Prospects and challenges for spectrum sharing by cognitive radios

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Harvard EE Seminar
Spectrum, spectrum, everywhere, but ...
Outline

- How much usable white-space is there?
- How can we understand sensing?
- Light-handed regulation: identity
- Light-handed regulation: deterrence
How much white-space is there in a single band?
Consider channel 39...
The pollution perspective: 15dB above noise
The pollution perspective: 10dB above noise
The pollution perspective: 5dB above noise
5dB above noise with -35dB spillover from next door
5dB above noise with -45dB spillover from next door
5dB above noise with -55dB spillover from next door
The protection perspective
The protection perspective: 4W
The protection perspective: 20W
The protection perspective: 100kW
The protection perspective: 1MW
How much to protect? 0.1dB margin
How much to protect? 1.0dB margin
How much to protect? 10dB margin
How much to protect? 1.0dB margin vs 5db pollution
How much to protect? 1 dB margin with adjacent
Can we sense these holes?
Can we sense these holes? 90%
Can we sense these holes? 99%
Can we sense these holes? FCC rules
How much white-space is there across bands?
... If we account for adjacent-channel effects?
How much white-space is there across bands?

<table>
<thead>
<tr>
<th>Detection Scheme/Rule</th>
<th>By Area</th>
<th>By Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LVHF</td>
<td>HVHF</td>
</tr>
<tr>
<td></td>
<td>2,5,6</td>
<td>7-13</td>
</tr>
<tr>
<td>Pollution (5dB,45dB adj.)</td>
<td>1.6</td>
<td>1.63</td>
</tr>
<tr>
<td>Geolocation</td>
<td>1.52</td>
<td>2.86</td>
</tr>
<tr>
<td>Geolocation with adj.</td>
<td>1.24</td>
<td>1.63</td>
</tr>
<tr>
<td>Sense -114dBm</td>
<td>0.985</td>
<td>0.409</td>
</tr>
<tr>
<td>-114dBm,-110dBm adj.</td>
<td>0.515</td>
<td>0.0635</td>
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</tbody>
</table>
... If we vary the allowed power?
What is the underlying public policy tradeoff?
What is the underlying public policy tradeoff?

![Diagram showing Achievable margins for 5dB pollution rule and Cumulative gain-loss, uniform population density vs. Margin (dB).]
How much usable white-space is there?

**How can we understand sensing?**

Light-handed regulation: identity

Light-handed regulation: deterrence
What are the right metrics for sensing?

\[ WPAR = \int_{r_n}^{\infty} P_{FH}(r) w(r) r dr \]

- \( P_{FH}(r) \): probability of finding a spectrum hole at distance \( r \).
- \( w(r) \): weighting function satisfying \( \int_{r_n}^{\infty} w(r) r \, dr = 1 \).
What are the right metrics for sensing?

\[
WPAR = \int_{r_n}^{\infty} P_{FH}(r) \cdot w(r) \cdot rdr
\]

\[
F_{HI} = \sup_{0 \leq r \leq r_n} \sup_{F_r \in \mathbb{F}_r} \mathcal{P}_{F_r}(D = 0 | r_{actual} = r)
\]

where \( \mathbb{F}_r \) is the uncertainty about the distribution \( F_r \) underlying algorithm \( D \).
Single-user sensing

\[ F_{HI} = 0.2 \]

\[ F_{HI} = 0.001 \]

\[ \tilde{w}(r) = \exp\{-\kappa (r - r_n)\} \]

\[ \kappa = 0.015 \text{ km}^{-1} \]

\[ r_n = 157 \text{ km} \]

\[ N = \infty \]
Single-user sensing: finite samples

Gains from increasing the number of samples ($F_{HI} = .1$)

![Graph showing gains from increasing the number of samples. The graph plot weighted probability of area recovered (WPAR) against number of samples (N). The graph includes lines for perfect detector, complete knowledge, and single quantile knowledge.]
Single-user sensing: SNR Walls

Without Uncertainty

With Uncertainty = 1 dB

$\bar{W}(r) = \exp\{-\kappa (r - r_n)\}$

$\kappa = 0.015$ km$^{-1}$

$r_n = 157$ km

$N = \infty$
Cooperation

Empirical performance under -114 dBm rule (channel 39)

Spatial Sensing Overhead (1 - WPAR)

Fear of Harmful Interference ($F_{HI}$)

$M = 1$

$M = 2$

$M = 5$

$M = 10$
Cooperation

Spatial Sensing Overhead (1 - WPAR) vs. Number of Cooperating Users (M)

- OR rule
- ML rule

$F_{HI} = 0.01$
Cooperation

Spatial Sensing Overhead (1- WPAR)

Fear of Harmful Interference ($F_{HI}$)

$M = 10$

0.8 Correlation uncertainty

0.5

0.2

0
Outline

- How much usable white-space is there?
- How can we understand sensing?
- **Light-handed regulation: identity**
  - Prior work:
    - Faulhaber ’05
    - Hall, Barbeau, Kranakis ’03
    - Brik, Banerjee, Gruteser, Oh ’08
    - Rasmussen and Capkun ’07
    - Rozovskiy and Kumar ’01
- **Light-handed regulation: deterrence**
Identity through taboos

Network ID
User ID
× Device ID

TX Identity: Band 1
Cannot transmit

TX Identity: Band 2

TX Identity: Band 3
Single secondary user case

- 5% overhead
- 10% overhead
- 25% overhead

- 0.1% background losses
- Worst case background losses

Percentage disruption due to interference vs. wait till conviction
Single secondary user case

![Graph showing identity overhead vs. wait till conviction with different disruption percentages and worst case background losses.]
Multiple Users: cooperation and/or “framing”

utility/interference imposed

number of codes implicated

5% overhead
10% overhead
25% overhead

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Multiple Users: noise-free non-strategic case

Time steps until conviction = 3000

Minimum enforcement overhead

Catch coalition of 4

Catch coalition of 3

Catch coalition of 2

Number of users
Multiple Users: coalitions and overhead

- 25% overhead
- 10% overhead
- 5% overhead

Effective overhead vs. number of users graph.
Noisy-case: An equal-rate MAC-framework

<table>
<thead>
<tr>
<th>Identifying Culprits</th>
<th>MAC channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$ Distinguishable Secondary Users</td>
<td>$N$ Distinct messages</td>
</tr>
<tr>
<td>$K$ Coalition size</td>
<td>$K$ different users</td>
</tr>
<tr>
<td>$T_c$ Time-to-identification</td>
<td>Codeword length $T_c$</td>
</tr>
<tr>
<td>$\gamma$ Taboo-fraction</td>
<td>$\gamma$ average cost-constraint on codewords</td>
</tr>
<tr>
<td>Users may/may-not cheat/interfere</td>
<td>MAC channel model</td>
</tr>
</tbody>
</table>

$$
\lim_{T_c \to \infty} \frac{\log N}{T_c} \leq \min_{k \leq K} \frac{I(X_1^k; Y|X_{k+1}^K)}{k}
$$
Outline

- How much usable white-space is there?
- How can we understand sensing?
- Light-handed regulation: identity
- **Light-handed regulation: deterrence**
  - Prior work:
    - Rose, Ulukus, Yates ’01
    - Popescu and Rose ’04
    - Etkin and Tse ’05
    - Huang, Berry, Honig ’04
    - Xu, Kamat, Trappe ’06
Single-band model

\[ P_{tx} = \frac{q}{q+p} \]

\[ p_1 \]

\[ q_1 \]

TX \quad No TX

No Cheat \quad False Alarm

Cheat \quad Legal TX

Jail

P_{catch}

P_{pen}
Single-band model

A 3D graph shows the relationship between Ptx and Pcheat, with different scenarios labeled:
- **Always cheat**
- **Never cheat**

Key parameters:
- Pcatch = 1
- Ppen = 0.6
Single-band model

\[ \beta = \text{pain of jail} \]

\[ P_{\text{catch}} = 0.1 \]

\[ P_{\text{pen}} \]

\[ \beta = 0.2 \]

\[ \beta = 0.4 \]

\[ \beta = 0.6 \]

\[ \beta = 0.8 \]

\[ \beta = 1 \]
Multiple-bands: need to have something to lose

<table>
<thead>
<tr>
<th>Band</th>
<th>Home</th>
<th>Expansion Band 1</th>
<th>Exp. Band 2</th>
<th>...</th>
<th>Exp. Band B</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility:</td>
<td>$\beta$</td>
<td>$1$</td>
<td>$1$</td>
<td>$...$</td>
<td>$1$</td>
<td>$\beta + B$</td>
</tr>
</tbody>
</table>
Multiple-bands: need to have something to lose

\[ P_{tx} = \frac{q}{q+p} \]

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Multiple-bands: need to have something to lose

\[ \beta = \text{home bands required to incentivize no cheating} \]

\[ P_{\text{pen}} \]

\[ B = 1 \]
\[ B = 3 \]
\[ B = 5 \]
\[ B = 7 \]
\[ B = 9 \]

\[ P_{\text{catch}} = 1 \]
The problem of false convictions

\[ \text{Ptx} = \frac{q}{q+p} \]

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The problem of false convictions

![Graph showing the relationship between Ppen and Pwrong for different values of Pcatch.]

- $P_{catch} = 1$
- $P_{catch} = 0.5$
- $P_{catch} = 0.1$

$B = 3$
The problem of false convictions

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The “overhead” needed for bandwidth expansion
The “overhead” needed for bandwidth expansion

![Graph showing the relationship between overhead and expansion for different values of Pwrong.

- Pwrong = 0.001
- Pwrong = 0.01
- Pwrong = 0.035
- Pwrong = 0.06
- Pwrong = 0.1
- Ptx = 0.55
- Pcatch = 1

Maximal Expansion]
The “overhead” needed for bandwidth expansion

\[ \text{Overhead} \]

\[ \text{Expansion} \]

\[ P_{\text{catch}} = 1 \]

\[ P_{\text{tx}} = 0.55 \]

\[ P_{\text{wrong}} = 0.02 \]

Maximal Expansion
Conclusion: Freedom isn’t free

<table>
<thead>
<tr>
<th>Interference management is primary’s responsibility</th>
<th>Interference management not primary’s responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary has permission</td>
<td>Markets</td>
</tr>
<tr>
<td>Secondary must take care</td>
<td>Denials</td>
</tr>
<tr>
<td></td>
<td>UWB/Spectrum Monitors</td>
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<tr>
<td></td>
<td>Opportunistic</td>
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</tbody>
</table>
“How much white space is there?”

“What is a spectrum hole and what does it take to recognize one?”

“A technical perspective on light-handed regulation for cognitive radios”

“Cognitive Radios for Spectrum Sharing”