Cognitive Radio: Fundamental Issues and Research Challenges

Simon Haykin
McMaster University
haykin@mcmaster.ca

1. The Turbo Receiver:

An Example of

Cognitive Information Processing

Figure - Block codes

2. Future of Cognitive Radio: Evolution or Revolution

Drivers:

- **Improved utilization of the radio spectrum**
- **Unused spectrum: Overwhelming driver:**
  US Department of Defense
- **Regulators:**
  Federal Communications Commission (FCC)
- **Standards Bodies**

Two viewpoints:

1. From the viewpoint of well-established wireless communication manufacturers, the development of cognitive radio is EVOLUTIONARY, building on the world-wide wireless telephone network already in place.

2. On the other hand, from the viewpoint of computer manufacturers eager to move into the wireless market, the development of cognitive radio is REVOLUTIONARY.

3. Historical Background on Cognition

(i) The Symposium on Information Theory, which was held at MIT in 1956.

Result of the Symposium:

Linguists began to theorize about language, which was to be found in the theory of digital computers:

THE LANGUAGE OF INFORMATION PROCESSING

(ii) In the same year, a few months later, The Dartmouth Conference was held at Dartmouth College:

Result of the Conference:

The start of research into what we nowadays call (after going through growing pains):

LEARNING MACHINES AND
LEARNING ALGORITHMS

4. Definition of Cognitive Radio Network

The cognitive radio network is an intelligent multiuser wireless communication system that embodies the following list of primary tasks:

(i) To perceive the radio environment (i.e., outside world) by empowering each user's receiver to sense the environment on a continuous-time basis

(ii) To learn from the environment and adapt the performance of each transceiver to statistical variations in the incoming RF stimuli

(iii) To facilitate communication between multiple users through cooperation in a self-organized manner

(iv) To control the communication processes among competing users through the proper allocation of available resources

(v) To create the experience of intention and self-awareness.

(vi) To accomplish all of these tasks in a reliable and robust manner.

5. Functional Block Diagram of Cognitive Radio Networks

(Distinct from traditional wireless networks)

(i) **Radio Scene Analyzer, encompassing:**
Spectrum access
- Interference power estimation
- Predictive modeling

(ii) **Feedback Channel**
(from the receiver to the transmitter)

(iii) **Dynamic Spectrum Analyzer, and Transmit-power Controller**

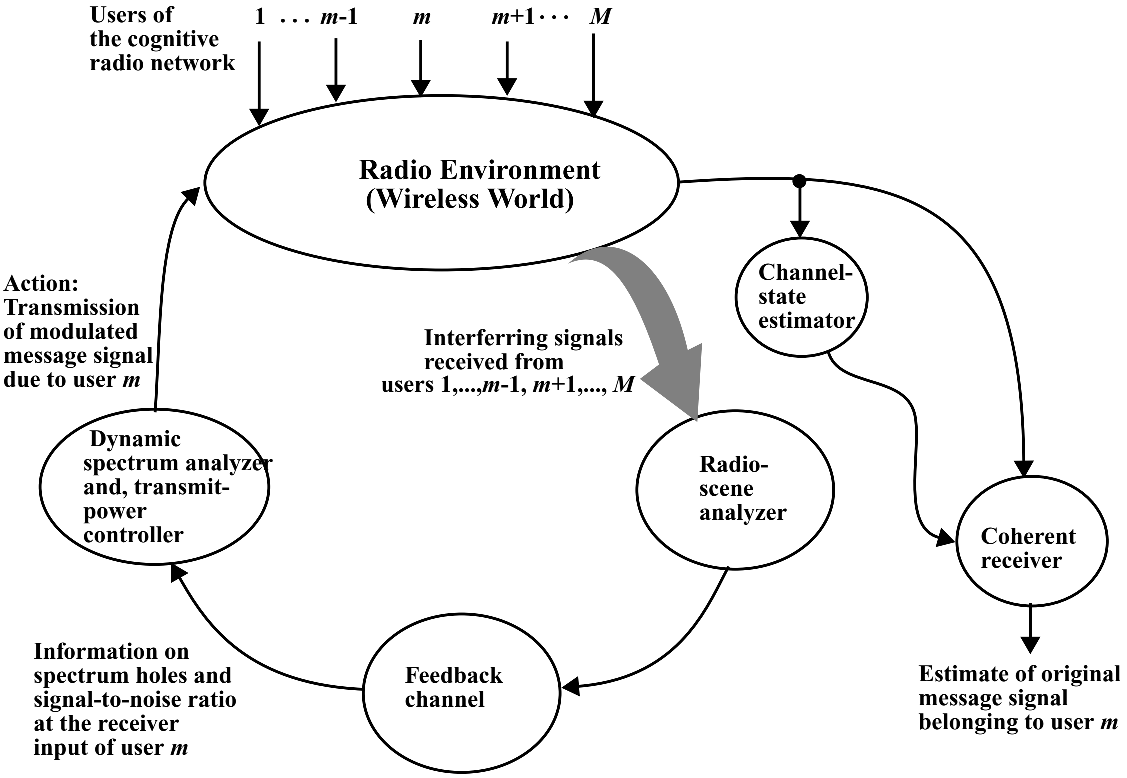


Figure 1. Cognitive signal-processing cycle for user *m* of cognitive radio network; the diagram also includes elements of the receiver of user *m*

6. Radio-scene Analysis

- **Spectrum holes:** What are they?

- **Interference temperature:** How to estimate it accurately?

- Basic problem:
  Nonparametric power spectrum estimation

- Method of choice:
  Multitaper method

Brief Outline of the Multitaper Method (Thomson, 1982)

1. **Orthogonal sequence of K Slepian tapers**, denoted by $\left\{ w_t^k \right\}_{t=1}^{N}$ where t denotes time, and $k = 0, 1, ..., K\text{-}1$.

2. **Associated eigenspectra**, defined by the Fourier transform:

$$Y_k(f) = \sum_{t=1}^{N} w_t^k x(t) \exp(-j2\pi f t), \qquad k = 0, 1, ..., K\text{-}1$$

   where $x(t)$ is the input signal.

3. **Energy distributions of the eigenspectra** are concentrated inside a resolution bandwidth of $2W$.

   Time-bandwidth product (Degrees of freedom):

$$2NW$$

   where N is the number of Slepian tapers.

- **Formula for the power spectrum estimate:**

$$\hat{S}(f) = \frac{\sum_{k=0}^{K-1} \lambda_k(f) \left| Y_k(f) \right|^2}{\sum_{k=0}^{K-1} \lambda_k(f)}$$

where λ_k is the **eigenvalue associated with the *k*th eigenspectrum**.

- **Iterative procedure for overcoming the "within-band leakage problem":**

$$\hat{S}^{(j+1)}(f) = \left[\sum_{k=0}^{K-1} \frac{\lambda_k \hat{S}_k(f)}{(\lambda_k \hat{S}^{(j)}(f) + \hat{B}_k(f))^2} \right] \left[\sum_{k=0}^{K-1} \frac{\lambda_k}{(\lambda_k \hat{S}^{(j)}(f) + \hat{B}_k(f))^2} \right]^{-1}$$

Note

- Paper by B. Boroujeny (University of Utah), to be published in the IEEE Trans. Signal Processing, shows that the multitaper method can be implemented by using the multifilter bank framework.

Joint Space-time Processing:

1. Use the multitaper method for spectrum estimation.
2. Employ sensors to **spatially sense the RF environment.**

- **Spatio-temporal matrix:**

$$\mathbf{A}(f) = \begin{bmatrix} a_1 Y_0^{(1)}(f) & a_1 Y_1^{(1)}(f) & \ldots & a_1 Y_{K\text{-}1}^{(1)}(f) \\ a_2 Y_0^{(2)}(f) & a_2 Y_0^{(2)}(f) & \ldots & a_2 Y_{K\text{-}1}^{(1)}(f) \\ \vdots & \vdots & & \vdots \\ a_M Y_0^{(M)}(f) & a_M Y_1^{(M)}(f) & \ldots & a_M Y_{K\text{-}1}^{(M)}(f) \end{bmatrix}$$

Apply the **singular value decomposition** to **A(*f*)** to compute:

$$\mathbf{A}(f) = \sum_{k=0}^{K\text{-}1} \sigma_k(f)\,\mathbf{u}_k(f)\,\mathbf{v}_k^{\dagger}(f)$$

Information on interference waveforms

Average power

Spatial distribution of interferences

6. Feedback Channel

“Global Feedback is the fasilitator of Cognition”

Required functions of the low data-rate feedback channel:
Sending relevant information from the receiver to the transmitter:

(i) Centre frequencies and bandwidths of spectrum holes

(ii) Combined variance of interference plus thermal noise in each spectrum hole

(iii) Estimate of output signal-to-noise ratio at the output of the transmitter-receiver link, which is needed by the adaptive modulator in the transmitter

7. Statistical Modeling of Cognitive Radio Networks

Assumptions:

The use of orthogonal frequency division multiplexing (OFDM)

Notations:

n = **one of the subcarriers in the OFDM signal**

$s(m, n)$ = **baseband signal radiated by the transmitter of user** m

$y(m, n)$ = **signal picked by the receiver of user** m

$g(m, k, n)$ = **combined effect of propagation path loss, and subcarrier amplitude reduction due to frequency offset in the OFDM**

$w(m, n)$ = **zero-mean Gaussian thermal noise at the receiver input of user** m **in** n**th subcarrier**

SINR = signal to interference-plus-noise (power) ratio

Formula for the SINR at the receiver input of user *m* on the *n*th subcarrier:

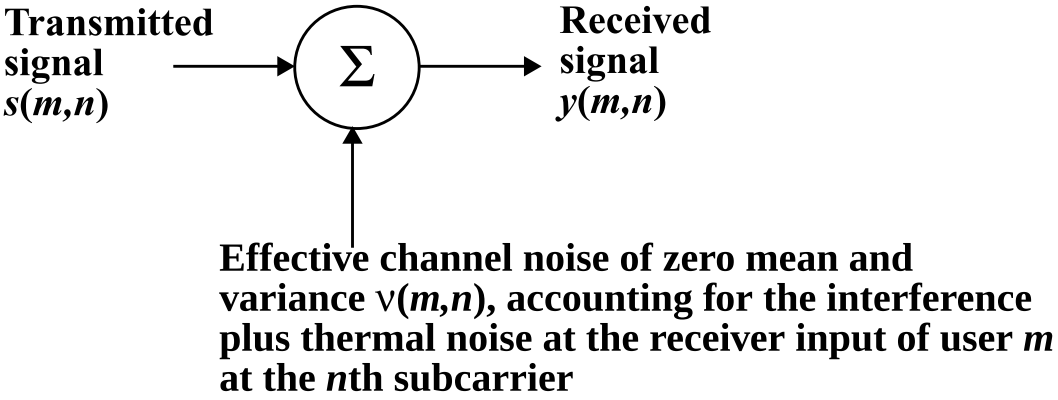
$$\mathrm{SINR}(m, n) = \frac{|g(m, m, n)|^2 P(m, n)}{\sum_{\substack{k=1 \\ k \neq m}}^{M} |g(m, k, n)|^2 |s(k, n)|^2 + \sigma_w^2(m, n)}$$

$$= \frac{P(m, n)}{\sum_{\substack{k=1 \\ k \neq m}}^{M} |\alpha(m, k, n)| P(k, n) + v(m, n)}$$

$$P(k, n) = |s(k, n)|^2$$

$$\alpha(m, k, n) = \frac{|g(m, k, n)|^2}{|g(m, m, n)|^2}$$

$$v(m, n) = \frac{\sigma_w^2(m, n)}{|g(m, m, n)|^2}$$



Transmitted signal $s(m,n)$

Σ

Received signal $y(m,n)$

Effective channel noise of zero mean and variance $\nu(m,n)$, accounting for the interference plus thermal noise at the receiver input of user *m* at the *n*th subcarrier

Figure 2. Depiction of the equivalent additive noise model for user *m* operating on subcarrier *n*.

8. The Transmit-power Control Problem

Given:

(i) a set of spectrum holes known to be adequate to support the data-transmission needs of *M* secondary users, and

(ii) measurements of the variance of interference plus noise at the receiver input at each of the *N* subcarriers of the OFDM for every user,

determine the transmit-power levels of the *M* secondary users so as to jointly maximize their data-transmission rates, subject to the constraint that the interference-temperature limits in the sub-frequency bands defining the spectrum holes are not violated.

9. The Multiuser Non-cooperative Cognitive Radio Networks Viewed as a Game-theoretic Problem

Definition of the Nash Equilibrium:

> **A Nash equilibrium is defined as an action profile (i.e., vector of players' actions) in which each action is a best response to the actions of all the other players.**

Assumptions:

1. **The players engaged in the game are all *rational*.**
2. **The underlying structure of the game is *common knowledge* to all the players.**

10. Iterative Water Filling

(i) ***Initialization j* = 0**

Unless prior knowledge is available, the power distribution across the users, *m* = 1,2,..., *M*, is set equal to zero.

(ii) ***Inner loop***

Maximize $R^{(j)}(m) = \sum_{n=1}^{N} \log_2\left(1 + \frac{P^{(j)}(m,n)}{\mathrm{IN}^{(j)}(m,n)}\right)$

subject to the constraint $\sum_{n=1}^{N} P^{(j)}(m,n) \le \bar{P}(m)$

$$\bar{P}(m) = \frac{\kappa T_{max} B_m}{|g(m,m,n)|^2} - \sum_{n=1}^{N}\left(\sum_{\substack{k=1 \\ k \ne m}}^{M} \alpha(m,k,n)P(k,n) + v(m,n)\right)$$

Maximize $\log_2\left(1 + \frac{P^{(j)}(m,n)}{\mathrm{IN}^{(j)}(m,n)}\right) - \lambda^{(j)}(m)P(m,n)$

(iii) ***Outer loop***

For user *m*, optimal power

$$P^{*(j)}(m,n) = \left(\frac{1}{\lambda^{*(j)}(m)} - \mathrm{IN}^{(j)}(m,n)\right)^{\dagger}$$

is computed, such that the total power constraint

$$\sum_{n=1}^{N} P^{*(j)}(m,n) - \bar{P}(m)$$

is satisfied; the dagger indicates the use of a positive value.

(iv) ***Confirmation step***

The condition

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\left|P^{(j)}(m,n) - P^{(j\text{-}1)}(m,n)\right| < \varepsilon$$

is checked for the prescribed tolerance ε at iteration *j*. If this tolerable condition is satisfied, the computation is terminated at j = *J*. Otherwise, the iterative process (encompassing both the inner and outer loops) is repeated.

Summarizing Remarks on Iterative-water Filling

- The algorithm functions in a self-organized manner, thereby making it possible for the network to assume an ad-hoc structure.

- It avoids the need for communication links (i.e., coordination) among the multiple users, thereby significantly simplifying the design of the network.

- By using convex optimization, the algorithm tends to converge relatively rapidly to a Nash equilibrium; however, once this stable point is reached, no user is permitted to change its transmit-power control policy unilaterally.

- Computational complexity of the algorithm is relatively low, being on the order of two numbers: the number of secondary users and the number of spectrum holes available for utilization.

- Robustness of the algorithm needs to be investigated.

11. Research Challenges

(i) Control Issues in Cognitive Radio in a Multiuser Environment

1. Control of primary resources:
   Channel bandwidth and transmit-power.

2. Possible options:
   - Robust control versus stochastic control
   - Decentralized versus centralized schemes

3. Algorithmic aspects with emphasis on equilibrium points:
   - Distributed implementation
   - Convergence properties
   - Optimality of performance
   - Computational and algorithmic complexity considerations

(ii) Self-organized Management of Spectrum in Cognitive Radio

"Self-organized (Hebbian-inspired) management of spectrum in a multiuser cognitive radio network”

1. Principles of self-organization:

- **Hebbian learning**
- **Competition**
- **Cooperation**
- **Redundancy**

(ii) Self-organized Management of Spectrum in Cognitive Radio (continued)

2. **Current approaches consider global optimization; they are equivalent to a famous group of optimization problems termed "graph colouring" known to be NP-hard. These approaches are practical only for small number of users and are not scalable. Moreover, with any change in the network configuration, the problem must be resolved again for entire network. Accordingly, a significant portion of network resources is wasted just for transmitting and receiving control packets from and to the base station.**

   On the other hand, in a decentralized approach any change in the environment requires simply local action with the result that no bandwidth is wasted. Furthermore, the Hebbian approach requires much less computation; it is scalable to any size, stable, and robust.

(iii) Emergent Behaviour of Cognitive Radio Networks

References

[1] S. Haykin, “Cognitive Radio: Brain-empowered Wireless Communications, IEEE J. Selected Areas in Communications, vol. 23, pp. 201-220, February.

[2] S. Haykin, “Fundamental Issues in Cognitive Radio”. in the book by V. Bhargava and E. Hussain, editors, Cognitive Radio Networks, Springer-Verlag, 2008.

[3] S. Haykin, “Cognitive Dynamic Systems”, Point-of-view article, Proc. IEEE, November 2007.

[4] S. Haykin, Cognitive Dynamic Systems, new book under preparation.

[5] J. Reed and S. Haykin, Future of Cognitive Radio: Evolution or Resolution, under preparation.

[6] S. Haykin, J. Reed, M. Shafi, and Geoffrey Li,
Two-volume Special Issue, the Proc. IEEE on Cognitive Radio, Fall 2008.

[7] S. Haykin, X. Wang, M. Di Benedetto, and Y. Hua, Special Issue on “Signal Processing Issues in Cognitive Radio networks”, IEEE Signal Processing Magazine, Fall 2008.

Lectures on Cognitive Radio

IBM Watson Research Center

University of Waterloo

University of Alberta

Nokia Helsinki Finland

UBC

Microsoft Seattle

Intel Palo Alto

International Workshop on CRNs, Vancouver