Capacity Optimization for UMTS: Bounds on Expected Interference

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joint work with:
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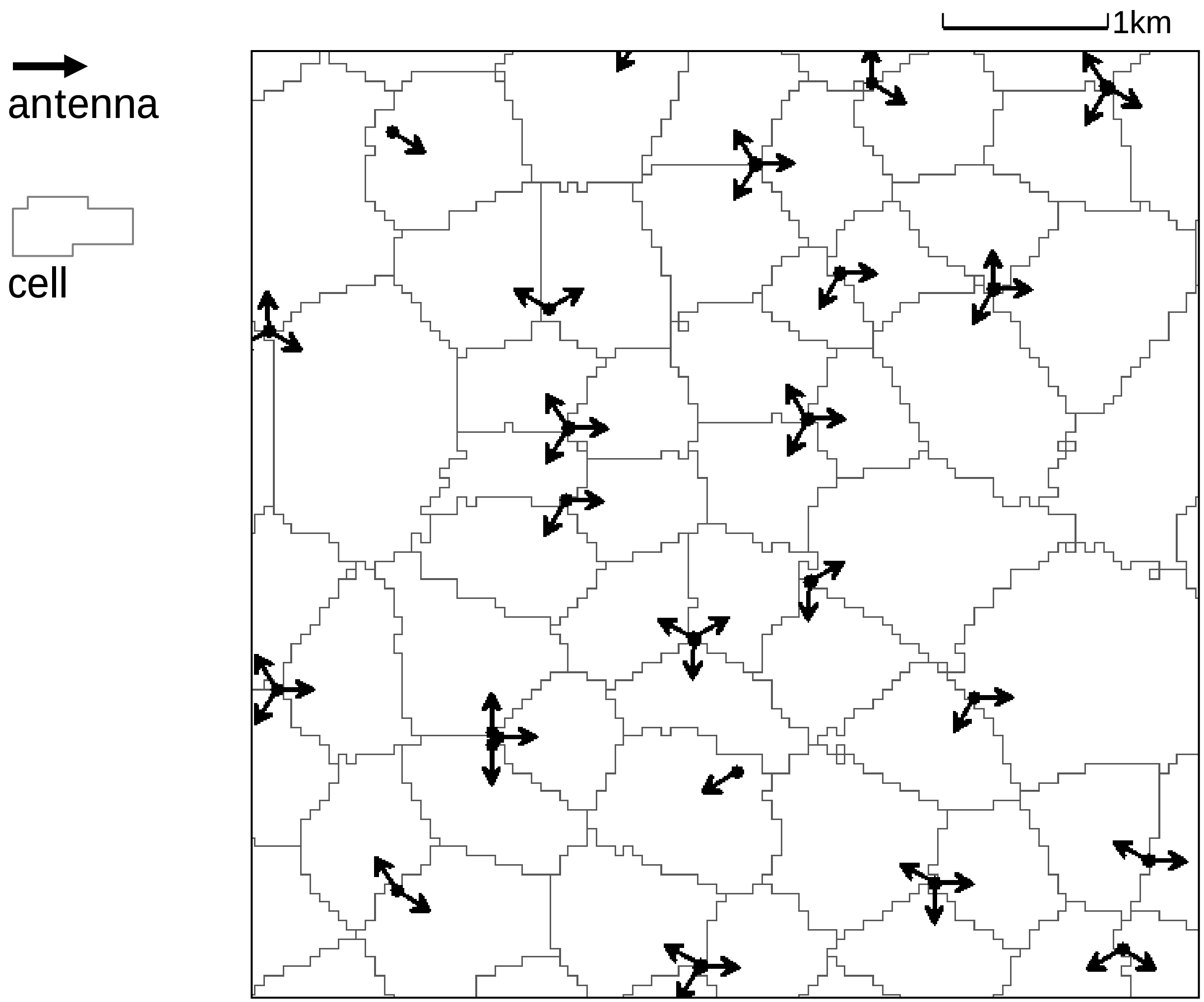
Radio Network Planning



schematic view of a radio network, Berlin

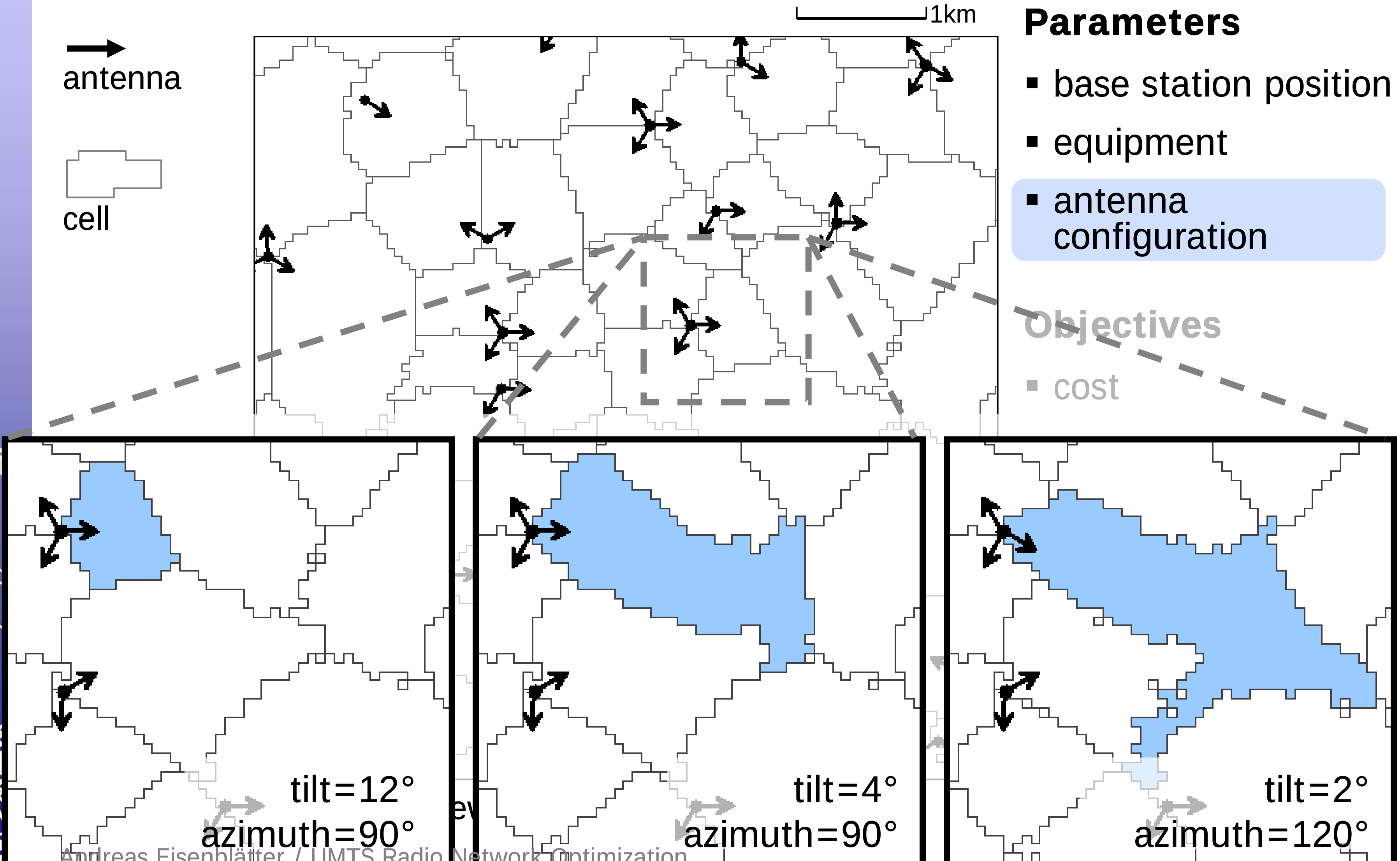
Parameters

- base station position
- equipment
- antenna configuration

Objectives

- cost
- coverage
- capacity

Radio Network Planning



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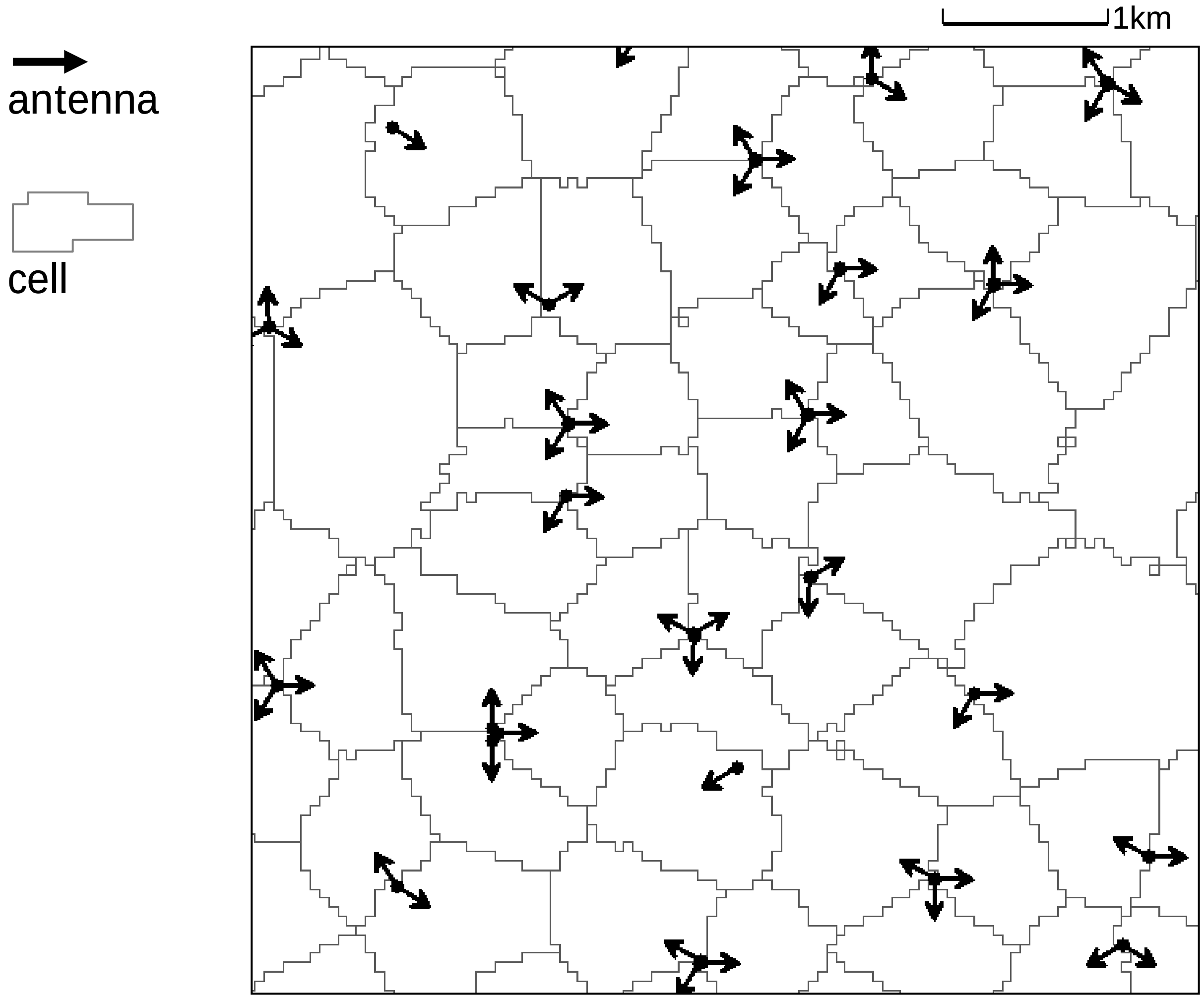

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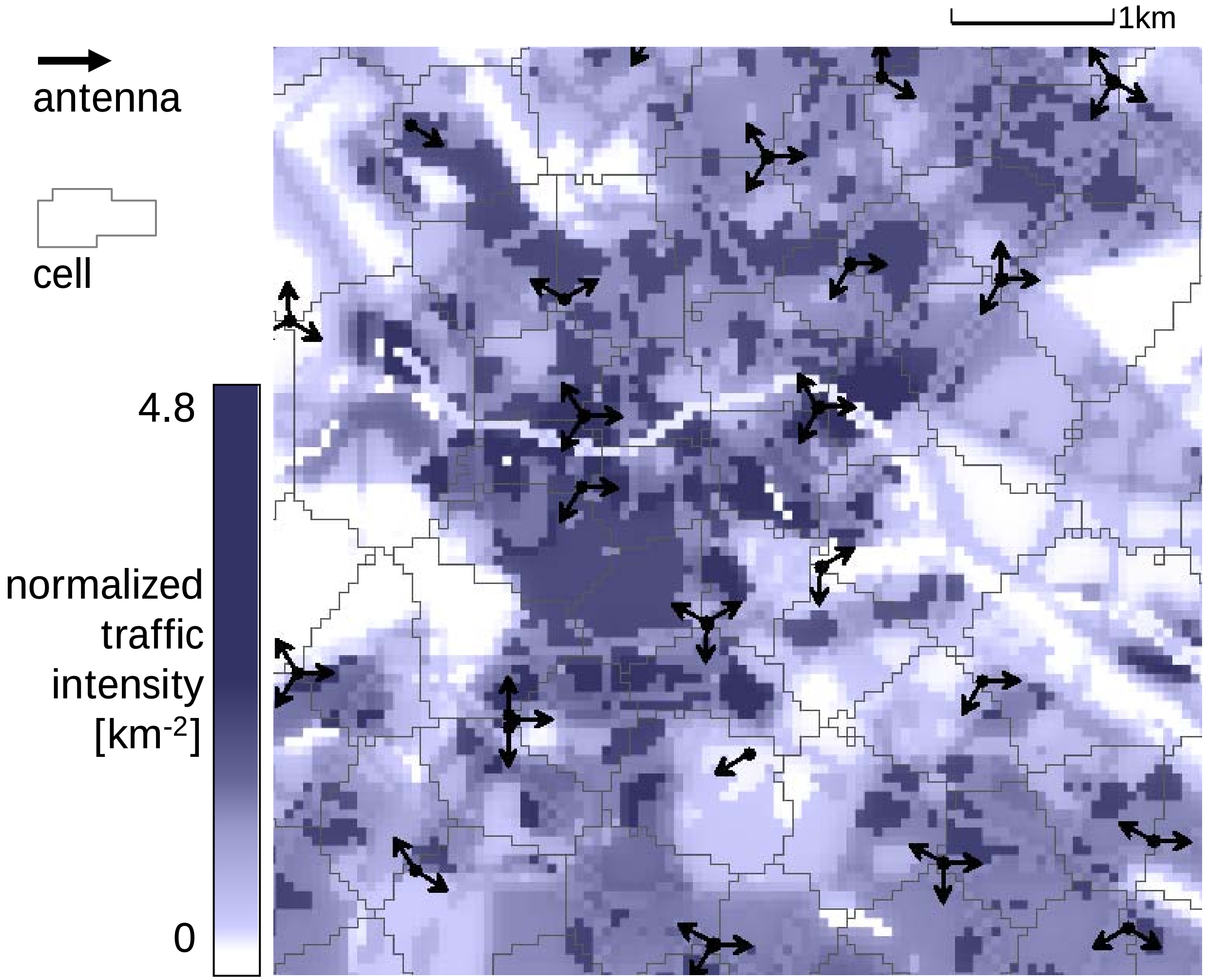

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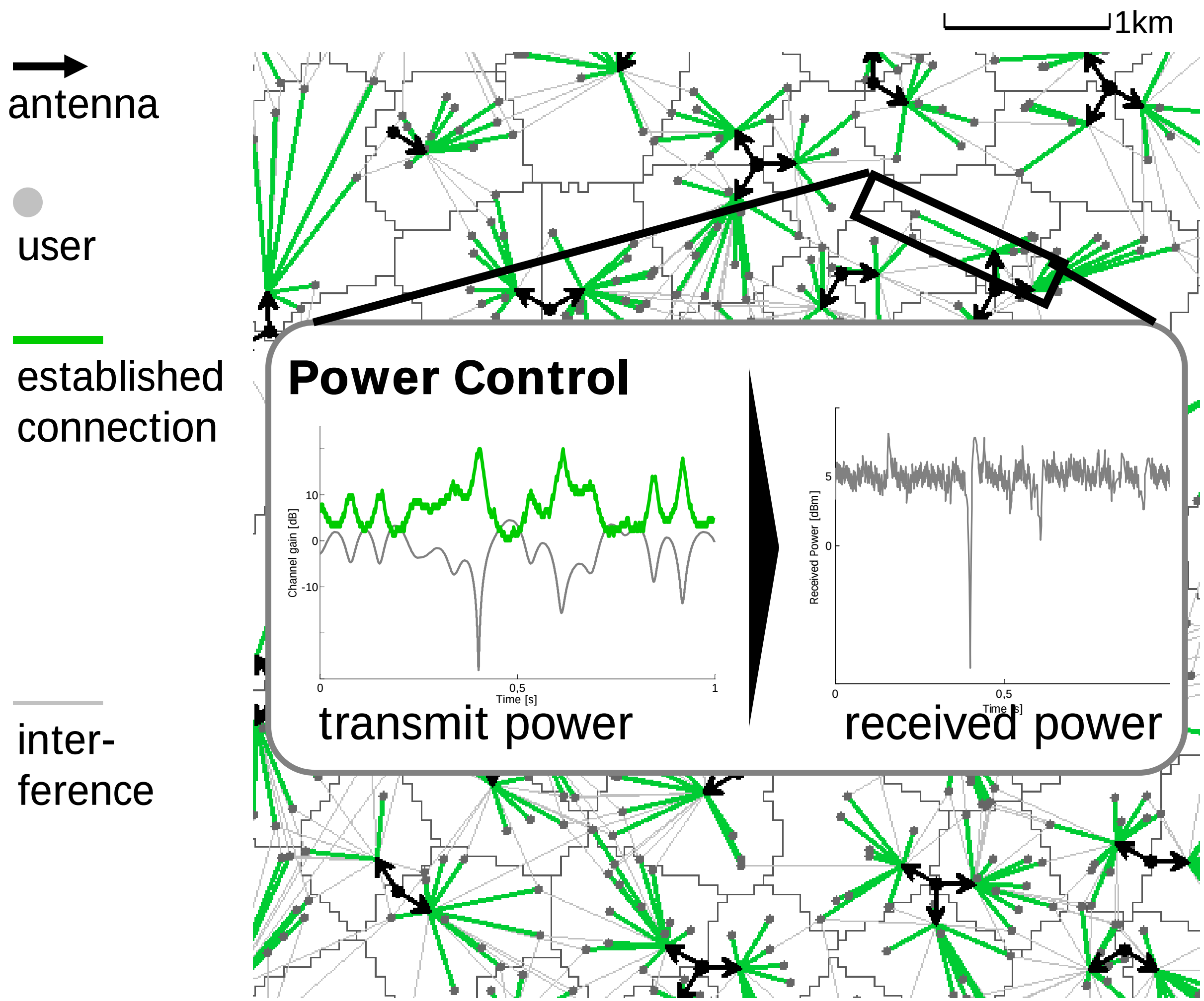
Capacity, Power Control, and Interference in UMTS



- on each link, the power is dynamically regulated
- limiting resource is cell power

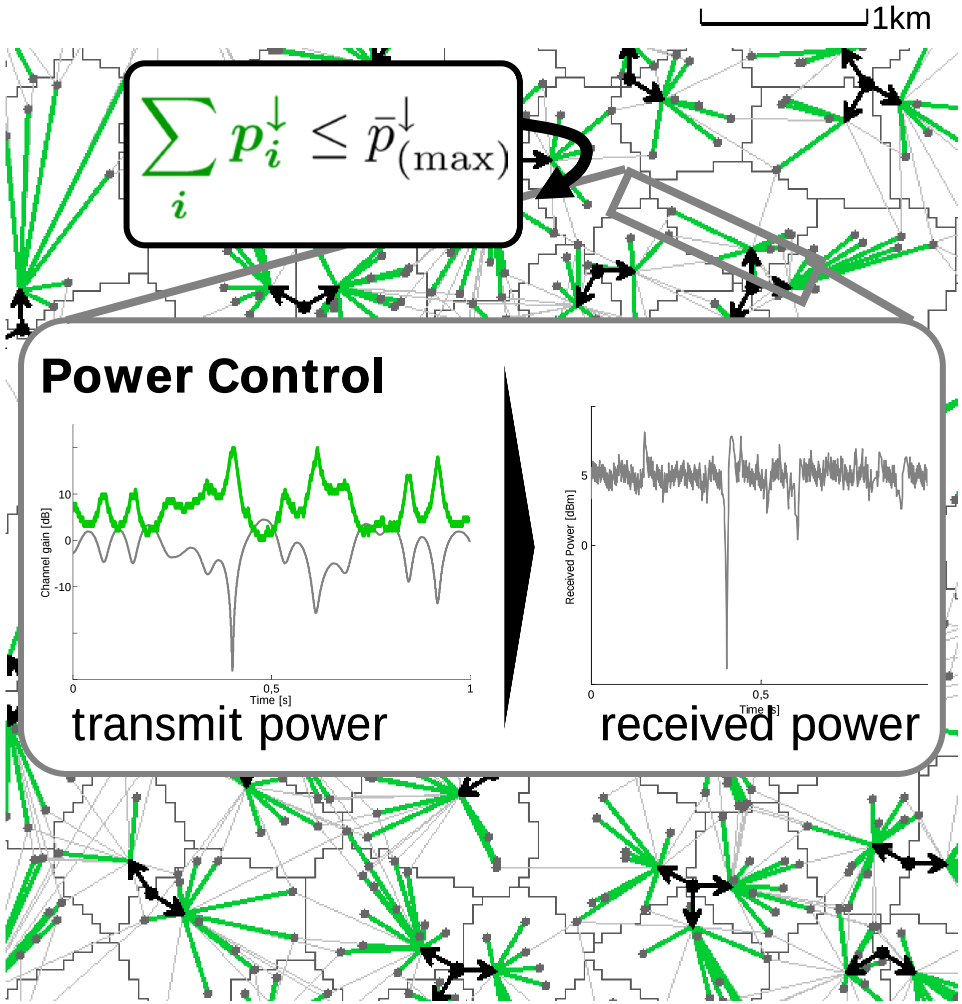
Capacity, Power Control, and Interference in UMTS

antenna

user

established connection

inter-ference



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Capacity, Power Control, and Interference in UMTS

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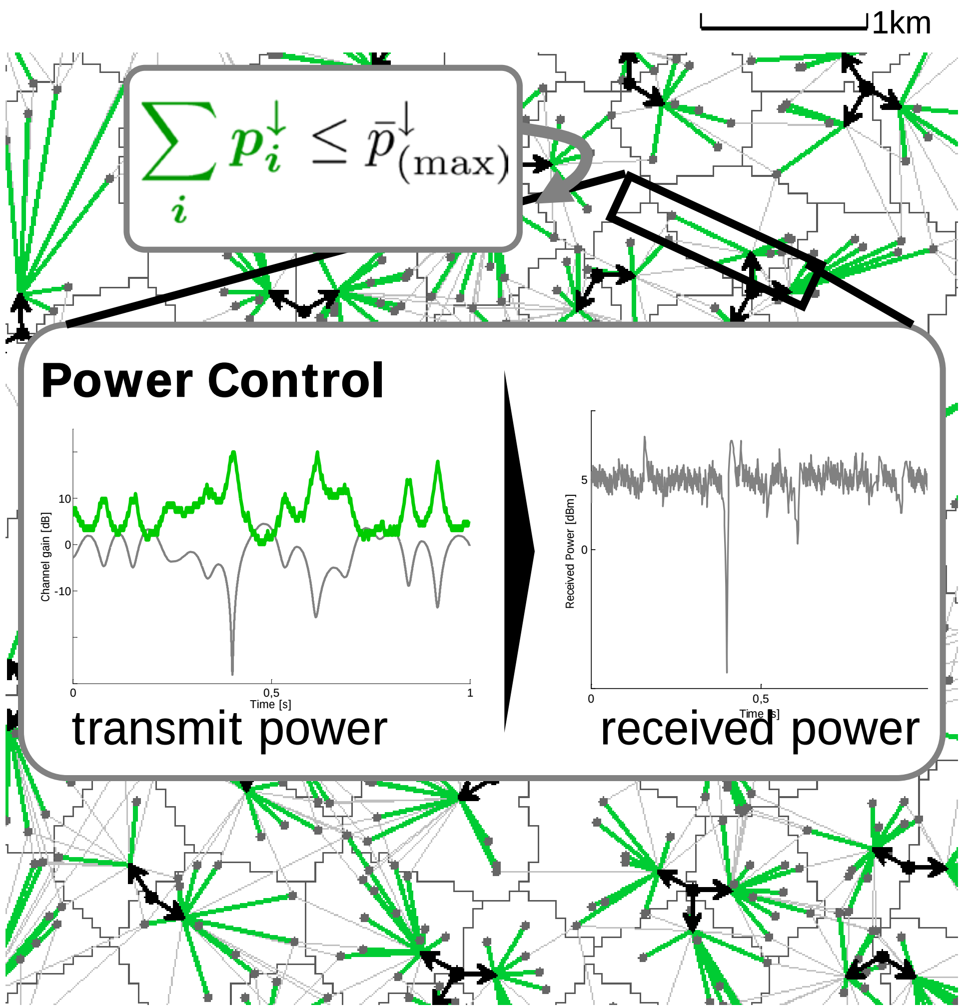


- on each link, the power is dynamically regulated
- limiting resource is cell power

Cell capacity depends on

- user positions
- user demand
- interference generated in neighboring cells
- the network design

Overview

- System Model: Interference Coupling Systems
- Capacity Maximization: Optimization Model and Methods
- Assessing the Quality of Optimization Results: Bounds

State-of-the-art: Detailed View on Network

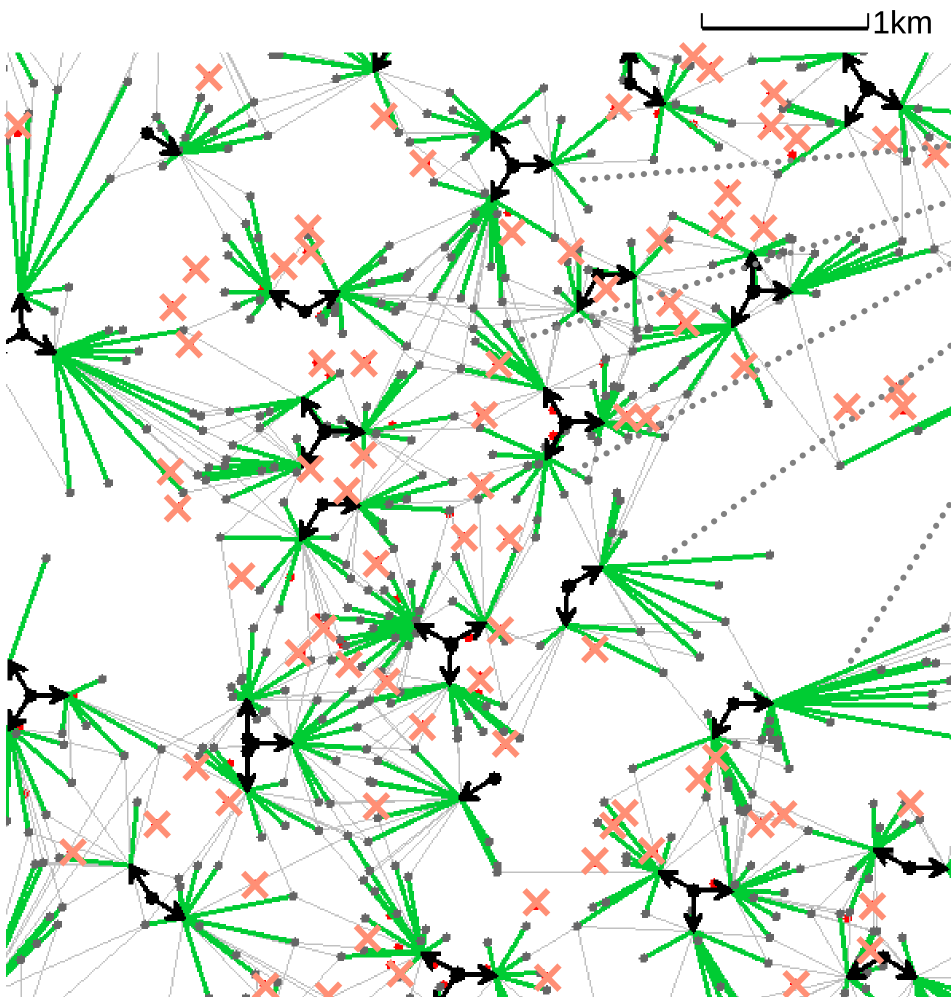
antenna

user

established connection

rejected user

inter-ference



static evaluation of a demand snapshot

CIR equation

$$\frac{\gamma^{\downarrow}_{im} p^{\downarrow}_{im}}{\gamma^{\downarrow}_{im}\omega^{\downarrow}_{m}\bar{p}^{\downarrow}_{i} + \sum_{j \neq i} \gamma^{\downarrow}_{jm}\bar{p}^{\downarrow}_{j}} = \mu^{\downarrow}_{m}$$

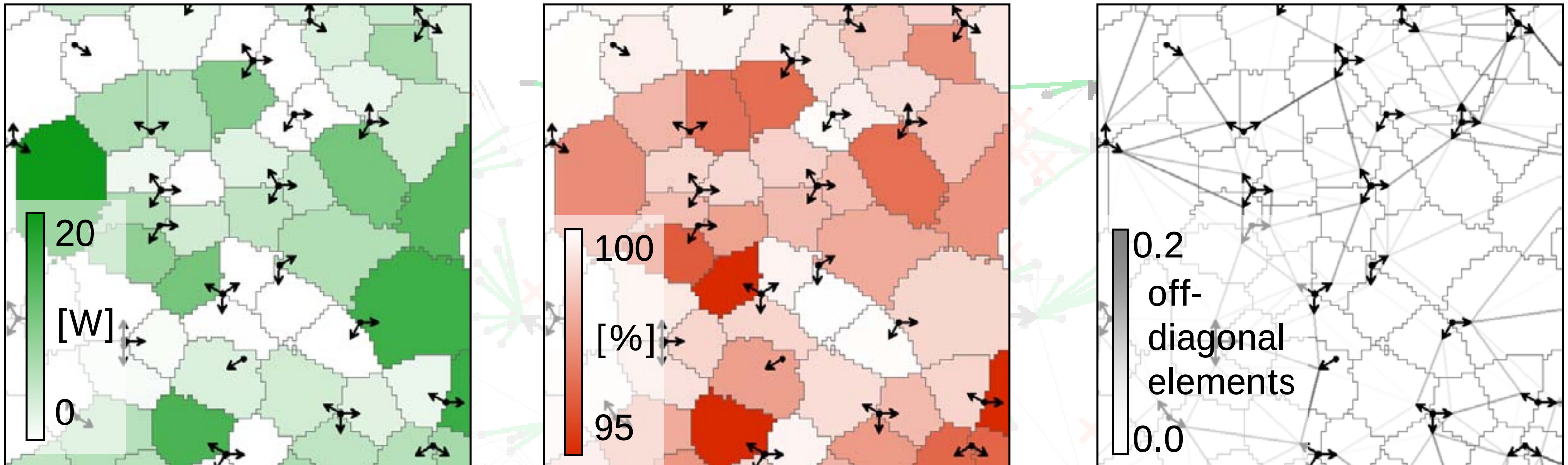
on each link

calculate cell powers

Network evaluation requires

- admission decision per user (algorithm)
- solving large equation system (user x user)

Top-Level View on Network Performance



cell power $\bar{p}^{\downarrow}$

fraction of served demand $\lambda^{\downarrow}$

interference coupling matrix $C^{\downarrow}$

Revised Interference Coupling Equation

$$\bar{p}^{\downarrow} = \mathrm{diag}(\lambda^{\downarrow}) C^{\downarrow} \bar{p}^{\downarrow} + p^{(c)}$$

How much power $\bar{p}^{\downarrow}$ is needed to serve a fraction $\lambda^{\downarrow}$ of the user demand $C^{\downarrow}$

virtually equivalent to classical model

(nonlinear equation system, cells x cells)

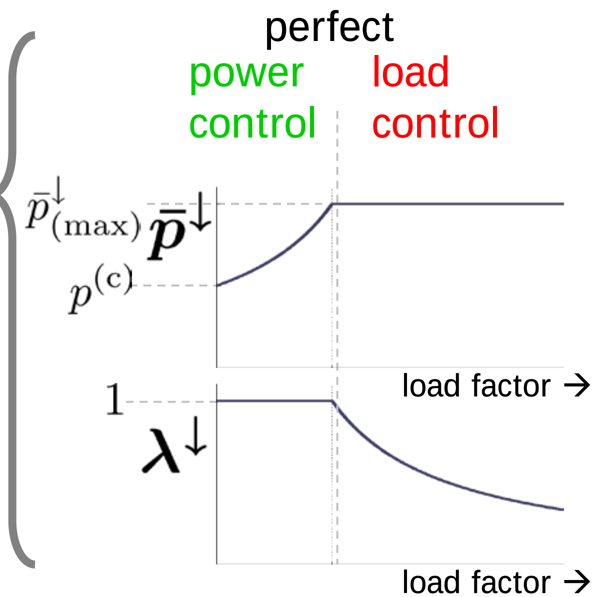
New System Model: Interference Coupling Complementarity System

$$\bar{\boldsymbol{p}}^{\downarrow} = \operatorname{diag}(\boldsymbol{\lambda}^{\downarrow}) C^{\downarrow} \bar{\boldsymbol{p}}^{\downarrow} + \boldsymbol{p}^{(\mathrm{c})}$$

$$0 = (\mathbf{1} - \boldsymbol{\lambda}^{\downarrow})^t (\bar{\boldsymbol{p}}^{\downarrow}_{(\max)} - \bar{\boldsymbol{p}}^{\downarrow})$$

$$\mathbf{0} \le \boldsymbol{\lambda}^{\downarrow} \le \mathbf{1}$$

$$\boldsymbol{p}^{(\mathrm{c})} \le \bar{\boldsymbol{p}}^{\downarrow} \le \bar{\boldsymbol{p}}^{\downarrow}_{(\max)}$$



Closed-form performance model: capacity function of matrix

Properties

- Solutions to classical model: spectral radius of *C* and bounds
- DL: unique solution
- UL: 0,1,...,n,...,1 solutions

Solution Algorithm

- iterative method (modified Gauß-Seidel)
- effort equivalent to solving an equation system

Analysis

Generalized pole equations: isolate interference from other cells

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From System Model to Optimization Model

System Model

performance is a function of the coupling matrix

Expected Coupling

expected matrix is a good representative

Optimization Idea

- Network design is characterized by a single matrix
- Optimization is matrix design
- What is a good coupling matrix?

Optimization Model

$$\bar{p} = C\,\bar{p} + p^{(c)}$$
$$\Leftrightarrow \bar{p} = (I - C)^{-1} p^{(c)}$$
$$= \sum_{k=0}^{\infty} C^k p^{(c)}$$

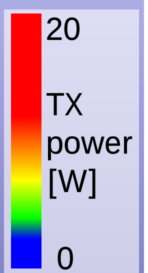
Neumann series

$$\min \quad \mathbf{1}^t \sum_{k=0}^{\infty} C(z)^k p^{(c)}$$
$$\text{s.t.} \quad C(z) \text{ expected coupling matrix for } z$$
$$\operatorname{trace}\big(C(z)\big) \geq \kappa$$
$$z \in \mathcal{F}$$

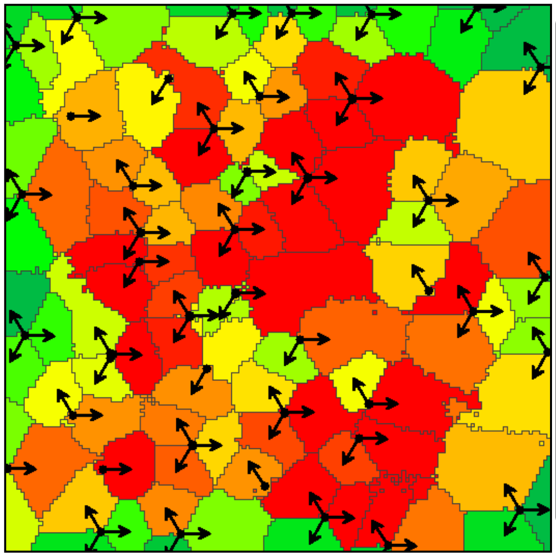
← constrain coverage

- minimize expected interference
- nonconvex in matrix
- critical: # configuration options, size/resolution of scenario

Optimization
Methods and Experiments (Berlin)



Start Configuration



- uniform settings, coverage maximization, greedy site reduction
- choose azimuth within ± 30°
- choose downtilt within 2-12°

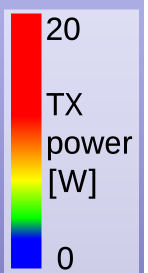
Local Search

- try all alternatives for a single antenna
- adopt improving one

MIP 4-opt Heuristic

- try modifications of 4 sectors at once
- find improvements with approximate MIP
- polish with local search

Optimization
Methods and Experiments (Berlin)



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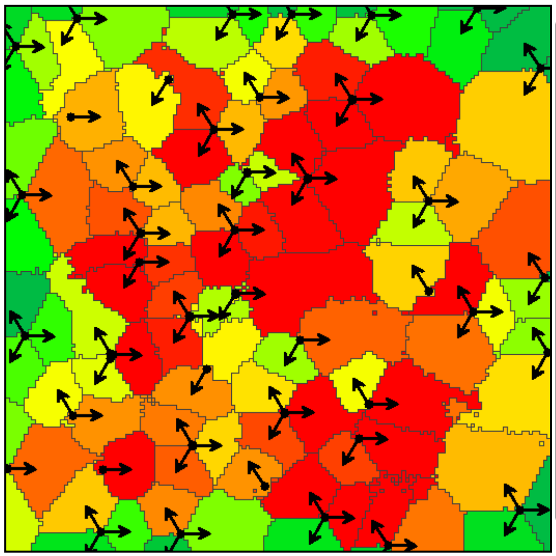

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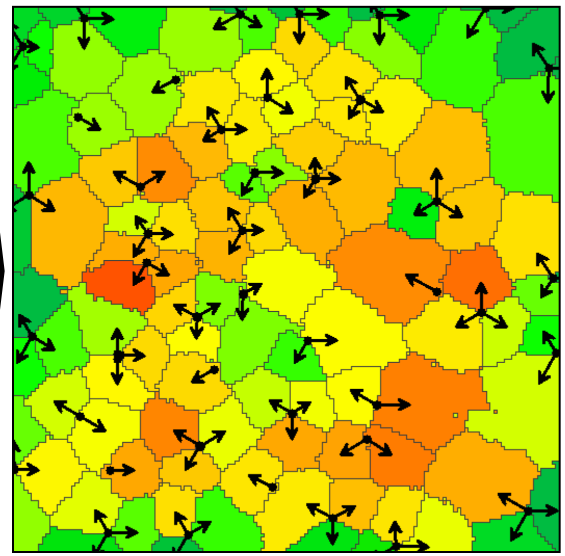

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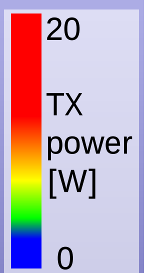

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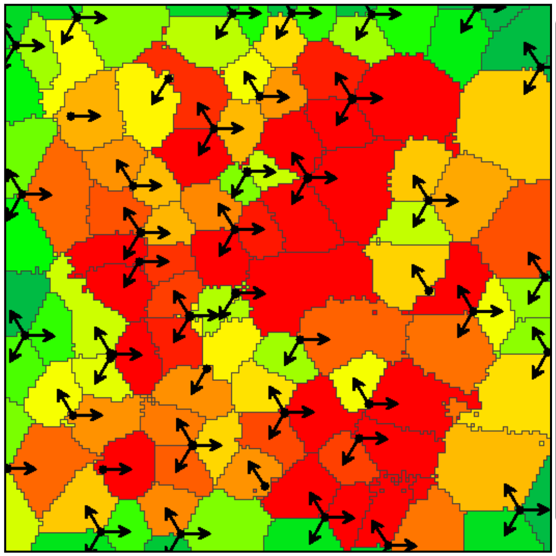

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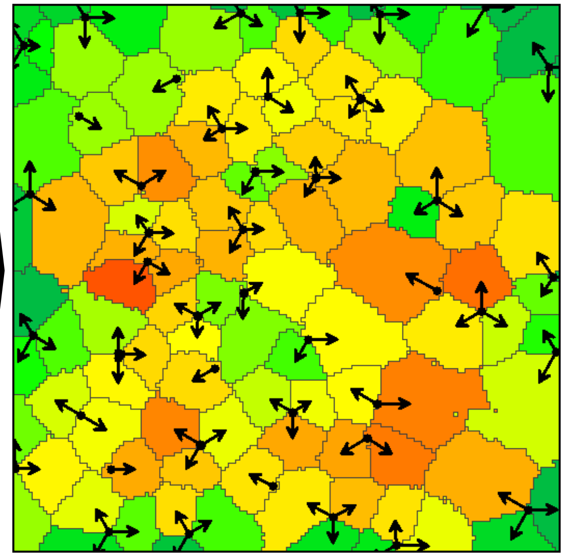

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Load
-15.9%

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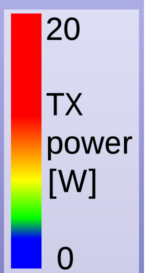

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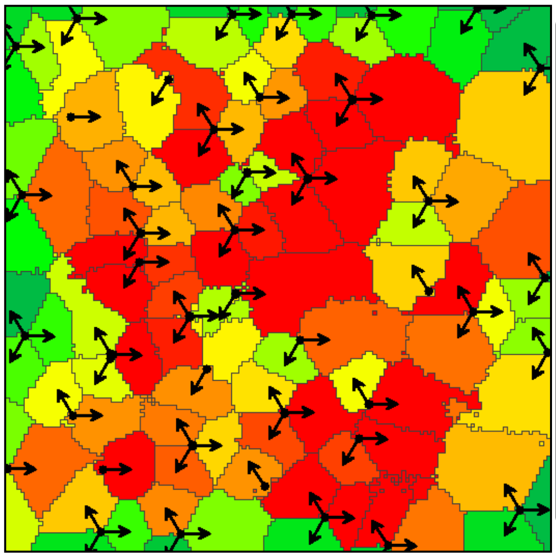

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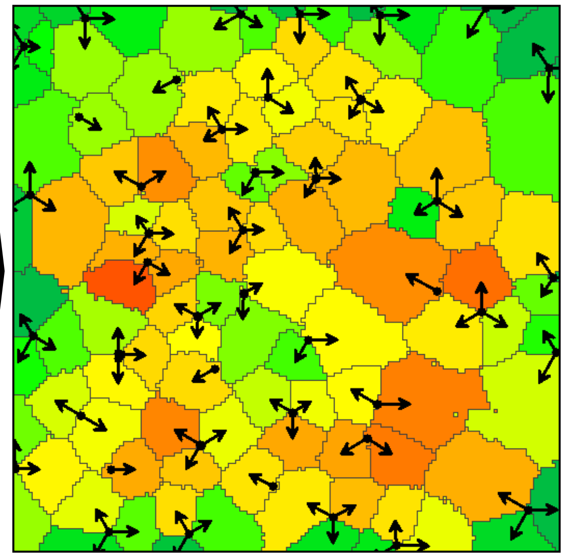
Local Search



- try all alternatives for a single antenna
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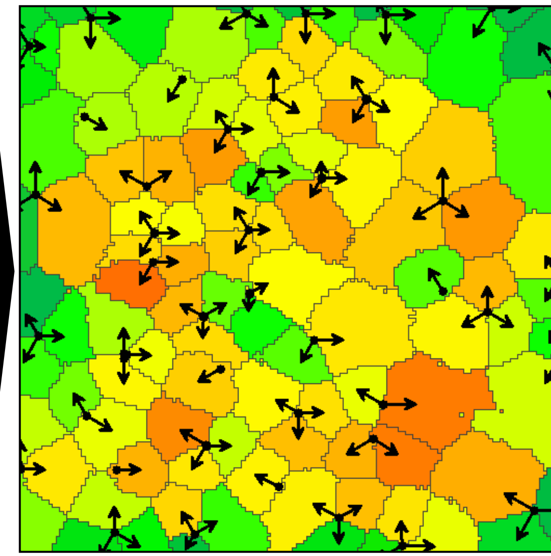
Load
-15,9%

MIP 4-opt Heuristic



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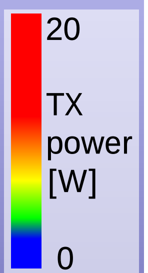

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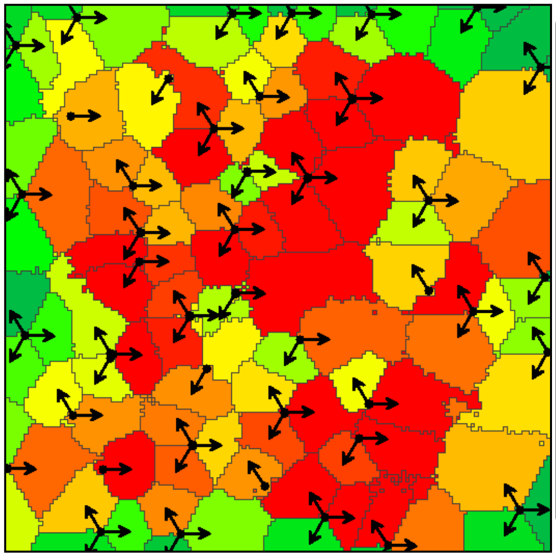

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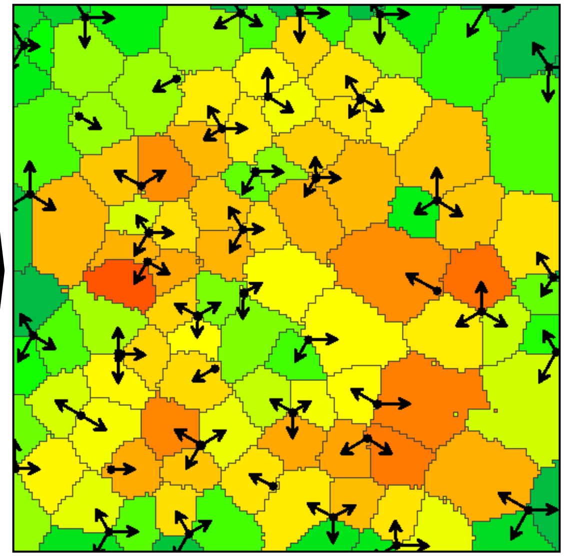
Local Search



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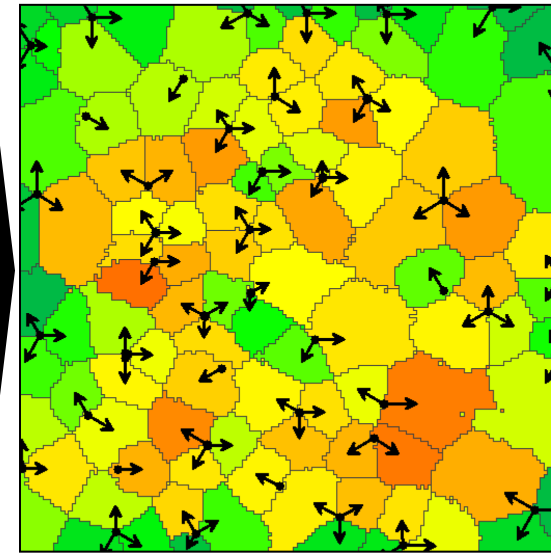
Load

-15.9%

MIP 4-opt Heuristic



- try modifications of 4 sectors at once
- find improvements with approximate MIP
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-17.3%

Overview

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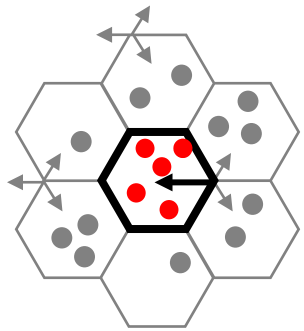
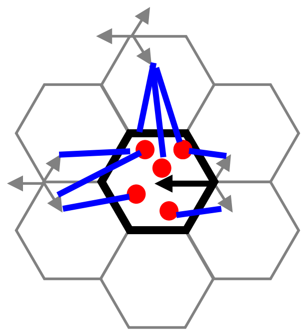
Derivation of Pole Equation



$$\bar{p}_i = \sum_{m \in M_i} \left(\ell_m \omega_m \, \bar{p}_i + \sum\nolimits_{j \neq i} \ell_m \frac{\gamma_{jm}}{\gamma_{im}} \, \bar{p}_j \right) + p_i^{(c)}$$

Detailed description of interaction between cells

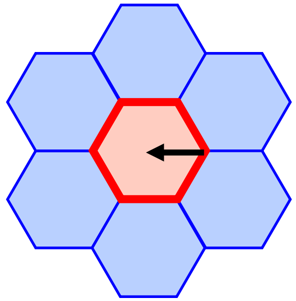


Other-to-own-cell interference $f_m := \frac{\sum_{j \neq i} \gamma_{jm} \bar{p}_j}{\gamma_{im} \bar{p}_i}$

$$\bar{p}_i = \frac{p_i^{(c)}}{1 - \sum_m \ell_m (\omega_m + f_m)}$$

- Single out coupling between cells

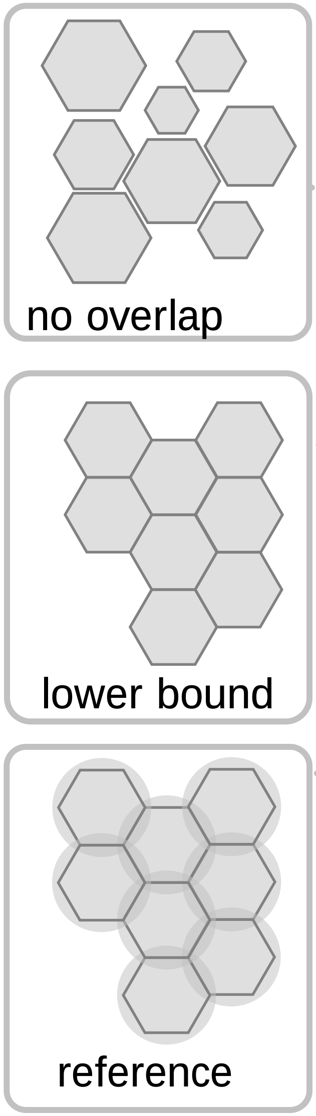
→ Alternative description

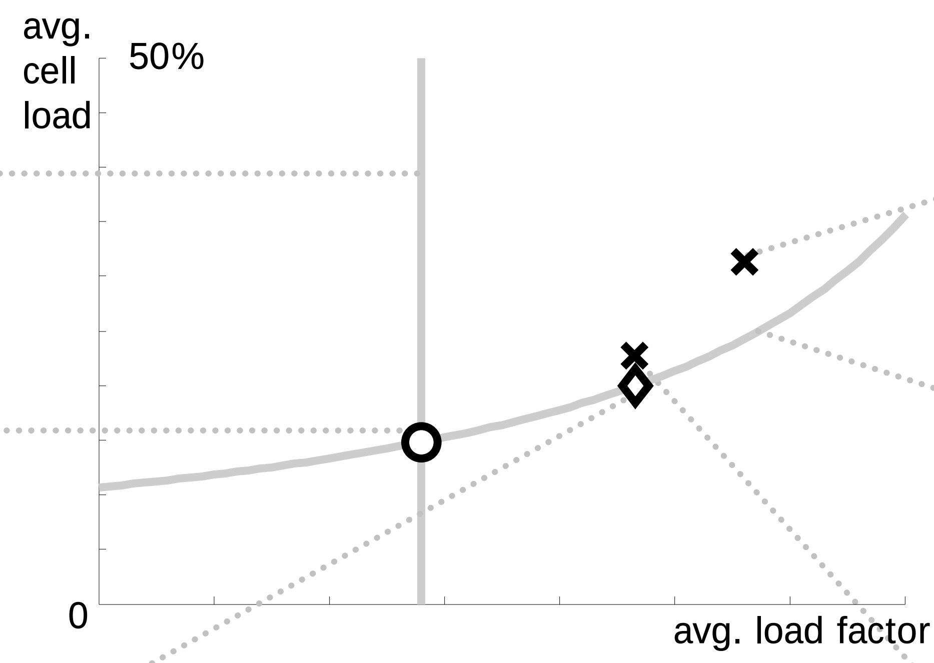


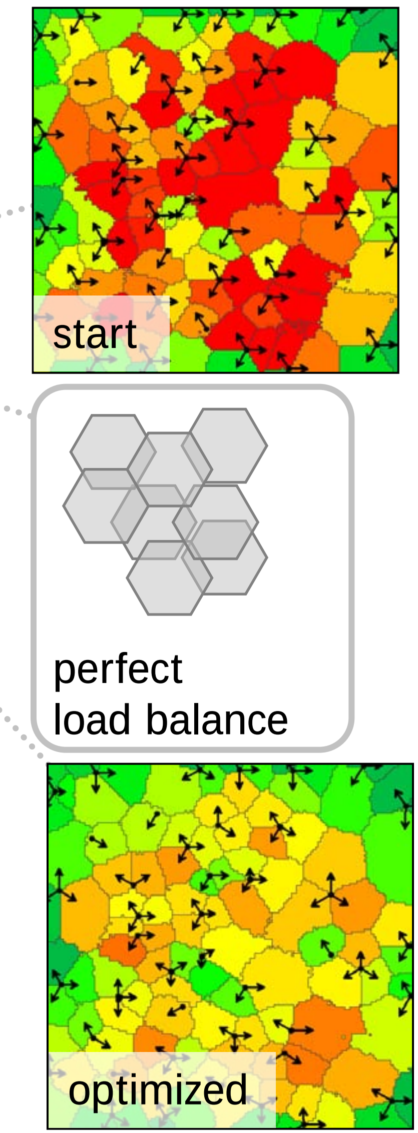
$$\bar{p} = \frac{p^{(c)}}{1 - N \ell (\bar{\omega} + \bar{f})}$$

- Regularity assumptions
- Simplified view of single cell
- Average other-to-own-cell interference ratio and orthogonality

Bounds for Capacity Optimization







	gap to lower bound	gap to reference
Berlin	34.7 %	12.0 %
Lisbon	23.4 %	8.4 %
Turin	47.2 %	13.0 %
Vienna	20.8 %	0.1 %

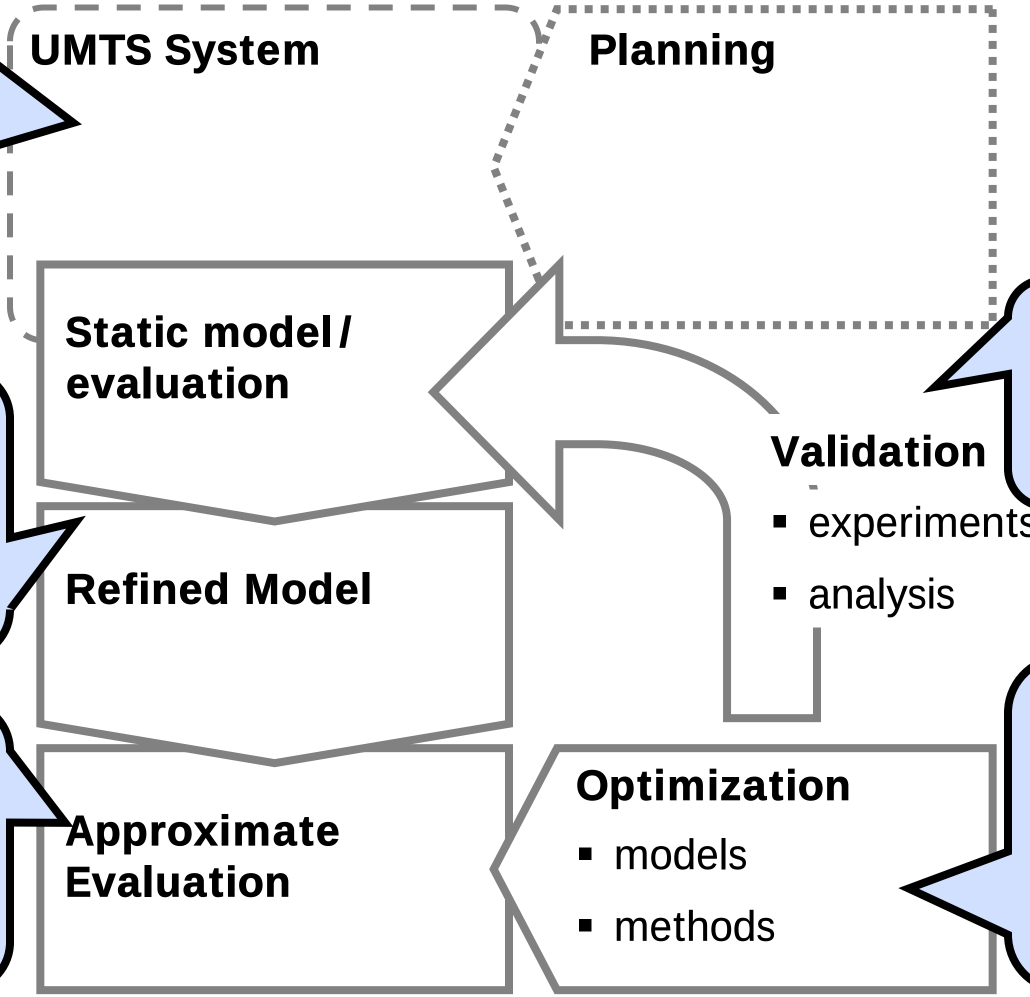
Conclusion

More details: PhD thesis by Hans-Florian Geerdes
“UMTS Radio Network Planning:
Mastering Cell Coupling for Capacity Optimization”

Capacity planning is difficult due to interference limitation

Understand capacity through coupling matrix (alone)

Expected coupling matrix is a sensible representative



Simple methods are successful in many cases

Interference minimization with objective featuring coupling matrix

Thank You!

Intuition of Interference Coupling: Neumann Series

$$\bar{\boldsymbol{p}} = \boldsymbol{C}\,\bar{\boldsymbol{p}} + \boldsymbol{p}^{(\mathrm{c})}$$

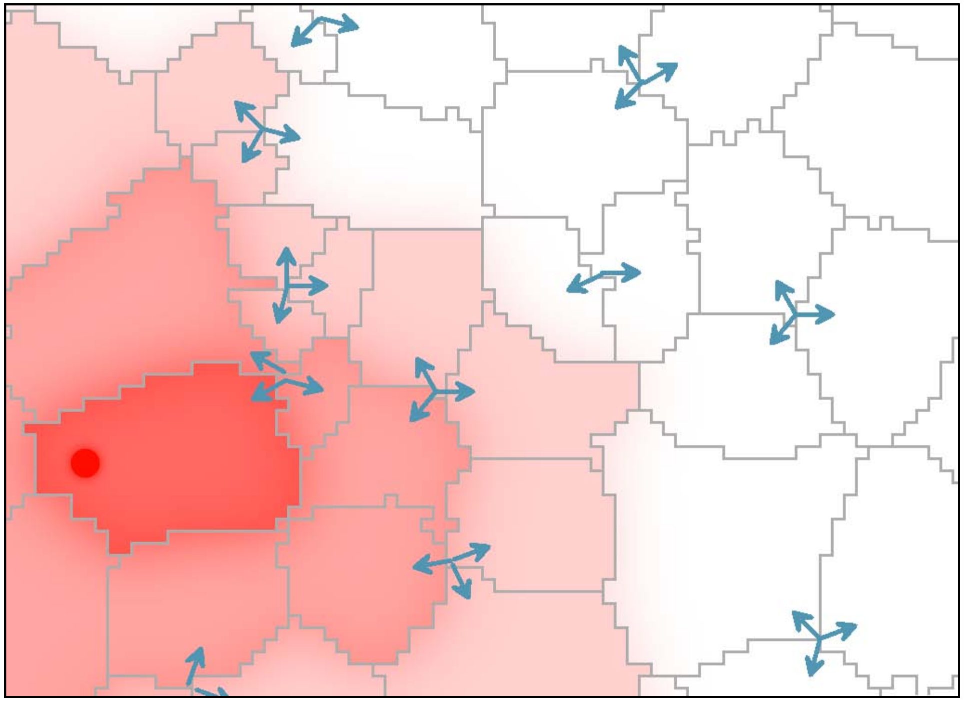
$$\Leftrightarrow \bar{\boldsymbol{p}} = (\boldsymbol{I} - \boldsymbol{C})^{-1}\boldsymbol{p}^{(\mathrm{c})} = \sum_{k=0}^{\infty} \boldsymbol{C}^k \boldsymbol{p}^{(\mathrm{c})}$$

$$\boldsymbol{I}\boldsymbol{p}^{(\mathrm{c})} + \boldsymbol{C}\boldsymbol{p}^{(\mathrm{c})} + \boldsymbol{C}^2\boldsymbol{p}^{(\mathrm{c})} + \boldsymbol{C}^3\boldsymbol{p}^{(\mathrm{c})} + \cdots$$

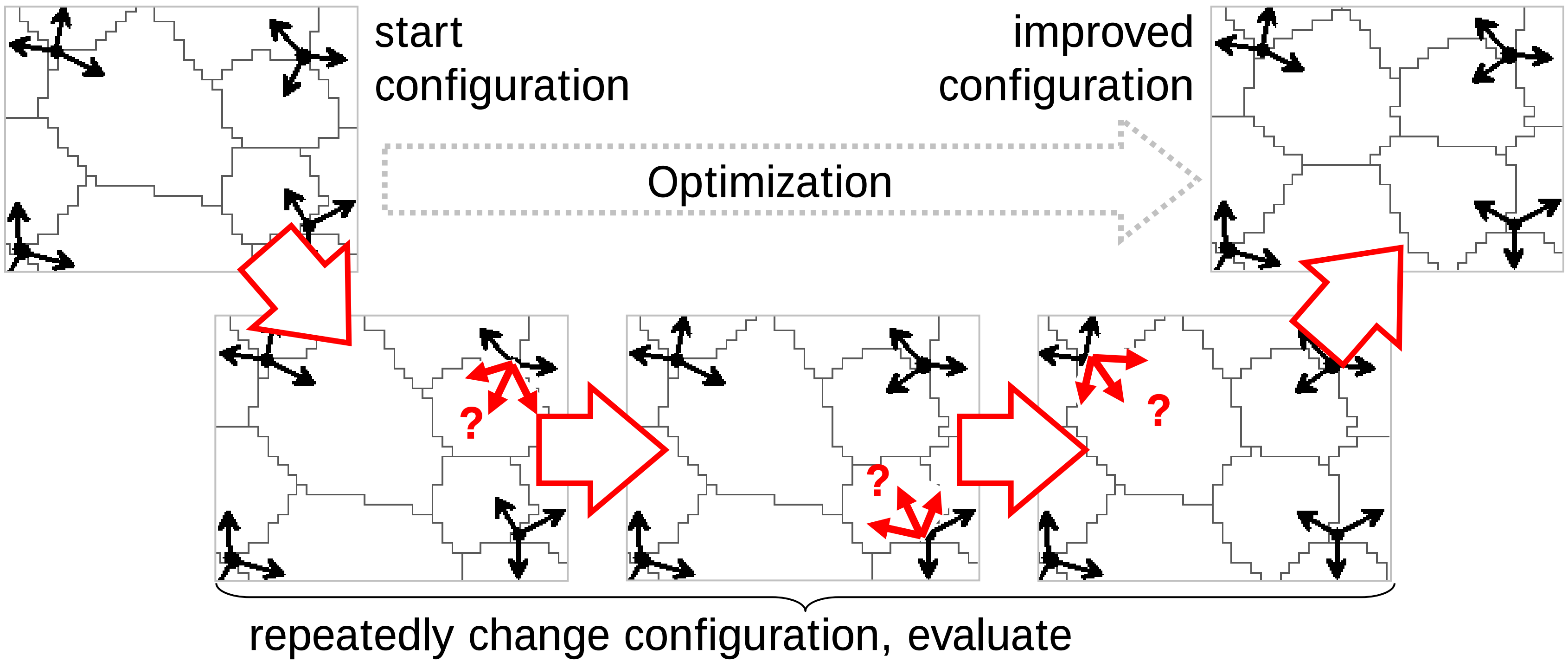
Problem

If too many users request service

- Series may not converge $(\rho(\boldsymbol{C}) \geq 1)$
- Cell power constraints may be violated



Local Search Scheme

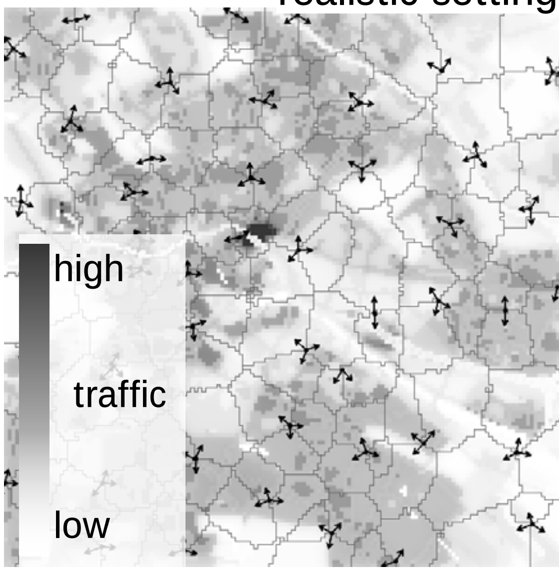


Refined Search Algorithms

- Tabu Search
- Genetic Algorithms
- Simulated Annealing
- ...

Mixed Integer Programming Formulation for Matrix Design

realistic setting

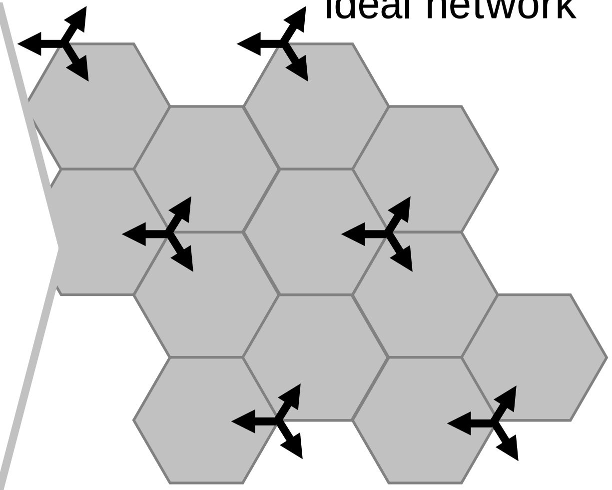


Optimization Model

$$
\begin{aligned}
\min \quad & \textstyle\sum_i p_i^{(c)}/(1-(1+\tilde{\imath})c(\boldsymbol{z})_{ii}) \\
& + \mathbf{1}^t(\boldsymbol{I}-\boldsymbol{C}_0)^{-1}\boldsymbol{C}(\boldsymbol{z}) \\
\text{s.t.} \quad & \operatorname{trace}(\boldsymbol{C}(\boldsymbol{z})) \geq \kappa \\
& \boldsymbol{C}(\boldsymbol{z}) \text{ coupling matrix} \\
& \boldsymbol{z} \in \mathcal{F}
\end{aligned}
$$

Convex approximation of objective function

ideal network



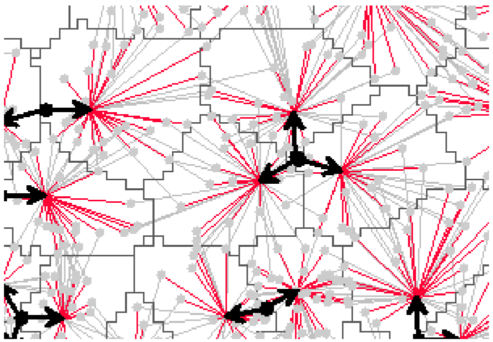
Matrix Design MIP Heuristic

$$
\begin{aligned}
\min \quad & (I + C(z)) \cdot p^{(c)} + \textstyle\sum_i p_i^{(c)}/(1-(1+\tilde{\imath})c(z)_{ii}) & \\
s.t. \quad & |A(z)| \geq |A(z_0)| & \\
& C_{ii}(z) = \sum_D \left(\int_{p \in A_i(D)} l_p \, dp \right) c_i^{(D)} & \forall\ i \\
& C_{ji}(z) = \sum_D \left(\int_{p \in A_i(D)} \frac{\gamma_{ip}}{\gamma_{jp}} l_p \, dp \right) c_i^{(D)} & \forall\ i, j \\
& |A(z)| = \sum_i \sum_D |A_i(D)| \cdot c_i^{(D)} & \\
& c_i^{(D)} = 1 \Leftrightarrow z_i = 1 \wedge z_j = 0 & \\
& c_{ij}^{(D)} = c_i^{(D)} \cdot z_j & \\
& c_i^{(D)} \in \{0,1\} & \forall\ i,\ D \\
& c_{ij}^{(D)} \in \{0,1\} & \forall\ i,\ j,\ D \\
& z_i \in \{0,1\} & \forall\ i
\end{aligned}
$$

- Design coupling matrix
- MIP model for calculating expected coupling matrix and approximated objective function
- Use in *k*-opt heuristic (k=4,5,6)
- Accept/reject MIP incumbents according to accurate nonlinear evaluation

Calculating DL Cell Powers: Interference-Coupling Equation System

Signal Quality Equations (per user)



- user parameters: orthogonality, activity, path loss, CIR target
- link powers

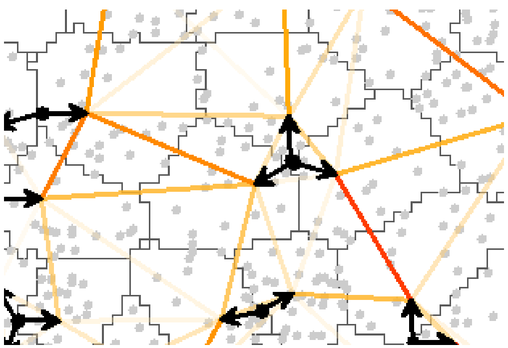
→ cell powers

(ignore noise)

$$\frac{\gamma_{im} p_{im}}{\gamma_{im}\omega_m(\bar{p}_i - \alpha_m p_{im}) + \sum_{j \neq i} \gamma_{jm} \bar{p}_j + \eta_m} = \mu_m$$

$$\bar{p}_i = \sum_{m \in M_i} \alpha_m p_{im} + p_i^{(c)}$$

Cell Coupling Equation System (per cell)



$$\bar{p}_i = \underbrace{\sum_{m \in M_i} \overbrace{\frac{\alpha_m \mu_m}{1 + \omega_m \alpha_m \mu_m}}^{=:\ell_m} \omega_m}_{=:c_{ii}} \bar{p}_i + \underbrace{\sum_{m \in M_i} \sum_{j \neq i} \overbrace{\frac{\alpha_m \mu_m}{1 + \omega_m \alpha_m \mu_m}}^{=:\ell_m} \frac{\gamma_{jm}}{\gamma_{im}}}_{=:c_{ij}} \bar{p}_j + p_i^{(C)}$$

→ aggregate user parameters, calculate cell powers directly

$$\bar{p} = C\,\bar{p} + p^{(c)}$$

- Describes power balance between cells
- Takes into account all relevant information on users

The Revised Pole Equation: Overcoming Restrictive Assumptions

Classical Definitions

$$f_m := \frac{\sum_{j \neq i} \gamma_{jm} \bar{p}_j}{\gamma_{im} \bar{p}_i}$$

$$\bar{f} := \frac{\sum_m f_m}{N}$$

- Other-to-own-cell interference ratio, straightforward average

Classical Pole Equation

$$\bar{p} = \frac{p^{(c)}}{1 - N\ell(\bar{\omega} + \bar{f})}$$

Revised Definitions

$$\iota_m := \frac{\sum_{j \neq i} \gamma_{jm} \bar{p}_j}{\omega_m \gamma_{im} \bar{p}_i}$$

- Include orthogonality loss factor

$$\bar{\iota}_i := \frac{\sum_m \omega_m \ell_m \iota_m}{\sum_m \omega_m \ell_m} = \frac{\sum_{j \neq i} c_{ij} \bar{p}_j}{c_{ii} \bar{p}_i}$$

- Weighted average according to user specific parameters

Revised Pole Equation

$$\bar{p}_i = \frac{p_i^{(c)}}{1 - (1 + \bar{\iota}_i) c_{ii}}$$

- Same simple structure
- Precise parameters per cell

Understanding the Behavior of a Single Cell with the Pole Equation

Pole equation describes dependency between load and cell power and the impact of orthogonality and interference for a single cell