Cognitive Radio for Green Communications and Networking

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Speaker: Jacques Palicot

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Outline

1. SUPELEC/SCEE research team
2. Introduction
3. The « Cognitive Radio » concept
4. CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction
   • At the component level
   • At the network level
5. Electromagnetic Pollution and Spectrum Resources Optimization
6. Recycling the Resources
7. Green Communications as a Mean for an Improved Public Health
8. Conclusion
outline

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SUPELEC ENGINEERING SCHOOL

• SUPELEC is a French "grande école" of engineering: École Supérieure d'Electricité
  • Academic institution created in 1894
  • Engineers in electronics, energy, information technology (telecommunications, computer sciences, etc.)
  • 3 campus in France: Paris, Rennes, Metz
  • Faculty: 150 / Research scientists: 90 / 2000 engineering students / 250 Ph.D. students
• SCEE research team
  – IETR - Institute of Electronics and Telecommunications of Rennes - CNRS 6164
  – Signal, Communication and Embedded Electronics
  – head: Prof. Jacques PALICOT

• Study and design of future communication systems based on Software Radio, Cognitive Radio and Green Radio concepts.
  – 8 professors-researchers / 15 Ph.D. / 3 post-docs
  – Average of 10 journal publications and 25 international conf. per year.
  – 2013-2014: Honggang ZHANG (Inter\textsuperscript{al} Chair)

• SCEE is a team of IETR lab (UMR CNRS 6164)
  – Communication Department

Where is IETR?

• Rennes
• Lannion
• Saint Brieuc
• Nantes
• Angers
• Saint Malo

www.ietr.fr
CR demonstrators

- **Opportunistic spectrum access**
  Acropolis Workshop’12

- **Real-time partial reconfiguration of FPGA**
  – CrownCom’10 in Cannes, SDR’07-09 in USA
  – in collaboration with CEA: FAUST platform

- **Blind standard recognition sensor**
  – CrownCom’10, Cannes, Funems’10, Firenze, ISWCS’11, York, DySPAN’11, Aachen.
  – USRP platform

- **Multi-level modeling – systemC HDCRAM**
  modeling and execution on USRP
  – SDR’10, Washington DC

Demonstrator: OSA

Demonstrator: 1) SU#1 is composed of a laptop executing a video service transmitted (simple BPSK modulation scheme) through a USRP (white box) at a RF frequency F1 of 600 MHz (respectively F2 of 650 MHz) – 2) RF signal generator is transmitting at a frequency different from 600 MHz – 3) a spectrum analyzer is used to observe in real-time what is the frequency used by SUs – 4) SU#2 is also composed of a laptop and a USRP platform converting radio signal at 600 MHz (respectively 650 MHz) to baseband so that laptop executes a video player to display the video stream transmitted through a SU channel.

Spectrum analyzer snapshot with SUs communicating at 650 MHz, while PU is at 600 MHz.
**Demonstrator: Blind Std Recognition Sensor (BSRS)**

- Real 2.4 GHz transmission with USRPs platforms
- Blind Bandwidth shape recognition (neural network)

**Presented in:**
- WUN CogCom (York, September 2010)
- CrownCom (Cannes, June 2010)
- FUNEMS (Florence, June 2010)
- DySPAN (Aachen, May 2011)

**Demonstrator: Partial Reconfiguration of FPGA**

- only a sub part of the FPGA can be reconfigured
- fast reconfiguration (few micro sec.)
- No video streaming interruption while reconfiguration
- Baseband IPs reconfiguration in NOC context

**Presented in:**
- CrownCom (Cannes, June 2010)
- WUN CogCom (York, September 2010)
International Chair on CGR

- International Chair of UEB/CominLabs
  - Professeur Honggang Zhang
    Zhejiang University - Chine
  - Topic: Cognitive Green Radio
  - Project: GREAT for (*Green Cognitive Radio for Energy-Aware wireless communication Technologies evolution*)
  - Since 1st December 2012 for 2 years

Two Books

- In French and in English

AICT Tutorial June 2013
Foreword

Wireless Communications of the 21st Century

Well known:
- demand in services, in throughput increase
- demand in ubiquitous connections
- Ecological issues

But: Spectrum rare and expensive
- Near Shannon capacity
- Increase in CO₂ emission

What could be done????

2 key Words

Intelligence
Sustainable Development

Cognitive Green Radio Concept

« We would like to decrease the electromagnetic level by sending the right signal in the right direction with the optimal power, only when it is necessary, for the same QoS. »

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Global Warming – The Most Dangerous Threat
Terrible Climate Change: Trans-Arctic Shipping Routes Navigable 21st-midcentury


Data Explosion - Exponential Traffic Growth (1/2)

Internet Applications

Traffic (Tbps)

Year

2010

2015

2020

Total Backbone

Internet Video

P2P

Wireless Data

Wireless Voice

Data Explosion - Exponential Traffic Growth (2/2)

What Happens in an Internet Minute?

And Future Growth is Staggering

Green Communications
Paradigm Change from Coverage- & Capacity-Driven to Energy-Efficiency Driven Era

Network Cost (Energy Consumption by Existing Technologies) vs Traffic Volume

Energy Consumption by Green Technologies

Time (Year)

Coverage Dominated, Capacity Dominated, Energy Efficiency Dominated

• First international workshop on Green Wireless\(^1\)
  – Currently, 3\% of the world-wide energy is consumed by the
    ICT infrastructure which causes about 2\% of the world-wide
    CO\(_2\) emissions
  – which is comparable to the world-wide CO\(_2\) emissions by
    airplanes or one quarter of the world-wide CO\(_2\) emissions
    by cars.

A positive way to interpret this fact may be the question
How ICT can contribute in decreasing the rest of 98\%?
• May economize (1 to 4 times) its own emission
• Great R&D challenge


• First international workshop on Green Wireless\(^1\)
  – Another challenge of future wireless radio systems is to globally
    reduce the electromagnetic radiation levels to have
    • a better coexistence of wireless system (less interference)
    • a reduced human exposure to radiations.

Cognitive Radio may have an important role

Green Communications and Green Spectrum: Is Cognitive Radio an
Enabler or Anyone else?\(^2\)
My answer: Yes, it is an enabler\(^3\)

\(^2\)J.Palicot, Honggang Zhang, Panel, CROWNCOM 2009, Germany June 2009
\(^3\)J.Palicot, « Cognitive Radio: An Enabling Technology for the Green Radio
Communications Concept », IWCMC, Leipzig, Germany June 2009
• Specific electricity* consumption in the residential sphere in FRANCE
  - Gain in consumption of white equipments (washing machine...) lost with the increase in consumption of brown equipments (TV set, PC...)
  - Multimedia equipments are the most power consuming equipments
    • New TV set with flat screens
    • Boxes (built without consumption consideration)
    • with termination of analog TV services
  - Standby mode: 10% of the specific electricity.
  - Cellular mobile consumption very low (< 1%, with new generation larger screen,...)

*Specific electricity: electricity used by equipments that can not use other energy (does not include heating, cooking...)


ICT Carbon footprint in France

• Carbon footprint in the residential sphere in FRANCE
  - ~40% of the ICT emission
• Carbon footprint in the professional sphere in FRANCE
  - ~60% of the ICT emission
• Multimedia equipments ~25% of the ICT emission
• Usage carbon footprint: low (French nuclear park)
• Production (conception, transport) footprint is preponderant.
  - Mobile phones footprint no more negligible

CO2 reduction at two levels:
- To reduce the ICT emission itself
- Use ICT to reduce emission of other human activities (transport, tele-working, e-commerce, ….)
  - First online IEEE conference on Green Communications

Keyword: Intelligence
- to put it everywhere
- Distributed Artificial Intelligence (DAI)

Use of Cognitive Radio Technology to meet these objectives

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Basics of Cognitive Radio

- Cognitive Radio & Networking
  - Input - Decision Making - Action
    - Environment awareness
    - External stimuli
    - Sensing
    - Interpretation & Learning
      - Reasoning
      - Interpretation
      - Learning
    - Implementation of Decision
      - Actuation
      - Parameter change

Conventional cognitive cycle

- Observation (sensors)
- Knowledge Base Rules
- Learning
- Decision Action

Outside world
“Generalized Handover” concept:
- Geographic mobility: Conventional «Horizontal Handover»
- Mobility between Networks, Standards, Services: «Vertical Handover»

Positioning
- GPS, Galileo
- DAB, DVB
- UMTS
- GSM
- WiMax
- Wi-Fi
- IEEE 802.15.1 Bluetooth
- IEEE 802.16 WiMax
- IEEE 802.15.4 Bluetooth

Increase of cells coverage
- MAN
- PAN
- LAN
- Wireless 2G
- Vertical Handover
- Horizontal Handover

Link with the Vertical and Horizontal sharing concept
Decentralized view associated with a local optimization of needs and resources versus a centralized view based on the worst case scenario needs.

- Ex 1: implementation of an equalizer independently of the channel IR

Sensors classification according to the environment

- electromagnetic environment: spectrum occupancy, Signal to Noise Ratio (SNR), multi-path propagation...
- hardware environment: battery level, power consumption, number of used gates,…
- network environment: telecommunication standards (GSM, UMTS, WiFi, etc.), operators and services available in the vicinity, traffic load on a link…
- user-related environment: localization, speed, time of day; user preferences, user profile (access rights, contract…), video and audio sensor (presence detection, face, voice recognition)…
The CR sensors according to the simplified three layer model

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Layers</th>
</tr>
</thead>
</table>
| Use profile (price, operator personal choices, ...)  
  Sound, Video, Speed, Position, Indoor, Outdoor, ... | Application and IHM |
| Vertical Handover, Standard Recognition, Load on a link, ... | Transport, Network |
| Access mode, Power, Modulation, Horizontal Handover, channel estimation, Direction of Arrival, Consumption, ... | Physical, Data Link |

Application layer sensors

- Application layer sensors ("Context Aware"):
  - Identify, analyse and interact with the user (audio, video, other, ...)
  - Effects on radio access
    - Video sensor
    - Obstacle: Unknown face characteristic points precise positioning, in real conditions.
    - Solution obtained thanks to the Appearance Active Models.
Intermediary layer sensors

- Dedicated pilot channel spectrum recognition
- Geo localization spectrum recognition
- Standards blind recognition

Physical layer sensors

- Bandwidth blind recognition
- Mono/Multi carriers detection
- FH/DS-SS Detection
- Available bands detection (Hole detection)
Decision Making: A matter of information

- Make a decision in a CR equipment or in a network is all about
  - depending on a goal (criteria)
  - adapt parameters (if possible => SDR)
  - in function of what the environment permits

- The way to solve it depends on the degree of information available on all this
  - SNR, holes, bands occupation rate

Criteria = f (Parameters; Environment)

Parameters: e.g., Carrier Frequency, Coding, Modulation, Tx Power, etc.

Environment: e.g., available standards, bands occupation rate, allocated bands, interference, etc.
• Depending on the degree of knowledge, different decision making solutions may be worth analyzing
  – the more a priori knowledge → left
  – the more uncertainty → right


Techniques for decision making

- Game theory
- Information /knowledge propagation (transfer)
- Machine learning techniques
- Statistical Signal Processing
- Swarm Intelligence
- Expert algorithms
- ...

- All could be applied in both collaborative or non-collaborative schemes.

Left side (high \textit{a priori}) decision approaches have been addressed a lot in the literature

- also in the CR field


Expert approach

• Based on the important amount of knowledge collected by telecom. engineers and researchers for years
  – theoretical considerations
  – environment measurements (channel imp.resp.)

• On-line adaptation of the equipment following a set of inference rules (obtained off-line)

• Issues
  – plan every situations the CR equipment meets
  – representation of knowledge (RKRL)

Genetic algorithms

• CR may be seen as a multi-criteria optimization issue
  – some relationship exists between observed metrics, parameters to adapt and criteria to satisfy

• Reflex → genetic algorithms
  – find best parameters to meet user’s expectations

• But quite much *a priori* knowledge is needed (in order to parameter the implemented GA)
Decision making and CR

- Often if not always mix techniques
- But we may expect that most of the time a CR equipment will have to make decisions
  - on a high number of criteria
  - with a lot of unknown, uncertainty
- Hardest case: a minimum of knowledge
- Example of dynamic configuration adaptation (DCA) and opportunistic spectrum access (OSA)
  ➔ a lot of unknown information

Decision making for DCA

- DCA: dynamic configuration adaptation
- Future scenario of full-free real-time link adaptation (just impact at PHY layer studied here)
- Depending on
  - the environment: propagation, network load, etc.
  - the equipment capabilities in terms of flexibility: constellation, channel coding, interleaving, etc.
  - the user: communication nature, required QoS, contract, location, speed, etc.
- What is the best configuration?
- At every instants?
Decision making for OSA

- OSA: opportunistic spectrum access
- A secondary user (SU) may access the spectrum dedicated to a primary user (PU)
- Depending on
  - the environment: bands availability, BW, etc.
  - the equipment capabilities in terms of flexibility: carrier frequency, filtering, constellation, etc.
  - the user: communication service, required QoS, location, etc.
- What is the best channel choice?
- At every instants? See later section 5

Decision theory in statistical signal processing

**Decision System**

- **Observation X** of a useful phenomenon $\theta$
- **Criterion**
- **Available Information**
- **Decision $\delta$** about the parameter value $\theta$

**Information**: statistical model, Probability Density Function (pdf) for X and eventually $\theta$

**Criterion**: average cost in bayesian models or others

**Constraints**: imposed solution like linear or affine solution in estimation theory

**Applications**: Detection, Classification, Estimation and Statistical Filtering theories
Sensors of radio environment metrics (Sensing)

- Channel estimation / SNR estimation / ISI Inter-Symbol Interference estimation / Channel capacity estimation / AOA estimation / etc….
- Each metric is represented by a random variable

Statistical modeling of these radio metrics: a statistical model for each metric to characterize its behavior

- Identify the probability density function (pdf) of each observed metric
- Estimate the probability density function parameters

Thresholds determination for qualification of metrics according to:

- Standard required performance (BER)
- User requirements (throughput)

Decision making by statistical hypothesis tests

- Likelihood ratios compare to thresholds
- Actions decision to take in order to adapt the equipment to the state of its environment
Why Reinforcement Learning?

Machine Learning

Why statistical?
Noise, uncertainty, large data sets, … Proven to be effective!

Policy: What to do
Reward: What is good
Value: What is good because it predicts reward
Model: What follows what

Basics of Reinforcement Learning
Reinforcement Learning

Multi Arm Bandit (MAB)
- Weight Driven (WD) University of York
  - Actor Critic (ACT)
  - Transfer Knowledge (TACT)

Exploration vs exploitation

- When a priori knowledge is missing
  - need to learn
  - reinforcement learning: try and regret/reward
- First solution
  - learn then exploit
  - but loose (time or wages) when learning
- Second solution
  - mix learning and exploitation
  - example of multi-armed bandit
  - MAB (machine learning domain)

Moreover:
- can follow variations
- if not stationary
MAB - Multi-Armed Bandit

- Las Vegas: which armed bandit to select for the best reward (in terms of money)?
- Multi-Armed Bandit (MAB) issue
  - $K$ possible choices $k \in [1,K]$ (machines)
  - Each choice has a mean performance $\mu_k$
  - At each time $t$, the gambler plays a machine and obtains a reward $r_t$
  - Objective: not to find $\mu_k$, but maximise the cumulative reward (his gain) or minimise regret


---

Naive approach

- Let's consider a uniform test of the machines during an exploration phase
- We obtain an approximative value of the empirical mean $\bar{X}_k$ for all machines
- The probability to choose a sub-optimal machine after the exploration phase is not null
  - either because exploration not long enough
  - bad scenari may exist statistically
  $\Rightarrow$ linear regret in $t$ (compared to the best choice)
Multi-Armed Bandits for CR decision making

• Three steps iterative process: at each time \( t \)
  1. The CR equipment senses the environment (simple example in DCA context: SNR)
  2. It chooses machine (configuration) \( k \) depending on an index \( B_{k,t} \), a function of the past rewards (data rate & BER) it expects for this environment (SNR) based on its previous experience
  3. It measures the obtained new reward and updates its table of rewards for configuration \( k \)


UCB for CR decision making using MAB

• OK if we had full information at each instant \( t \), but what if it is badly estimated (\( \bar{X}_k \neq \mu_k \))?
• A bias may be added in function of the number of activations of each configuration
• Upper Confidence Bound (UCB) index

\[
B_{k,t,T_k(t)}(t) = \bar{X}_{k,T_k(t)}(t) + A_{k,t,T_k(t)}(t)
\]

– for each arm \( k \), in function of time \( t \)
   - \( \bar{X} \): empirical mean of the reward
   - \( A \): bias (avoid forgetting good solutions)
   - \( T_k \): number of times config. \( k \) has been chosen

Simplicity: just a sum! (for each arm)
UCB for CR decision making using MAB

- **Strategy**: the higher UCB index for a configuration, the better the reward
  - select the configuration with biggest index
- **UCB**: optimistic estimation of the reward
  - adds the mean of the measured reward
  - with a positive bias weighted by time & number of activations (several ways exist)
- **Role of the bias**
  - avoid eliminating a good configuration if a bad measure has been done (or vice versa)

Regret notion

- Regret is what has been lost compared to the choice of the best configuration at each $t$
  \[ R_t = t\mu^* - \sum_{m=0}^{t-1} r_m \]
  $\mu^*$: reward of the best configuration
- **Cumulative regret**
  - under certain conditions, it can be proven that asymptotically UCB converges to the best solution (depending on the policy)
  \[ \lim_{t \to \infty} \frac{E[R_t]}{t} = 0 \]
  \[ \lim_{t \to \infty} \frac{\sum_{m=0}^{t-1} r_m}{t} = \mu^* \]
Weight Driven (WD)

- Band choice probability:
  \[ P(c) = \frac{w_c}{\sum_{c \in E} w_c} \]

- Weights function:
  \[ W_i = f_1 w_{i-1} + f_2 \]
  \[ f_1 \text{ et } f_2 \text{ equal +1 if reward, } f_2 \text{ à -1 if not.} \]

- Preferred set:
  - If a channel weight greater than a predefined threshold then it belongs to the predefined set.
  - Then when the set is full, exploitation phase
    - Other channels which are not in the set are no more choose, may never used the best one.
Reinforcement Learning: Actor-Critic Approach

Block Diagram of Reinforcement Learning
- The learning system and the environment are both inside the feedback loop.
Markov Decision Processes (MDPs)

In Reinforcement Learning, the environment is modeled as an MDP, defined by:

- $S$ – set of states of the environment
- $A(s)$ – set of actions possible in state $s \in S$
- $P(s,s',a)$ – probability of transition from $s$ to $s'$ given $a$
- $R(s,s',a)$ – expected reward on transition $s$ to $s'$ given $a$
- $\gamma$ – discount rate for delayed reward

Discrete time, $t = 0, 1, 2, \ldots$

Basics and Advantages of Transfer Learning

Learning Process of Traditional Machine Learning

- Different Tasks
- Learning System
- Learning System

Learning Process of Transfer Learning

- Different Tasks
- Different Tasks
- Knowledge
- Learning System
Basics and Features of Transfer Reinforcement Learning

Source Task

Environment

Action Source

State Source

Reward Source

Agent

Target Task

Environment

Action Target

State Target

Reward Target

Agent

Source Task Q-value Function Approximator

Action and State Variable Mappings

Target Task Q-value Function Approximator

Inter-Task Mapping

Features of Transfer Actor-Critic Learning

Knowledge Transfer

Actor

Policy

Critic

Value function

TDerror

Cost

Environment

Classical Actor-Critic Algorithm

Transfer Actor-Critic Algorithm
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- To decrease the transmission power by putting off unused or unnecessary functions (locally)
- Equipments are designed to run correctly in the worst situation
- An efficient and computationally costly equalizer is always running
- But, locally, in many situations the channel is good and the equalizer is not necessary
- Using the Channel Impulse estimator sensor CR will take into account and therefore put off the equalizer function if the channel is good.

Energy consumption gain

Using SSP-DM

Sensors of radio Environment

\[ SNR_p = \frac{\|h_0\|^2 \sigma_s^2}{\sigma_b^2} \]

\[ ISI = E\left\{ \left( \sum_{i=1}^{L-1} h_i s[i-k-1] \right)^2 \right\} - \sum_{i=1}^{L-1} \|h_i\|^2 E\{s[i-k-1]^2\} \]

Statistical model

\[ (\hat{x}_{SNR_p}, \ldots, \hat{x}_{SNR_p}) \rightarrow X_{SNR_p} \sim N(\tilde{\mu}_{SNR_p}, \tilde{\Sigma}_{SNR_p}) \]

\[ (\hat{x}_{ISI}, \ldots, \hat{x}_{ISI}) \rightarrow X_{ISI} \sim N(\tilde{\mu}_{ISI}, \tilde{\Sigma}_{ISI}) \]


4- CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Component Level (2/15)

Complexity Gain

Using SSP-DM

Maximum Gain 91%

Complexity Gain starts at 9%

Activating some functions so as to decrease the transmitting power

Possible CR sensors to activate these gains:
- SNR
- Channel Impulse Response
- Direction of Arrival
- Blind standard recognition

Example: The SNR sensor gives (locally) a very good value. Then Tx and Rx agree to use a channel code to decrease the power.

If choice of power decrease then indirect gains (HPA efficiency, less temperature,...)

Function migration, in reconfigurable hardware, for temperature and power consumption management

relationship between temperature and consumption, leakage power example
Function migration, in reconfigurable hardware, for temperature and power consumption management


Reference temperature provided by the System monitor versus measured counter cycle value.

Thermograph obtained by interpolating the sensors responses.
Use of Partial Reconfiguration to decrease FPGA size

Big FPGA FOR SEVERAL STANDARDS

Small FPGA USING Partial Reconfiguration of functions in real time to offer the same standards

Consumption sharing at the Base Station

- Transceiver killing 19%
- Power Amplifier 22%
- Power Supply 10%
- Cabling 1%
- Transmit Power 3%
- Central Equipment 8%
- Combining/Duplexing 9%
- Cooling Fans 13%
- Transceiver Power Conversion 9%

Optimization of the transmitted power at the High Power Amplifier level using PAPR, ACPR & hole spectrum sensors

Optimization of the transmitted power at the High Power Amplifier level using PAPR, ACPR & hole spectrum sensors

Solution 1: Large IBO >> Low PA efficiency

\[ P_{\text{out}} \quad \text{Power Amplifier efficiency} \]
\[ P_{\text{sat}} \quad P_{\text{in}} \quad \text{IBO Low efficiency zone} \]
\[ P_{\text{m1}} \quad P_{\text{m2}} \quad P_{\text{out}} \text{ Power Amplifier efficiency} \]

IBO after spectrum insertion or amplification of another signal with higher PAPR without taking PAPR into account

Solution 2: Insertion with PAPR constraint >> High PA efficiency


Optimization of the overall network by intelligent and dynamical BS management

- Relaying Technique: is being studied in 3GPP as a technology that offers the possibility to extend coverage and increase capacity
- ON/OFF schemes for constant QoS (need to extend some coverage) (see https://www.ict-earth.eu/default.html)
- wired backhauling rather than wireless backhauling in order to become greener
- Improved RRM in heterogeneous multi RAT context
- Network coding approach
- Decrease cell size
- MIMO techniques see Massive MIMO approach by Bell Labs within GREENTOUCH

1Peter Briggs, Rajesh Chundury, Jonathan Olsson, "Carrier Internet for Mobile Backhaul", IEEE Communications Magazine, October 2010, Vol 48, N° 10, PP94-100
Network Management

- The terminal or the Base Station could recognize the spectrum occupancy and therefore decide which band (with the associated power) is the best from the point of view of electromagnetic radiation. This could be performed thanks to the standard recognition sensor.

- It is always better to have a local wireless connection or a wired indoor connection and to have a roof connection with the cellular network.


Energy Saving for Greener Cellular Mobile Networks

"Tidal Effect" of Cellular Networks' Traffic Flow & Loads

12pm  6pm  12am  6am  12pm
Representative Patterns of Traffic Loads during One Day (Cellular Networks)

Normalized load of three different cell sectors over 3 weeks. The moving average of each cell over one second has been plotted. The cells show high load (Top), varying load (Middle), and low load (Bottom).

Source: Daniel Willkomm et al., “Primary User Behavior in Cellular Networks and Implications for Dynamic Spectrum Access”.
E-commerce website: 292 production web servers over 5 days. (Traffic varies by day/weekend, power doesn’t.)

Traffic records from 9 MSCs and SGSNs with about 7000 BSs with coverage of 780 km²

Both GSM and UMTS BSs traffic from January to December in 2012, serving about 3 million subscribers

4- CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Network Level (8/16)

Measured Traffic Loads Variation Patterns at BSC (One Week)

Same Behavior everywhere in the world

4- CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Network Level (9/16)

Typical Examples of Measured Base Stations’ Traffic Loads in Zhejiang (China)

Average on several BS at BSC level.

4- CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Network Level (10/16)

Network Energy Saving through BS Switching on/off (Sleep Mode)

4- CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Network Level (11/16)

Stochastic BS Switching Operation with Actor-Critic Learning

Stochastic BS Switching Operation with Actor-Critic Learning (2)

Scenario
- A region $\mathcal{L} \subseteq \mathbb{R}^2$ served by a set of BSs $\mathcal{B} = \{1, \ldots, N\}$;
- A BS switching operation controller to turn on/off some BSs in a centralized way;
- A traffic load density as $\gamma(x) = \frac{\lambda(x)}{\mu(x)} < \infty$: arrival rate per unit area $\lambda(x)$ and file size $\frac{1}{\mu(x)}$;

Actor-Critic Learning: Markov Decision Process

An MDP $M = \langle \mathcal{S}, \mathcal{A}, p, C \rangle$,
- $\mathcal{S}$: the state space;
- $\mathcal{A}$: the action space;
- $p$: a state transition probability function;
- $C$: a cost function.

$\cdots \quad S_t \quad a_t \quad S_{t+1} \quad a_{t+1} \quad S_{t+2} \quad a_{t+2} \quad S_{t+3} \quad \cdots$
### Numerical Analysis

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation area</td>
<td>1.5km * 1.5km</td>
</tr>
<tr>
<td>Maximum transmission power</td>
<td></td>
</tr>
<tr>
<td>Macro BS</td>
<td>20W</td>
</tr>
<tr>
<td>Micro BS</td>
<td>1W</td>
</tr>
<tr>
<td>Maximum operational power</td>
<td></td>
</tr>
<tr>
<td>Macro BS</td>
<td>865W</td>
</tr>
<tr>
<td>Micro BS</td>
<td>38W</td>
</tr>
<tr>
<td>Height</td>
<td></td>
</tr>
<tr>
<td>Macro BS</td>
<td>32m</td>
</tr>
<tr>
<td>Micro BS</td>
<td>12.5m</td>
</tr>
<tr>
<td>Intra-cell interference factor</td>
<td>0.01</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>1.25MHz</td>
</tr>
<tr>
<td>File requests</td>
<td></td>
</tr>
<tr>
<td>Arrival rate</td>
<td>$5 \times 10^{-5} \sim 10^{-4}$</td>
</tr>
<tr>
<td>File size</td>
<td>100kbyte</td>
</tr>
<tr>
<td>Constant power percentage</td>
<td>0.1 ~ 0.9</td>
</tr>
</tbody>
</table>

---

**Energy Saving by Actor-Critic Learning (BS Switching & Sleep Mode)**

Performance comparison between Actor-Critic learning framework (LF) based energy saving scheme and the state-of-the-art (SOTA) scheme (JSAC, Sept. 2012) under various static/variant traffic arrival rates.

4. CO2 Emission Decrease Obtained Thanks to Power Consumption Reduction-Network Level

Stochastic BS Switching Operation with Transfer Reinforcement Learning


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6. Recycling the Resources
7. Green Communications as a Mean for an Improved Public Health
8. Conclusion
5- Electromagnetic Pollution and Spectrum

Resources Optimization

Electromagnetic Pollution

- Increase in the absolute level of electromagnetic noise.
- Increase the noise level on many frequency bands.
- Astronomical and meteorology communities are concerned over this increase of noise level (debate within URSI)

- Ironically, the technology that has made possible so many exciting astronomical discoveries is now jeopardizing the future of observational astronomy. 

- Almost everyone can relate, first-hand, to the issue of light pollution. It is more difficult for people to relate to the astronomical windows in the electromagnetic spectrum.  

- Radio-astronomy signals coming from the universe are millions of times weaker than signals used by human communication systems. Radio-astronomers would consider that a cellular phone on the Moon is a strong radio source.


Frequency Spectrum Resources

- **Today** spectrum allocation is fixed, done for a long period
- The frequency spectrum is underused.
- "Hic et Nunc" frequency spectrum occupancy concept.

- Optimize the spectrum use: Green spectrum

From a worldwide sustainable development point of view, this spectrum should be shared between countries and continents.

Honggang ZHANG, "Cognitive Radio for Green Communications and Green Spectrum", COMNETS 08 Co-located with CHINACOM 08, August 25-27, 2008, Hangzhou, China
Spectrum use optimization: Green spectrum

- CR is obviously an enabler because it was one of its main objectives.

Holes (or whatever the term) in the spectrum

Opportunistic Communications (5 phases)

- Filtering phase
- Detection phase (sensing itself)
- Characterisation phase.
- Learning and Decision phase
- Insertion phase (modulation with good PSD), under sensor constraints as ACPR, PAPR, etc.

But this implies advance signal processing algorithms which are computationally expensive and then consume power!

Honggang Zhang, "Cognitive Radio for Green Communications and Green Spectrum", COMNets 08 Co-located with CHINACOM 08, August 25-27, 2008, Hangzhou, China

Opportunistic Spectrum Access - OSA

- In a radio network of primary users (PU)
- Secondary users (SU) are allowed to use free frequencies
- At the condition that SUs leave the occupied frequency as soon as a PU wants to use it
Secondary user requirement

- Secondary users need to incorporate cognitive radio (CR) features in the equipments
  - sensors
  - reconfigurable radio capabilities
  ➔ in addition to usual radio processing
- Sensor
  - detection of primary user at the same frequency
- Reconfigurable operators
  - carrier frequency, etc.
  ➜ Learning means to predict the band availability

No a priori knowledge

K Machines = K frequency bands

Specific Case of Multi-Armed Bandit
Primary network hypothesis

- Primary network: bands occupation
  - time is slotted

Secundary network

- minimum interference with PUs
- sense PUs activity with imperfect sensing
- available spectrum: shared among SUs

Secundary network hypothesis

- At every iteration, a SU selects (sense) only one channel
  - analog front end is not more complex than usual (only one band at a time)
  - learning is done step by step
  - SU tests (explore) a band and transmits (exploit) only if this band is sensed as free

<table>
<thead>
<tr>
<th>T1s</th>
<th>T2s</th>
<th>Transmission?</th>
<th>Reward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selects a channel</td>
<td>Observes the channel</td>
<td>Communicate if possible</td>
<td>Performance Evaluation</td>
</tr>
</tbody>
</table>

- impact of sensing errors?
- effect of SUs' collaboration?
• Hypothesis

- Each arm is a frequency band
- All bands have the same bandwidth (same reward per band in terms of data rate)
- Reward if \{0,1\}
  - 0 if the band is already occupied by PU
  - 1 if the band is free

- UCB$_1$

\[
B_{k,t,T_k}(t) = X_{k,T_k}(t) + A_{k,t,T_k}(t) \Rightarrow A_{k,t,T_k}(t) = \frac{\alpha \cdot \ln(t)}{T_k(t)}
\]


Effect of sensing errors I

- 10 channels
- for several false alarm probabilities

~x2 more trials to obtain the same knowledge with \( P_{fa} = 40 \% \)
Percentage of optimal Channel choice

- Smaller the set is, faster the algorithm choose the optimal channel (if it belongs to the set)
- But divergence may occur

Percentage of optimal Channel choice

- Smaller $\alpha$ is, faster UCB converges (more reliability to previous experiments).
Cumulative Regret

- Smaller $\alpha$ is, smaller the regret is (less exploration)
- Small regret for WD algorithm depending on the set dimension

---

decreasing electromagnetic pollution and by the same way decreasing the transmitting power: Beam forming to decrease the radiation level

The question here is: can an operator accept to use this gain for the same user number instead of increasing the user number?

• Activating some functions so as to decrease the transmitting power

Possible CR sensors to activate these gains
- SNR
- Channel Impulse Response
- Direction of Arrival
- Blind standard recognition
- ....

Example: The SNR sensor gives (locally) a very good value. Then Tx and Rx agree to use a channel code to decrease the power

If choice of power decrease then indirect gains (HPA efficiency, less temperature....)

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– Recycling the resources

• Recycling of the equipments
  » Clearly an industrial & operator problem
  » Mobile phone price is often included in the contract
  » No motivation to increase the equipment life time

• SoftWare Radio (SWR) may decrease the number of devices (multistandard, multimode, ...)
• SWR Technology may increase the equipment life time

– Recycling the resources

• Recycling of the radio waves
  – The radio waves exist if & only if there is sufficient energy to generate them
  – Almost all the radio waves are lost (particularly in broadcasting systems)
    » to use these waves in such a way that they generate small quantity of energy. (energy harvesting)
    » to use the waves for learning the electromagnetic environment (as done by sensors of CR), in order to better use these radio waves.
7. Green Communications as a Mean for an Improved Public Health

- Human aspects
  - Health aspect (Human exposure aspect)
    - There is a great reduction (> 30 dB) in the direction opposite the main lobe. Therefore, a great part of the radiation (max. 50%) is absorbed by the human body.
  - Social aspects
    - How it is possible to use wireless communications in order to help in the reduction of CO₂ emission in human being activities?
    - How it is possible to use wireless communications for helping the development of underdeveloped countries?
Beam forming: to avoid transmitting power in the human body

Proposed Algorithm

1. Activate DoA sensor, which determines the relative position of the BS and the terminal.
2. User interface requests the user to turn in the right direction.
3. Form the main beam towards the BS.

Of course, there remain some questions:
• This is difficult to execute for fast moving terminals.
• This implies advanced signal processing algorithms which are computationally expensive and consume power. Therefore a power consumption budget should be done carefully.
• This solution is not yet validated by experiments.

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• Electromagnetic radiation problem should be taken into account:
  – For the future networks design,
  – For the future standards definition & normalization,
  – For the future smart terminals.

• Promote the use of Cognitive Radio for Green Radiocommunications

  – Validation of our proposals through real platforms and measurements.


Conclusion (1/4)

Environmental-friendly Green Communications:
  – A paradigm change from traditional coverage- & capacity-driven to energy-efficiency driven communications and networks (Smart, Sustainable, and Self-harmonized greener ICT).

Cognitive Green Radio Communications:
  – Besides spectrum and energy, intelligence is the THIRD kind of resource, but without limitation of scarcity.
  – Learning and decision making algorithms under green constraint can play a significant role in enabling energy- and spectral-efficient greener future communications.
  – Effective energy saving can be realized by using various learning approaches in mobile cellular networks.

Cognitive Green Communications: From Concept to Reality!

Conclusion (2/4)
Conclusion (3/4)

• Questions:
  – Can an operator accept to use the technological gain for the same user number (decreasing the transmitted power) instead of increasing the user number?
  – Is there a market for CR terminals that takes into account this ecological aspect of electromagnetic transmission?
  – Is there a financial argument for operators willing to find the best compromise between health, spectrum efficiency, power consumption and cost etc.?
  – Can an operator/manufacturer make a selling point out of the fact that its mobile phones transmit less radiation than those of its competitors?
  – Are users prepared to pay more for a less polluting mobile phone?
  – …

Conclusion (4/4)

• Green Communications and Green Spectrum: Is Cognitive Radio an Enabler or Anyone else?
  – My answer: Yes, it is an enabler

• Cognitive Radio:
  – Thanks to sensors in a broad sense
  – Thanks to efficient decision making algorithms under green constraint
  – Can reach Green Radio Communications

Cognitive Green Radio Concept

• We strongly believe that:
  Bringing progress to people, improving their confidence in this technological field, and dissipating their fears of radio evolution is instrumental in providing the radio domain with a good prospect in the 21st century. Green Cognitive Radio Communications developments should provide this confidence.

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