Cognitive Radios: A Network Perspective

Luiz DaSilva
Stokes Professor in Telecommunications
Trinity College, Dublin
Ireland

University of York
12.03.2012
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.

Spectrum crunch

- Smartphones use 24x more data than regular phones.
- Tablets use 122x more data than smartphones.

How to deal with this?

- More efficient utilization of spectrum.
- New wireless network architectures (small cells, seamless integration of different wireless technologies).
evolvable:
Elegant paths to the future. Adaptive and flexible where it should be. Understanding of points of inflexibility.

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

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

This talk

Channel Selection by Autonomous, Frequency-Agile Radios
The Role of Learning in Dynamic Spectrum Access
Coalition Formation by Wireless Providers and UEs
Incorporating Dynamic Spectrum Access into LTE+ Networks and Beyond

The problem – M autonomous transmitter/receiver pairs search for a channel to be used opportunistically, among N possible channels, when the primary user is not active

- For each pair of radios, throughput is affected by its own selection of channels as well as by other radios’ selections and by primary user activity
- There is the potential to learn from past choices and observations

Channel Selection by Autonomous, Frequency-Agile Radios

Objective – A mechanism to enable CRs to autonomously arrive at collision-free sensing orders
- Problem is complicated by the presence of the PU and by the possibility of false alarms

Proposed approach (somewhat over-simplified)
- Sensing orders selected from a Latin square
- Initially, each CR selects a sensing order with equal probability
- Whenever successful, or if it finds all channels busy, the CR selects the same sensing order in the next slot
- In the case of a collision, the CR multiplicatively decreases the probability of picking the same sensing order, by a factor $\gamma$, with all other sensing orders equally likely

All permutations of 4 channels
A Latin square
Channel Selection by Autonomous, Frequency-Agile Radios

\[ P[\text{false alarm}] = 0.2 \]

\[ N = 10 \]
\[ P[\text{PU present}] = 0.3 \]
\[ \text{TTC} = \text{time to arrive at collision-free sensing orders} \]

\[ M = 10 \]

\[ \text{Convergence:} \]

[Thm] When \( N = M \), and \( 0 \leq P[\text{false alarm}] < 0.5 \), for any \( 0 < \gamma < 1 \) the network converges to collision-free sensing orders

[Note] When \( N > M \), convergence to collision-free sensing orders is even faster (\( N = M \) is the ‘worst case’ for convergence)

[Proposition] When \( P[\text{PU present}] = 0 \), the expected number of slots until collision-free sensing orders are obtained is \( O(N) \)
Analytical results:

- An (ugly) analytical expression for $M=2$
- A bound for $M > 2$

\[
P\{N, M = 2, \theta\} = \frac{1}{N} P(S) + \left(\frac{N-1}{N}\right) P(D)
\]

\[
= \sum_{\theta=0}^{N-1} \left(1 - \theta_0\right) \left(1 - P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right)
\]

\[
+ \sum_{\theta=0}^{N-1} \left(1 - \theta_0\right) \left(1 - P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right) \times \sum_{\theta=0}^{N-1} \left(1 - \theta_0\right) \left(1 - P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right)
\]

\[
\cong \frac{1}{N-1} \sum_{\theta=0}^{N-1} \left(1 - \theta_0\right) \left(1 - P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right)
\]

\[
+ \sum_{\theta=0}^{N-1} \left(1 - \theta_0\right) \left(1 - P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right) \prod_{\theta=1}^{\theta+1} \prod_{\theta=1}^{\theta+1} \left(\theta_0 + \left(1 - \theta_0\right) P(D)\right)
\]

Comparison:

RPS: random sensing order selection from all permutations of channels

LS: random sensing order selection from a Latin square

rand-AP/LS: randomize after collision

$M \times P[N, M, \theta]$: average # of successful transmissions in a time slot
**Comparison:**

RPS: random sensing order selection from all permutations of channels

LS: random sensing order selection from a Latin square

rand-AP/LS: randomize after collision

MxP[N,M,θ]: average # of successful transmissions in a time slot

---

**The Role of Learning in Dynamic Spectrum Access**

- Interested in determining under what circumstances learning is beneficial in DSA problems
- Machine learning 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 modelled as a two-state Markov chain, with independent channels
- Q learning (full observability)
- For the secondary user, changing channels incurs a cost

**Lempel-Ziv complexity – real data**

- Spectrum occupancy measurements conducted by RWTH Aachen and by us at Trinity College
- ISM band (2.4 GHz) shown
The Role of Learning in Dynamic Spectrum Access

Machine learning + 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 (when reward parameter b is small enough)

The Role of Learning in Dynamic Spectrum Access

• Effect of the structure of the graph on the ability to learn

![Graph showing the effect of the structure of the graph on the ability to learn](image)

Shown as a function of the number of links in the interference graph

Coalition Formation by Wireless Providers and UEs

• 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

Coalition Formation by Wireless Providers and UEs

• Dynamic pricing – providers form coalitions to charge UEs for access to the spectrum
• UEs set their transmit power to maximize their payoff
• Hierarchical game: looking for the Stackelberg equilibrium
• Proposed a distributed mechanism to set prices/transmit power, proved that it is guaranteed to converge to within an $\varepsilon$-distance of the SE


Incorporating DSA into LTE+ Networks and Beyond

• What architectural changes are needed for LTE+ to be able to augment licensed spectrum with additional spectrum that is available opportunistically?
• Proposed an evolution of the architecture itself and described signal and control planes for DSA-related functions (e.g., spectrum leases, coordinated sensing, etc.)
• Also considered the deployment of HetNets

Incorporating DSA into LTE+ Networks and Beyond


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)
- More flexible regimes of utilization of spectrum
- Virtual networks built on multi-provider infrastructure and heterogeneous access technologies
On the interwebs

About CTVR... www.ctvr.ie

Papers... luizdasilva.wordpress.com

On email... dasilval@tcd.ie