Efficient Relaying for Cognitive Radios

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Understanding and Utilization of 3-D (Time, Frequency, Space) Spectrum Holes

- NSFC Key Project Group (10 Million)
- NSFC Young Investigator Project
- Ministry of Education Project
- Beijing NSF Key Project (REM Measurement)
- Industrial Projects
- ...
Understanding Spectrum Holes

- Cognitive Radio is designed to make use of spectrum holes!
- But what is a spectrum hole?

Diagram:
- Frequency
- Time
- Space!
- 3-D
- Distributed
- Highly Dynamic

3-Dimensional model illustrating the concept of spectrum holes in terms of frequency, time, and space.
3-D Spectrum Holes

Techniques for Detecting 3-D Holes

- Radio Environment Map (REM)
- Primary User Localization
- ...

In this talk, let us focus on how to make use of these 3-D spectrum holes!

In 2-D case, it is efficient to accumulate multiple holes.
Efficient Utilization of 3-D Holes

Direct transmission may result in large interference range!

More 3-D holes can be utilized by transmitting in low power!
Multi-hop Relay with Low Power

Relaying may reduce the interference range of SUs!

Multi-hop relaying may make full use of geographical holes!
Accumulating 3-D Holes

Multi-hop relaying can accumulate distributed 3-D holes!
Relaying w/o PU

Each link is assigned a fixed rate!

Regular packet can reduce protocol complexity
Relaying Issues in CR

Spectrum holes can never guarantee a given target rate

Regular packet can induce very low efficiency and poor QoS

Adaptation to holes may result in high protocol overhead
Rateless coding can adapt to spectrum holes without much signaling.

Distributed! Adaptive to access opportunity! Efficiently accumulate multiple 3-D holes!
Physical Layer Designs

A cross layer perspective
System Performance

Throughput efficiency

\[
\max_l \frac{1 - P_e(l)}{1 + \bar{\epsilon}(K)} R(1 - h(l)) \\
\text{s.t.} \quad K = \lceil m/l \rceil \quad \text{Message size constraint} \\
1 \leq l \leq m, l \in \mathbb{Z}
\]

Packet error probability for convolutional codes over fading channels

\[
P_e \leq 1 - \int_0^\infty \left(1 - \min\left[1, \sum_{d=d_f}^{\infty} a(d) P_2(d | \gamma)\right]\right)^l f(\gamma) \, d\gamma
\]

Average decoding overhead

\[
\bar{\epsilon} = \frac{E[K'] - K}{K}
\]

Estimation: Gaussian Mixture Model (GMM)

\[
\hat{\epsilon} = \int x f(x) \, dx = \sum_{j=1}^J \pi_j \int x \mathcal{N}(x; \mu_j, \sigma_j^2) \, dx
\]

Asymptotic analysis

\[
\bar{\epsilon} = \sum_{i \geq 1} \Pr(\epsilon \geq \frac{i}{K}) = \sum_{i \geq 1} \left(1 - (1 - \lambda(1 - \omega(1 - y_{i-1}(i/K))))^K\right)
\]

CRC overhead

\[
h(l) = \frac{l_{\text{crc}}}{l}
\]
Efficient Scheduling of Multiple Relays

Transmission in the 1st hop

Transmission delay will be increased with the number of relays that are required to decode a message!
Efficient Scheduling of Multiple Relays

Transmission in the 2nd hop

With more relays decoding a message in the 1st hop, transmission delay will be decreased!
Maximize average end-to-end throughput

$$\max_L \frac{N}{\max \left( E[T_{SR}^{(L)}], E[T_{RD}^{(L)}] \right)}$$

$$E[T_{SR}^{(L)}] = a_1 E[T_{d(L)}^{SR}] + b_1$$

$$E \left[ T_{d(L)}^{SR} \right] = E \left[ T_{d(L-1)}^{SR} \right] +$$
$$\sum_y \left( 1 - \sum_x G_{1:M-L+1,L}(y | x) g_{T_{d(L-1)}^{SR}}(x) \right)$$

$$E[T_{RD}^{(L)}] = a_2 \frac{\tilde{N} - E[\tilde{N}_{d,L}]}{1 - \epsilon_{id,L}} \Pr \left( \tilde{N}_{d,L} < \tilde{N} \right) + b_2$$
Multi-hop relaying may deliver packets over large distance with low transmission power.
From Dist Model to Fluid Model

To maximize the utilization of 3-D holes, transmission power of SUs may adapt to these holes.

Rateless coded multi-hop relaying can achieve high spectral efficiency in a distributed manner!
Efficient Multi-hop Relaying

Spatial Reuse within one Band

Spatial reuse & chain cooperation within multiple Bands

Chain cooperation accumulates holes in multiple dimensions
From Geographical to Spatial

- For indoor applications, geographical spectrum holes hardly exist!
- Intuitively, directional antenna helps!

Spatial Spectrum Holes!
A QoS Model for CRNs

**Objective**

- Messages are generated at a constant rate
- They are expected to be delivered within a given period $T$ seconds

**Assumptions**

- Slow fading: wireless channel remains constant during $T$ seconds
- Channel gains are assumed to be known to each relay
- PUs’ presence or absence is assumed to be i.i.d. across timeslots

$Pr\{\Theta[n] = 0\} = 1 - p$

$Pr\{\Theta[n] = 1\} = p$
Direct Transmission

- 1 idle timeslot per transmission
- No diversity

\[ \| h \|^2 \]

\[ \frac{2^k - 1}{\text{SNR}} \]

Outage threshold

Packet

PU Network

SU Network
Cooperative Diversity

- 2 idle timeslots per transmission
- Achieve diversity gain

Can be utilized?

\[ \| h_{s,r} \|^2 \]

\[ 2^k - 1 \times \text{SNR} \]

Outage threshold

\[ \| h_{r,d} \|^2 \]

Outage threshold

packet

\[ 1 \]

\[ 2 \]

packet
Beamforming for Cognitive Radios

- **Beamforming - Directional Transmission**
  - Making use of spatial spectrum holes
  - Achieve diversity gain
Cooperative Beamingforming

PU Network

No interference!

SU Network

Cooperative beamforming

With only one antenna in each SU
A Geometric Approach

Objective
- zero-forcing to PU
- maximizing SNR of SU

ZFBF weight vector
- orthogonal projection

Received signal
\[ y_d(s) = h^\dagger g \tilde{x} + z_d(s) \]
Diversity Gain of ZFBF for CR

The distribution of
\[ \alpha = | h^\dagger g |^2 \]

\[ f_\alpha (x) = \frac{1}{(L-1)!} x^{L-1} e^{-x}, \quad x \geq 0. \]

\[ L = K \quad N_r \quad L > 0 \]

the number of decoding relays
the number of primary receivers
Scheduling: A Cross-layer Perspective

**Queueing model – tandem queueing**
- More service to queue 2

**PHY Layer model – cooperative beamforming**
- More spatial hole for the 2nd hop
How to Efficiently Schedule Two Hops?

A simple scheduling protocol
- source and relays **take turns** transmitting packets by accessing available timeslots

**NOT optimal!**
Opportunistic Scheduling

- Opportunistic scheduling protocol
  - Give higher priority to the 1st hop
  - It is optimal to serve constant rate delay-sensitive traffics

Source

Relays

Destination

Packet

Successfully delivered

2 packets

 opportunistically scheduled
Analysis of PHY

**PHY Outage**

- Fading in the 1\textsuperscript{st} hop
- Fading in the 2\textsuperscript{nd} hop

Channel fading

<table>
<thead>
<tr>
<th>Source</th>
<th>Relays</th>
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Outage threshold

Slow fading

Message

Packet
Analysis of PHY

- PHY Outage
  - Fading in the 1st hop
  - Fading in the 2nd hop

Slow fading

channel fading

Outage threshold

message

outage

SNR

packet

1 2
Beyond PHY

Outage event

- Fading in either one of the hops
- Queueing timeout due to PU

Outage threshold

Slow fading
The overall average outage probability

\[ f_{sys} = \Pr\{t > T\} = 1 - s_{phy} \times s_{mac} \]

\[ = f_{phy} + (1 - f_{phy}) \times f_{mac} \]

\[ f_{phy} = f_1 + f_2 = 1 - \sum_{K=K_t}^{K} f(K) \sum_{l=0}^{K-N_t-1} \frac{1}{l!} g_2^l e^{-g_2} \sim g_c (\frac{N_c R \Gamma(\frac{3}{2})}{\gamma})^{K+1-K_{th}} \]

\[ f_{mac} = 1 - s_{mac} = 1 - (1 - f)^{n_p} \]

Scheduling parameter

- \( R \): physical layer
- \( n_p \): MAC layer

Can be optimized!
A Cross Layer Optimization

Optimization problem

\[
\min_{n_p \in \{1, \ldots, n_p^m\}} \quad 1 - (1 - f_{\text{phy}}(n_p))(1 - f_{\text{mac}}(n_p))
\]
Random Packet Arrival

**Model**
- Packet arrival follows Bernoulli processes
- PUs’ presence or absence is assumed to be i.i.d. across timeslots
- Wireless channel follows i.i.d. Rayleigh fading across timeslots

**Objective**
- Optimize the end-to-end throughput

Pr\{a[n] = 1\} = \lambda

Pr\{\Theta[n] = 0\} = 1 - p

Pr\{\Theta[n] = 1\} = p

arrival
delivered
Opportunistic Scheduling with Token

- **Scheduling**
  - 1st Hop
  - 2nd Hop
    - Strategy 1: Clear all
    - Strategy 2: Push

- **Markov Chain Model**
Lyrtech Based Prototype Design

RF Frontend

VHS-ADC/VHS-DAC

Baseband Processor

GPIO

RapidChannel
Thanks You!

Q & A