Distributed Transmit Power Allocation for Relay-Assisted Cognitive-Radio Systems

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2007 Asilomar Conference, Pacific Grove, CA, USA

November 6, 2007

Introduction

Cognitive-Radio (CR) Systems

- Utilize **unused** or **partially occupied** frequency bands in **adaptive, unlicensed** fashion $\Rightarrow$ More **efficient** spectrum utilization
- **Spectrum sensing** $\Rightarrow$ Dynamically adjust **transmission parameters** (carrier frequency, bandwidth, transmit power, ...)
- CR capabilities will be relevant, e.g., for **UWB systems**

Relay-Assisted CR Systems

- CR systems will naturally operate at **low transmit powers** to limit **interference** experienced by **primary users**
- **Example:** Transmit power of UWB devices **limited** by FCC spectral mask

$\Rightarrow$ **Relay assistance** attractive to improve **coverage** and **performance** of CR systems

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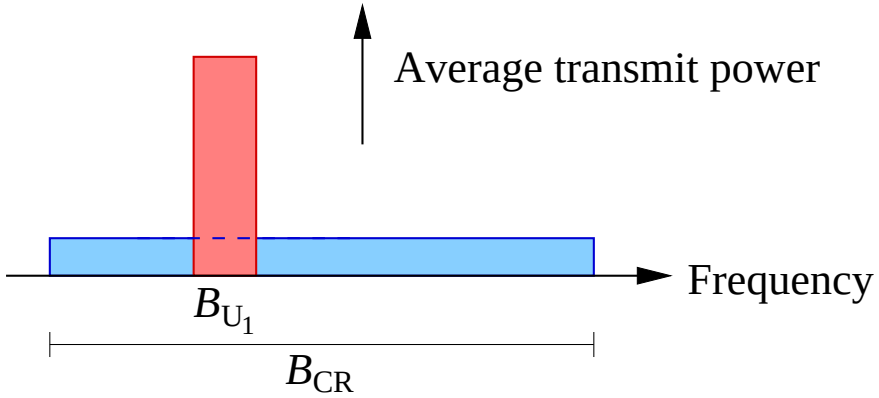
Introduction

Here:

- **Frequency band** chosen by CR system not completely unoccupied, but contains one or more **licensed** narrowband users
- **Distributed** transmit power allocation schemes for CR systems assisted by **cooperating** relays



Goal: Optimize performance of CR system while limiting interference level seen by primary user(s)

Overview

- **System Model and Problem Formulation**
- **Distributed Transmit Power Allocation Schemes**
- **Numerical Performance Results**
- **Conclusions**

Overview

- **System Model and Problem Formulation**
  - Basic Assumptions and Transmission Protocol
  - Illustration of the Centralized Optimization Problem
- **Distributed Transmit Power Allocation Schemes**
- **Numerical Performance Results**
- **Conclusions**

System Model

Basic Assumptions

- Wideband or UWB CR system based on **CDMA**
- Source S and destination D assisted by N_r **perfectly synchronized relays** $\mathrm{R}_1, ..., \mathrm{R}_{N_\mathrm{r}}$ using orthogonal spreading codes
- N_p **primary users** $\mathrm{U}_1, ..., \mathrm{U}_{N_\mathrm{p}}$ within frequency band of CR system
  - Bandwidth ratio $\rho_j := B_{\mathrm{U}_j}/B_\mathrm{CR} < 1$ $(j = 1, ..., N_\mathrm{p})$
  - ξ_j: Maximum sum interference power tolerated by U_j
- **Quasi-static** scenario; **block fading** with channel impulse responses (CIRs)

$$\mathbf{h}_{\mathrm{X,Y}} := [\, h^{(0)}_{\mathrm{X,Y}},\ \ldots,\ h^{(L_{\mathrm{X,Y}})}_{\mathrm{X,Y}} \,]^\mathrm{T},$$

$\mathrm{X}, \mathrm{Y} \in \{\mathrm{S}, \mathrm{D}, \mathrm{R}_1, ..., \mathrm{R}_{N_\mathrm{r}}, \mathrm{U}_1, ..., \mathrm{U}_{N_\mathrm{p}}\}$

$\Rightarrow$ Corresponding CIR energies: $\alpha_{\mathrm{X,Y}} := \sum_{l=0}^{L_{\mathrm{X,Y}}} |h^{(l)}_{\mathrm{X,Y}}|^2$

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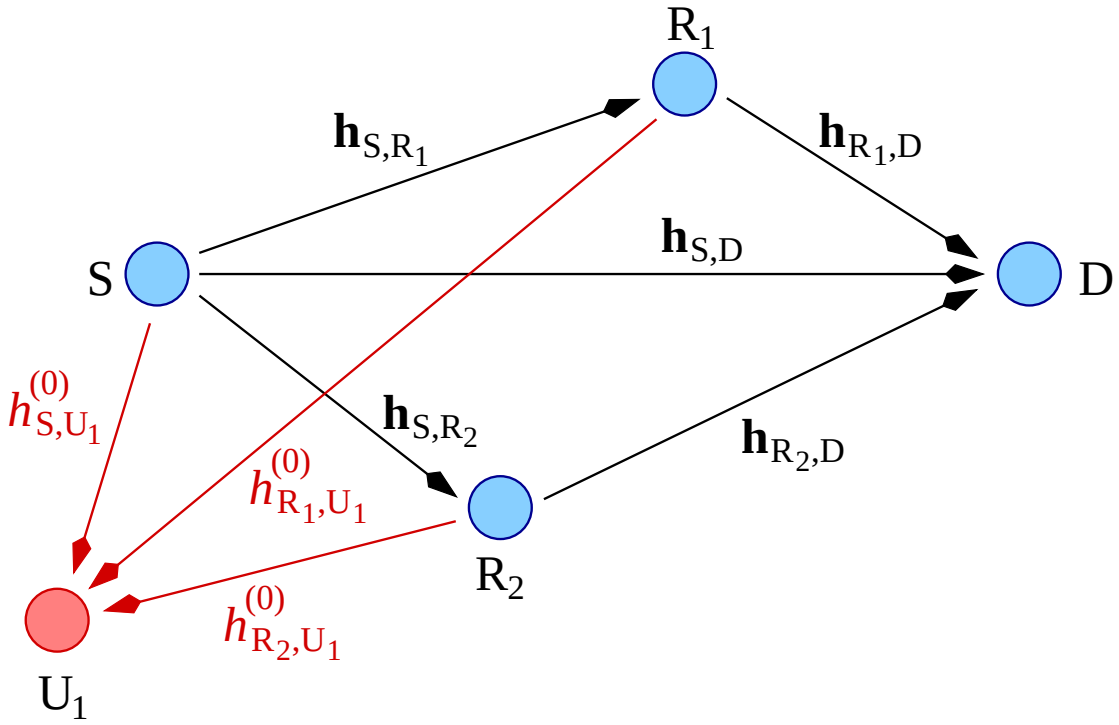
System Model



Further Assumptions (require some network acquisition phase)

- D **perfect knowledge** of $\mathbf{h}_{\mathrm{S,D}}$ and $\mathbf{h}_{\mathrm{R}_i,\mathrm{D}}$ $(i = 1, ..., N_\mathrm{r})$
- R_i $(i = 1, ..., N_\mathrm{r})$ **perfect knowledge** of $\mathbf{h}_{\mathrm{S},\mathrm{R}_i}$
- S and R_i $(i = 1, ..., N_\mathrm{r})$ **aware** of channel power gains $\alpha_{\mathrm{S},\mathrm{U}_j}$ or $\alpha_{\mathrm{R}_i,\mathrm{U}_j}$ in direction of $\mathrm{U}_1, ..., \mathrm{U}_{N_\mathrm{p}}$

Transmission Protocol

Transmission protocol consists of **two orthogonal time slots**:

Time Slot I

- S broadcasts **coded message** to $\mathrm{R}_1, ..., \mathrm{R}_{N_\mathrm{r}}$ and D
- **Transmit power** P_S adjusted such that all interference constraints are met:

$$\rho_j \, P_\mathrm{S} \, \alpha_{\mathrm{S},\mathrm{U}_j} \leq \xi_j \quad (j = 1, ..., N_\mathrm{p})$$

  Moreover, maximum power constraint $P_\mathrm{S} \leq P_{\mathrm{S},\max}$
- R_i $(i = 1, ..., N_\mathrm{r})$ performs **optimal MRC** of signal received from S
- Relays receiving coded message with MRC output SNR $\geq$ threshold value γ_th assumed to **decode correctly**

Transmission Protocol

Transmission protocol consists of **two orthogonal time slots**:

Time Slot II

- These $N_{\mathrm{r}}' \leq N_{\mathrm{r}}$ relays broadcast **short beacon signal** to inform other relays and destination
- Participating relays **re-encode** message and simultaneously **retransmit** it
- D performs **optimal MRC** of signals from S and R_i $(i = 1, ..., N_{\mathrm{r}}')$
- **Transmit powers** of participating relays shall be chosen such that all interference and power constraints are met
- MRC output SNR γ_{D} at destination shall be **maximized** to establish quick connection between S and D

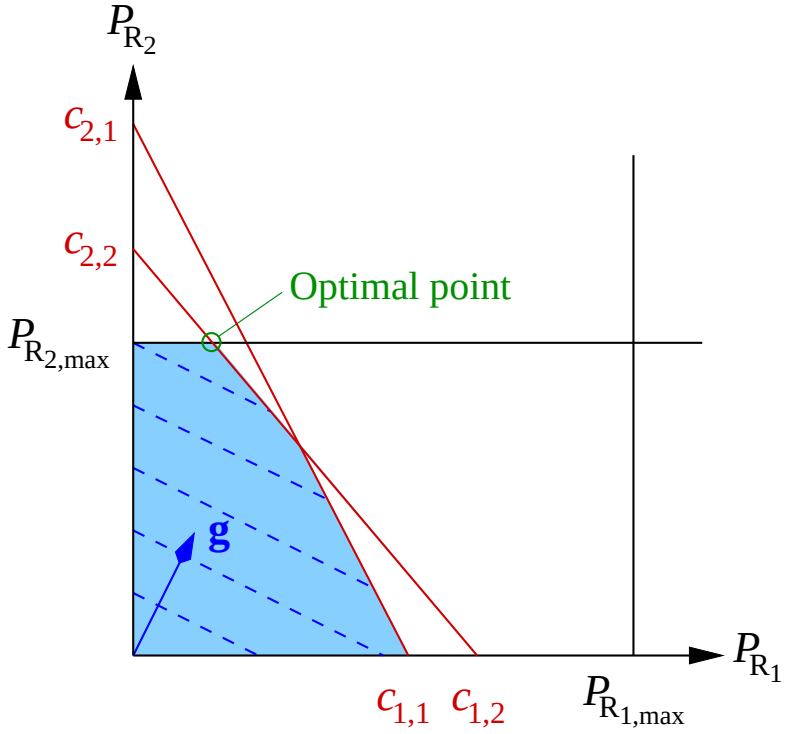
Optimization Problem

- **Linear** optimization problem:

$$\begin{aligned} &\text{maximize} && \gamma_{\mathrm{D}} = \frac{1}{\sigma_{\mathrm{n}}^2}\left(\sum_{i=1}^{N_{\mathrm{r}}'} P_{\mathrm{R}_i}\,\alpha_{\mathrm{R}_i,\mathrm{D}} + P_{\mathrm{S}}\,\alpha_{\mathrm{S,D}}\right) \\ &\text{subject to} && \rho_j \sum_{i=1}^{N_{\mathrm{r}}'} P_{\mathrm{R}_i}\,\alpha_{\mathrm{R}_i,\mathrm{U}_j} \leq \xi_j, \qquad j = 1, ..., N_{\mathrm{p}} \\ & && P_{\mathrm{R}_i} \leq P_{\mathrm{R}_i,\max}, \qquad i = 1, ..., N_{\mathrm{r}}' \end{aligned}$$

- Parameters ρ_j, ξ_j, $P_{\mathrm{R}_i,\max}$ assumed to be **known** throughout CR network
- **Optimal solution** can be found using linear programming techniques (e.g. Simplex algorithm)

Graphical Illustration



- Optimal solution requires **central** node C with knowledge of **all** channel power gains $\alpha_{\mathrm{R}_i,\mathrm{D}}$ and $\alpha_{\mathrm{R}_i,\mathrm{U}_j}$ $(i = 1, ..., N_\mathrm{r}',\ j = 1, ..., N_\mathrm{p})$
- Values $\alpha_{\mathrm{R}_i,\mathrm{D}}$, $\alpha_{\mathrm{R}_i,\mathrm{U}_j}$ **communicated** to C; then C computes optimal transmit powers and **feeds** solution **back** to relays

$\Rightarrow$ Develop **distributed** power allocation schemes to **reduce** signaling overhead

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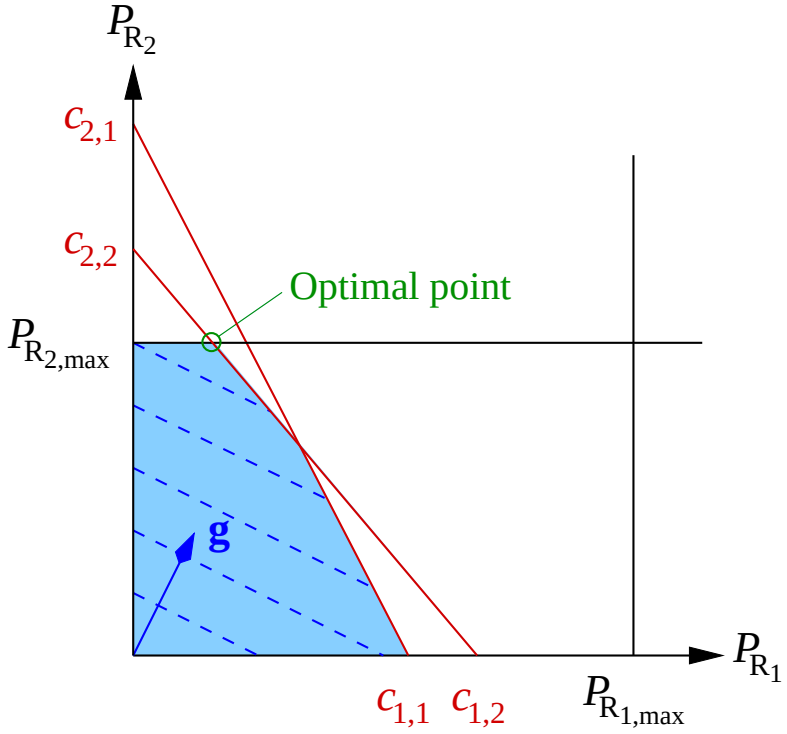

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  - Distributed Scheme with Limited Feedback (LF)
  - Distributed Quasi-Optimal (QO) Power Allocation
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Fully Decentralized (FD) Transmit Power Allocation

- Fully decentralized, i.e., performed **solely** by relays
- Based on beacon signals N_{r}' **known** throughout CR network
- R_i $(i = 1, ..., N_{\mathrm{r}}')$ adjusts **transmit power** as

$$P_{\mathrm{R}_i} := \min \left\{ P_{\mathrm{R}_i,\max}, \min_{j \in \{1,...,N_{\mathrm{p}}\}} \left\{ \frac{\xi_j}{\rho_j \, N_{\mathrm{r}}' \, \alpha_{\mathrm{R}_i,\mathrm{U}_j}} \right\} \right\}$$

$\Rightarrow$ Sum interference power at U_j at most ξ_j $(j = 1, ..., N_{\mathrm{p}})$, **without** any further **interaction** between relays

Moreover, $P_{\mathrm{R}_i} \leq P_{\mathrm{R}_i,\max}$ $(i = 1, ..., N_{\mathrm{r}}')$ guaranteed

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Distributed Scheme with Little Feedback (LF)

- Very little **feedback** from destination to improve FD solution
- Starts with FD scheme, D **measures** MRC output SNR γ_{D}
- D tests if switching to **single** transmitting relay R_k improves γ_{D} ($\gamma'_{\mathrm{D}} > \gamma_{\mathrm{D}}$)
- 'Best' relay chosen according to **largest** channel power gain $\alpha_{\mathrm{R}_i,\mathrm{D}}$ (i.e., largest component of $\mathbf{g}$), disregarding interference constraints
- **Enhanced** little feedback (ELF) scheme: 'Best' relay chosen taking interference constraints into account
- $\gamma'_{\mathrm{D}} > \gamma_{\mathrm{D}} \;\Rightarrow\;$ D sends **beacons** to participating relays

$\Rightarrow$ Relays **re-adjust** transmit powers as

$$P_{\mathrm{R}_i} := \begin{cases} \min\left\{ P_{\mathrm{R}_k,\max}, \min\limits_{j\in\{1,\ldots,N_{\mathrm{p}}\}} \left\{ \dfrac{\xi_j}{\rho_j\, \alpha_{\mathrm{R}_k,\mathrm{U}_j}} \right\} \right\}, & i=k \\ 0 & \text{else} \end{cases}$$

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Distributed Quasi-Optimal (QO) Power Allocation

- **Feedback** from the destination (similar to LF scheme)
- **Congenerous** primary users, i.e., $\xi_1/\rho_1 = ... = \xi_{N_\mathrm{p}}/\rho_{N_\mathrm{p}} =: \theta$
- Starts with FD scheme, D **measures** MRC output SNR $\gamma_{\mathrm{D},i}$ for each relay
- From this D determines **applied transmit powers** P_{R_i}

$\Rightarrow$ **Worst-case estimates** for $\alpha_{\mathrm{R}_i,\mathrm{U}_j}$ $(j = 1, ..., N_\mathrm{p})$:

$$\tilde{\alpha}_{\mathrm{R}_i,\mathrm{U}_j} := \frac{\theta}{N_\mathrm{r}' \, P_{\mathrm{R}_i}} \geq \alpha_{\mathrm{R}_i,\mathrm{U}_j}$$

- D computes **(quasi-)optimal** transmit powers (using values $\tilde{\alpha}_{\mathrm{R}_i,\mathrm{U}_j}$) and **feeds** solution **back** to relays (similar to optimal centralized scheme)

$\Rightarrow$ Interference constraints (and power constraints) **always** met

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Simulation Setup

- All link lengths **normalized** w.r.t. S–D link; S and D have **fixed positions** at $(-0.5, 0)$ and $(+0.5, 0)$, respectively
- $N_\mathrm{r} = 20$ **relays** and $N_\mathrm{p} \geq 1$ **primary users**; **random positions** within square areas of side length 0.8, center points $(0, 0)$ and $(x_\mathrm{p}, 0)$, respectively
- Identical **maximum transmit powers** P_max for all nodes within CR network
- Quasi-static **Rayleigh** fading, **path-loss** exponent $p = 2$
  - Links associated with primary users: **flat** fading $(L_{\mathrm{X,Y}} = 0)$
  - Links within CR network: **frequency-selective** fading $(L_{\mathrm{X,Y}} = 9)$
- All simulation results **averaged** over $1,000$ random locations of relays and primary users; 100 channel realizations per spatial constellation

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Single Primary User

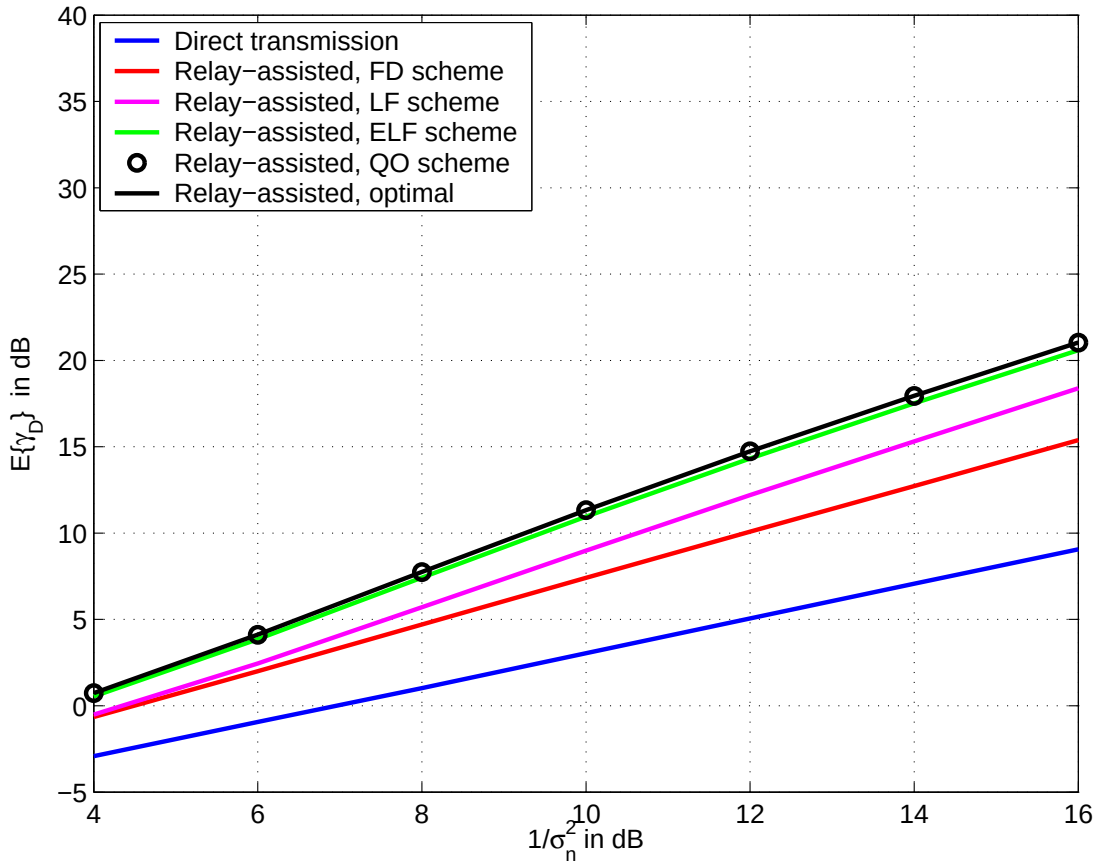
Example:

Maximum transmit power $P_{\max} = 1$

Threshold SNR $\gamma_{\text{th}} = 10$ dB

$N_{\text{p}} = 1$, $\xi_1 = 0.1$, $\rho_1 = 0.5$

—— $x_{\text{p}} = 0$, - - - $x_{\text{p}} = 5$



⇒ Already FD scheme significantly outperforms direct transmission; QO scheme performs very close to optimum centralized solution

Single Primary User

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Threshold SNR $\gamma_{\text{th}}=10$ dB

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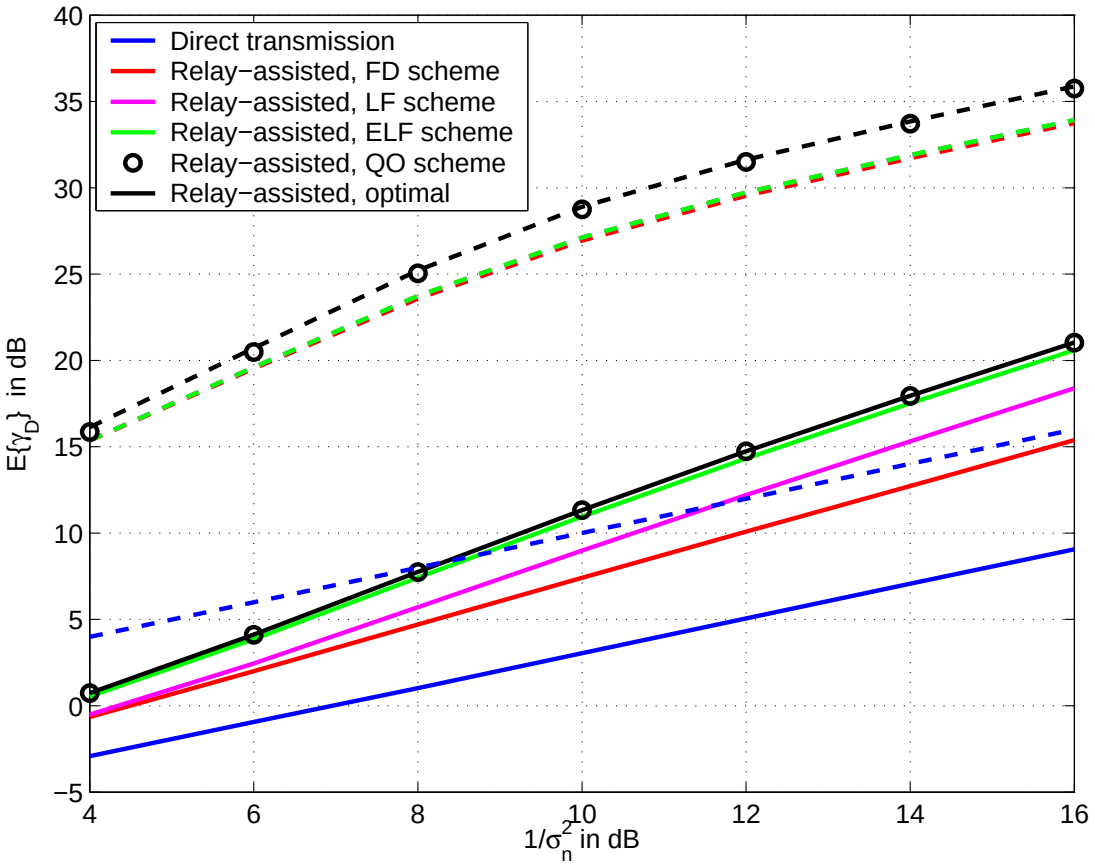


⇒ For larger distances of primary users FD, LF, and ELF scheme similar; significantly larger gains over direct transmission than for $x_{\text{p}}=0$

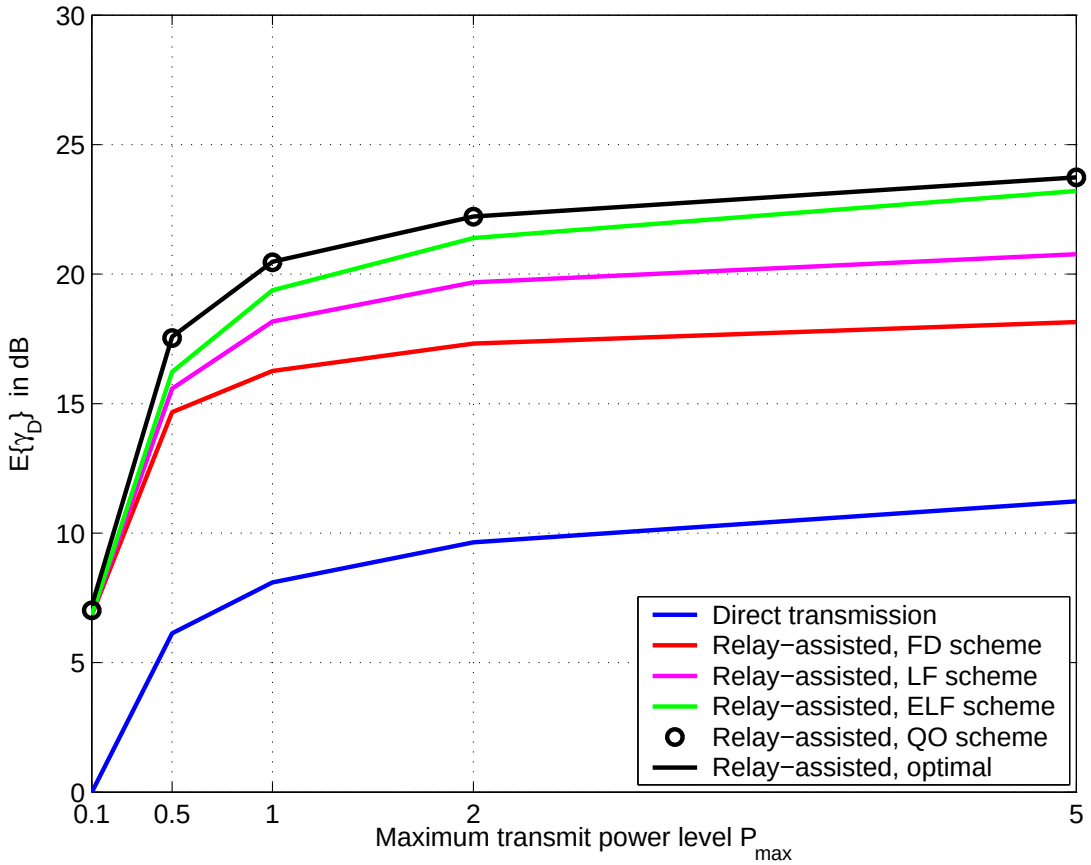
Single Primary User

Example:

Threshold SNR $\gamma_{\mathrm{th}} = 10$ dB

$N_{\mathrm{p}} = 1,\ \xi_1 = 0.1,\ \rho_1 = 0.5,\ x_{\mathrm{p}} = 1$

SNR $1/\sigma_{\mathrm{n}}^2 = 10$ dB



$\Rightarrow$ For low values of $P_{\max}$ all schemes perform very close to optimum; for large values of $P_{\max}$ flat behavior due to interference constraint

Multiple Primary Users

Example:

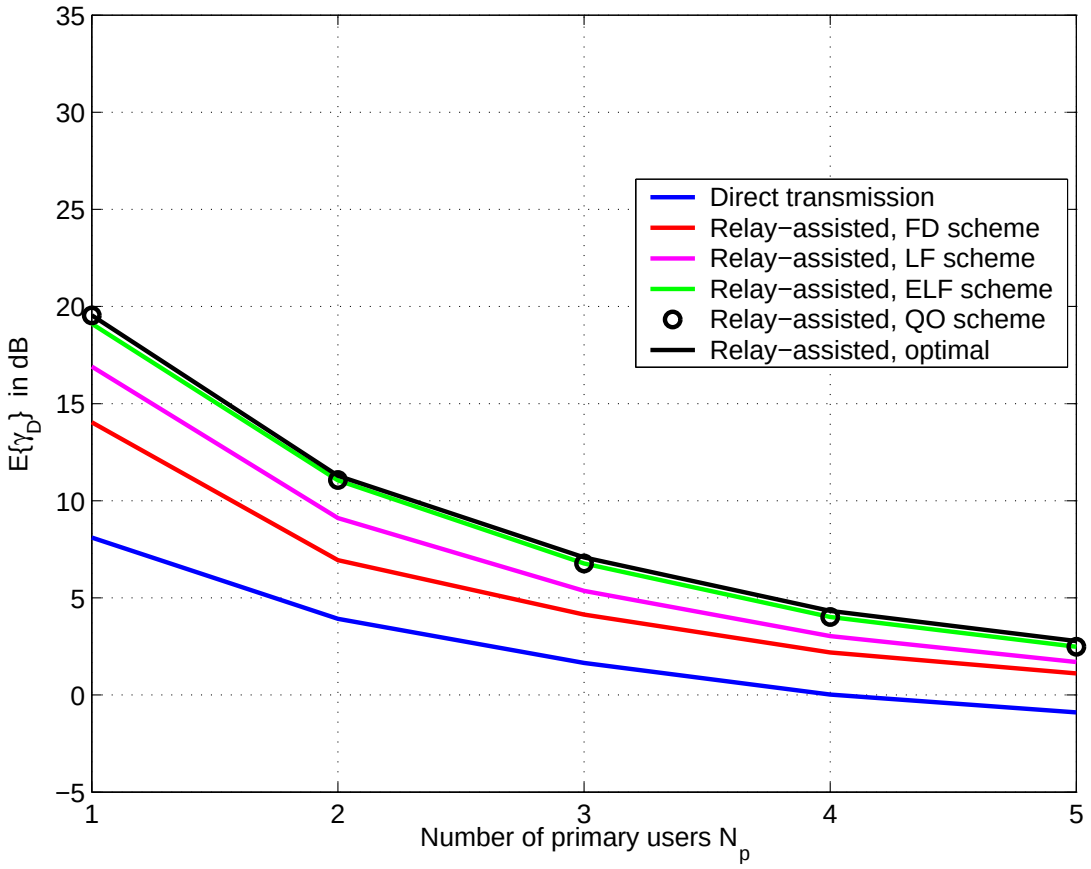
Maximum transmit power $P_{\max} = 1$

Threshold SNR $\gamma_{\text{th}} = 10$ dB

$\xi_j = 0.1$, $\rho_j = 0.5$ for all j

—— $x_{\text{p}} = 0$, - - - $x_{\text{p}} = 5$

SNR $1/\sigma_{\text{n}}^2 = 15$ dB



$\Rightarrow$ For $x_{\text{p}} = 0$ notable performance degradation as N_{p} grows; still significant improvements over direct transmission

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Threshold SNR $\gamma_{\text{th}} = 10$ dB

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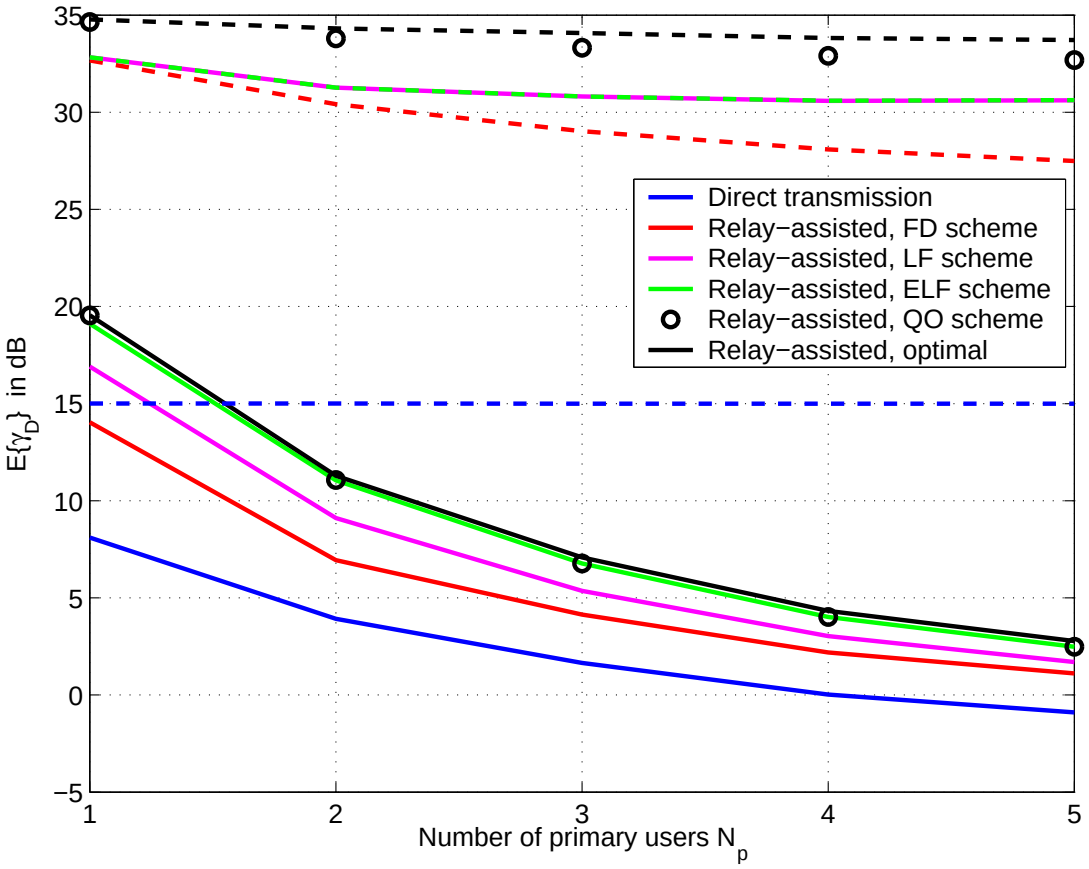

$\Rightarrow$ For larger x_{p} performance degrades gracefully with growing N_{p}; LF and ELF scheme similar, QO scheme still close to optimum

Conclusions

- **Distributed** transmit power allocation schemes for **relay-assisted CR systems** in the presence of single or multiple **primary users**
  - **FD scheme:** Significant **performance improvements** over direct transmission, without interaction between relays or feedback from destination
  - **LF schemes:** Further **performance gains** utilizing little feedback from destination
  - **QO scheme:** Performance very **close to optimal** centralized solution
- **Future work:**
  - More sophisticated solutions for multiple non-congenerous primary users?
  - Impact of non-perfect channel knowledge and time-varying channel conditions?