A Networked Approach to Spectrum Sensing in Cognitive Radio Systems

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Joint work with Chris Headley, Jesse Reed, Brian Choi, and Amy Malady.

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"From thought to practice"

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Introduction

- The application of cognition to communications radios and networks opens new and exciting opportunities for improving the transmission of information
- First application (?): Opportunistic spectrum re-use – e.g., 802.22
- In an opportunistic spectrum access scenario, harmful interference and performance degradation may result if spectrum sensing is not reliable
    - Fact: Skepticism
    - History: Overlay analog cellular network, UWB (DAA – e.g., Europe)
    - More research is needed

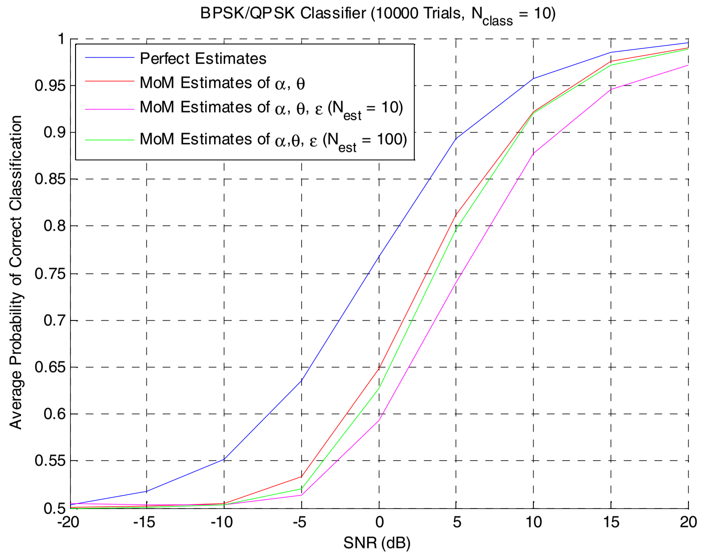
Spectrum Sensing

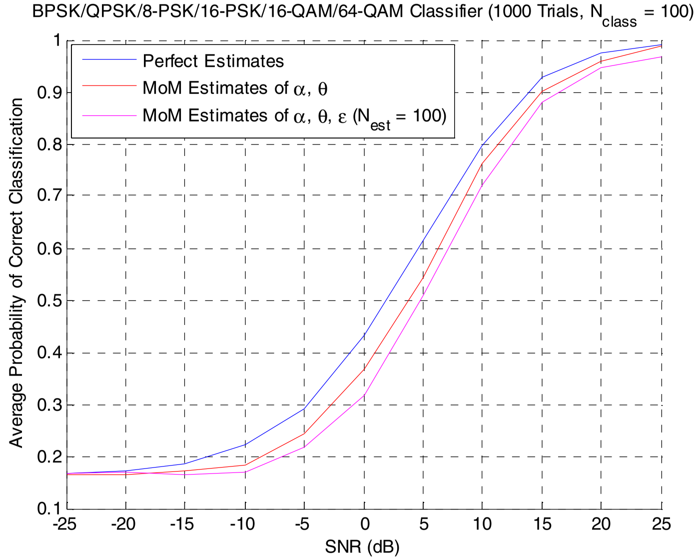
- Does it fall into the “beaten to death” category?
- Commercial systems → first time
  Military systems → hard to know, different requirements and applications
- Opportunistic spectrum access requires guarantees
- Do these guarantees lead to reasonable requirements?

Problem: Theoretical bounds on the spectrum sensing performance

Spectrum Sensing: Unknown Channel

- Complex task:
  - No knowledge of the transmitted data and many unknown parameters (signal power, carrier frequency and phase offsets, timing info)
  - No channel knowledge
- Example: The development of signal detection and classification algorithms for multipath fading channels is surprisingly scarce





Problem: Performance limits of sensing algorithms for realistic implementations and practical scenarios?

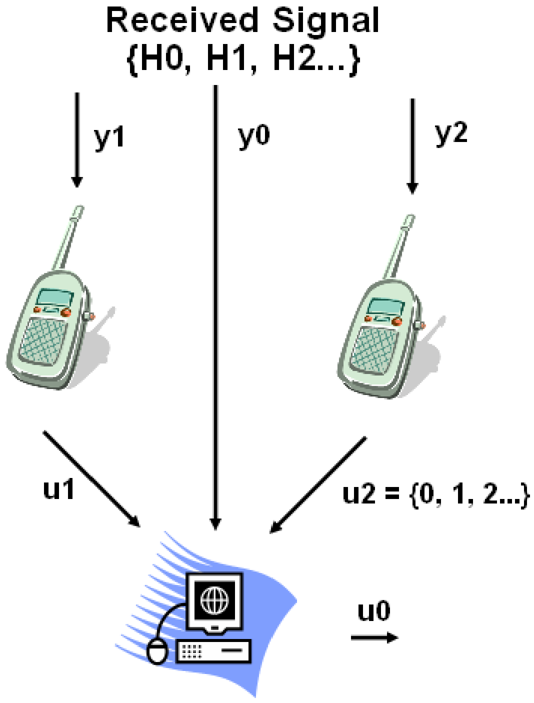
Distributed Sensing

- User 2 might not detect the primary user
- Together, users 1, 2, and 3 have a higher probability of detecting and classifying other systems
  → diversity
  → hidden nodes

Why? It only makes sense
- Reduce detection requirements of individual sensors
- Take advantage of the radio signal variability
- Spectrum utilization is a spatial phenomenon

- Node-processing
  → Detection/classification algorithms
  → Decision making (“data reduction”)
  → Data association (space, time, frequency)
- Network-processing
  → Data fusion
  → Data transmission (who? when? what?)
  → Data association (space, time, frequency)

Distributed Sensing Algorithm Example



Fusion center:

$$\gamma_0 : \frac{p(y_0|H_1)}{p(y_0|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \prod_{i=1}^{N} \frac{P(u_i|H_0)}{P(u_i|H_1)}$$

Radios:

$$\gamma_i : \frac{p(y_i|H_1)}{p(y_i|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \frac{P(u_0=1|u_i=1,H_0) - P(u_0=1|u_i=0,H_0)}{P(u_0=1|u_i=1,H_1) - P(u_0=1|u_i=0,H_1)}$$

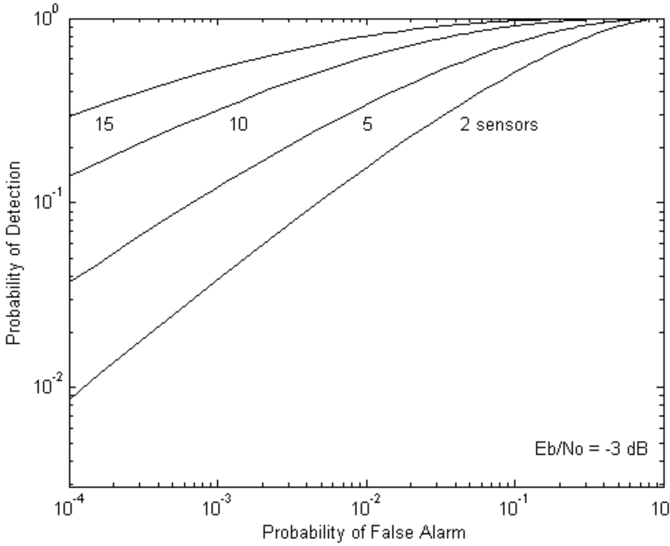
$$P(u_0=1|u_i=k,H) = \sum_{u_1} \underset{\neq i}{\cdots} \sum_{u_n} P(u_0=1|u_1,\cdots,u_i=k,\cdots,u_N,H)$$

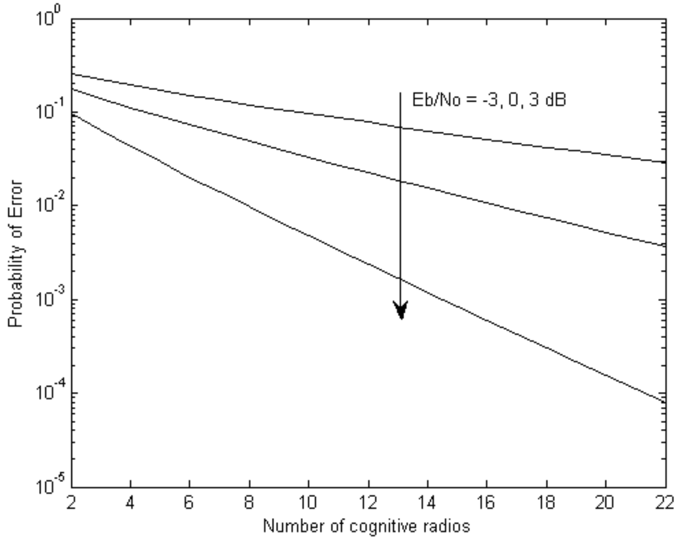
Example: Two independent sensors, H_0 N(0,1), and H_1 N(1,1).

$P(H_0) = 0.4$
1 sensor → thr = 0.67
2 sensors → thr = 1.25
Fusion rule: OR

$P(H_0) = 0.6$
1 sensor → thr = 1.5
2 sensors → thr = 0.8
Fusion rule: AND

Distributed Sensing: Examples





Distributed detection of a known signal in AWGN, with optimal thresholds obtained by a Gauss-Seidel iterative algorithm.

TABLE I
PROBABILITY OF CLASSIFICATION FOR THE SINGLE RADIO CASE

	Hypothesis				
	Noise	BPSK	QPSK	FSK	MSK
Noise	0.9721	0.0020	0.0003	0.0000	0.0150
BPSK	0.0062	0.9780	0.0015	0.0067	0.0780
QPSK	0.0000	0.0000	0.9357	0.0000	0.0420
FSK	0.0001	0.0103	0.0001	0.9933	0.0022
MSK	0.0216	0.0097	0.0624	0.0000	0.8628

TABLE III
PROBABILITY OF CLASSIFICATION FOR THE DISTRIBUTED CASE (3 RADIOS WITH FUSION CENTER)

	Hypothesis				
	Noise	BPSK	QPSK	FSK	MSK
Noise	0.9985	0.0000	0.0000	0.0000	0.0000
BPSK	0.0001	0.9998	0.0000	0.0008	0.0003
QPSK	0.0000	0.0000	0.9949	0.0000	0.0027
FSK	0.0000	0.0000	0.0000	0.9992	0.0000
MSK	0.0014	0.0002	0.0051	0.0000	0.9970

Distributed modulation classification (AWGN), using a cyclic feature-based classifier and optimal thresholds obtained by a Gauss-Seidel iterative algorithm.

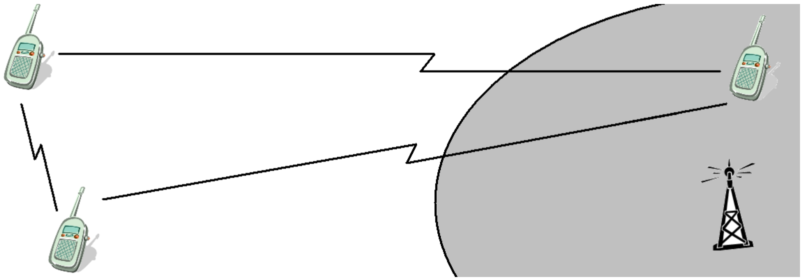
Problem: Theoretical bounds on the distributed spectrum sensing performance

Distributed Sensing: Complexity

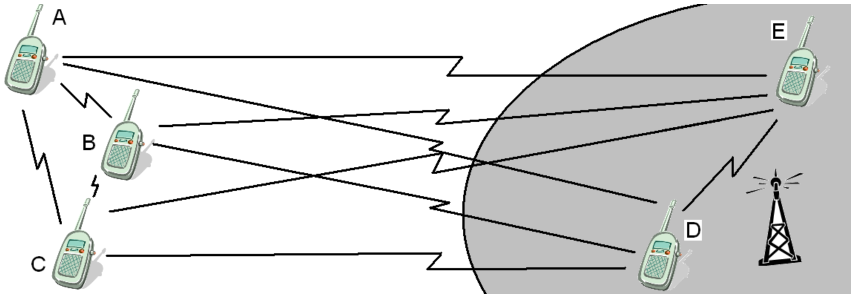
- Problem: “On the complexity of decentralized decision making and detection problems, ... our results point to the inherent difficulty of decentralized decision making and suggest that optimality may be an elusive goal” [Tsitsiklis’85]
- Possible approaches:
  - Iterative, message-passing algorithms
  - Graphical methods
    - Distributed detection problems are very well represented by graphical models. Such models, including Bayesian networks, capture the diverse interdependencies among a set of variables (node observations and decisions) and the nodes’ connections
    - The integration of this set of variables is then captured in a probabilistic inference problem (e.g., belief propagation)
- Other important issues: network configuration, power/bandwidth requirements, data association…

Problem: Design of *efficient*, *low-complexity* algorithms for distributed spectrum sensing

Spatial Aspects of Distributed Sensing

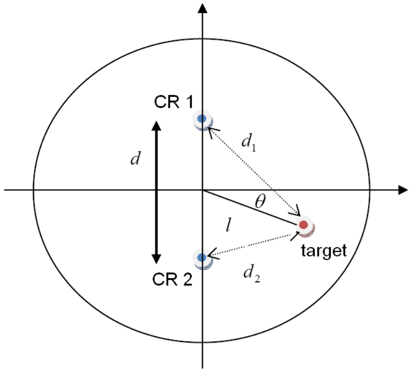


Measure of reliability



Correlation

Positioning (you and your peers):
Assume that experimental research says that *on average* the observations of radios separated by one yard have correlation coefficient 0.6. How can two cognitive radios that are separated by this distance (and know of this fact) take advantage of this average correlation when performing sensing?

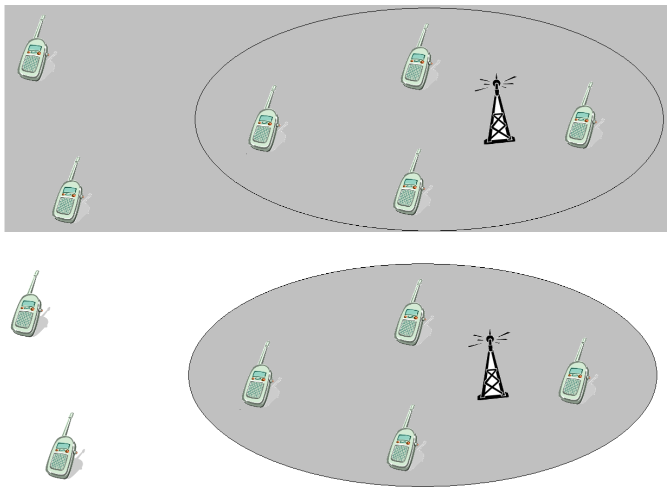


Example: Correlation coefficient of SNR estimates

d	1	10	50	100
ρ	0.49	0.47	0.41	0.35

(R = 1000, SNR_t = 70 dB)

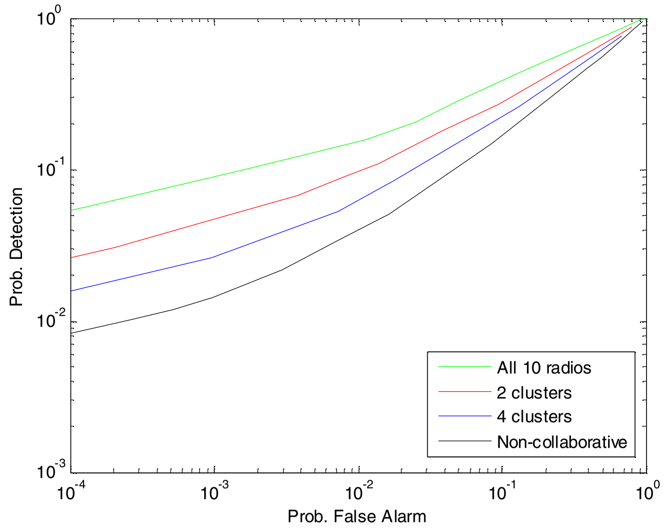
Spatial Spectrum: Clustering

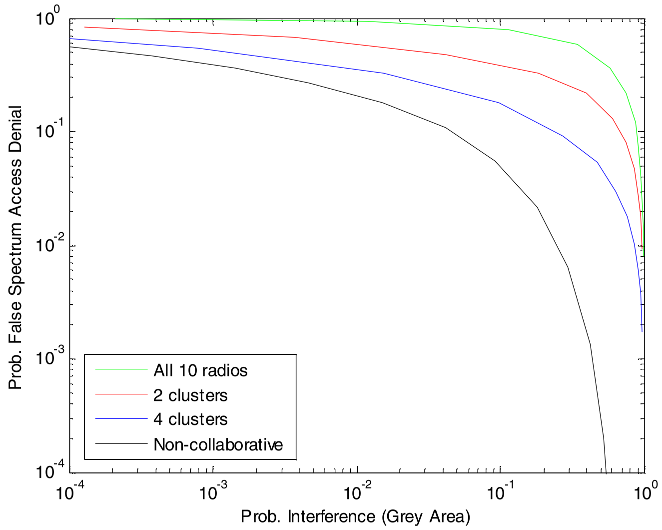


→ Do we really want a global decision?

→ Put things in perspective: no need for CRs in Seattle to know what's happening in Blacksburg

→ Granularity vs. power/bandwidth savings (warning: minimum number of radios is required to achieve a given reliability)





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Problem: How should a network of cognitive radios configure itself in order to perform spectrum sensing?

The 10 100 1000 1 Project

A CR ad-hoc network…

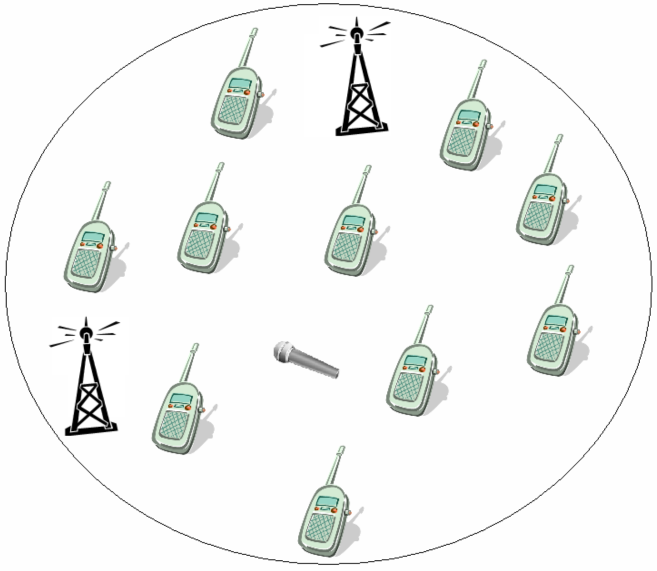
… of 10 cognitive radios that

… by transmitting a total of 100 bits each

… by performing 1000 DSP operations

… and in under 1 second

collaboratively perform spectrum sensing

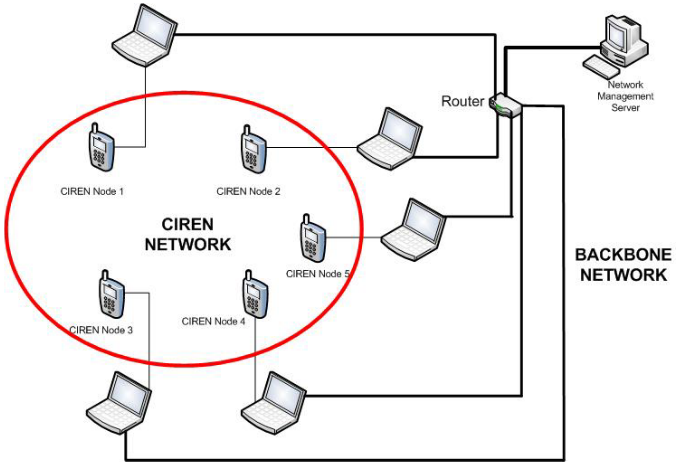


Question: What is the best reliability we can achieve in such a scenario?

Goal: Probability of interference to primary system equal to 0.01% and probability of "false denial" equal to 1% for 99.9% of the time.

VT CR Network Testbed (VT-CORNET)

- **Focus and contribution: PHY, cognitive engine, and cognition at network level**
- **Institute for Critical Technology and Applied Science (ICTAS)**



Architecture

- New ICTAS building, controlled remotely, ceiling
- 48 nodes to be installed: 12/floor x 4 floors
- USRP + RF Frontend: New Motorola chip (100MHz to 4GHz)
- Software: *Any* platform. First stage: OSSIE, an implementation of the Joint Tactical Radio System's Software Communication Architecture (SCA)

Some aspects of CRN that need experimental verification & testing

- Model accuracy: Algorithms, protocols, applications
- Collect performance and QoS measurements for further analysis
- Realistic conditions
- Verify legitimate operation of cognitive engines

Problem: How can we increase confidence in the technology – developers, regulators, users?

Conclusions

We have a lot of work to do:

- Theoretical bounds on the spectrum sensing performance
- Performance limits of sensing algorithms for realistic implementations and practical scenarios
- Theoretical bounds on the distributed spectrum sensing performance
- Design of efficient, low-complexity algorithms for distributed spectrum sensing
- How can (partial and complete) position information be used to improve spectrum sensing?
- How should a network of cognitive radios configure itself in order to perform spectrum sensing?
- How can we increase confidence in the technology – developers, regulators, users?