Cognitive downlink beamforming for interference control in femtocells

Marius Pesavento, Dana Ciochina, Alex Gershman

TECHNISCHE UNIVERSITÄT DARMSTADT

Communication Systems Group
Institute of Telecommunications
Technische Universität Darmstadt

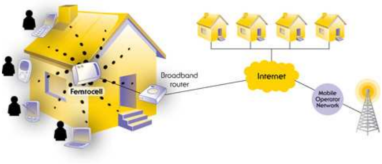
Overview

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation: femtocell interference scenarios
- Problem statement
- Previous work
- Uplink - downlink duality
- Iterative algorithm
- Relation to Lagrange dual problem
- Simulation results

Femtocells

Home-Basestation



Why femtocells?

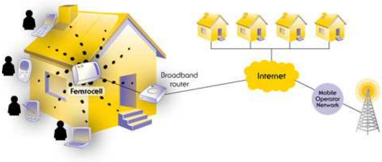
- Consumer: improved (indoor) coverage, bundling of services: fixed mobile convergence (FMC).
- Operators: reduced investments and costs for network operation, smaller cells $\Rightarrow$ improved coverage and capacity, win customer loyalty.
- Femtocells are integral part of 3GPP standards UMTS/LTE and LTE-Advanced.

Change of paradigm: cell-planning versus self-contained deployment.

Femtocells

Home-Basestation

TECHNISCHE UNIVERSITÄT DARMSTADT



Why femtocells?

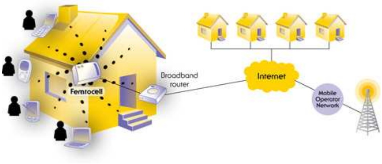
- Consumer: improved (indoor) coverage, bundling of services: fixed mobile convergence (FMC).
- Operators: reduced investments and costs for network operation, smaller cells $\Rightarrow$ improved coverage and capacity, win customer loyalty.
- Femtocells are integral part of 3GPP standards UMTS/LTE and LTE-Advanced.

Change of paradigm: cell-planning versus self-contained deployment.

Femtocells

Home-Basestation

TECHNISCHE UNIVERSITÄT DARMSTADT



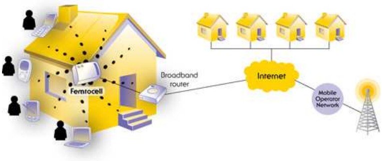
Why femtocells?

- Consumer: improved (indoor) coverage, bundling of services: fixed mobile convergence (FMC).
- Operators: reduced investments and costs for network operation, smaller cells $\Rightarrow$ improved coverage and capacity, win customer loyalty.
- Femtocells are integral part of 3GPP standards UMTS/LTE and LTE-Advanced.

Change of paradigm: cell-planning versus self-contained deployment.

Femtocells

Home-Basestation



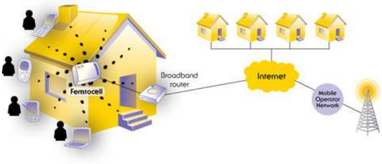
Why femtocells?

- Consumer: improved (indoor) coverage, bundling of services: fixed mobile convergence (FMC).
- Operators: reduced investments and costs for network operation, smaller cells $\Rightarrow$ improved coverage and capacity, win customer loyalty.
- Femtocells are integral part of 3GPP standards UMTS/LTE and LTE-Advanced.

Change of paradigm: cell-planning versus self-contained deployment.

Femtocells

Home-Basestation



Why femtocells?

- Consumer: improved (indoor) coverage, bundling of services: fixed mobile convergence (FMC).
- Operators: reduced investments and costs for network operation, smaller cells $\Rightarrow$ improved coverage and capacity, win customer loyalty.
- Femtocells are integral part of 3GPP standards UMTS/LTE and LTE-Advanced.

Change of paradigm: cell-planning versus self-contained deployment.

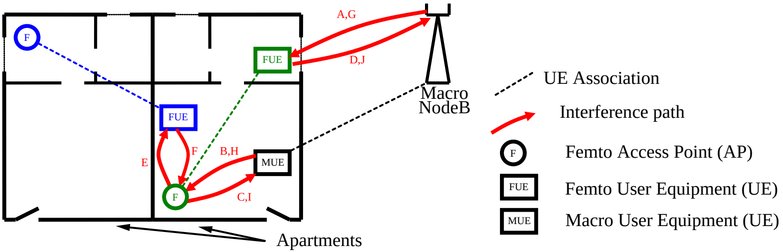
Interference Scenarios in Femtocells

As identified by FemtoForum

TECHNISCHE UNIVERSITÄT DARMSTADT

		Victim				
		Femto UE Downlink Rx	Femto AP Uplink Rx	Macro UE Downlink Rx	Macro NodeB Uplink Rx	Neighbour Femto UE Downlink Rx
Aggressor	Macro NodeB DL Tx	A, G 4				
	Macro UE UL Tx		B, H 3			
	Femto AP DL Tx			C, I 2		E 6
	Femto UE UL Tx				D, J 1	
	Neighbour Femto UE UL Tx		F 5			

femtoforum driving convergence worldwide



What is cognitive radio?

TECHNISCHE UNIVERSITÄT DARMSTADT

Idea was first presented in a paper by Mitola in 1999.

One out of many definitions:

- Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node **changes its transmission or reception parameters** to communicate efficiently avoiding interference with **licensed** or **unlicensed** users.
- This alteration of parameters is based on the active **monitoring** of several factors in the external and internal **radio environment**, such as radio frequency spectrum, user behavior and network state.

What is cognitive radio?

TECHNISCHE UNIVERSITÄT DARMSTADT

Idea was first presented in a paper by Mitola in 1999.

One out of many definitions:

- Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node **changes its transmission or reception parameters** to communicate efficiently avoiding interference with **licensed** or **unlicensed** users.
- This alteration of parameters is based on the active **monitoring** of several factors in the external and internal **radio environment**, such as radio frequency spectrum, user behavior and network state.

What is cognitive radio?

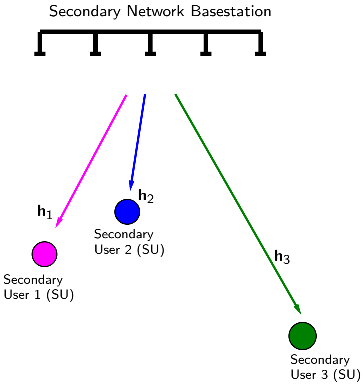
Idea was first presented in a paper by Mitola in 1999.

One out of many definitions:

- Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node **changes its transmission or reception parameters** to communicate efficiently avoiding interference with **licensed** or **unlicensed** users.
- This alteration of parameters is based on the active **monitoring** of several factors in the external and internal **radio environment**, such as radio frequency spectrum, user behavior and network state.

Secondary Network

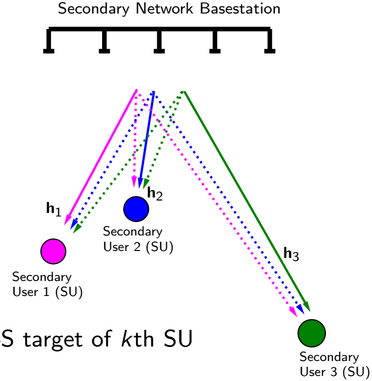
Quality of Service (QoS) Requirements



Secondary Network

Quality of Service (QoS) Requirements

TECHNISCHE UNIVERSITÄT DARMSTADT



γ_k QoS target of kth SU

K single antenna SUs
N_t antennas at the SNB

Symbols of SUs $s_1, \dots, s_K$

Powers $p_1, \dots, p_K$

Beamformers $\mathbf{u}_1, \dots, \mathbf{u}_K$

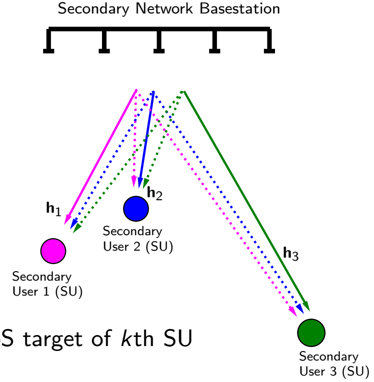
Transmitted signal vectors
$\mathbf{x}(n) = \sum_{k=1}^{K} \sqrt{p}_k \mathbf{u}_k s_k(n)$

Received signal at the kth SU
$y_k(n) = \mathbf{h}_k^T \mathbf{x}(n) + z_k(n)$

Channel covariance $\mathbf{R}_k \triangleq \mathrm{E}\{\mathbf{h}_k \mathbf{h}_k^H\}$

Cognitive Radio Network

Quality of Service (QoS) Requirements



γ_k QoS target of kth SU

Optimization problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K, p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$p_k \geq 0, \quad k = 1, \ldots, K$$

Literature

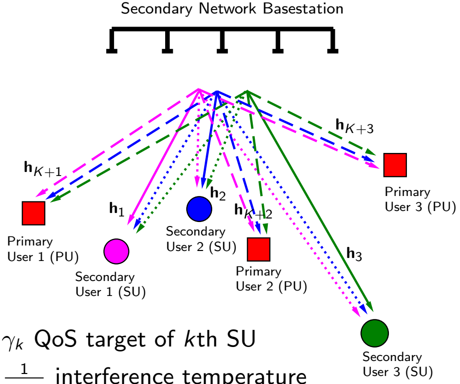
Semi-definite relaxation: [Boche/Schubert,'02; Bengsson/Ottersten,'01]

Iterative solution: [Bengsson/Ottersten,'01]

Cognitive Radio Network

Maximum Interference Constraints

TECHNISCHE UNIVERSITÄT DARMSTADT



γ_k QoS target of kth SU

$\frac{1}{\gamma_{K+l}}$ interference temperature at lth PU

$\mathbf{R}_1, \ldots, \mathbf{R}_K$ channel cov. of SUs

$\mathbf{R}_{K+1},\ldots,\mathbf{R}_{K+L}$ channel cov. of PUs

Optimization problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K, p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$\mathrm{I}_l^{\mathrm{DL}} \triangleq \sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i \leq \frac{1}{\gamma_{K+l}}$$

$$p_k \geq 0;\ k = 1, \ldots, K;\ l = 1, \ldots, L$$

Literature

Semi-definite relaxation: [Cumanan et al.,'08]

Optimality?

Semi-definite relaxation

Cumanan et al.,'08

TECHNISCHE UNIVERSITÄT DARMSTADT

Original optimization problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k - \gamma_k \sum_{\substack{i=1\\i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i \geq \gamma_k \sigma_k^2$$

$$\gamma_{K+l} \sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i - 1 \leq 0$$

$$p_k \geq 0;\ k = 1,\ldots,K;\ l = 1,\ldots,L$$

Equivalent problem

substituting $\mathbf{W}_k = p_k \mathbf{u}_k \mathbf{u}_k^H$

$$\min_{\mathbf{W}_1,\ldots,\mathbf{W}_k} \sum_{k=1}^{K} \mathrm{tr}\{\mathbf{W}_k\}$$

Subject to

$$\mathrm{tr}\{\mathbf{W}_k \mathbf{R}_k\} - \gamma_k \sum_{\substack{i=1\\i\neq k}}^{K} \mathrm{tr}\{\mathbf{W}_i \mathbf{R}_k\} \geq \gamma_k \sigma_k^2$$

$$\gamma_{K+l} \sum_{i=1}^{K} \mathrm{tr}\{\mathbf{R}_{K+l} \mathbf{W}_i\} \leq 1$$

$$\mathbf{W}_k \succeq 0;\ \mathbf{W}_k^H = \mathbf{W}_k;\ \mathrm{rank}\{\mathbf{W}_k\} = 1$$

$$p_k \geq 0;\ k = 1,\ldots,K;\ l = 1,\ldots,L$$

Semi-definite relaxation

Cumanan et al.,'08

TECHNISCHE UNIVERSITÄT DARMSTADT

Original optimization problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k - \gamma_k \sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i \geq \gamma_k \sigma_k^2$$

$$\gamma_{K+l} \sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i - 1 \leq 0$$

$$p_k \geq 0;\ \ k = 1, \ldots, K;\ \ l = 1, \ldots, L$$

Equivalent problem

substituting $\mathbf{W}_k = p_k \mathbf{u}_k \mathbf{u}_k^H$

$$\min_{\mathbf{W}_1,\ldots,\mathbf{W}_k} \sum_{k=1}^{K} \text{tr}\{\mathbf{W}_k\}$$

Subject to

$$\text{tr}\{\mathbf{W}_k \mathbf{R}_k\} - \gamma_k \sum_{\substack{i=1\\ i\neq k}}^{K} \text{tr}\{\mathbf{W}_i \mathbf{R}_k\} \geq \gamma_k \sigma_k^2$$

$$\gamma_{K+l} \sum_{i=1}^{K} \text{tr}\{\mathbf{R}_{K+l} \mathbf{W}_i\} \leq 1$$

$\mathbf{W}_k \succeq 0;\ \ \mathbf{W}_k^H = \mathbf{W}_k;$ ~~$\text{rank}\{\mathbf{W}_k\} = 1$~~

$$p_k \geq 0;\ \ k = 1, \ldots, K;\ \ l = 1, \ldots, L$$

Problem reformulation

TECHNISCHE UNIVERSITÄT DARMSTADT

Original optimization problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$\mathrm{I}_l^{\mathrm{DL}} \triangleq \sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i \leq \frac{1}{\gamma_{K+l}}$$

$$p_k \geq 0;$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Problem reformulation

TECHNISCHE UNIVERSITÄT DARMSTADT

Equivalent problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{1}{\sum_{i=1}^{K} p_i \mathbf{u}_k^H \mathbf{R}_{K+l} \mathbf{u}_i} \geq \gamma_{K+l}$$

$$p_k \geq 0$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Problem reformulation

TECHNISCHE UNIVERSITÄT DARMSTADT

Equivalent problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{1}{\sum_{i=1}^{K} p_i \mathbf{u}_k^H \mathbf{R}_{K+l} \mathbf{u}_i} \geq \gamma_{K+l}$$

$$p_k \geq 0$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Equivalent problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} = \gamma_k$$

$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{1}{\sum_{i=1}^{K} p_i \mathbf{u}_k^H \mathbf{R}_{K+l} \mathbf{u}_i} \geq \gamma_{K+l}$$

$$p_k \geq 0$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Problem reformulation

TECHNISCHE UNIVERSITÄT DARMSTADT

Equivalent problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_K} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} \geq \gamma_k$$

$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{1}{\sum_{i=1}^{K} p_i \mathbf{u}_k^H \mathbf{R}_{K+l} \mathbf{u}_i} \geq \gamma_{K+l}$$

$$p_k \geq 0$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Equivalent problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_{K+L}} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} = \gamma_k$$

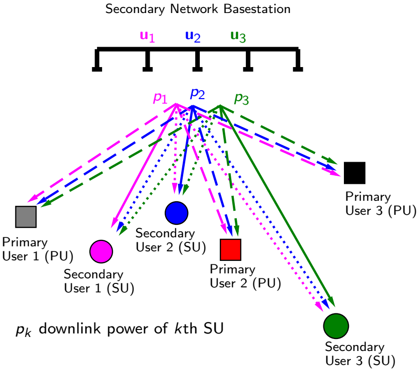
$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{p_{K+l}}{\sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i} = \gamma_{K+l}$$

$$p_k \geq 0; \;\; p_{K+l} \leq 1$$

$$k = 1, \ldots, K; \;\; l = 1, \ldots, L$$

Uplink-downlink duality

Downlink beamforming

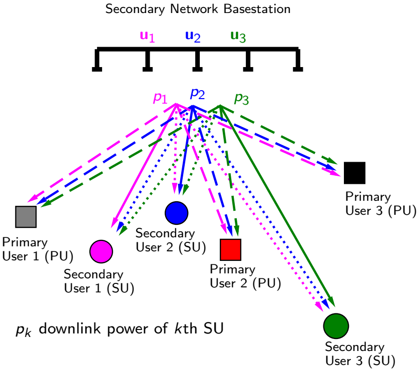


p_k downlink power of kth SU

Uplink-downlink duality

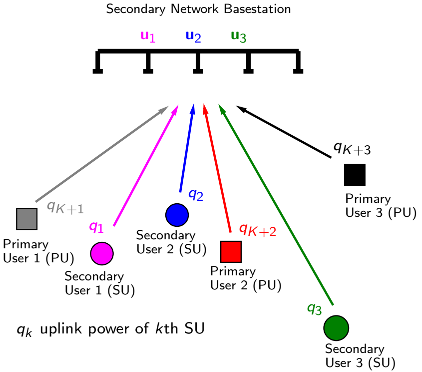
TECHNISCHE UNIVERSITÄT DARMSTADT

Downlink beamforming



p_k downlink power of kth SU

Virtual uplink beamforming



q_k uplink power of kth SU

Duality: The optimal uplink and downlink beamformers are identical; however their individual powers are generally different!

Uplink-downlink duality

TECHNISCHE UNIVERSITÄT DARMSTADT

Downlink problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,p_1,\ldots,p_{K+L}} \sum_{k=1}^{K} p_k$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{DL}} \triangleq \frac{p_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\sum_{\substack{i=1\\ i\neq k}}^{K} p_i \mathbf{u}_i^H \mathbf{R}_k \mathbf{u}_i + \sigma_k^2} = \gamma_k$$

$$\mathrm{SINR}_{K+l}^{\mathrm{VDL}} \triangleq \frac{p_{K+l}}{\sum_{i=1}^{K} p_i \mathbf{u}_i^H \mathbf{R}_{K+l} \mathbf{u}_i} = \gamma_{K+l}$$

$p_k \geq 0$; $p_{K+l} \leq 1$

$k = 1, \ldots, K$; $l = 1, \ldots, L$

Virtual uplink problem

$$\min_{\mathbf{u}_1,\ldots,\mathbf{u}_K,q_1,\ldots,q_{K+L}} \sum_{k=1}^{K} \gamma_k \sigma_k^2 q_k - \sum_{l=1}^{L} p_{K+l} q_{K+l}$$

Subject to

$$\mathrm{SINR}_k^{\mathrm{VUL}} \triangleq \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1\\ i\neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k} = 1$$

$q_k \geq 0$

$p_{K+l} \leq 1$

$k = 1, \ldots, K$; $l = 1, \ldots, L$

Unique optimum solution

Relation of uplink-downlink dual to Lagrange dual

TECHNISCHE UNIVERSITÄT DARMSTADT

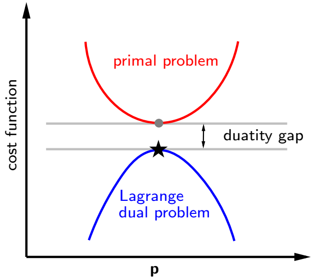
Lagrange dual of downlink problem

$$\max_{q_1,\ldots,q_{K+L}} \sum_{k=1}^{K} \gamma_k \sigma_k^2 q_k - \sum_{l=1}^{L} q_{K+l}$$

Subject to

$$\mathbf{I} - q_k \mathbf{R}_k + \sum_{\substack{i=1 \\ i\neq k}}^{K+L} \gamma_i q_i \mathbf{R}_i \succcurlyeq 0$$

$$q_i \geq 0; \quad k = 1, \ldots, K; \quad l = 1, \ldots, L$$



Lemma: The virtual uplink problem and the Lagrange dual of the downlink problem have identical solution i.e. the duality gap is zero.

The problem can be solved using convex optimization. From this the optimality of the semi-definite relaxation approach by Cumanan'08 immediately follows.

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization Initialize $q_k(1) = 1$ for $k = 1, \dots, K + L$

Iteration For $t = 1, 2, \dots$ until convergence, iterate

Step 1 **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \dots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t);\ k = 1, \dots, K$

Step 2 **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \dots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if } \min\{p_l, \dots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence **SU and PU downlink power computation.**

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization Initialize $q_k(1) = 1$ for $k = 1, \dots, K + L$

Iteration For $t = 1, 2, \dots$ until convergence, iterate

Step 1 **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \dots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t)$; $k = 1, \dots, K$

Step 2 **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \dots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if } \min\{p_l, \dots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence **SU and PU downlink power computation.**

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization Initialize $q_k(1) = 1$ for $k = 1, \ldots, K + L$

Iteration For $t = 1, 2, \ldots$ until convergence, iterate

Step 1 **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \ldots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t)$; $k = 1, \ldots, K$

Step 2 **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \ldots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if} \quad \min\{p_l, \ldots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence **SU and PU downlink power computation.**

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization Initialize $q_k(1) = 1$ for $k = 1, \dots, K+L$

Iteration For $t = 1, 2, \dots$ until convergence, iterate

Step 1 **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \dots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t)$; $k = 1, \dots, K$

Step 2 **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \dots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if } \min\{p_l, \dots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence **SU and PU downlink power computation.**

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization Initialize $q_k(1) = 1$ for $k = 1, \ldots, K+L$

Iteration For $t = 1, 2, \ldots$ until convergence, iterate

Step 1 **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \ldots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t)$; $k = 1, \ldots, K$

Step 2 **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \ldots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if} \ \min\{p_l, \ldots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence **SU and PU downlink power computation.**

Iterative algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Initialization: Initialize $q_k(1) = 1$ for $k = 1, \ldots, K+L$

Iteration: For $t = 1, 2, \ldots$ until convergence, iterate

Step 1: **Beamformer update:** Find

$$\mu_k = \max_{||u_k||=1} \frac{q_k \mathbf{u}_k^H \mathbf{R}_k \mathbf{u}_k}{\mathbf{u}_k^H \left(\sum_{\substack{i=1 \\ i \neq k}}^{K+L} q_i \gamma_i \mathbf{R}_i + \mathbf{I} \right) \mathbf{u}_k}; \quad k = 1, \ldots, K$$

SU uplink power update: $q_k(t+1) = \frac{1}{\mu_k} q_k(t)$; $k = 1, \ldots, K$

Step 2: **PU downlink power update:** Find $p_{K+l}(t+1)$ for $l = 1, \ldots, L$

PU uplink power update:

$$q_{K+l}(t+1) = \begin{cases} p_{K+l}(t+1) q_{K+l}(t), & \text{if } \min\{p_l, \ldots, p_K\} \geq 0 \\ q_{K+l}(t+1), & \text{otherwise.} \end{cases}$$

At convergence: **SU and PU downlink power computation.**

Benefits of iterative approach

TECHNISCHE UNIVERSITÄT DARMSTADT

Complexity For N_t Tx antennas and K SU the complexity order of the new iterative algorithm grows as $\mathcal{O}\{KN_t^2\}$ per iteration with the problem size. The complexity of the semi-definite program base algorithm [Cumanam et al. '08] grows as $\mathcal{O}\{(KN_t)^3\}$ per iteration with the problem size and requires approx. $\mathcal{O}\{(KN_t)^{0.5}\}$ iterations until convergence.

Implementation The iterative algorithm enjoys simple implementation and does not require the use of interior point software as for the SDP approach.

Adaptivity The iterative approach can easily be modified to work in adaptive scenarios. This is not straight forward in the case for the SDP approach.

Benefits of iterative approach

TECHNISCHE UNIVERSITÄT DARMSTADT

Complexity For N_t Tx antennas and K SU the complexity order of the new iterative algorithm grows as $\mathcal{O}\{KN_t^2\}$ per iteration with the problem size. The complexity of the semi-definite program base algorithm [Cumanam et al. '08] grows as $\mathcal{O}\{(KN_t)^3\}$ per iteration with the problem size and requires approx. $\mathcal{O}\{(KN_t)^{0.5}\}$ iterations until convergence.

Implementation The iterative algorithm enjoys simple implementation and does not require the use of interior point software as for the SDP approach.

Adaptivity The iterative approach can easily be modified to work in adaptive scenarios. This is not straight forward in the case for the SDP approach.

Benefits of iterative approach

TECHNISCHE UNIVERSITÄT DARMSTADT

Complexity For N_t Tx antennas and K SU the complexity order of the new iterative algorithm grows as $\mathcal{O}\{KN_t^2\}$ per iteration with the problem size. The complexity of the semi-definite program base algorithm [Cumanam et al. '08] grows as $\mathcal{O}\{(KN_t)^3\}$ per iteration with the problem size and requires approx. $\mathcal{O}\{(KN_t)^{0.5}\}$ iterations until convergence.

Implementation The iterative algorithm enjoys simple implementation and does not require the use of interior point software as for the SDP approach.

Adaptivity The iterative approach can easily be modified to work in adaptive scenarios. This is not straight forward in the case for the SDP approach.

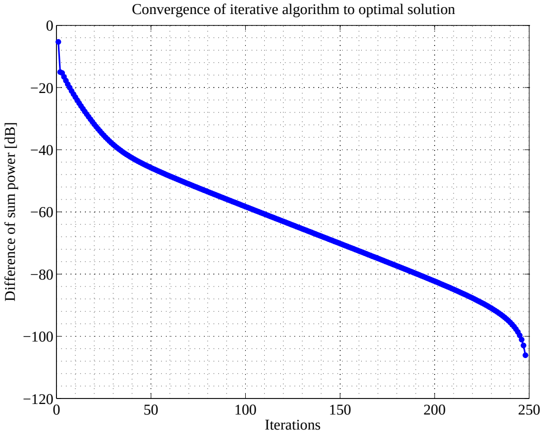
Simulation setup

TECHNISCHE UNIVERSITÄT DARMSTADT

- $K = 5$ SU, $L = 5$ PU, $N_t = 9$ Tx at the SU basestation.
- PU interference temperature: -6dB.
- SU SINR targets $\gamma_1 = 4.51$dB, $\gamma_2 = 4.45$dB, $\gamma_3 = 8.08$dB, $\gamma_4 = 5.37$dB, $\gamma_5 = 4.45$dB.
- Noise variance of -10dB.
- Rayleigh fading channel gains.
- Relative SU DL powers distribution at optimum: $p_1 = 0.15$, $p_2 = 0.12$, $p_3 = 0.29$, $p_4 = 0.27$, $p_5 = 0.16$.
- Optimal virtual PU DL powers: $p_{K+1} = p_{K+2} = p_{K+3} = p_{K+4} = p_{K+5} = 1$.

Simulation results

Error of the transmit power versus number of iterations



Simulation setup

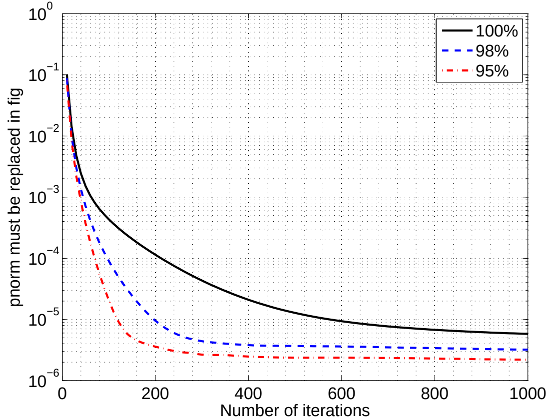
TECHNISCHE UNIVERSITÄT DARMSTADT

- $K = 5$ SU, $L = 5$ PU, $N_t = 9$ Tx at the SU basestation.
- PU interference temperature: -6dB.
- random SU SINR targets $\gamma_k \in [0,\ 10]$dB.
- Noise variance of -10dB.
- Rayleigh fading channel gains.

Simulation results

Histogram of number of iterations until convergence

TECHNISCHE UNIVERSITÄT DARMSTADT



Conclusions

- Cognitive interference control in DL transmit beamforming.
- Established uplink-downlink duality.
- Showed the equivalence with the Lagrange dual problem.
- Proposed a computational efficient iterative algorithm.
- Simulation results showed the convergence of the algorithm to the optimal solution.
- Future work: Robustness to channel mismatch, address the admission problem.