Cognitive networks: the pursuit of evolvable, sustainable, and submissive networks

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About me...
CTVR

- CTVR is a national centre for telecommunications research.
- It is head-quartered in Trinity College and spans six institutions around Ireland.
- Our mission is to carry out industry-informed research in telecommunications to the highest of standards.
- We work both in the optical and wireless domains.
**evolvable:**
Elegant paths to future. Adaptive and flexible where it should be. Understanding of points of inflexibility.

**submissive:**
Not biased towards any one model of ownership. No un-necessary rule-setting or resource labelling.

**sustainable:**
Persistent awareness of resource constraints e.g. man-power, energy, bandwidth, processing power, space, storage etc.
‘traditional’ radio

+ reconfigurability =

software-defined radio

+ awareness + adaptation (+ learning) =

cognitive radio
Is ‘cognitive radio’ here to stay?

- If not the buzzword, then at least the concepts behind it
- Runtime reconfigurability in radios
- Autonomous adaptations in response to the environment (including the network)
- In the dynamic spectrum access arena, more flexible regimes of utilization of spectrum
interests

fundamental principles that will allow the wireless network of the future to evolve into new architectures characterized by increasing autonomy and ubiquity of wireless services

ability to learn

distributed and autonomous decision making

transient ownership of resources
Sustainable, evolvable, submissive: cognitive networks

*Cognitive networks* – perceive their environment, then decide, learn and act from the results, with network-wide goals.

Organization of **wireless access networks**, including spectrum management, and distributed adaptations by cognitive radios to meet end-to-end objectives.

Interaction between **wireless access and wired networks**, including assignment of users to access points, energy efficiency, flexibility to user mobility.

Tools

From cognitive radios to cognitive networks

• Spectrum etiquette for distributed channel selection
• Effects of imperfect network information on radio adaptations
• Small / large cell coexistence and resource management
• Analytical (game theory) + experimental

Distributed coordination for heterogeneous networks (collaboration with UCC)

• Sensing and sharing in wireless access and multi-hop networks
• Heterogeneous handover optimisation
• Transport protocols to handle mismatch at wireless/optical boundary
• Analytical (optimisation) + experimental
From Cognitive Radios to Cognitive Networks

Current practice

Resource management for cognitive radios acting in a network
- **local adaptations** (power, channel, ...)
- **local goals** (max SINR, min BER, ...)
- **perfect information** (can observe channel, neighbors’ actions)

Extensions

Local adaptations to meet end-to-end or **network-wide goals** (throughput, network connectivity, ...)

**Information** available to adaptive radios is **limited**, due to cost of propagating network state information or **inaccuracy** in observing one’s local environment

![Observation-Orientation-Action (OOA) diagram](image)
Game theory and cognitive communications

A set of analytical tools from economics and mathematics to predict the outcome of complex interactions among rational entities in the context of cognitive radio...

Models of interactions among adaptations performed by cognitive radios in a network

Design of incentive structures for efficient resource sharing in a cognitive network

Economic models of spectrum markets

(...)

Coordination for heterogeneous and multi-hop networks

• Distributed spectrum sharing for multi-hop topologies and HetNets (relays, coexistence between small and large cells)

• Adaptations: channel selection, transmit power

• Goals: network-wide spectrum efficiency, fairness, network connectivity, coverage

• Cooperative game theory, coalition formation

Types of coalition in equilibrium as a function of link range


**Dynamic pricing coalition for cognitive radio networks**

- Hierarchical framework:
  - Primary users distributedly form coalitions to decide chargeable secondary users and the prices;
  - Secondary users use optimal transmit power to maximize their payoffs

- Adaptations: Spatial spectrum sharing, SNR wall

- Goals: max utility for both primary and secondary users under interference constraints, fairness criteria for primary users in each coalition

- Stackelberg game, dynamic coalitional formation, fairness criteria.

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Imperfect monitoring

• Impact of incomplete or erroneous information about channel or network conditions or neighbor activity on effectiveness of radio adaptations

• Framework is games of imperfect public/private monitoring

Utility fn: imperfect public monitoring

\[ \pi_i(\alpha) = \int_{p \in \Omega} u_i(\alpha_i, p) \cdot dF(p; \alpha) \]

\( \pi \) is the expected utility

\( p \) is the public signal

Need to model the distribution of \( p \), parameterized by the action vector \( \alpha \)

Price of ignorance in topology control adaptations upon departure of one radio

Machine learning and the cognitive cycle

• ‘A branch of AI where a computer generates rules based on data that is fed into it.’
• The ability to learn from past actions/experiences is a component of cognition
• Interested in assessing the applicability and benefit of learning in cognitive communications
Patterns

• ML algorithms rely on identifying patterns – but is there enough pattern in the observed wireless environment to learn from?
• And what metric can we use to quantify the presence of patterns?
• Lempel-Ziv complexity – approaches the entropy rate of the system
Lempel-Ziv complexity – synthetic data

• Single-agent learning

• A secondary user looking for an available channel

• Primary user activity modeled according to a two-state Markov chain, with independent channels

• Q learning (full observability)

• For the secondary user, changing channels incurs a cost

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Probability of successfully selecting a channel, as a function of LZ complexity and probability that a free channel exists

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How much better does Q-learning perform, as compared to random channel selection?
Lempel-Ziv complexity – ISM band

- Single-agent learning
- A secondary user looking for an available channel
- Primary user activity – spectrum occupancy measurements performed at RWTH Aachen
- Q learning (full observability)
- ISM band (2.4 GHz) shown

Probability of successfully selecting a channel, as a function of LZ complexity and probability that a free channel exists

How much better does Q-learning perform, as compared to random channel selection?

Lempel–Ziv complexity – GSM1800 and DECT

GSM1800

DECT
Learning and game theory

- Game theory is multi-agent decision theory

- Can concepts from the two fields be brought together to help understand adaptations in a cognitive network?

- Initial application: autonomous channel selection

- Each secondary user is modeled as a learning automaton (linear reward-inaction scheme)

- We can prove convergence to a Nash equilibrium

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Interference graph – colours represent channels that can be selected by a secondary user for exclusive use (green) or (blue) for shared use


Probability of convergence, averaged over all possible 7-node interference graphs
Effects of the structure of the graph on the ability to learn

Shown as a function of the number of links in the interference graph
New models of resource ownership – DSA & LTE+

• What changes would be required in the architecture of LTE+ to support DSA?

• Licensed carriers: support data-bearing channels and signaling for access requests

• DSA carriers: provide additional capacity, bootstrapped by licensed carriers

<table>
<thead>
<tr>
<th>Operator</th>
<th>Current Technology</th>
<th>Migrating Technology</th>
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<tr>
<td>[中国移动通信 CHINA MOBILE]</td>
<td>GSM, EDGE TD-HSDPA</td>
<td>TD-LTE</td>
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<td>[vodafone]</td>
<td>GSM, UMTS, HSDPA LTE, CDMA2000 1x EV-DO</td>
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<td>[Sprint]</td>
<td>CDMA2000 1x, 1xEV-DO</td>
<td>WiMax, LTE</td>
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</tbody>
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An LTE/LTE+ architecture that enables DSA

**LTE Network Elements**
- eNB: Evolved Node B
- E-UTRAN: Evolved Universal Terrestrial Radio Access
- HSS: Home Subscriber Server
- MME: Mobility Management Entity
- PDG: Packet Data Gateway
- 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
Signalling and control planes

- **cUE Service Supporting Procedures**
  - cBS Registration and Neighbor Discovery
  - Cooperative Sense Procedure
  - Spectrum Lease Request Procedure
  - Spectrum Sharing Procedure
  - Service Request and Reporting

- **Primary and Secondary User Alarms and Responses**
  - New Primary Alerting
  - IR Interference Alarm
  - High Interference Spectrum Lease
  - Rogue Transmitter Detection
  - Spectrum Unavailable Alarm

SAP - Registration and Reporting Control Planes
CREW federation modes

**MODE 1**

**CREW PORTAL**

**IBBT/IMEC**

**TCD**

**TUB**

**MODE 2**

**CREW PORTAL**

**IBBT/IMEC**

**TCD**

**TUB**

**RELOCATE NODES & CREATE NEW COMBINATIONS**

**MODE 3**

**CREW PORTAL**

**IBBT/IMEC**

**TCD**

**TUB**

**STEP 1**

**STEP 2**

**REPLAY ONE BEHAVIOUR IN OTHER TESTBED**
Tradeoffs among spectrum sensing platforms

- Variety of both COTS and more custom advanced sensing platforms compared experimentally
- Under same conditions, at same time, in same location.
- Observed what conditions required more advanced (costly) sensing platforms.


Experiments in progress
Harmonisation of CPC at European level should remain on standardisation level until technical and commercial uncertainties have been solved.

Usage of a data base seems to be the most feasible and flexible way forward to provide reliable real time information updates on spectrum usage. The manager of the CR database will have to collect information from regulatory agencies and from incumbent data bases. It will exchange information with the CR device which will allow it to emit under certain conditions.
CREW open call

- 20% of the budget for the CREW project is set aside to fund new partners who wish to perform experiments using the federated testbeds

http://www.crew-project.eu/
COGnitive radio systems for efficient sharing of TV white spaces in EUropean context (2010-2012)
COG-EU objectives

• To design, implement and demonstrate enabling technologies based on cognitive radio to support mobile/portable applications over TVWS with protection of incumbent systems (DVB, PMSE-wireless microphones)

• To investigate innovative business models and spectrum policies for TVWS exploitation based on secondary market regimes, to increase spectrum utilization enabling innovative wireless services

• COGEU aims to inform EU policy in relation to the enabling of efficient spectrum sharing and usage over TVWS at the European level.
Interested in...

• Architectures and resource management mechanisms that make wireless networks more sustainable, submissive, evolvable
• Broader interpretation of ‘cognitive’ systems, beyond spectrum management applications
• Research problems that are informed by industry and the regulatory landscape
• Meaningful, multi-year collaborations with complementary research groups
On the interwebs

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