Sensing-Throughput Tradeoff for Cognitive Radio Networks

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Outlines

• Motivations for Cognitive Radio
• Spectrum sensing
• Problem statement
• Single User Scenario
  - AWGN channel scenario
  - Rayleigh fading channel scenario
• Multi-slots Sensing
• Decision fusion cooperative sensing scheme
• Conclusion
Motivations for Cognitive Radio

- Spectrum Scarcity
Motivations for Cognitive Radio

- Spectrum Underutilization

FCC spectrum measurements
Cognitive Radio Cycle
Spectrum Sensing

Power

Frequency

Spectrum in use

"Spectrum hole"

Dynamic spectrum access

Time
Single User Sensing Mode
Hidden node Problem
Cooperative sensing Mode
Energy detection terminology

- Received signal at CR receiver
  \[ y(n) = h_{ps} \theta x_p(n) + w(n) \]
  \[ \theta = \begin{cases} 
  1 & H_P = H_1 \\
  0 & H_P = H_0 
\end{cases} \]

- Statistic Metric
  \[ M = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2 \]

- Decision
  \[ \begin{cases} 
  M > \lambda & \text{then decide } H_1 \\
  M < \lambda & \text{then decide } H_0 
\end{cases} \]
Detection & false alarm probabilities

\[ P_d = pr(M > \lambda | H_1) \quad \& \quad P_f = pr(M > \lambda | H_0) \]

Probability of mis-detection

Probability of false alarm
**Problem Statement**

\[
\max_{\tau} R(\tau) = R_0(\tau) + R_1(\tau)
\]

s.t.: \( 0 < \tau < T, \ P_d(\tau) \geq \ P_d \)

- Optimization Carried in Scenarios:
  - Single User Scenario
  - Multi-slot Spectrum Sensing
Single User Scenario

Generate random vector $\Theta$ indicates PU status

$\Theta=1 \rightarrow$ Generate PU data
$\Theta=0 \rightarrow$ No data

Multiply with channel gain coefficients & AWGN added

From N received samples, decision metric is evaluated

Compared with $\lambda$, decision vector is obtained

Compared decision and $\Theta$ vectors to evaluate $P_d$ & $P_f$
• Test Metric

\[ M = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2 \]

\[ M_{H_0} = \frac{1}{N} \sum_{n=1}^{N} |w(n)|^2 \]

\[ M_{H_1} = \frac{1}{N} \sum_{n=1}^{N} \left| (h_{ps} x_p(n) + w(n)) \right|^2 \]

\[ P_f = Q \left( \left( \frac{\lambda}{N_0} - 1 \right) \sqrt{N} \right) \]

\[ P_d = Q \left( \left( \frac{\lambda}{(\gamma+1)N_0} - 1 \right) \sqrt{N} \right) \]

• Threshold

\[ \lambda = (\gamma + 1)N_0 \left( \frac{1}{\sqrt{\tau f_s}} Q^{-1}(P_d) + 1 \right) \]

\[ P_f = Q \left( (\gamma + 1)Q^{-1}(P_d) + \gamma \sqrt{N} \right) \]

\[ N = \tau f_s \]

• So,

\[ P_f(\tau) = Q \left( (\gamma + 1)Q^{-1}(P_d) + \gamma \sqrt{\tau f_s} \right) \]
Simulation Results

ROC curve in case of AWGN noise channel
Probability of false alarm
Probability of mis-detection

Noise only case
Rayleigh fading channel (-5 dB parameter)

ROC curve of Rayleigh flat fading channel compared with AWGN noise channel
False alarm and detection probabilities vs. the number of samples (AWGN channel)
Prob. of detection & false alarm vs. $N$ (AWGN noise only case)
Prob. of detection and false alarm vs. $N$ (for flat Rayleigh faded channel case with parameter $= 0.2$)
Throughput Evaluation

- There are two scenarios in calculating secondary user throughput

Scenario I
PU absent & no. false alarm

- Channel Shannon capacity
  \[ C_0 = \log_2(1 + SNR_s) \]
- Prob. of its occurrence
  \[ (1 - P_f)P(H_0) \]
- Then, SU throughput be
  \[ R_0(\tau) = \frac{T - \tau}{T} (1 - P_f(\tau))P(H_0)C_0 \]

So, the total throughput is
  \[ R(\tau) = R_0(\tau) + R_1(\tau) \]

Scenario II
PU exist & no. mis- detection

- Channel Shannon capacity
  \[ C_1 = \log_2 \left(1 + \frac{P_s}{P_p + N_0}\right) = \log_2 \left(1 + \frac{SNR_s}{SNR_p + 1}\right) \]
- Prob. of its occurrence
  \[ (1 - P_d)P(H_1) \]
- Then, SU throughput be
  \[ R_1(\tau) = \frac{T - \tau}{T} (1 - P_d)P(H_1)C_1 \]
The achievable throughput (AWGN channel)

Acheivable Throughput for single SU scenario

Sensing time (ms)

Achievable throughput (bits/Sec/Hz)

Total Throughput R
Dominant throughput R₀
The Normalized throughput (AWGN)
The achievable throughput (Rayleigh Channel)

Acheivable Throughput for single SU scenario (Rayleigh channel)

Sensing time (ms)

Achievable throughput (bits/Sec/Hz)

Total Throughput $R$

Dominant throughput $R_0$
The Normalized throughput (Rayleigh Channel)
Multi-slot Spectrum Sensing

![Graph showing the probability of false alarm vs. sensing time for different values of M (1 to 4).]
Decision fusion cooperative sensing scheme

\[ \frac{1}{N} \sum_{n=1}^{N} |y_1(n)|^2 \geq \lambda_1 \quad D_1 = 1 \quad D_1 = 0 \]

\[ \frac{1}{N} \sum_{n=1}^{N} |y_M(n)|^2 < \lambda_M \quad D_M = 1 \quad D_M = 0 \]

\[ \sum_{i=1}^{M} D_i \geq K \quad \text{decide 1} \quad \sum_{i=1}^{M} D_i < K \quad \text{decide 0} \]

\[ K = 1 \quad \text{AND \ - \ rule} \quad K = M \quad \text{OR \ - \ rule} \quad K = \left\lceil \frac{M}{2} \right\rceil \quad \text{Majority \ - \ rule} \]
Superiority of cooperative sensing

The ROC curve for OR fusion rule with variable number of users.

The graph shows the probability of false alarm and probability of mis-detection for different numbers of users (N_SU = 1, N_SU = 2, N_SU = 3, N_SU = 10). The curves indicate that cooperative sensing significantly improves detection accuracy compared to the non-cooperative scheme (N_SU = 1).
Conclusion

• The sensing-throughput trade off problem is highlighted in the AWGN and Rayleigh fading channels.
• The throughput curve in both channels has concave shape so, a unique solution is found.
• Optimal sensing time in AWGN noise channel of 2.667 ms is resulted (For a frame length of 100 ms)
• While, optimal sensing time for Rayleigh fading be 7 ms.
• Also, the Rayleigh fading reduces the SU transmission throughput.
• Multi-slot sensing it a type of time diversity improves the false alarm probability.
Thank You