Software Testbed for Cognitive Radio Networks: Work in Progress

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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.
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

![Block Diagram]

- **Transmitter**: Control-Management Engine
- **Receiver**: Sensing-Predictive Engine
- **Feedback Channel**: Noisy compressed version of information-bearing signal on the environment
- **Communication Channel**: Received signal
- **Transceiver of Cognitive Radio unit $j$**: Transmitter
- **Transceiver of Cognitive Radio unit $k$**: Receiver
- **Compressed version of information-bearing signal on the environment obtained by the receiver of CR unit $k$**

*Communication signal produced by the transmitter of CR unit $j$*
References