

Fundamental Issues in Cognitive Radio

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Outline of Lecture

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

Definition

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

- to perceive the radio environment (i.e., outside world) by empowering each user's receiver to sense the environment on a continuous-time basis
- to learn from the environment and adapt the performance of each transceiver to statistical variations in the incoming RF stimuli
- to facilitate communication between multiple users through cooperation in a self-organized manner
- to control the communication processes among competing users through the proper allocation of available resources
- to create the experience of intentions and self-awareness

1. Signal-processing and Communication-theoretic Vision of Signal Processing

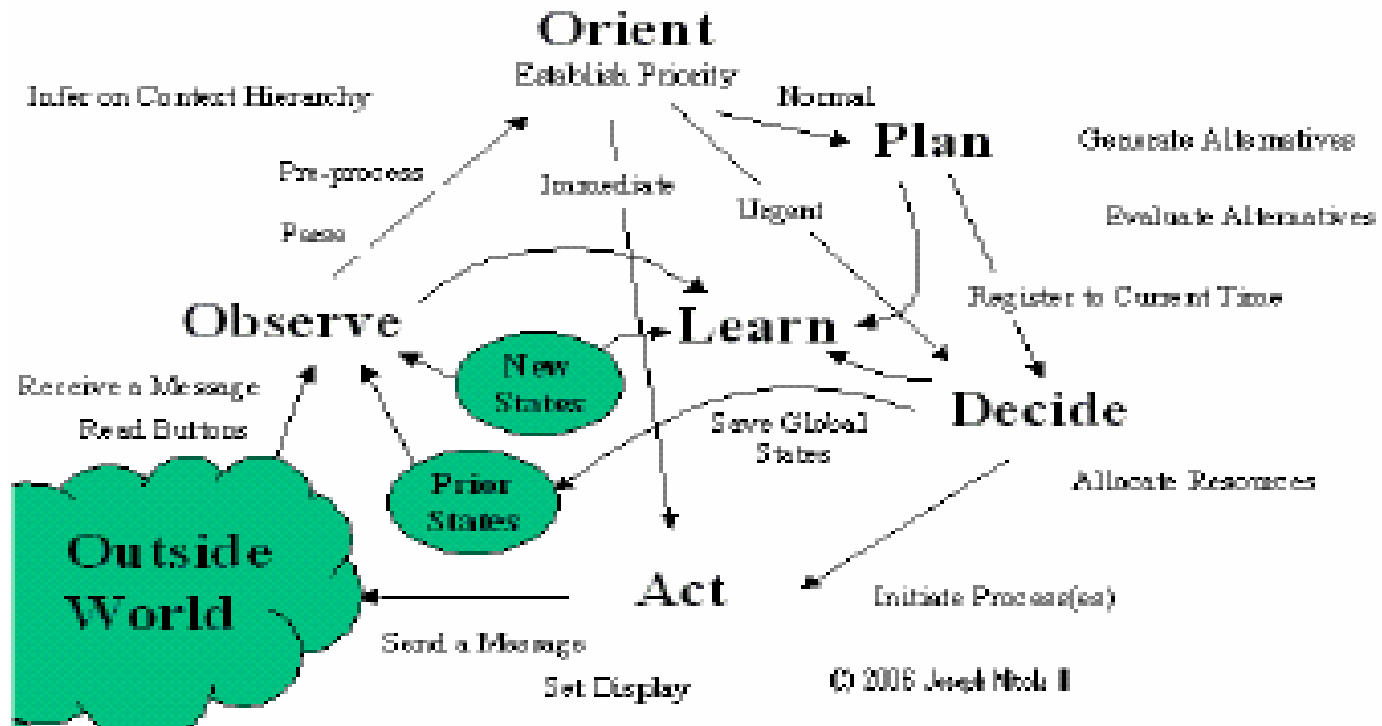


Figure 1. Cognitive computer cycle. (Figure c) 2004 Joseph Mitola III reprinted with permission from "Cognitive Radio Architecture" (c) 2006 Wiley Interscience, Hoboken, NJ, p. 135.

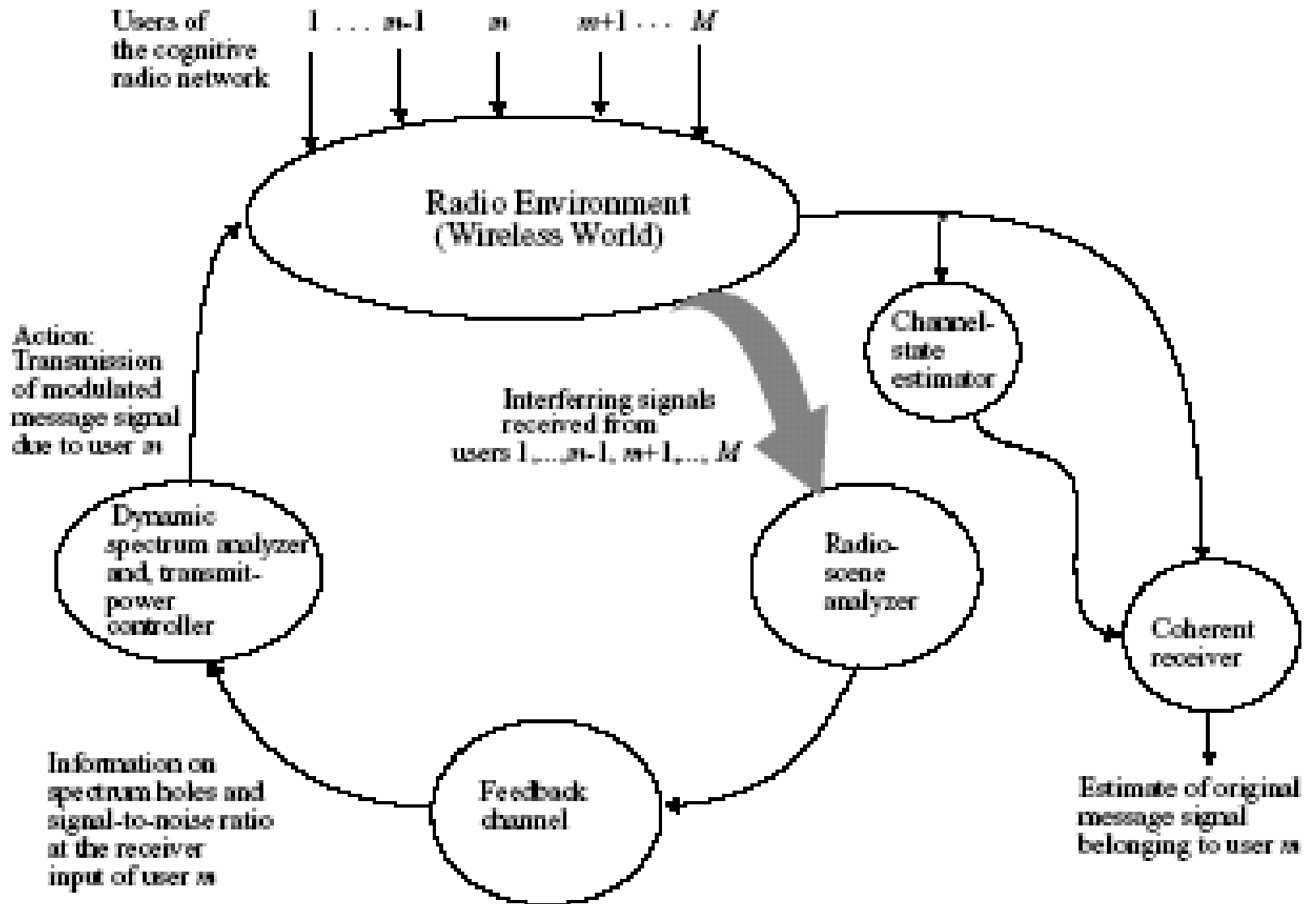


Figure 2. Cognitive signal-processing cycle for user m of cognitive radio network; the diagram also includes elements of the receiver of user m

2. Radio-scene Analysis

- Spectrum holes: How to learn about them?
- The multitaper method (MTM)
- The MTM-SVD procedure for joint spectrum-hole identification and adaptive beamforming

2. Radio-scene Analysis (cont'd)

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

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

Given a time series $\{x_t\}_{t=1}^N$, the multitaper spectral estimation procedure determines two things:

1. An orthonormal sequence of K Slepian tapers denoted by $\left\{ w_t^{(k)} \right\}_{t=1}^N$
2. The associated eigenspectra defined by the Fourier transforms

$$Y_k(f) = \sum_{t=1}^N w_t^{(k)} x(t) e^{-j2\pi ft}, \quad k = 0, 1, \dots, K-1$$

$x(t)$ = input data

$w_t^{(k)}$ = Slepian taper (weight)

Adaptive MTM

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

$$(iii) \quad d_k(f) = \frac{\sqrt{\lambda_k} \hat{S}(f)}{\lambda_k \hat{S}(f) + \mathbf{E}[B_k(f)]} \quad k = 0, 1, \dots, K-1$$

$$\hat{B}_k(f) = (1 - \lambda_k) \sigma^2 \quad k = 0, 1, \dots, K-1$$

Space-time Procession

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

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

3. Feedback Channel

- Centre frequencies and bandwidths of spectrum holes
- Combined variance of interference plus thermal noise in each spectrum hole
- Measure of output signal-to-noise ratio at the output of the transmitter-receiver link, which is needed by the adaptive modulator in the transmitter

4. Multiuser Cognitive Radio Networks

- Cooperation is used to facilitate *communication* across the nodes of the network without any fixed infrastructure
- Competition is used to provide *control* over the power transmitted from each individual node of the network to maintain the interference temperature at a receiving node below a prescribed limit.

5. Dynamic Spectrum Management

Requirements:

1. Secondary users of the spectrum's unoccupied subbands must coexist with the primary users.
2. Interference temperature at the receiver input of each user in the network does not exceed a prescribed limit.

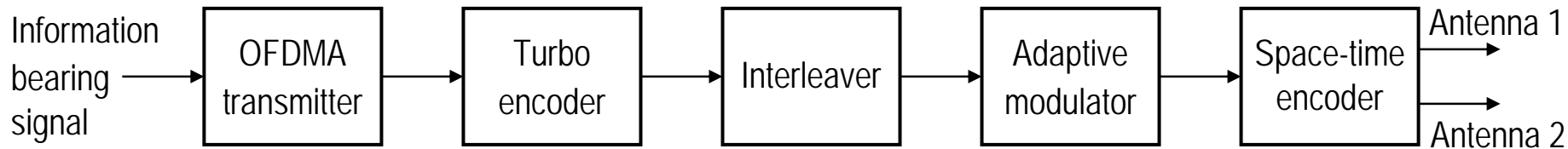


Figure 3. Block diagram of adaptive OFDM transmitter

6. Statistical Modeling of Cognitive Radio Networks

Method of Modulation: OFDM

$$s(m, n) = c_n \exp[j2\pi n(f_0 - \Delta f)t], \quad \Delta f: \text{frequency offset}$$

$$y(m, n) = \sum_{k=1}^M g(m, k, n)s(k, n) + w(m, n)$$

$$y(m, n) = g(m, m, n)s(m, n) + \sum_{\substack{k=1 \\ k \neq m}}^M g(m, k, n)s(k, n) + w(m, n)$$

$$\begin{aligned}
\text{SINR}(m, n) &= \frac{|g(m, m, n)|^2 P(m, n)}{M \sum_{\substack{k=1 \\ k \neq m}} |g(m, k, n)|^2 |s(k, n)|^2 + \sigma_w^2(m, n)} \\
&= \frac{P(m, n)}{M \sum_{\substack{k=1 \\ k \neq m}} \alpha(m, k, n) P(k, n) + v(m, n)}
\end{aligned}$$

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

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

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

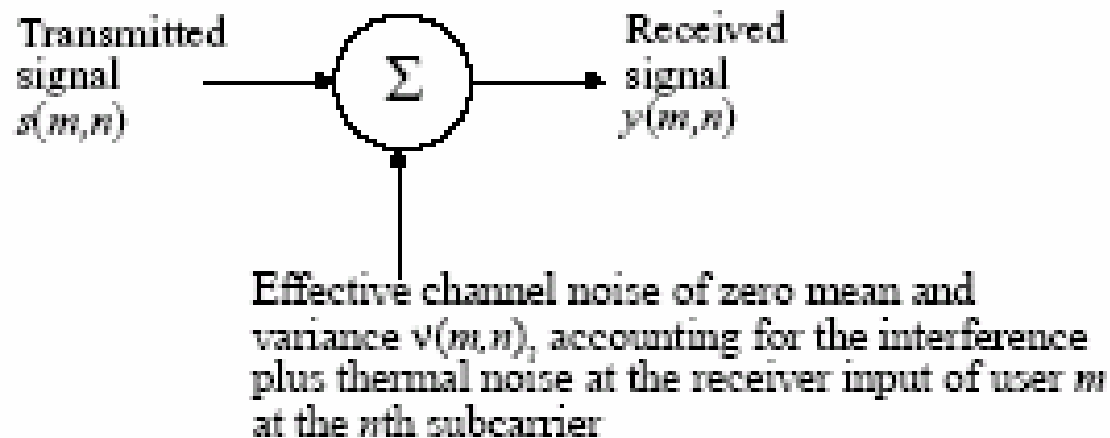


Figure 4. Depiction of the equivalent additive noise model for user m operating on subcarrier n .

7. 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 subfrequency bands defining the spectrum holes are not violated.

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

Definition of 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 a game are all rational.
2. The underlying structure of the game is common knowledge to all the players.

9. Iterative Water Filling

(i) *Initialization* $j = 0$

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

(ii) *Inner loop*

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

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

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

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

(iii) *Outer loop*

For user m , optimal power $P^{*(j)}(m, n) = \left(\frac{1}{\lambda^{*(j)}(m)} - \text{IN}^{(j)}(m, n) \right)^\dagger$

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.

(ii) *Confirmation step*

The condition $\sum_{m=1}^M \sum_{n=1}^N |P^{(j)}(m, n) - P^{(j-1)}(m, n)| < \epsilon$

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.

10. Emergent Behaviour of Cognitive Radio Networks

State of the world:

- (i) *Positive emergent behaviour*, which is characterized by order, and therefore a harmonious and efficient utilization of the radio spectrum by all primary and secondary users of the cognitive radio. (The positive emergent behaviour may be likened to Maynard Smith's evolutionary stable strategy.)
- (ii) *Negative emergent behaviour*, which is characterized by disorder, and therefore a culmination of traffic jams, chaos, and unused radio spectrum.

Criterion for stability:

Given a multiuser non-cooperative cognitive radio network based on OFDM and designed on iterative waterfilling, look to the Nash equilibrium as the basis for designing a maximum likelihood processor capable of detecting the emergence of disorderly behaviour in the network.

References

- [1] J. Mitola, Cognitive Radio Architecture: The Engineering Foundations of Radio XML, Wiley, 2006.
- [2] S. Haykin, “Cognitive Radio: Brain-empowered Wireless Communications, IEEE J. Selected Areas in Communications, vol. 23, pp. 201-220, February.
- [3] V. Bhargava and E. Hussain, ed., Cognitive Radio Networks, Springer-Verlag, 2007.

[Point of View: Cognitive Dynamic Systems](#)