A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications

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Overview

- Cognitive Radio
- Multidimensional Spectrum Awareness
- Challenges
- Spectrum Sensing Methods
- Cooperative Spectrum Sensing
- Some Examples from Current Standards
- Conclusion

Cognitive Radio

- **FCC definition:** “A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.”

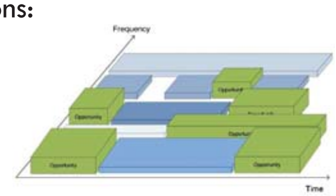
Cognitive Radio: Definitions

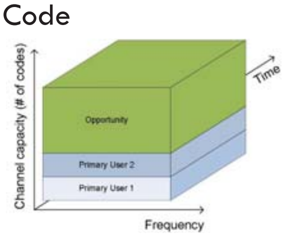
- **Primary User:** A user who has higher priority or legacy rights on the usage of a specific part of the spectrum
- **Secondary User:** A user who has a lower priority and therefore exploits the spectrum in such a way that it does not cause interference to primary users.
- **Spectrum Sensing:** The task of obtaining awareness about the spectrum usage and existence of primary users in a geographical area.

Multidimensional Spectrum Awareness: Radio Space

There are a number of dimensions that can be considered for CR applications:

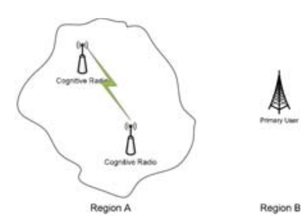
- Frequency
- Time
- Code



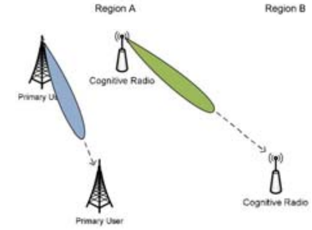


Multidimensional Spectrum Awareness: Radio Space

- Geographical Space



- Angle of Arrival



Challenges: Hardware

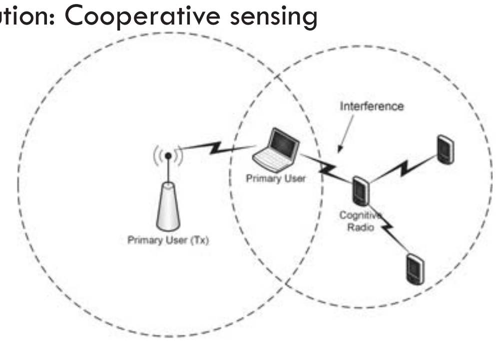
- High resolution analog to digital converters with large dynamic range are required.
- CR has to scan a potentially large band of frequencies to find an opportunity, antennas and power amplifiers have to be designed accordingly.
- High speed digital signal processors are required for low delays.

Challenges: Hardware

Single-Radio Architecture	Dual-Radio Architecture
Specific time-slots are allocated for sensing	One radio monitors the channel
Simple and costs less	Higher cost, complexity
Lower spectrum efficiency	High spectral efficiency
Lower sensing accuracy	Higher accuracy and power consumption

Challenges: Hidden Primary Users

- Similar to CSMA, a hidden primary user as depicted below may cause collisions.
- Solution: Cooperative sensing



Challenges: Spread Spectrum

- Frequency Hopping: The narrowband signal is dynamically switched in frequency.
- Direct Sequence: The signal is spread to a much wider band.
- Result: The signal power is spread to a wider band, which makes it difficult to detect users.
- Solution: Perfect synchronization and pattern knowledge

Challenges: Sensing Duration & Frequency

- Secondary users should vacate their frequency bands as soon as a primary user starts transmitting. This requires frequent sensing of the channel.
- Reliably detecting primary users is a function of the sensing duration.
- Reliability of detection vs. speed of detection tradeoff.
- Vacating speed vs. underutilization of secondary users tradeoff.

Challenges: Fusing Decisions in Cooperative Sensing

- For soft decisions, the log-likelihood or likelihood ratio tests may be employed.
- The data may be combined using SC or EGC.
- For hard decisions, AND, OR, M-out-of-N techniques may be employed.
- Soft decisions outperform hard decisions when the number of users is small

Challenges: Security

- Malicious users may try to emulate primary users (PUE), denying access to secondary users at will.
- A public key encryption may be used for protection whereby primary users are required to transmit an encrypted (signature) value.
- Secondary users have to demodulate the signals of primary users
- Cannot be used with analog modulation

Spectrum Sensing Methods: Energy Detector

- Most common method due to its low complexity
- Threshold selection is a challenge
- Bad performance under low SNR conditions

Assume the received signal is as follows:

$$y(n) = s(n) + w(n)$$

then the metric to threshold will be:

$$M = \sum_{n=0}^{N} |y(n)|^2$$

Spectrum Sensing Methods: Energy Detector

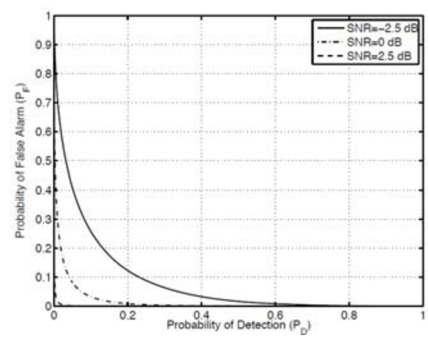
The decision is made between the following states:

$$H_0 : y(n) = w(n),$$
$$H_1 : y(n) = s(n) + w(n).$$

The performance of the method can be quantified by P_F, probability of false alarm and P_D, probability of detection. When w and s are modeled as zero-mean normally distributed with variances σ_{w^2} and σ_{s^2} the metric follows a chi-squared distribution with 2N degrees of freedom.

Spectrum Sensing Methods: Energy Detector

- The P_D vs. P_F curve is as follows:



Spectrum Sensing Methods: Energy Detector

- The threshold depends on the noise variance.
- Estimation of noise variance is an important issue, slight inaccuracies may degrade performance.
- The noise variance may be estimated from the autocorrelation of the received signal.
- The threshold may be iteratively determined by confining P_F to confidence intervals.
- Fading and shadowing have to be considered for realistic scenarios.

Spectrum Sensing Methods: Waveform-Based Sensing

- Fixed patterns are usually utilized in wireless systems such as preambles, pilot signals, spreading sequences, etc.
- In the presence of such a pattern the received signal can be correlated with it for sensing. In this case the decision metric will be:

$$M = \begin{cases} Re\left[\sum_{n=1}^{N} y(n)s^*(n)\right], if\ H_0 \\ Re\left[\sum_{n=1}^{N} w(n)s^*(n)\right], if\ H_1 \end{cases}$$

Spectrum Sensing Methods: Cyclostationarity-Based Sensing

- Cyclostationary features are caused because of periodicities in the signal or can be intentionally introduced.
- Instead of the power spectral density, cyclic spectral density(CSD) is used. Since noise is assumed to be WSS, and the signal is cyclic it can be easily detected.

CAF: $R_{y^{\alpha}}(\tau) = E\left[y(n+\tau)y^{*}(n-\tau e^{-j2\pi\alpha n})\right]$

CSD: $S(f,\alpha) = \sum_{\tau=-\infty}^{\infty} R_{y^{\alpha}}(\tau)e^{-j2\pi f\tau}$

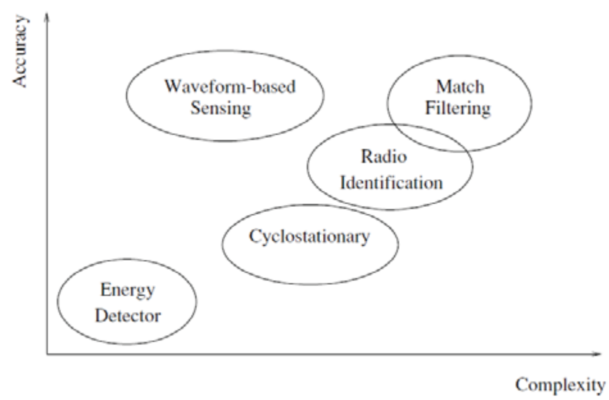
Spectrum Sensing Methods: Radio Identification Based Sensing

- By identifying the transmission technology, complete knowledge about the spectrum characteristics can be obtained.
- In some cases the CR may want to communicate with the primary system.
- Detected energy, channel bandwidth and shape, cyclic frequencies, spectral correlation density, etc. features may be used for identification.

Spectrum Sensing Methods: Matched Filtering

- Optimum method if there is complete knowledge of the transmitted signal.
- Requires a very short time to reach a given probability of false alarm.
- Required number of samples grows as O(1/SNR)
- Primary users' signals have to be demodulated, knowledge of modulation scheme, pulse shaping, etc. needed.

Spectrum Sensing Methods: Comparison



Cooperative Sensing

- Can solve problems that arise due to noise uncertainty, fading and shadowing.
- Decreases false alarm rate significantly.
- Can solve the hidden primary node problem.
- Efficient algorithms needed for sharing information
- Most effective when radios experience independent fading or shadowing

Cooperative Sensing: Centralized Sensing

- A central unit collects all the information from CRs, identifies and broadcasts opportunity information.
- Hard or soft decisions can be preferred.
- If the number of users is large hard decisions are preferred so as not to waste bandwidth with opportunity information.
- Another threshold can be employed to decide on the reliability of the data and censor some of the users

Cooperative Sensing: Distributed Sensing

- Users again share information on opportunities among each other, but every user decides for himself.
- No dedicated AP needed to gather all information.
- Less costly.
- Coordination among users may be a problem.
- Sharing the final decision instead of sensing information may be employed.

Cooperative Sensing: External Sensing

- An external node or network performs all the sensing instead of the CRs and broadcasts the opportunity information.
- Spectrum efficiency is increased and power consumption is reduced since CRs do not waste time or power by sensing the channel.
- Can efficiently solve the hidden primary user problem and uncertainties due to shadowing and fading.

Examples from current Systems: IEEE 802.11k

- A noise histogram report is generated based on measurements which display all non 802.11 energy on a channel.
- AP collects the data and uses it to regulate access.
- The information is used to balance the load of APs in a network as well.

Examples from current Systems: Bluetooth

- Adaptive Frequency Hopping (AFH) feature is introduced to reduce interference with other 2.4 GHz systems.
- AFH identifies the transmissions in the ISM band and avoids their frequencies.
- Identification is performed by gathering channel statistics such as BER, received signal strength indicator, etc.

Questions and Discussion