# Spectrum Leasing via Vertical Cooperation in Spectrum Sharing Networks

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# Outline

1. Cognitive Network
2. Vertical Cooperation
3. Problem Formulation
4. Solution
5. Numerical Analysis
6. Conclusions and Future work

# Cognitive Network

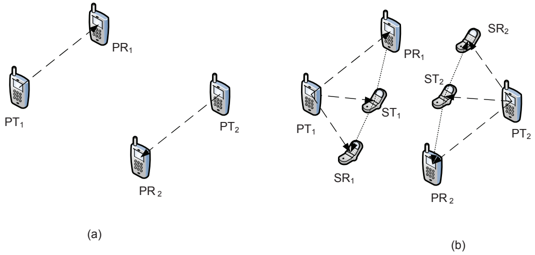


Figure: Example of (a) a standalone primary network with spectrum reuse, and (b) coexisting primary and secondary network with spectrum leasing.

Suppose in a hierarchical cognitive radio network:

- Multiple primary transmitter (PT) and receiver (PR) pairs
- Multiple secondary transmitter (ST) and receiver (SR) pairs
- Sharing the same radio spectrum
- Guaranteeing the performance of primary pairs

# Outline

# Vertical Cooperation Scheme

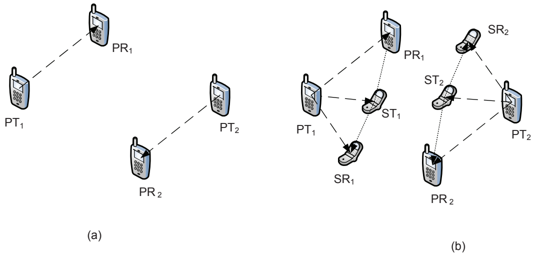


Figure: Example of (a) a standalone primary network with spectrum reuse, and (b) coexisting primary and secondary network with spectrum leasing.

A primary pair could choose

(i) to transmit signal directly

(ii) to select one secondary pair for relaying

# Vertical Cooperation Scheme

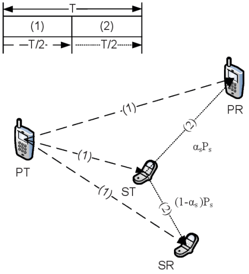


Figure: Power splitting relaying

(1) PT transmits primary signal, received by PR, ST and SR;

(2) (a) ST transmits regenerated signal, (Decode-and-Forward Relaying): primary signal: $\alpha_s P_s$, secondary signal: $(1 - \alpha_s)P_s$,
  (b) PR decodes primary signals
  (c) SR decodes secondary signals

# Outline

# Problem Formulation

Denote

| | |
|---|---|
| $P_s$, $P_s^{\max}$ | transmission power of secondary user $s$ |
| $R_s$ | achievable rate of secondary user $s$ |
| $R_p$, $R_p^{\text{req}}$ | achievable rate of primary user $p$ |
| $\beta_p^s$ | binary variable, 1 if $s$ and $p$ cooperate, otherwise 0 |
| $\mathcal{S}$, $\mathcal{P}$ | set of secondary and primary users |
| $I$ | interference |
| $B$ | bandwidth |

# Problem Formulation

The following optimization problem aims to maximize the minimum rate of secondary users

$$\max_{P_s, \alpha_s, \beta} \quad \min_{s \in \mathcal{S}} R_s \tag{1a}$$

$$\text{s.t.} \quad R_p \geq R_p^{\text{req}}, \forall p \tag{1b}$$

$$0 \leq P_s \leq P_s^{\text{max}}, \forall s \tag{1c}$$

$$0 \leq \alpha_s \leq 1, \forall s \tag{1d}$$

$$\beta_p^s \in \{0, 1\}, \forall p, s \tag{1e}$$

$$\sum_{s \mathcal{S}} \beta_p^s \leq 1, \forall p \tag{1f}$$

$$\sum_{p \in \mathcal{P}} \beta_p^s \leq 1, \forall s \tag{1g}$$

# Problem Formulation

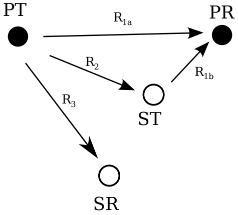


Figure: Illustration of $R_p$

In this work, we consider asynchronous system, and use following achievable rate model:

$$R_p^{\text{dir}} = B \log_2 \left( 1 + \frac{P_p G_{pd}}{\sigma^2 + I_d} \right), \quad R_s^{\text{dir}} = B \log_2 \left( 1 + \frac{P_s G_{sd}}{\sigma^2 + I_d} \right),$$

while the achievable rate within cooperation:

$$R_p^{\text{cop}} = \frac{1}{2} \min\{R_1, R_2, R_3\}, \quad R_s^{\text{cop}} = \frac{1}{2} R_s$$

# Problem Formulation

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Consider average interference model:

$$I_p = \sum_{w \in \mathcal{P}_{-p}} \left\{ \left( 1 - \sum_s \beta_w^s \right) P_w G_{wp} + \frac{1}{2} \sum_s \beta_w^s \left( P_w G_{wp} + P_s G_{sp} \right) \right\} + \sum_s \left( 1 - \sum_{w \in \mathcal{P}_{-p}} \right) P_s G_{sp}$$

It is Mixed-Integer and non-convex problem (MINCop) that in general is NP-hard.

# Outline

# Solution



Problem (1) is divided into two optimization problems:

(i) Given $\beta$, a power allocation problem

(ii) A secondary user selection problem

Power allocation Problem:

- Feasibility check approaches
- The solution method is based on the use of three intermediate optimization problems
- We see in the following the details of these problems

# Solution

Consider the following problem equivalent to problem (1):

$$\max_{P_s,\alpha_s,\beta,t} \quad t \tag{2a}$$

$$\text{s.t.} \quad R_s \geq t\,, \forall s\,, \tag{2b}$$

$$\text{Eq. (1b)} \sim \text{(1g)} \tag{2c}$$

Consider also following optimization problem aiming to minimize the sum of transmission power with fixed $\beta$

$$\min_{P_s,\alpha_s} \quad \sum_s P_s \tag{3a}$$

$$\text{s.t.} \quad R_s \geq t, \forall s \tag{3b}$$

$$\text{Eq. (1b)} \sim \text{(1d)}\,,$$

# Solution

**Lemma**

*Let $\beta$ be fixed. Then for secondary users, the maximum minimum achievable rate, $t'$, is feasible for problem (2) if and only if it is feasible for problem (3).*

It indicates that maximum feasible $t$ for problem (3) is the optimal $t^*$ for problem (2). Please keep it in mind.

# Solution

Furthermore, given $t$, consider the following optimization problem:

$$\min_{P_s, \alpha_s} \quad \sum_s P_s \tag{4a}$$

$$\text{s.t.} \quad P_s^{\text{dir}} \geq \frac{2^t - 1}{G_{ss'}}(\sigma^2 + I_{ss'}) \tag{4b}$$

$$P_s^{\text{cop}} \geq \frac{4^t - 1}{(1 - \alpha_s) G_{ss'}}(\sigma^2 + I_{ss'}) \tag{4c}$$

$$P_s^{\text{cop}} \geq \frac{A}{\alpha_s G_{sp'}}(\sigma^2 + I_{sp'}) \tag{4d}$$

$$0 \leq \alpha_s \leq 1, \forall s\,, \tag{4e}$$

where $A = 4^{R_p^{\text{req}}} - 1 - P_p G_{pp'}/(\sigma^2 + I_{pp'})$.

# Solution

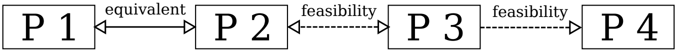


Figure: Problem relationship summary

**Proposition**

*Given feasible t, if optimal solutions for problem (4) are feasible for problem (3), then they are also optimal for problem (3). Otherwise, t is infeasible for problem (3).*

The relationship among problem (1) $\sim$ (4) is summarized in figure above.

# Solution

**Lemma**

*If there exists $P_s$ that is feasible for problem (4), then there exists a unique optimal power allocation $P_s^*$ such that constraint (4b), (4c) and (4d) hold at equality.*

motivates the following equations describing problem (4) in matrix form:

$$\mathbf{P}_s = \mathbf{D}(\gamma)\mathbf{q}\,, \tag{5}$$

$$\mathbf{q} = \mathbf{H}\mathbf{P}_p + \mathbf{G}\mathbf{P}_s + \boldsymbol{\eta}\,, \tag{6}$$

where $\gamma$ is SINR, and $\mathbf{P}_s^*$ can be obtained by solving previous equations.

Based on this observation, recall the main idea to attempt solving problem (1):

(i) Given $\beta$, we propose:
   (a) Given $t$, find the optimal $P_s^*$ for problem (4),
   (b) Check the feasibility of $P_s^*$ for problem (3)
   (c) Update $t$, and goto step (a)

(ii) Update $\beta$, and goto step (i)

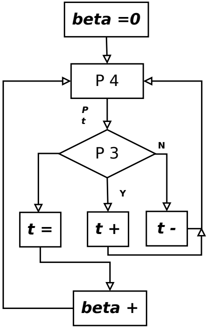


Figure: Summary of the solution.

# Solution

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Previously we proposed methods to find $P_s^*$ given $t$ and $\beta$

How to update $t$ and $\beta$:

$t$ bi-search algorithm

$\beta$ (i) Brute-force search, i.e., exhaustive search

(ii) greedy algorithm:

- (a) considers one step forward only
- (b) ensures improvement
- (c) locally searches the primary user or secondary user in bottleneck first

# Outline

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# Numerical Analysis

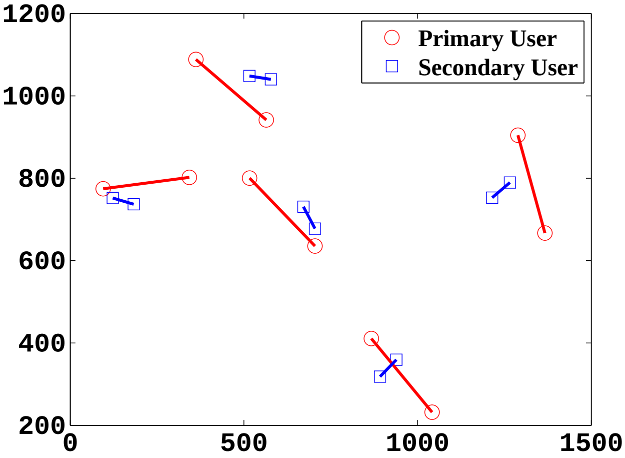


Figure: An example of the topologies used in simulations.

# Numerical Analysis

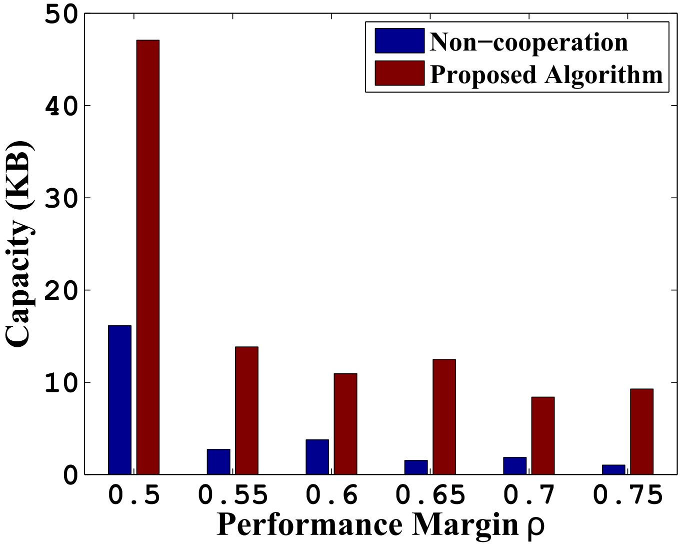


Figure: Performance comparison between the proposed algorithm and the strategy that does not allow cooperation. Note that we use different $R_p^{\mathtt{req}}$'s in different cases, where $R_p^{\mathtt{req}} = \rho R_p^{\mathtt{standalone}}$.

# Outline

# Conclusions

We proposed

- a fast algorithm for secondary user power allocation problem: $\log_2 C/\epsilon$
- a greedy algorithm for secondary user selection, or allocation, problem

while the performance of primary users are guaranteed.

# Future Work

- Distributed power allocation algorithm
- Distributed selection algorithm
- Convergence analysis
- Optimality analysis
- ...

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# Thank you

# Acknowlwdgement

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Figure: This work was performed within the EU FP7 project Hydrobionets

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