Cognitive Radio: Brain-Empowered Wireless Communcations

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Overview

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- Channel-state estimation
- Transmit-power control
- Spectrum management
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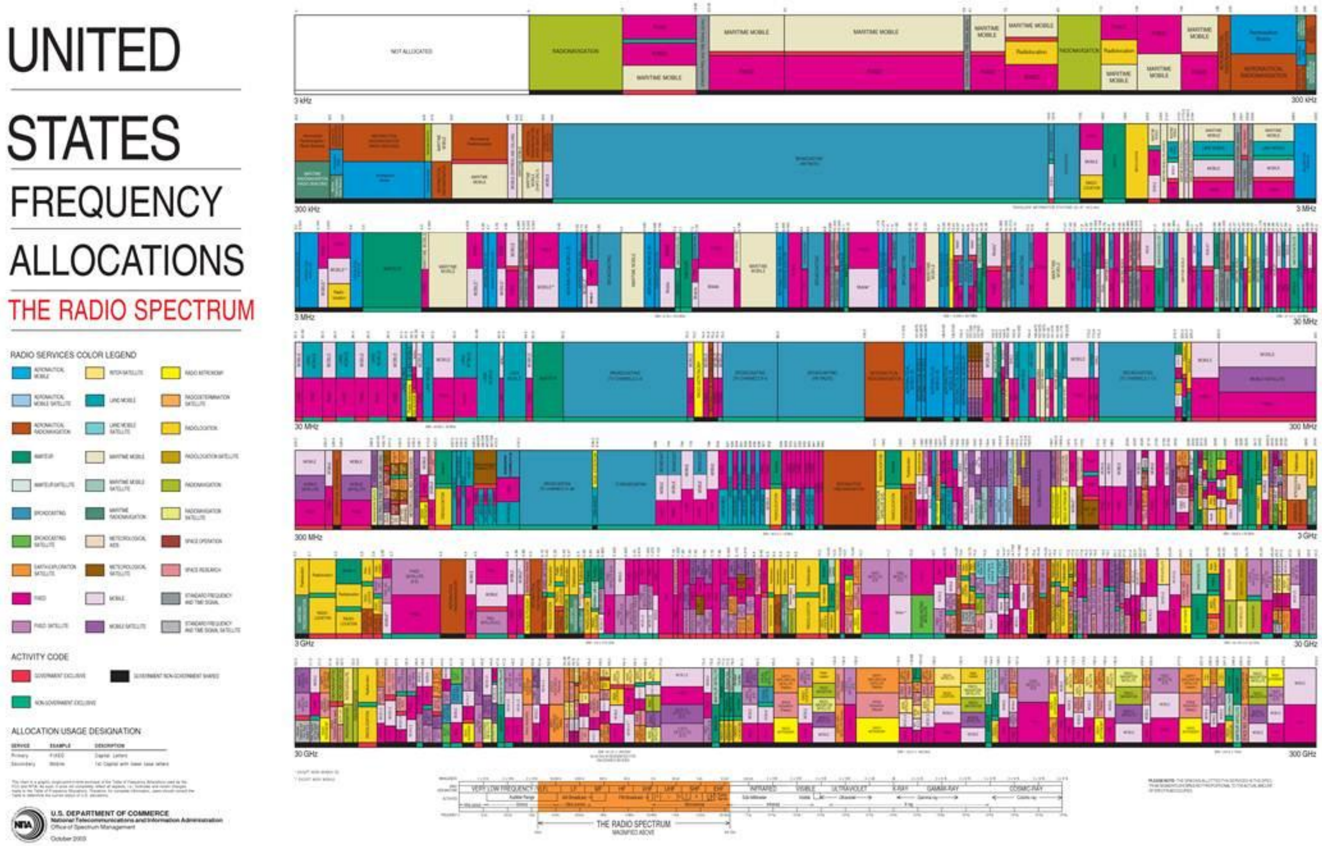
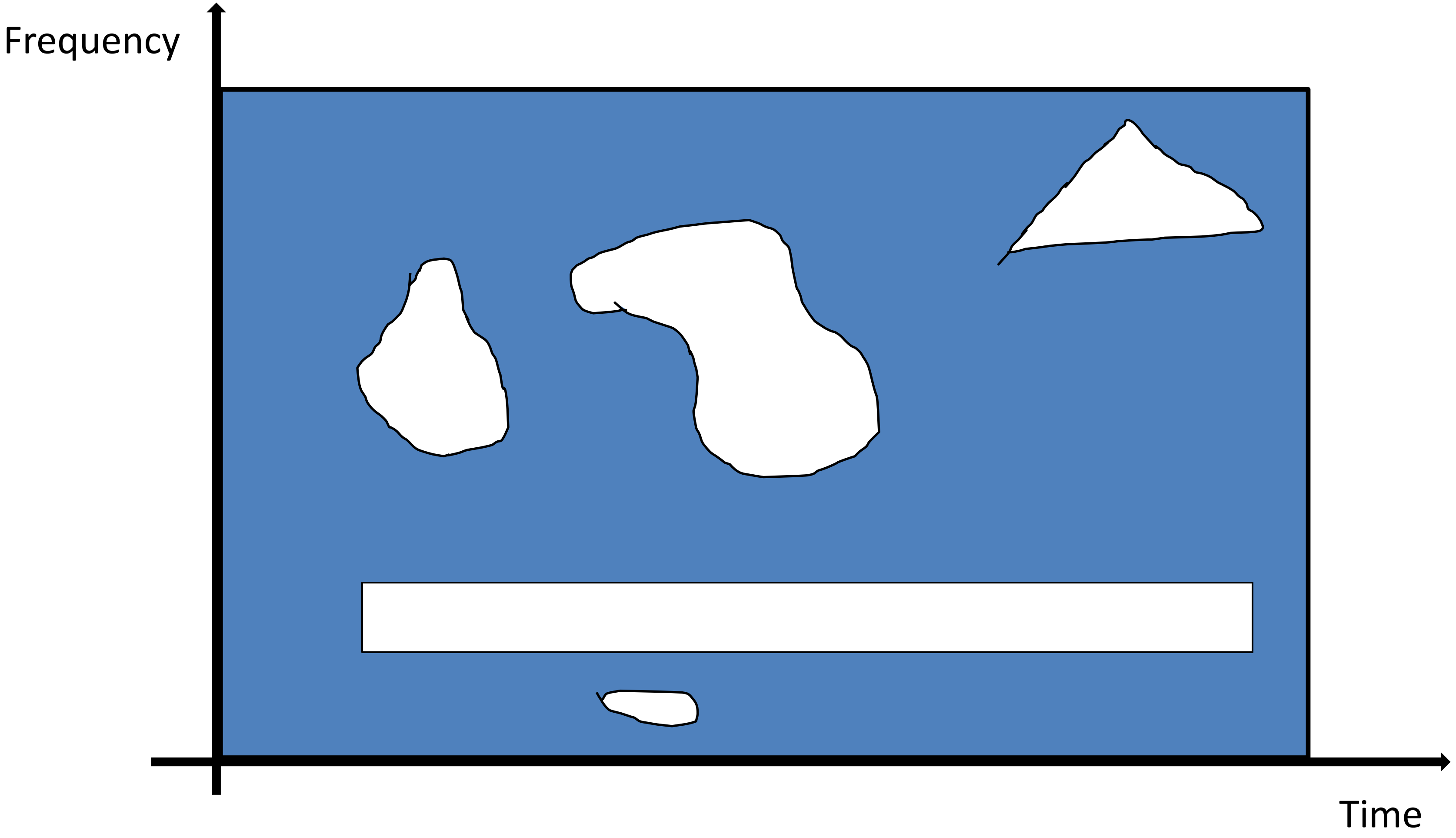
Motivation



UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM

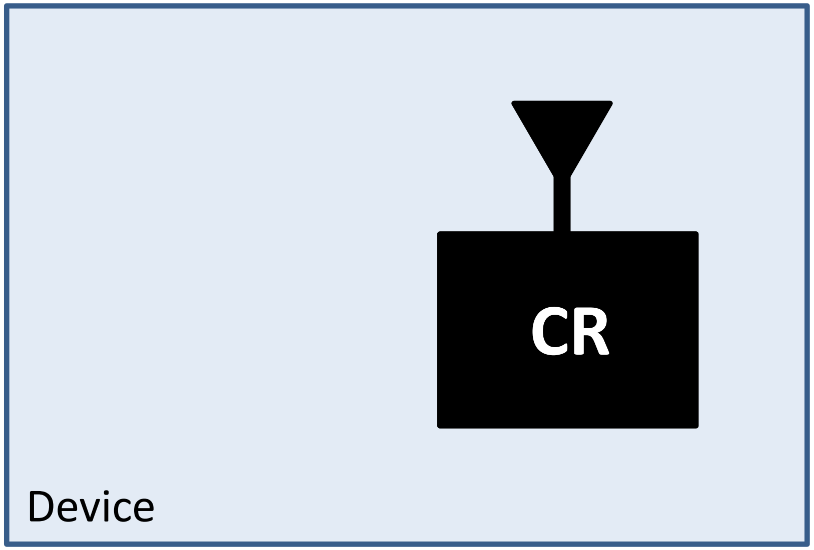
Motivation

Wireless Spectrum Usage



Background

- Mitola, Maguire ('99)- *Cognitive Radio: Making Software Radios More Personal*
- Mitola ('00) – *Cognitive Radio Dissertation*



- Use any portion of spectrum
- Sense neighboring devices
- Adjust power
- Adjust transmission parameters
- Determine location

Introduction

- "The primary purpose of this paper is to build on Mitola' visionary dissertation by presenting detailed expositions of signal processing and adaptive procedures that lie at the heart of cognitive radio."

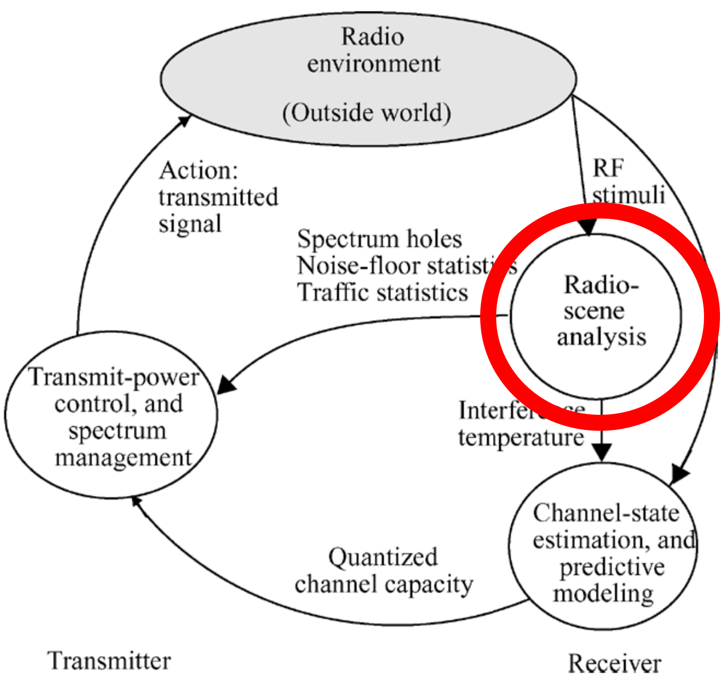
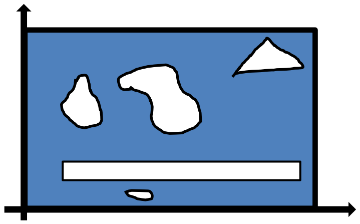


Fig. 1. Basic cognitive cycle. (The figure focuses on three fundamental cognitive tasks.)

Radio Scene Analysis

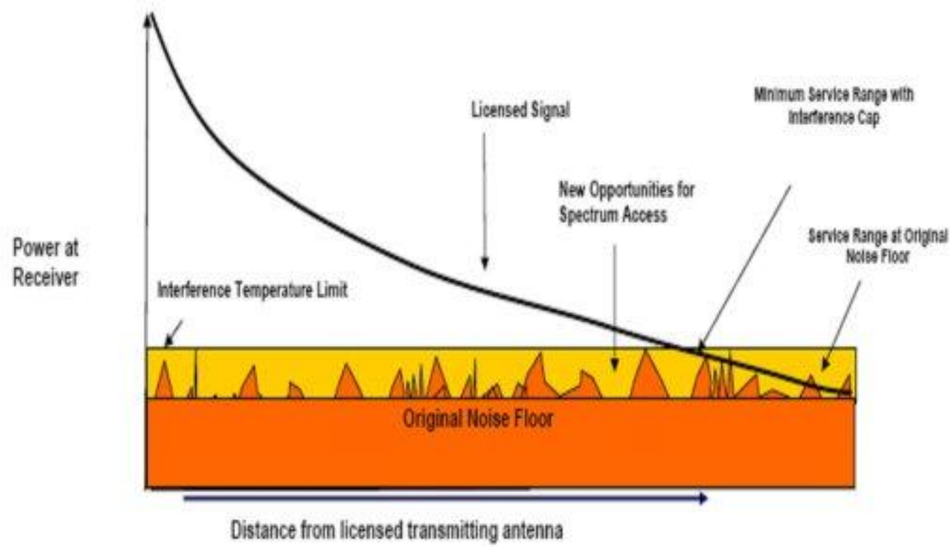
- Two objectives:
  - Estimate interference temperature
  - Detect spectrum holes



Radio Scene Analysis

- Interference Temperature (T_{max}): acceptable level of interference at receiver
- Use channel if interference < interference temperature

$$PSD \leq T_{max}k, \qquad k = 1.3907 * 10^{-23} \frac{J}{K}$$



Interference Temperature Model (from FCC ET DOC 03-289)

Image: Virginia Polytechnic Institute

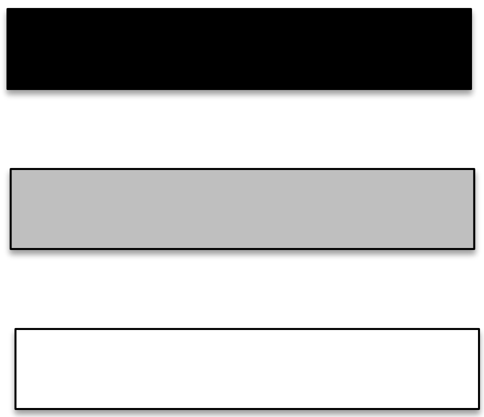
Radio Scene Analysis

- Estimate interference temperature
  - Want the statistics of the signal over time and frequency
  - Break the incoming signals into pseudostationary bursts
  - Use multitaper spectral estimation (Thomson)
    - Single sample, average over orthogonal tapers
    - Unbiased estimator, computationally feasible, nearly optimal for wideband signals

  - Can also use many sensors (eg: building) in combination with multitaper spectral estimation in order to get a more reliable reading
    - Generate a matrix of measurements, perform SVD, the largest singular value estimates interference temperature

Radio Scene Analysis

- Detecting spectrum holes
  - Classification:



High power local interferers, some of the time

Low power interferers, partially occupied

No interferers, ambient noise

  - Decision Statistic:

$$D(t) = \sum_{l=0}^{L-1} \sum_{v=0}^{M-1} |\sigma_l(f_{low} + v \cdot \Delta f, t)|^2 \Delta f$$

    - If $D(t) \leq$ Threshold, declare spectrum hole

Radio Scene Analysis

- Issues:
  - Path loss/shadowing
  - Prediction for future use
    - Continuous monitoring, alternative routes

Channel-state Estimation

- CSI usually estimated via:
  - Differential detection
    - Simple
  - Pilot transmissions
    - Better performance
    - Power/bandwidth inefficient

- Instead, use semi-blind training
  - Short training sequence
  - Then, channel tracking
    - Particle filter

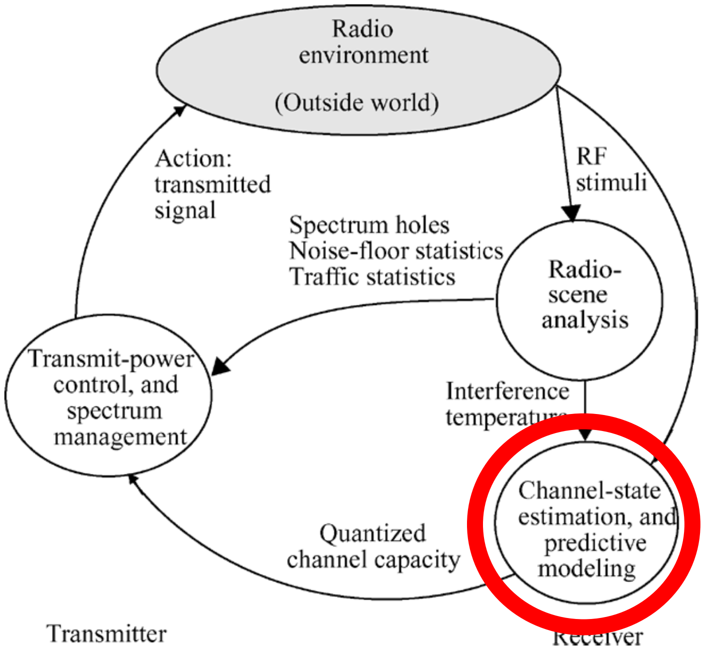
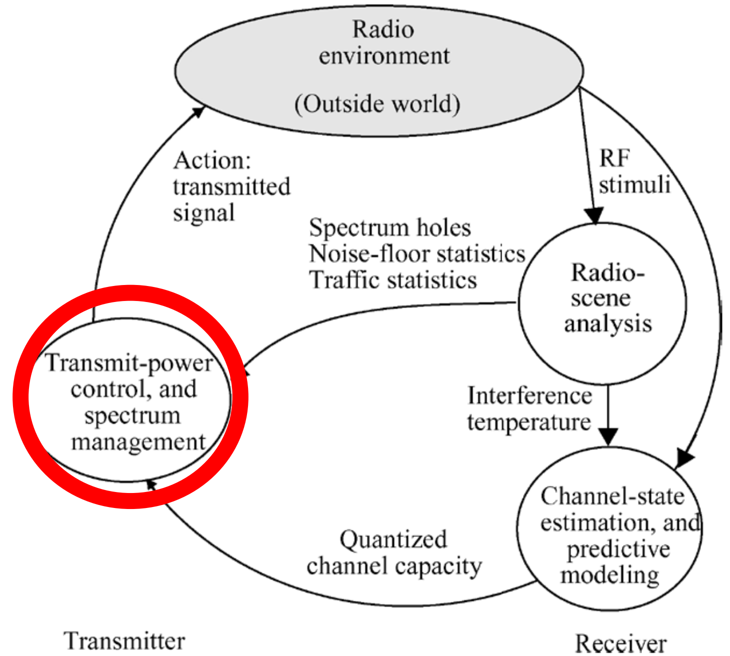


Fig. 1. Basic cognitive cycle. (The figure focuses on three fundamental cognitive tasks.)

Transmit-power Control

- Two approaches to power control:
  - Cooperative
  - Noncooperative

- Cooperative:
  - Etiquette and protocol
    - Eg: traffic lights
  - Cooperative ad hoc
    - Transmit-receive schedule shared between nearest neighbors



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Noncooperative Transmit-power Control

- Limited number of spectrum holes
- Two solutions:
  - Game theory
    - Noncooperative repeated stochastic game
  - Iterative water-filling

Noncooperative Transmit-power Control

- Stochastic Games defined by:
  - Set of players
  - Set of possible states
  - Set of actions
  - Probabilistic state transition function
  - Payoffs
- Nash Equilibrium
  - Set of player actions in which each action is a best response to all other players' actions
  - Stable
- Repeated stochastic game
  - Mixed strategy leads to at least one Nash equilibirum

Noncooperative Transmit-power Control

- Limitations
  - Assumes rationality, flawless execution, knowledge of other player’s equilibrium strategy
  - Exploitable
- Improvement via “no-regret” algorithm (reinforcement learning)
  - Harder to be exploited
  - Ensures overall regret is low

Noncooperative Transmit-power Control

Iterative Water-filling

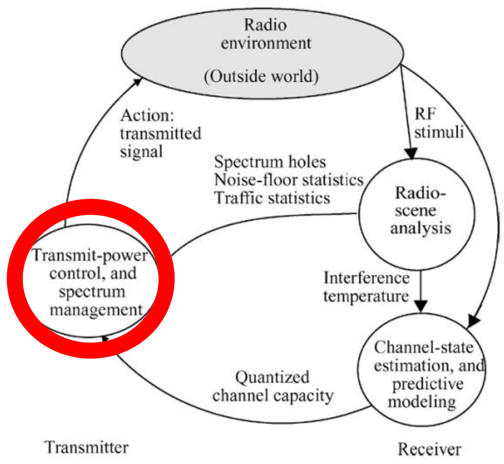
- Maximize the performance of each unserviced transceiver, regardless of what all the other transceivers do, subject to the constraint that the interference-temperature limit not be violated
  - Two user case: leads to a Nash equilibrium
  - More than two leads to iterative algorithm:
    - 1. Set all transmit powers to zero
    - 2. (Inner loop) First user performs WF, second user treats first user as interference and performs WF, etc…
    - 3. (Outer loop) Check to make sure each user is getting right amount in actual data rate
    - 4. If target rates are satisfied, end. Else, WF performed again by each user treating all other users as interference
  - Tries to minimize power needed to achieve target rates
    - Requires that set of target rates is achievable
    - Central agent to determine rates are achievable

Noncooperative Transmit-power Control

- “No-regret” Algorithm vs. Iterative WF
  - WF has fast convergence, “top-down”
  - “No-regret” prevents exploitation, “bottom-up”

Dynamic Spectrum Management

- Select a modulation strategy that adapts to time-varying conditions and assures reliable communications
  - eg: OFDM
- Need traffic model to predict duration of spectrum hole vacancy



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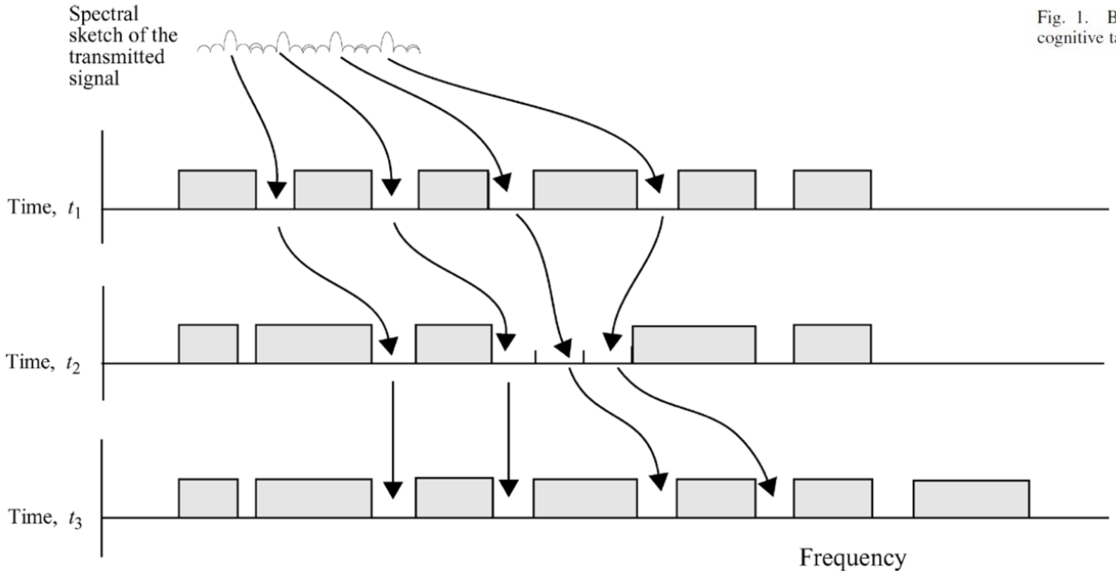

Emergent Behavior

- Cooperation, competition, exploitation can lead to overall system behavior which is:
  - Positive: order, efficient use of the spectrum
  - Negative: disorder, traffic jams, unused spectrum

- Want to:
  - Detect negative emergent behavior quickly
  - Corrective measures

Conclusion

"Disruptive, but unobtrusive technology"

References

- 1. Haykin, S., *Cognitive radio: Brain-empowered wireless communications.* Selected Areas in Communications, IEEE Journal on, 2005. **23**(2): p. 201-220.
- 2. Mitola, J. and G.Q. Maguire, *Cognitive radio: Making software radios more personal.* Ieee Personal Communications, 1999. **6**(4): p. 13-18.
- 3. Prasad, R.V., et al., *Cognitive functionality in next generation wireless networks: standardization efforts.* Communications Magazine, IEEE, 2008. **46**(4): p. 72-78.