Keynote Talk
Cognitive Radio Activities at Orange Labs: Challenges and Opportunities

Dr. Bena Sayrac
Orange Labs

CROWNCOM 2010
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Outline

- Efficient use of resources is crucially important
- Cognitive Radio means intelligence in radio
- Orange Labs carries out research on Cognitive Radio as a part of its Open Innovation policy
- We conduct spectrum measurements
- One of the most important technical challenges lies in sensing
  - What information can be extracted from spectrum measurements?
  - Is sensing reliable?
  - What can be done to overcome the technical implementation challenges of sensing?
- Our research provides contributions to collaborative projects and standardization
- We contributed to IST FP7 project E3
- We are contributing to IST FP7 project Faramir
- And here are a few conclusions and further thoughts…
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Efficient use of resources is crucially important

- Wireless landscape is increasingly heterogeneous and complex with higher and higher demand for broadband data
  - Migration from a mono-frequency, mono-technology, mono-layered, single service environment to a multi-frequency, heterogeneous (2G+3G+WLAN), multi-layered (macro+micro+pico+femto) and a multi-service (voice+data+streaming) setting
  - Market forecasts announce the arrival of a mobile data tsunami due to use of user-friendly mobile devices (smartphones, netbooks, 3G dongles etc.) and easy-to-consume mobile applications
  - More and more challenging for mobile operators to manage and optimize their network(s) satisfying user demands
  - Efficient use of resources is becoming crucially important

- The importance of radio spectrum (already a very valuable resource) is drastically increasing
  - Under-utilized or not? Spectrum measurement campaigns in Europe and USA
  - Not possible to give a general answer to this question immediately
  - Depends on factors like time, frequency band, location, context, threshold, allowed error margin etc.
  - Needs a rigorous and thorough investigation with sound analysis methods
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Cognitive Radio means intelligence in radio

- Since 1999, attracted a lot of attention in the wireless community
- In November 2008, FCC released a second report adopting rules that allow unlicensed white-space devices to operate in the unused portions of the TV spectrum ➔ Dynamic Spectrum Access
- First trials with sample test devices have already been conducted in USA
- The term "Cognitive Radio" is being used to mean several different concepts: from reconfigurable base stations to game theoretic approaches of collaboration between terminals.
- Generally, it is used to mean "Dynamic Spectrum Access"…
- Mitola's original concept of Cognitive Radio is much more larger: it means a "Smart Radio" that is aware of its environment (not only radio), adapts its functioning accordingly and learns from experience
- It covers a very broad concept of "utilization of intelligence in the radio" which has vast implications and some of which are not immediately deployable

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Orange Labs carries out research on Cognitive Radio as a part of its Open Innovation policy

- We believe that Cognitive Radio has the potential to render the future wireless systems much more efficient
- However, there are important steps to be undertaken for Cognitive Radio systems to realize that potential
- Orange follows closely what is going on in the field of Cognitive Radio…
- …by contributing to standardization, regulation…
- …and to collaborative projects via its R&D branch Orange Labs
- This presentation gives some of the research activities carried out in Orange Labs that focus on sensing
- The technical studies presented here is not the exhaustive list
- A lot of research work exists on Self-Organizing Networks, Dynamic Spectrum Allocation, Joint Radio Resource Management for heterogeneous networks, spatio-temporal modeling of user traffic patterns etc.
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We conduct spectrum measurements

<table>
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<tr>
<th>Measurement campaign</th>
<th>Frequency bands (MHz)</th>
<th>Spectral resolution</th>
<th>Measurement period</th>
<th>Temporal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2R campaign during the 2006 World cup in Germany</td>
<td>400–2600</td>
<td>2 MHz</td>
<td>350 minutes</td>
<td>4 seconds</td>
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<td>Dense urban environment</td>
<td>935–960</td>
<td>200 kHz</td>
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<td></td>
<td>1805–1880</td>
<td>200 kHz</td>
<td>270 minutes</td>
<td>1 second</td>
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<td></td>
<td>2000–2600</td>
<td>1 MHz</td>
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<tr>
<td>Dense urban environment Max-hold acquisition mode Traffic measurements</td>
<td>935–960</td>
<td>100 kHz</td>
<td>1 week</td>
<td>1 min</td>
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<tr>
<td></td>
<td>1805 – 1880</td>
<td>200 kHz</td>
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We conduct spectrum measurements

- ISM band measurements with the SDR platform in Orange ILAB Beijing
- Measurement platform on GNU Radio / USRP
- Use multiple measurement points and do simultaneous measurements
- Analysis of spatio-temporal statistics
- Construct interference cartography
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The most important technical challenges lie in sensing

What information can be extracted from spectrum measurements?
- Spectrum utilization level
- RATs present around
- Combination of geo-location information with sensing data

Is sensing reliable?
- Detection of measurement errors
- A reliable prediction of spectrum occupancy in case of the lack of explicit detection of measurement errors

What can be done to overcome the technical implementation challenges of sensing?
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Spectral occupancy can be determined autonomously

- **Representation** of the power distribution by Gaussian Mixture Models
- Determine the spectral occupancy through **decision theory**
- **Threshold** chosen to balance false alarm and missed detection probabilities
- Optimization of number of Gaussian components to **trade off** between model accuracy and complexity through Bayes Information Criterion
- Estimate the spectral occupancy of **GSM900** and **DCS1800** downlink bands during major events (football matches)
- **Percentage** of measured power samples that are greater than the threshold:

<table>
<thead>
<tr>
<th></th>
<th>Before match</th>
<th>During match</th>
<th>After match</th>
</tr>
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<tbody>
<tr>
<td>DCS1800 band in Kaiserslautern</td>
<td>0.77</td>
<td>0.73</td>
<td>0.80</td>
</tr>
<tr>
<td>DCS1800 band in Dortmund</td>
<td>0.71</td>
<td>0.68</td>
<td>0.75</td>
</tr>
<tr>
<td>GSM900 band in Dortmund</td>
<td>0.75</td>
<td>0.70</td>
<td>0.88</td>
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What can be done to overcome the technical implementation challenges of sensing?
Supervised learning solutions exist for RAT recognition

**Features:**
- power probability distributions
- Discrete Wavelet Transform subband energies
- AutoRegressive Moving Average (ARMA) coefficients
- entropy-based statistical complexities

**Feature selection algorithms:**
- Linear Discriminant Analysis
- Recursive Features Elimination
- Principal Component Analysis
- Spectral Clustering

**Classification algorithms:**
- Support Vector Machines (SVM),
- the k-Nearest Neigh- bors (kNN)
- the C4.5 decision tree algorithms

**RAT range in MHz**

<table>
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<th>RAT</th>
<th>Range</th>
</tr>
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<tbody>
<tr>
<td>PMR</td>
<td>450 – 470</td>
</tr>
<tr>
<td>DVB-T</td>
<td>470 – 860</td>
</tr>
<tr>
<td>GSM 900 UL</td>
<td>890 – 915</td>
</tr>
<tr>
<td>GSM 900 DL</td>
<td>935 – 960</td>
</tr>
<tr>
<td>DCS 1800 UL</td>
<td>1710 – 1785</td>
</tr>
<tr>
<td>DCS 1800 DL</td>
<td>1805 – 1880</td>
</tr>
<tr>
<td>UMTS UL</td>
<td>1885 – 2025</td>
</tr>
<tr>
<td>UMTS DL</td>
<td>2110 – 2200</td>
</tr>
<tr>
<td>WIFI</td>
<td>2400 – 2500</td>
</tr>
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Allows the terminal to make informed decisions on **which technology to camp**, and to **adapt** its transmission to the wireless environment especially in a **flexible** spectrum management context.
Supervised learning solutions exist for RAT recognition

Performance of combinations of supervised learning and feature selection methods

Normalized confusion matrix of the best performing combination: LDA+SVM
For example, in the first line 3% of the GSM UL class elements are recognized as belonging to the DCS UL class

Alternative solution for RAT recognition is possible: Cognitive Pilot Channel (CPC)

- Network-assisted solution: the network provides the user terminals with the necessary radio awareness at a given time and place.
- Terminals use this information to optimize their operational parameters with the aim of a more efficient use of the radio resources.
- From the operator perspective, this has been investigated in an intra-operator scenario, based on the use/adaptation of existing technologies (such as GSM or WiFi) with two approaches:
  - **Out-band CPC**, a physical channel provides CPC service, outside the bands assigned to the component RATs. No support due to difficulties in harmonization.
  - **In-band CPC**, conceived as a logical channel within the technologies (e.g. GSM or WiFi) of the heterogeneous radio environment, which offered the advantage of no regulatory change in the spectrum assignments.
The most important challenges lie in sensing

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What can be done to overcome the technical implementation challenges of sensing?
Interference Cartography provides efficient resource management

- A map of the measured total interference perceived at each mesh point
- Valid for a limited time $\Delta t$
- Efficient radio resource (esp. spectrum) and interference management

Spatial interpolation: Krigging

Measurement Collection Module
Measurement Analysis

Target IC Quality

List of (Measurement, location)

Estimation of additional measurements needed

IC Construction or Update

IC Update

IC Database
Interference Cartography provides efficient resource management

- Dense urban measurements on UMTS downlink
- Krigging to obtain the IC
- Ongoing work on IC (PhD thesis)


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What can be done to overcome the technical implementation challenges of sensing?
Local spectrum mining is a solution for automated monitoring of measurement errors

- Statistical modelling of measurement data by Gaussian Markov Random Fields
- Model parameters characterize the local structure of the measured spectrum
- Maximum Likelihood parameter estimation to find the model parameters
- Clustering of the parameter vectors by k-means

Anomaly detection in the DCS1800 spectrum measurements

Rare events

Anomaly detection in the UMTS spectrum measurements
The most important challenges lie in sensing

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What can be done to overcome the technical implementation challenges of sensing?
If there is no explicit information on sensing errors, it is still possible to reliably predict channel occupation statistics.

- **On/off model** for primary user activity
- **Introduction of a collisions/opportunities enumerator** that accounts for detection imperfections:
  - False alarm: missed opportunity to use the spectrum
  - Non detection: collision with other users

\[
P_n(Y, Z) = \sum_{m=0}^{n} P(m, n)((1 - P_{ND}) + P_{ND}Y)^{m}(P_{FA} + (1 - P_{FA})Z)^{n-m} = \sum_{i,j=0}^{n} A_{i,j}Y^{i}Z^{j}
\]

- \(P(m,n)\) is the probability of having \(m\) occupied slots over \(n\) consecutive slots
- \(A_{i,j}\) is the probability of \(i\) collisions and \(j\) successful opportunities over \(n\) consecutive time-slots
If there is no explicit information on sensing errors, it is still possible to reliably predict channel occupation statistics.

\[ PFA = 0.05 \quad PND = 0.85101024509387 \]
If there is no explicit information on sensing errors, it is still possible to reliably predict channel occupation statistics.

Proba(i collisions, j opportunités réussies)

\[ A(i, j) \]

\[ P(\text{idle to busy}) = P(\text{busy to idle}) = 0.1 \]
\[ n = 50 \text{ time-slots} \]
\[ \text{SNR} = -10 \text{ dB} \]

\[ \text{PFA} = 0.35 \quad \text{PND} = 0.45848384261137 \]

- Ongoing work: choice of best \( (P_{FA}, P_{ND}) \) operating point on the ROC for a predetermined goal that is a function of \( A_{i,j} \):
  - \( P(\text{collisions < threshold, M successful opportunity detections}) \)
  - Future work: use of erasure correcting codes to compensate lost packets in collisions
  - a possible degree of freedom to tackle collisions
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What can be done to overcome the technical implementation challenges of sensing?
Multi-Armed Bandit works out the Exploration Exploitation Dilemma

- Analogy with the gambler's dilemma in a casino
- Deterministic and probabilistic MABs on IEEE802.11 bands (stationary)
  - Modelling idle durations by a generalized Pareto distribution
- Optimization of MAB parameters through
  - Semi-dynamic tuning
  - Online tuning
  - Meta Learning


A dyadic (binary) tree partitioning is proposed to reduce the number of sensing measurements

- A low-complexity spectrum sensing method based on a spectrum representation with a dyadic (binary) tree
- Evaluation of the accuracy of this representation through a rate-distortion criterion
- Pruning algorithm for the dyadic tree that minimizes the number of sensing operations for a predetermined value of sensing accuracy
- Tailoring the pruning algorithm to the missed detection and collision requirements
- Adaptive version that performs efficient sensing in slowly varying environments
A dyadic (binary) tree partitioning is proposed to reduce the number of sensing measurements

- Tested on real spectrum measurements taken on the [400-910]MHz range
- Examined the sensitivity of the proposed algorithm to sensing imperfections

- A mean distortion of 11.4% and a mean collision probability of 5.6% for sensing only 30% of the total spectrum
- A gain of 50% compared to conventional energy detection in terms of the number of required measurements per channel in the low SNR region


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- Contribution to IST FP6 project E2R on Dynamic Spectrum Allocation and Joint Radio Resource management
- Cognitive Pilot Channel work has been a contribution to IST FP7 project E3 and ETSI RRS standardization
- Interference cartography is investigated within the framework of the IST FP7 project Faramir
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We contributed to IST FP7 project E3

- End-to-End-Efficiency
- Main objective is the introduction of cognitive systems in the wireless world
- Increasing the efficiency of wireless network operations through reconfigurability
- Based on cognitive and distributed self-organisation principles
- IP with 23 partners with telecom operators, manufacturers, regulators and universities

FT/Orange contributions on:
- Dynamic spectrum management and Joint Radio Resource Management (JRRM) (WP3)
- Cognitive Pilot channel (CPC) (WP5)
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- Flexible and spectrum-Aware Radio Access through **Measurements** and modelling In cognitive Radio systems

- The main goal is to research and develop techniques for increasing the radio environmental and spectral awareness of future wireless systems
  - Spectrum sensing hardware efficiently integrated to handheld devices
  - Measurements performed at multiple nodes in a cooperative fashion on a network level
  - **Radio Environmental Map** providing basis for system optimization

- FP7 STREP with 10 partners

- FT/Orange contributions on:
  - Scenarios and use cases
  - Measurement campaigns
  - Spectrum usage models
  - Radio Environmental Maps (PhD thesis ongoing)
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- Cognitive Radio has the potential to increase efficiency in resource utilization, including spectrum utilization.

- Not a mature technology today, necessitating reliable and consistent technical solutions in many aspects including knowledge acquisition, security, regulation, interference management, responsibility etc.

- Further studies must be carried out to quantify the real utilization of spectrum for different attributes like time, frequency band, location, context, threshold, allowed error margin etc.

- We believe that sensing is one of the most important technological bottlenecks of Cognitive Radio. Reliable sensing is the key element in the deployment of Cognitive Radio systems. Issues like low SNR sensing, hidden node problem, data handling, QoS guaranty, passive device detection etc. must be reliably solved.

- Orange/FT follows closely what is going on in the field of Cognitive Radio and carries out research with the aim of using the cognitive concepts to increase the efficiency of its resource utilization.
Thank you…

Questions?
Backup
IEEE 1900.4

- To address radio resource management, reconfiguration management in composite wireless network
  - Multiple Radio Access Technologies
  - IEEE 802.xx, Cellular 2nd, 3rd generation
- In Dynamic Spectrum Access context
  - also addresses optimization of resources in fixed spectrum allocation
- Policy-based management: Network-device distributed decision making
  - Event-Condition-Action Policies
  - Policies are sent by network to terminals via a "radio enabler"
- IEEE Std 1900.4 standard was published on February 27th 2009
- Since April 2009, 1900.4 is working on two projects:
  - P1900.4.1: Protocols for the 1900.4 architecture
  - P1900.4a: Amendment of 1900.4 for access to White Spaces.
ETSI Reconfigurable Radio Systems (RRS)

- Created in 2008, based on a post-project fellowship
- "Main responsibility is to carry out standardization activities related to Reconfigurable Radio Systems encompassing both Software Defined Radio (SDR) and Cognitive Radio (CR)".
- Pre-standardization phase at the moment (definition of scenarios, use cases and requirements)
- 4 WPs
  - WP1 – System aspects
  - WP2 – Radio equipment architecture
  - WP3 – Cognitive management and control
  - WP4 – Public safety
- Orange/FT contribution mainly on
  - WP1: scenarios, use cases and requirements
  - WP3: J-RRM, CPC
Automatic extraction of spectral states corresponding to different wireless environment characteristics reflecting different levels of spectrum usage

- Redundancy elimination with PCA
- Clustering with the k-means algorithm
- Estimation of the number of states through rate-distortion minimization

- With the a priori knowledge on the environmental events, detection of the before/after match periods, first/second halves of the match, the half-break and the night periods
- Can be used in constructing efficient policies and decisions

- Results on downlink DCS1800 bands

Traffic prediction from wireless environment sensing

- Spectrum occupation ≠ user activity
- Need to predict user traffic for realistic spectrum utilization

- Power level distributions
- Linear decompositions through Principal Component Analysis

Clustering: k Nearest Neighbours
Linear Discriminant Analysis
Traffic prediction from wireless environment sensing

GSM traffic prediction, observation time 10min

- Location dependence of the proposed prediction method -> location-invariant

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<td>1</td>
<td></td>
<td>14.2</td>
<td>9.0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>9.7</td>
<td>10.6</td>
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A hybrid decision approach for the association problem in heterogeneous networks

- Association problem in the context of distributed decision making in a heterogeneous cognitive network

- Avoid completely decentralized solutions in which all decisions are taken by the mobiles, due to well known inefficiency problems that may arise when each mobile is allowed to optimize its own utility

- Propose hybrid association methods that combine benefits from both decentralized and centralized design

- We assume that the mobiles follow the instructions of the base stations. Otherwise the association decision is left to the mobiles, which make the decision based on a Bayesian game theoretic model

- We make use of the IEEE 1900.4 framework that proposes scenarios and solutions to allow information exchange between the network and the user terminals.
A hybrid decision approach for the association problem in heterogeneous networks

- The aim is to allow devices to optimally **choose** among the available radio resources so that the overall efficiency and capacity of the resulting **composite network** is improved.

- We assume that, using the logical channel proposed by the IEEE 1900.4, the network **broadcasts** an **aggregated load information** that takes values in some finite set.

- Aggregated load information composed of HSDPA and LTE:
Advanced signal processing and statistical learning techniques

- Sensing algorithm based on a dyadic (binary) tree partitioning reduces the amount of sensing data with controlled false alarm and missed detection probabilities
- It makes use of partitioning trees and rate-distortion theory
- RAT detection study makes use of a multitude of feature extraction, supervised classification, clustering and feature selection algorithms
- AMD dual core 2GHz processor results