An Image Processing Approach to Distributed Access for Multiantenna Cognitive Radios

Mauro Biagi, Valentina Polli, Jose Alberto Andrade Freitas
Dept. of Information, Electr. and Comm. Eng., “Sapienza” University of Rome

September 21, 2010
• Introduction and Related Works

• System Model

• Spectrum Occupancy and Image Processing

• Time - Frequency Access

• Numerical Results

• Conclusions
Conventional wireless medium management has always been based on exclusive bandwidth usage in order to prevent mutual interference.
Conventional wireless medium management has always been based on exclusive bandwidth usage in order to prevent mutual interference.

Need for new technologies to face the evergrowing demand for bandwidth and the inefficient employment of the licensed spectrum across space, time and frequency.
Conventional wireless medium management has always been based on exclusive bandwidth usage in order to prevent mutual interference. Need for new technologies to face the evergrowing demand for bandwidth and the inefficient employment of the licensed spectrum across space, time and frequency.

**Cognitive Radio**
leveraging on system capabilities (observe, decide, act, learn) to develop
dynamic, flexible and autonomous *spectrum access*
Cognitive Access

- spectrum sensing

- spectrum access
Cognitive Access

- spectrum sensing
  - energy detection
  - matched filter detection
  - cyclostationary detection

- spectrum access
Cognitive Access

- spectrum sensing
  - energy detection
  - matched filter detection
  - cyclostationary detection

- spectrum access

simplicity
Cognitive Access

- spectrum sensing
  - energy detection
  - matched filter detection
  - cyclostationary detection

- spectrum access

simplicity
accuracy
Cognitive Access

- **spectrum sensing**
  - energy detection
  - matched filter detection
  - cyclostationary detection
  - simplicity

- **spectrum access**
  - probability of occupancy
  - optimization
  - accuracy
Cognitive Access

- **spectrum sensing**
  - energy detection
  - matched filter detection
  - cyclostationary detection

- **spectrum access**
  - probability of occupancy
  - optimization

**common features**

**Sensing**: spectrum as a collection of channels (mostly carriers)

**Access**: suitability criterion for secondary users transmissions
Cognitive Generalized Access *

- Channel as a resource available in:
  - Time
  - Frequency
  - Code

- Access performed through:

Cognitive Generalized Access *

- Channel as a resource available in - Time
  - Frequency
  - Code

- Access performed through:

  1. Interference acquisition - $T_L$
Cognitive Generalized Access *

- Channel as a resource available in
  - Time
  - Frequency
  - Code

- Access performed through:

1. Interference acquisition - $T_L$
2. Channel estimation - $T_E$

Cognitive Generalized Access *

- Channel as a resource available in:
  - Time
  - Frequency
  - Code

- Access performed through:

1. Interference acquisition - $T_L$
2. Channel estimation - $T_E$
3. Data transmission - $T_{PAY}$

Cognitive Generalized Access *

- Channel as a resource available in:
  - Time
  - Frequency
  - Code

- Access performed through:

SIGNAL SHAPING

Interference shape affects spectrum availability

Cognitive Generalized Access *

- Channel as a resource available in
  - Time
  - Frequency
  - Code

- Access performed through:

  Interference shape affects spectrum availability

  Find solutions to fill up the "holes"

**Cognitive radios**
- power-limited \( P_{\text{max}} \)
- multiantenna \((t \times r)\)
- noncooperative

**Channel**
- Multiple Input Multiple Output (MIMO) \( H_{i,j}(f_k) \) \((r \times t)\)
- additive Multiple Access Interference (MAI)
- block fading
Interference acquisition:
primary users communications organized on a time frequency grid

received signal

\[ y(t) = \sum_{k} \sum_{l} y_{kl}(t) = \sum_{i} \sum_{k} \sum_{l} s_{kl}^{(i)} * h_{j}^{(i)}(t) + n(t) + e(t) \]
Interference acquisition:
primary users communications organized on a time frequency grid

received signal

\[ y(t) = \sum_{k} \sum_{l} y_{kl}(t) = \sum_{i} \sum_{k} \sum_{l} s_{kl}^{(i)} * h_{j}^{(i)}(t) + n(t) + e(t) \]

Wigner-Ville Transform (WVT)

\[ Y_{WV}(t,v) = \int_{R} y(t + \frac{\tau}{2})y^*(t - \frac{\tau}{2})e^{-j\tau v} d\tau \]

\[ Y_{WV}(t,v) = \int_{T_j} \left[ \sum_{i} \sum_{k} \sum_{l} s_{kl}^{(i)}(t + \frac{\tau}{2}) * h_{j}^{(i)}(t + \frac{\tau}{2}) + n(t + \frac{\tau}{2}) + e(t + \frac{\tau}{2}) \right] \cdot \left[ \sum_{i} \sum_{k} \sum_{l} s_{kl}^{(i)}(t - \frac{\tau}{2}) * h_{j}^{(i)}(t - \frac{\tau}{2}) + n(t - \frac{\tau}{2}) + e(t - \frac{\tau}{2}) \right]^* e^{-j\tau v} d\tau \]
Interference acquisition:
primary users communications organized on a time frequency grid

received signal

\[ y(t) = \sum_k \sum_l y_{kl}(t) = \sum_i \sum_k \sum_l s_{kl}^{(i)} * h_j^{(i)}(t) + n(t) + e(t) \]

Wigner-Ville Transform (WVT)

\[ Y_{WV}(t,v) = \int_R y(t + \frac{\tau}{2})y^*(t - \frac{\tau}{2})e^{-j\pi v} d\tau \]

\[ Y_{WV}(t,v) = \int_{T_f} \left[ \sum_i \sum_k \sum_l s_{kl}^{(i)}(t + \frac{\tau}{2})*h_j^{(i)}(t + \frac{\tau}{2}) + n(t + \frac{\tau}{2}) + e(t + \frac{\tau}{2}) \right] \cdot \left[ \sum_i \sum_k \sum_l s_{kl}^{(i)}(t - \frac{\tau}{2})*h_j^{(i)}(t - \frac{\tau}{2}) + n(t - \frac{\tau}{2}) + e(t - \frac{\tau}{2}) \right]^*e^{-j\pi v} d\tau \]

2D representation of spectrum occupancy
Marking occupied/free zones and select transmission opportunities
Marking occupied/free zones and select transmission opportunities

Canny processing
- Good detection
- Good localization
- Single response

Edge Detection
Marking occupied/free zones and select transmission opportunities

Canny processing
- Good detection
- Good localization
- Single response
Marking occupied/free zones and select transmission opportunities

**Canny processing**
- Good detection
- Good localization
- Single response

**Time-Frequency Slot (TFS)**
- Evaluation of free-area indicators $F_{k,l}$
- Sorting

Edge Detection
Slot partitioning

Interference slope analysis
Signal Shaping

- Slot partitioning
- Interference slope analysis
- Mask definition
Signal Shaping

Slot partitioning

Interference slope analysis

Mask definition

Mask compliance criterion

\[ \min_{\{a_k\}} \max_{w \in \Xi} \left( |E(w)| \right) = \min_{\{a_k\}} \max_{w \in \Xi} \Delta(w) \left[ S_m(w) - \sum_{k=0}^{L} a_k \cos(wk) \right] \]

Constraints

\[ C_{ij} \geq C^* \]
\[ P_i \leq P_{\text{max}} \]

\[ C_{ij} = \frac{1}{T_s} \frac{1}{M} \sum_{m=1}^{M} \int_{f_k - \frac{B}{2}}^{f_k + \frac{B}{2}} \log_2 \left( 1 + \frac{P_i |H_j^{(f)}(f)|^2 |S_m(f)|^2}{(N_0 + I_m(f))\Gamma} \right) df \]
Signal Shaping

- **Slot partitioning**
- **Interference slope analysis**
- **Mask definition**

**Mask compliance criterion**

\[
\min_{\{a_k\}} \max_{w \in \Xi} \left( |E(w)| \right) = \min_{\{a_k\}} \max_{w \in \Xi} \Delta(w) \left[ S_m(w) - \sum_{k=0}^{L} a_k \cos(wk) \right]
\]

**Constraints**

- \[ C_{ij} \geq C^* \]
- \[ P_i \leq P_{\text{max}} \]

\[
C_{ij} = \frac{1}{T_s} \frac{1}{M} \sum_{m=1}^{M} \int_{f_k - \frac{B}{2}}^{f_k + \frac{B}{2}} \log_2 \left( 1 + \frac{P_i |H_j^{(f)}(f)|^2 |S_m(f)|^2}{(N_0 + I_m(f)) \Gamma} \right) df
\]
Algorithm

Shaping computed through a simple iterative algorithm
Shaping computed through a simple iterative algorithm

MIMO Channel State Information to optimize power allocation among transmit antennas (Water-Filling)
Shaping computed through a simple iterative algorithm

Interference slope analysis to optimize mask definition
Simulation parameters

\[ C^* = 200 \text{ kbps} \quad B = 50 \text{ kHz} \]

\[ T_s = 1 \mu s \quad \Gamma = 10 \quad (\text{BER} = 10^{-6}) \]

\[ P_{\text{max}} = 0.01 \mu W \]
Chirp-like Interference

Simulation parameters

\[ C^* = 200 \text{ kbps} \quad B = 50 \text{ kHz} \]

\[ T_s = 1 \mu s \quad \Gamma = 10 \ (\text{BER} = 10^{-6}) \]

\[ P_{\text{max}} = 0.01 \mu W \]

primary user occupancy
Numerical Results

Chirp-like Interference

Simulation parameters

\[ C^* = 200 \text{ kbps} \quad B = 50 \text{ kHz} \]
\[ T_s = 1 \mu s \quad \Gamma = 10 \ (\text{BER} = 10^{-6}) \]
\[ P_{\text{max}} = 0.01 \mu \text{W} \]

primary user occupancy  
secondary user allocation

![Simulation results](image1)

![Simulation results](image2)
### Generic-shaped Interference

**Simulation parameters**

\[
\begin{align*}
C^* &= 200 \text{ kbps} \quad B = 50 \text{ kHz} \\
T_s &= 1\mu s \quad \Gamma = 10 \quad (\text{BER} = 10^{-6}) \\
P_{\text{max}} &= 0.01\mu W
\end{align*}
\]

Central high energy signal components usually preclude secondary user access.
Generic-shaped Interference

Simulation parameters

\[ C^* = 200 \text{ kbps} \quad B = 50 \text{ kHz} \]
\[ T_s = 1\mu s \quad \Gamma = 10 \quad (\text{BER} = 10^{-6}) \]
\[ P_{\max} = 0.01\mu W \]

central high energy signal components usually preclude secondary user access

allocation on unemployed portions of the spectrum
Numerical Results

Performance Analysis

Time-Frequency vs Cognitive Generalized Access

MORE accessing users employing LESS antennas

![Graph showing performance analysis](image-url)
Time-Frequency vs Cognitive Generalized Access

MORE accessing users employing LESS antennas
Main features of the proposed access strategy are:

- the simplicity of the algorithm;
- the capability to understand the interference slope and suitably adapt the emission masks;
- the new availability criterion which allows to widen the transmission possibilities and enhance spectrum utilization;
- the adaptivity to several performance measures.