Cognitive Radio Resource Management

Prof. Luiz DaSilva

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About me...
Objectives of Cognitive Radio Resource Management

Approaches for Allocation of Wireless Resources

Functional Architectures for Cognitive RRM

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**Radio Resource Management (RRM)**

- Efficient allocation of resources in a wireless network
  - Orthogonal channels, through frequency, time, code
  - ... or at least allocations that result in tolerable amount of interference

- Achieved through...
  - Transmit power control
  - Spectrum / channel allocation
  - Access to the medium / scheduling
  - Multi-antenna use (beamforming, MIMO)
  - Multi-transceiver use
**Goals**

- **Goals of the individual radio**
  - Maximize SINR, data rate, throughput
  - Mitigate the effects of noise, interference
  - Maximize access to the medium
  - Maximize battery life

- **Goals of the network**
  - Ensure efficient use of spectrum resources
  - Maximize aggregate throughput
  - Avoid undue contention for resources
  - Ensure appropriate coverage

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**What is different in Cognitive RRM?**

- Greater ability of the terminal to reconfigure (software-defined radio)
- Radios may be capable of working with multiple Radio Access Technologies (RATs)
- Frequency agility
- Opportunistic use of spectrum, or dynamic spectrum management
Cognitive Radio Resource Management

- Dynamic allocation of resources (e.g., spectrum) when radios have increased ability to adapt and reconfigure (frequency agility, multiple RATs, etc.)
- Higher degree of autonomy from the radios (radios may participate in the resource management decisions)
- Coexistence: competition and cooperation in the use of resources
- Allocation of traffic to different RATs that are supported in the network

Flexible Spectrum Management

**Coordinated**
- Vertical handovers
- Spectrum sharing/pooling
- Spectrum broker
- Virtual operators
- Real-time spectrum auctions

**Autonomous**

*Shared bands*
- Opportunistic multi-band random access
- Cooperative access, coalition formation

*Licensed bands*
- Secondary access, interruptible by primary user
- Femto/macro-cell coexistence
- Dynamic multi-homing
**Coordinated Example**

- Spectrum broker controls access to part of the spectrum
  - Grants a time-bound lease to operators, specifying spatial region, maximum power, exclusive or non-exclusive usage rights
  - Region under broker control may have base stations of several providers

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**Autonomous, Non-Cooperative Example 1**

- Topology control in ad hoc networks
  - Each node sets its transmission power and channel of operation to achieve some connectivity objective
  - Access to the medium is random (unscheduled)
Autonomous, Non-Cooperative Example 2

- Opportunistic spectrum access
  - Secondary user detects white space and shapes its signal to fit into it
- No explicit cooperation with incumbent is required, as long and interference does not exceed pre-determined limit

![Graph of frequency vs magnitude](image)

Autonomous, Cooperative Example

- Cooperative spectrum sharing
  - Multiple secondary users in a multi-channel environment negotiate spectrum usage
  - Information dissemination regarding probability of incumbent activity and economic incentives may be part of the negotiation

![Image of two people shaking hands](image)
Approaches

- Classical optimization
- Game theory
- Heuristics
- Meta-heuristics
- Multi-objective approaches

... and combinations of these

Parameters

<table>
<thead>
<tr>
<th>Application</th>
<th>Source coding rate, priority, packet arrival rate, ...</th>
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</thead>
<tbody>
<tr>
<td>Network</td>
<td>Route selection, cost metric, cooperation, ...</td>
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<tr>
<td>MAC</td>
<td>Transmission time and channel, service rate, priority, ...</td>
</tr>
<tr>
<td>Physical</td>
<td>Transmit power, modulation, channel coding rate, channel selection, resource blocks, ...</td>
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</tbody>
</table>
**Optimization Goals**

<table>
<thead>
<tr>
<th>Category</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Min distortion, min delay, ...</td>
</tr>
<tr>
<td>Network</td>
<td>Min route length, min energy expended, ...</td>
</tr>
<tr>
<td>MAC</td>
<td>Max aggregate throughput, min buffer overflow probability, min delay, ...</td>
</tr>
<tr>
<td>Physical</td>
<td>Min aggregate power, max throughput, max rate/Joule, max spectral efficiency, min BER, ...</td>
</tr>
</tbody>
</table>

**Constraints**

<table>
<thead>
<tr>
<th>Category</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Limited source rate, strict delay requirements, ...</td>
</tr>
<tr>
<td>Network</td>
<td>Max number of hops, ...</td>
</tr>
<tr>
<td>MAC</td>
<td>Limited time/frequency slots, limited information about other mobiles, ...</td>
</tr>
<tr>
<td>Physical</td>
<td>Max transmit power per node and/or channel, available modulation constellation, available channel coding rate, ...</td>
</tr>
</tbody>
</table>
Classical Optimization

- Find an optimal allocation of resources to meet a certain goal
- Linear / non-linear / integer / MILP
- May assume centralized decision making and/or full information
- Complexity issues

\[
\begin{align*}
\text{min} & \quad f(\mathbf{x}) \\
\text{subject to} & \quad h_i(\mathbf{x}) = 0 \quad i = 1,2,\ldots,m \\
& \quad g_j(\mathbf{x}) \leq 0 \quad j = 1,2,\ldots,r \\
& \quad \mathbf{x} \in S
\end{align*}
\]

Classical Optimization Example

- Given...
  - A set of source-destination pairs in the network and associate rate requirements
- Find the optimal...
  - Assignment of frequency bands to each pair
  - Scheduling of sub-bands for transmission and reception
  - Multi-hop routing
- That minimizes...
  - The total bandwidth used in the network
Classical Optimization Example: Formulation

Min \[ \sum_{i \in \mathcal{N}} \sum_{m \in \mathcal{M}_i} \sum_{k \in \mathcal{T}_m} W^{(m)} x_{ij}^{(m,k)} \]

s.t. \[ \sum_{m \in \mathcal{M}_i} u^{(m,k)} = 1 \quad (m \in \mathcal{M}_i) \]

\[ \sum_{k \in \mathcal{T}_m} x_{ij}^{(m,k)} \leq 1 \quad (i \in \mathcal{N}, m \in \mathcal{M}_i, 1 \leq k \leq K^{(m)}) \quad (10) \]

\[ \sum_{k \in \mathcal{T}_m} x_{ij}^{(m,k)} + \sum_{k \in \mathcal{T}_m} x_{ij}^{(m,k)} \leq 1 \quad (i \in \mathcal{N}, m \in \mathcal{M}_i, j \in \mathcal{T}_m) \]

\[ 1 \leq k \leq K^{(m)}, p \in \mathcal{T}_m, p \neq 0 \quad (10) \]

\[ \sum_{k \in \mathcal{T}_m} f_{ij}(l) - \sum_{m \in \mathcal{M}_i} \sum_{k \in \mathcal{T}_m} W^{(m)} \log_2 \left( 1 + \frac{Q_{ij}}{\eta} \right) x_{ij}^{(m,k)} \leq 0 \quad (i \in \mathcal{N}, j \in \mathcal{T}_n) \]

\[ \sum_{j \in \mathcal{T}_n} f_{ij}(l) - \sum_{j \in \mathcal{T}_n} f_{ij}(l) = 0 \quad (i \in \mathcal{N}) \]

\[ \sum_{j \in \mathcal{T}_n} f_{ij}(l) = 0 \quad (i \in \mathcal{N}, i \neq s(l), d(l)) \]

\[ x_{ij}^{(m,k)} = 0 \text{ or } 1, \quad u^{(m,k)} \geq 0 \quad (i \in \mathcal{N}, m \in \mathcal{M}_i, j \in \mathcal{T}_m, 1 \leq k \leq K^{(m)}) \]

\[ f_{ij}(l) \geq 0 \quad (i \in \mathcal{N}, j \in \mathcal{T}_n, i \neq s(d(l)), j \in \mathcal{T}_n, s(l) = s(l)) \]

where \( W^{(m)}, Q, \eta, \) and \( v(l) \) are all constants, and \( x_{ij}^{(m,k)}, \)
\( u^{(m,k)}, \) and \( f_{ij}(l) \) are all optimization variables.


Distributed Optimization

- Optimization problems where each variable and constraint is owned by an agent
- Consider a network of \( n \) agents: \( \mathcal{N} = \{1, \ldots, n\} \)
- Agents want to cooperatively find:

\[ \min_{\mathbf{x} \in \mathbb{R}^n} \sum_{i=1}^{n} f_i(\mathbf{x}) \]

- Objective function \( f_i(\mathbf{x}): \mathbb{R}^n \rightarrow \mathbb{R} \) is known to agent \( i \)
- Agents periodically exchange information and estimate their impact on the objective function
- More tailored to distributed scenarios with incomplete information
**Game Theory**

- Mathematical models of conflict and cooperation among intelligent, rational decision makers
- Can be used to study the distributed resource allocation decisions made by decision-makers (network nodes, radio providers) to achieve some goal (maximize performance, minimize resource utilization)
- A game consists of...
  - A set of two or more players
  - Sets of possible actions for each player
  - A set of preference relationships for each player over each action tuple

**Cooperative and Non-Cooperative Game Theory**

- Non-cooperative
  - Players make decisions independently
- Cooperative
  - Players are allowed to enter into agreements, form coalitions, etc.
  - External entity assumed to exist to enforce contracts
  - It is possible to model/predict the outcome of a bargaining process without modeling the process itself
Non-Cooperative Game Theory Example

- SINR maximizing power control game
  \[ \Gamma = \langle N, A, \{u_i\} \rangle \]
- Set of players: cognitive radios in a certain region
- Set of actions: each radio \( i \in N \) sets its transmit power \( P_i \) to maximize its utility function
  \[
  u_i(p) = \frac{h_p}{\sqrt{M} \sum_{k \in N \setminus \{i\}} h_k p_k + \sigma}
  \]
- where \( M \) is the statistical cross-correlation of the signals

Cooperative Game Theory Example

- Cooperative spectrum sharing game
- Set of players: cognitive radios in a given region
- Set of actions: each player selects a subset of a total of \( K \) channels to occupy (each with bandwidth \( B/K \)), and the power allocation on each of those channels to maximize utility function
  \[
  u_i = \frac{B}{K} \sum_k \log_2(1 + SINR_k)
  \]
- Radios can bargain with one another to achieve an efficient solution


Typical Results of Game Theoretic Analysis

• Equilibria
  – Stable operating points for the network from which, once reached, no player has an incentive to deviate

• Convergence properties (non-cooperative games)
  – Indication of whether through an adaptive process players will arrive at an equilibrium

• Expected outcome of bargaining (cooperative games)
  – Indication of whether a more efficient outcome can be arrived at through cooperation

• Design of incentives/disincentives
  – Examples: auctions, mechanism design

Heuristics

• Approximations that seek a “good enough,” rather than an optimal, solution for the problem

• Appropriate when...
  – Problem is too complex for an optimization solution to be found in reasonable amount of time
  – Environment changes too rapidly
  – Adaptations and resource allocation decisions must be made under partial information
  – Heuristic solution can be shown to do not much worse than the optimum
Heuristics Examples

- Linear or parameterized approximations to objective functions
  - May allow non-convex problems to be treated as convex
  - May be reasonable approximations under some conditions (high SNR, large number of channels, etc.)
- Simple adaptations that can be shown to give good results with high probability
  - Adaptations based on local conditions, without taking into account global state of the network

Meta-Heuristics

- Heuristic methods for solving a class of computational problems for which there is no practical (e.g., polynomial time) solution
  - Use some black box procedures that are themselves heuristics
- Examples
  - Hill-Climbing or greedy Algorithm
  - Tabu search
  - Simulated annealing
  - Genetic algorithms
Meta-Heuristics Example

- Island genetic algorithm applied to the channel allocation problem in cognitive networks
  - Protocol model of interference
- An island genetic algorithm divides the population into subpopulations, or islands, that interact through the migration of individuals to other islands
- Seek channel assignment that maximizes sum-capacity
- Start with a valid channel assignment, perform mutation and cross-over of individuals with high fitness function

Multi-Objective Optimization

- Alternatives
  - Combine all objective functions into an aggregate objective function, such as a weighted sum (but how to assign weights?)
  - Look for solutions in the Pareto frontier

\[
\begin{align*}
\text{min} & \quad \begin{bmatrix} \mu_1(\mathbf{x}) & \mu_2(\mathbf{x}) & \ldots & \mu_p(\mathbf{x}) \end{bmatrix}^T \\
\text{subject to} & \quad h_i(\mathbf{x}) = 0 & \quad i = 1,2,\ldots,m \\
& \quad g_j(\mathbf{x}) \leq 0 & \quad j = 1,2,\ldots,r \\
& \quad \mathbf{x} \in S
\end{align*}
\]

**The Pareto Frontier**

- Given an allocation of resources involving some tradeoff, say performance and cost, a *Pareto improvement* is a movement from one allocation to another that can make at least one individual better off without making any individual worse off.
- A solution is *Pareto optimal or Pareto efficient* if no Pareto improvement is possible.
- The set of all solutions to a multi-objective optimization that are Pareto optimal is the *Pareto frontier*:
  - No objective can be further improved without making at least one other objective worse off.

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**Pareto Frontier: Visualization**

[Diagram showing Pareto Frontier, Feasible Point, Infeasible Point, Utopia Point, and Pareto Points in a multi-objective optimization context.]
Considerations in the Selection of an Approach

- Time scale in which resource allocation must be made and time scale in which environment changes
  - Fairly static (optimization) versus dynamic (heuristics)
- Centralized (optimization) versus decentralized (game theory, distributed optimization, heuristics)
- Processing complexity
  - Real-time adaptations (heuristics) versus establishment of baseline ideal results (optimization)

IEEE 1900.4

- “Architecture and Enablers for Optimized Radio and Spectrum Resource Usage”
- Defines a management system that decides actions required to optimize radio resource usage and QoS in heterogeneous wireless environments
- Spectrum assignment (carrier frequency, signal bandwidth, radio interface used in the assigned spectrum) to radio access networks (RANs) can be dynamically changed
- Or... spectrum assignment to RANs is fixed, but a RAN can operate concurrently in multiple bands
- Terminals are reconfigurable and may or may not be capable of multi-homing
  - Multihoming = capability to simultaneously maintain more than one active connection with RANs
**IEEE 1900.4 Resource Management**

- Reconfiguration decisions are made by the terminal (TRM) and by the network (NRM).
- Logical communication channel between TRM and NRM can be realized in-band (using an existing RAN also used for data) or out-of-band (specifying a dedicated physical channel for this communication).


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**IEEE 1900.4 Reference Usage Cases**

- Dynamic spectrum assignment example: a spectrum band is shifted from 802.16e to 802.11n due to shifts in demand.
- Dynamic spectrum sharing example: 802.22 systems using VHF/UHF bands opportunistically.
- Distributed radio resource usage optimization example: joint optimization of resource assignment by terminals and network.

IEEE 1900.4 System Architecture

- RAN context information (optimization objectives, radio capabilities, measurements,...)
- Radio resource selection policies

Terminal context information (terminal capabilities, user preferences, required QoS, measurements, geo-location info, ...)

IEEE 1900.4 Functional Architecture

- Terminal reconfiguration decision and control
- Information extraction, collection, and storage
- RAN reconfiguration, selection, and control
- Radio resource selection policies
- Network reconfiguration decision and control
- Spectrum assignment and evaluation
- Policy derivation
- Policy efficiency evaluation

IEEE 1900.4 entities
- Internal interfaces of NRM and RMC functions related to context awareness and given as implementation example
- Internal interfaces of NRM and RMC functions related to decision making and given as implementation example
- External interfaces of NRM and RMC functions related to context awareness
- External interfaces of NRM and RMC functions related to context awareness and given as implementation example
Bringing Dynamic Spectrum Access to 4G (LTE+) and Beyond

- Licensed spectrum is augmented with dynamic access to additional bands
- Coordinated by Spectrum Accountability Server (SAS)
- Signalling to control access to additional bands uses the licensed carriers
- Data transported over licensed and dynamically allocated carriers


Architecture for DSA in LTE+

LTE Network Elements
- eNB: Evolved Node B
- E-UTRAN: Evolved Universal Terrestrial Radio Access
- HSS: Home Subscriber Server
- MME: Mobility Management Entity
- PGW: Packet Gateway
- SGW: Signaling Gateway

SA Network Elements
- cBS: cognitive Base Station
- cRAN: cognitive Radio Access Network
- cUE: cognitive User Equipment
- GDB: Geolocation Data Base
- SAS: Spectrum Accountability Server
**Architectural Components**

- CBS
- IP Reachable
- Spectrum Trending
- Traffic Trending
- Spectrum Agile Radio
- RRC - Spectrum Sensing
- SAP: Spectrum Accounting Protocol
- X2e-Cooperative Sense
- X2e- Spectrum Trading

**Signalling Endpoints**

- IR
  - IP Connect TV
  - Service Loss
  - Service Loss Reporting
- cUE
  - Spectrum Agile Radio
  - RRC - Spectrum Sensing

- N-PDG
  - H-cUE
  - IR
- N-cUE
  - IR
  - IR
  - IR
  - IR

- N-: Neighbor
- H-: Home
- IR: Integrated Receiver
- SAP: Spectrum Accountability Protocol

- OPERATOR A
  - Spectrum Agile Radio
  - RRC - Spectrum Sensing
  - X2e- Cooperative Sense
- OPERATOR B
  - Spectrum Agile Radio
  - RRC - Spectrum Sensing
  - X2e- Cooperative Sense
**cBS Registration and Neighbour Discovery**

![Diagram of cBS Registration and Neighbour Discovery]

**Spectrum Lease Request Procedure**

![Diagram of Spectrum Lease Request Procedure]

**Procedure Note:**
This process could be executed during the maintenance window or on demand on a call by call basis.
**Spectrum Sharing Procedure**

- **Demand Trigger:**
  - Calculate Lease Request
  - SAP: Spectrum Lease Request
  - Evaluate Spectrum Availability
  - SAP: Spectrum Lease Response
  - Spectrum Unavailable
  - X2e-ST: Spectrum Lease Request
  - Evaluate Spectrum Availability
  - X2e-ST: Spectrum Lease Response
  - Spectrum Available
  - X2e-ST: Spectrum Release Order
  - X2e-ST: Spectrum Release ACK
  - Add Spectrum to Available Pool

**Procedure Notes:**
- This process could be done during the maintenance window or on demand.

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**Service Request and Reporting Procedure**

- **Connect_cUE**
  - RRC: Connection Request
  - Licensed spectrum
  - RRC: Carrier Optimization
  - RRC: Carrier Handoff Order
  - Channel reassignment
  - RRC: Carrier Handoff Complete
  - Determine Carrier Use and Availability
  - SAP: Report Service KPI
  - Piggybacked on Spectrum Release ACK or Periodic
  - Report Service KPI
  - Successful/Dropped/Lost/Blocked
  - Service Response
  - Carrier Assignment Available
  - Determine Carrier for Use
  - Change Carrier
  - cUE Service
  - Report Service KPI
  - Record and Report Statistics

**Procedure Notes:**
- This process is done on demand.
- The RRC optimization procedure is one of the first open issues.
- Reporting Service Usage could also be combined in the spectrum lease release.
Performance Analysis: Scenario

Performance Analysis: Spectrum Availability

Fig. 16. Cumulative distribution functions for duty cycles of the four different DSA carrier types used in our simulation.

<table>
<thead>
<tr>
<th>Band Descriptor</th>
<th>P_0 [dBm]</th>
<th>P_D [dBm]</th>
<th>P_3 [dBm]</th>
<th>f_0 [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV 770 MHz AB</td>
<td>0.819</td>
<td>0.342</td>
<td>0.0414</td>
<td>1.103</td>
</tr>
<tr>
<td>GSM 1800 DL AB</td>
<td>0.193</td>
<td>0.065</td>
<td>0.0716</td>
<td>1.302</td>
</tr>
<tr>
<td>DECT 1900 MHz AB</td>
<td>0.053</td>
<td>0.0</td>
<td>1.689</td>
<td>4.927</td>
</tr>
<tr>
<td>ISM 2.4 GHz AB</td>
<td>0.144</td>
<td>0.0</td>
<td>0.840</td>
<td>5.947</td>
</tr>
</tbody>
</table>

TABLE 1: Band parameters used to determine DSA channel duty cycle from [10]
Performance Analysis: Results

**Heterogeneous Networks**

- Operator-deployed and/or user-deployed small cells
  - Significant improvement in overall capacity
- Small cells add complexity to RRM problem
  - Vertical handover
  - Femto-femto and macro-femto channel allocation and interference
- The RRM task also becomes increasingly de-centralized
  - Less planning of infrastructure deployment
Incorporating Indoor Small Cells


Summary

- Radio resource management refers to the allocation of wireless resources to fulfill network and user objectives.
- In cognitive radio networks, must take into account increased reconfiguration capabilities of the radios, frequency agility, coexistence between primary and secondary users, multiple radio access technologies.
- Essentially, an optimization problem.
- Functional architectures being standardized (IEEE 1900) and proposed in the literature for 4G networks and beyond.
On the interwebs

Papers... luizdasilva.wordpress.com

On email... dasilval@tcd.ie

About CTVR... www.ctvr.ie

Wireless @ Virginia Tech... wireless.vt.edu