

# **Cognitive Radio: Research Challenges**

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# Outline of The Lecture

- 1. Introductory Remarks**
- 2. The Essence of Human Cognition in the Simplest Terms Possible**
- 3. The Motivation behind Cognitive Radio**
- 4. Cognitive Radio Networks**
- 5. Major Functional Blocks Constituting a Cognitive Radio**
- 6. Spectrum Sensing**
- 7. Transmit-Power Control**
- 8. Dynamic-Spectrum Management**
- 9. Emergent Behaviour of Cognitive Radio Networks**
- 10. Concluding Remarks**

**References**

**Acknowledgements**

**Growth of Cognitive Radio  
during the last  
3 to 4 years  
(Starting with about 6 to 8  
Reports and Conference Papers)**

**IEEE Papers: 1154**

**Springer Papers: 189**

**Elsevier Papers: 33**

**Cognitive Radio Paper (Haykin):cited 631 times**

## Personal Perspective

- **Under the umbrella of Cognitive Dynamic Systems, what I have been working on for much of my professional career, namely,**

**Signal Processing**

**Communication Theory**

**Control Theory**

**Radar Systems**

**Neural Networks and Learning Machines**

**which have all come into focus for the first time.**

# **Cognitive Radio:**

# **“Thinking Outside the Box”**

# 1. Introductory Remarks

- **Cognitive Radio is growing in leaps and bounds, both in depth and breadth, all over the world.**
- **The question is: Why this surge of interest in a topic so relatively new?**
- **The answer is twofold:**
  - (i) Cognitive Radio solves a pressing need:  
Underutilization of a precious natural resource:  
The Radio Spectrum.**
  - (ii) Research Challenge:  
Cognitive radio is challenging in ways few, if any,  
other wireless technologies are today.**

## **Introductory Remarks (continued)**

- **It is not just cognitive radio that is attracting the attention of researchers all over the world. Rather, it is:**

**Cognitive Radar**

**Cognitive Car**

**⋮**

**Cognitive Information Processing**

**Cognitive Control**

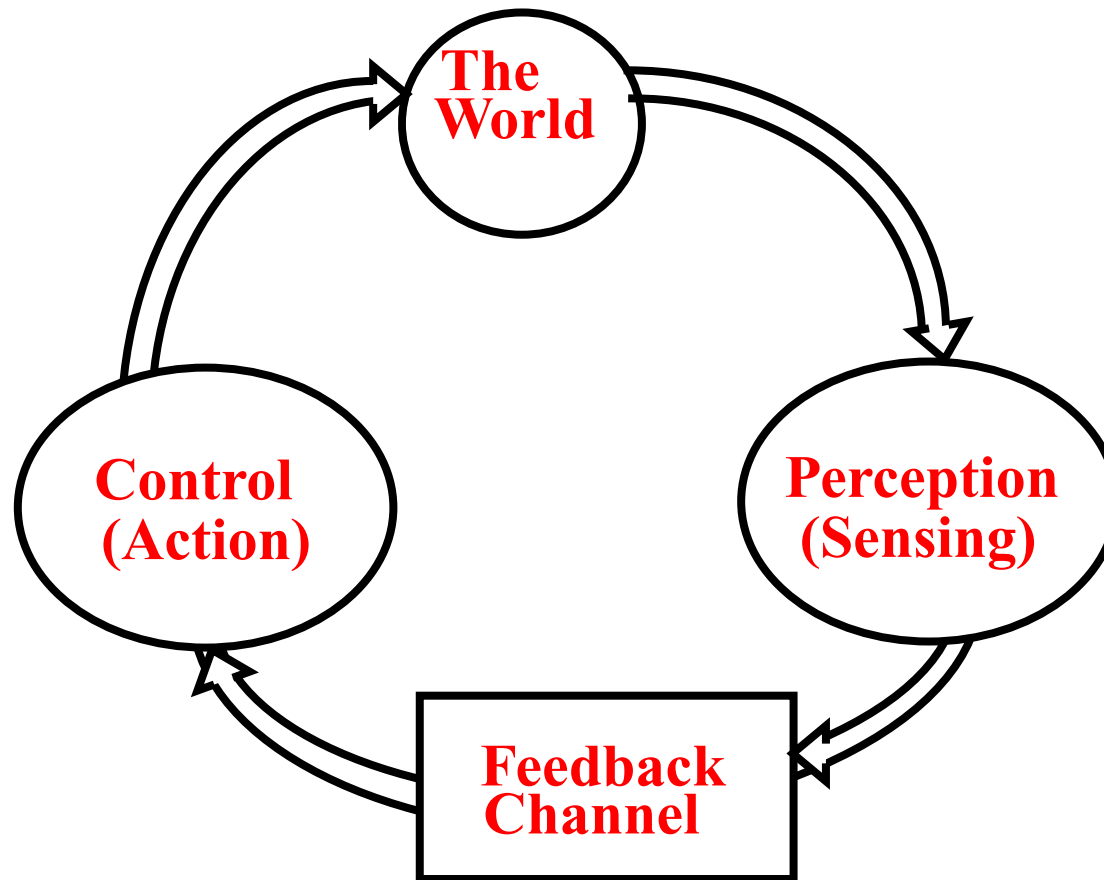
**Cognitive Computation (including software)**

**Cognitive Optimization**

- **What I am leading up to is the new discipline:**

**“Cognitive Dynamic Systems”**

## 2. The Essence of Human Cognition in the Simplest Terms Possible



**Figure 1. Human Cognitive Cycle in its most basic form**



# Tasks of a Human Mind

An extract taken from the book:

**“The Computer and the Mind”**

by

**Johnson-Laird**

- **to perceive the world;**
- **to learn, to remember, and to control actions;**
- **to think and create new ideas;**
- **to control communication with others;**
- **to create the experience of feelings, intentions, and self-awareness.**

**Johnson-Laird, a prominent psychologist and linguist, went on to argue that**

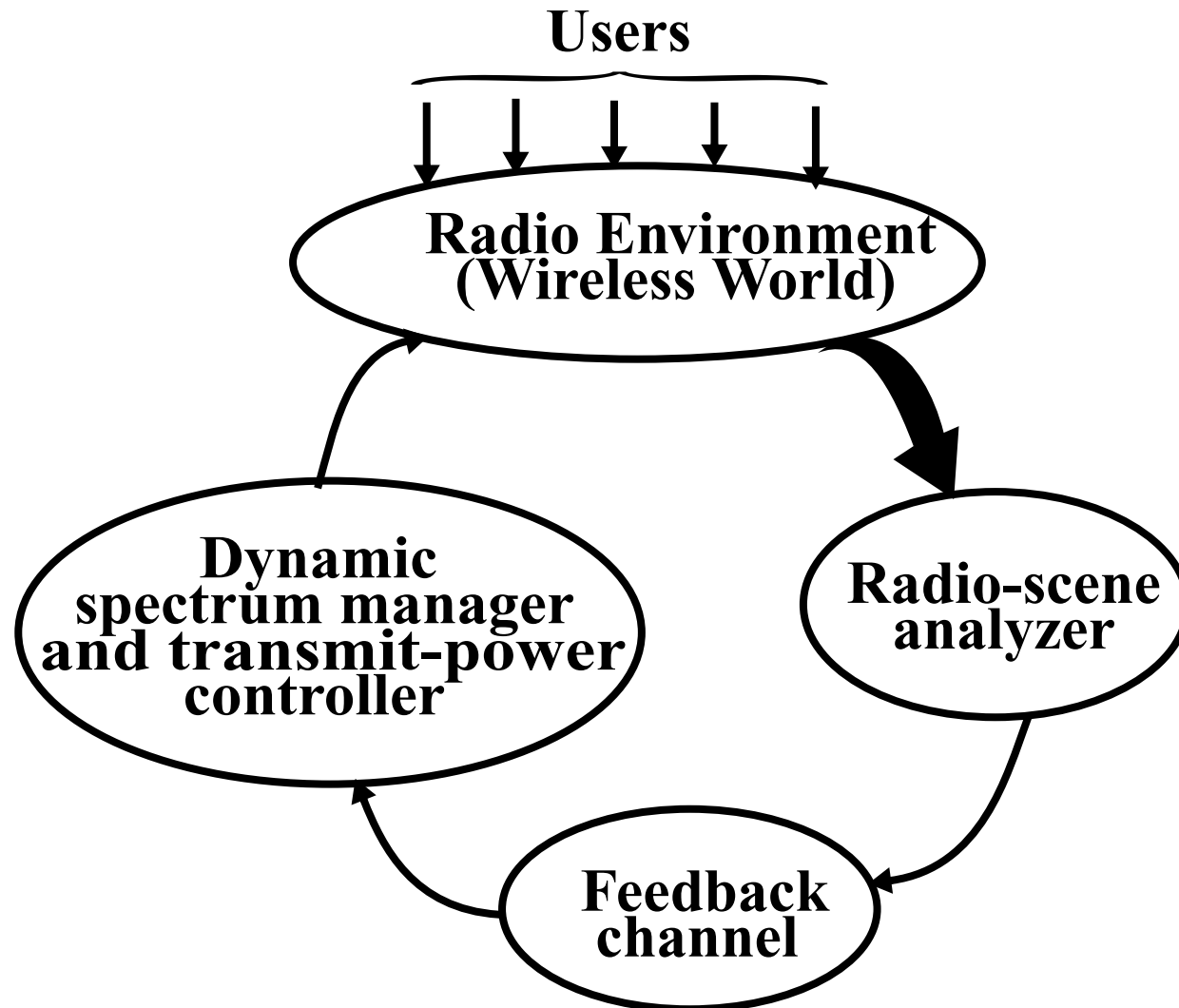
**THEORIES OF THE MIND SHOULD BE MODELLED IN COMPUTATIONAL TERMS.**

# 3. Motivation Behind Cognitive Radio

- **Significant underutilization of the radio spectrum**
- **Basically Cognitive Radio solves the spectrum underutilization problem in a tightly inter-coupled pair of ways:**
  - (i) Sense the radio environment to detect spectrum holes in terms of both time and location.**
  - (ii) Control employment of the spectrum holes by secondary users efficiently, subject to the constraint:**

**The total power in each spectrum hole does not exceed a prescribed limit.**

# 4. Cognitive Radio Networks



**Figure 2. Basic signal-processing cycle, as seen by a single user (transceiver).**

# Cognitive Radio Defined

The cognitive radio network is a **complex** multiuser wireless communication system capable of **emergent behaviour**.

It embodies the following functions:

- 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 (transmitter-receiver) 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 *intention and self-awareness*.

# Primary objectives of Cognitive Radio Networks

1. To facilitate *efficient utilization of the radio spectrum* in a fair-minded way.
2. To provide *highly reliable communication* for all users of the network.

# 5. Major Functional Blocks of Cognitive Radio

Function	Action
1. Spectrum sensing	<b>Detect</b> spectrum holes, estimate their power contents.
2. Predictive modeling	<b>Predict</b> availability of spectrum hole is employment by secondary user.
3. Transmit- power control	<b>Maximize</b> data rate of each user subject to power constraints
4. Dynamic spectrum management	<b>Control</b> distribution of spectrum holes fairly among secondary users
5. Packet routing	<b>Route</b> the packets across the network efficiently

# 6. Spectrum Sensing

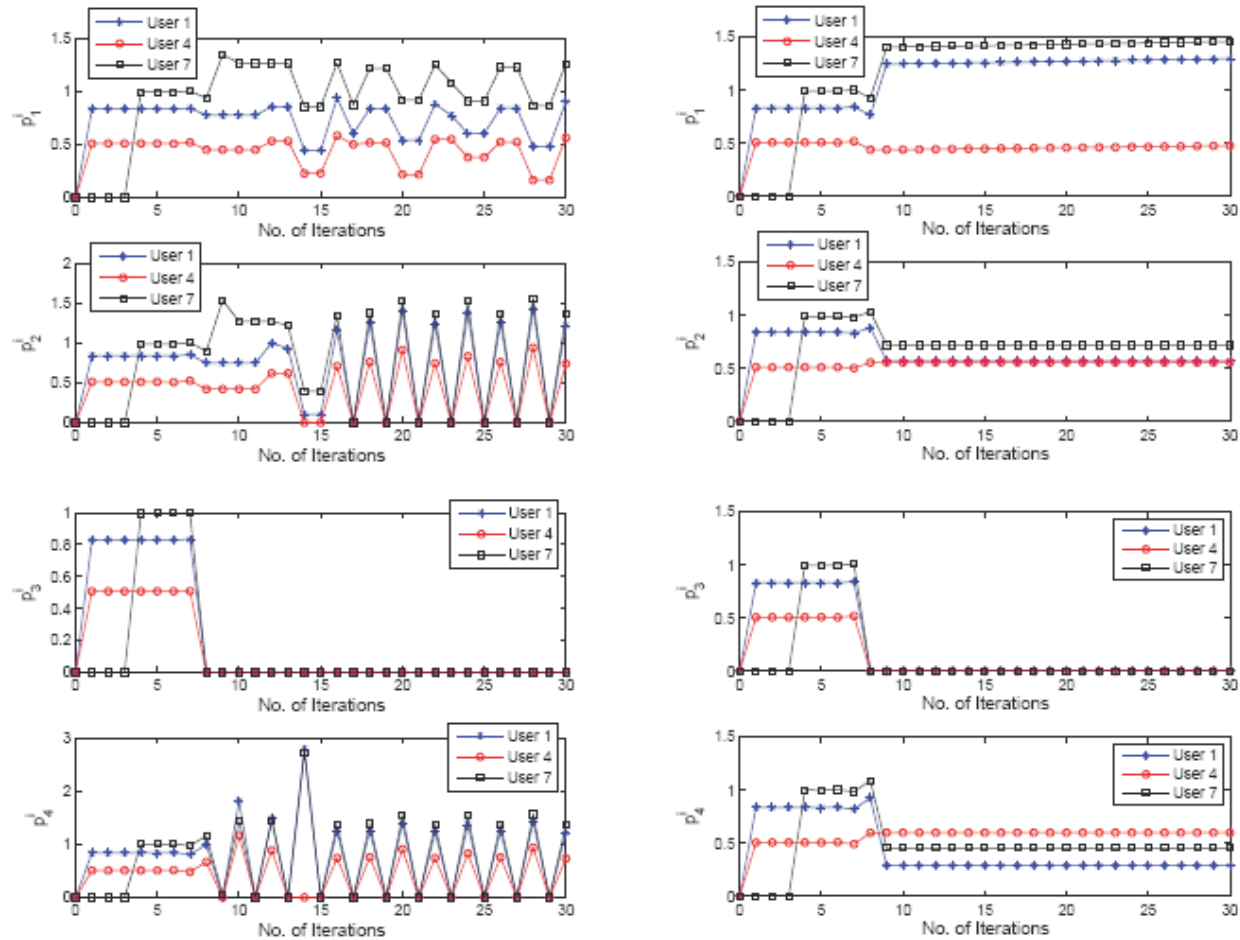
## Potential Candidates

- (i) Energy detection:  
Parametric (Model-dependent)**
  
- (ii) Cyclostationarity method:  
(Nonparametric)**
  
- (iii) Multitaper method:**
  - **Nonparametric**
  - **Close to optimality in the maximum likelihood sense**
  - **Expandable to include**
    - (a) Spatio-temporal processing**
    - (b) Temporal-frequency processing by incorporating the Loève transform**

# 7. Transmit-power Control

- **A cognitive radio network is a hybrid dynamic system**
  - **Continuous dynamics**
  - **Discrete events**
- **Theoretical analysis of the resource allocation problem with consideration of both equilibrium and transient behaviours.**
- **Formulating the transmit power control problem within iterative waterfilling algorithm (IWFA) framework based on the concept of interference temperature.**
  - **Robust non-cooperative game**
  - **Max-min optimization**
  - **Worst-case analysis regarding a specified uncertainty-set**
- **Modelling the network as a constrained piecewise affine (PWA) system using a variational inequality (VI) reformulation of IWFA and theory of projected dynamic systems (PDS).**
- **Providing tools from control theory to facilitate the analysis of sensitivity and stability of the whole network considering uncertainty and multiple time-varying delays.**





**Figure 3. Resource allocation results of simultaneous IWFA and robust IWFA, when 2 new users join a network of 5 users, a subcarrier disappears, and interference gains are changed randomly to address the mobility of the users.**

# 8. Dynamic-Spectrum Management: Time- and Location-dependent Optimization Problem

## 8.1 Centralized Approach

- (i) Centre for collecting radio-scene information on all users
- (ii) *Globally optimal* solution for the problem
- (iii) *Impractical* for two main reasons:
  - High complexity
  - Non-scalability

# Dynamic Spectrum Management (continued)

## 8.2 Decentralized Approach:

- **Utilization of neurobiological principles of self-organization, with emphasis on learning.**
- **Emphasis on cognitive radio information on a local-neighbourhood basis.**
- **Complexity is proportional to the user-density, and therefore scalable to any size.**
- **Provision of a stable solution with less complexity.**
- **Suboptimal but satisfactory solution.**

# 9. Emergent Behaviour of Cognitive Radio Networks

- **Seemingly irreducible phenomena.**
- **Phenomena not explicitly programmed.**
- ***Positive emergent behaviour:* a harmonious and efficient utilization of the radio spectrum by all primary and secondary users of the cognitive radio (i.e. co-operation without or with minimal coordination).**
- ***Negative emergent behaviour:* characterized by disorder (i.e. traffic jams, chaos, and unused radio spectrum).**
- **Emergency networks: swarm intelligence.**

# 10. Concluding Remarks

- **The Study of Cognitive Dynamic Systems (encompassing cognitive radio, Cognitive radio, etc.) will be one of the most influential scientific endeavours in the 21st century:**

**Computer Thinking will be the Driving Force**

- **Cognitive Radio is already being considered as the candidate for the 5th Generation of Wireless Communications.**

## **Two New Books to watch out for:**

### **1. Neural Networks and Learning Machines**

**Simon Haykin**

**Prentice-Hall, 3rd edition**

**November 2008**

### **2. Foundations of Cognitive Dynamic Systems**

**Simon Haykin**

**Cambridge University Press**

**(In preparation)**

# References

## A. Papers

**S. Haykin, “Cognitive Radio: Brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications, Special Issue on Cognitive Networks, vol. 23, pp. 201-220, February. invited**

**S. Haykin, “Fundamental Issues in Cognitive Radio”, In Cognitive Wireless Communications Networks, edited by Vijay Bhargava and Ekram Hossain, 2007, Springer.**

**P. Setoodeh and S. Haykin, “Robust Control for Cognitive Radio, Proc. IEEE, Feb. 2009. Accepted for publication subject to revision.**

**S. Haykin, J. Reed, and D.J. Thomson, “Spectrum Sensing for Cognitive Radio”, ibid, under preparation.**

## **B. Patents**

**S. Haykin, “Operating Environment Analysis Techniques for Wireless Communication Systems - Transmit Power Control”, US Provisional 60/617,639.**

**S. Haykin, “Operating Environment Analysis Techniques for Wireless Communication Systems - Radio Scene Analysis”, US Provisional 60/617,638.**

## **C. Special Issue**

**S. Haykin, J. Reed, G. Li, and M. Shafi. “Cognitive Radio”, Two-volume Special Issue, Proc. IEEE, Feb. 2009.**



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