Throughput and Delay Scaling of General Cognitive Networks

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Outline

Introduction
- Backgrounds
- Motivation and Result

System Models
- Basic Models
- Operation Rules

The Hybrid Protocol Model
- Definition
- Feasibility

Transmission Opportunities
- Cell Partitioning Round-Robin Mode
- Independent Relay Mode

Optimal Performance Scaling

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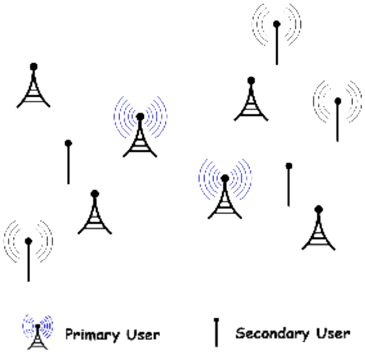
Optimal Performance Scaling

Cognitive Networks

- Primary users (with priority) and secondary users (opportunistic).
- Form two networks overlapping in all dimensions.
  - spatial, temporal, spectral
- Both networks could be arbitrary ad hoc networks.



What is the throughput and delay performance of the primary and secondary networks?

Throughput & Delay in Cognitive Networks

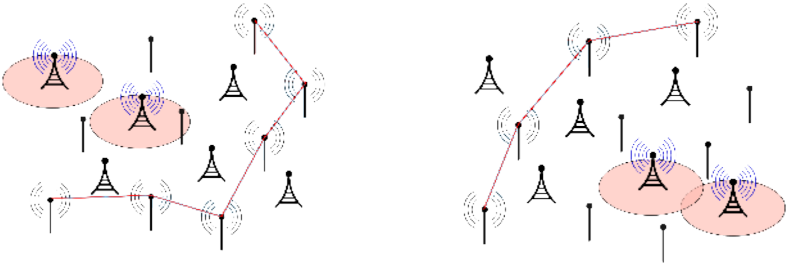


Figure: Opportunistic channel access.

- Secondary users suffer from throughput and delay penalty.
- Depends on how the primary network operates.

What is the throughput and delay performance of the primary and secondary networks?

Related Previous Works

- Sang-Woon Jeon et al., submitted to TIT [14]
  - Study two overlapping static ad hoc networks.
  - Preservation regions to protect primary networks.
  - Almost all secondary users could achieve the same throughput scaling as standalone networks.
- Changchuan Yin et al., TON, 2011 [15]
  - Two overlapping static ad hoc networks.
  - Both networks can achieve the same delay-throughput tradeoff as the optimal one for standalone networks.
- Cheng Wang et al., MASS, 2009 [18]
  - Investigate multicast capacity in cognitive networks.
  - Identify numerous sub-regimes, and in most cases multicast capacity is the same as or close to that in standalone networks.

Motivation

- All previous works consider specific primary networks with predefined communication schemes, and then design secondary protocols accordingly.
  - But primary networks could be arbitrary and diverse.
- All report similar or same results as standalone networks.
  - May imply a stronger and more general conclusion exists.

Figure: Various kinds of primary users in White Spaces networks.

Motivation

The Problem

What is the performance of a general cognitive networks with arbitrary primary users?

- Mobility? TDMA? CSMA?, etc.

Are there some general conditions that the cognitive networks can perform as well as standalone networks and how?

Results

Yes, if:

- A1) Primary network operates at a SINR level slightly larger than reception threshold.
  - such that there are opportunities for secondary users.
- A2) Primary network employs round-robin TDMA style scheduling schemes; or its traffic flows choose relays independently for routing.
  - such that the opportunities are sufficient.
- A3) $r_{\max}^{\gamma-2} = o(R_{\min}^{\gamma}/R_{\max}^{2})$, where R, r are transmission ranges of primary and secondary networks.
  - such that the primary scheduling is “homogeneous” and secondary users can conveniently detect opportunities.

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Assumptions

- Network extension: a unit square.
- n primary users $\{X_i\}_{i=1}^{n}$ and m secondary users $\{Y_j\}_{j=1}^{m}$.
- Independently and identically distributed (i.i.d.) in the network extension.
- Random permutation traffic, no cross network traffic.

Interference Model

The Physical Model: a transmission between two primary users is successful if the SINR at receiver satisfies:

$$SINR = \frac{\text{Received Power}}{N_0 + I_{P\to P} + I_{S\to P}} \geq \alpha \quad (1)$$

where,

$I_{P\to P}$: Interference from other primary TXs

$I_{S\to P}$: Interference from all secondary TXs

- If successful, transmits with bandwidth W.
- Define the physical model for secondary users similarly.
- Similar results also hold for the *Gaussian Channel Model*.

Asymptotic Capacity

Definition

Asymptotic per-node capacity $\lambda(n)$ of the network is said to be $\Theta(g(n))$ if there exist two positive constants c and c' such that:

$$\begin{cases} \lim_{n\to\infty} \text{Pr}\{\lambda(n) = cg(n) \text{ is feasible}\} = 1 \\ \lim_{n\to\infty} \text{Pr}\{\lambda(n) = c'g(n) \text{ is feasible}\} < 1 \end{cases}$$

Operation Rules

- Essential difference between cognitive networks and normal (standalone) networks.
- Should be as general as possible.
- To formulate the concept of *priority*:
  - Primary users disregard secondary users.
  - Secondary users must take care of both themselves and primary users.

Operation Rules

Rule 1 (the scheduling decision model of primary users)

A transmission is eligible to be scheduled if:

$$\frac{\text{Received Power}}{N_0 + I_{P\to P}} \geq \alpha + \epsilon \quad (2)$$

- Note that $I_{S\to P}$ is not included, i.e., the primary scheduler may not be aware of secondary users.
- Though it could be arbitrarily small, the allowance ϵ is necessary to provide opportunities for secondary users.

Operation Rules

Rule 2 (scheduling decision model of secondary users)

Given a set of primary transmissions satisfying Eq. 2 (Rule 1), a secondary transmission is eligible to be scheduled if it guarantees that the set of all primary and secondary links indeed satisfies the physical model (e.g., Eq. 1).

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Why this model?

- The operation rules are general to define, intuitive to understand, but awkward to use:
  - Complexity: depends on location, power, and aggregate interference.
  - Very difficult for secondary users to detect opportunities.
- We need a simpler criterion for secondary users to identify potential transmission opportunities.

The Hybrid Protocol Model

Definition

let $\mathcal{A} \in \{p, s\}$, and nodes $i, j \in \mathcal{A}$. Denote d_{ij} as the distance between them. Then a transmission from i to j is considered successful under the hybrid protocol model if

$$d_{kj} > (1 + \Delta_{\mathcal{AB}}) d_{ij}$$

for any other node $k \in \mathcal{B}$, $\mathcal{B} \in \{p, s\}$ transmitting simultaneously.

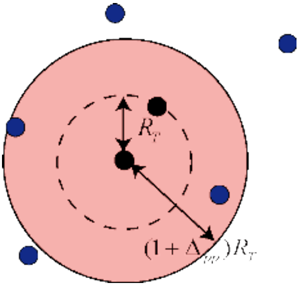

Figure: Guard zone for other PUs interfering with the transmitting PU.

- Simplicity: only involves *pairwise distance*.

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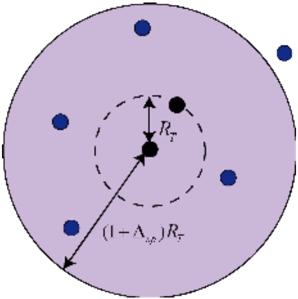

Figure: Guard zone for other SUs interfering with the transmitting PU.

- Simplicity: only involves *pairwise distance*.

Hybrid Protocol Model vs. Operation Rules

The hybrid protocol model (HP) should be consistent with the operation rules:

- Any primary schedule allowed by Rule 1 must also be allowed by HP (HP should be *flexible*).
- Any schedule allowed by HP must be indeed physical feasible, thus satisfying Rule 2 (HP should be *stringent*).

How?

- Adjust protocol parameters Δ_{pp}, Δ_{ps}, Δ_{sp} and Δ_{ss}.
- Control underlying parameters such as transmission power.

HP is Flexible

Lemma

For any $\alpha + \epsilon$ specified by Rule 1, let $\Delta_{pp} \leq (\alpha + \epsilon)^{\frac{1}{\gamma}} - 1$, then all feasible schedules of Rule 1 are feasible under HP.

Intuition

Decreasing Δ_{pp} will allow for more concurrent primary transmissions, even at a very poor SINR.

- Therefore HP complies with Rule 1.

Physical Feasibility of HP

Key Challenges:

- Ensure secondary transmissions harmless to primary network: upper bound $I_{\mathsf{S}\to\mathsf{P}}$.
- Establish secondary links given uncontrollable interference from primary network: upper bound $I_{\mathsf{P}\to\mathsf{S}}$.

Secondary users should employ flexible power control.

Upper Bounding $I_{\mathrm{S}\to\mathrm{P}}$: Main Idea

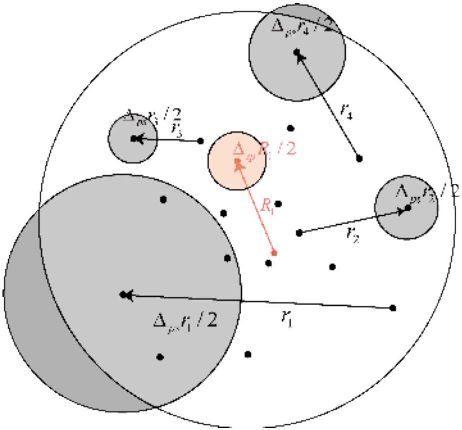

Figure: Hybrid protocol model: transmissions consume area.

Upper Bounding $I_{\mathrm{S}\to\mathrm{P}}$: Main Idea

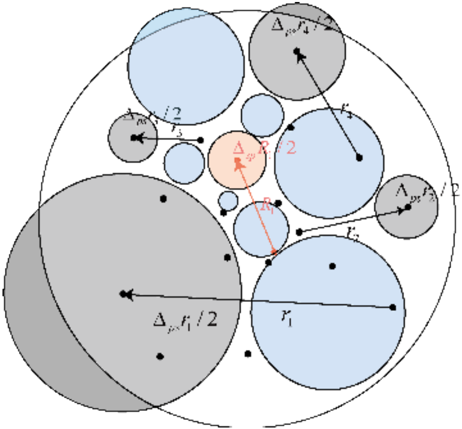

Figure: The amount of interference that can be "plugged" around the receiver is upper bounded.

Upper Bounding $I_{\mathrm{S}\to\mathrm{P}}$: Main Idea

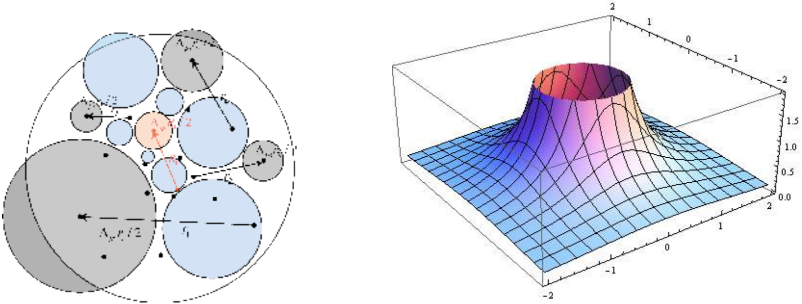

Figure: By carefully tuning secondary transmission power, the interference that primary users suffer can be bounded by integral.

Physical Feasibility of HP: Main Idea

- Similarly we can bound $I_{\mathsf{P}\to\mathsf{S}}$.
- $I_{\mathsf{S}\to\mathsf{P}}$ is roughly bounded by $CR_{ij}^{2-\gamma}$ and $I_{\mathsf{P}\to\mathsf{S}}$ by $R_{\min}^{-\gamma}$.
- If $r_{\max}^{\gamma-2} = o(\frac{R_{\min}^{\gamma}}{R_{\max}^{2}})$, then we can indeed find a proper C, such that the SINR of any primary and secondary users is larger than physical reception threshold.

Therefore HP is physical feasible.

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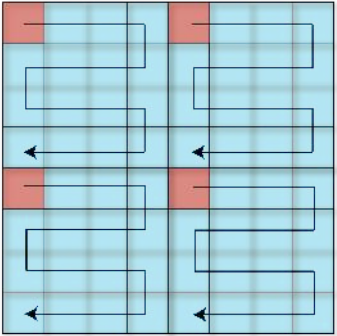
Optimal Performance Scaling

Cell Partition Round-Robin Scheduling

- Tessellate the network into cells.
- Group non-interfering cells into the same color, allow concurrent transmissions in cells with the same color.
- Different groups take turns to be active, such that every cell has constant fraction of time to transmit.

Cell Partition Round-Robin Scheduling



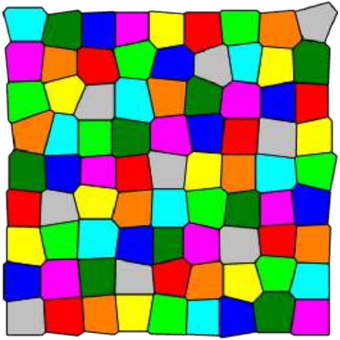


Figure: Simple 16-TDMA (the left figure) and its general form: Voronoi Cells (the right figure).

Availability of Transmission Opportunities

Intuition

As a result of the hybrid protocol model, for any secondary user i, we can find a corresponding nearby primary cell V, such that i is able to transmit without interfering the primary network whenever V is activated.

- Secondary users have constant fraction of time to be active.
- Only wait constant time before the opportunities occur.

Thus same throughput & delay scaling as standalone networks.

Independent Relay Routing

- Tessellate network into arbitrary cells.
- Packets are forwarded along these cells hop by hop following arbitrary path.
- Different traffic flows choose relays independently in cells.

Independent Relay Routing

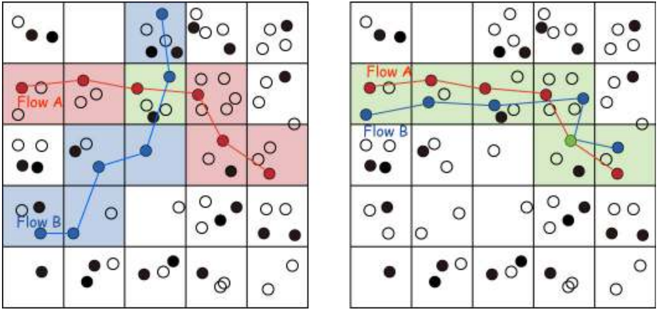


Figure: Two examples of independent relaying.

Availability of Transmission Opportunities

Theorem

If a secondary link is muted from transmission for a constant fraction of time, then with high probability there also exists a constant fraction of time that it can transmit without constraint.

Intuition: muted and triggered region.

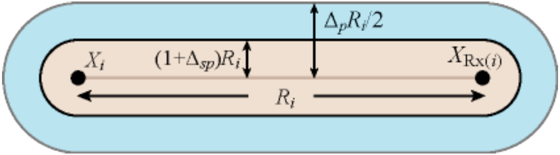


Figure: Muted region (in pink) and triggered region (in blue).

Availability of Transmission Opportunities

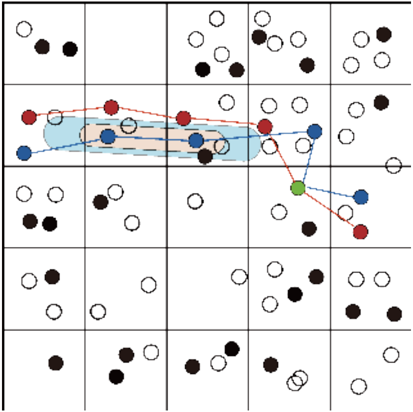


Figure: Region muted and triggered by a specific link in the network.

Availability of Transmission Opportunities

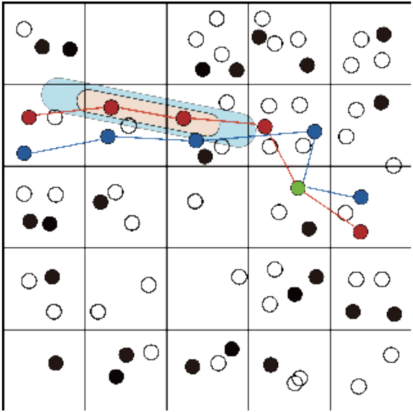


Figure: Region muted and triggered by a specific link in the network.

Availability of Transmission Opportunities

Lemma

Whether a secondary link is muted or triggered can be characterized by random Bernoulli trials, i.e., if muted with probability p_1, then constant $c > 0$ exists such that triggering probability $p_2 > cp_1$.

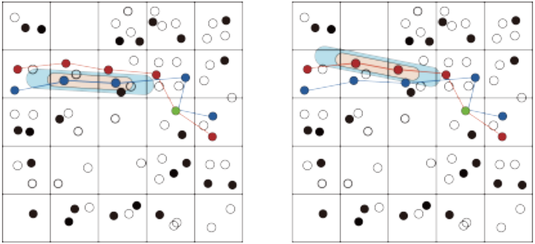


Figure: Regions muted and triggered by specific links in the network.

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Performance Scaling for General Cognitive Networks

Theorem

For any schemes that satisfies conditions A1)-A3) (pp. 9), and achieves throughput λ_s and delay D_s in case that the secondary network were standalone, there exists a corresponding scheme which can achieve throughput $\Theta(\lambda_s)$ and delay $\Theta(D_s)$ when primary network is present and Operation Rules 1 and 2 apply.

Static Wireless Ad Hoc Networks

Corollary

In static cognitive networks, the optimal throughput delay tradeoff is $D_p = \Theta(n\lambda_p)$, $\lambda_p \le \Theta(1/\sqrt{n})$ for primary network and $D_s = \Theta(m\lambda_s)$, $\Theta(n\lambda_p/m) < \lambda_s \le \Theta(1/\sqrt{m})$ for secondary network, if $\Theta(1/\sqrt{m}) > \Theta(n\lambda_p/m)$.

[1] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Optimal throughput delay scaling in wireless networks: part i: the fluid model,"IEEE/ACM Trans. on Networking, 2006.

Networks with Random Walk Mobility

Corollary

If primary nodes move according to random walk model, then the optimal throughput delay tradeoff for primary network is $D_p = \Theta(n\lambda_p)$ if $\lambda_p \leq \Theta(1/\sqrt{n})$, $D_p = \Theta(n \log n)$ if $\Theta(1/\sqrt{n}) < \lambda_p \leq \Theta(1)$. And the optimal throughput delay tradeoff for secondary network is $D_s = \Theta(m\lambda_s)$, $\Theta(n \min(1/\sqrt{n}, \lambda_p)/m) < \lambda_s \leq \Theta(1/\sqrt{m})$, if $\Theta(1/\sqrt{m}) > \Theta(n \min(1/\sqrt{n}, \lambda_p)/m)$.

[1] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Optimal throughput delay scaling in wireless networks: part i: the fluid model,"IEEE/ACM Trans. on Networking, 2006.

Hybrid Networks

Corollary

If primary network is equipped with $k = \Omega(\sqrt{n})$ base stations, the capacity of it is $\lambda_p = \Theta(k/n)$, and the optimal throughput delay tradeoff for the secondary network is $D_s = \Theta(m\lambda_s)$, $\Theta(\sqrt{\lambda_p n}/m) < \lambda_s \leq \Theta(1/\sqrt{m})$, if $\Theta(1/\sqrt{m}) > \Theta(\sqrt{\lambda_p n}/m)$.

[2] B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks," in IEEE Infocom, 2003.

CSMA Networks

Corollary

If the primary network employs independent relay protocol and CSMA protocol. The capacity of primary network is $\Theta(\frac{1}{\sqrt{n \log n}})$. The optimal throughput delay tradeoff for secondary network is $D_s = \Theta(m\lambda_s)$, $\Theta(\sqrt{n}/m\sqrt{\log n}) < \lambda_s \leq \Theta(1/\sqrt{m})$, if $m = \Omega(n^M)$ for some constant $M > 1$.

[3] C.-K. Chau, M. Chen, and S. C. Liew, "Capacity of large-scale CSMA wireless networks," in Proc. ACM Mobicom, 2009.

Networks with General Mobility

Corollary

If the mobility of primary users can be described by a stationary spatial distribution with support of diameter $f(n) = \omega(\frac{1}{\sqrt{n}})$, then the capacity of primary network is $\lambda_p = \Theta(f(n))$. The optimal throughput delay tradeoff for secondary network is $D_s = \Theta(m\lambda_s)$, $\Theta(\sqrt{n}/m) < \lambda_s \leq \Theta(1/\sqrt{m})$, if $m = \omega(n)$.

[4] M. Garetto, P. Giaccone, and E. Leonardi, "Capacity scaling in delay tolerant networks with heterogeneous mobile nodes," in Proc. of ACM MobiHoc, 2007.

And More ...

- Multicast networks
- MIMO networks
- Clustered networks
- ...

Summary

- The hybrid protocol model for opportunity detection
- Round-robin scheduling and independent relay routing
- Examples that cognitive networks achieve the same performance scaling as standalone networks: static networks, mobile networks, hybrid networks, CSMA networks ...

Questions?

Thanks for listening.