Cooperate to Access: Revisiting Spectrum Leasing

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(joint work with R. Pickholtz[2], I. Stanojev[1], S. Savazzi[3], Y. Bar-Ness[1] and U. Spagnolini[3])

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The New York Times

March 18, 2008, 6:14 pm

Going Once…Going Twice…The 700 Mhz Spectrum is Sold

… After 260 rounds of bidding over more than seven weeks the government auction has ended for the 700 Mhz wireless spectrum.
The winning bids totaled $19,592,420,000. That’s nearly double the amount the commission had hoped to raise from the spectrum being abandoned next year as television stations switch to new frequencies.

"raised more money than any [FCC] auction has ever raised"

The New York Times

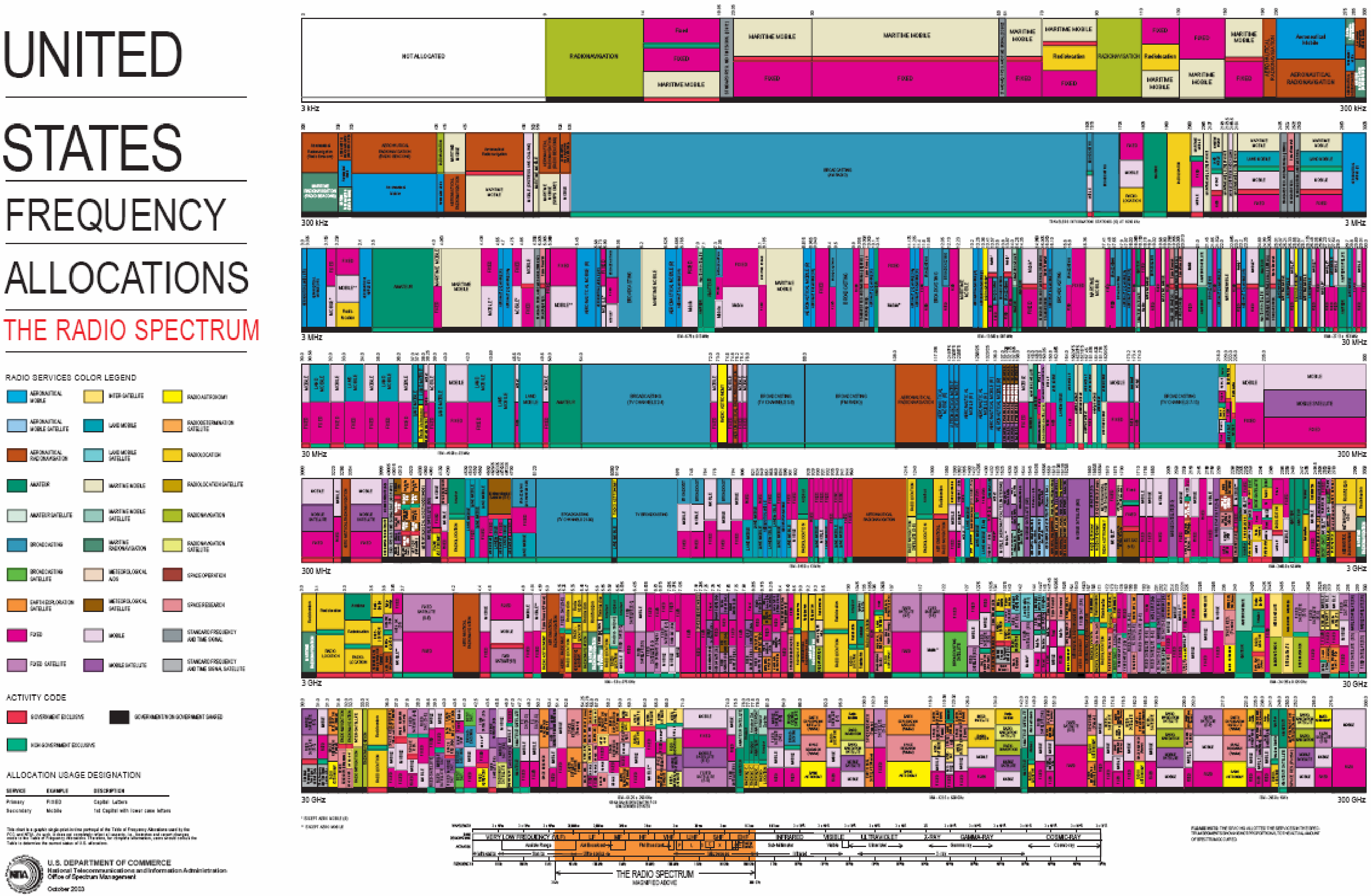
Verizon, AT&T win FCC auction, Google wins open spectrum
Thu Mar 20, 2008 7:43 PM ET

While the language of the ruling has not been made public, it appears that any company that buys the new spectrum will have to *leave it open to devices it does not approve or control*.

… it appears to signal a *shift in how policy makers and, in turn, companies, will approach access to and control of future wireless networks*.

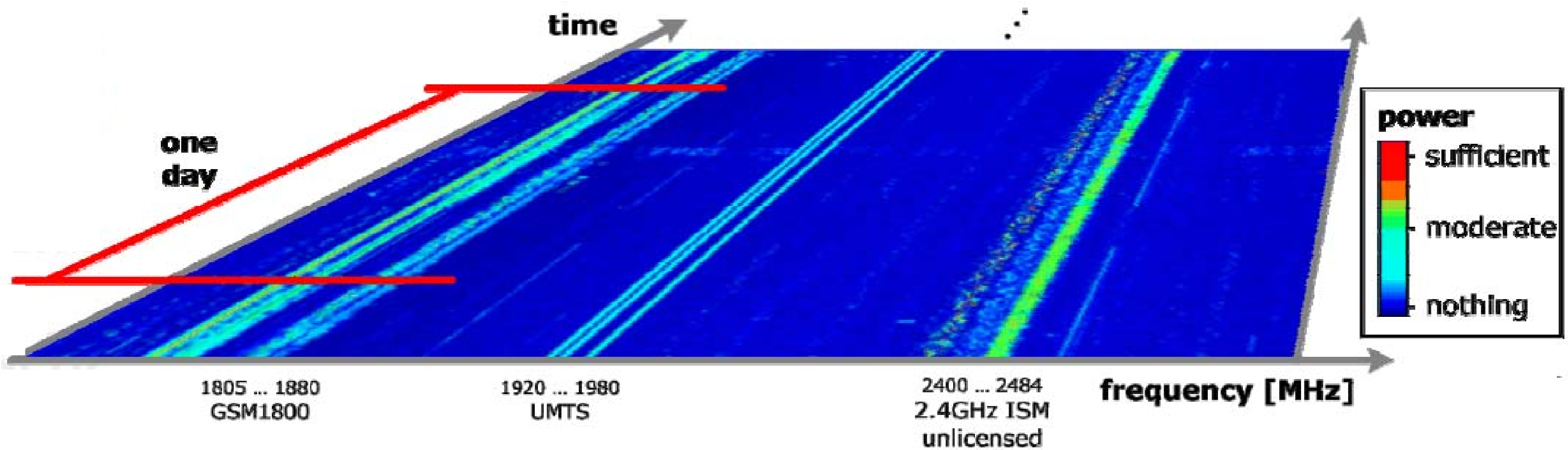
The ruling did not go far enough for some consumer activist groups, but even those groups applauded parts of it. In recent weeks, Google and other technology interests pressed the commission to create an open-access wireless network — in contrast to today’s closed cellular networks — and *to permit owners of the spectrum to sell portions of it wholesale to other companies*.

Scarcity of Spectrum?



Scarcity of spectrum?

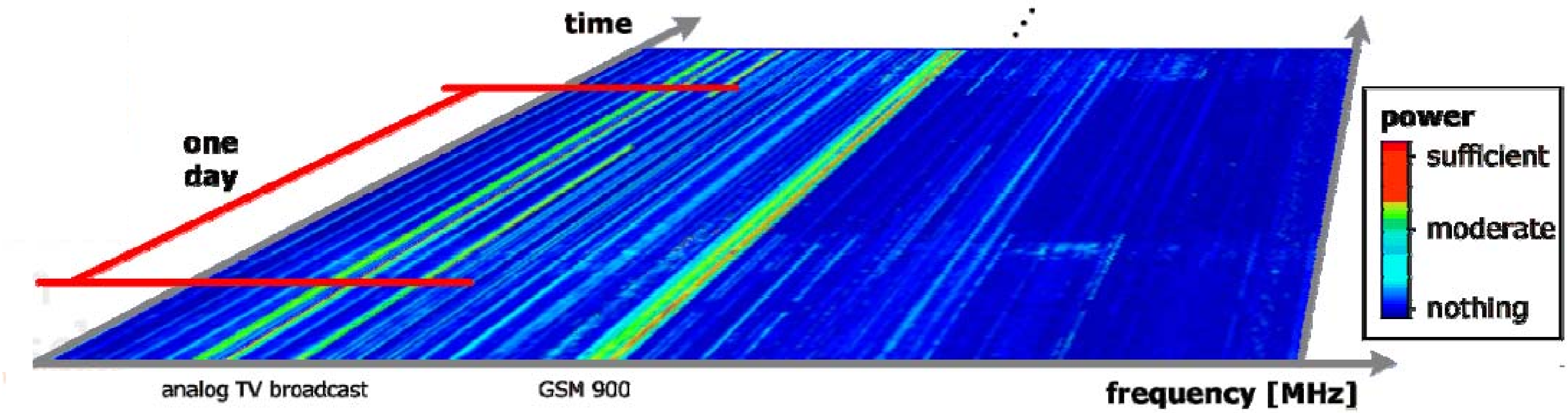
Measurements around 2GHz:



…90% of the time, many licensed frequency bands remain unused
(FCC report, Nov. 2002)

Scarcity of spectrum?

Measurements below 1GHz:



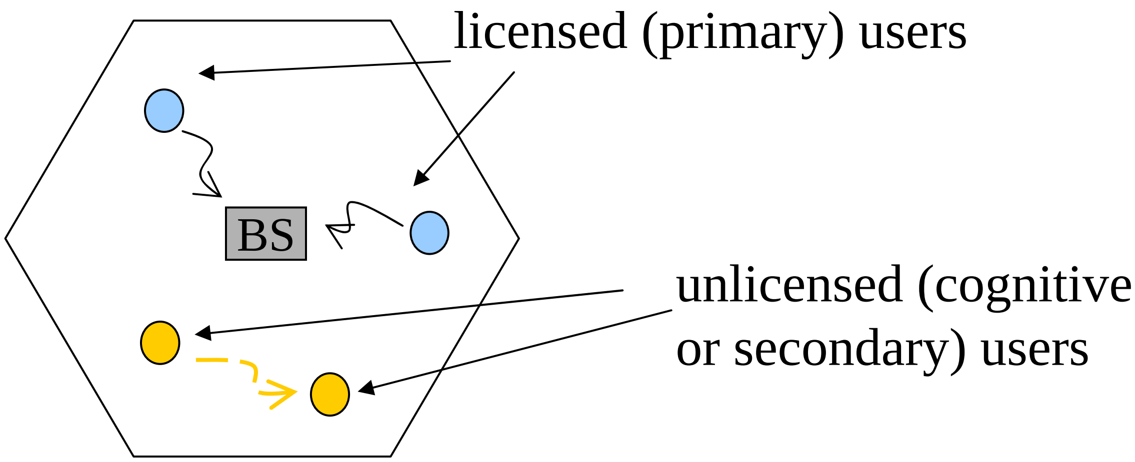
…90% of the time, many licensed frequency bands remain unused
(FCC report, Nov. 2002)

FCC, Secondary Markets Initiative: *"remove regulatory barriers and facilitate the development of secondary markets in spectrum usage rights among Wireless Radio Services."*

Secondary Spectrum Access

(… or Cognitive Radio)

- Coexistence of primary and secondary nodes in the same bandwidth:



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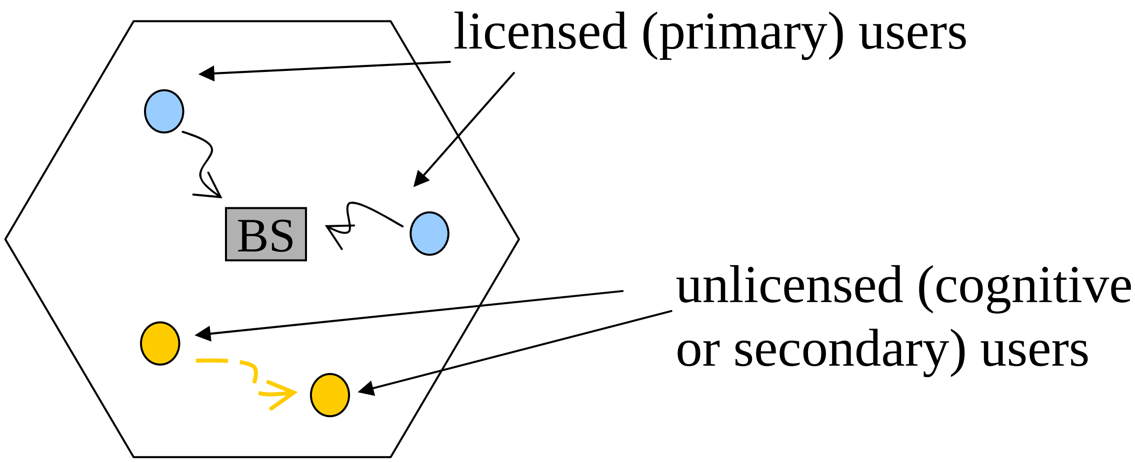

1) ***Commons* model:**

- primary users are oblivious to the presence of secondary nodes.
- the activity of the secondary users should be *trasparent* to the primary.

2) ***Property-rights* model:**

- primary users *own* the spectrum and can decide to lease it to secondary nodes.

Commons vs. Property-Rights

- In the technical literature on communications, the **commons model** has been studied almost exclusively: information theory [Devroye et al. 06] [[Jovicic, Viswanath arxiv], partially observable Markov chains [Zhao et al. 07], queuing theory [Simeone et al. 07].

- IEEE 802.22 standard for Wireless Regional Area Network (WRAN) utilizing white spaces in TV bands (VHF/UHF TV bands between 54 and 862 MHz) based on the **commons model**.

- The commons model presents very relevant implementation challenges (sensing, interference).

Commons vs. Property-Rights

- The property-rights model has been less studied in the communication community.

- Pricing via profit maximization [Acharya and Yates 07], auction theory [Huang et al. 07]

- **Can the property-right model be implemented using communications technology?**

Cooperation

- Cooperation: “Relaying” of packets for enhanced quality-of-service [Sendonaris et al. 03].

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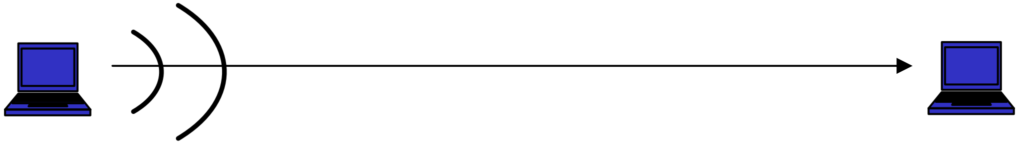

Cooperation

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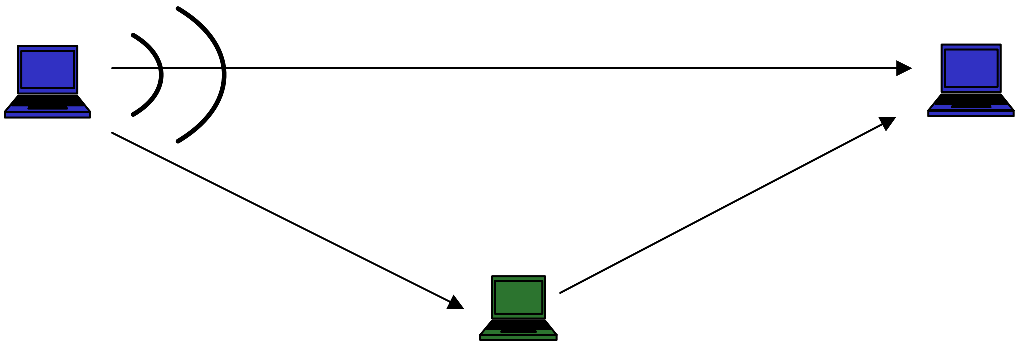


[Cover and El Gamal 79]

Property-Rights Access via Cooperation

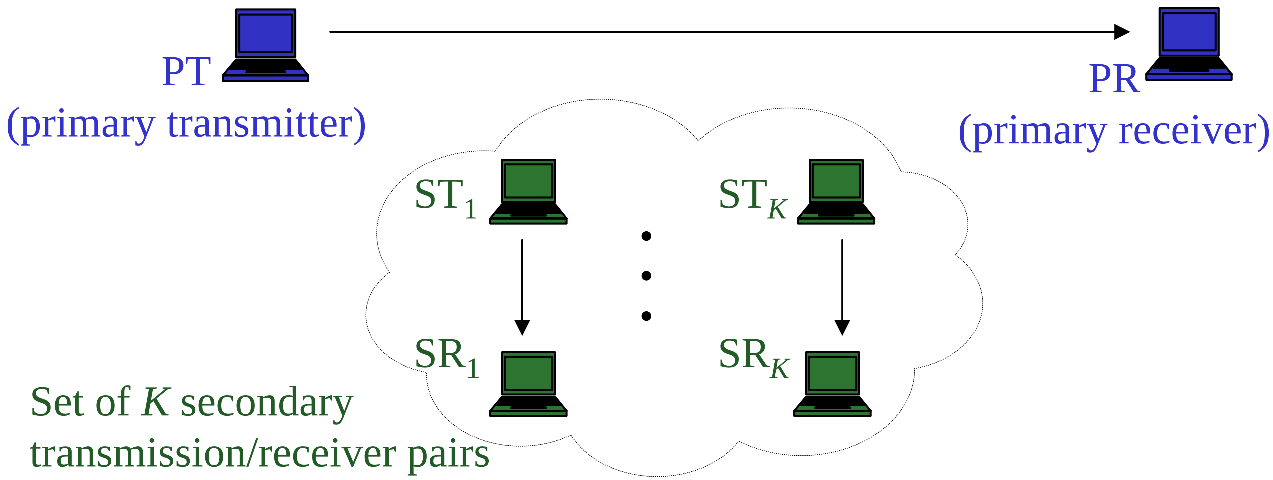
- **Main idea**: Retribution to primary nodes for spectrum access in the form of *cooperation*.

=

- Primary nodes will be willing to lease the owned bandwidth for a fraction of time if, in exchange for this concession, they will benefit from enhanced quality-of-service thanks to cooperation with the secondary nodes.

- Secondary nodes have the choice about whether to cooperate or not with the primary on the basis of the amount of cooperation required by the primary and the corresponding fraction of time leased for secondary transmissions.

Our Case-Study

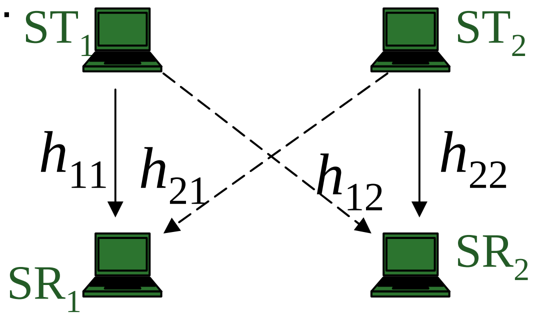


- Primary transmit-receive pair that owns the spectrum.
- Ad hoc network of K secondary (**competitive**) communications on the same bandwidth.
- Fading channels h_{ij}

A bit of Game Theory

- Non-cooperative game theory: competing decision makers.

- Ex.:



Each link is interested in maximizing:

$$\underbrace{u(P_i, P_{-i}) = \log\left(1 + \frac{|h_{ii}|^2 P_i}{1 + |h_{-i,i}|^2 P_{-i}}\right)}_{\text{Rate}} \underbrace{- cP_i}_{\text{Cost of power}}$$

s.t. $P_i \leq P_{\max}$

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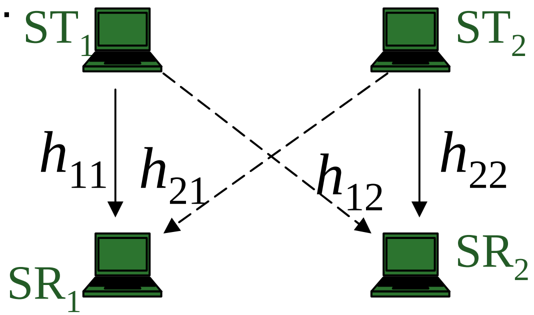

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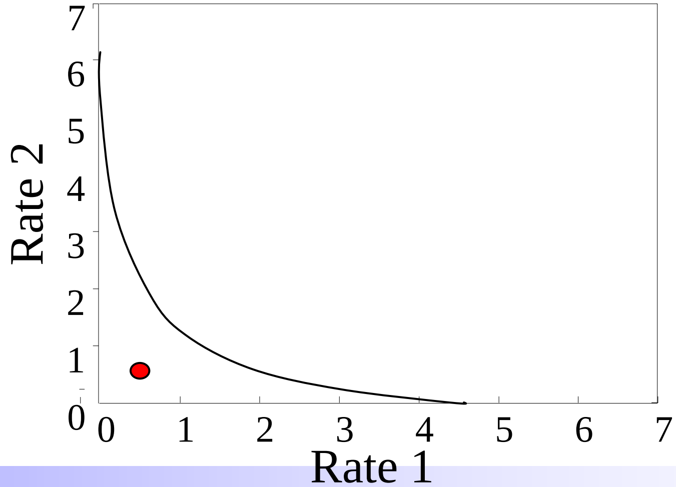
s.t. $P_i \le P_{\max}$

- Nash equilibrium: no user has incentive to deviate unilaterally

$$\begin{cases} \dfrac{\partial u_1}{\partial P_1} = 0 \\ \dfrac{\partial u_2}{\partial P_2} = 0 \end{cases}$$



$|h_{ii}|^2=1, |h_{-i,i}|^2=0.8, c=0.1$
$P_{max}=20dB$

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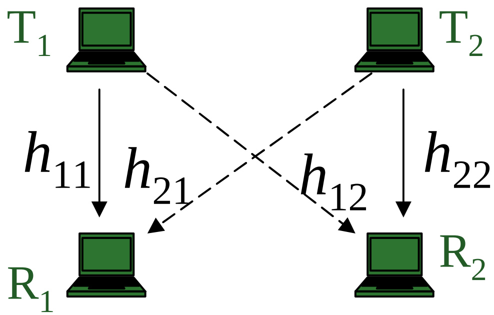

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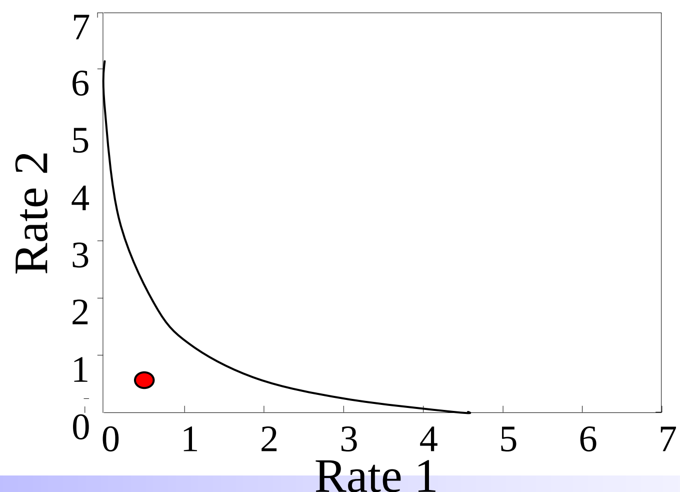

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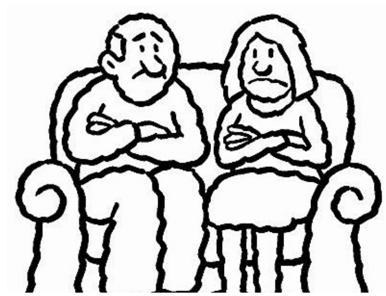
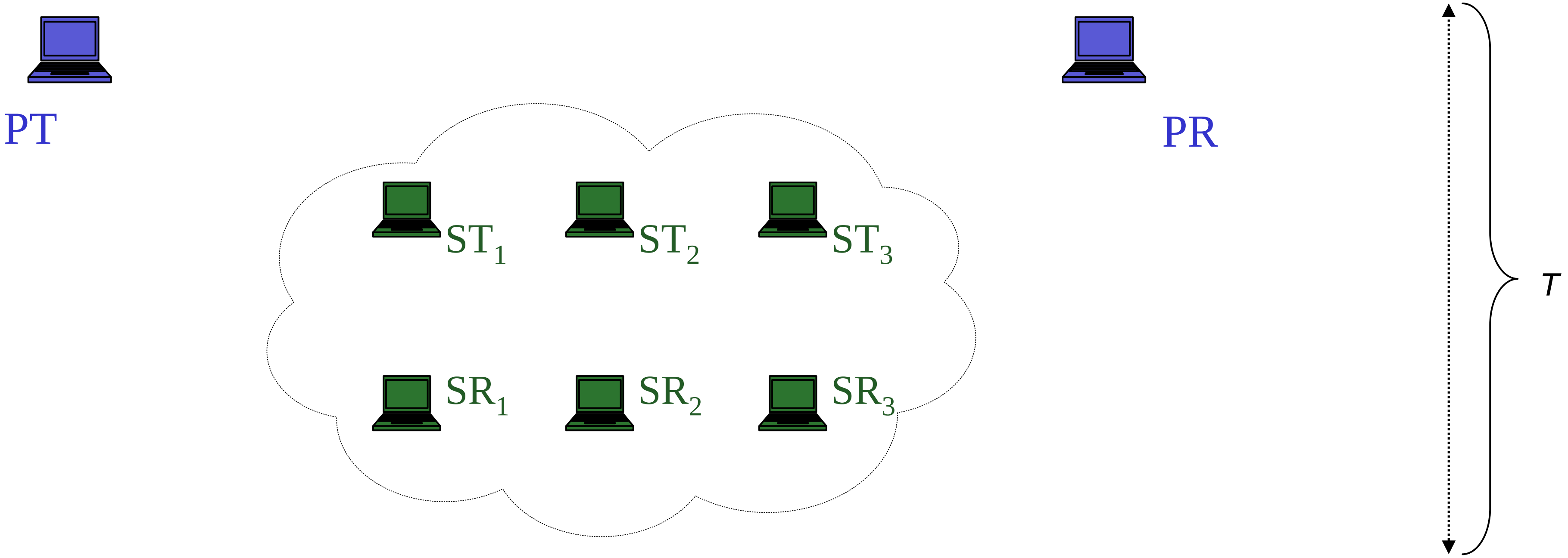
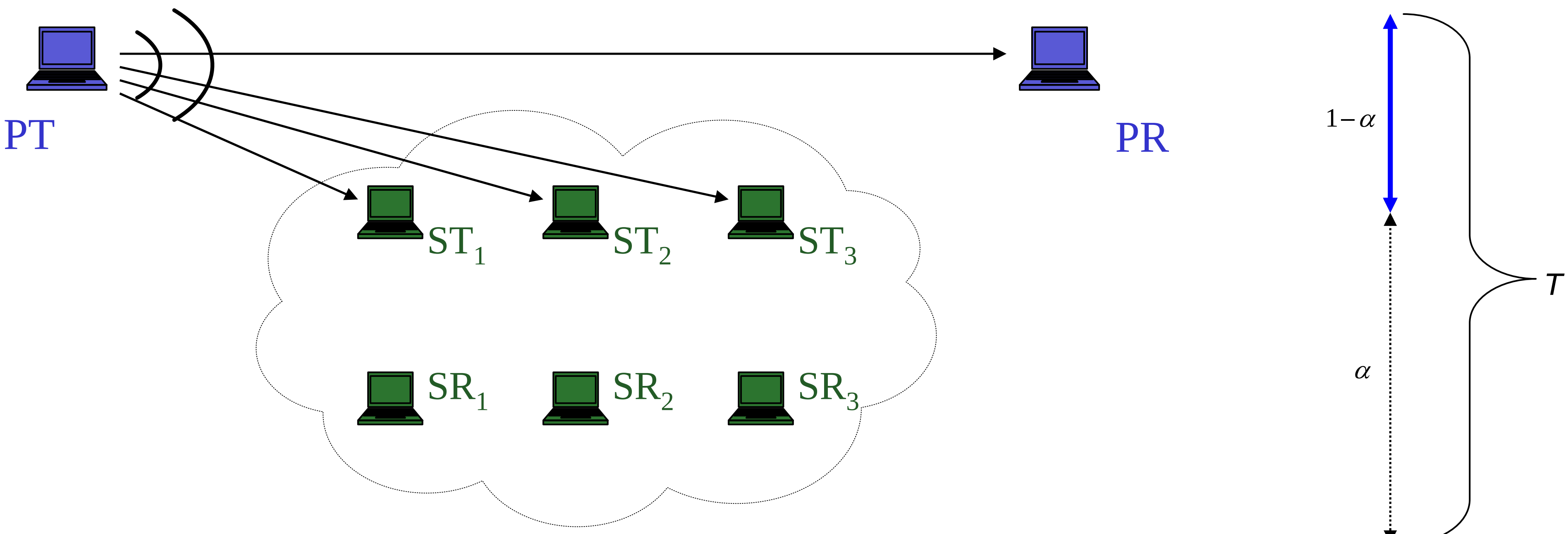


Spectrum Leasing via Cooperation



Spectrum Leasing via Cooperation

- PT communicates directly with PR for a fraction of time $(1-\alpha)$.



Spectrum Leasing via Cooperation

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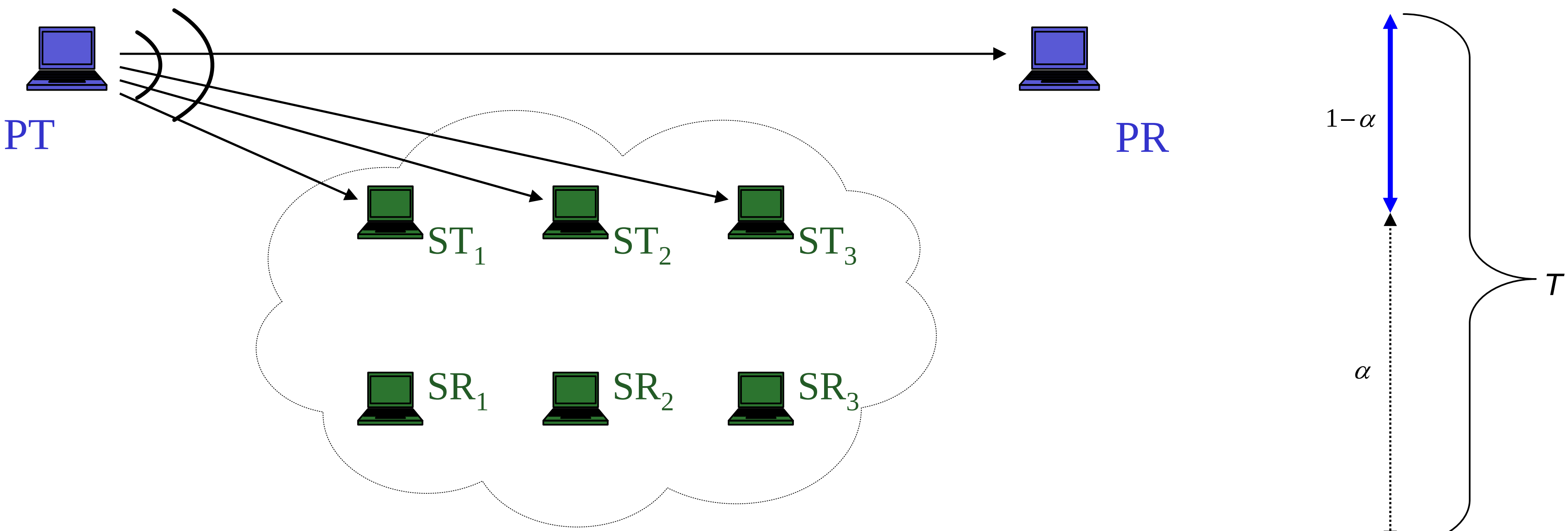
- Remaining period of α can be *leased* to a subset of secondary that decoded the message (in exchange for cooperation).



Spectrum Leasing via Cooperation

- PT communicates directly with PR for a fraction of time $(1-\alpha)$.
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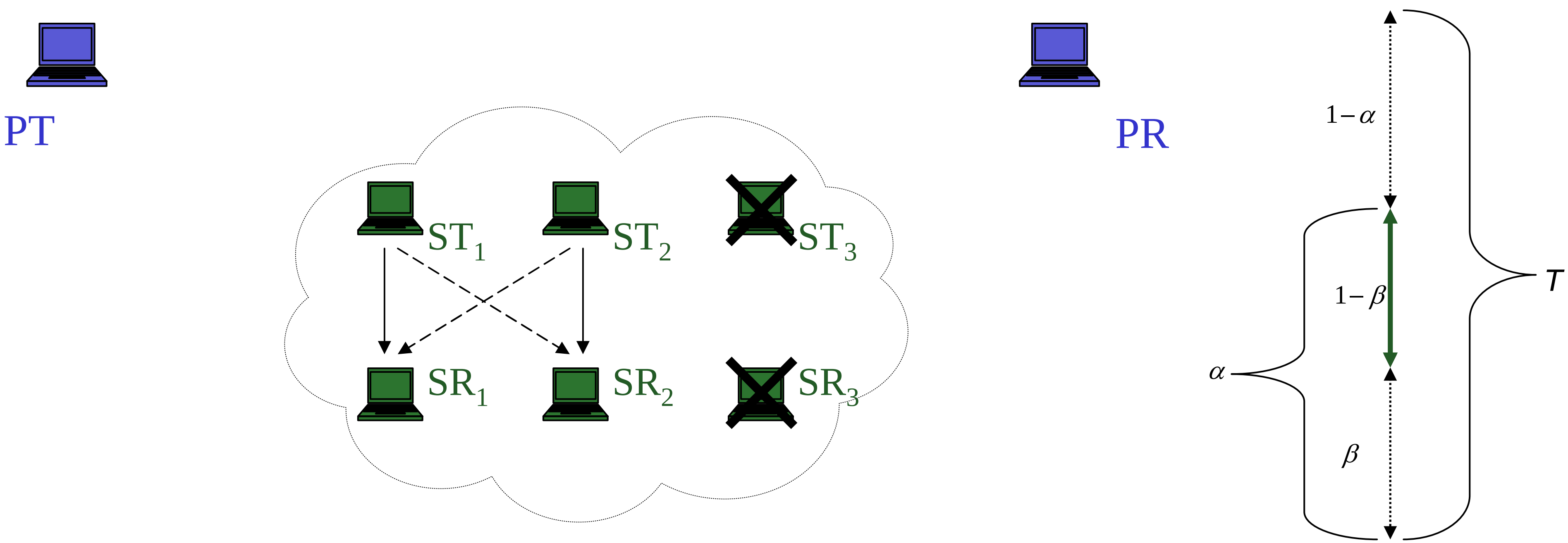
- Secondary nodes transmit own data for a fraction $(1-\beta)$ of the leased time.



Spectrum Leasing via Cooperation

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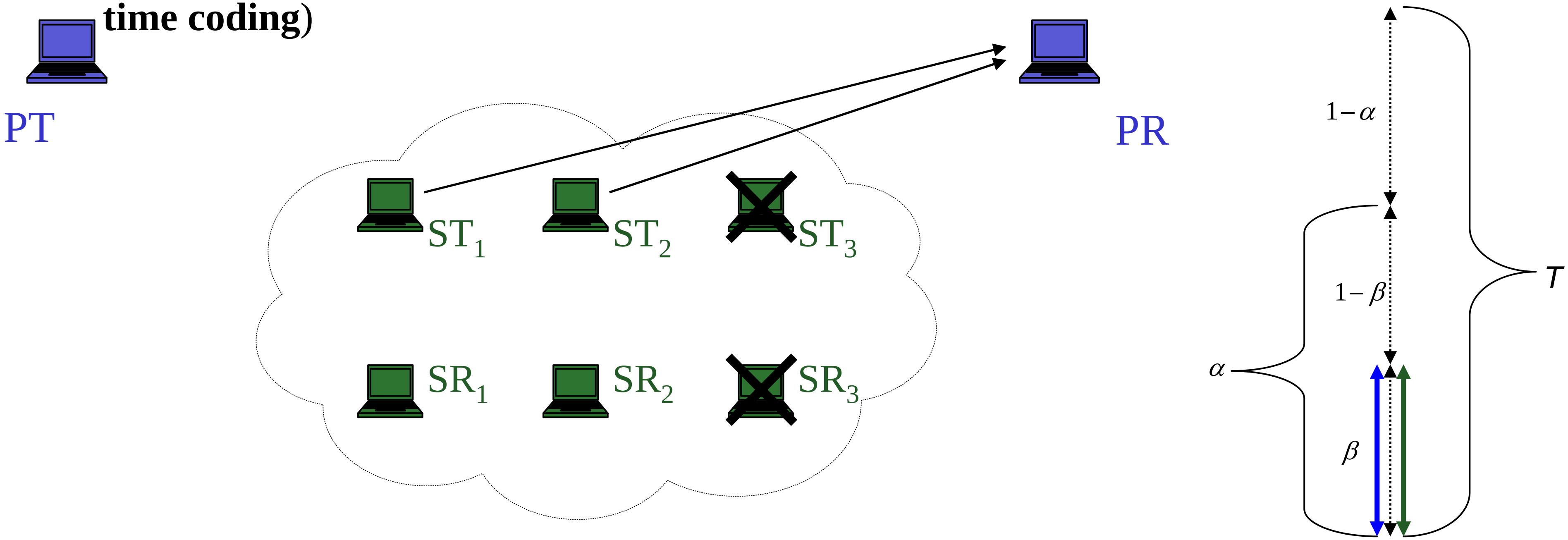
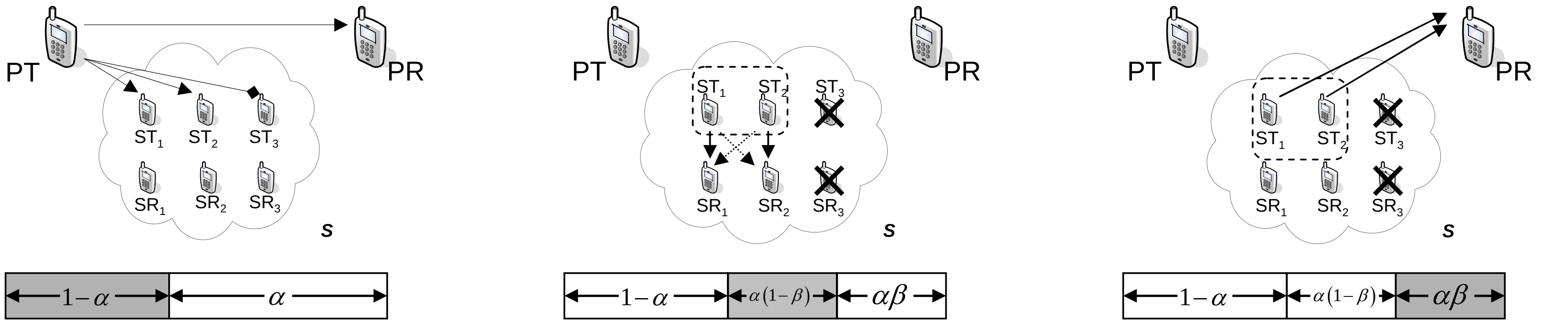
- Remaining period of α can be *leased* to the set of secondary that decoded the message (in exchange for cooperation).
- Secondary nodes transmit own data for a fraction $(1 - \beta)$ of the leased time.
- In the last fraction of time, primary traffic is relayed (**cooperation via distributed space-time coding**)

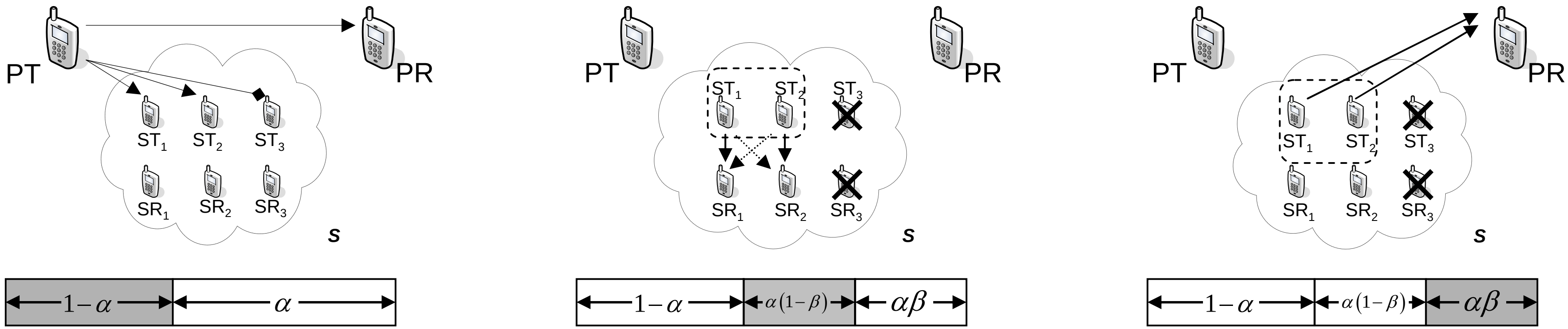


Spectrum Leasing: Primary Decision Process



- Primary link's goal: maximize its own rate R_P.
- Optimization space:
  - time fraction α to be leased to the secondary network
  - fraction β required from secondary to cooperate
  - subset $\mathcal{S}$ of secondary terminals to receive the spectrum
- Constraints:
  - Maximum primary transmit power P_p
  - *Equilibrium constraint*: Being competitive, the STs settle for a transmit power given by a **Nash equilibrium**

Spectrum Leasing: Primary Decision Process



$$\max_{\alpha,\beta,\mathcal{S}} \; R_{\mathrm{P}}(\alpha,\beta,\mathcal{S})$$

$$\text{s.t. } \mathcal{S} \subseteq \mathcal{S}_{tot}, \; 0 \leq \alpha,\beta \leq 1$$

$$R_{\mathrm{P}}(\alpha,\beta,\mathcal{S}) = \begin{cases} R_{\mathrm{dir}} & \text{for } \alpha = 0 \\ R_{\mathrm{coop}}(\alpha,\beta,\mathcal{S}) & \text{for } \alpha > 0 \end{cases}$$

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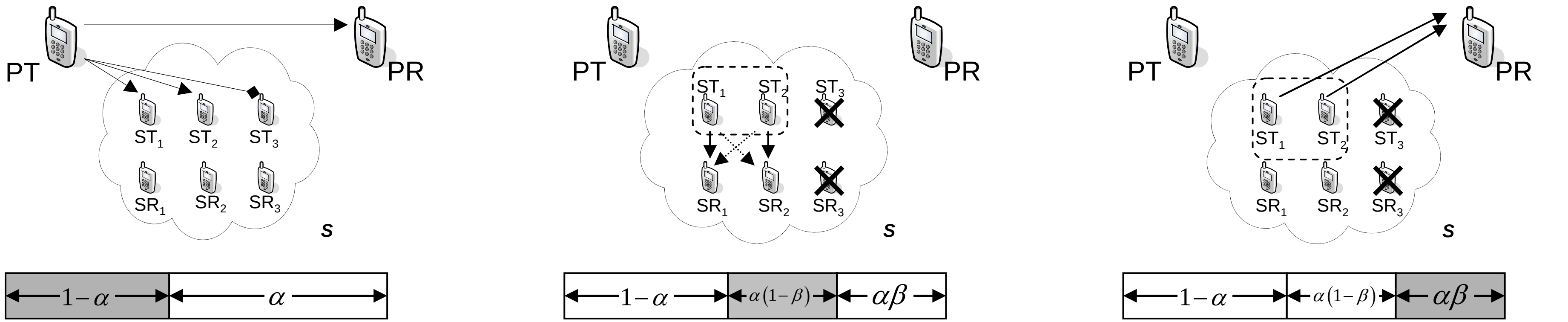

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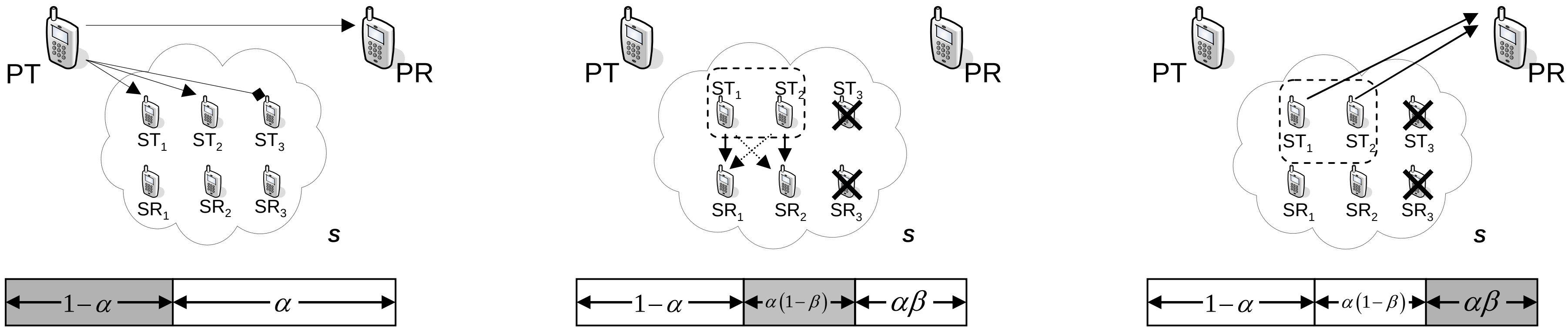

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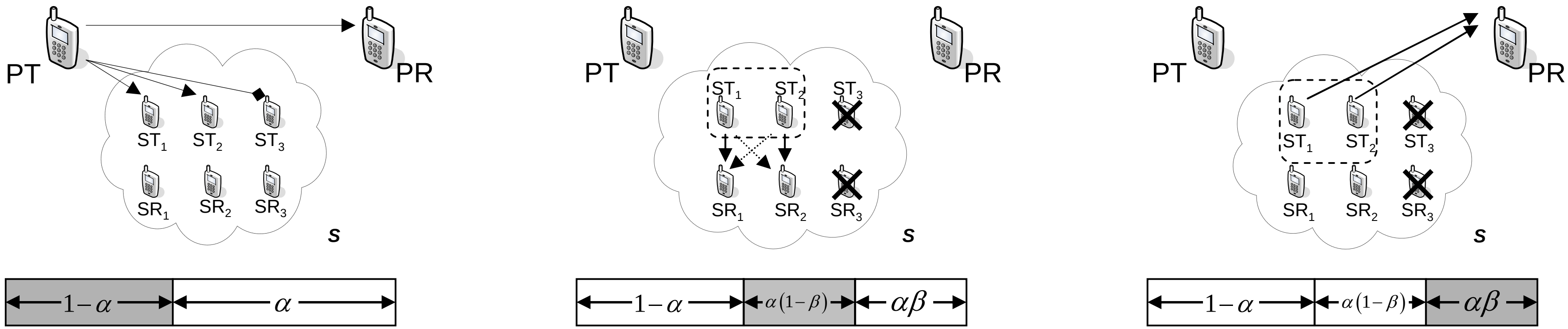
- $R_{\mathrm{coop}}(\alpha,\beta,\mathcal{S}) = \min\{(1-\alpha)R_{\mathrm{PS}}(\mathcal{S}), \alpha\beta R_{\mathrm{SP}}(\alpha,\beta,\mathcal{S})\}$

  with $R_{\mathrm{PS}}(k) = \log_2\left(1 + \frac{|h_{\mathrm{PS},k}|^2 P_{\mathrm{P}}}{N_0}\right)$ $\quad R_{\mathrm{SP}}(k,\beta) = \log_2\left(1 + \sum_{i=1}^{k} \frac{|h_{\mathrm{SP},i}|^2 \hat{P}_i(k,\beta)}{N_0}\right)$

Spectrum Leasing: Secondary Decision Process

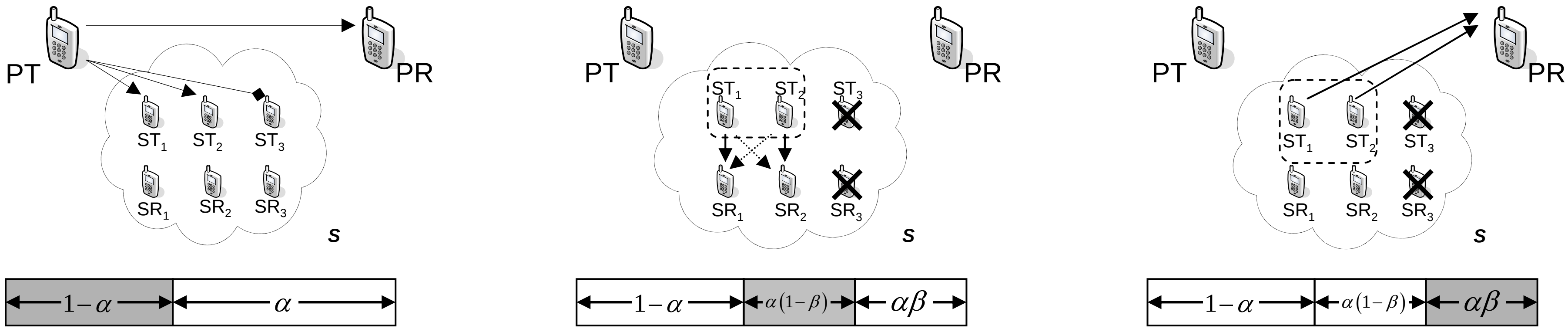


- If selected by the primary, the secondary can decide how much power to employ.
- This decision is made competitively by the secondary transmitters.
- Optimization criterion: maximize own rate *discounted by the cost of transmission power*

$$u_i(P_i, \mathbf{P}_{-i}) = (1-\beta)R_i(P_i, \mathbf{P}_{-i}) - c \cdot P_i$$

- Constraints:
  - Maximum secondary power
  - Leasing parameters (α, β) selected by the primary.

Spectrum Leasing: Secondary Decision Process



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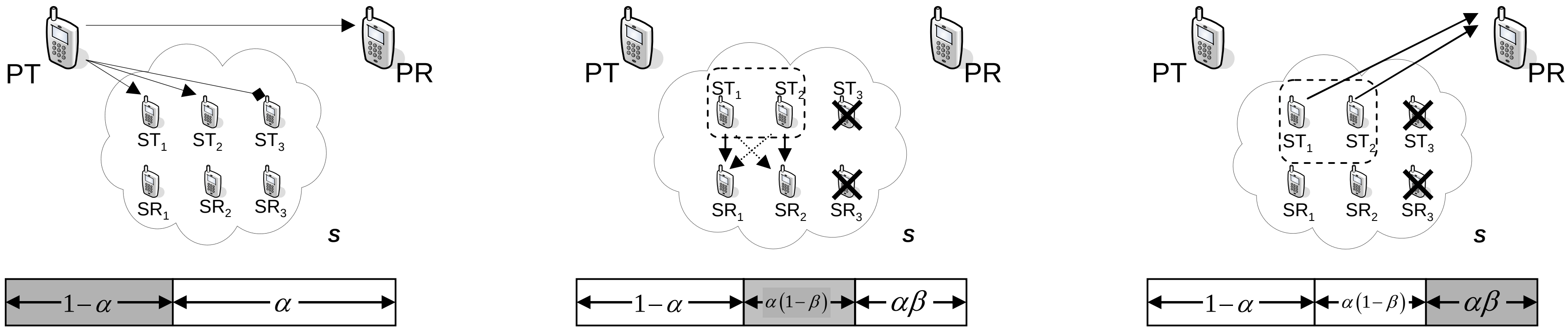
Spectrum Leasing: Secondary Decision Process



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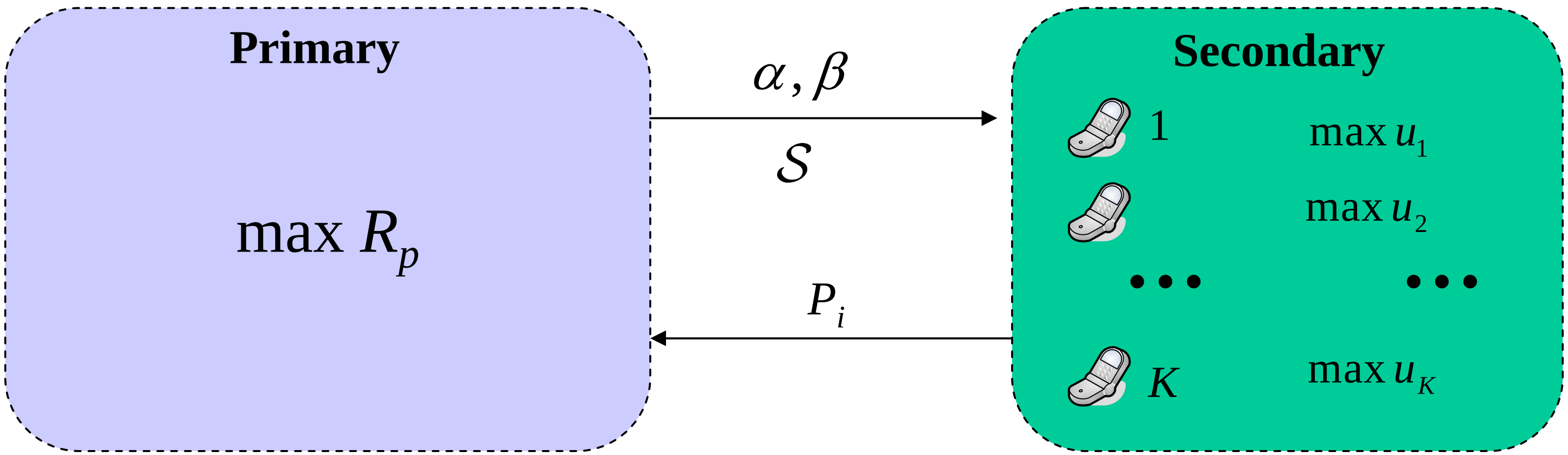
$$u_i(P_i, \mathbf{P}_{-i}) = (1-\beta)R_i(P_i, \mathbf{P}_{-i}) - c \cdot P_i$$

- Non-cooperative game.
- Equilibrium solution provided by the Nash equilibrium:

  The powers selected by the secondary nodes selected by the primary are such that no secondary has any incentive to change its power if the others don’t.

A System View of the Decision Process



- **Hierarchical decision process**
- **Stackelberg game:**
  - Primary is the *leader* (with α, β and S as the playing strategy).
  - Secondary network is the *follower* (with transmitting powers as the strategy).
  - The leader can predict the behavior of the follower

A Note on the Protocol

- **Control channel:**
- The primary link to be aware of the number and identity of secondary nodes.
- Exchange of Channel State Information (CSI) parameters among different nodes (e.g., between secondary network and primary transmitter).
- Delivering the decision of the primary.

… The need for a control channel, and the consequent reduction in spectral efficiency, is the price to be paid for the implementation of spectrum leasing.

Some analytical results

Proposition 1: The power control game at the secondary network has always a NE. Moreover, a sufficient condition for the NE to be unique is

$$\sum_{j\in\mathcal{S},\, j\neq i} \frac{\left|h_{\mathrm{S},ij}\right|^2}{\left|h_{\mathrm{S},ii}\right|^2} < 1.$$

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Proposition 2: The optimal fraction of time α leased for secondary transmission and cooperation is strictly positive if and only if there exists a subset of secondary nodes *S* such that the following condition is satisfied

$$\frac{\hat{\beta} R_{SP}(\hat{\beta},\mathcal{S}) \cdot R_{PS}(\mathcal{S})}{\hat{\beta} R_{SP}(\hat{\beta},\mathcal{S}) + R_{PS}(\mathcal{S})} > R_{\mathrm{dir}}$$

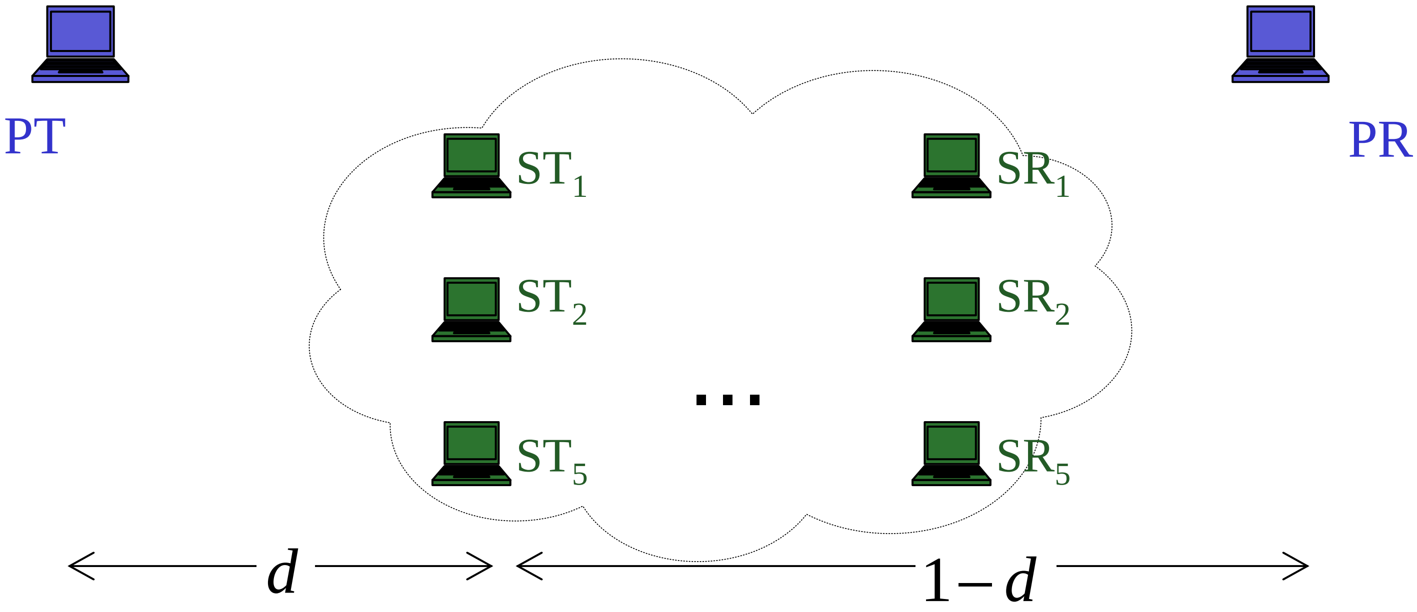
where the optimal β is the solution of the optimization problem

$$\hat{\beta} = \arg\max_{\beta\in[0,1]} \beta R_{SP}(\beta,\mathcal{S}).$$

Moreover, conditioned on (*) (i.e., on α>0), the optimal fraction α for a given subset *S* reads

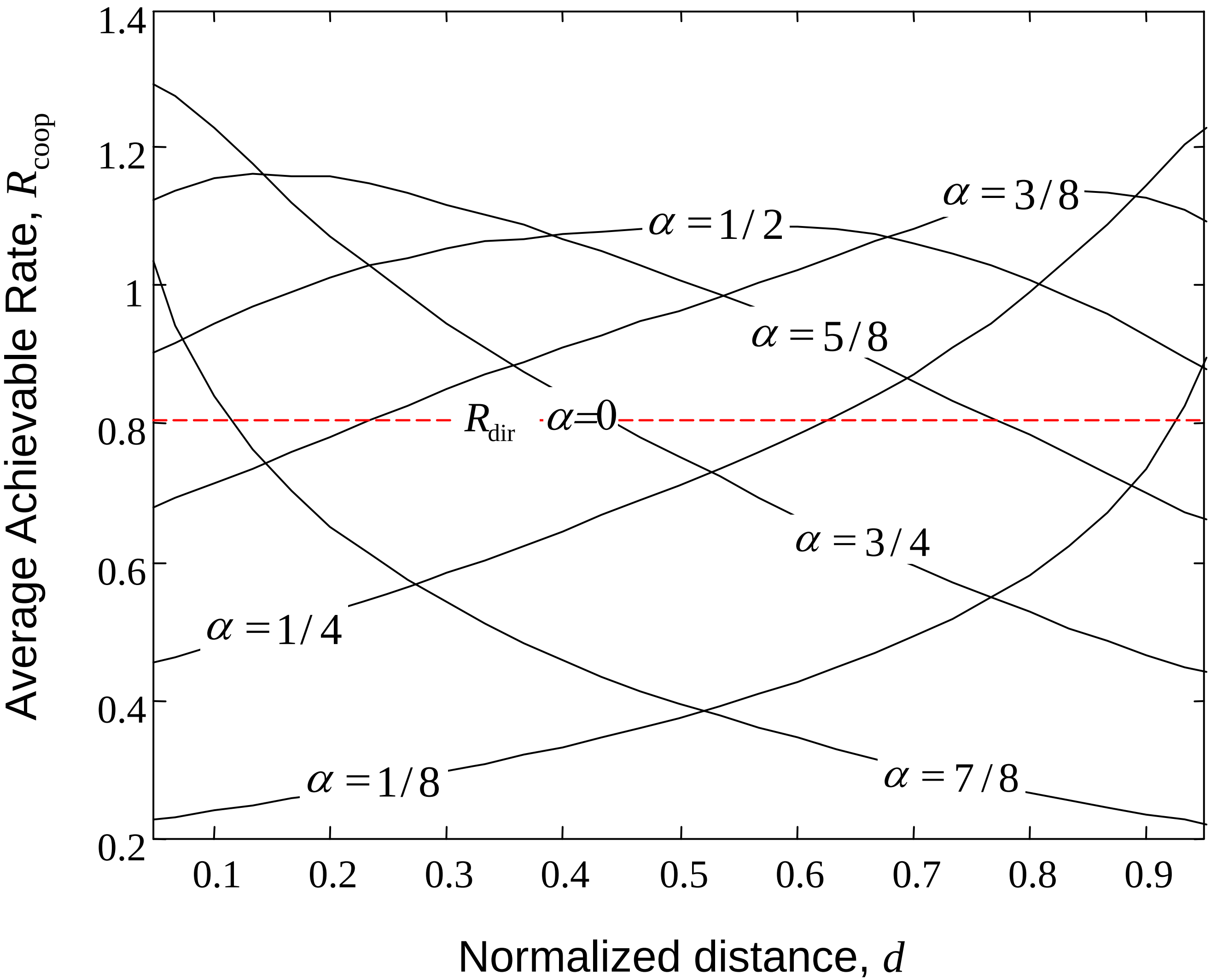
$$\hat{\alpha}_{\mathrm{coop}} = \frac{1}{1+\frac{\hat{\beta} R_{SP}(\hat{\beta},\mathcal{S})}{R_{PS}(\mathcal{S})}}.$$

Some numerical results



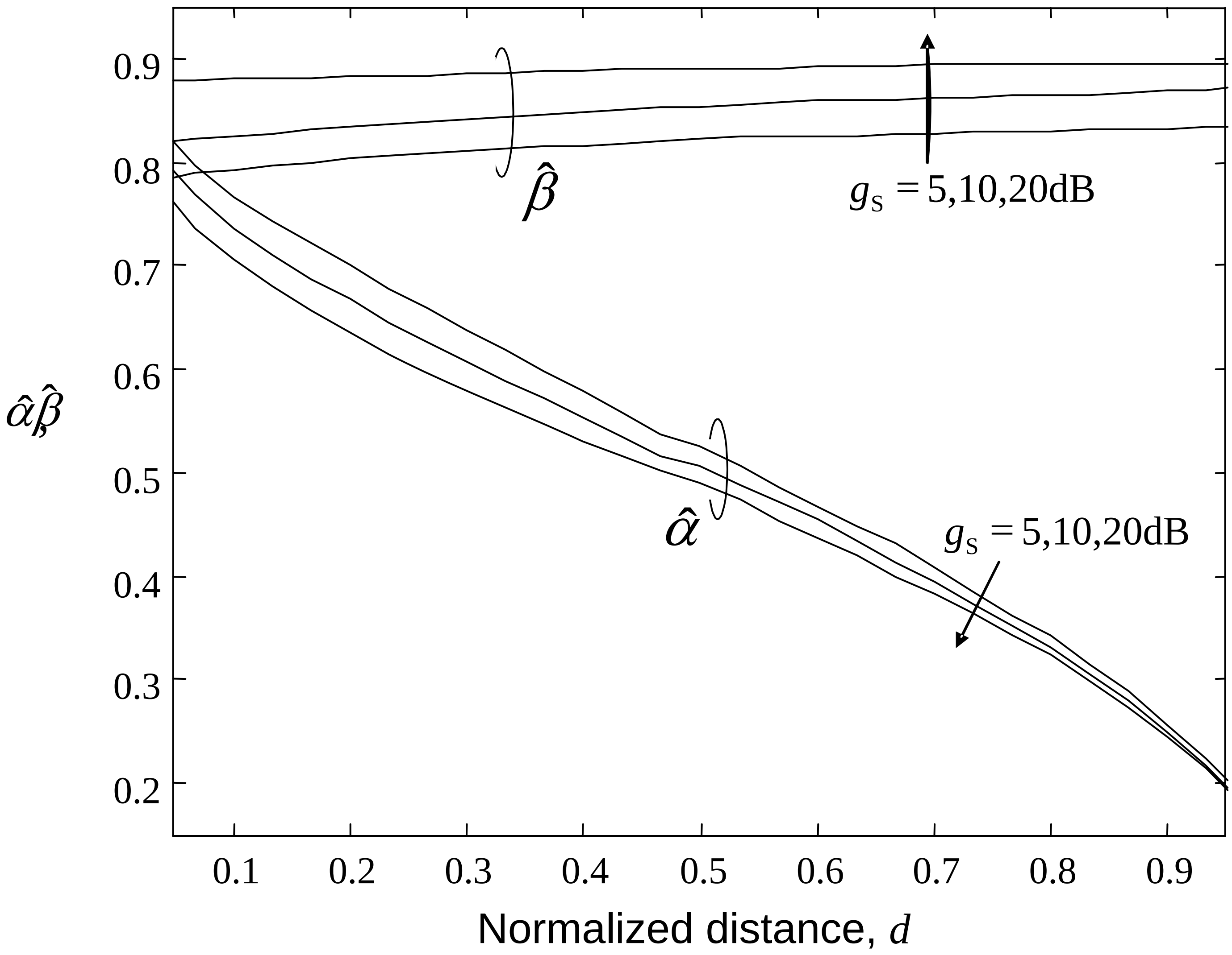
- Path loss model (exp=2) and Rayleigh fading.
- $P_p=1$, $SNR=P_p/N_0=0$dB, c=0.1, K=5 and $g_S=10$dB.

Some numerical results



… as the distance d increases, the optimal α *decreases.*

Some numerical results



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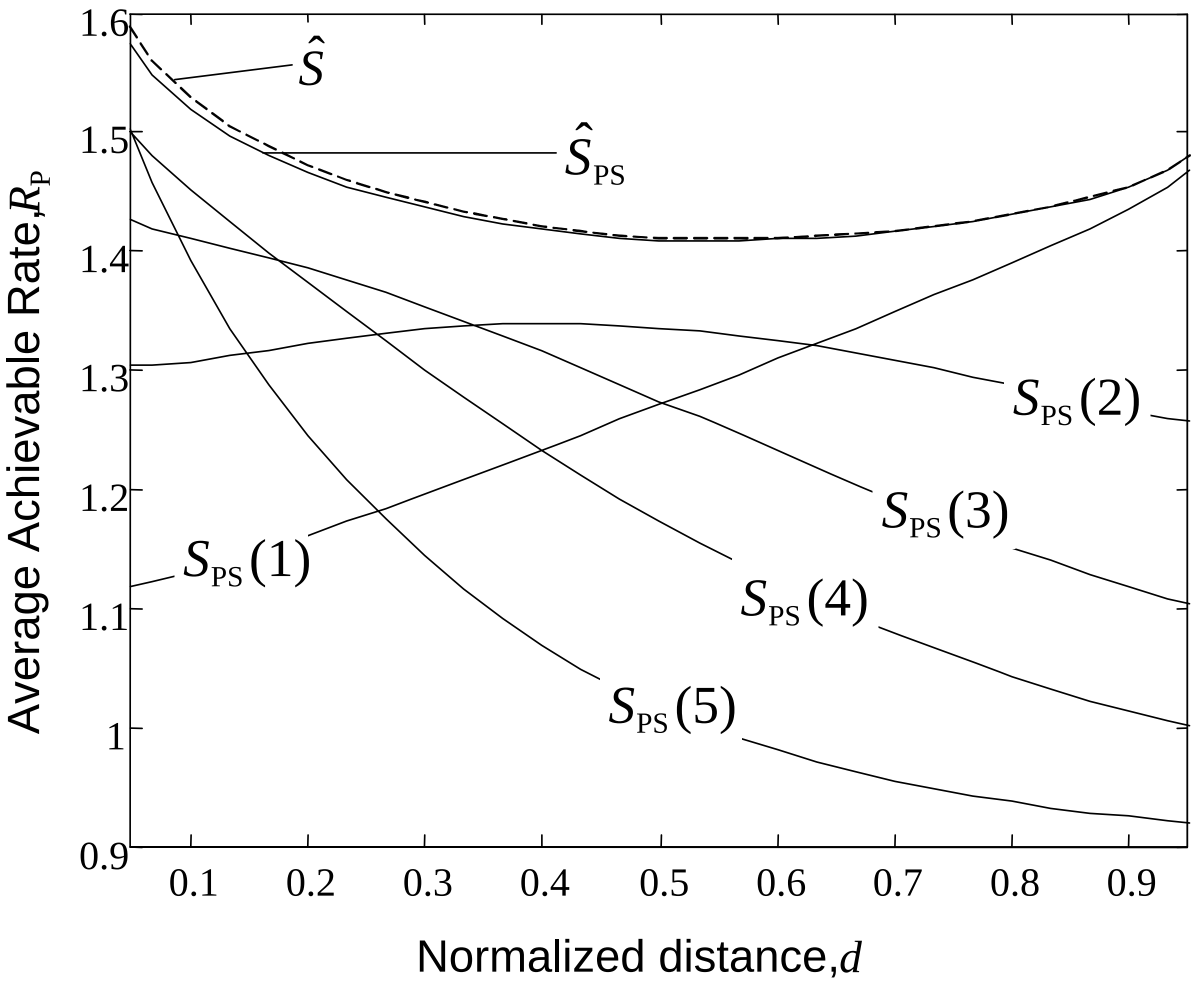
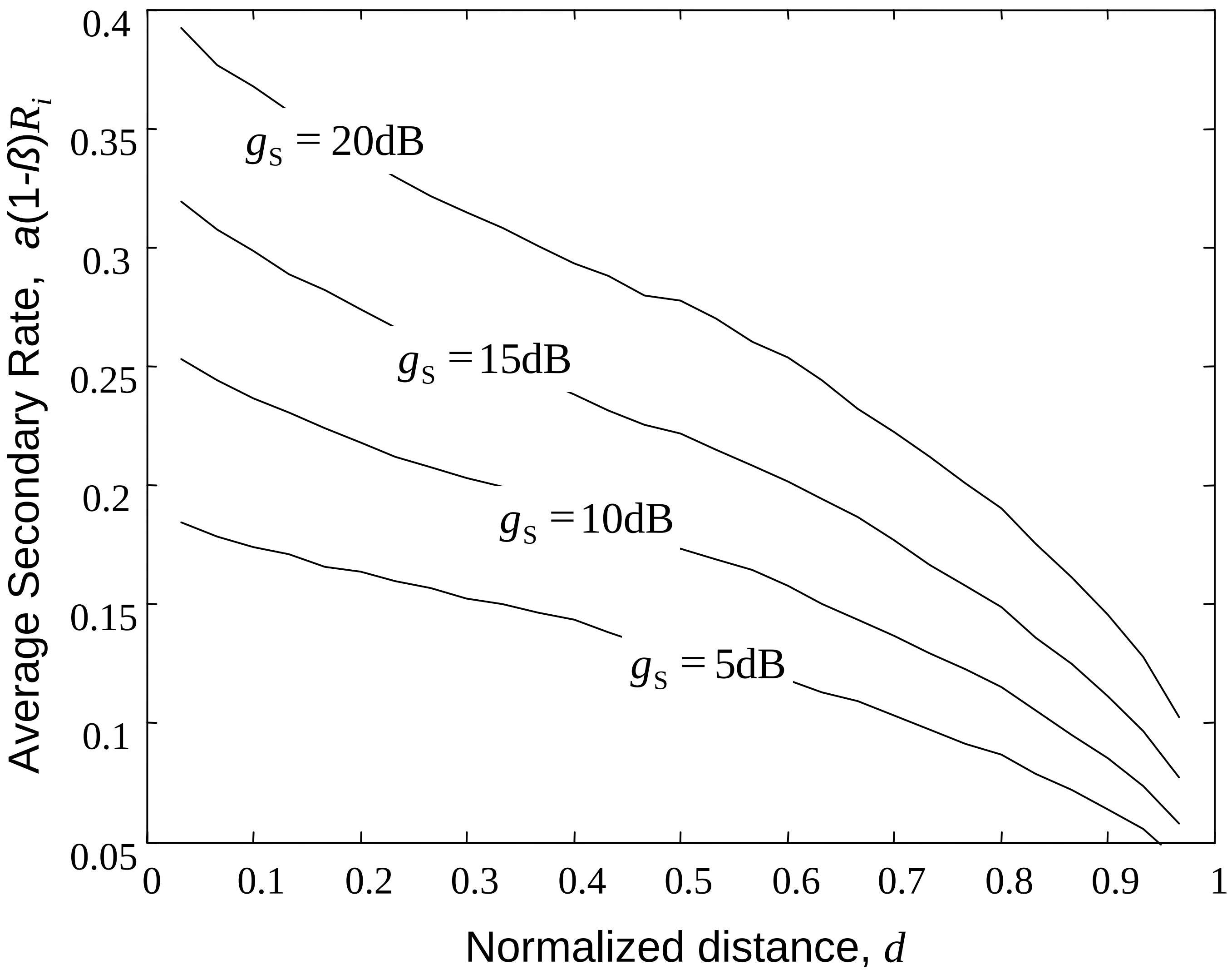


… for large distances it is more convenient to cooperate only with the secondary users with the best instantaneous channel, exploiting multiuser diversity.

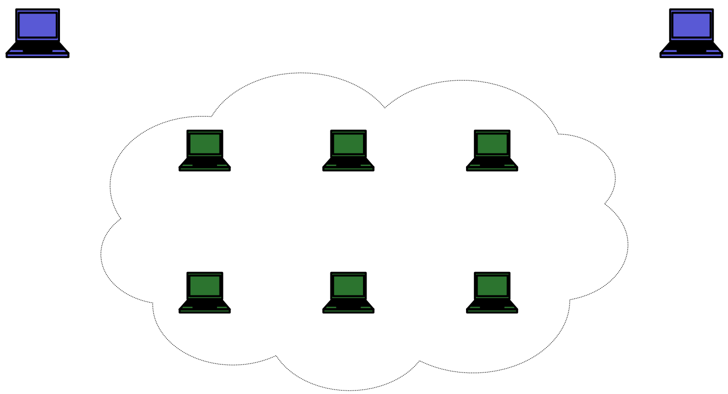
Some numerical results



Since a larger distance entails a smaller optimal leased time α, the secondary rate decreases as the distance increases.

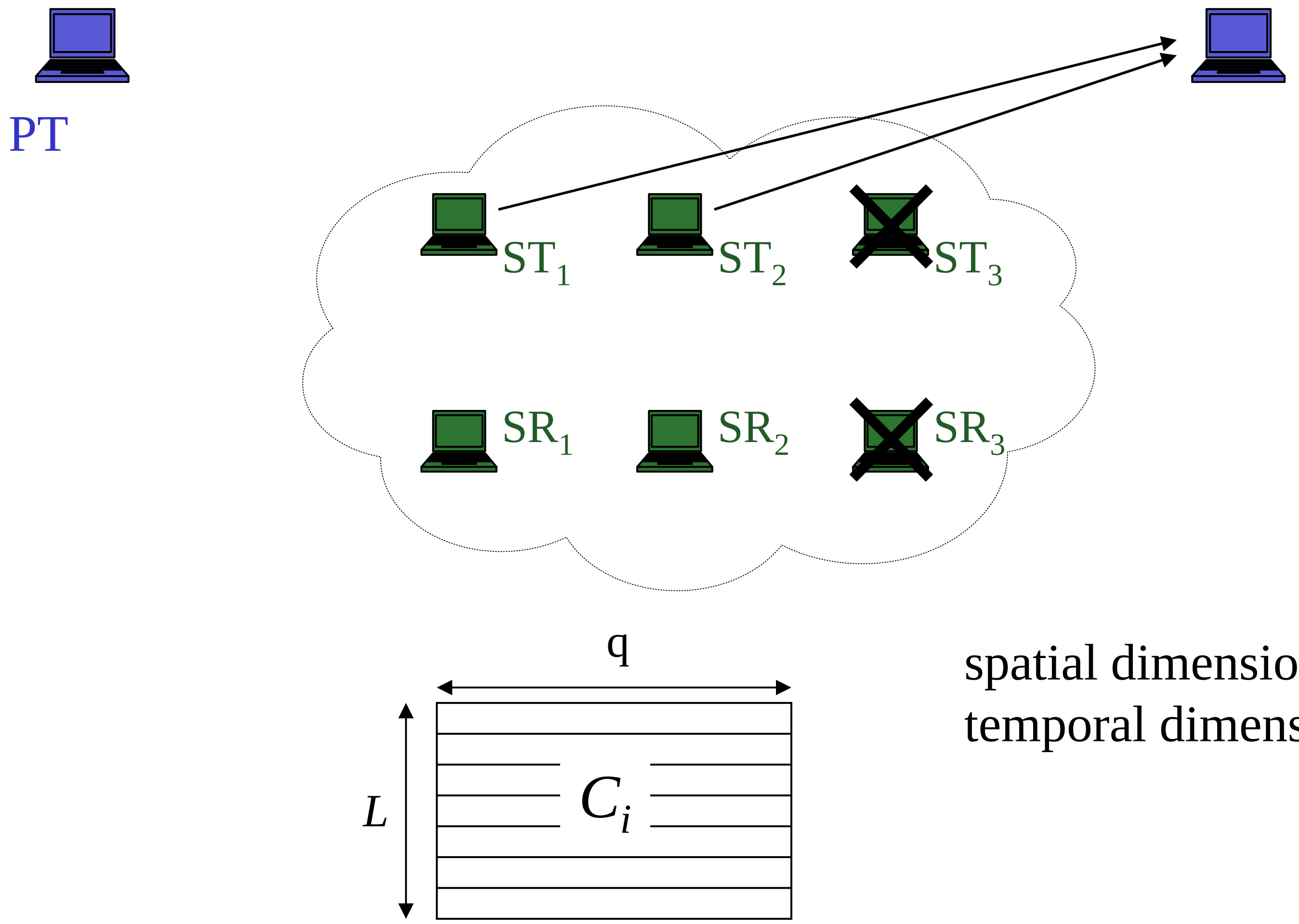
Practical Issues

- The analysis has implicitly assumed:
  - Full Channel State Information (CSI) at the primary
  - Long transmitted codewords (information theory)



- With no CSI:
  - Outage probability for any fixed selected rate
  - System optimization can only be based on statistical performance measures
  - The set of secondary transmitters able to decode the primary message is a random quantity: *randomized distributed space-time codes* [Sirkeci-Mergen and Scaglione 07]

Randomized Distributed Space-Time Codes



spatial dimension L,
temporal dimension q

[Sirkeci-Mergen and Scaglione 07]

Primary Decision Process with no CSI

$$\min_{\alpha,\beta,\mathbf{C}_i} \quad \mathrm{P}_{out}(\alpha,\beta,\mathbf{C}_i)$$
$$\text{s.t.} \begin{cases} \mathbf{C}_i \in \mathcal{C},\ 0 \le \alpha,\beta \le 1, \\ \alpha N_S,\ \alpha\beta N_S,\ \alpha\beta N_S/q_i \in \mathcal{N} \end{cases}$$

- The primary attempts to minimize the outage probability (for given BER requirement).

$$\mathrm{P}_{out}(\alpha,\beta,\mathbf{C}_i) = \begin{cases} \mathrm{P}_{out,\mathrm{dir}} & \text{for } \alpha = 0 \\ \mathrm{P}_{out,\mathrm{SP}}(\mathcal{S},\alpha,\beta,\mathbf{C}_i) & \text{for } \alpha > 0 \end{cases}$$

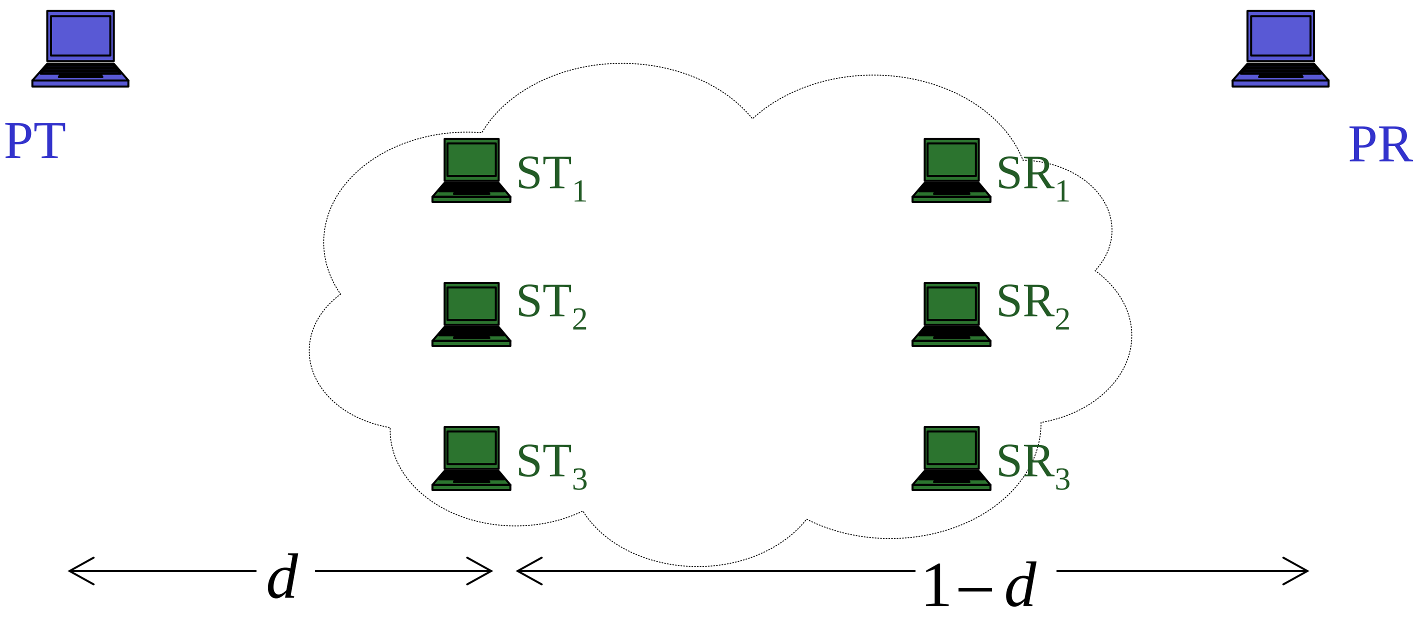
- C_{i} is a space-time codebook, taken from a list of available codes

code	q	L	R_{STC}
C_1	2	2	1
C_2	4	3	3/4
C_3	8	3,4	3/4
C_4	15	5	2/3
C_5	30	5,6	2/3
C_6	56	7	5/8

spatial dimension L,
temporal dimension q

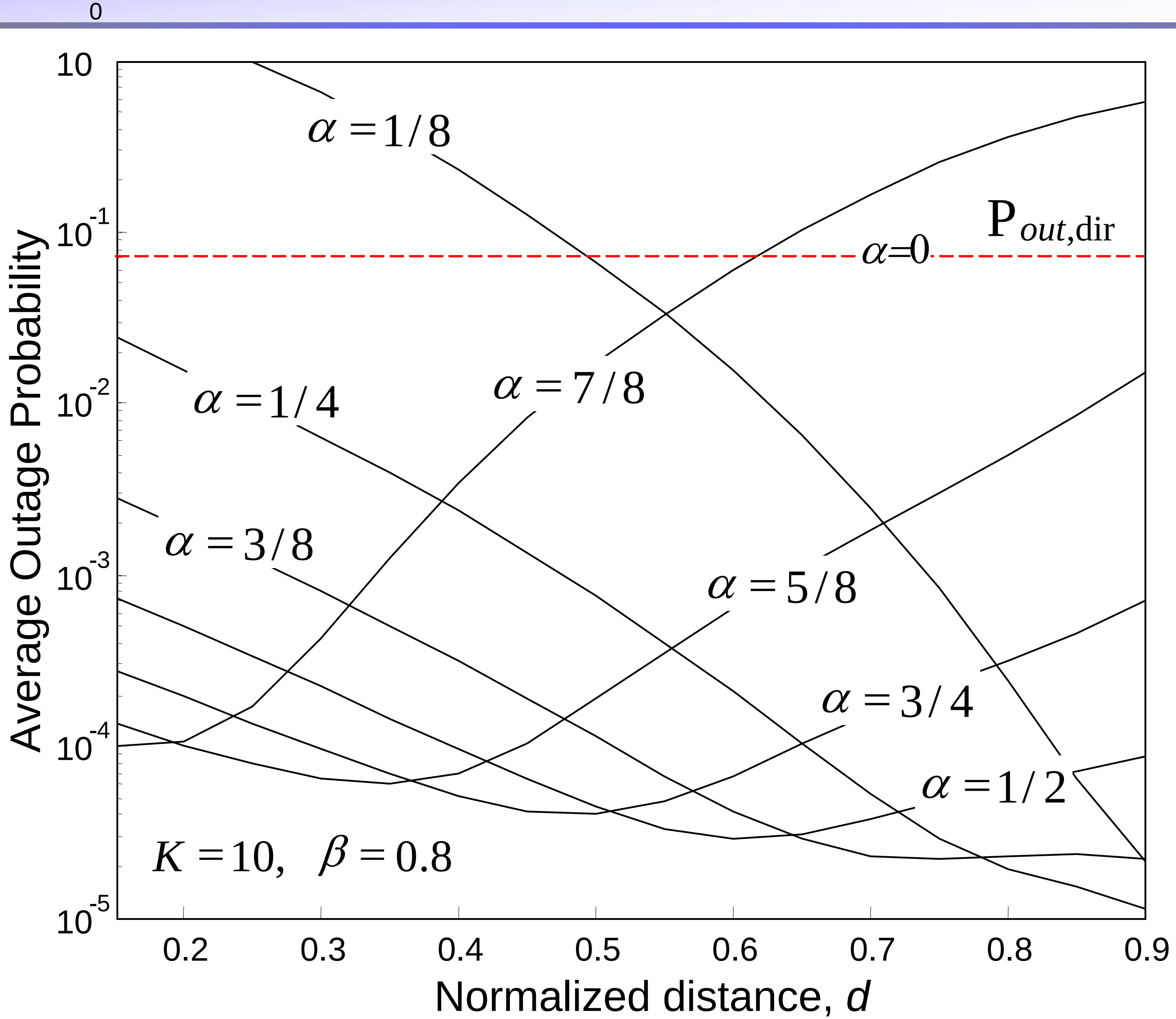
- With randomized distributed space-time codes, each active secondary chooses a codeword randomly from C_{i}

Some numerical results



- Path loss model (exp=2) and Rayleigh fading.
- $N_0=1$, target rate R_p=0.3, target BER 10^{-3}, number of symbols per slot N_S=80 and energy cost c=0.1.

Some numerical results



… the optimal fraction of leased time α tends to decrease for increasing distance d.

Concluding remarks

- **Can the property-right model of secondary spectrum access be implemented based on communications technology?**
- Yes, by exploiting cooperation for remuneration.
- Analysis of a case study based on Stackelberg games.
- Practical implementation based on randomized distributed space-time coding.

O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, R. Pickholtz, "Spectrum leasing to cooperating ad hoc secondary networks," *IEEE Journ. Selected Areas Commun.*, vol. 26, no. 1, pp. 203-213, Jan. 2008.

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