# Spectrally Agile Waveforms for Dynamic Spectrum Access

Alexander M. Wyglinski, Ph.D.

Associate Professor of Electrical and Computer Engineering

IEEE Vehicular Technology Society Distinguished Lecturer

## Presentation outline

- Introduction
- The Information Age
- Wireless Innovation Laboratory
- Understanding, Securing, and Accessing Spectrum
- Concluding Remarks
- More Information

# Introduction

**Definition:** Cognitive radio

A cognitive radio, as defined by the researchers at Virginia Polytechnic Institute and State University, is "a software defined radio with a cognitive engine brain".

http://en.wikipedia.org/wiki/Cognitive_radio

## So what *is* Cognitive Radio?

+

?

## Cognitive radio means …

Intelligence

*Environmental Awareness*

Agile

Adaptation

Optimization

Learning

Flexible

Opportunistic

Cooperative

**Autonomous**

Spectrally Efficient

***Dynamic Spectrum Access***

# The Information Age

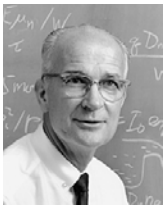
## Several Key Innovators

Marconi

Shannon

Bardeen

Brittain



Shockley

Wireless Transmission

Digital Communications

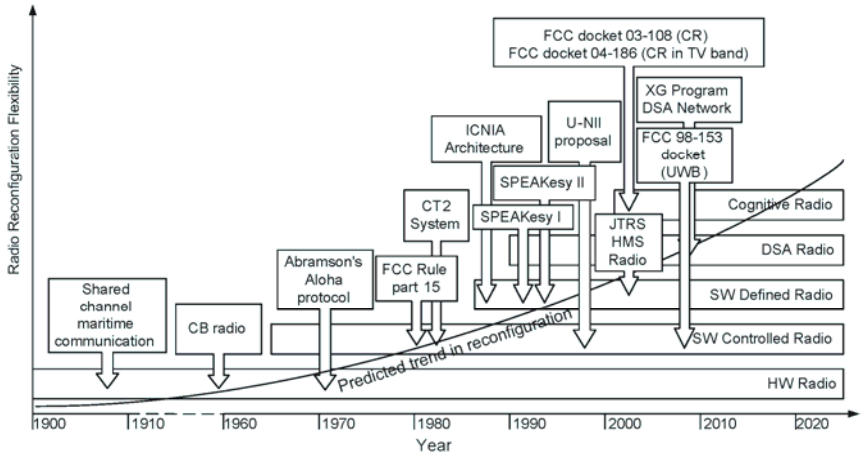
Transistors

Source: Wikipedia

## Progress of Technology



## Evolution of Wireless Systems




"*Cognitive Radio Communications and Networks: Principles and Practice*"
By A. M. Wyglinski, M. Nekovee, Y. T. Hou (Elsevier, December 2009)

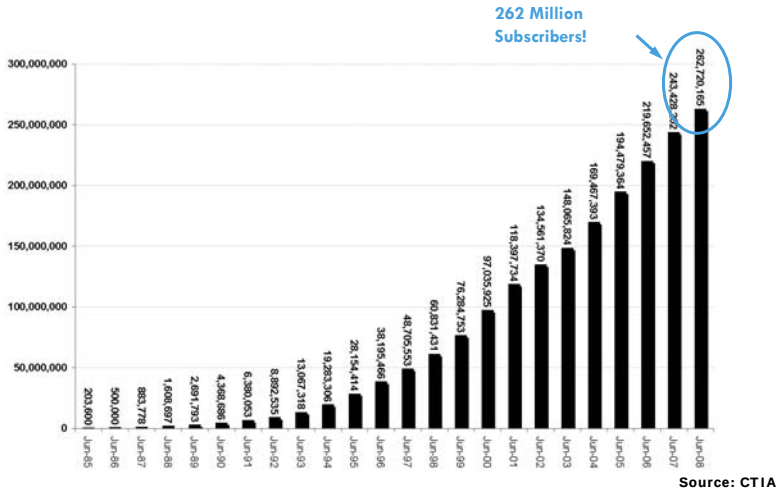
## Quick Survey

How many of you:

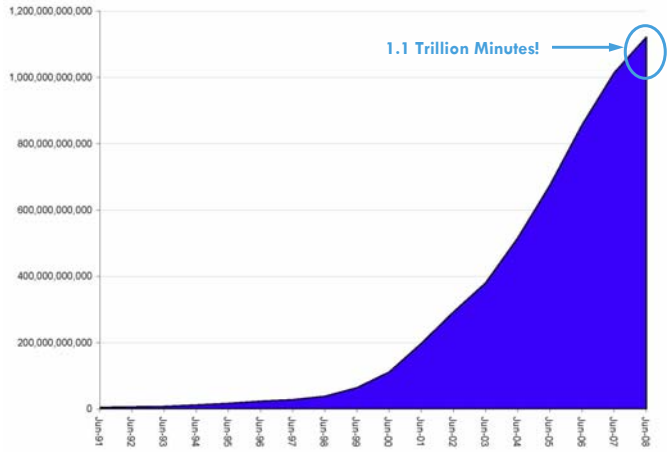
- Own a cell phone?
- Use a laptop with WiFi?
- Use an ATM?
- Fly on a plane?
- Traveled in a car?



## Increasing Demand



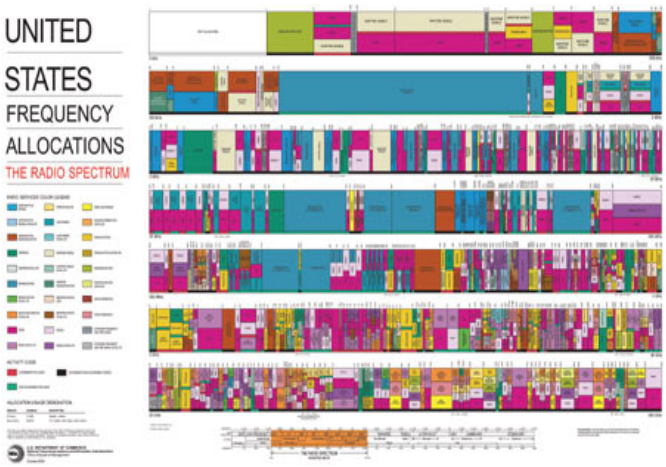
## Increasing Demand




Source: CTIA

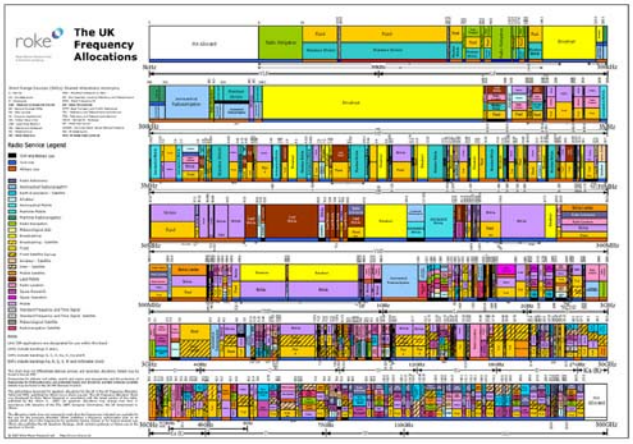


## US Spectrum Scarcity!




Source: NTIA

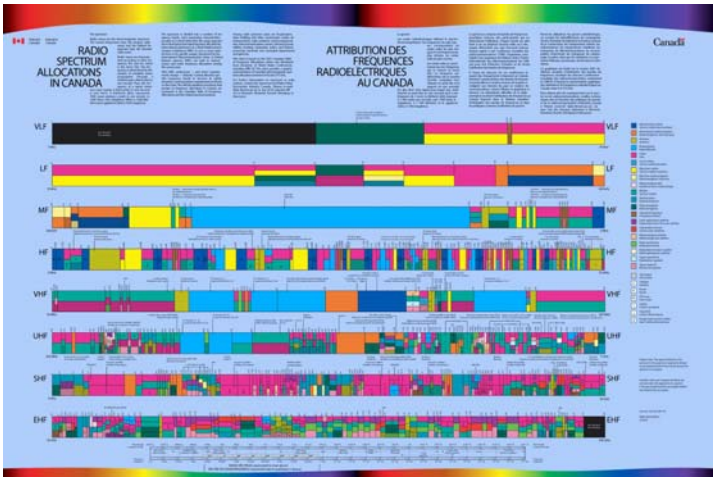
## Across the Pond in the UK!




Source: Roke Manor



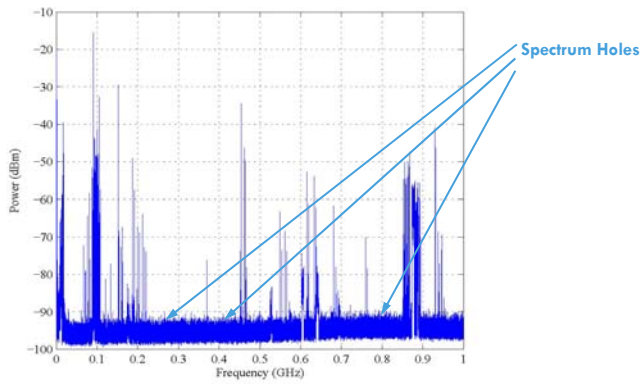
## Oh Canada!




Source: Industry Canada

## Apparent Scarcity

- Measurement studies have shown that in both the time and frequency domains that spectrum is *underutilized*

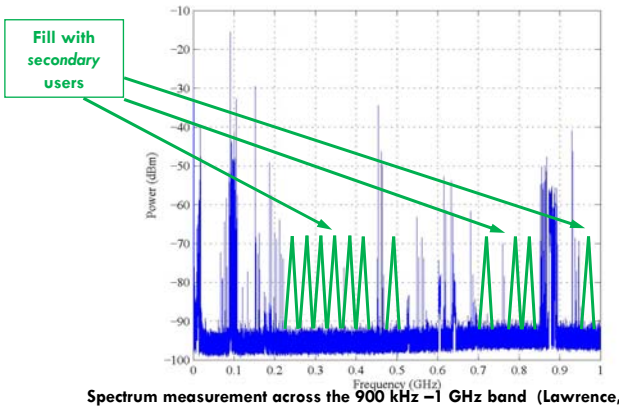



**Spectrum measurement across the 900 kHz –1 GHz band (Lawrence, KS, USA)**



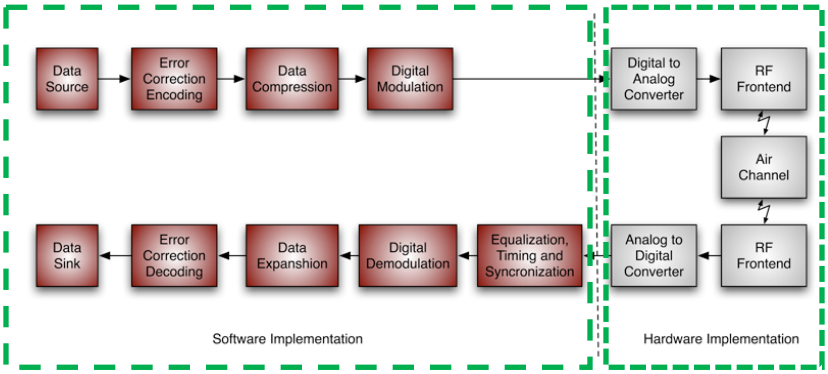
## Potential Solution

- Dynamic Spectrum Access (DSA)




**Spectrum measurement across the 900 kHz –1 GHz band (Lawrence, KS, USA)**

# Enabling Transmission Agility




**PROGRAMMABLE** **FIXED**



# Sample SDR Platforms

**Universal Software Radio Peripheral 2 (USRP2) Unit.**

**COSMIAC FPGA board currently being retrofitted for better memory access, to add USB functionality and to make the board SPA compatible.**

# Mitola & Cognitive Radio

Mitola

Cognitive Radio

An Integrated Agent Architecture for Software Defined Radio

Dissertation

Doctor of Technology

Joseph Mitola III

Royal Institute of Technology (KTH)

Teleinformatics

Electrum 204

SE-164 40 Kista

Sweden

TRITA-IT AVH 00:01

ISSN 1403-5286

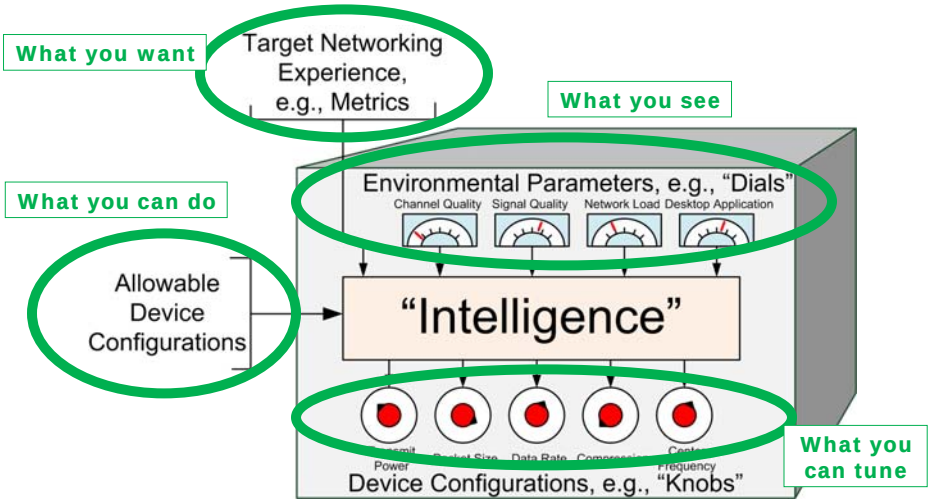
ISRN KTH/IT/AVH--00/01--SE

This dissertation is submitted in partial fulfillment of the degree of Doctor of Technology.

8 May, 2000



# Cognitive Radio: A Black Box Model

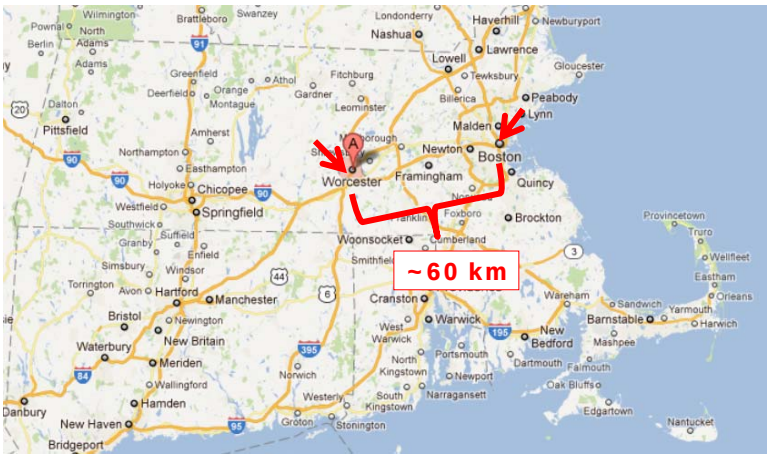


# Wireless Innovation Laboratory

## Who is Alex Wyglinski?

- Associate Professor, WPI ECE
- Director, *Wireless Innovation Laboratory*
  - 8 Ph.D. students, 5 M.S. students
- Distinguished Lecturer, IEEE Vehicular Technology Society (2012-2014)
- Technical Editor, IEEE Communications Magazine
- Editor, IEEE Transactions on Wireless Communications
- General Co-Chair, IEEE VTC 2015-Fall (Boston, MA, USA)
- ~35 journal publications, ~75 conference papers, 9 book chapters, 2 books
- Served or is serving as PI/co-PI for several federal and industrial grants

# Where is WPI?






# What is WPI?

- Founded in 1865; 3rd oldest US polytechnic
  - Model for most engineering schools in US
  - Nationally ranked as 64th Best College in U.S.
    (2011 US News Rankings)
  - Voted one of the Top 10 Best U.S. Colleges for "Young Einsteins" by Unigo
    (together with MIT, CalTech, Princeton, Dartmouth, Stanford, Johns Hopkins, Case Western, Georgia Tech, and Cornell)
- 3800 students & 220 faculty
  - ECE: 318 undegraduate, 250 graduate, 21 faculty

## What is "*Lehr und Kunst*"?

- Project-based education at the core of "*The WPI Plan*"
- Many ECE students conduct their senior capstone design projects (called "*Major Qualifying Projects*" or MQPs) at off-campus locations:
  - MIT Lincoln Laboratory
  - MITRE (Bedford Campus)
  - General Dynamics (Groton Campus)
  - Silicon Valley
  - Wall Street
  - Etc …



## Wireless Innovation Laboratory

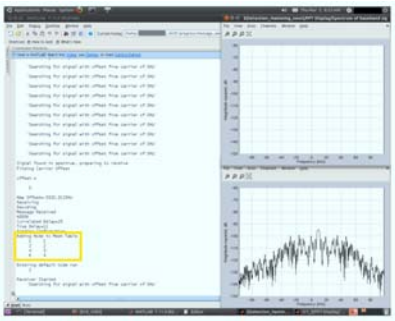
- 2 USRP (Version 1) software-defined radio platforms
- 14 USRP (Version 2) software-defined radio platforms
- 15 USRP (Version N210) software-defined radio platforms
- 1 Agilent CSA N1996A 0-3 GHz spectrum analyzer (with battery packs)
- 1 Mini-discone antenna (100 – 1600 MHz, with 3' tripod)
- 1 WG horn antenna (0.7 – 18.0 GHz, with tripod)
- 1 Xilinx Virtex 5 HW-V5-ML506-UNI-G Prototyping Board
- 25 complete licenses of MATLAB and Simulink with associated toolboxes and blocksets
- 2 OPNET licenses


## WI Lab External Sponsorship

Worcester Polytechnic Institute

## SDR Activities at WPI

Photograph of a supervised laboratory session for ECE4305 "Software-Defined Radio Systems and Analysis" during February 2011.



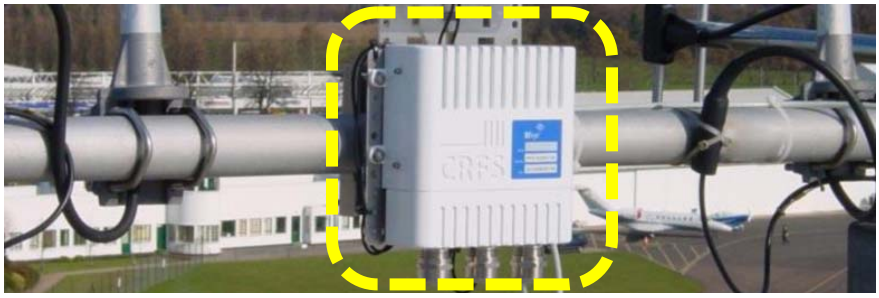
Screen capture of a functioning ECE4305 course design project in MATLAB showing four SDR units forming an ad hoc wireless network.

**http://www.sdr.wpi.edu/**

Worcester Polytechnic Institute

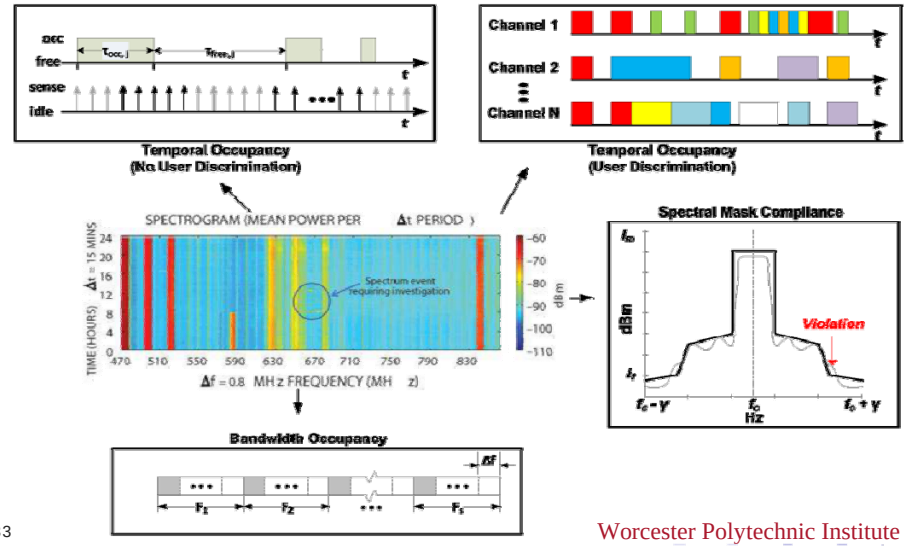
# Understanding Spectrum

## Current state of the art




RFEye Spectrum Monitoring Solution

# Probabilistic model

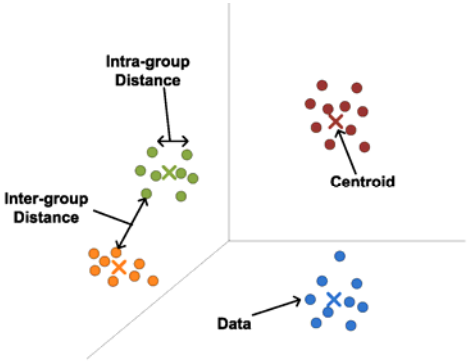




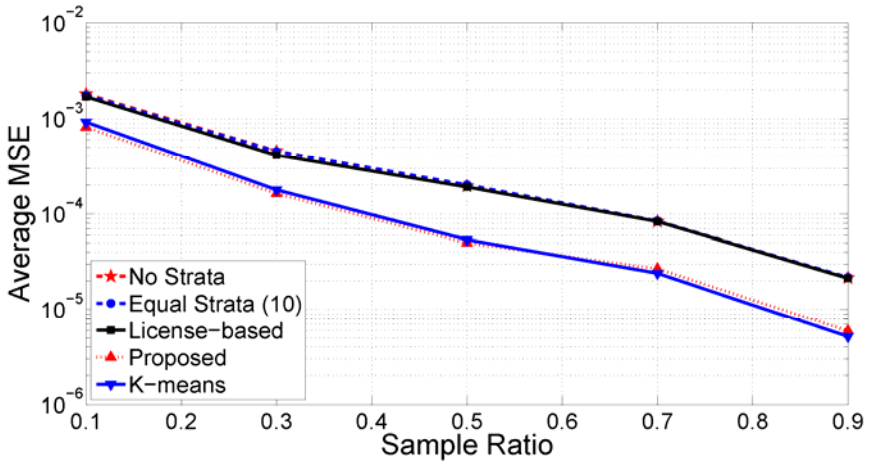



# Random sampling concept

- Random sampling facilitates statistical characterization
- Random sampling designs
  - Systematic, SRS, stratified, cluster,…
- Data grouping and sample allocation are crucial to effective characterization
- Benefits
  - Dimensionality reduction, summarization, estimator variance reduction, sampling bias reduction



## Results

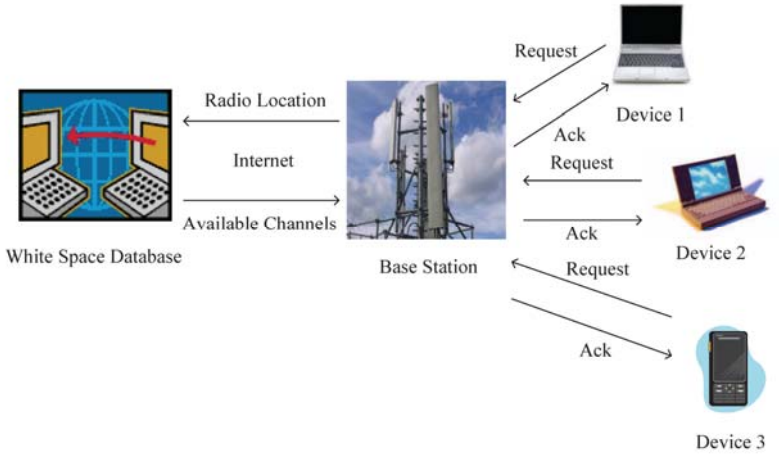







# Securing Spectrum

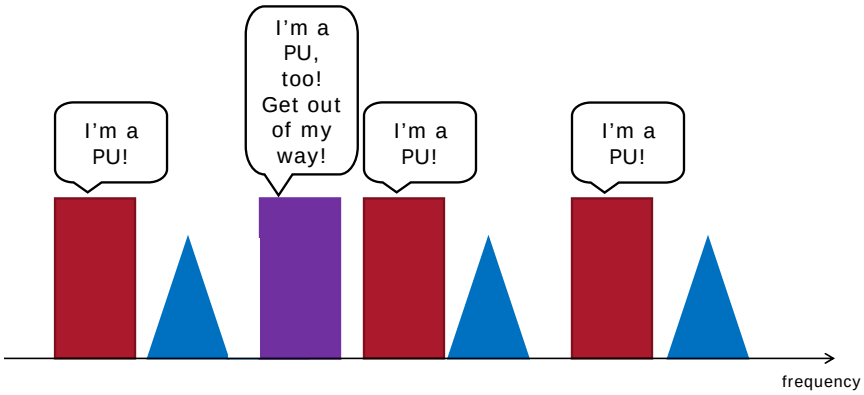
## How is DSA currently managed?








## Potential vulnerability

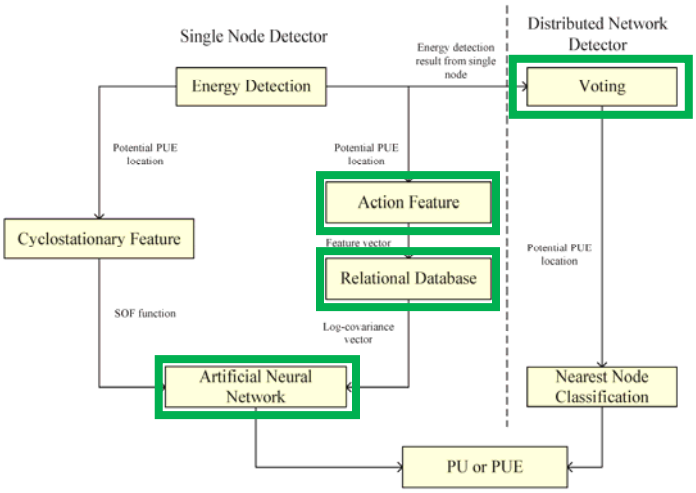


# Existing techniques

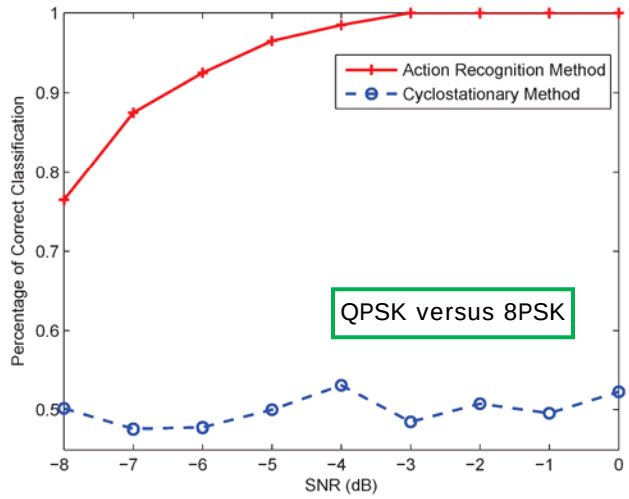
- Energy Detection
  - Possess a significant probability of missed detection
- Localization-based Detection
  - Can only be employed for stationary primary transmitters with known coordinates
- Analytical Model-based Detection
  - Only works well for a specific network model
- Signature-based Detection
  - Require special hardware or software



# Our approach



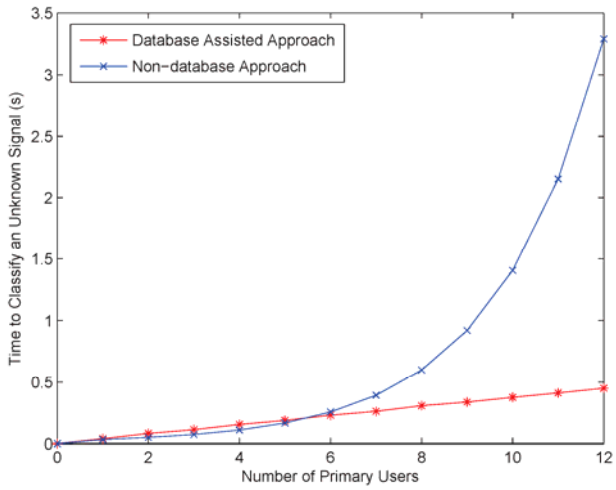
# Results








# Results



# Accessing Spectrum

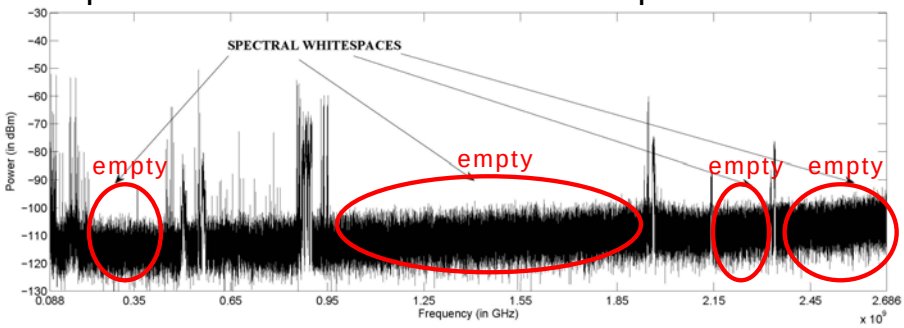


## Opportunistic Spectrum Access

- Opportunistic spectrum access (OSA) is a significant paradigm shift in the way wireless spectrum is accessed
  - Instead of PUs possessing exclusive access to licensed spectrum, SUs can temporarily borrow unoccupied frequency bands
  - SUs must respect the incumbent rights of the PUs with respect to their licensed spectrum
- OSA enables greater spectral efficiency and facilitates greater user and bandwidth capacity

# OSA Motivation

- The utilization efficiency of "prime" wireless spectrum has been shown to be poor



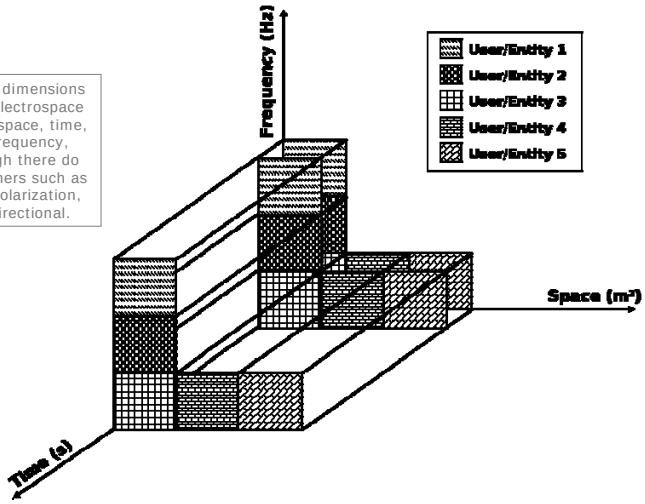

**A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42º16.36602, W71º48.46548)**

A. M. Wyglinski, M. Nekovee, Y. T. Hou (Eds.). "*Cognitive Radio Communications and Networks: Principles and Practice.*" (Chapter 6) Academic Press, December 2009.



# Leveraging the Electrospace

Several dimensions of the electrospace include space, time, and frequency, although there do exist others such as code, polarization, and directional.



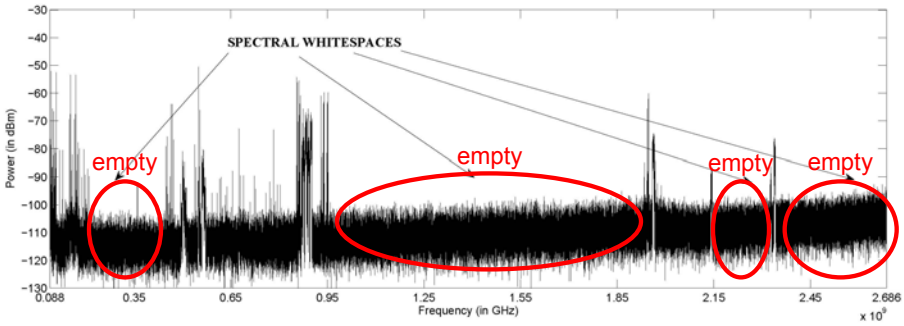

"*Cognitive Radio Communications and Networks: Principles and Practice*"
By A. M. Wyglinski, M. Nekovee, Y. T. Hou (Elsevier, December 2009)

## Several Possible Approaches

- Secondary transmission in licensed spectrum can be classified into three categories:
  - Cooperative Approach
    - Primary and secondary users coordinate with each other regarding spectrum usage
  - Underlay Approach
    - Secondary signals transmitted at very low power spectral density; undetected by primary users
    - e.g., ultra wideband (UWB)
  - Overlay Systems
    - Secondary signals fill in the spectrum unoccupied by primary users



## Spectral Opportunities!

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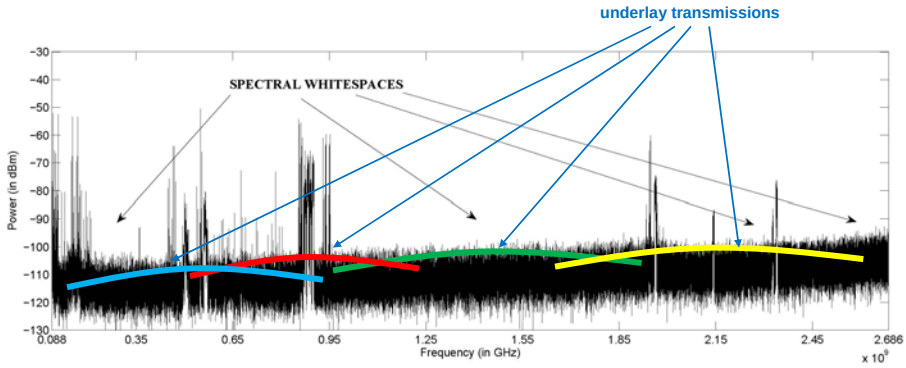
A. M. Wyglinski, M. Nekovee, Y. T. Hou (Eds.). "*Cognitive Radio Communications and Networks: Principles and Practice.*" (Chapter 6) Academic Press, December 2009.

# Underlay Solution

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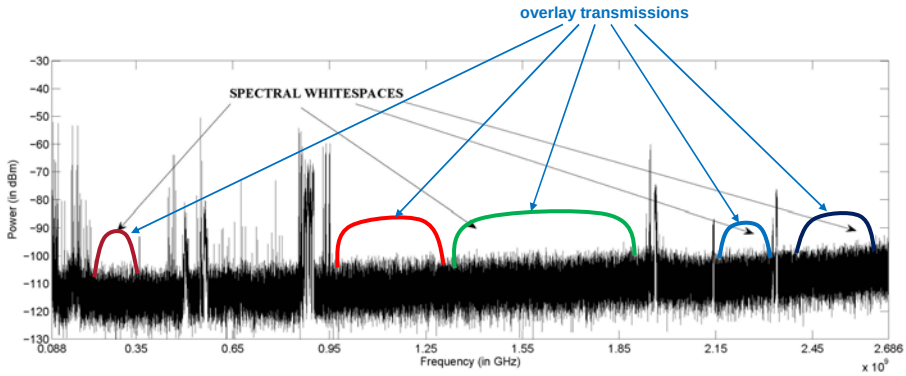
# Overlay Solution

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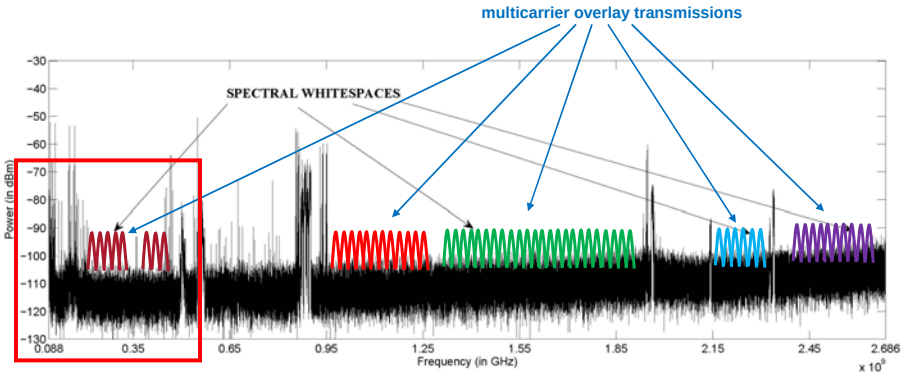
A. M. Wyglinski, M. Nekovee, Y. T. Hou (Eds.). "*Cognitive Radio Communications and Networks: Principles and Practice.*" (Chapter 6) Academic Press, December 2009.

## Multicarrier-Based OSA

- Multicarrier modulation is a variant of the conventional frequency division multiplexing (FDM)
  - **Orthogonal Frequency Division Multiplexing** (OFDM) an efficient form of multicarrier modulation
- In order to utilize unused portions of licensed spectrum, several subcarriers can be turned OFF to avoid interfering with the primary signals
- Each subcarrier experiences flat-fading and hence high data-rates are possible if several unused bands of secondary spectrum are available



## Multicarrier Overlay Solution

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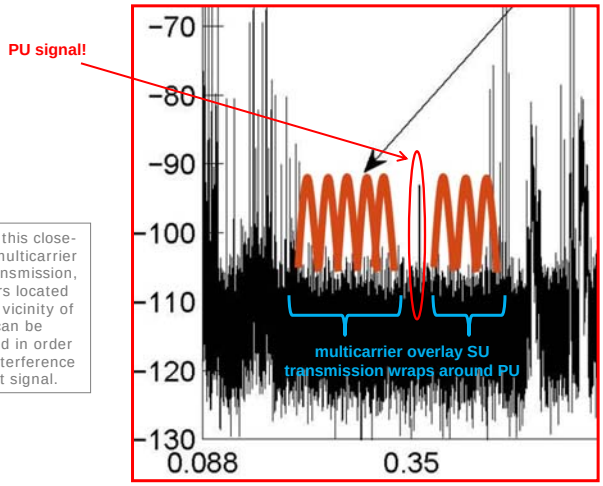
A. M. Wyglinski, M. Nekovee, Y. T. Hou (Eds.). "*Cognitive Radio Communications and Networks: Principles and Practice.*" (Chapter 6) Academic Press, December 2009.

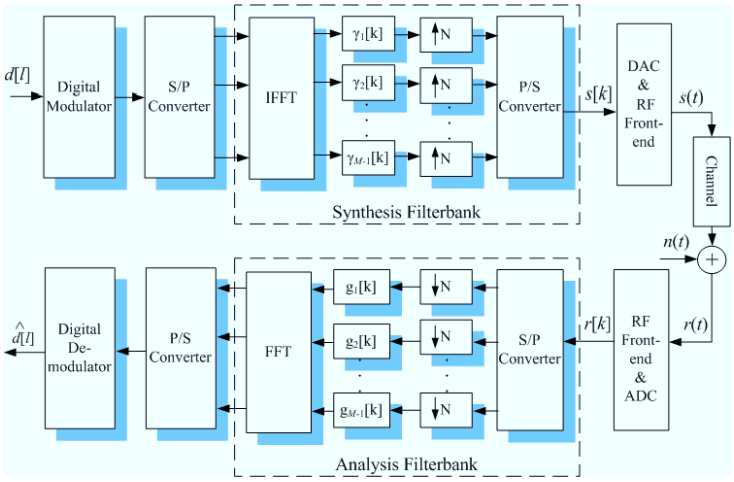
## Spectral Agility In Action!

As seen in this close-up of the multicarrier overlay transmission, subcarriers located within the vicinity of a PU can be deactivated in order to avoid interference with that signal.






## Spectrally Agile Multicarrier




H. Bogucka, A. M. Wyglinski, S. Pagadarai, A. Kliks, "Spectrally Agile Multicarrier Waveforms for Opportunistic Wireless Access", IEEE Communications Magazine, June 2011.

## Major Issue: Out-of-band Emission

- Out-of-band (OOB) interference problem with OFDM-based cognitive radios
- Power spectral density of the transmit signal over one subcarrier:

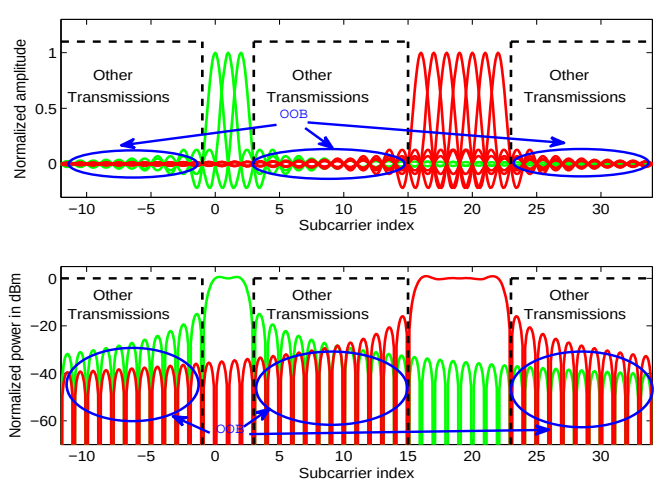
$$\Phi_{ss}(f) = A^2 T \left( \frac{\sin \pi f T}{\pi f T} \right)^2$$

- Mean relative interference to a neighboring legacy system subband:

$$P_{Interference}(n) = \frac{1}{P_{Total}} \int_n^{n+1} \Phi_{ss}(f) df$$



## Sinc Pulses Have High OOB Levels!

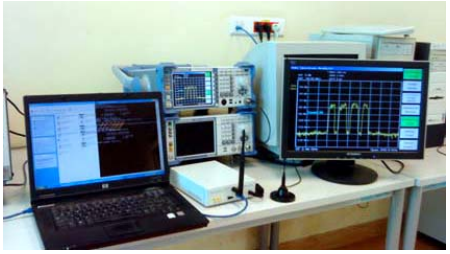


## Several Solutions

- Cancellation Carriers
  - Non-data bearing subcarriers whose phase and amplitude values cancel OOB
- Modulated Filter Banks
  - Attenuates OOB in stopband region
- Combine cancellation carriers (CCs) with modulated filter banks (MFBs) to attenuate OOB emissions



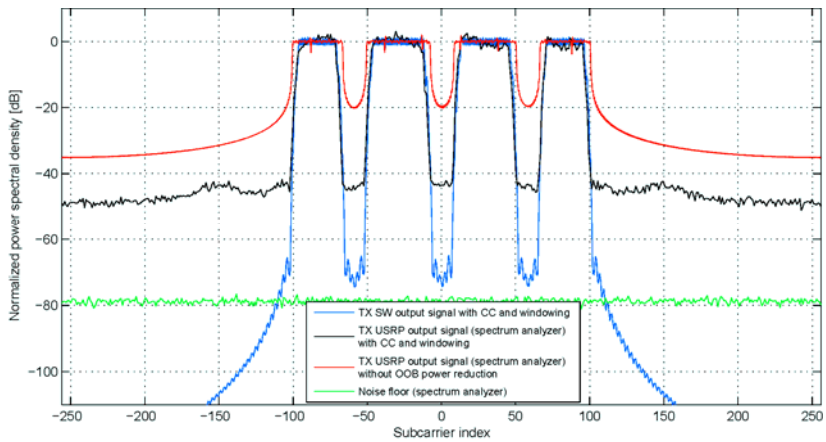
## Hardware Experimentation



**Photograph of a spectrally agile wireless transceiver test-bed at Poznan University of Technology, Poznan, Poland.**

**Photograph of a spectrally agile wireless transceiver test-bed at Worcester Polytechnic Institute, Worcester, MA, USA.**

## Results




P. Kryszkiewicz, H. Bogucka, A. M. Wyglinski. "Protection of Primary Users in Dynamically Varying Radio Environment: Practical Solutions and Challenges." Accepted for publication in the EURASIP Journal on Wireless Communications and Networking, December 23, 2011



## Concluding Remarks

## These are interesting times!

- Numerous advances in cognitive radio, dynamic spectrum access, and software-defined radio have recently occurred
  - Secondary access of digital TV spectrum
  - Ratification of IEEE 802.22, IEEE 802.11af standards
- Today's wireless landscape is quickly changing due to new capabilities of wireless transceiver devices
  - Largely due to smaller, faster processing devices resulting from applications such as smart phones



## Still room for improvement

- There still exists a substantial amount of research that is needed to make future wireless devices such as cognitive radio more reliable
  - Ensuring minimal interference to other wireless transmissions
  - Enabling real-time decision-making and transmission operations
  - Making RF spectrum access more reliable for everyone involved

# More Information

## Contact info

Professor Alexander Wyglinski

Department of Electrical and Computer Engineering
Worcester Polytechnic Institute
Atwater Kent Laboratories, Room AK230

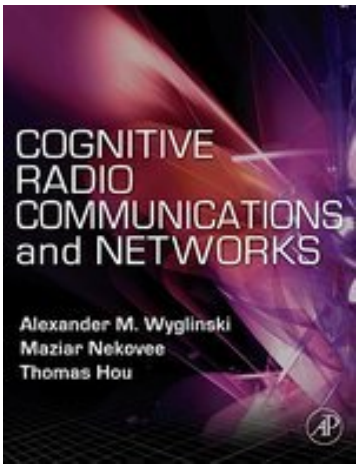
508-831-5061

alexw@ece.wpi.edu

http://www.wireless.wpi.edu/

## Cognitive radio textbook

- Available since December 2009 (Academic Press)
- 20 chapters
- End-of-chapter problems (with solutions guide)
- Presentation slides for most chapters
- Covers physical and network layers, in addition to current platforms and standards






## New SDR textbook

- January 2013 Publications Date (Artech House Publishers)
- 9 comprehensive chapters
  - Fundamentals in signals & systems, probability, and digital communications
  - "Hands on" approach to learning digital communication concepts using SDR and Simulink
  - End-of-chapter problems
  - Corresponding course lecture slides

http://www.sdr.wpi.edu/