Spectrally Agile Waveforms for Dynamic Spectrum Access

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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".

So what *is* Cognitive Radio?

Cognitive radio means ...

Intelligence    Agile    Spectrally Efficient
Adaptation     Flexible    Dynamic Spectrum Access
Opportunistic  Cooperative  Autonomous

Environmental Awareness Learning Optimization
The Information Age

Several Key Innovators

Marconi

Shannon

Bardeen

Brittain

Shockley

Wireless Transmission

Digital Communications

Transistors


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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

262 Million Subscribers!

Source: CTIA
Increasing Demand

Source: CTIA

US Spectrum Scarcity!

Source: NTIA
Across the Pond in the UK!

The UK Frequency Allocations

Source: Roke Manor

Oh Canada!

Source: Industry Canada

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Apparent Scarcity

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

Potential Solution

- Dynamic Spectrum Access (DSA)

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

Sample SDR Platforms

Universal Software Radio Peripheral 2 (USRP2) Unit.

COSMAC FPGA board currently being retrofitted for better memory access, to add USB functionality and to make the board SPA compatible.
Cognitive Radio: A Black Box Model

What you want
- Target Networking Experience, e.g., Metrics

What you see
- Environmental Parameters, e.g., "Dials"
- "Intelligence"

What you can do
- Allowable Device Configurations

What you can tune
- Device Configurations, e.g., "Knobs"
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?

Worcester Polytechnic Institute

~60 km

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 undergraduate, 250 graduate, 21 faculty

Worcester Polytechnic Institute
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  
- 1.4 USRP (Version 2) software-defined radio platforms  
- 1.5 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

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/

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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

QPSK versus 8PSK

Results

Time to Classify an Unknown Signal (s)

Number of Primary Users

Database Assisted Approach
Non-database Approach
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 (N42°16.36602, W71°48.46548)

Leveraging the Electrospase

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

A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42°16.36602, W71°48.46548)

Underlay Solution

A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42°16.36602, W71°48.46548)

Overlay Solution

A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42°16.36602, W71°48.46548)

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

A snapshot of PSD from 88 MHz to 2686 MHz measured on July 11th 2008 in Worcester, MA (N42°16.36602, W71°48.46548)

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

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:
  \[ P_{\text{Interference}}(n) = \frac{1}{P_{\text{Total}}} \int_{n}^{n+1} \Phi_{ss}(f) df \]

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

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

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Cognitive radio textbook

- 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/