Adaptive Wireless Networks Using Cognitive Radios as a Building Block

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Talk Outline

- Introduction: the future wireless network and related R&D challenges
- Dynamic spectrum management & cognitive radio concepts
- Cognitive radio technologies: selected results
  - Coexistence of 802.11 and 802.16 in unlicensed bands
  - CSCC spectrum etiquette
  - Adaptive networks and ad-hoc self-organization
  - Cognitive radio hardware
- Concluding remarks
Introduction
Introduction:
Future Wireless Network Scenario

Growing role for fast, low-cost short-range radios
Heterogeneous systems with multiple radio standards (3G, 4G, WLAN, UWB,..)
Self-organizing ad-hoc access networks
Increasing use of unlicensed spectrum and dynamic sharing methods
Uniform IP core network
Wide range of applications (→ “ubiquitous wireless services”)
Introduction: Wireless Technology Trends

**Primary Applications**

- **Telephony; PC/LAN**
  - VOIP, H264, HTTP, etc.
  - Location-aware services

- **Cellular networks**
  - Ethernet + WLAN
  - Mobile IPv6, etc.

- **IP-based networks**
  - for both Cellular & WLAN
  - Beyond IP networks (e.g. content aware routing)
  - Cross-layer techniques

- **Sensor nets**
  - Applications: Embedded wireless devices
  - Self-organizing multi-hop

- **Beyond IP networks**
  - Infrastructure net;
  - Ad-hoc low-tier networks

**Network Architecture**

- **Radio Technology**
  - 2G/CDMA & TDMA
  - ~1 Mbps WLAN
  - ~1995-2000
  - Higher speed, OFDM

- **IP-based networks**
  - ~1 Mbps 3G/WCDMA
  - ~10-54 Mbps WLAN
  - ~2000-2005
  - New spectrum policies
  - Cognitive radio

**Adaptive Radio Networks**

- **~100 Mbps+**
  - 4G/OFDM, 802.16 & WLAN;
  - ~500 Mbps UWB, etc.
  - ~2010+
Introduction: Key Technologies for Future Wireless Systems

- New radios for heterogeneous access
  - Low-power sensor radios
  - High-speed WLAN and 4G/802.16
  - Faster 4G cellular, 802.16, etc.

- Spectrum-sharing for dense networks
  - Dynamic spectrum/cognitive radio for frequency coordination
  - Spectrum etiquette protocols

- Ad-hoc wireless networks
  - Self-organizing networks capable of scaling organically
  - Discovery, MAC and routing protocols for reliable ad-hoc services

- Pervasive computing software
  - Dynamic binding of application agents and sensors
  - Real-time orchestration of sensors and actuators

Focus of this talk
Dynamic Spectrum Management & Cognitive Radio
Motivation for Dynamic Spectrum and Cognitive Radio Techniques:

- Static allocation of spectrum is inefficient
  - Slow, expensive process that cannot keep up with technology
- Spectrum allocation rules that encourage innovation & efficiency
  - Free markets for spectrum, more unlicensed bands, new services, etc.
- Anecdotal evidence of WLAN spectrum congestion
  - Unlicensed systems need to scale and manage user “QoS”
- Density of wireless devices will continue to increase
  - ~10x with home gadgets, ~100x with sensors/pervasive computing
- Interoperability between proliferating radio standards
  - Programmable radios that can form cooperating networks across multiple PHY’s
Spectrum Management: Frequency allocation today ...
Spectrum Management: Policy Concepts

- Unlicensed bands with spectrum etiquette
  - More ISM/U-NII bands with simple coordination rules

- Property Rights
  - Fee simple ownership with non-interference easements

- Spectrum clearinghouse
  - Packets are sent with access tokens with pricing determined by congestion

- Open access
  - No coordination rules, technology expected to evolve towards co-existence

- Cognitive radio bands
  - Agile/smart radios capable of adaptive strategies for interference avoidance
Spectrum Management: Problem Scope

- Dense deployment of wireless devices, both wide-area and short-range
- Proliferation of multiple radio technologies, e.g. 802.11a,b,g, UWB, 802.16, 4G, etc.
- How should spectrum allocation rules evolve to achieve high efficiency?
- Available options include:
  - Agile radios (interference avoidance)
  - Dynamic centralized allocation methods
  - Distributed spectrum coordination (etiquette)
  - Collaborative ad-hoc networks
Cognitive Radio: Definitions

- The term “cognitive radio” used to denote new generation of adaptive wireless devices capable of dynamic spectrum coordination
  - Baseline capability includes spectrum scanning and frequency agility
  - Fast adaptation of transmitted signal to fit into changing radio environment
  - Capable of higher-layer spectrum etiquette or negotiation protocols
  - May also participate in ad-hoc networks formed with other cognitive radios
  - Interoperability with multiple radio technologies based on SDR capabilities
Cognitive Radio: R&D Status

- Policy and technology R&D on cognitive radio still at an early stage. Recent activities include:
  - FCC notice of rulemaking for specific “underlay” data services in UHF TV bands
  - More general notice of proposed rulemaking on new unlicensed cognitive bands
  - Software defined cognitive radios developed at Vanu Inc., GNU/Utah
  - XG policy framework being developed by DARPA
  - System studies and prototyping at Mitre, Rutgers/WINLAB, Stevens, others....
  - New National Science Foundation research initiative (“NeTS ProWIN”), 2004

- Cognitive radio has the potential for significant improvements in spectrum efficiency, performance and interoperability between unlicensed band services
Cognitive Radio: Design Space

- Broad range of technology & related policy options for spectrum
- Need to determine performance (e.g. bps/Hz or bps/sq-m/Hz) of different technologies taking into account economic factors such as static efficiency, dynamic efficiency & innovation premium

Protocol Complexity (degree of coordination)

Hardware Complexity

Unlicensed Band + simple coord protocols

Internet Server-based Spectrum Etiquette

Unlicensed Band with DCA (e.g. 802.11x)

Internet Spectrum Leasing

Static Assignment

Radio-level Spectrum Etiquette Protocol

Ad-hoc, Multi-hop Collaboration

“cognitive radio” schemes

“Open Access” + smart radios

UWB, Spread Spectrum

UWB, Spread Spectrum

Agile Wideband Radios

Ad-hoc, Multi-hop Collaboration

Internet Spectrum Leasing

Unlicensed Band with DCA (e.g. 802.11x)
Cognitive Radio: Reactive Algorithms

- Reactive (autonomous) methods may be used to avoid interference via:
  - **Frequency agility**: dynamic channel allocation by scanning
  - **Power control**: power control by interference detection and scanning
  - **Time scheduling**: MAC packet re-scheduling based on observed activity

![Diagram showing Cognitive Radio concepts including frequency agility, power control, and time scheduling.](image-url)
Cognitive Radio: Limitations of Reactive Schemes

- Reactive schemes (without explicit coordination protocols) suffer from certain limitations:
  - Near-far problems possible at the receiver
  - Inability to predict future behavior of other nodes
  - Only detects transmitters, not receivers, but interference is a receiver property

![Diagram showing coverage areas and hidden terminal problem]
Cognitive Radio: Spectrum Policy Server

- Internet-based Spectrum Policy Server can help to coordinate wireless networks
  - Needs connection to Internet even under congested conditions (...low bit-rate OK)
  - Some level of position determination needed (..coarse location OK?)
  - Spectrum coordination achieved via etiquette protocol centralized at server

- Internet
- Access Point
- WLAN operator A
- WLAN operator B
- Master Node
- Ad-hoc Bluetooth Piconet
- Wide-area Cellular data service

Spectrum Policy Server
www.spectrum.net

AP1: type, loc, freq, pwr
AP2: type, loc, freq, pwr
BT MN: type, loc, freq, pwr

Etiquette Protocol
Common spectrum coordination channel (CSCC) can be used to coordinate radios with different PHY

- Requires a standardized out-of-band etiquette channel & protocol
- Periodic tx of radio parameters on CSCC, higher power to reach hidden nodes
- Local contentions resolved via etiquette policies (independent of protocol)
- Also supports ad-hoc multi-hop routing associations
Adaptive Wireless Networks: Ad-Hoc Collaboration

- Cognitive radios can organize themselves into a multi-hop adaptive network in order to achieve better system performance
  - Multi-hop collaboration can increase spectrum efficiency, reduce power consumption and potentially also improve throughput
  - Cognitive radio scans for active nodes and executes discovery algorithm
  - Bootstrapped PHY to selected nodes adapts to high bit-rate, low power/range
  - Control protocol between nodes used to negotiate ad-hoc network parameters and to exchange routing tables

Adaptive Wireless Network Node
(…functionality can be quite challenging!)
Adaptive Wireless Network: Simple cellular/WLAN example

- Multi-mode (cellular, WLAN) or cognitive radio capable of ad-hoc association can be used to improve cellular services
- System may also include provisioned “radio forwarding nodes”
- Radio paths (single or multi-hop) selected adaptively based on current cellular radio link quality and proximity to other nodes
Cognitive Radio Techniques: Selected Research Results
Reactive Schemes: Case study of 802.11 & 16 in shared unlicensed band

- 802.11b (~500m) and 802.16a (~10Km) coexist by applying reactive schemes to avoid interference

**Dynamic Frequency Selection (DFS):**
- Radio Scans each channel and calculates interference power level
- Typical scanning interval is averaged 100ms
- Choose the channel with least interference for communication

**Power Control (PC):**
- The receiver senses interference power level and calculates the minimum required transmit power and feedback to the transmitter
- The transmitter uses minimum transmit power for communication
### 802.11 & 16 Co-Existence: Simulation Parameters

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>802.16a: UBR (Poisson arrival), UDP packet, 512 Bytes datagram</th>
<th>802.11b: IEEE 802.11 BSS mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC protocol</td>
<td>TDMA</td>
<td>IEEE 802.11 BSS mode</td>
</tr>
<tr>
<td>Channel Model</td>
<td>AWGN, two ray ground propagation model, no fading</td>
<td></td>
</tr>
<tr>
<td>Bandwidth/channels</td>
<td>20 MHz / 4 non-overlapping chs</td>
<td>22MHz / 11 overlapping chs</td>
</tr>
<tr>
<td>Bit Rate</td>
<td>13Mbps</td>
<td>2Mbps</td>
</tr>
<tr>
<td>Radio parameters</td>
<td>OFDM (256-FFT, QPSK)</td>
<td>DSSS (QPSK)</td>
</tr>
<tr>
<td>Background Noise</td>
<td></td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Rx Noise Figure</td>
<td>9 dB</td>
<td>9 dB</td>
</tr>
<tr>
<td>Receiver Sensitivity</td>
<td>-80dBm (@BER 10^-6)</td>
<td>-82dBm (@BER 10^-5)</td>
</tr>
<tr>
<td>Antenna Height</td>
<td>BS 15m, SS 1.5m</td>
<td>1.5m</td>
</tr>
<tr>
<td>Tx Power/Max range</td>
<td>33dBm / 3.2Km</td>
<td>20dBm / 500m</td>
</tr>
<tr>
<td>Default channel</td>
<td>Channel 1: centered at 2412GHz</td>
<td>Channel 1: centered at 2412GHz</td>
</tr>
<tr>
<td>Available channels</td>
<td>4 (non-overlap)</td>
<td>12 (overlapping)</td>
</tr>
</tbody>
</table>
802.11 & 16 Co-Existence: Power Control Results

- Observations:
  - 802.16 throughput can improve up to 3 times at the expense of 802.11 throughput degradation < 10% (e.g. at D=2.5Km)
  - If two systems are too near to each other, power control may not work

4 links for 802.11 hotspot, each has Poisson arrival with mean 3ms
802.11 hotspot is 3Km away from 802.16 BS
CSCC Spectrum Etiquette Protocol

- CSCC (Common Spectrum Coordination Channel) can enable mutual observation between neighboring radio devices by periodically broadcasting spectrum usage information.

Service channels

Edge-of-band coordination channel

Periodic Announcements: User ID (MAC Address), Frequency Band, Power Level, Service Type, Technologies used, Priority, Cost/Price Bids, Multi-hop Forwarding capabilities, etc.
CSCC: Protocol Stack

CSCC-PHY: 1Mbps 802.11b with 10 mW power (~100 m range)
CSCC-MAC: Simple periodic broadcast with randomization (100ms~seconds) to eliminate repeated collisions
### CSCC: Packet Format

CSCC radio (802.11) MAC Address (48bits)

... MAC Address

... Device Name and Description (64bits)

... and Description

Priority (8b) | Price_bid(8b)

... Duration (32b)

CSCC packet used in WLAN-Bluetooth prototype at WINLAB
CSCC: Proof-of-Concept Experiments

- Different devices with dual mode radios running CSCC
- $d=4$ meters are kept constant
- Priority-based etiquette policy
CSCC: Experimental Parameters

<table>
<thead>
<tr>
<th></th>
<th>WLAN nodes</th>
<th>Bluetooth nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobility</strong></td>
<td>Static without mobility</td>
<td>BT1 static, BT2 position varies</td>
</tr>
<tr>
<td><strong>Traffic Model</strong></td>
<td>100M bytes data by TCP</td>
<td>1.5M bytes data using Stop-and-wait scheme</td>
</tr>
<tr>
<td><strong>MAC protocol</strong></td>
<td>IEEE 802.11b at 11Mbps</td>
<td>Bluetooth ACL data link</td>
</tr>
<tr>
<td><strong>Data card</strong></td>
<td>Cisco Aironet 350 series DS (at channel #1)</td>
<td>Ericsson BT w/ USB (hopping over whole band)</td>
</tr>
<tr>
<td><strong>CSCC MAC</strong></td>
<td>IEEE 802.11 &amp; periodic announcements at 1Mbps</td>
<td></td>
</tr>
<tr>
<td><strong>CSCC card</strong></td>
<td>Cisco Aironet 350 series DS (at channel #11)</td>
<td></td>
</tr>
</tbody>
</table>
**CSCC Results: Throughput Traces**

- **Observations:**
  - WLAN session throughput can improve ~35% by CSCC coordination
  - BT session throughput can improve ~25% by CSCC coordination

**WLAN = high priority**

- WLAN session with BT2 in initial position

**Bluetooth = high priority**

- BT session with BT2 in initial position
Adaptive Wireless Networks: Ad-hoc Discovery and Self-Organization

- Spectrum etiquette channel used to initiate discovery and network bootstrap
- Expanded beacon signals transmitted by each radio in CSCC
- Note that each link may use a different PHY/MAC -> cognitive radio switches between links dynamically, while using mutually agreed routing protocol

Example of Beacon Payload
Adaptive Networks: Ad-hoc Discovery Protocol Implementation

WINLAB’s “SOHAN” 802.11-based ad-hoc prototype demonstrates aspects of self-organization that can be extended to cognitive radio.
Adaptive Networks: Discovery Algorithm

Performance Results

- NS-2 extended to support
  - Hierarchical net with APs, FNs, MNs
  - Multiple interfaces
  - Multiple 802.11 channels

- Distributed and optimal centralized algorithms
  - 2 APs, 4 FNs, 10 SNs
  - CBR traffic of 64 byte packets
  - 1000 m x 1000 m area
  - 1 Mbps 802.11 radios

...significant reductions in routing overhead & energy used
Adaptive Networks: Ad-Hoc Routing/Discovery Implementation
Adaptive Networks: “SOHAN”

Experimental Results

Experimental Setup

Packet delivery ratio

Gains in system capacity and per-user throughput achievable relative to WLAN BSS mode or comparable “flat” ad-hoc mesh, particularly when FN’s use multiple radio channels...
Cognitive Radio: Hardware Platforms

- Next-generation software-defined radio supporting fast spectrum scanning, adaptive control of modulation waveforms and collaborative network processing
- Facilitates efficient unlicensed band coordination and multi-standard compatibility between radio devices
Cognitive Radio: Hardware Platforms

- Vanu Inc. SDR programmable radio based on commodity processors. Supports multiple standards on handheld device.

Vanu Inc. Software Defined Radio
Source: http://www.vanu.com/products.html
Requirements include:

- ~Ghz spectrum scanning,
- Etiquette policy processing
- PHY layer adaptation (per pkt)
- Ad-hoc network discovery
- Multi-hop routing ~100 Mbps+

WINLAB’s “network centric” concept for cognitive radio prototype
(under development in collaboration with GA Tech & Lucent Bell Labs)
Concluding Remarks
Concluding Remarks: ORBIT Testbed

- Open-access next-generation wireless network testbed being developed at Rutgers for NSF network research testbeds (NRT) program
- Large scale “radio grid emulator” for evaluating new concepts for future wireless networks, e.g. ad-hoc networks, cognitive radio protocols, ...
- Also, outdoor “field trial network” with open-interface 3G & WLAN for real-world application work
Concluding Remarks: ORBIT Radio Grid
ORBIT: Field Trial System

3G Base Station
3G Coverage Area

3G Base Station
3G Coverage Area

802.11x Access Points/ Radio Routers

802.11x Access Points/ Radio Routers

“Open API” 802.11a,b,g ORBIT radio node

Lucent “Base Station Router” with IP interface
Concluding Remarks

- Future wireless networks need ~100-1000x increases in density and bit-rate of radios → motivates better spectrum coordination methods
- Spot shortages of spectrum will occur if present static allocation is continued → significant improvement achieved with dynamic allocation
- Cognitive radio technologies can be characterized in terms of the combination of hardware complexity and level of protocol coordination
- Possible cognitive radio schemes include
  - Agile radio with interference avoidance
  - Spectrum etiquette protocols: spectrum server, CSCC...
  - Adaptive networks via ad-hoc collaboration
- Early technical results now available for some of these methods, but very different complexity factors and market implications…
Concluding Remarks

- Future research areas in cognitive radio include:
  - New concepts and algorithms for agile radio and spectrum etiquette protocols
  - Architecture and design of adaptive wireless networks based on cognitive radios
  - Detailed evaluation of large-scale cognitive radio systems using alternative methods
  - Spectrum measurement and field validation of proposed methods
  - Cognitive radio hardware and software platforms

- User-level field trials of emerging cognitive radios and related algorithms/protocols may also be useful to gain experience
  - Controlled testbed experiments comparing different co-existence methods
  - Large-scale “spectrum server” trial for 802.11x coordination
  - Experimental deployments in proposed US FCC cognitive radio band

- Success with cognitive radio technologies should lead to major improvements in spectrum efficiency, performance and interoperability