Performance Analysis for a Fully Decentralized Transmit Power Allocation Scheme for Relay-Assisted Cognitive-Radio Systems

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Introduction

Cognitive-Radio (CR) Systems

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

Relay-Assisted CR Systems

- Focus on **CR networks** consisting of many **low-power transceivers** for short-range transmission ($\Rightarrow$ wireless sensor networks, personal area networks)

$\Rightarrow$ **Relay assistance** attractive to achieve **connectivity** and guarantee certain **performance** of CR systems

- **Available relays:** Inactive **cognitive devices** or **dedicated** cognitive relays
- So far only few papers on **cognitive relaying** techniques available

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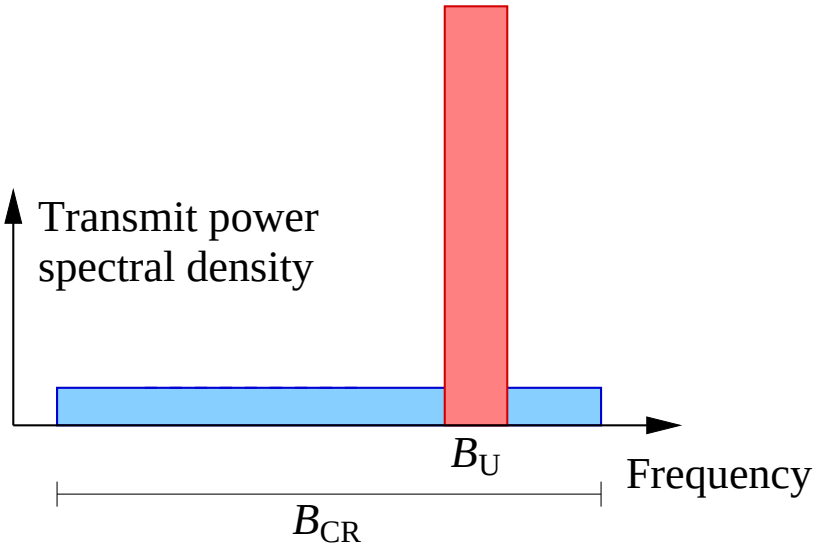
Introduction

Novel aspects

- **Frequency band** chosen by CR relay network not completely unoccupied, but accommodates active **primary** (e.g., licensed) narrowband link
- Fully **decentralized** transmit power allocation (FD-TPA) scheme for CR relay network

⇒ **Goal:** Optimize performance of CR system while limiting interference level experienced by primary link



Overview

- **System Model and Problem Formulation**
  - Transmission Protocol and Centralized Optimization Problem
  - Fully Decentralized Transmit Power Allocation (FD-TPA) Scheme
- **Performance Analysis**
- **Numerical Performance Results**
- **Conclusions**

System Model

Basic Assumptions

- Short-range 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 (spreading length N_{sp})
- **Primary link** $\mathrm{U}_1 \rightarrow \mathrm{U}_2$ active (e.g. WLAN link) in band of CR system
  - Small bandwidth ratio $\rho := B_{\mathrm{U}}/B_{\mathrm{CR}} \ll 1$
  - Relatively large transmit power P_{U_1} employed by primary transmitter U_1
  - Small maximum sum interference power ξ tolerated by primary receiver U_2
- **Quasi-static** scenario; **block fading** with channel impulse responses (CIRs)

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

$\mathrm{X}, \mathrm{Y} \in \{\mathrm{S}, \mathrm{D}, \mathrm{R}_1, ..., \mathrm{R}_{N_{\mathrm{r}}}, \mathrm{U}_1, \mathrm{U}_2\}$

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

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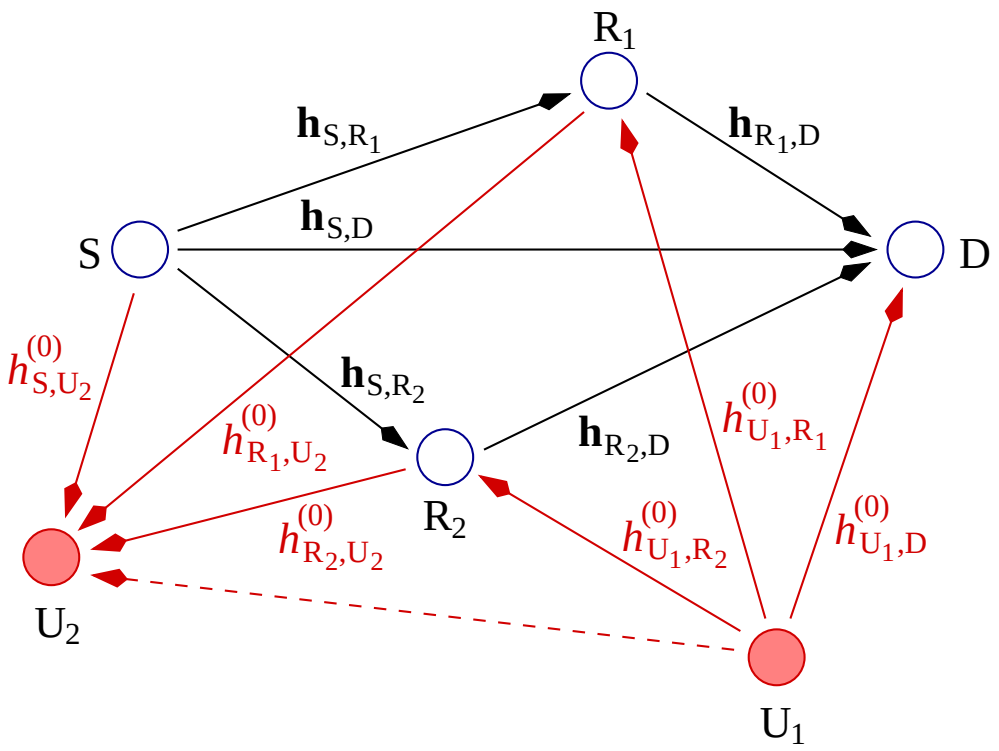
System Model



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 $\mathbf{h}_{\mathrm{S},\mathrm{R}_i}$ and $\mathbf{h}_{\mathrm{R}_{i'},\mathrm{R}_i}$ $(i' \neq i)$
- S and R_i $(i = 1, ..., N_\mathrm{r})$ **aware** of CIR energies $\alpha_{\mathrm{S},\mathrm{U}_2}$ or $\alpha_{\mathrm{R}_i,\mathrm{U}_2}$ in direction of primary receiver U_2

Transmission Protocol

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

Time Slot I

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

$$\rho\, P_\mathrm{S}\, \alpha_{\mathrm{S},\mathrm{U}_2} \leq \xi$$

  Moreover, maximum power constraint $P_\mathrm{S} \leq P_{\mathrm{S},\max}$
- CR nodes $\mathrm{Y} \in \{\mathrm{R}_1, ..., \mathrm{R}_{N_\mathrm{r}}, \mathrm{D}\}$ employ **simple despreading** for primary interference suppression and perform **optimal MRC** of received signal $\Rightarrow$

$$\gamma_{\mathrm{S}\to\mathrm{Y}} := \frac{P_\mathrm{S}\alpha_{\mathrm{S},\mathrm{Y}}}{\sigma^2_{\mathrm{i},\mathrm{Y}} + \sigma^2_{\mathrm{n},\mathrm{Y}}}, \qquad \sigma^2_{\mathrm{i},\mathrm{Y}} := \frac{P_{\mathrm{U}_1}\alpha_{\mathrm{U}_1,\mathrm{Y}}}{N_\mathrm{sp}}$$

- Relays receiving message with MRC output SINR $\gamma_{\mathrm{S}\to\mathrm{R}_i} \geq \gamma_\mathrm{th}$ assumed to **decode correctly** (γ_th: threshold SINR)

Transmission Protocol

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

Time Slot II

- If $\gamma_{\mathrm{S}\rightarrow\mathrm{D}} < \gamma_{\mathrm{target}}$, D initiates **relaying process** by broadcasting beacon signal (γ_{target}: target SINR at destination)
- Those $N_{\mathrm{r}}' \leq N_{\mathrm{r}}$ relays R_i that have **decoded successfully** broadcast beacon signal to inform other relays and destination
- Participating relays R_i **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 R_i shall be chosen such that interference constraint and all power constraints are met
- MRC output SINR γ_{D} at destination shall be **maximized** to establish quick connection between S and D

Optimization Problem

- **Linear** optimization problem:

$$\begin{aligned} &\text{maximize} && \gamma_{\mathrm{D}} = \frac{1}{\sigma_{\mathrm{i,D}}^2 + \sigma_{\mathrm{n,D}}^2} \sum_{i=1}^{N_{\mathrm{r}}'} P_{\mathrm{R}_i}\, \alpha_{\mathrm{R}_i,\mathrm{D}} + \gamma_{\mathrm{S}\to\mathrm{D}} \\ &\text{subject to} && \rho \sum_{i=1}^{N_{\mathrm{r}}'} P_{\mathrm{R}_i}\, \alpha_{\mathrm{R}_i,\mathrm{U}_2} \leq \xi \\ & && P_{\mathrm{R}_i} \leq P_{\mathrm{R}_i,\max}, \qquad i = 1, \ldots, N_{\mathrm{r}}' \end{aligned}$$

- Parameters $\rho = B_{\mathrm{U}}/B_{\mathrm{CR}}$, ξ, and $P_{\mathrm{R}_i,\max}$ **known** throughout CR network
- **Optimal solution** can be found using linear programming techniques; requires **central** node C with knowledge of **all** CIR energies $\alpha_{\mathrm{R}_i,\mathrm{D}}$ and $\alpha_{\mathrm{R}_i,\mathrm{U}_2}$
- Values $\alpha_{\mathrm{R}_i,\mathrm{D}}$, $\alpha_{\mathrm{R}_i,\mathrm{U}_2}$ **communicated** to C; then C computes optimal transmit powers and **feeds** solution **back** to relays $\Rightarrow$ Signaling overhead

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Decentralized Scheme

Fully Decentralized Transmit Power Allocation (FD-TPA) Scheme

- FD-TPA scheme **maximizes** MRC output SINR at destination node D according to **best effort** strategy
- Fully decentralized, i.e., performed **solely** by relays (no feedback from D)
- **No exchange** of channel information or transmit power values

- Based on beacon signals N_{r}' **known** throughout CR network
- Relay R_i $(i = 1, ..., N_{\mathrm{r}}')$ adjusts **transmit power** as

$$P_{\mathrm{R}_i} := \min\left\{P_{\mathrm{R}_i,\max}, \frac{\xi}{\rho\, N_{\mathrm{r}}'\, \alpha_{\mathrm{R}_i,\mathrm{U}_2}}\right\}$$

$\Rightarrow$ Sum interference power at U_2 at most ξ, **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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- System Model and Problem Formulation
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Performance Analysis

- Desirable to have **analytical expressions** for assessing the **performance** of the FD-TPA scheme compared to non-cooperative transmission
- We derive expression for **CDF** of overall MRC output SINR γ_{D} at destination, treating CIR energies $\alpha_{\mathrm{X,Y}}$ as **random** variables (Rayleigh fading)
- Analysis rather **complicated** as relaying is only performed if $\gamma_{\mathrm{S}\to\mathrm{D}} < \gamma_{\mathrm{target}}$
- Final result requires **numerical evaluation** of certain integrals as closed-form solution does **not** seem **feasible**

Main steps in derivation

- Event $\mathcal{E}^{(\alpha)}$: Source accomplishes γ_{target} on its own ($\gamma_{\mathrm{S}\to\mathrm{D}} \geq \gamma_{\mathrm{target}}$)
  - $\Rightarrow$ Conditional event probability $\Pr\{\mathcal{E}^{(\alpha)} \mid P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}\}$
  - $\Rightarrow$ Conditional CDF $C^{(\alpha)}\left(\gamma_{\mathrm{D}} | P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}\right)$
- Event $\mathcal{E}^{(\beta_\kappa)}$: Source does not accomplish γ_{target}, set of active relays $\mathbb{I}_{\mathrm{r}}^{(\kappa)}$
  - $\Rightarrow$ Conditional event probability $\Pr\{\mathcal{E}^{(\beta_\kappa)} \mid P_{\mathrm{S}}\}$
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Performance Analysis

Main steps in derivation (cont'd)

- Source transmit power P_{S}, relay transmit powers P_{R_i}, and interference power $\sigma^2_{\mathrm{i,D}}$ at destination are random variables depending on $\alpha_{\mathrm{S,U_2}}$, $\alpha_{\mathrm{R}_i,\mathrm{U_2}}$, $\alpha_{\mathrm{U_1,D}}$
- Derive closed-form expressions for conditional event probabilities, conditional CDFs, and PDFs $p_1(P_{\mathrm{S}})$, $p_2(\sigma^2_{\mathrm{i,D}})$, $p_3(P_{\mathrm{R}_i})$

$\Rightarrow$ Average CDF of γ_{D} can be calculated via numerical integration

$$\bar{C}(\gamma_{\mathrm{D}}) = \int_0^{\infty}\int_0^{P_{\mathrm{S,max}}} \Pr\{\mathcal{E}^{(\alpha)} \,|\, P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}\}\, C^{(\alpha)}\left(\gamma_{\mathrm{D}} | P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}\right) p_1(P_{\mathrm{S}})\, p_2(\sigma^2_{\mathrm{i,D}})$$

$$+ \left(1 - \Pr\{\mathcal{E}^{(\alpha)} \,|\, P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}\}\right)\left(\sum_{\kappa=0}^{\psi-1} \int_0^{P_{\mathrm{R}_{i_{N_{\mathrm{r}}'}}},\mathrm{max}} \cdots \int_0^{P_{\mathrm{R}_{i_1},\mathrm{max}}} \Pr\{\mathcal{E}^{(\beta_\kappa)} \,|\, P_{\mathrm{S}}\}\right.$$

$$\times\, C^{(\beta_\kappa)}\left(\gamma_{\mathrm{D}} | P_{\mathrm{S}}, \sigma^2_{\mathrm{i,D}}, P_{\mathrm{R}_{i_1}}, \ldots, P_{\mathrm{R}_{i_{N_{\mathrm{r}}'}}}\right) p_3(P_{\mathrm{R}_{i_1}}) \cdots p_3(P_{\mathrm{R}_{i_{N_{\mathrm{r}}'}}})$$

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Setup for Numerical Evaluations

- All link lengths **normalized** w.r.t. S–D link; S and D have **fixed positions** at $(-0.5, 0)$ and $(+0.5, 0)$; **reference SNR** $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}}$
- $N_\mathrm{r} = 5$ **relays** R_i with positions $(0, 0)$, $(0, \pm 0.2)$, $(0, \pm 0.4)$ available
- Identical **maximum transmit powers** $P_\mathrm{max} = 1$ for all CR nodes
- **Threshold SINR** at R_i $\gamma_\mathrm{th} = 10$ dB, **target SINR** at D $\gamma_{\mathrm{D},\mathrm{target}} = 10$ dB
- **Primary** transmitter U_1/receiver U_2 located at $(0, d+10)$ and $(0, d)$
- Average **transmit power** of U_1 $P_\mathrm{U} = 10,000$; bandwidth ratio $\rho = 0.1$
- Maximum interference power tolerated by U_2 $\xi = 0.01$

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Numerical Performance Results

Case 1:

SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}} = 5$ dB

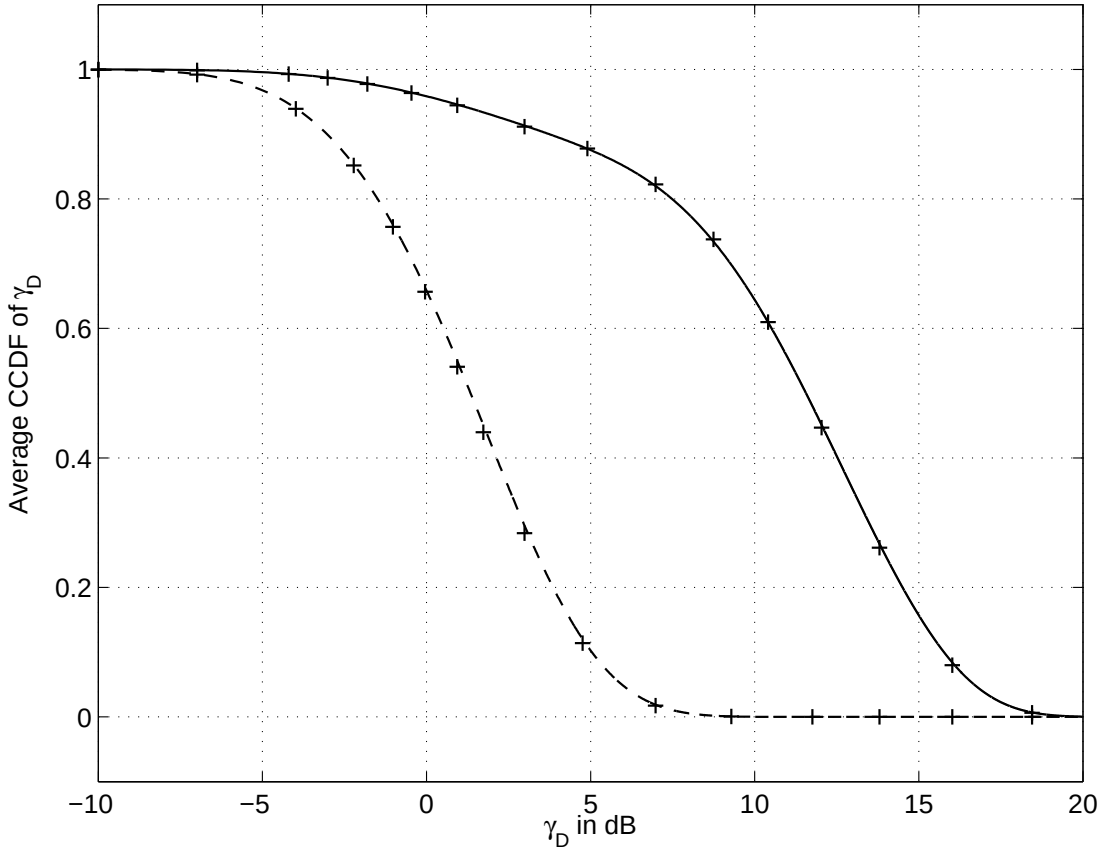
Spreading length $N_{\mathrm{sp}} = 10$

Distance to primary users $d = 3$

- - - Non-cooperative transmission

—— FD-TPA scheme

\+ Simulation



FD-TPA scheme significantly outperforms non-cooperative transmission

Numerical Performance Results

Case 2:

SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}} = 5$ dB

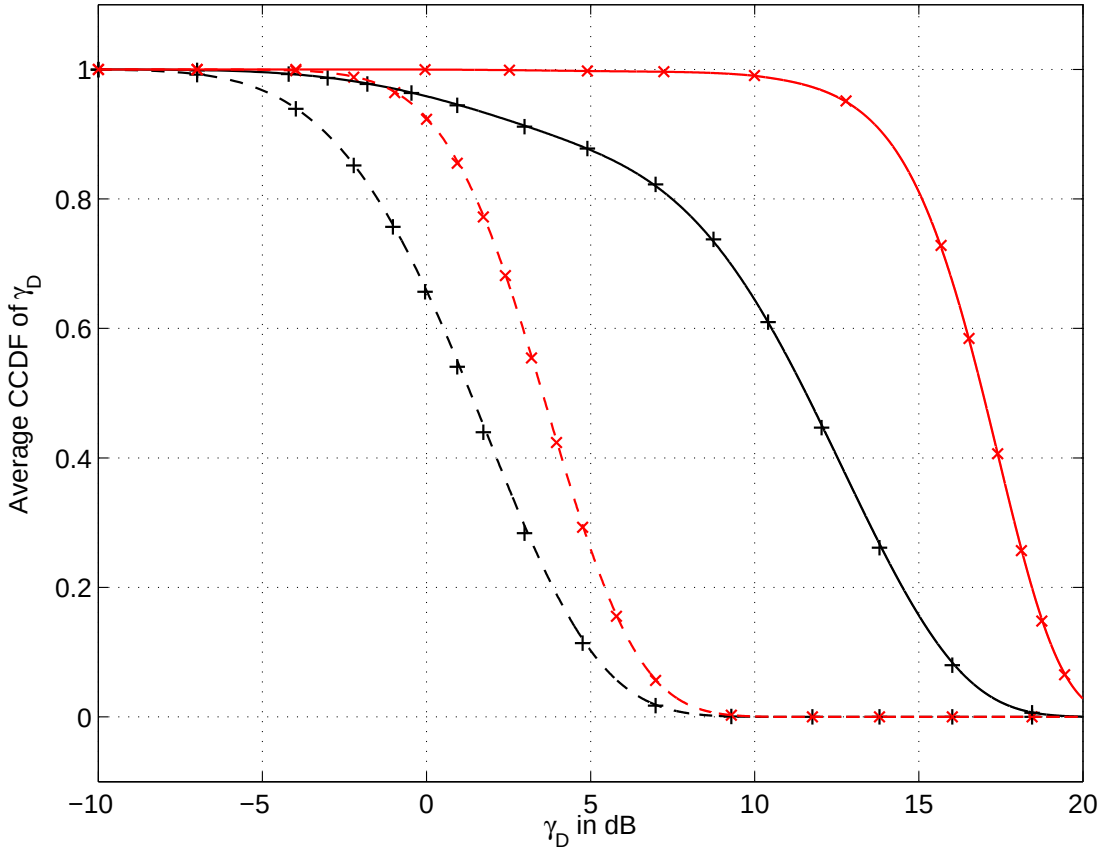
Spreading length $N_{\mathrm{sp}} = 10$

Distance to primary users $d = 12$

- - - Non-cooperative transmission

—— FD-TPA scheme

x Simulation



Performance improves with growing distance d to primary users

Numerical Performance Results

Case 3:

SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}} = 5$ dB

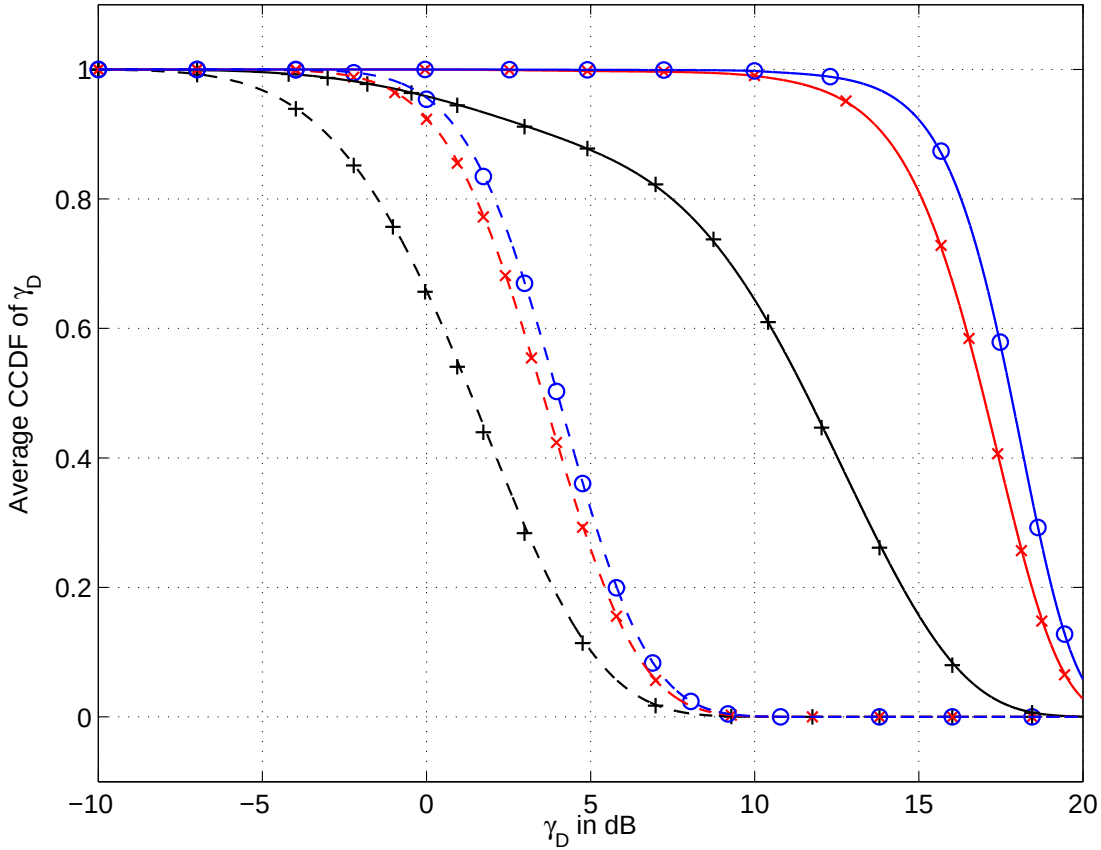
Spreading length $N_{\mathrm{sp}} = 20$

Distance to primary users $d = 12$

- - - Non-cooperative transmission

—— FD-TPA scheme

o Simulation



Performance improves with growing spreading length N_{sp}

Numerical Performance Results

Case 4:

SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}} = 10$ dB

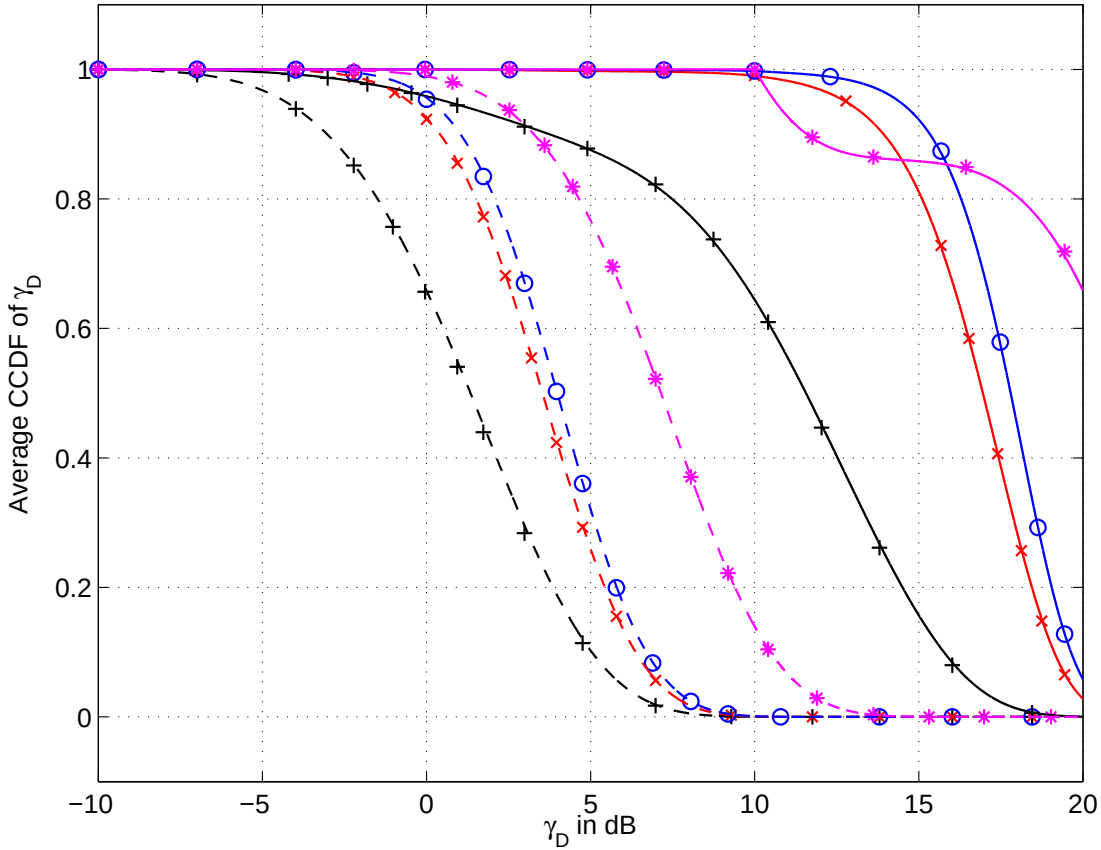
Spreading length $N_{\mathrm{sp}} = 10$

Distance to primary users $d = 12$

- - - Non-cooperative transmission

—— FD-TPA scheme

* Simulation



Performance improves with growing SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}}$

Numerical Performance Results

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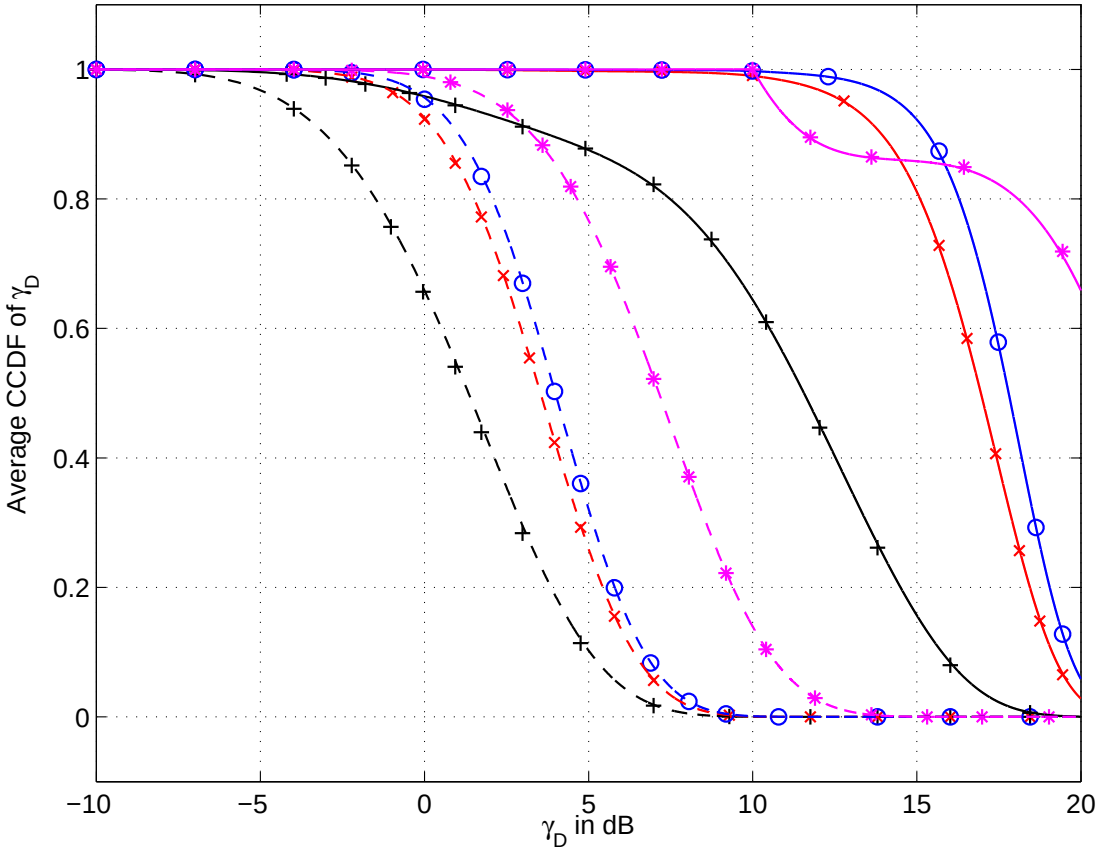

Semi-analytical and simulation-based performance results in good accordance

Numerical Performance Results

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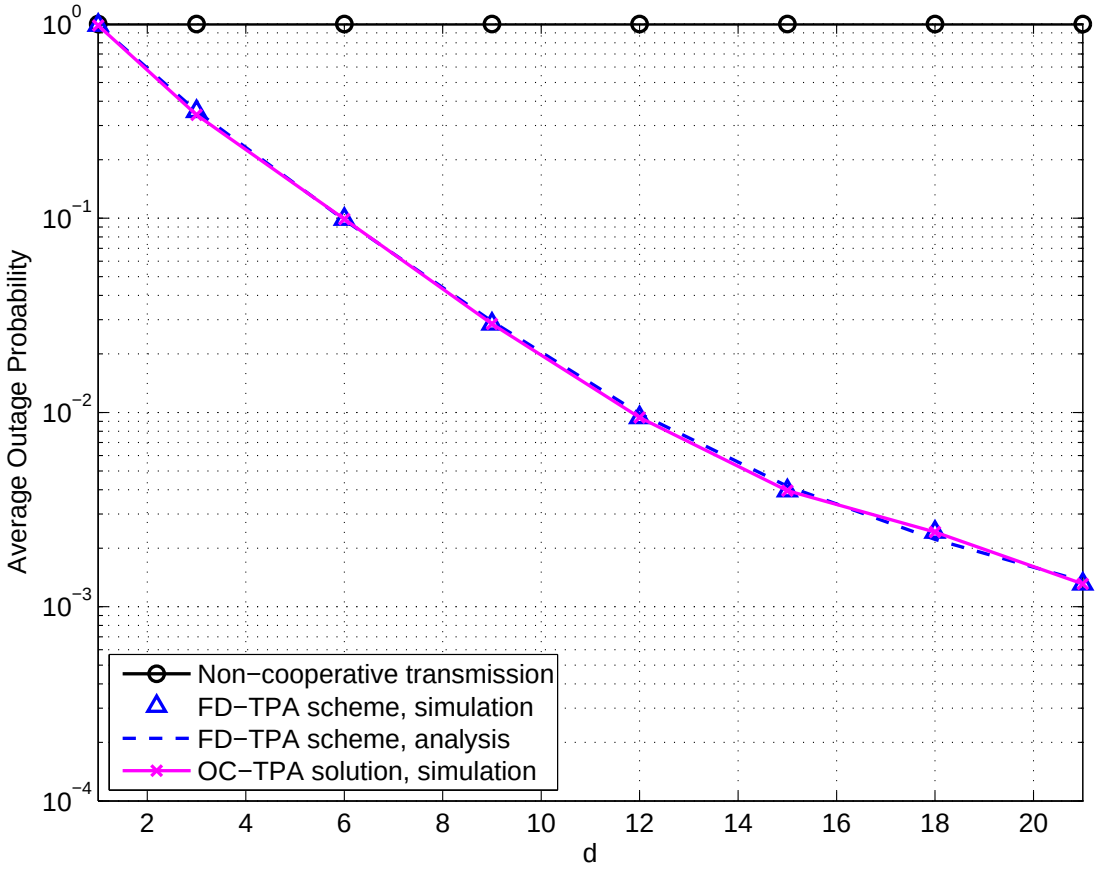
Spreading length $N_{\mathrm{sp}} = 10$

Variable distance to primary users



Outage probability for FD-TPA scheme decreases significantly with growing distance d and is very close to optimal centralized (OC) solution

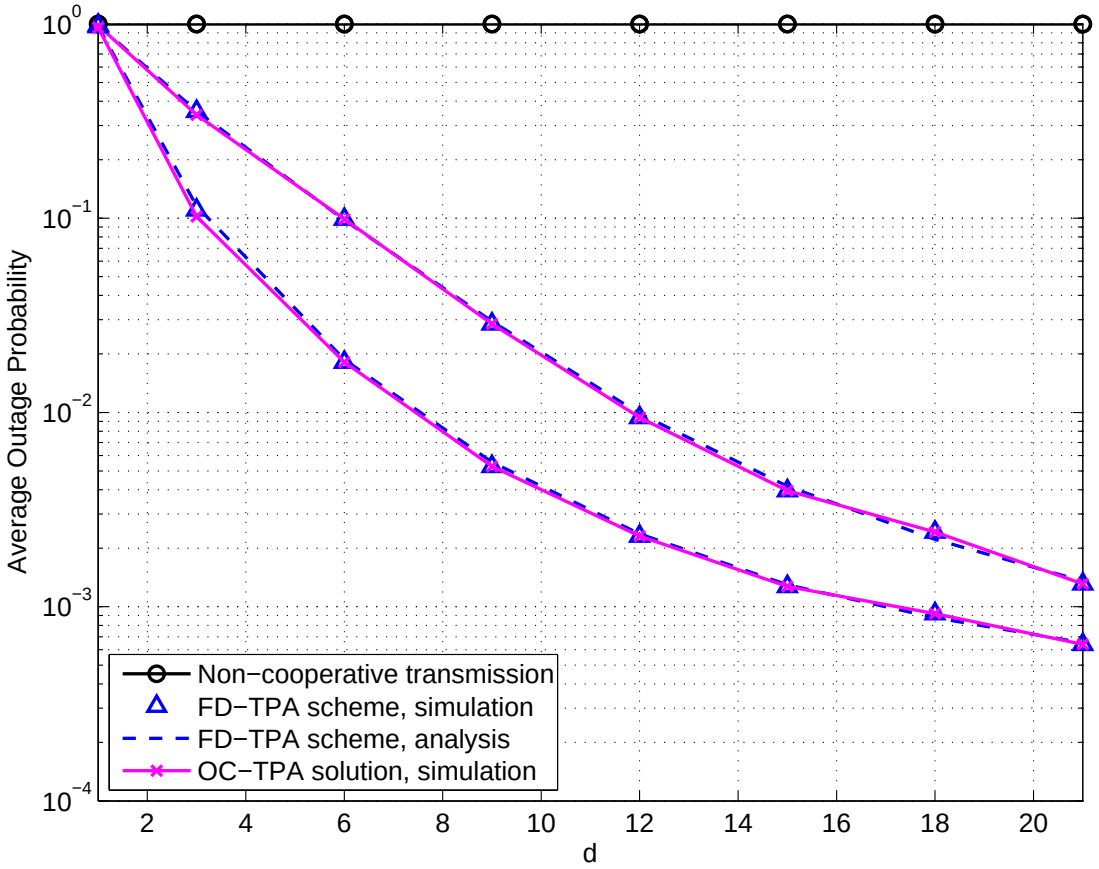
Numerical Performance Results

Case 2:

SNR $\bar{\gamma}_{0,\mathrm{S}\to\mathrm{D}} = 5$ dB

Spreading length $N_{\mathrm{sp}} = 20$

Variable distance to primary users



Outage probability for FD-TPA scheme decreases significantly with growing distance d and is very close to optimal centralized (OC) solution

Conclusions

- Fully **decentralized** transmit power allocation (FD-TPA) scheme for **relay-assisted CR systems** in the presence of active **primary link**
- FD-TPA scheme **maximizes SINR** at destination node of CR network while **limiting interference** experienced by primary receiver
- **Performance analysis** showed that FD-TPA scheme offers **significant improvements** over non-cooperative transmission and performs **closely** to optimal centralized solution

- **Future work:** Decentralized multi-hop solutions for further performance improvements (especially when primary system is very close by)