# Cognitive Dynamic Systems

**Simon Haykin**
**Cognitive Systems Laboratory**
**McMaster, University**
**Hamilton, Ontario, Canada**

**email: haykin@mcmaster.ca**
**Web site: http://soma.mcmaster.ca**

# Outline of The Lecture

1. Cognition
2. New Generation of Engineering Systems Enabled with Cognition
3. Exponential Growth of Cognitive Radio
4. Cognitive Radio Signal-processing Cycle
5. Spectrum Sensing
6. Transmit-power Control
7. Emergent Behaviour of Cognitive Radio Networks
8. Final Remarks

# 1. Cognition

## The Human Brain

- **The human brain is the most *powerful cognitive dynamic system* in existence.**

- **For an *"artificial"* dynamic system to assume the cognitive capabilities of the human brain, at the minimum it must have the capacity to perform the following tasks:**

  **(i) learning and memory;**
  **(ii) planning;**
  **(iii) attention; and**
  **(iv) interaction with the world (environment)**

# The Perception-Action Cycle

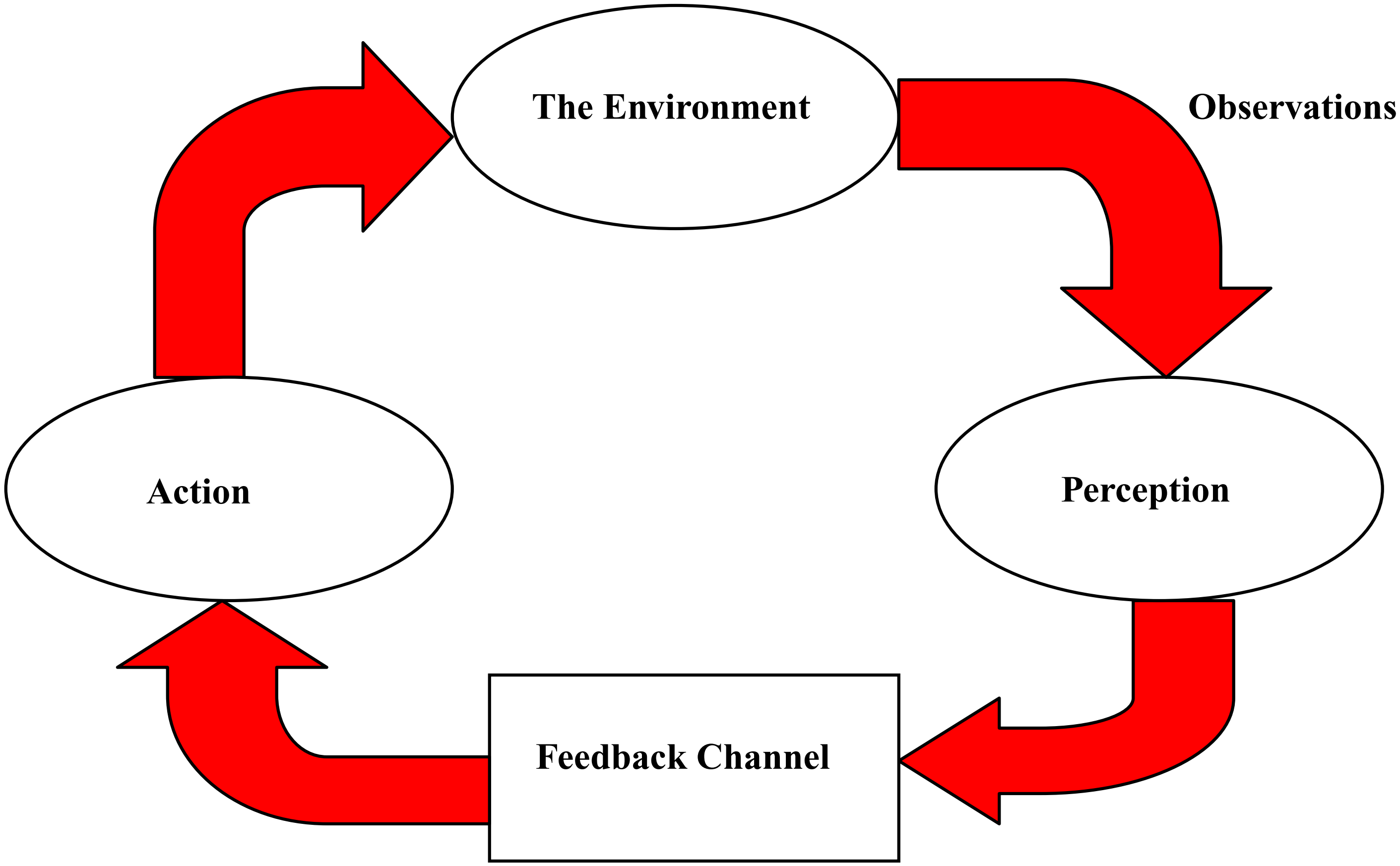


**Figure 1:**

## Explanatory Notes on the Perception-Action Cycle:

1. **Perception of the Enviornment involves:**

    - **learning and memory;**
    - **attention**

2. **Action performed on the environment involves:**

    - **planning; and**
    - **control**

# Distributed Feedback:
# Fundamental Principle of Biology

**This principle is embodied in the cybernetic cycle of interactions of the brain with its environment:**

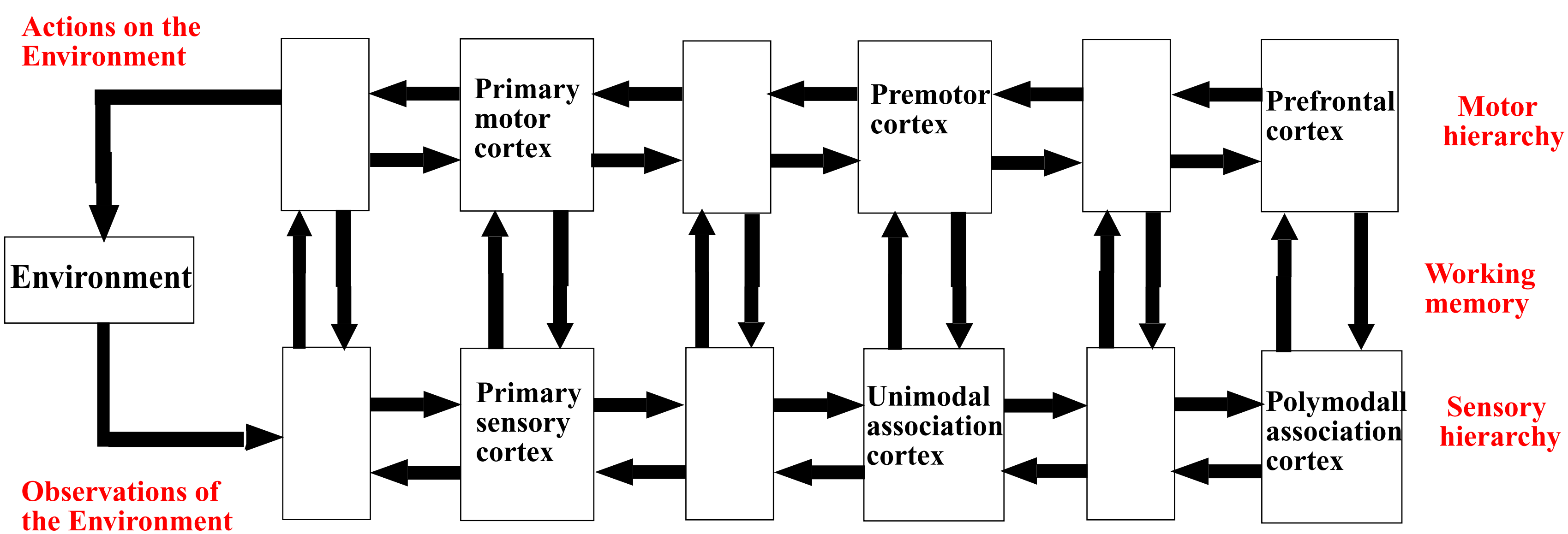


**Figure 2: Cybernetic cycle of the brain**
**(This figure is adapted from J.M. Fuster, 2003).**

## Message taken from the brain's cybernetic cycle

(i) **Engineering paradigm:**
**"Divide and Conquer"**
**whereby a highly complex problem is broken down into a number of simpler ones.**

(ii) **Extraction of features of features of the outside world (Selfridge, 1958).**

(iii) **Hierarchical structure.**

(iv) **Global as well as local feedback.**

**Concluding Remark:**
**Global Feedback is the Facilitator of Cognition**

# 2. New Generation of Engineering Systems Enabled with Cognition

**In the context of engineering systems,**

- **adaptivity was a hallmark of the 20th century**
- **in the 21st century, local feedback will naturally retain its engineering importance, however:**

**It will be cognition that will play center stage in the design of the next generation of engineering systems that will have societal impacts on many fronts.**

## Examples of Cognitive Dynamic Systems

**(i) In my Cognitive Systems Laboratory at McMaster University:**

**Cognitive Mobile Assistants:**

- **Memory-impaired patients**
- **Social networking**

**Systems:**

- **Cognitive radio**
- **Cognitive radar**
- **Cognitive energy systems**

**(ii) Other Examples:**

- **Cognitive Computing**
- **Cognitive Car**

# 3. Exponential Growth of Cognitive Radio

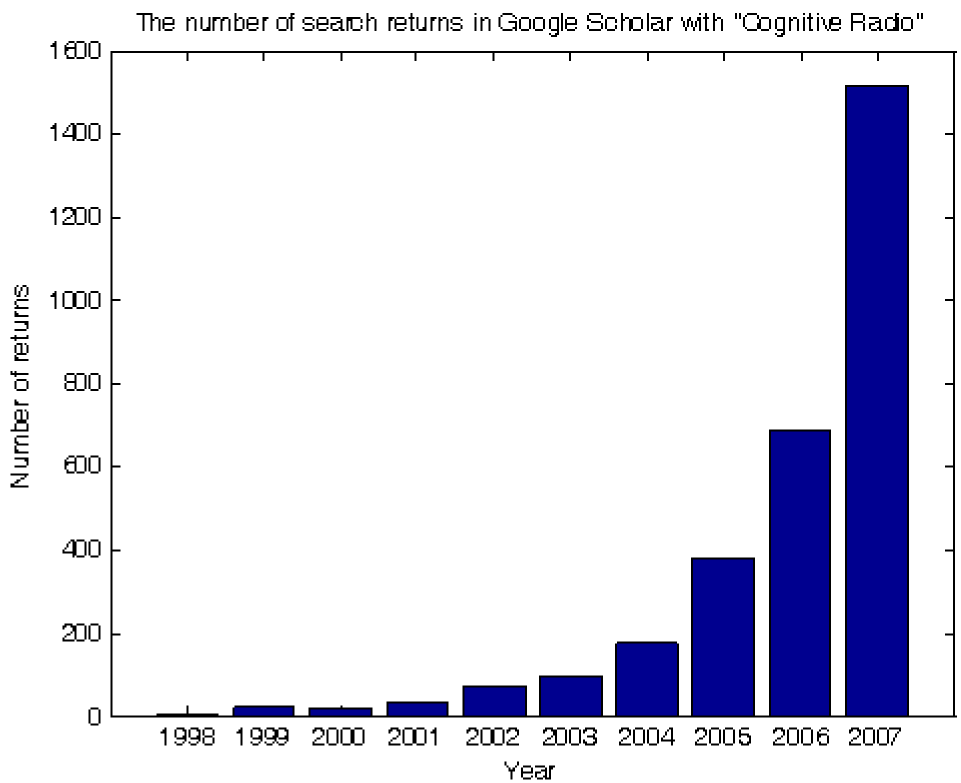


**Figure 3:**
**(Scanning the Issue, Proc. IEEE, April 2009).**

## Cognitive Radio is fast becoming a reality:

## Digital Television Band

**In November 2008, the Federal Communications commission (FCC) in the United States ruled that access to the ATSC-digital television (DTV) band be permitted for wireless devices.**

**For the first time ever, the way has been opened for the creation of white spaces[1] for use by low-power cognitive radios.**

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1. In reality, the spectrum holes are *not* white spaces due to the unavoidable presence of interferers and/or the generation of man-made noise (e.g., ignition-engine noise).

# 4. Cognitive Radio Signal-processing Cycle

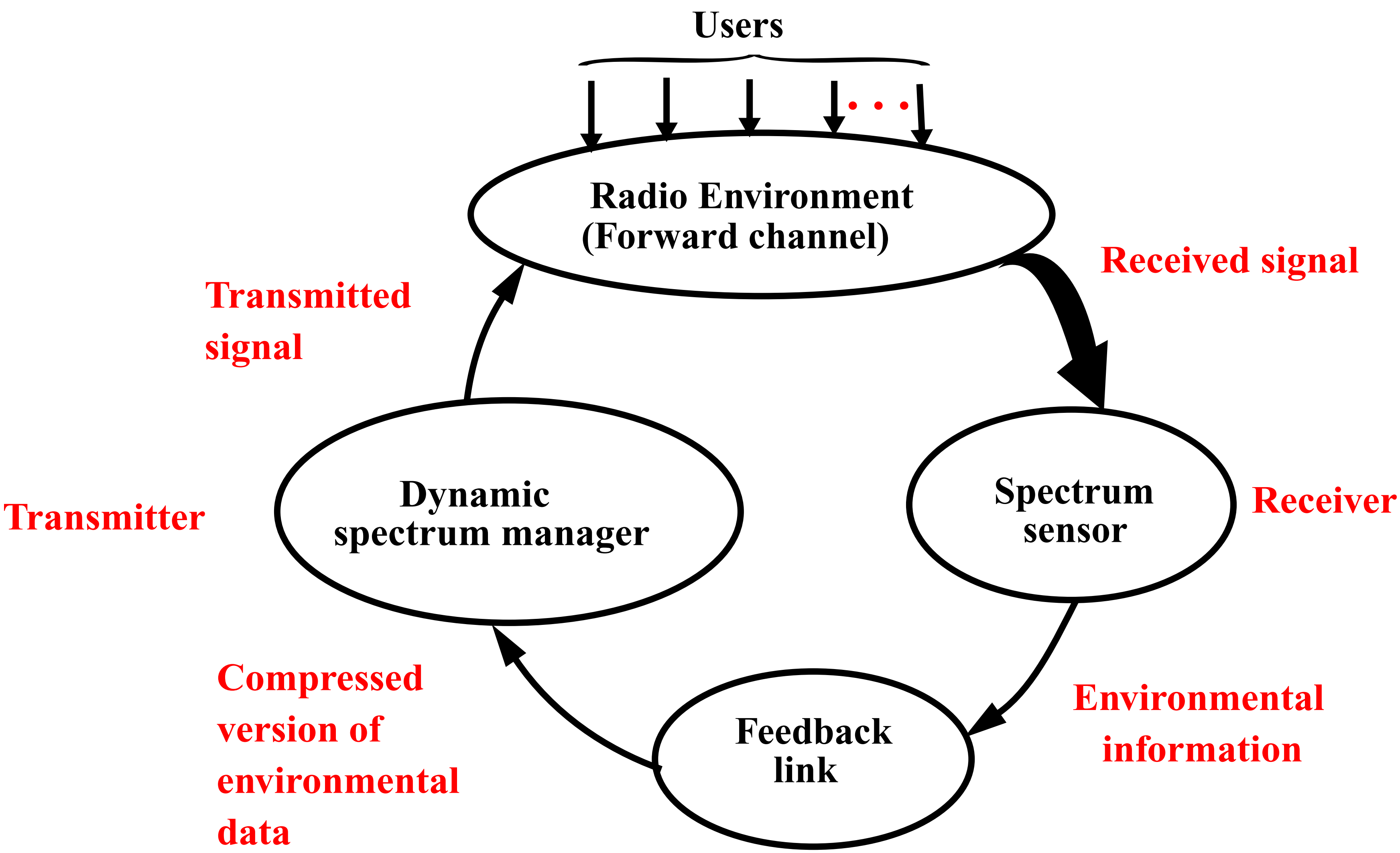



**Figure 4:**

# 5. Spectrum Sensing:

**Parametric methods: Binary hypothesis-testing based on**

- **Pilot detection;**
- **energy detection; and**
- **cyclostationarity**

**Nonparametric (model-independent) Spectrum Estimator:**

- **Multitaper method**

# Spectrum Sensing: Problem Statement

**Objective:**

**Design a spectrum sensor that is computationally efficient, embodying the three essential dimensions of sensing**

- **time;**
- **frequency; and**
- **space**

**in a coherently integrated fashion**

# Desirable Attributes of Spectrum Sensing

- nonparametric formulation;
  accurate identification of spectrum holes, hence spectral resolution;
- accurate estimation of the angles of arrival of interferers;
  hence improved utilization of the radio spectrum;
- near-optimal performance in the maximum-likelihood sense;
- signal classification by exploiting the cyclostationarity property of communication signals;
- regularization, hence inmproved stability; and
- quick computation in a cost-effective manner.

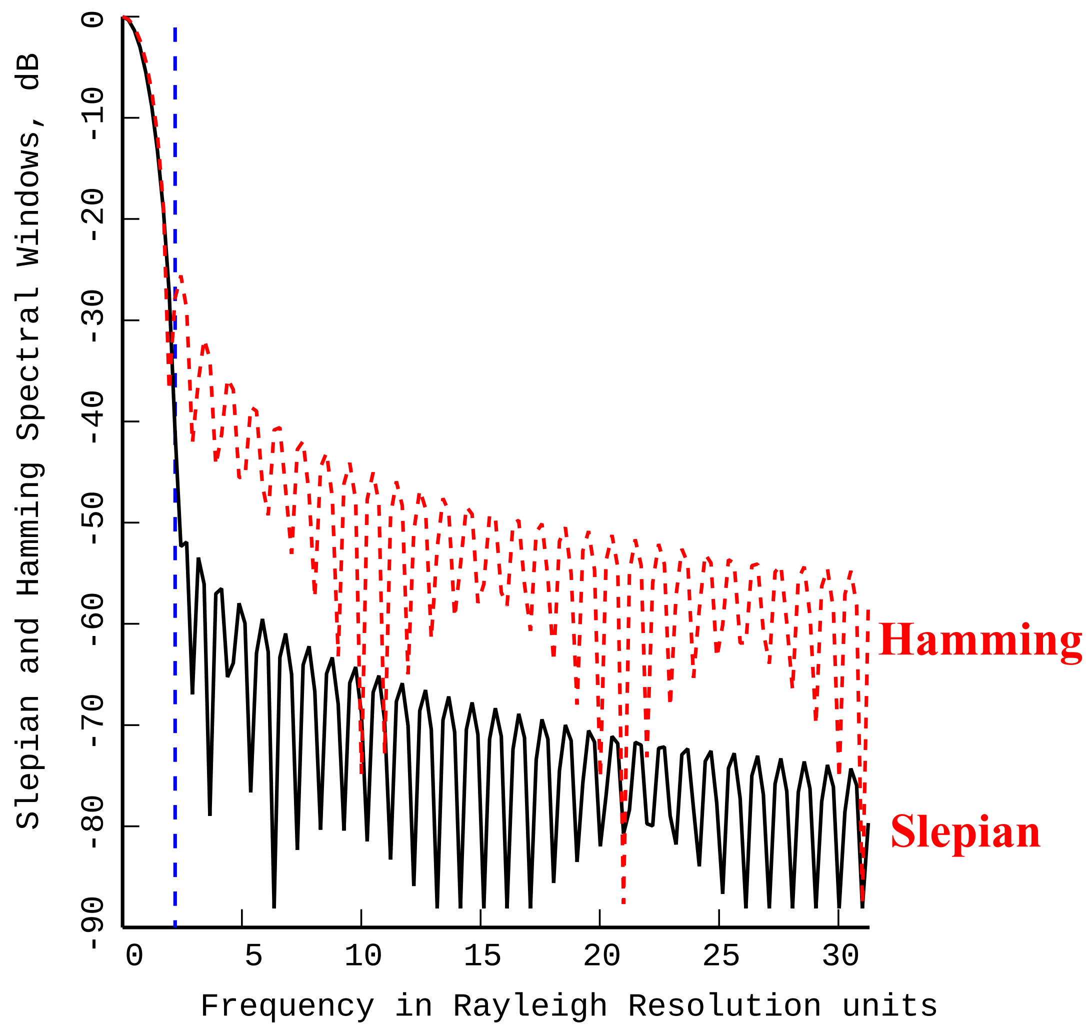
The multi-taper method satisfies these rather stringent requirements, (Thomson, 1982).

**Important Property of Slepian Sequences on which the multi-taper method (MTM) is based:**

**The Fourier transform of a Slepian sequence (window) has the maximal energy concentration inside a prescribed bandwidth under a finite sample-size constraint.**

**Simply put, there is no other window in the digital signal processing (DSP) literature that satisfies this property.**

# Figure 5: Comparison of the Slepian Window with the Hamming Window



## Attributes of Multi-taper Spectral Estimation

(i) The multi-taper spectral estimator is applicable in an "automatic" fashion.

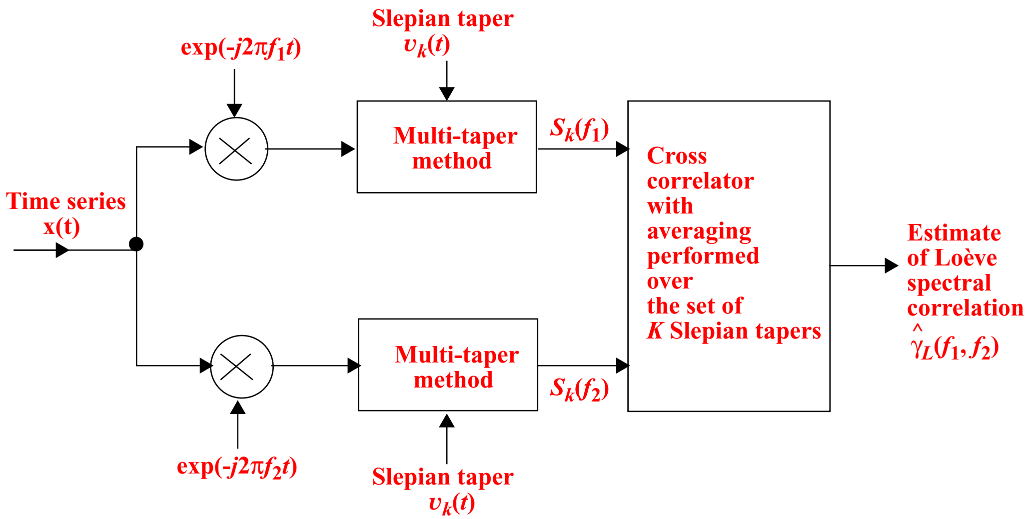
(ii) The *bias* is decomposed into two quantifiable components:

- *local bias*, due to frequency components residing inside the band $f - W$ to $f + W$;
- *broadband bias*, due to frequency components outside this band.

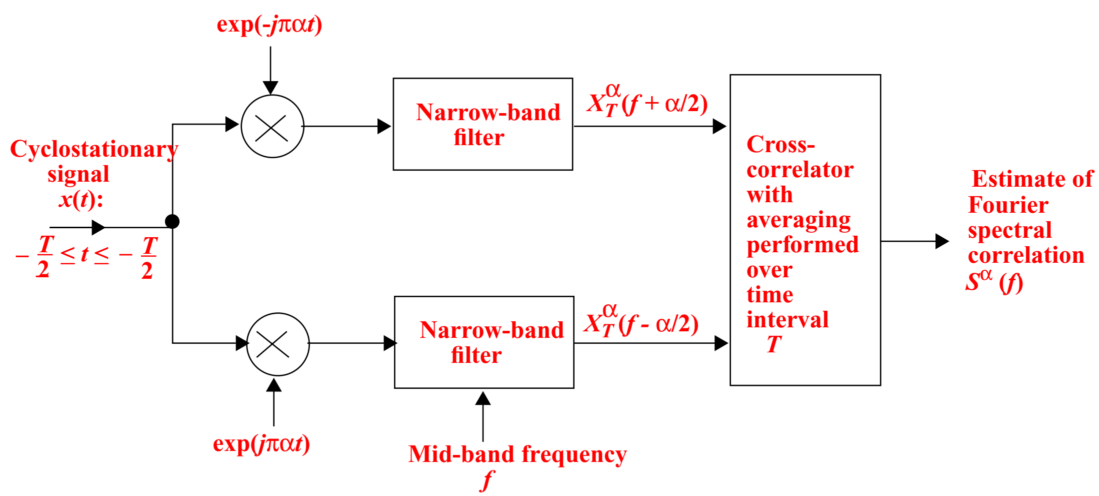
(iii) Multi-taper spectral estimator offers an easy-to-quantify *tradeoff between bias and variance*.

(iv) The degrees of freedom vary from six to ten, depending on the time-bandwidth product $NW$, where $N$ is the number of data points and $2W$ is the bandwidth

(v) Multi-taper spectral estimation may be viewed as a form of *regularization*.




**(a) Loève theory assuming nonstationarity**




**(b) Fourier theory assuming cyclostationarity**

# Figure 6: Illustrating the one-to-one correspondences between the Loéve and Fourier theories for cyclostationarity

# Contrasting Two Theories on Cyclostationarity

**The traditional treatment of cyclostationarity follows Gardner's framework, rooted in the traditional Fourier-transform theory of stationary processes with an important modification: introduction of parameter $\alpha$ (having the same dimension as frequency) in the statistical characterization of cyclostationary processes.**

**The more rigorous treatment of cyclostationarity follows Thomson's framework which combines the following two approaches:**

- **the Loève transform for dealing with nonstationary processes; and**
- **the multitaper method for resolving the bias-variance dilemma through the use of Slepian sequences.**

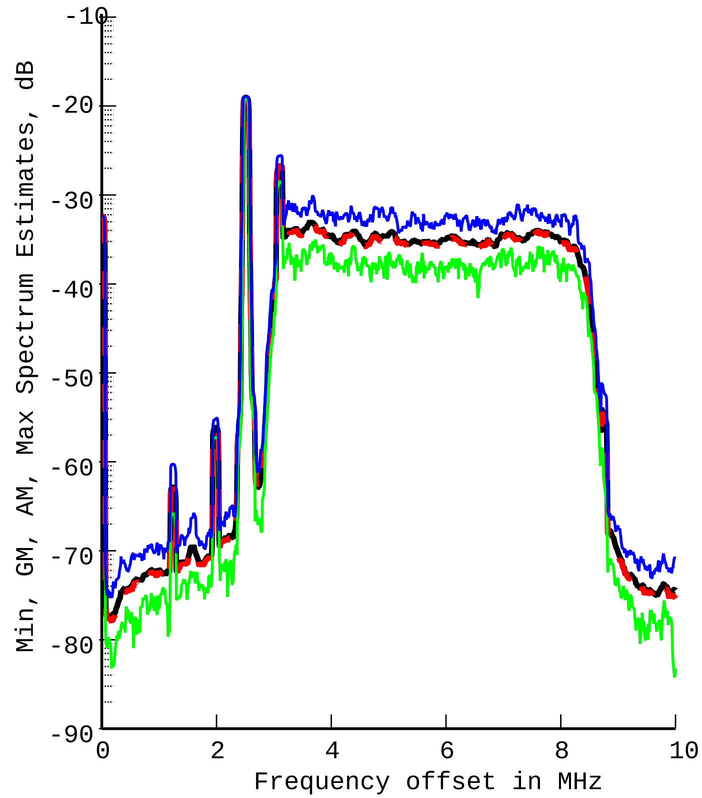
**This two-pronged mathematically rigorous theory for the time-frequency analysis of nonstationary processes has a *built-in capability to adapt* to the underlying statistical periodicity of the signal under study.**

**Simply put, it is nonparametric and therefore *robust.***

# Experimental Results: Digital TV

**Figure 7: Multi-taper spectral estimates of real-life ATSC-DTV data.**

**The lower (green) and upper (blue) curves represent the minimum and maximum estimates over 20 sections, with each section containing 2,200 samples (i.e., 110 microseconds).**




**When the figure is expanded, we see two closely overlapping curves: the arithmetic mean (upper black) and geometric mean (blue)**

# 6. Transmit-power Control

**Objective:**

**Design a transmit-power controller within a non-cooperative game-theoretic framework (i.e., set of convex optimization problems):**

- **max-min optimization for robustification; and**
- **worst-case analysis on a specified uncertainty set.**

**Iterative water-filling (IWA) is one approach of solving the problem.**

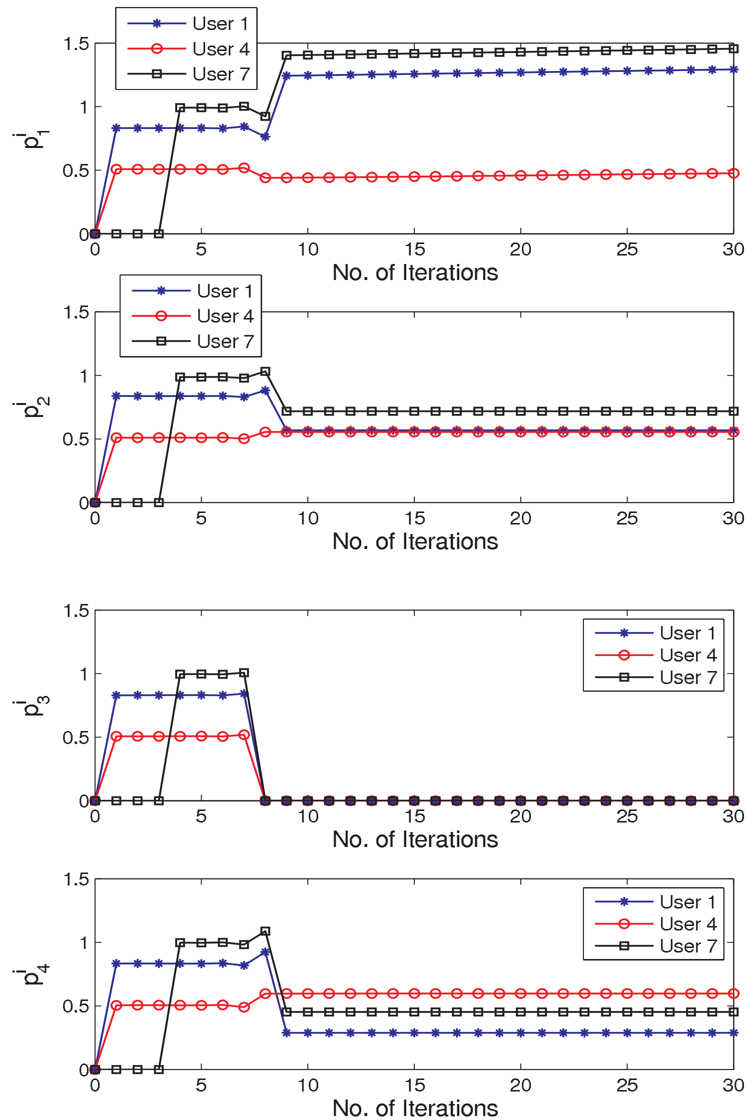
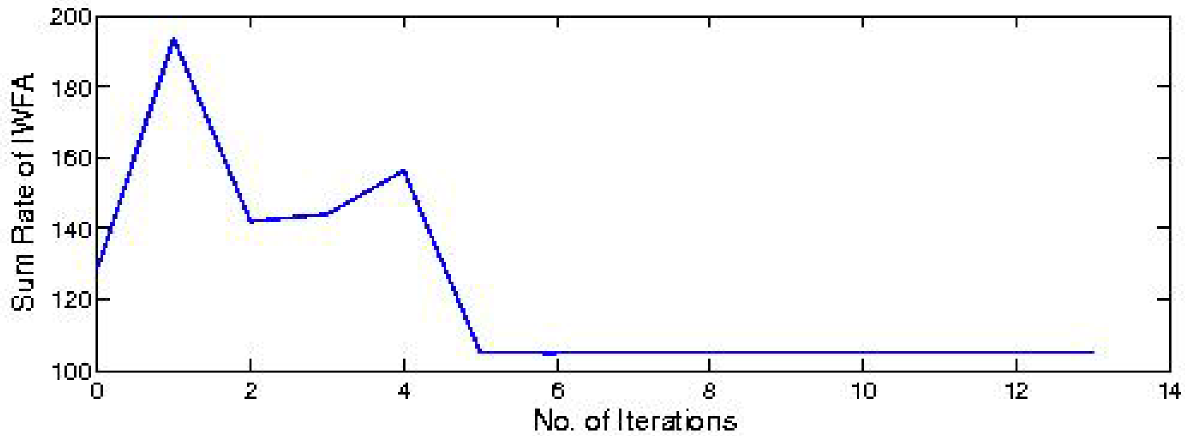



**Figure 8: Resource allocation results of robust iterative water-filling algorithm (IWFA), when 2 new users join a network of 5 users, a subcarrier disappears, and interference gains are changed randomly to address the mobility of the users.**

(b)




(a)

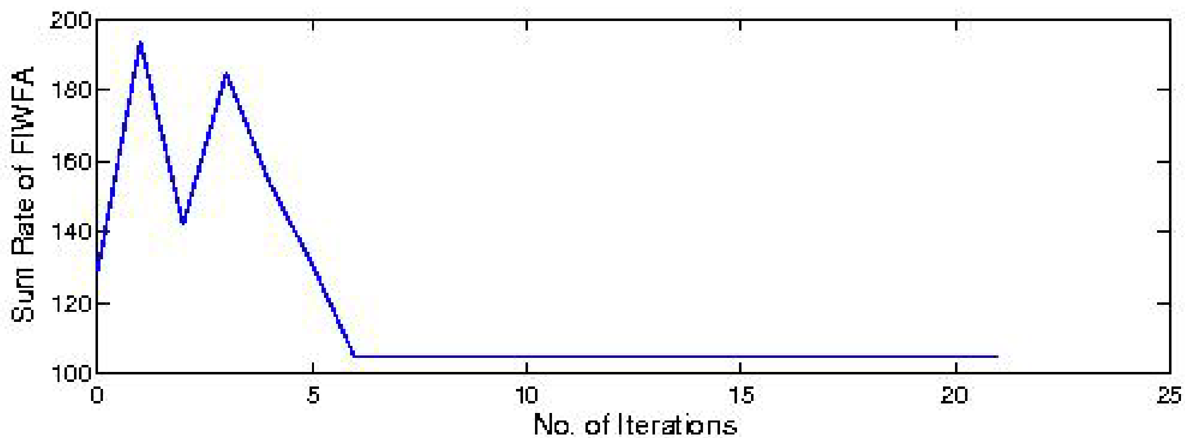



**Figure 9: Comparison of the two IWF algorithms and its new fast version**
**(a) classical version**
**(b) fast version (new)**

# 7. Emergent Behaviour of Cognitive Radio Networks

**The cognitive radio network is a hybrid, nonlinear and time-varying closed-loop feedback control system, which involves:**

- **continuous dynamics, and**
- **discrete events.**

**Above all, the network is a complex system characterized by a complicated and irreducible phenomenon, namely:**

**Emergent Behaviour**

## Limiting (critical) factors affecting the emergent behaviour of the network:

(i) **Nonstationary character of spectrum holes.**

(ii) **Interfering signals from primary (legacy) users and other secondary (cognitive radio) users.**

(iii) **Time-varying number of cognitive radio users.**

(iv) **Unpredictable human behaviour of the cognitive-radio users.**

(v) **Transmission delay of wireless communication across the forward channel (from transmitter to receiver) and the feed-back link (from receiver to transmitter).**[2]

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2. The use of diversity is assumed to tame the notoriously unreliable behaviour of the channels.

# Two Kinds of Behaviour in a Self-organized Network

**(i) Positive Emergent Behaviour**

**This first kind of behaviour embodies a harmonious and efficient utilization of the radio spectrum by all primary (legacy) users as well as secondary (cognitive radio) users with minimal coordination.**

**Underlying Protocol: Best response strategy adopted by each secondary user, leading to a Nash equilibrium.**

**(ii) Negative Emergent Behaviour**

**This second kind of behaviour is characterized by disorder (i.e., traffic jams, chaos, and wasted subbands of the radio spectrum).**

**It can arise due to one of two factors:**

- **inadequate number of spectrum holes to cope with the needs of a large number of secondary users; or**
- **one or more greedy secondary users who, knowingly, ignore the underlying protocol of the network.**

## Study of the Emergent Behaviour of the Network

### (i) Theoretical Study:

**The emergent behavior is being studied on the basis of a model of the network, using control theory.**

### (ii) Experimental Study using Software Testbed[3]:

**In the final analysis, emergent behaviour of a cognitive radio network is the litmus test for assessing the overall performance of the network.**

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3. The testbed has been completed, and it's ready for testing. .

# 8. Final Remarks

**Large-scale Engineering Applications:**

> **Cognition is the key to a new generation of dynamic systems, which will open the way for innovative large-scale engineering applications that will make significant differences to our daily lives.**

**Overall Sub-optimality as the Design Objective:**

> **At the local level we may seek optimality, but at the global level we may have to settle on the "best" sub-optimal, and reliable solution for the application at hand, given limited resources.**

**This is precisely what the human brain does on a daily basis.**

## Looking into the Past and the Future

In the 20th century, we looked to mathematics and physics for new and innovative ideas.

In the 21st century, we will be looking to the human brain for inspiring ideas, supported by

- signal processing;
- control theory;
- information theory;
- mathematics;
- physics;
- biology;
- evolutionary computation; and
- the computer and computational thinking

for the theory and design of cognitive dynamic systems aimed at large-scale engineering applications.

## Interplay between Cognitive Dynamic Systems and the Human Brain:

**In pursuing a new generation of dynamic systems with cognition as the enabler, we are naturally motivated by the human brain.**

**In the course of time, we may well find that the new cognitive dynamic systems so engineered help us understand some functions of the brain itself.**

## New Book:

Simon Haykin, Cognitive Dynamic Systems
Cambridge University Press, 2010.