Policy-based Spectrum Sharing in Cognitive Radio Networks

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Overview

(1) Introduction

(2) Policies for Spectrum Navigation

(3) Applying the DARPA XG Policy Language

(4) Spectrum Sharing Strategies

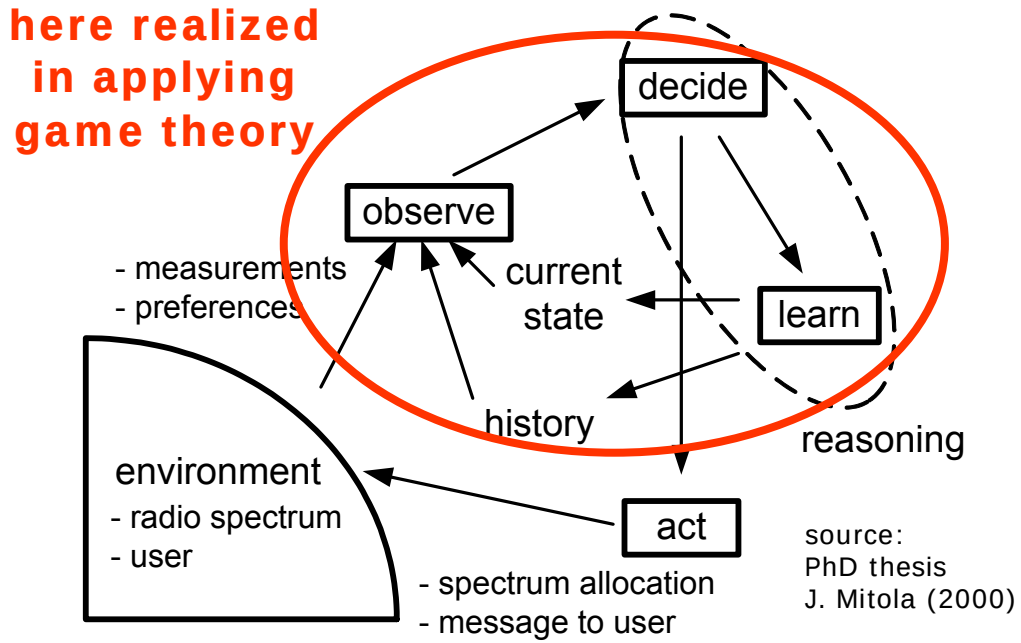
- Application of Game Theory Specified in XG Policy Language

(5) Conclusion and Outlook

Cognitive Radio

Cognition:

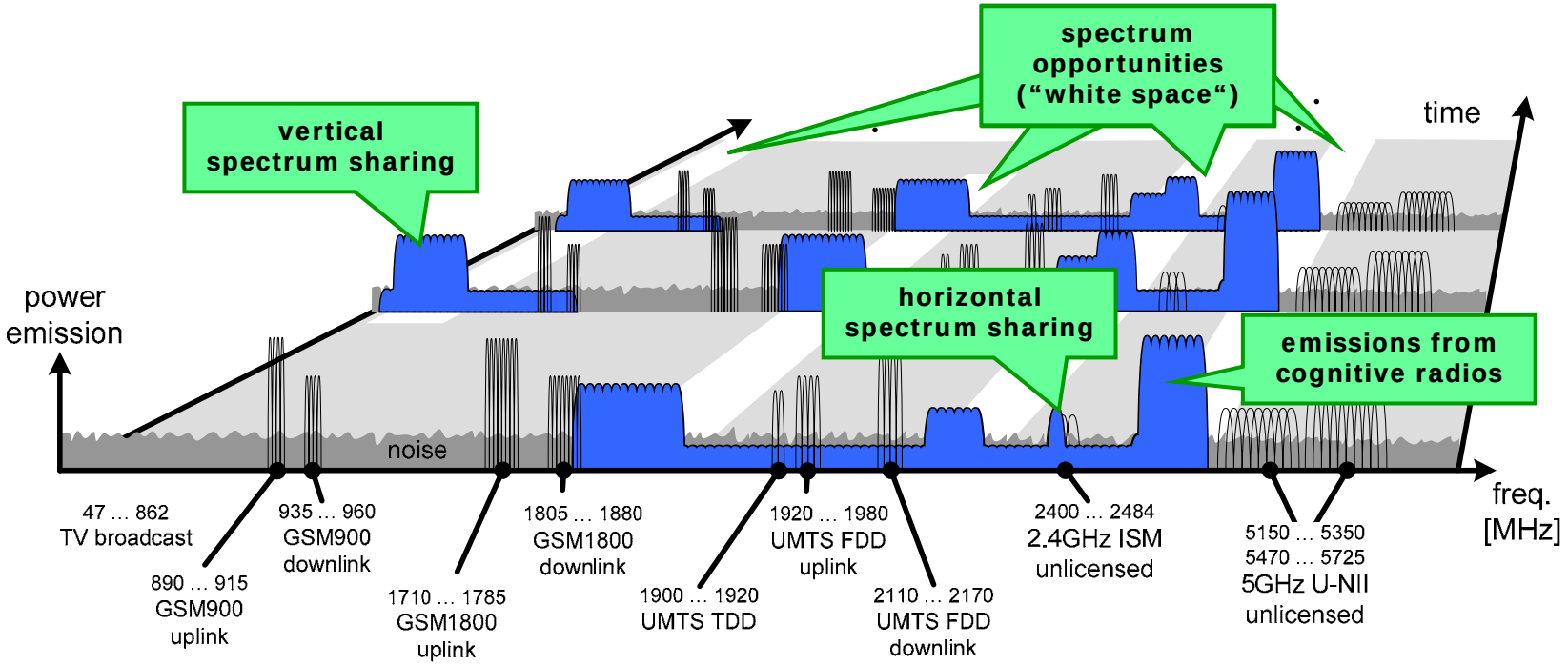
- Observation of spectrum utilization
- Deciding about spectrum allocation
- Learning from past spectrum utilization
- Acting in specifying current spectrum usage



Cognitive Radio:

- Changes transmitter parameters based on interaction with local environment (FCC, 2003)
- Intelligent wireless communication system that is aware of its environment (Haykin, 2005)
- Two primary objectives:
  (i.) highly reliable communication, whenever and wherever, including Quality-of-Service
  (ii.) efficient utilization of radio spectrum

Spectrum Sharing of Cognitive Radios

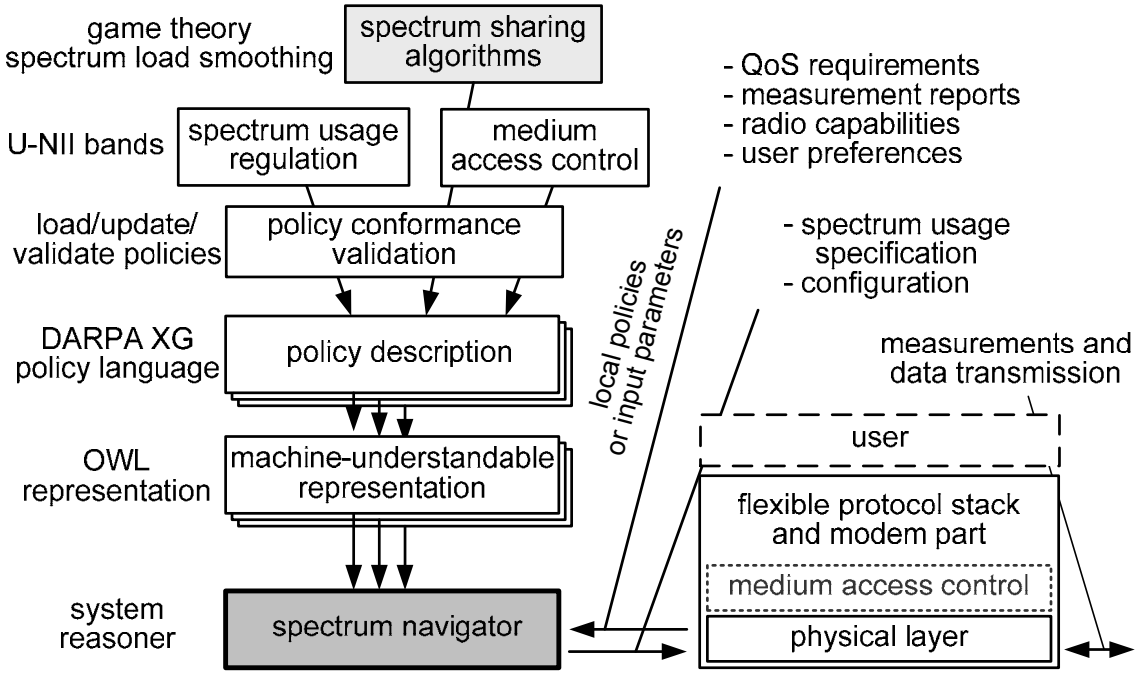


- Low-power re-use of the licensed spectrum by spreading the emitted signal over a large frequency band → Ultra-Wide Band
- Cognitive radio: Opportunistic spectrum access to under-utilized spectrum whether or not the frequency is assigned to licensed, primary services
- Horizontal spectrum sharing, as sharing between equals
  Example: IEEE 802.11 Wi-Fi, spectrum etiquette
- Vertical spectrum sharing, as sharing with incumbent radios
  Example: IEEE 802.22 ↔ TV broadcasts

Policies and Reasoning

- Policy: Selection of facts that determine the spectrum usage
  - Policies have their origin in spectrum usage restrictions imposed by a regulating authority
- Policy makers may design spectrum sharing algorithms or operator-specific policies
  - Policy framework: A machine-understandable representation of these policies plus a set of reasoning instances (here: spectrum navigator)
- Reasoning: Making decisions based on what was learned from the past
  - Knowledge domain: Described with a machine-understandable knowledge base
- Traceability of decision-making: Spectrum sharing algorithms will be visible to the outside world
  - To provide transparency to the regulator

Spectrum Navigation

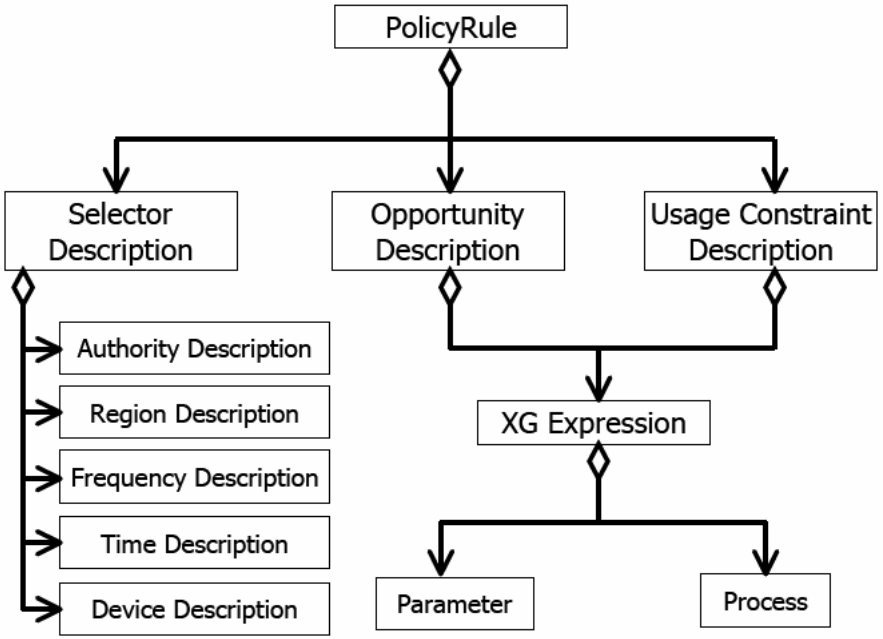


- Policy adaptation: Dynamic combination of multiple policies
- Policy conformance validation: Responsible for downloading, updating and validating policies
- Identification of spectrum opportunities based on measurements of spectrum utilization
- Consideration of QoS requirements and user preferences

  → **Distinct specification of spectrum usage**

DARPA XG Policy Language

- XML based specification of policies in shorthand notation
- Automatic translation to OWL representation
- Publicly available



- Selector description: Used to filter policies to a specific environment
- Opportunity description: Specifies under which conditions spectrum is considered as unused
- Usage constraint description: specifies the behavior of the cognitive radio when using a spectrum opportunity
- Parameters: Values contained in a policy like power levels
- Processes: Enable the execution of functions with input and output parameters

Regulation with Policies - Example

- Policy for using U-NII Band at 5.15-5.25 GHz expressed in shorthand notation of the DARPA XG policy language

policy description

U-NII Band at 5.15-5.25 GHz

Maximum transmission power: 40 mW

Usage description of limiting **MaxTransmitPower** to **TransmitLimit**

Policy for using the U-NII Band at 5.15-5.25 GHz when it is regarded as opportunity described in **BandUnused**

```
(SelDesc (id S1)
(authDesc US-FCC)
(freqDesc U-NII_US)
(regnDesc US)
(timeDesc Forever)
(devcDesc 802.11device))
```

```
(freqDesc U-NII_US
(frequencyRanges U-NII_1 U-NII_2 UNII_3))
```

```
(FrequencyRange (id U-NII_1)
(min 5.15)
(max 5.25)
(unit GHz))
```

```
(Power (id TransmitLimit)
(magnitude 40.0) (unit mW))
```

```
(UseDesc (id LimitTransmitPower)
(xgx "(<=
MaxTransmitPower TransmitLimit)"))
```

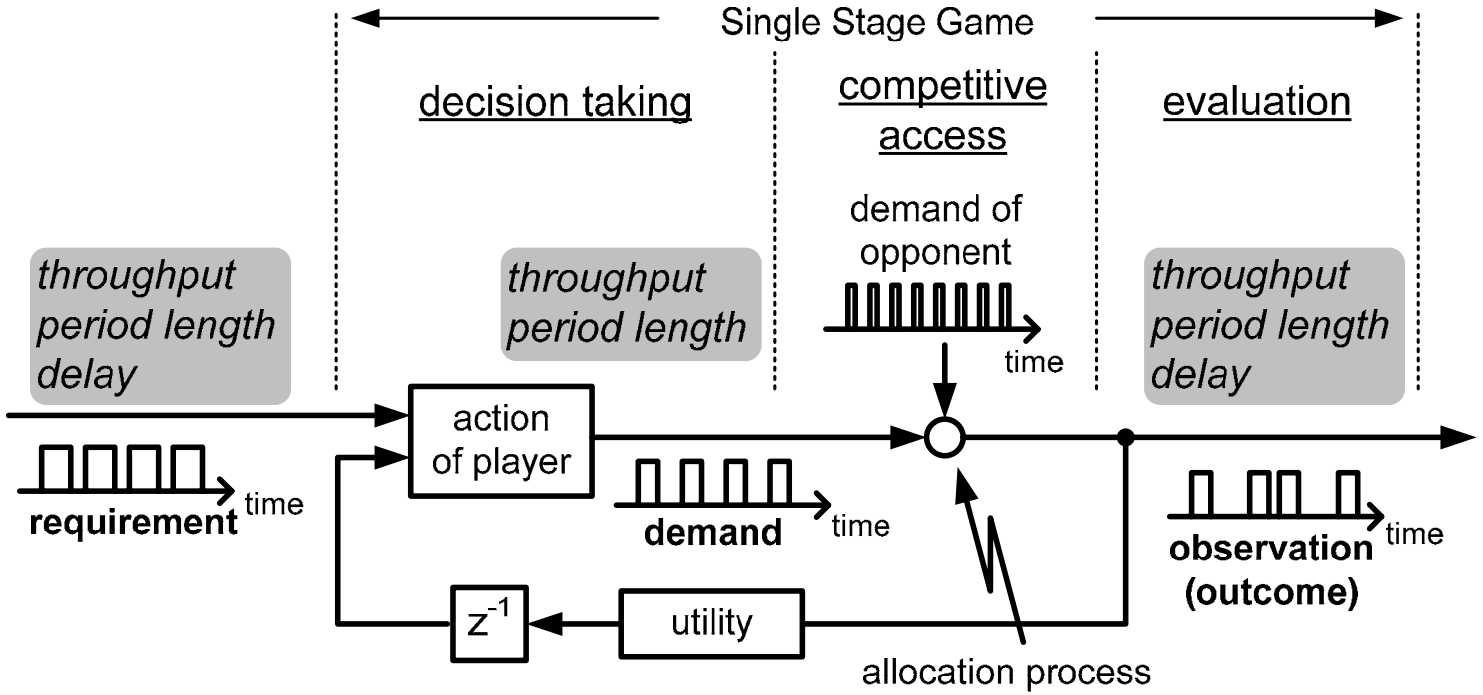
```
(PolicyRule (id P1) (selDesc S1)
(deny FALSE) (oppDesc BandUnused)
(useDesc LimitTransmitPower))
```

Applying Game Theory in Spectrum Sharing

- Competition between independent radios for allocating shared spectrum modeled as a stage-based game
- Players, representing radios, interact repeatedly in radio resource sharing games
- Solution concepts derived from game theory allow analysis
- Players decide about when and how often to attempt a medium access
- Action in a Single Stage Game implies certain behavior: Cooperation and defection
- In Multi Stage Games, players apply strategies in order to maximize their observed utility
- Utility: Summarizing value for successfully supported Quality-of-Service
- Strategies determine whether competing radios cooperate or ignore the presence of other radios

Applying Game Theory – Player

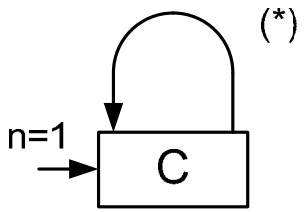
- Competitive access to shared spectrum
- Observed QoS as outcomes of a Single Stage Game



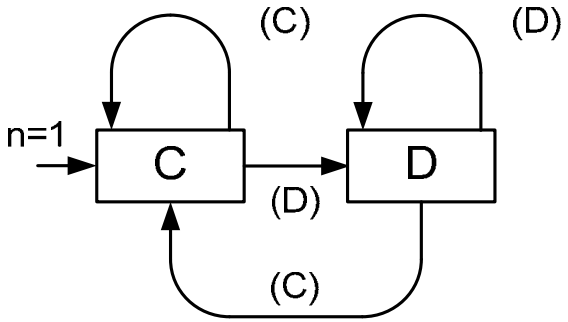
- Repeated Single Stage Games form a Multi Stage Game
- Players may interact during Multi Stage Games

Strategies in Multi Stage Games

- Strategies describe the alternatives a player has for an action within a Multi Stage Game
- Consideration of interaction with opponent player
- Strategies can be defined with state machines:



(a) COOP



(b) TitForTat

Spectrum Sharing Strategies as Policy

- Device capabilities of cognitive radio
- Usage descriptions defining specific actions per Single Stage Game

Capability description of parameters and processes a cognitive radio has to provide in order to apply game theory based policies

Duration of a Single Stage Game provided by the cognitive radio

Behavior of defection resulting to a distinct action: Best response to expected opponent's action **oppAction** to optimize own utility, **SelfCooperating:=FALSE**

Behavior of cooperation resulting to a distinct action, **SelfCooperating:=TRUE**

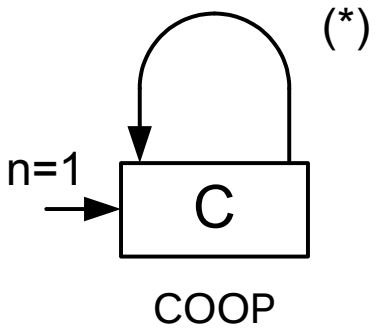
policy description

1	(DeviceCap (id GameTheoryProfile) (hasPolicyDefinedParams STAGEduration Theta_dem Delta_min Theta_req Delta_dem) (hasPolicyDefinedBehaviors ObserveStage ClassifyBehavior BestResponse))
2	(TimeDuration (id STAGEduration) (boundBy Device) (unit msec))
3	(Boolean (id OpponentCooperating)) (Boolean (id SelfCooperating))
4	(useDesc (id Defect) (xgx "(and (:= Theta_dem BestResponse(oppAction)) (:= Delta_dem BestResponse(oppAction)) (:= SelfCooperating BoolFalse)))
5	(useDesc (id Cooperate) (xgx "(and (:= Theta_dem Theta_req) (:= Delta_dem Delta_min) (:= SelfCooperating BoolTrue)))

Spectrum Sharing Strategies as Policy

- Opportunity description characterizes the outcome of a Single Stage Game
- Reflects the behavior of both players in the last stage
- Policy rule: Describes reaction on opponent's behavior in taking the own behavior into account
- Group of policy rules: Composes strategy in grouping all state transitions of the state machine

state machine



policy description

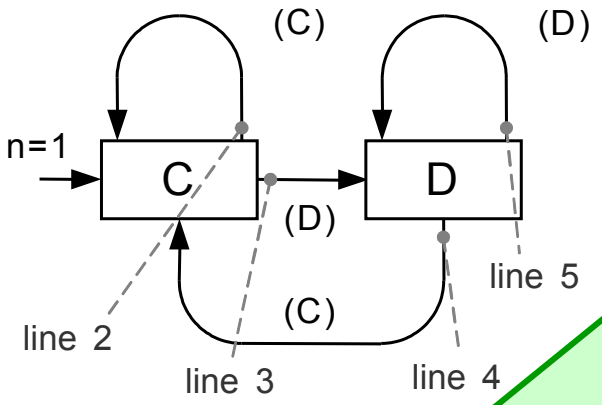
```
(PolicyRule (id StrategyCOOP) (selDesc S1)
(deny FALSE) (oppDesc AnyOpp)
(useDesc Cooperate))
```

policy rule **StrategyCOOP**; the player always cooperates independent from the characterization of a spectrum opportunity

Spectrum Sharing Strategies as Policy

- Example: Dynamic trigger strategy TitForTat – player cooperates (C) as long as opponent cooperates and defects (D) in case of opponent defection

state machine



policy description

1	`(PolicyGrp (id StrategyTitForTat) (equalPrecedence TRUE) (polMembers TFTCoop1 TFTCoop2 TFTDefect1 TFTDefect2))`
2	`(PolicyRule (id TFTCoop1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop_OpponentCoop) (useDesc Cooperate))`
3	`(PolicyRule (id TFTDefect1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop_OpponentDef) (useDesc Defect))`
4	`(PolicyRule (id TFTCoop2) (selDesc S1) (deny FALSE) (oppDesc OwnDef_OpponentCoop) (useDesc Cooperate))`
5	`(PolicyRule (id TFTDefect2) (selDesc S1) (deny FALSE) (oppDesc OwnDef_OpponentDef) (useDesc Defect))`

policies are grouped to compose the **`StrategyTitForTat`**; all policies have equal precedence; each state transition is reflected by a policy (here: 4)

Conclusion and Outlook

- Description of spectrum sharing algorithms in a machine-understandable way is one of the most challenging tasks to be provided by a policy language
- Distinction into spectrum opportunity and usage constraint facilitates hierarchical structuring of the algorithm's policy description
- Usage of DARPA XG Policy Language for regulation is extended with aspect of specifying distinct parameters for access to spectrum
- Next step: Software defined medium access specified in same policy language at example of IEEE 802.11e EDCA
- Crucial Point: Combination of all valid policies
  → realization of reasoning

spectrum sharing algorithms can be described in a common policy language

Thank you for your attention !

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Applying Game Theory – Utility

- Players try to maximize observed utilities based on their individual utility function
- Defined by the QoS requirements of supported applications