Smart-Radio-Technology-Enabled Opportunistic Spectrum Utilization

Xin Liu
Computer Science Dept.
University of California, Davis

Purdue University, 2005
Spectrum, Spectrum

- Spectrum is expensive and heavily regulated
- 3G spectrum auction in EU
  - $35 billion in England, $46 billion in Germany
- 2005 PCS Broadband auction: $2 billion in US

Q: Is spectrum really that scarce and expensive?
Spectrum Usage I

1850-1900MHz Band

Source: Shared Spectrum Company
1990-2100MHz band

Source: Shared Spectrum Company
Spectrum Usage III

2300-2360MHz band  Source: Shared Spectrum Company
Spectrum Occupancy Is Low

- Shared Spectrum’s measurements indicate
  - low occupancy bands
  - high occupancy bands
  - Under 3GHz, over 62% of white space
    - White space: more than 1MHz wide 10 minutes long
- Similar measurements from others
- FCC Spectrum Policy Task Force Report
  - The limiting factor: spectrum access instead of physical scarcity of spectrum
  - Due to legacy command-and-control regulation
  - More flexible regulations needed
Command-&-Control

- 70-year old spectrum regulation legacy
- Then
  - Analog devices fixed to band
  - Long range applications
  - Interference a significant challenge
- Now
  - Digital, capable, less expensive device
  - Dense usage (e.g., WLAN)
- Demand for PRODUCTIVE use
Cognitive Radio

Joseph Mitola III

Dissertation: “cognitive radio: an integrated agent architecture for software defined radio”

Definition

- To detect user communication needs as a function of use context
- To provide radio resources and wireless services most appropriate to those needs
FCC Definition

- “A cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates”.

- “The majority of CR will probably be SDRs (Software Defined Radios), but neither having software or being field programmable are requirements of a cognitive radio.”
Smart-Radio Technology

- The ability to
  - Active negotiation/communication
  - Passive sensing and decision making
  - Adapt its transmission parameters

- Known as
  - Software-defined radio, cognitive radio, programmable wireless, spectrum agile radio, brainy radio, etc.
Spectrum Access

- More unlicensed band
  - Success of IEEE 802.11
  - Move bands from old and inefficient users
- Secondary market
  - Synthesize property right
  - Interruptible leasing
  - Real-time auction, leasing, etc.
- Give priority, but not exclusion
  - Legacy users have strict priority
  - Non-interfering-based access
Current Activities

- DARPA XG Program
  - Military applications
- NSF NeTS Program
  - ProWiN (Programmable Wireless Networks)
- FCC initiatives
  - Interference temperature metric
  - Unlicensed operation in TV bands
  - Secondary market rule making
  - Ultra-wide band
XG Architecture

Source: XG Preston Marshall
Interference Temperature

- Interference temperature (FCC)
  - Metric for interference that takes into account the actual (RF) energy from transmissions of spectrum-based devices
  - Set a maximum cap on the aggregate of these transmissions
  - Receiver side
- Current approach: specify and limit transmit powers of individual devices
- More intense use of spectrum
- Predictability of interference to existing services.
Potential Approaches

Approaches
- Self-sensing based approach
- Feedback from primary receiver
- A grid of monitoring stations with broadcast capability

Actions
- Channel selection
- Power control
- Change antenna shape/direction
- Cease transmission
CORVUS

- CORVUS: A cognitive radio approach for usage of virtual unlicensed spectrum
  - A white paper from Berkeley
- Spectrum pooling from different bands
- Dedicated logical channels for control and exchange of sensing information
  - Universal and group control channel
  - Dedicated band, UWB, ISM band
- PHY: sensing, channel est., & transmission
- LINK: group & link management, MAC
Availability

- Software defined radio
- GNU radio
- A few platforms supported by NSF
  - Univ. of Kansas, Univ. of Colorado, Stevens, WINLAB
- Venu Inc.
- Cal-Radio
- WLAN devices
Who will benefit

- Conventional answer: new entrants and small players
  - Easier spectrum access
  - Less infrastructure cost
  - Novel applications

- Answer 2: Incumbent wireless carriers
  - Carriers are consumers of spectrum
  - Much less expensive spectrum access and uncertainty
  - Existing infrastructure support for sensing/collaboration

- Answer 3: You and me
A More General View

- Smart-radio technology enables more efficient spectrum usage
  - Example: WLAN
- Application scenarios
  - Dense and heterogeneous wireless systems
  - Self-organizing wireless networks
  - Broadband multihop mesh wireless access
  - True global roaming
Our Project

- Understand the impact and the properties of the white space
  - Inherent properties
  - How to capture it
- Share the white space dynamically and efficiently
  - Develop algorithms and protocols
Characteristics of White Space

- Performance metrics:
  - Effective Non-Opportunistic Bandwidth
  - Space-bandwidth product
- Spatial Correlation
- Temporal Correlation
Premises

- Primary users
  - Spectrum owners
  - Strict priority
  - May not be required to retrofit the needs of other users

- Secondary users
  - Equipped with smart devices
  - Opportunistic access based on availability
  - Follow etiquettes/regulations set by primary/FCC
  - Channel availability determined by traffic/topology of primary users
Measure White-Space Utilization

- The impact of fully utilizing white space
  - Ex: 62% of white space under 3G.
  - Is it equivalent to gaining 3x0.62GHz?
- Secondary nodes observe different channel availabilities
  - Depending on the location, time, pattern of primary users
- Quantify the impact of the heterogeneity
System Model

Primary users (I,II,III,IV)

Secondary users (1-5)
ENOB: Effective Non-Opportunistic Bandwidth

- Equivalent non-opportunistic bandwidth required to achieve the same performance as in the case of opportunistic spectrum availability.
- Non-opportunistic band: always available to the users as in the traditional command-and-control manner.
- Depends on channel availability correlations of interfering users.
- A metric to quantify the impact of correlation.
A Naïve Example

- Two secondary nodes opportunistically access a primary channel
- Observes independent channel availability with prob. $p$
- They interfere with each other
- Assume one unit of throughput per unit of bw.
A Naïve Example Cont’d

- Total throughput:
  - \[ W(p^*p x_1 + 2p(1-p)x_1 + (1-p)(1-p)x_0) = Wp(2-p) \]
- ENOB = \( Wp(2-p) \)
  - 62% white space under 3G
    - \( W = 3 \text{GHz}, p = 0.62 \)
  - ENOB = 2.76 GHz
  - instead of \( Wp = 3 \times 0.62 = 1.86 \text{GHz} \)
Intuitions

- Spectrum is not being “created” by secondary users.
- Exploit spectrum holes created by primary users.
  - Different secondary users have diff. availability
- Spectrum opportunity and its property are determined by primary users
  - Communication range, transmission power, traffic pattern, density, topology, etc.
- ENOB: a metric to quantify the degree of spatial reuse and statistical multiplexing between primary and secondary users.
  - Analogy: effective bandwidth used to capture statistic multiplexing gain.
  - Depends on correlations of channel availability among users
  - Depends on sharing criterion
Consider the dependency of channel availability among users

- Evenly spaced nodes
- $p_0$: prob. a node observes the channel avail.
- $p_c$: prob. node i observes given i-1 does
A Chain Topology

\[ p_0 = 0.1 \]

\[ p_0 = 0.7 \]

\[ \text{Eqv. Bw.} \]

\[ N = 2 \]
\[ N = 9 \]
Different Schemes

- Node 1 interferes with all others
- Nodes observe channel availability independently

Objectives:
- maxsum
- maxmin
- maxT1
ENOB cont’d
ENOB Summary

- A metrics to quantify the effect of opportunistic channel availability
- Its value depends on
  - Topology, traffic pattern of primary, etc.
  - Channel availability dependency
  - Channel allocation algorithm/objective
Space-Bandwidth Product

- Product of space and bandwidth utilization
- Quantify the ability to utilize spectrum holes in space and frequency dimensions
- A TV station has a larger footprint than a WLAN
- For broadcasting:
  - Equivalent to channel-user product
Heterogeneous Footprints

- Assume footprints do not overlap
- Homogeneous primary users with random deployment
  - 46% space utilization
- After primary footprints settled, smaller secondary users
  - $46\% + (1 - 0.46) \times 46\% = 71\%$
- Another layer of hierarchy
  - 81% space utilization
Heterogeneity
Observations

- NO cost at primary users
- Gain from heterogeneity in footprint
- Sequence is also important
  - Higher utilization if larger devices being allocated first
  - Ex: WLANs exploit TV channels
Spatial Correlation

- Correlation is a function of dist.
- Primary: Poisson with density $\lambda$
- Footprint w. radius $R$
- $P(A|B)$ vs. $P(A)$
Characteristics Summary

- **ENOB**: equivalent non-opportunistic bandwidth
  - Metric for exploiting spectrum holes that is different from different secondary users.
  - Temporal impact to be addressed

- **Space-bandwidth product**
  - Metric for spectrum holes in space and spectrum
  - Heterogeneity is inherently beneficial

- **Spatial and temporal correlation**
Channel Evacuation

- When primary users come back to a channel, secondaries in the channel need to evacuate as fast and as reliable as possible.
- Detection of the return of primaries:
  - Reliable detection
  - Not all users will detect
- Scheme to disseminate such information:
  - Time for evacuation
  - Peak/average interference during evacuation
Channel Evacuation Cont’d

- One or more users detect primary
- In-band signaling
- No simultaneous transmission and reception
- Subject to interference from both primary and other secondary transmissions
- May not have global information regarding the topology
- Constraints on delay and interference during evacuation
ESCAPE Protocol

- PHY: predefined spread warning message that declares “primary-active”.
- MAC: repeat the warning message as it wishes
- Routing: flooding
  - no prior knowledge needed on network topology
Intuition

- Spreading code: good interference tolerance property
- Different copies (from different nodes) of the warning message is a form of multi-path
  - M-seq code has superior suppression property
  - If Rake receiver is available, benefits can be reaped.
- If two warning message synchronize in a chip-level, signal is indeed enhanced.
  - Different from spreading ALOHA.
Performance Metrics

- **Primary**
  - Time to evacuate
  - Peak aggregated interference
  - Average aggregated interference
  - Evacuation failure probability

- **Secondary**
  - Time to evacuate
  - False-alarm rate (when no warning message is sent, one is detected falsely).
Procedure

- Transmits using its access scheme when needed. When not transmitting, listening.
- If received warning message, replay the warning message for N times.
- If an ack for a transmission not received, listen for a period of time.
Repetition is Important

\[ L_t \quad L_s \]

Packet

\[ L_a \]

Warning

\[ L_w \quad L_i \]

Listen

Purdue University, 2005
Performance Evaluation

- Tolerance to
  - Multiple copies of warning message
  - Primary transmission
  - Other secondary transmission
- M-sequence 127 code
- 16 symbols in a warning message
- Detection probability vs. false alarm rate
- Need to keep false alarm rate really low
Good Autocorrelation

M-seq 127

random 127
Multiple Warning Message

\[ Pp=1; Ps=1; nw=[1 \ 5 \ 10 \ 40 \ 80 \ 160]; ns=1 \]

\[ \text{Detection} \]

\[ \text{False Alarm} \]

\[ \text{nw} \uparrow \]
Interference from Primary
Interference from Secondary

![Graph showing detection rate versus false alarm with different nums values.]

- Pp=0; Ps=2; nw=5
- Detection graph with marks for nums=5, 10, 20, 40.
Notes

- Superior self-suppression capability
- Interference tolerance
  - Primary
  - Secondary
- Rake receiver improves performance
- Keep false alarm low
  - Possibly different thresholds
Interference vs. Evacuation Time

- Tradeoff between peak/average interference and time to evacuate
  - Transmission power
  - Code length
- Topology
  - 10x10 Grid
  - Random with 100 nodes
- Assuming only white Gaussian noise
- One repetition

Purdue University, 2005
Impact of Transmission Power

**Grid**

**Random**

Purdue University, 2005
Impact of Code Length

- Keep energy per warning message fixed
- Using the same bandwidth
  - Same single chip-length
  - Longer code implies longer time for transmission and lower transmission power
- Same detection vs. false alarm curve when only primary and other secondary transmission
  - Different threshold needed.
- When multiple warning messages exist, longer code shows better performance
Impact of Code Length (Grid)

Twice the length,
Twice the time,
Half the peak intf,
Total intf. is fixed.
Code Length (Random)
Power and Code Selection

- Constraint 1: peak intf. to primary
  - Assume all secondary transmit
    - All detect
    - Repetition after receiving a warning message
  - Set the peak transmission power
  - Select a code with sufficient interference tolerance capability
Power and Code Selection Cont’d

- Constraint 2: time to evacuate
  - Physical constraint on code length
  - Warning transmission power comparable to other secondary transmissions
    - Feasible
    - Good interference tolerance
    - Cause collision for other secondary transmission
  - Select a code with sufficient interference tolerance capability
  - If constraint violated, increase power
  - If desire less peak intf, decrease power
Initialization Phase

- Build evacuation group
  - For collaborative detection
  - Based on suitable geo area
  - Potentially different wireless networks
- Select appropriate power and code
- Propagate information to each member
Simulation

- 5x5 grid
- Interference from one (loud) primary user
  - 3 dB higher
- Interference from random transmissions of secondaries who not receiving the warning
  - Interference & no reception
  - 3 dB higher
- Warning spreading code: m-sequence 31
- Repetition: 1, 2, 3, 5

Metrics
- Evacuation time
- Peak interference
- Failure rate
Failure Histogram
Peak Interference Histogram
Evacuation Time Histogram
Where do We Stand?

- **History**
  - Command-and-Control spectrum access
  - Inefficient spectrum usage

- **Current**
  - Rapid proliferation of wireless services and high demand for spectrum
  - Policy evolutions & radio technology advances

- **Future**
  - More spectrum and more flexible/efficient usage
  - Advanced DSP and radio technologies
  - Cool applications
Thank You!

Purdue University, 2005
System Model Cont’d

- Footprint to abstract the space occupancy of a user (transmission).
  - Ex: service contour of a TV station

- Footprint may or may or not overlap
  - Ex: service contours of different TV stations
  - Ex: coverage area of cellular base stations