to determine if it is operating in the presence of primary users (like radar), in a bad channel, or in the presence of other WLANs.
- **Decision**: based on the situation encountered, it has to decide to change its communication variables such the frequency of operation (DFS) and/or adjusts the transmit power (TPC)
- **Action**: The WLAN has then to implement this decision

Necessary concepts

Game Theory is a set of mathematical tools used to model and analyze interactive decision processes. The simplest model of game is the **normal form game** described by:

- a finite set of players (agents or decision makers) $N = \{1, \ldots, n\}$,
- an action space A, formed from the cartesian product of each player's action set, $A = A_1 \times A_2 \times \ldots \times A_n$,
- a set of **utility** functions $u = \{u_1, \ldots, u_n\}$ representing the player's preferences or valuation, and depends on $a \in A$.

We denote by a_i an action chosen by player i and a_{-i} actions chosen by all of the other players.

Equilibrium

Players are assumed to act selfishly in their own self-interested (non-cooperative game). This kind of game are analyzed to identify steady-states known as **Nash** equilibrium.

Nash Equilibrium

A particular nuple $a^* \in a$ is called a Nash Equilibrium (NE) if no player can improve its payoff, $u_i(a^*)$, by unilaterally changing its action.

$$\forall i \quad a_i^* = \arg\max_{a_i} u_i(a_i, a_{-i}^*).$$

Application to Cognitive Radio

The interactions of a network of cognitive radios can be mapped into a game.

- Each node in the network that implements the decision step of the cognition cycle is a player.
- The various alternatives available to a node forms the node's strategy set.
- A cognitive radio's observation and orientation steps combine to form a player's utility function.

Relevant Game Models

Potential Games

Considering a non-cooperative game, a function P is called a potential if for each player i, each action vector $a = (a_i, a_{-i})$ and each strategy a_i' :

$$P(a_i', a_{-i}) - P(a_i, a_{-i}) = u_i(a_i', a_{-i}) - u_i(a_i, a_{-i}).$$

Each game having such a function is called a **potential game** and gives relation between equilibrium of the game and solution of a global optimization problem.

Relevant Game Models

Properties of a Potential Game

- **Existence of NE**: Potential games with a compact action space always have at least one NE.
- **Identification of a NE**: All maximizers of P are NE.
- **Convergence**: Potential games have finite improvement path property (BR), so when nodes act in a selfish manner play converges to a NE.
- **Stability**: For repeated games, the potential function can be useful in order to construct a Lyapunov function.

Relevant Game Models

Supermodular Games

A game can be identified as a **supermodular game** if all players' strategy set is compact and utility functions satisfy the following relation:

$$\frac{\partial^2 u_i(a)}{\partial a_i \partial a_j} \geq 0, \quad \forall j \neq i$$

Remark: For potential games, there is such a necessary condition:

$$\frac{\partial^2 u_i(a)}{\partial a_i \partial a_j} = \frac{\partial^2 u_j(a)}{\partial a_j \partial a_i}, \quad \forall j \neq i$$

Relevant Game Models

Properties of a Supermodular Game

- **Existence of NE**: All supermodular games have at least one NE.
- **Convergence**: There exists a sequence of selfish adaptations that leads to a NE. For example, Best Responses (BR) dynamic will converge to a NE.
- **Stability**: Possibility of defining Lyapunov function in some particular cases.

Summary

Context

Channel-change decision maker is analyzed in symmetric interference scenarios where two or more similar networks reside on the same channel. The networks are assumed to have **intelligent** access points capable of making decisions regarding which channel to operate on.

- Existence of a protocol whereby any network can request its member devices to dynamically switch to a new channel.
- Capabilities defined in 802.11h standard.

Game Model

We consider two similar 802.11 networks that are currently residing on the same wireless communication channel. Each network has two strategies:

- *remain*: to remain on the current channel (R),
- *change*: to change to some other channel (C) with a channel-change delay of v.

Two-Network Many-Channel Game

Assumption: A large enough number of channels is available so that when a network changes its channel, it goes to a channel that has no interference.

Matrix game with transmission cost:

$$\begin{pmatrix} (v+1, v+1) & (v+1, 1) \\ (1, v+1) & (m+1, m+1) \end{pmatrix}$$

Two-Network Many-Channel Game

Pure strategies

- $v \geq m$: the strategy R is dominant for each player and it is a NE.
- $v < m$: there are two NE which are (C, R) and (R, C).

Mixed strategies

Each network chooses to change channel with probability p. We obtain the following expected utilities:

$$U_C = p(v+1) + (1-p)(v+1) = v+1,$$

and

$$U_R = p + (1-p)(m+1) = m + 1 - mp.$$

Two-Network Many-Channel Game

Mixed strategies

NE condition: Any user has no motivation to deviate from its strategy $(p^*, 1 - p^*)$ given that the other user has chosen this mixed strategy. Thus,, under NE, we have $U_C = U_R$.

- $v \geq m$: $p^* = 0$,
- $v < m$: $p^* = 1 - \frac{v}{m}$.

Two-Network Two-Channel Game

Matrix game with transmission cost:

$$\begin{pmatrix} (v+m+1, v+m+1) & (v+1, 1) \\ (1, v+1) & (m+1, m+1) \end{pmatrix}$$

Same equilibria in the pure strategy case and for the mixed:

$$p^* = \frac{1}{2}(1 - \frac{v}{m}),$$

if $v < m$.

Partial conclusions

Game theoretic models for 802.11h, kind of cognitive WLAN, competitive channel non-cooperative game.

- Analysis using matrix games
- Comparison with the social optimum (centralized solution)
- Both single-stage and multi-stage games.

Summary

Context

An ad-hoc network of cognitive radio links operating in master-slave fashion. Each link j is implementing a waveform with bandwidth B and carrier f_j. The master node on each link j directs the link to adjust f_j so that the interference on link j is minimized.

- Players are the set of links, N.
- Each player's action set is the set of frequencies, F.
- A utility function for any player j is given by

$$u_j(f) = \sum_{k \in N \setminus j} \sigma(f_j, f_k),$$

with $\sigma(f_j, f_k) = \min\{|f_j - f_k|, B\}$.

Results

This game is a **potential** game with a potential function given by:

$$P(f) = \sum_{j=1}^{|N|} \sum_{k=j+1}^{|N|} \sigma(f_j, f_k).$$

Note that while the existence of NE, convergence and stability are assured by virtue of being a potential game, there are actually numerous NE in this network and there are no NE that are globally stable.

Context

An ad-hoc network of cognitive radio links operating in master-slave fashion. Each link j has a number of channels C and an action a_j corresponds to a choice of zero to many channels to simultaneous operate on.

- Players are the set of master nodes, N.
- The action set of each player is given by the power set of the channel set, 2^C.
- A utility function for any player j is defined by:

$$u_j(a) = \sum_{c \in a_j} f_c(\sigma_c(a)),$$

with $\sigma_c(a)$ is the number of links simultaneously operating on channel c given the action vector a.

Results

This game is a **potential** game with a potential function given by:

$$P(a) = \sum_{c \in \bigcup_{i=1}^{n} a_i} \left(\sum_{k=1}^{\sigma_c(a)} f_c(k) \right).$$

Note that while the existence of NE, convergence and stability are assured by virtue of being a potential game, there are actually numerous NE in this network and there are no NE that are globally stable.

Context

An ad-hoc network of cognitive radio links operating in master-slave fashion. All links are operating on the same channel using a waveform that has spreading factor K. Each master node j has power levels $P_j = [0, P^{max}]$ and directs the link to change transmit power level to achieve a target SINR γ_j.

- Players are the set of master nodes, N.
- The action set of each player is given by its set of power, P_j.
- A utility function for any player j is defined by:

$$u_j(p) = \left(\gamma_j - \log(h_{jj} p_j) + \log\big(\frac{1}{K} \sum_{k \in N \setminus j} h_{kj} p_k + N_0\big) \right)^2 .$$

Results

This game is a **supermodular** game and this network is assured of having a NE and is assured of converging assuming each link acts in its own locally optimal manner.

Partial Conclusion

Cognitive radios interactions like a normal form game in several contexts. Possibility of addressing issues of existence, identification, convergence and stability depending on structural ga me properties.

Summary

Sensing Mechanisms

Information Revealing Games

Each cognitive mobiles senses permanently its radio interface to obtain information about all available channels.

- Many parameters change the channel state: radio technology, power,...
- How these informations induce preferences for the mobile and utility.
- Help of IT ?
- Mechanisms of sensing (802.11k) ?

Cooperation for sensing

Cooperative incentives

In a context of cognitive radios, cooperation sensing is very important as a concept of distributed sensing. In cognitive radio environment, achieving maximal throughput often requires coordination and cooperation.

- competitive control: coordination between mobiles (participation if it can gain from it)
- cooperative-game concept for fairness sharing and assignments

Learning in Games

Game-theoretic learning

Not possible with a normal form game formulation. A field of Game theory is called **game-theoretic learning** and the ideas are:

- mixed strategy generation
- the success of selected strategy is recorded for future reference
- relation to stochastic games

Hierarchical Games

Multi-level Games

A typical hierarchical game is the Stackelberg game. For example, an AP proposes different technologies with different parameters (QoS, throughput, price,...) and CR compete for the access.

- High level: the leader (AP) decides networks parameters.
- Low level: the followers (CRs) compete for their best access.

Evolutionary Games

Population Dynamics

The objective is to find an emergent strategy in a big population. The key issue that will shape the evolution of CR is **trust**, which is two-fold:

- trust by the users of CR,
- trust by all other users who might interfere with.

EGT and bio-inspired approaches might offer very interesting insight of reputation and trust mechanisms.

Summary

Conclusions

CR Games

Adding cognition to radio systems leads to a game principle for evaluating protocols and architectures. We have seen a large number of game models (recent and simple) with interesting properties in the context of cognitive radios.

The End

THANK YOU !

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