Enabling Dynamic Spectrum Allocation in Cognitive Radio Networks

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Unlicensed bands become over-crowed!
Spectrum Shortage

No Spectrum Available to Be Allocated in
Spectrum Allocation Table from 30 MHz to 30 GHz in US
Introduction & Motivation

Artificial Spectrum Shortage

Dissertation Focus:

* Tackle spectrum shortage problem by *improving* spectrum utilization and *efficiency*

Source:
Shared Spectrum Company

5% 30MHz ~ 30GHz
Limitations of Existing Spectrum Allocation Methods

Command & Control

- In US, FCC controls how to allocate the spectrum
- Extremely unbalanced spectrum utilization
  - TV bands: 15% in 2004*
  - Over-crowed unlicensed band

Fixed Channelization

- Further divide spectrum into fixed channels of equal bandwidth
- Limit network capacity and cause unfairness across a network

Source: FCC released date sheet
Dynamic Spectrum Allocation

- The key idea
  - Actively **detect** unused spectrum
  - Dynamically **create suitable # of channels**
    - Maximize spectrum utilization
    - Improve spectrum efficiency, minimize interference
  - Adaptively **adjust channel bandwidth**
    - Consider local user/traffic distribution

- New hardware support: **Cognitive Radio**
  - Unused band detection
  - Reconfigurable radio parameters
## Apply Concept of Dynamic Spectrum Allocation

### Exploit White Spaces in TV bands
- A complete hardware-software system, KNOWS
  - Reliably detects unused freq
  - Efficiently shares spectrum
- b-SMART: a distributed dynamic spectrum allocation algorithm

### Improve Spectrum Efficiency in WLANs
- A dynamic channelization structure
  - Accommodates # of neighboring APs
  - Allocates bandwidth considering user distribution
- A scalable MAC design
  - Handles various user populations
  - Exploits rate diversity
Key Contribution

- The concept of Dynamic Spectrum Allocation
  - **KNOWS** exploits white spaces in *licensed bands*
    - Remarkable 200% throughput improvement as compared with fixed allocation schemes
  - **Dynamic channels** improve spectrum efficiency in *unlicensed bands*
    - Significantly improve system throughput and fairness in WLANs
Outline

- Introduction & Motivation
- Dissertation Overview
- KNOWS System Design and Evaluation
- New Channelization Structure for WLANs
- Conclusions
KNOWS: Problem Formulation

Resource
- White Space
- Cognitive Radios
  - Sensing
  - Reconfigurability

Goal
- Support Data Networking in the TV bands

Functionality
- Robust White Space Detection
- Dynamic Access to White Space

Features
- Simple, distributed
- Efficient, practical
White Spaces in TV bands

- Open TV channel 21-51
  - 512 MHz ~ 698 MHz
- Unlicensed in 2009
- Low frequency band
- Primary users
- Dynamic
- Fragmented
- Uneven size

![Diagram of frequency spectrum with "White spaces" highlighted]
KNOWS Design Overview

Physical-layer Capability

- Spectrum sensing
  - Every 30min required by FCC
- Highly reconfigurable
  - Frequency, bandwidth, power
- How many transceivers?
  - **ONE**
- **Design highlights**
  - One scanner/receiver
  - One transceiver

MAC-layer Function

- Collaborative sensing
- Parallelism & connectivity
- Adaptive bandwidth
- **Design highlights**
  - **CMAC:**
    - Based on a control channel
  - Spectrum Allocation Table
  - **b-SMART:** distributed dynamic spectrum allocation algorithm

Hardware Platform

- Scanner/Receiver
  - Scan: 400MHz ~ 928MHz
  -Recv: 900 ISM band, 5MHz
- Reconfigurable transceiver
  - Can dynamically adjust channel-width and center-frequency from 400MHz to 928MHz
  - Contiguous 5, 10, 20, 40 MHz
  - Power control

Transceiver can tune to contiguous spectrum bands only!
KNOWS Architecture

Network Layer (TCP/IP)

MAC (Medium Access Control)

b-SMART (Spectrum Allocation Engine)

Spectrum Allocation Table

PHY Layer

Reconfiguration Interface

Reconfigurable Radio

Scanner Receiver
KNOWS Architecture

Network Layer (TCP/IP)

CMAC (Medium Access Control)

b-SMART (Spectrum Allocation Engine)

Spectrum Allocation Table

PHY Layer

Reconfiguration Interface

Reconfigurable Radio

Scanner Radio

Next!
CMAC Overview

- **RTS**
  - Indicates intention for transmitting
  - Contains suggestions for available time-spectrum block (b-SMART)

- **CTS**
  - Spectrum selection (received-based)
  - Announces selected time-spectrum block \((f, \Delta f, t, \Delta t)\)

- **DTS**
  - Data Transmission reSerVation
  - Announces reserved time-spectrum block to neighbors of sender
The above depicts a possible Spectrum Allocation Table

1) Primary users (fragmentation)
2) In multi-hop → neighbors have different views
b-SMART

• Which time-spectrum block should be reserved...?
  ◦ \((f, \Delta f, t, \Delta t)\) How long...? How wide...?
• b-SMART (distributed spectrum allocation over white spaces)
• Design Principles

1. Try to assign each flow blocks of bandwidth \(B/N\)

\[B: \text{Total available spectrum}\]
\[N: \text{Number of disjoint flows}\]

2. Choose optimal transmission duration \(\Delta t\)

Long blocks: Higher delay

Short blocks: More congestion on control channel
b-SMART

- Upper bound $T_{\text{max}} \approx 10\text{ms}$ on maximum block duration
- Nodes always try to send for $T_{\text{max}}$

1. Find bandwidth $\Delta f$, for which the time used to out packets in current queue is closest to $T_{\text{max}}$

2. If $\Delta f \geq \lfloor B/N \rfloor$ then $\Delta f := \lfloor B/N \rfloor$

3. Find placement of $(\Delta f, \Delta t)$ block that minimizes finishing time and non-overlap with any other block

4. If no such block can be placed due to prohibited bands then $\Delta f := \Delta f / 2$
KNOWS: Performance Evaluation

- Simulate in QualNet
- Total 80MHz, 1MHz to 1.2Mbps
- Bandwidth: 5, 10, 20, 40 MHz
- Control channel: 5MHz
- Switch overhead: 50 µs
- Backlogged UDP flows, and TCP flows
KNOWS in Single Hop Network

Aggregate Throughput of Disjoint UDP flows

Throughput (Mbps)

# of flows

KNOWS significantly outperforms systems based on fixed allocations!
KNOWS in Chain Network

KNOWS significantly improve throughput and reduces interference.
KNOWS Summary

- KNOWS: hardware-software system
  - Detect unoccupied frequencies in licensed TV bands
  - Support dynamic spectrum allocation using b-SMART

- Performance Evaluation
  - Analysis results match simulation results
  - Quantify the effect of fragmentation, traffic type, application type, multiple-hop network, routing protocols, mobility
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Fixed Channels in WLANs

Unbalanced Traffic Distribution
- AP usage in WLANs tends to be unbalanced
- User populations served by APs fluctuate considerably

Limitations of Fixed Channels
- Limit Network Capacity
  - # of neighboring APs is small
- Cause Interference
  - # of neighboring APs is large
- Deteriorate Per-client Fairness
Dynamic Channelization Structure

The key idea:

- Dynamically create suitable # of channels
  - Accommodate # of neighboring APs
- Adaptively adjust channel bandwidth
  - Consider user/traffic distribution

Yuan Yuan, Paramvir Bahl, Ranveer Chandra, Thomas Moscibroda and Yunnan Wu, *UnChannelize the Channels in WLANs*. Proceedings of ACM MobiCom Poster, Montreal, Canada 2007
Simulation Study in Large Scale Offices

### Qualnet Settings:
- IBM trace data, 50 APs
- 1000m x 1000m flat
- 80MHz spectrum,
- Switch overhead: 50us
- 1 MHz -> 1.2 Mbps

- **GreedyRaising**: enables dynamic channels
- **RaC**: channel selection algorithm based on fixed channels
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Spectrum Shortage Problem

- A critical problem to solve to support fast growth of wireless technologies

Key Contribution

- Dynamic Spectrum Allocation significantly improves spectrum utilization and efficiency
  - KNOWS exploits white spaces in licensed bands
  - Dynamic channels improve spectrum efficiency in unlicensed bands
Future Work

- Deploy KNOWS system, measure performance and further improve the design
- Further study performance of dynamic channels
- Apply Dynamic Spectrum Allocation in market-based approach
  - Maximize revenue
  - Reduce interference
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Yuan Yuan
Ph.D defense

QUESTIONS?