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

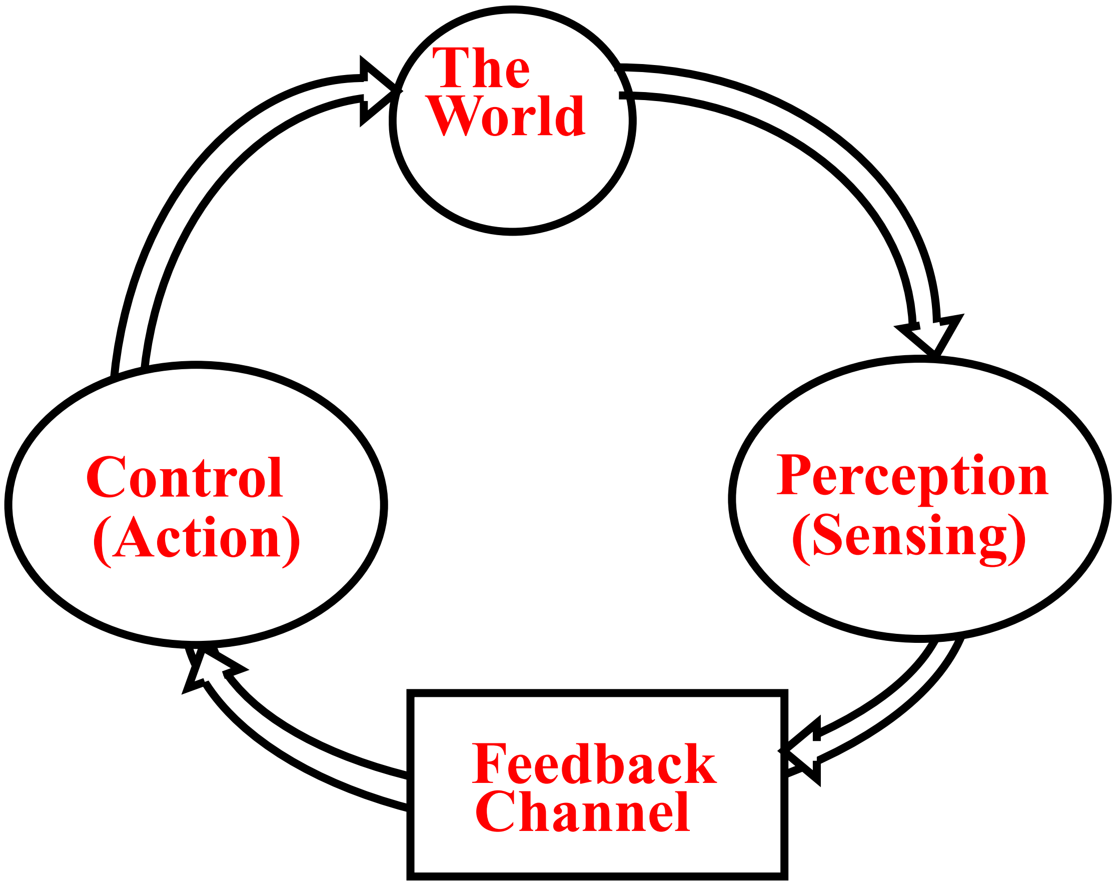

Figure 1. Human Cognitive Cycle in its most basic form

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

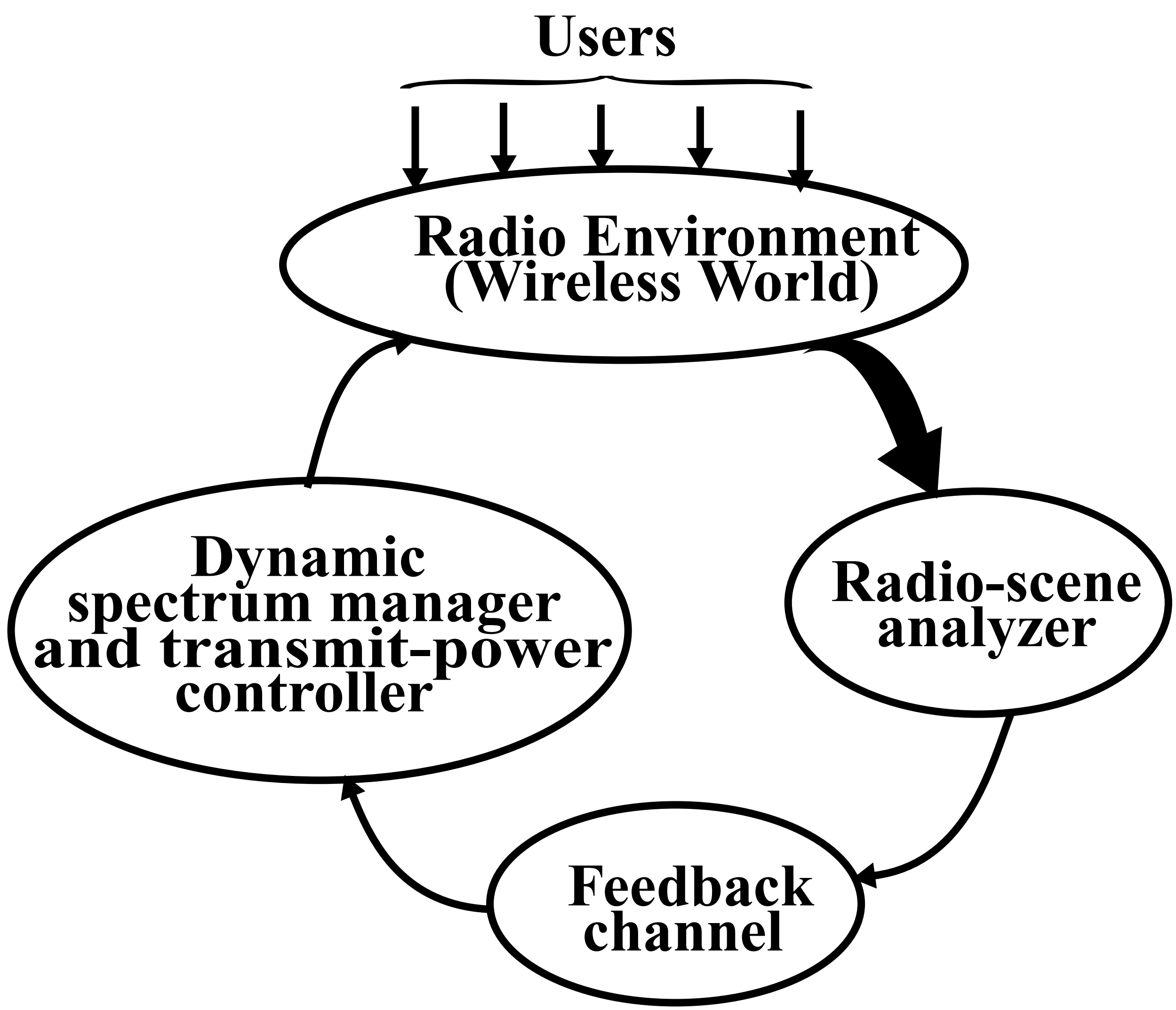

Figure 2. Basic signal-processing cycle, as seen by a single user (transceiver).

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	Detect spectrum holes, estimate their power contents.
2. Predictive modeling	Predict availability of spectrum hole is employment by secondary user.
3. Transmit- power control	Maximize data rate of each user subject to power constraints
4. Dynamic spectrum management	Control distribution of spectrum holes fairly among secondary users
5. Packet routing	Route 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
  - o Continuous dynamics
  - o 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 ofinterference temperature.
  - o Robust non-cooperative game
  - o Max-min optimization
  - o 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 andmultiple time-varying delays.

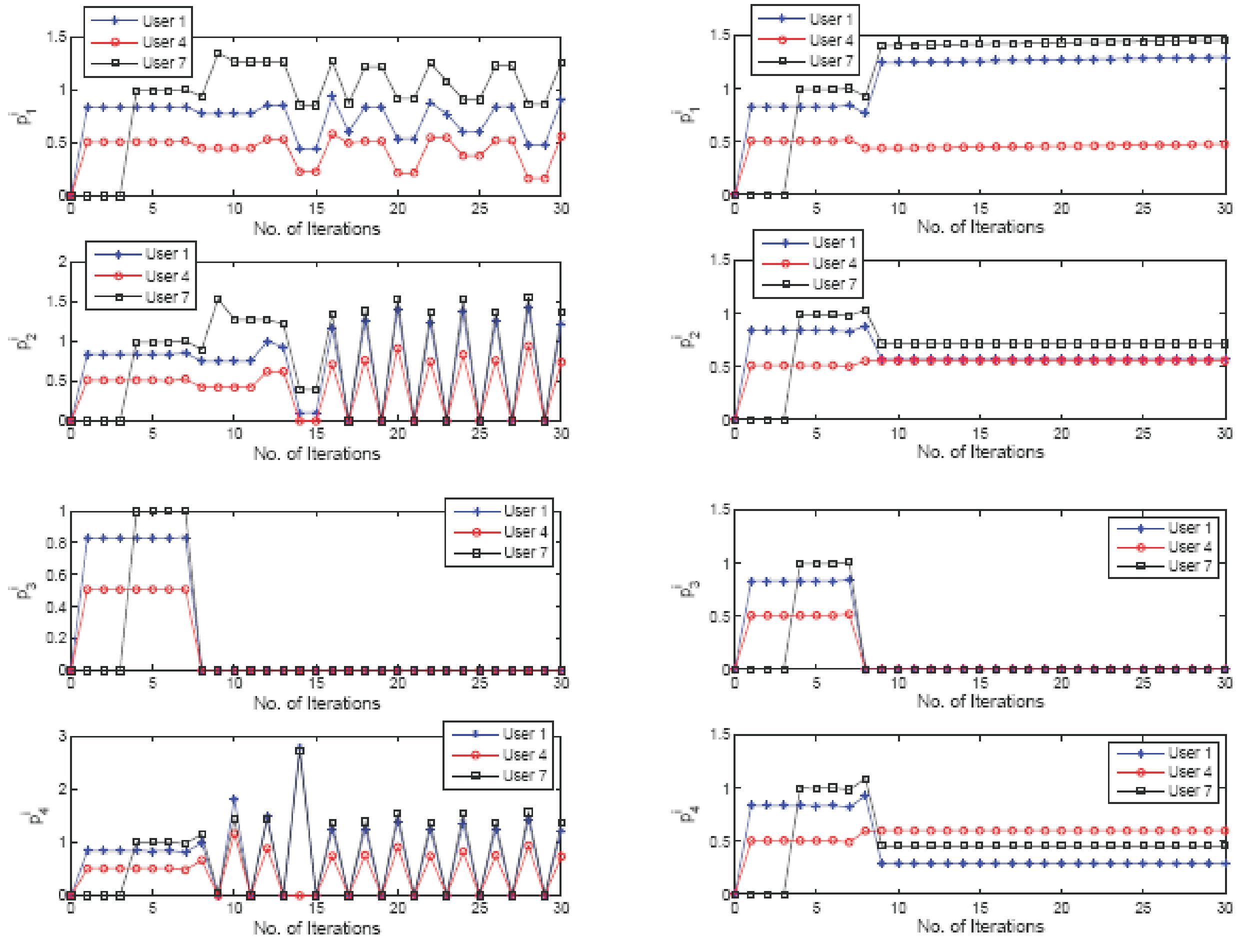

Figure 3. Resource allocation results of simultaneous IWFA and robust IWFA, when 2 new users join a network of 5 users, a subcarrier disappears, and interference gains are changed randomly to address the mobility of the users.

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)

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

B. Patents

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C. Special Issue

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