Software Testbed for Cognitive Radio Networks: Work in Progress

Simon Haykin
McMaster, University
Hamilton, Ontario, Canada

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

Outline of the Lecture

1. **Primary objectives of the software testbed**

2. **The major functional blocks of the testbed at the receiving end:**

   (i) Spectrum sensing
   (ii) Predictive modeling

3. **The major functional blocks of the testbed at the transmitting end:**

   (i) Transmit-power control
   (ii) Dynamic spectrum management

4. **Receiving and transmitting ends viewed together**

5. **Emergent behaviour of cognitive radio networks:**

   (i) Homogeneous networks
   (ii) Heterogeneous networks

6. **Block diagram of the software testbed**

References

1. Primary Objectives of the Software Testbed

- **Flexibility to accommodate different configurations and different applications**

- **Experimental study of the emergent behaviour of a cognitive radio network under varying operating and environmental conditions for both:**

  (i) Homogeneous networks
  (ii) Heterogeneous networks

2. The Major Functional Blocks of the Testbed at the Receiving End: Spectrum Sensing

- **Desirable properties of the spectrum sensor:**

  (i) It is nonparametric (i.e., model-independent)

  (ii) It provides an accurate assessment of the local neighborhood in terms of
  - **distinguishing features of the environment;**
  - **spatio-temporal information, capable of creating the sense of attention**

  (iii) It is reliable

  (iv) It is near-optimal (in its information-gathering capability) in the maximum likelihood sense

Spectrum Sensing (continued)

The method of choice that satisfies all four requirements:

THE MULTITAPER METHOD
(David Thomson, 1982)

- **Through the use of multiple windows, (based on an orthogonal set of Slepian sequences), MTM resolves the bias-variance dilemma.**
- **The MTM is expandable into a space-time processor that provides:**
  - **(i) estimate of the average power at each frequency;**
  - **(ii) spatial distribution of interferers;**
  - **(iii) multitaper coefficients of interferer's waveforms.**
- **Combined with the Loève transform, it extracts modulation-based features: cyclostationarity.**

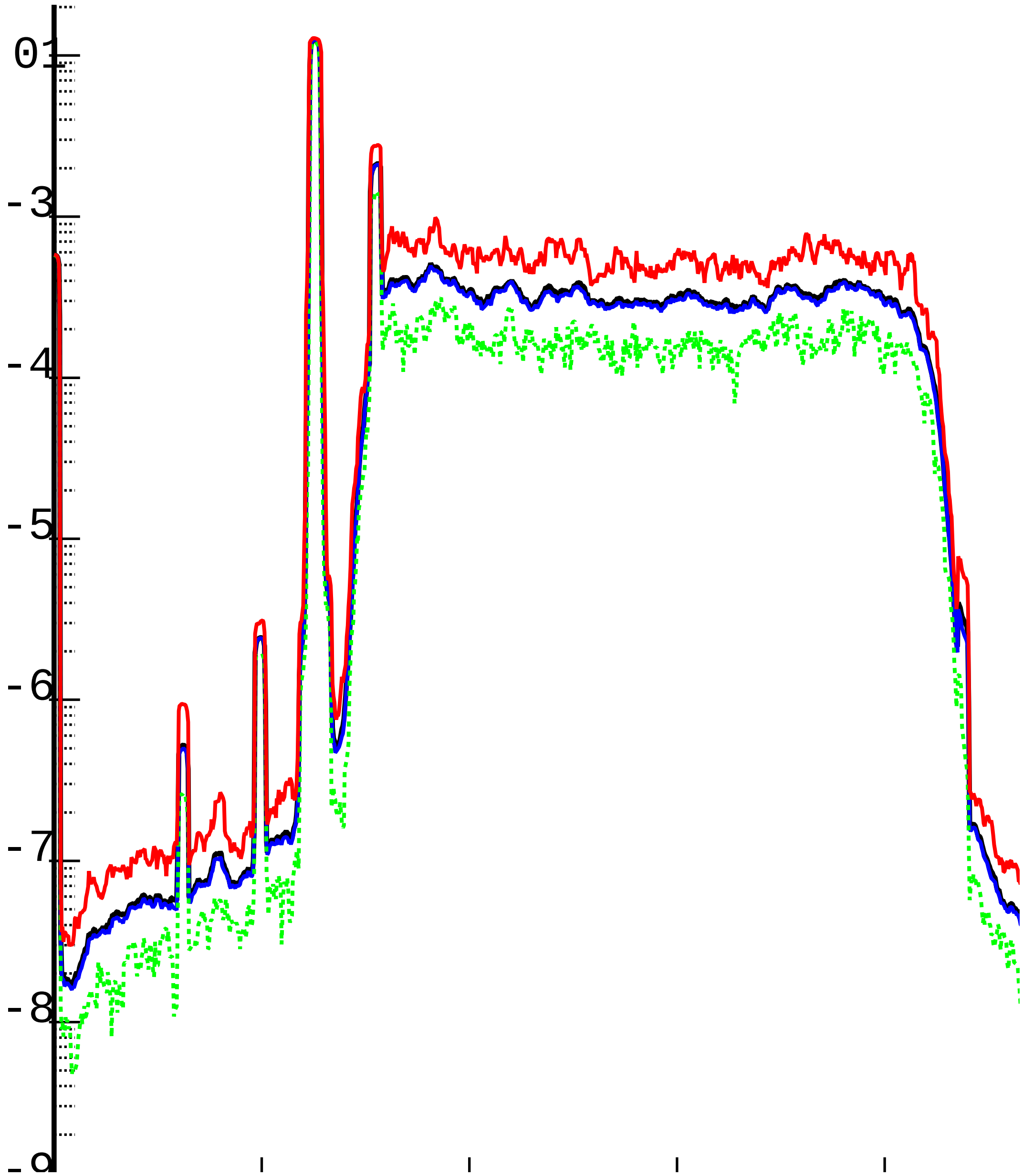


Figure 1: The MTM applied to wideband ATSC-Digital television signals

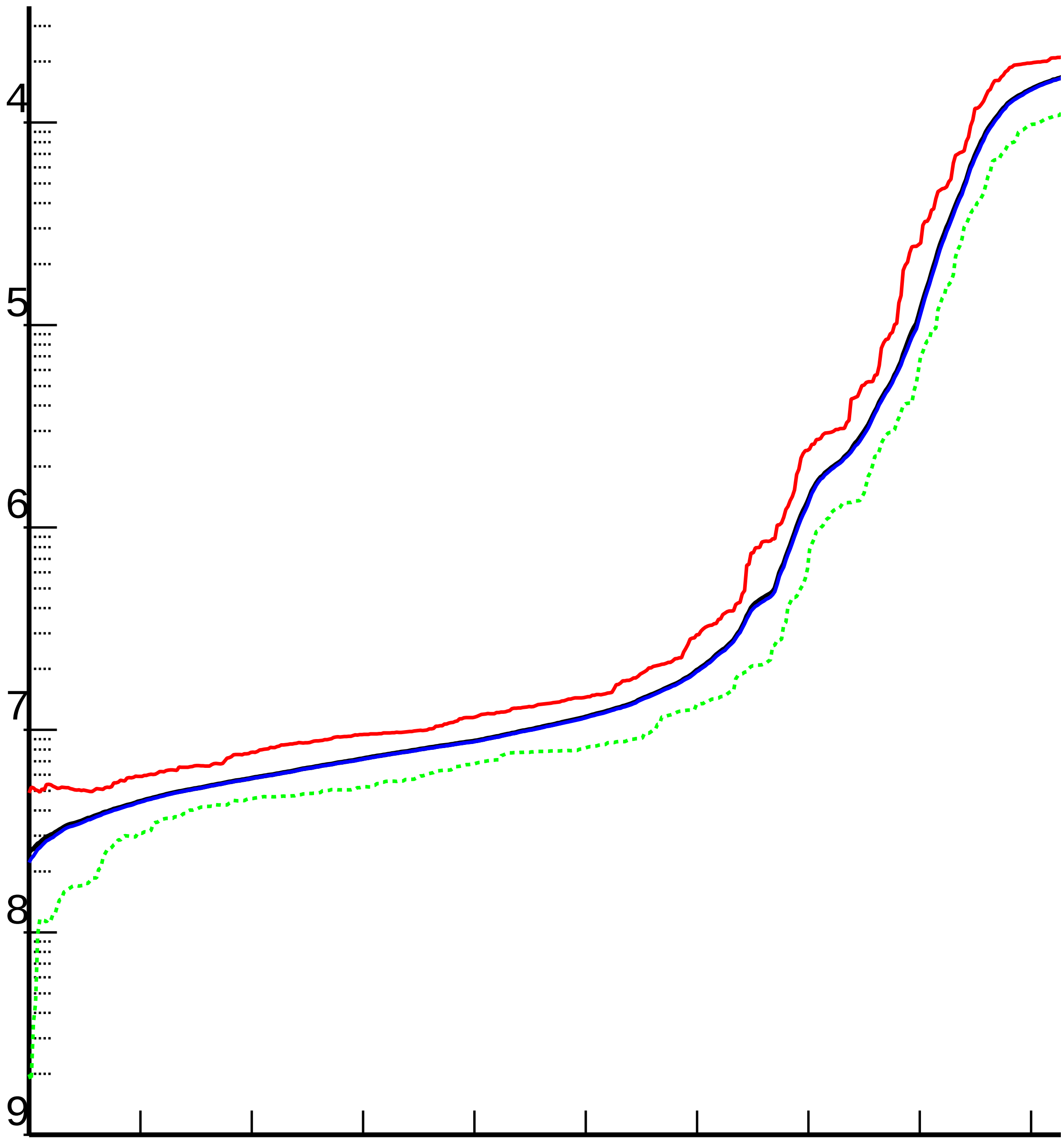


Figure 2: Available bandwidth resolving capability of the MTM

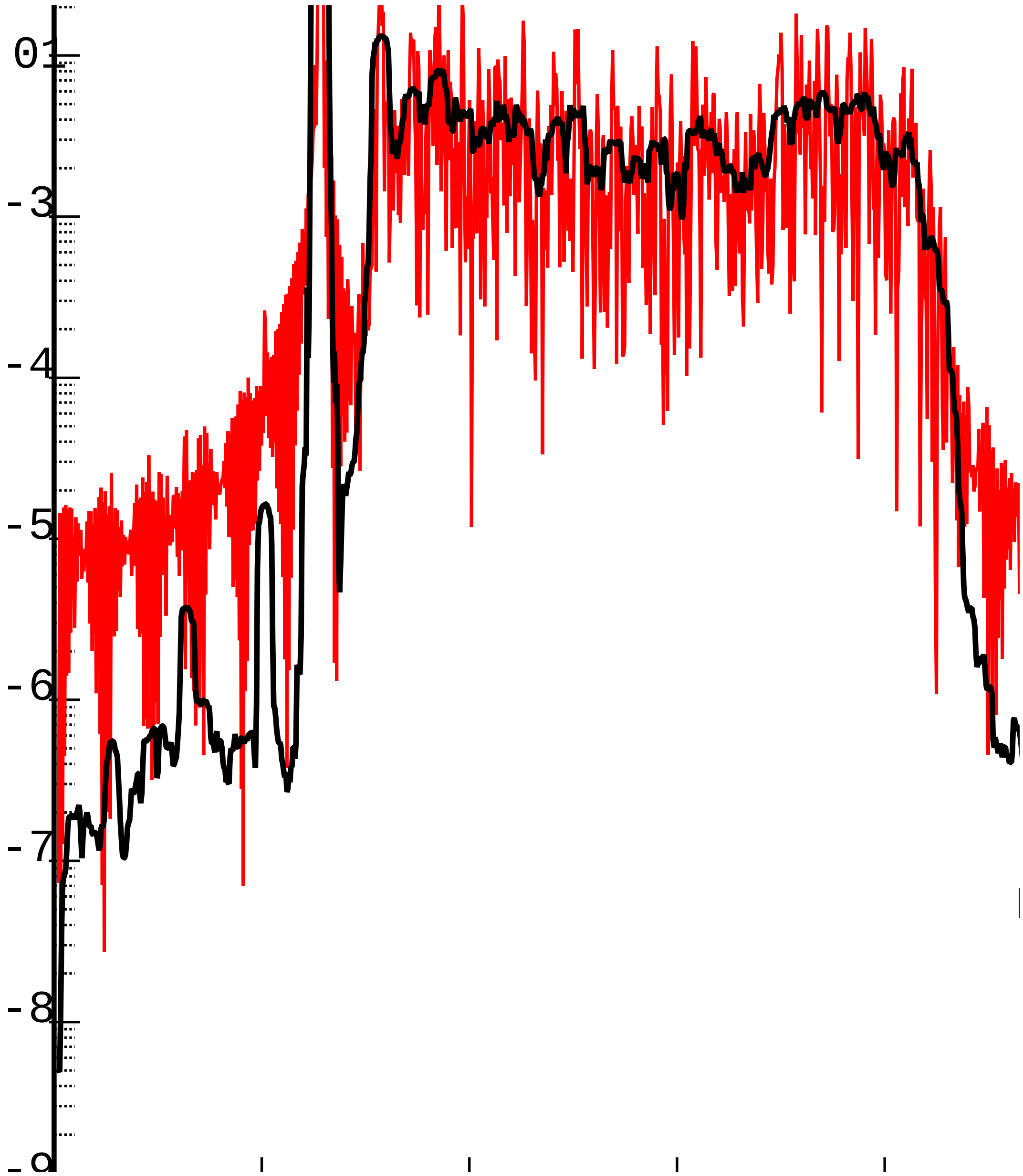


Figure 3: The periodogram applied to ATSC-DTV signal

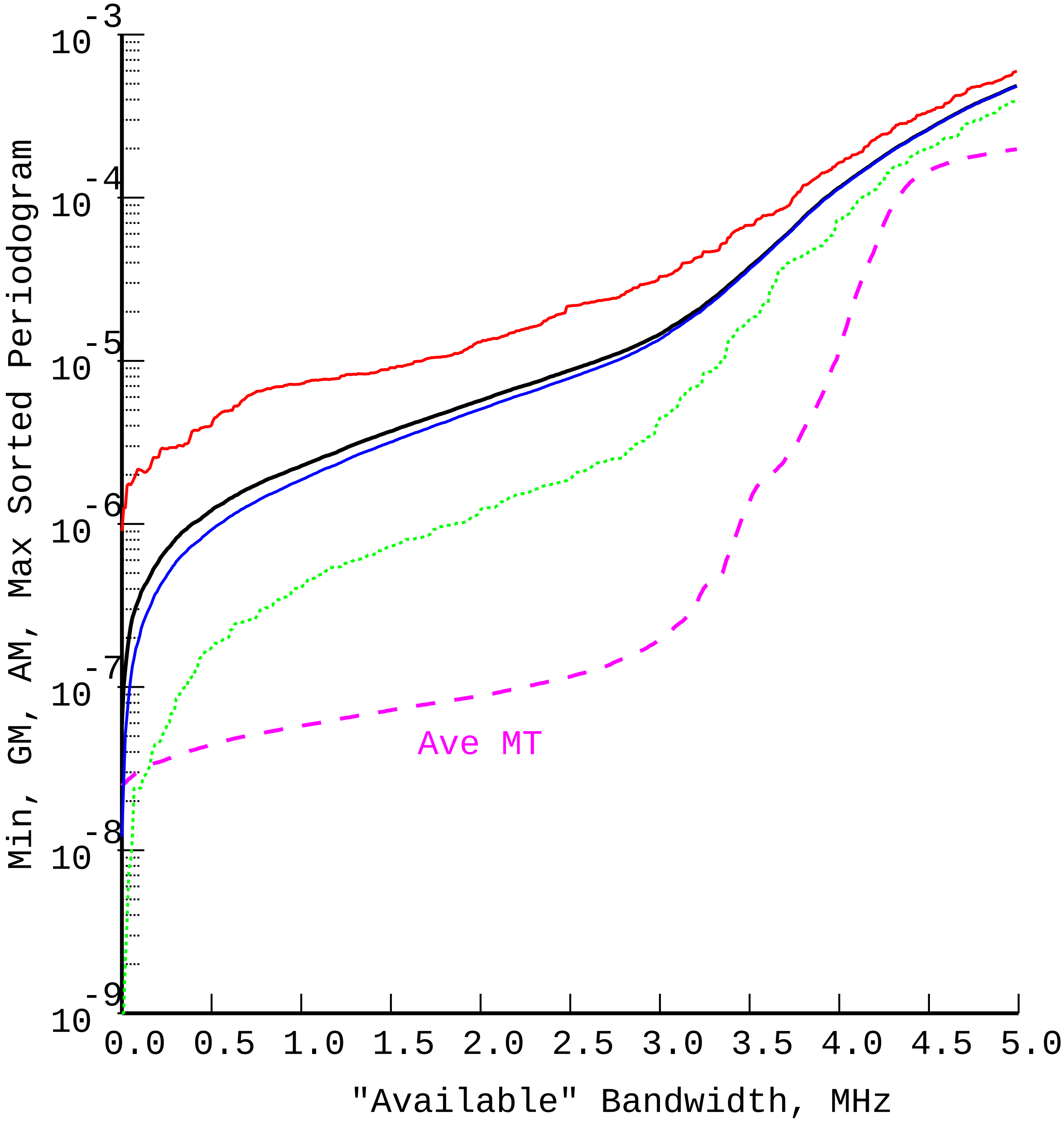


Figure 4: Available resolving capability of the periodogram

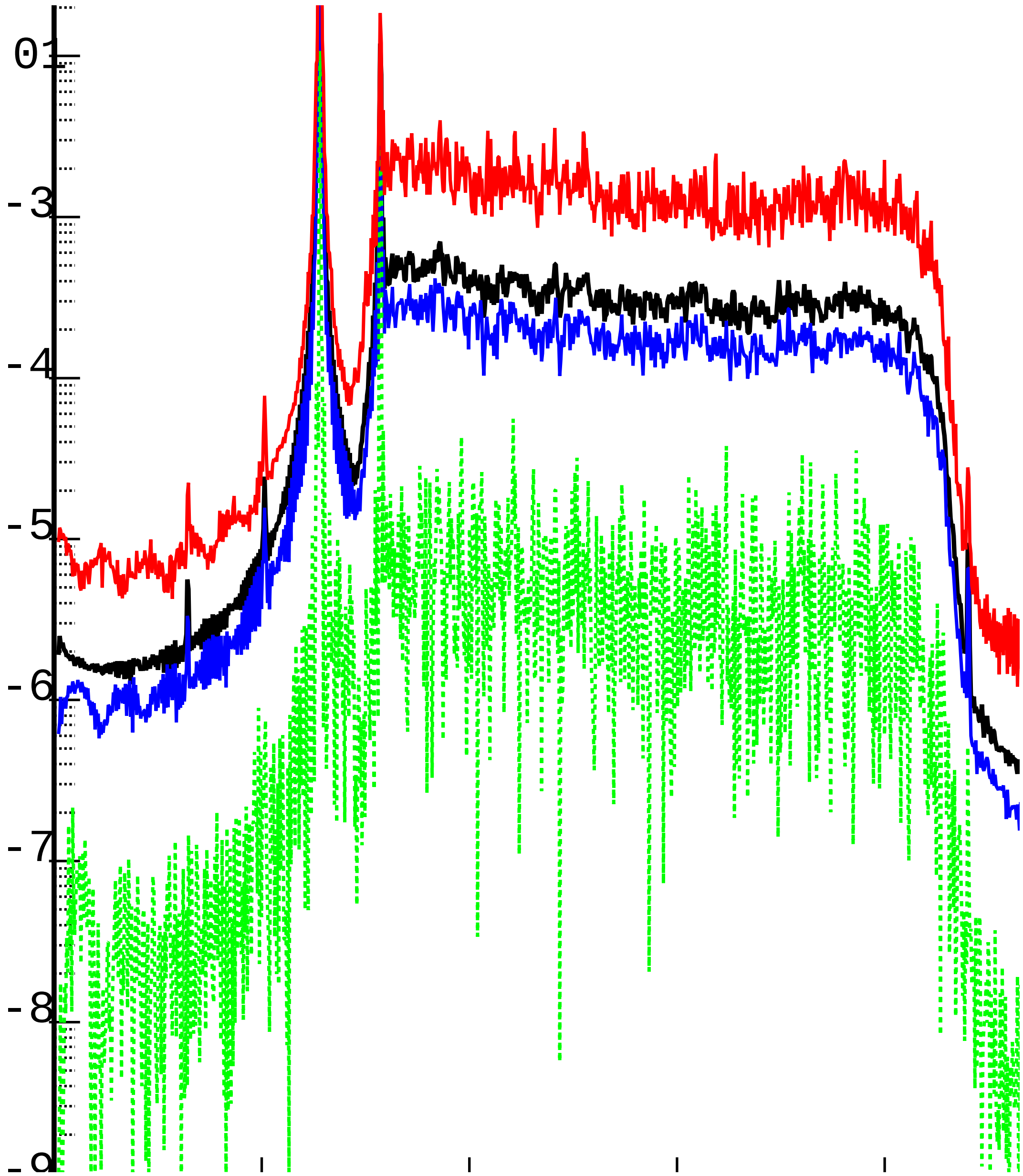


Figure 5: Comparison of the MTM and periodogram spectra

3. The Major Functional Blocks of the Testbed at the Receiving End: Predictive Modeling

- **Requirement:**
  Enable a secondary user to determine the likelihood that a spectrum hole remains available for communication for a desired duration into the future.

- **Temporal difference (TD) learning: An approximate form of dynamic programming.**

- **TD networks expand on the learning capability of TD-learning.**

3. Major Functional Blocks of the Software Testbed at the Transmitting End:
(i) 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 the iterative waterfilling algorithm (IWFA) framework:**
  - **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 and multiple time-varying delays.**

(i) Transmit-power Control (continued)

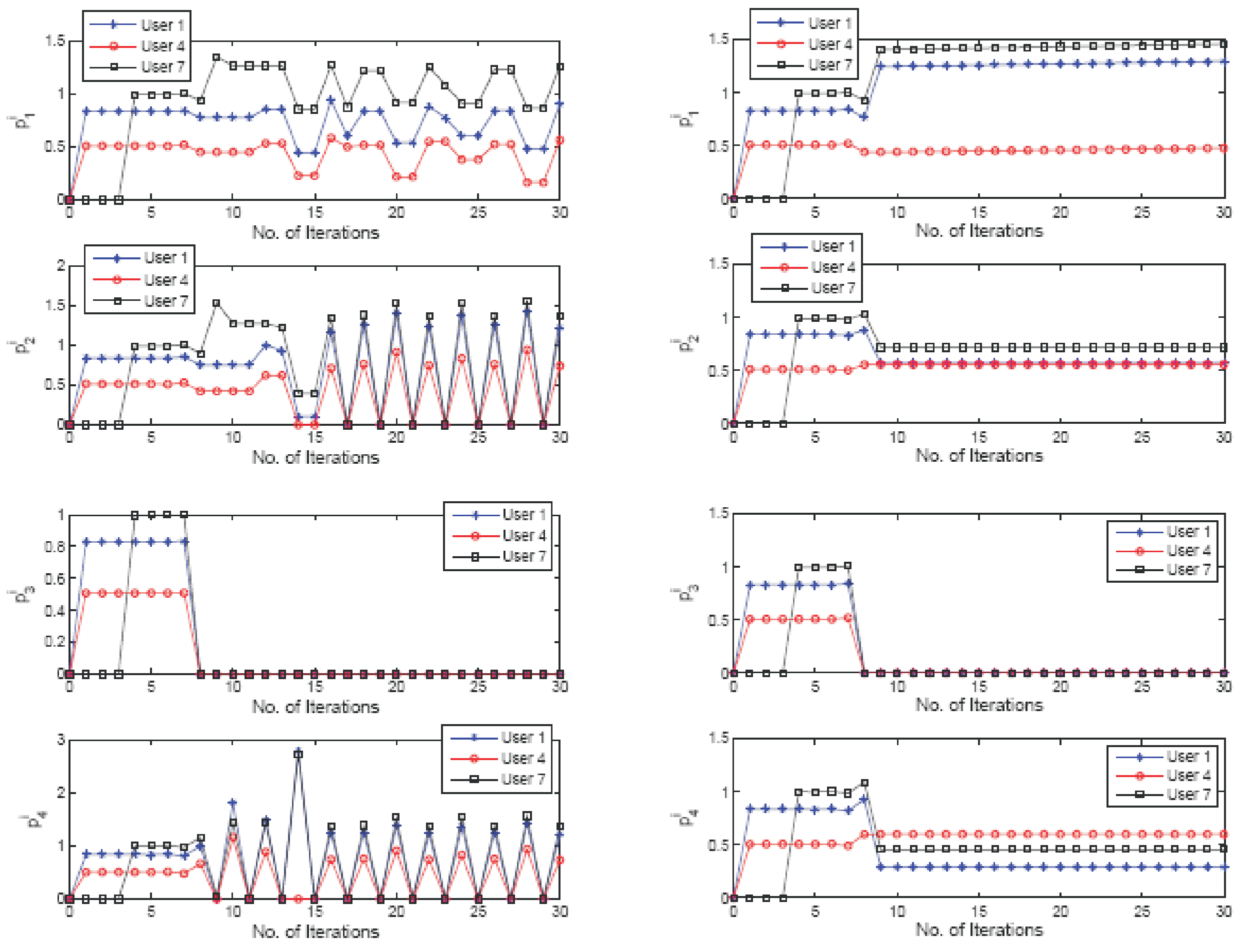


Figure 6: Resource allocation results of simultaneous IWFA and robust IWFA, when 2 new users join a network of 5 users, a subcarrier disappears, and interference gains are changed randomly to address the mobility of the users.

The Major Functional Blocks of the Testbed at the Transmitting End:
(ii) Dynamic spectrum management (DSM)

- **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.**

4. Receiving and Transmitting Ends Viewed Together

- **Rationale Behind the TPC and DSM:**

  Both are rooted in information.

  (i) TPC exploits iterative waterfilling, rooted in Shannon's rate distortion theory.

  (ii) DSM exploits iterative inverse-waterfilling, which combines competition and cooperation among users.

Receiving and Transmitting Ends Viewed Together (continued)

- **Reinforcement Learning: Interaction with the environment**

  (i) The receiver perceives the environment by extracting multidimensional information on the environment:
  - **spectrum holes across the frequency band**
  - **average power of each spectrum hole**
  - **features identifying the user of each spectrum hole**
  - **directions of interferers**

  (ii) The transmitter acts on this information to establish reliable communication across a link that connects the CR transmitter (at one end) to the CR receiver (at the other end)

  (iii) Net result: Punish or reward.

5. Emergent Behaviour of Cognitive Radio Networks

- **The network viewed as a global closed-loop feedback system, embodying all four functional blocks of the testbed, feedback channel, and communication channel**

Emergent Behaviour of Cognitive Radio Networks (continued)

- **State of the World as seen by a user of the network:**

  (i) Spectrum holes: directly observable through the use of spectrum sensing and predictive modeling at the receiver.

  (ii) Behavior of other users in the network: Unobservable.

  (iii) Partially observable world.

Emergent Behaviour of Cognitive Radio Networks (continued)

- **Two kinds of emergent behaviour:**

  (i) Positive behavior: All users in the network operate in an orderly manner.

  (ii) *Negative behavior*: One or more users in the network act differently, hence the emergence of disorder leading to traffic jams, chaos, etc.

Emergent Behaviour of Cognitive Radio Networks (continued)

- **Possible causes of Negative Behaviour:**

  (i) ***Homogeneous Networks***

  Number of users in excess of the available number of spectrum holes by a wide margin.

  (ii) ***Heterogeneous Networks***

  Users in the network use different software models for implementing the functional blocks of the cognitive radio.

Emergent Behaviour of Cognitive Radio Networks (continued)

- **The Karush-Kuhn-Tucker (KKT) conditions**

  (i) KKT conditions are satisfied
  - Nash equilibrium

  (ii) The KKT conditions provide a window on the unobservable state of the world.

- **Criterion for detecting the onset of negative behaviour:**

  - **Nonlinear sequential state estimation for tracking evolution of the KKT conditions across time.**

Emergent Behaviour of Cognitive Radio Networks (continued)

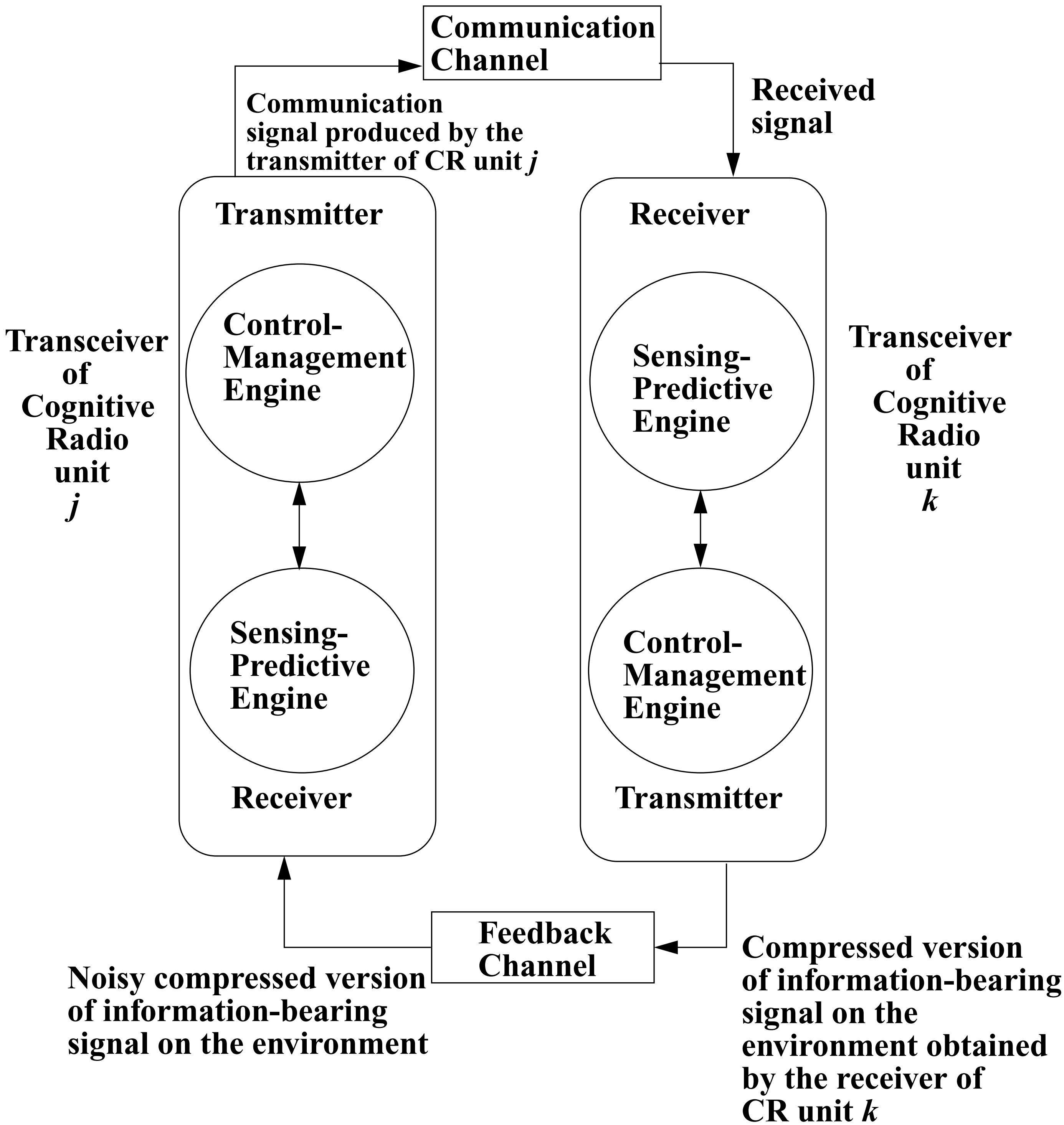
Possible Cure for Mitigating Negative Behaviour:

(i) Pricing for the use of spectrum holes.

(ii) Collaboration among users of the network
- Reduced utilization of the spectrum.

There is No Free Lunch

6. Summarizing Block Diagram of the Software Testbed



References

1. **David Thomson, "Spectrum Estimation and Harmonic Analysis", Proc. IEEE, vol. 20, pp. 1055-1096, Sept. 1982.**
2. **Simon Haykin, "Cognitive radio: Brain-empowered wireless communications", *IEEE. J. Selected Areas in Communications*, vol. 32(2), pp. 201-220, Feb. 2005.**
3. **Simon Haykin, Fundamental Issues in Cognitive Radio. In E. Hossain and V.K. Bhargava (Editors), Springer, 2007.**
4. **Simon Haykin, David Thomson, and Jeff Reed, "Spectrum Sensing for Cognitive Radio", *Proc. IEEE*, vol. II: Fundamental Issues, March 2009.**
5. **Peyman Setoodeh and Simon Haykin, "Robust transmit-power control for cognitive radio", *Proc. IEEE*, vol. II: Fundamental Issues, March 2009.**
6. **Farhad Khozeimeh and Simon Haykin, "Dynamic spectrum management for cognitive radio: An overview", *Wireless Communications and Mobile Computing*, 2007.**
7. **Simon Haykin, Cognitive Radio Networks: Work in progress. In S. Haykin and R. Liu (Editors), Handbook on Sensors and Networks, Wiley, 2009.**