07M2 Lecture

Capacity and Coverage Planning for the UMTS Radio Interface

Hans-Florian Geerdes

Block Course at TU Berlin

"Combinatorial optimization at work“

October 4 – 15, 2005

Martin Grötschel

- Institut für Mathematik, Technische Universität Berlin (TUB)
- DFG-Forschungszentrum “Mathematik für Schlüsseltechnologien” (MATHEON)
- Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)

groetschel@zib.de http://www.zib.de/groetschel

Overview

- Introduction
- Coverage Planning
  - Set Covering + Variants
- Capacity Planning
  - "Soft Capacity" in UMTS
  - Link-Power Based Models
  - Coupling Based Models

Hans-F. Geerdes

What Is UMTS?

UMTS

Universal Mobile Telecommunications System

- A new **technology**
- Cellular radio interface for wireless communication
- A major PR catastrophe
- Hot

Hans-F. Geerdes

Generations of Mobile Telecommunications Systems

1G	2G	3G	4G
1980s	1990s	2000s	2010 ??

- Analogue
- Voice Only

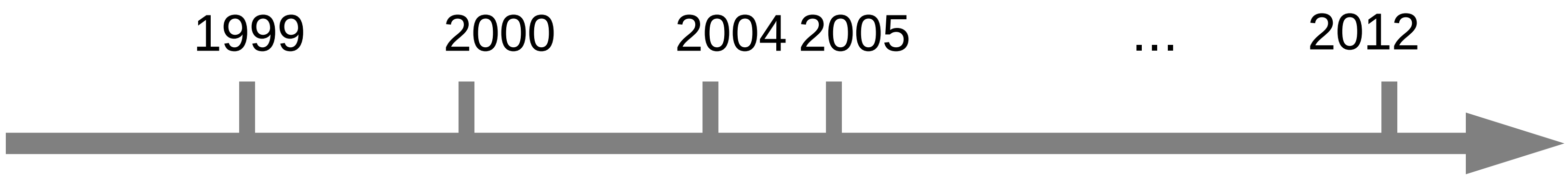
- Digital
- Voice & Data
- **GSM** mass market
- PCS
- cdmaOne/IS95

- **UMTS**, WiFi/WLAN, cdma2000
- Data Rates ≥ 384 kbit/s
- Various Services

- more **services**
- more bandwidth
- fresh spectrum
- new technology
- **W-CDMA** radio transmissions

Hans-F. Geerdes

History and Future



Standardization

- Frequency band auctions (€ 50 billion in Germany)

Deployment

- 01.01.2004:
  25% of population

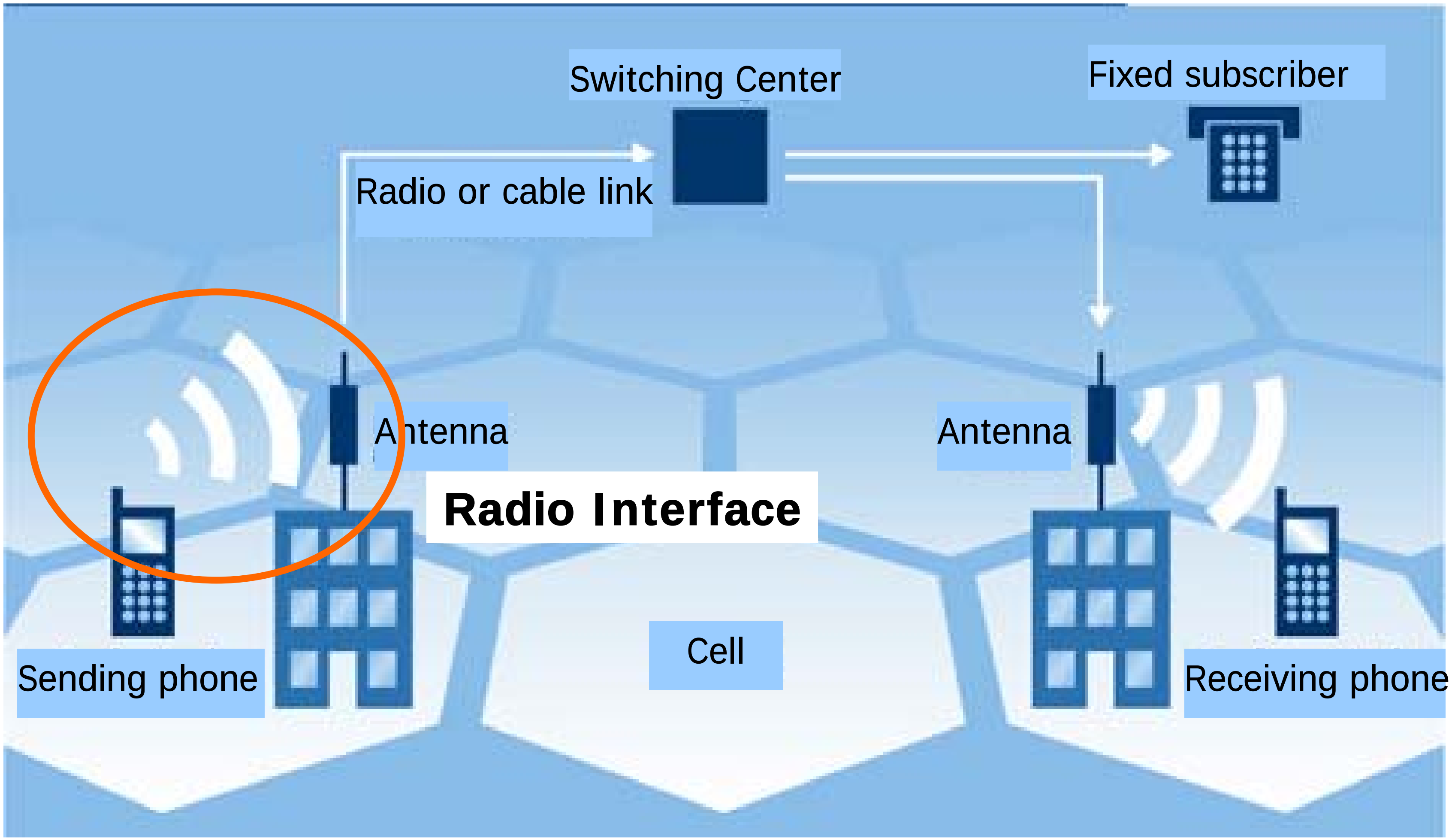
Extension

Commercial Exploitation

→ UMTS is here already and will be around

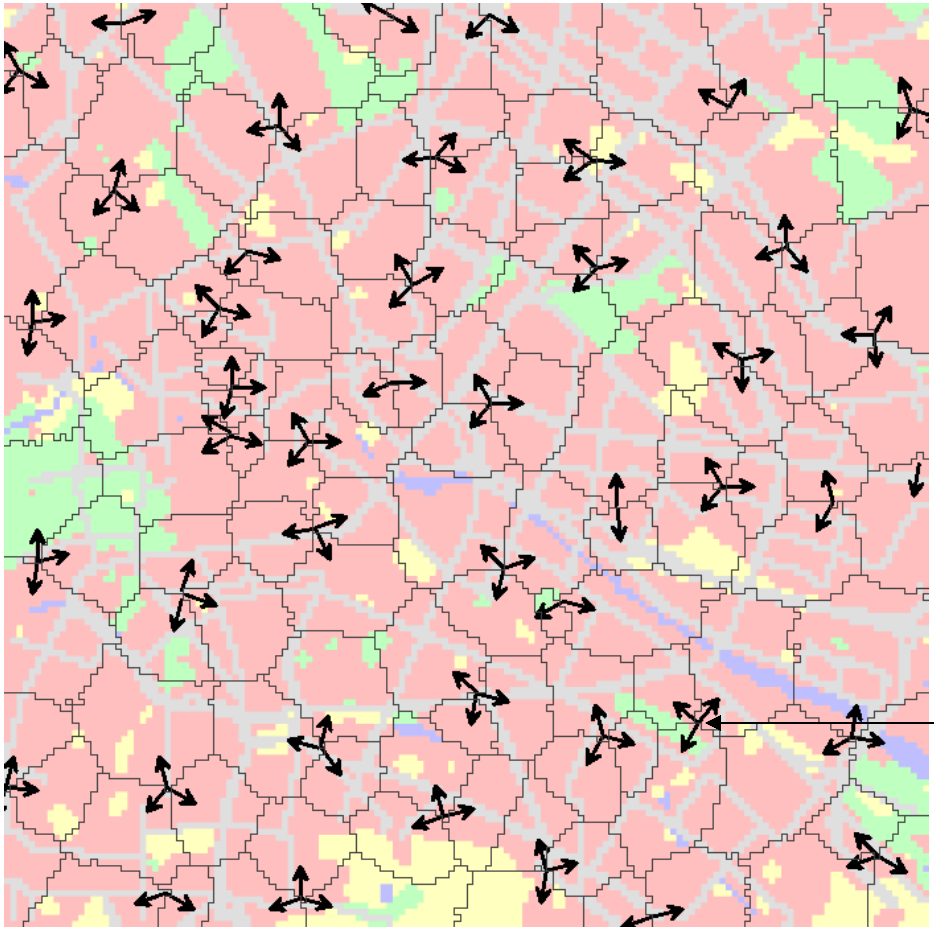
Hans-F. Geerdes

Cellular Wireless Networks



Hans-F. Geerdes

Radio Network



- Set of antennas
- Configuration specified for each antenna

Typically
three antennas
per mast
(„three-sectorized“)

Hans-F. Geerdes

Radio Network Planning

Goal To create a radio network that provides the users with seamless wireless services.

Subproblems

- Coverage Planning
- Capacity Planning

Degrees of Freedom

- Base Station Placement
- Antenna Configuration
  - Height
  - Direction (Azimuth, Tilt)
  - Antenna Pattern
- Radio Resource Management

Hans-F. Geerdes

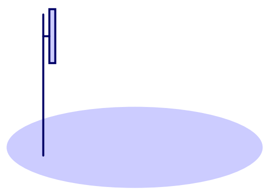
Evaluation of UMTS Radio Networks

$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} \geq \text{Threshold}$$

→ CIR constraints for each user in three cases:

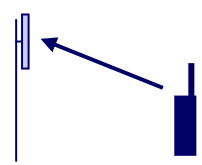
Pilot

- Association to network and individual cells
- Coverage and quality of pilot signal



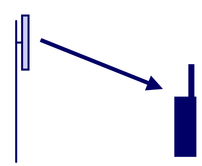
Uplink (UL)

- Mobile to base
- Load is measured as total received power at base station



Downlink (DL)

- Base to mobile
- Load is measured as total emitted power at base station



Hans-F. Geerdes

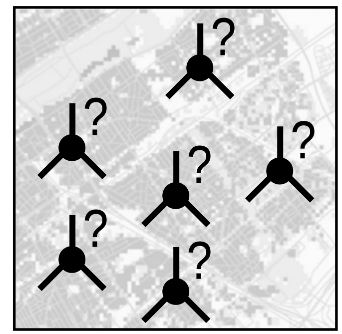
Network Design Problems

Green Field Planning

- No premises
- Design network "from scratch"
- Not relevant in practice

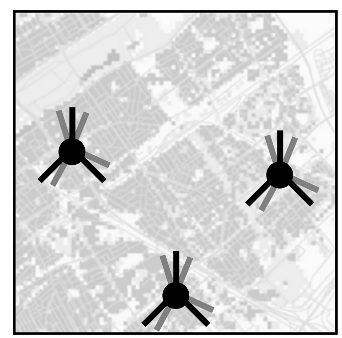
Site Selection

- Set of existing sites from "legacy" network
- Choose subset for UMTS network



Network Tuning

- Improve quality of existing network
- Technical constraints on allowed changes



Hans-F. Geerdes

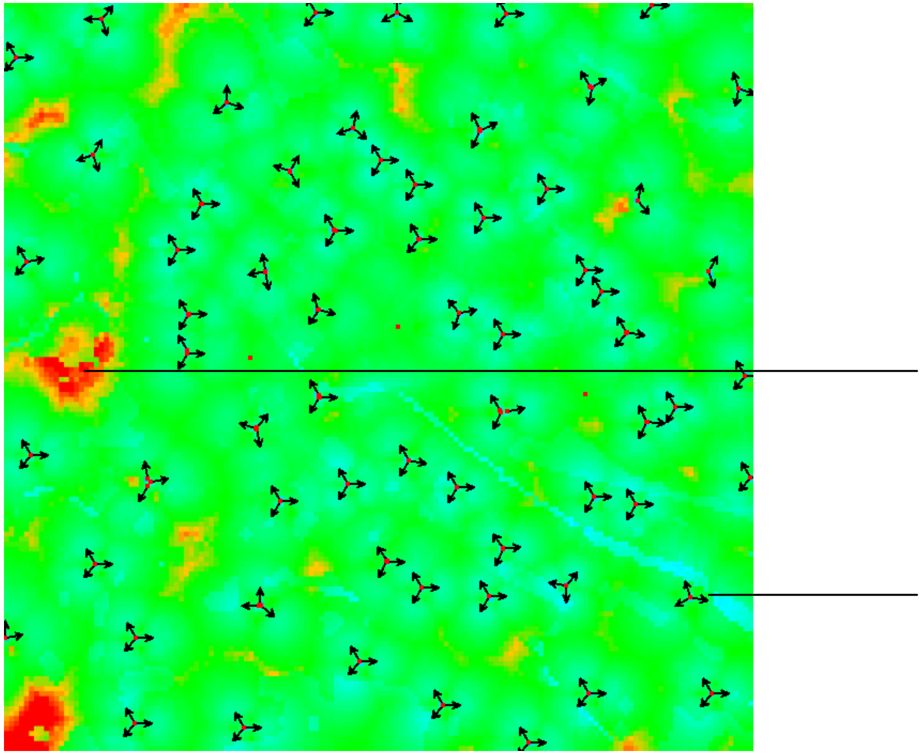
Overview

- Introduction
- Coverage Planning
  - Set Covering + Variants
- Capacity Planning
  - “Soft Capacity” in UMTS
  - Link-Power Based Models
  - Coupling Based Models

Hans-F. Geerdes

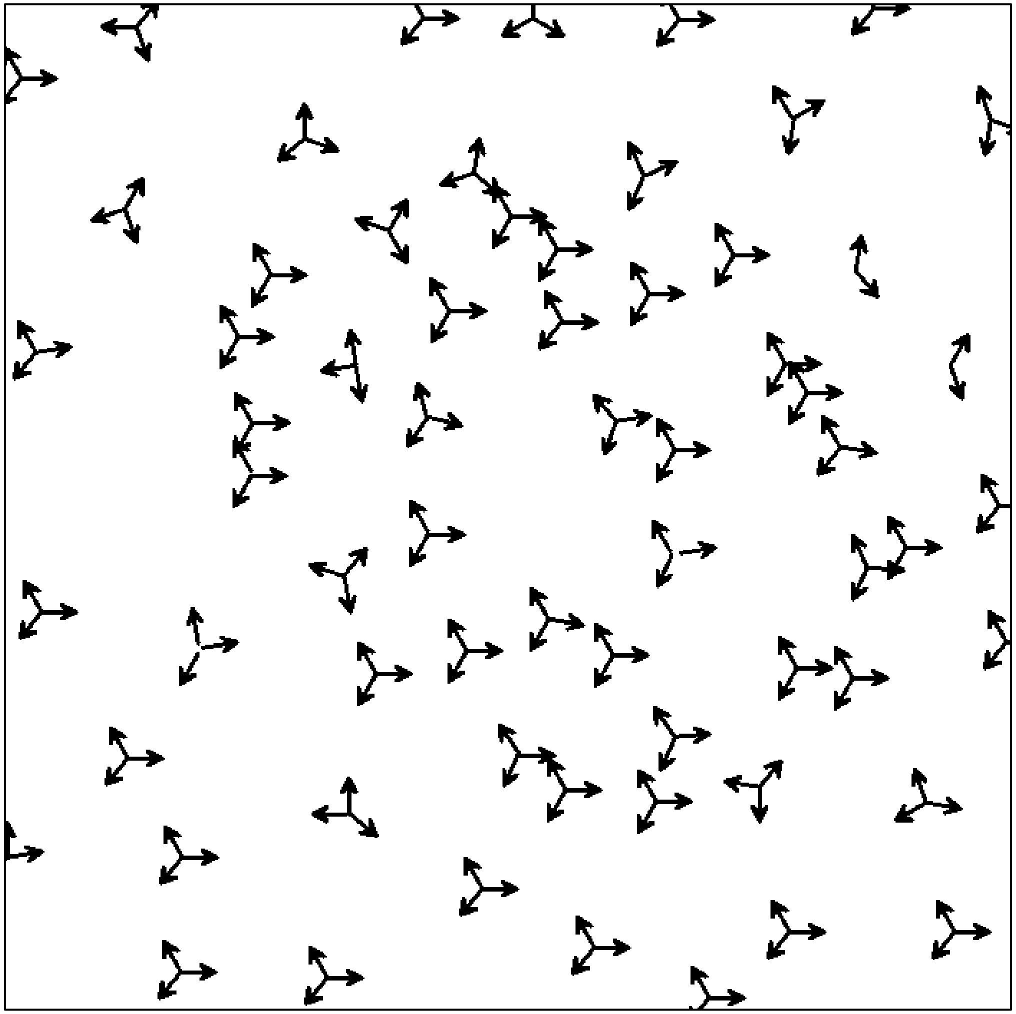
Coverage Planning

Goal	Provide sufficient signal strength in the whole planning area.



Hans-F. Geerdes

A Coverage Planning Problem



Input

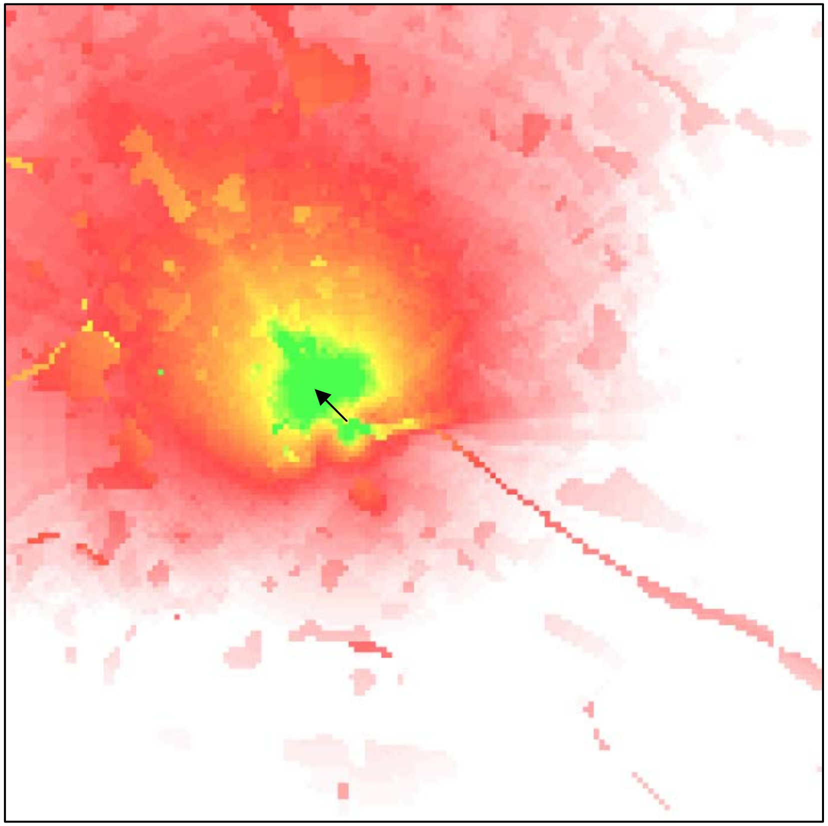
A set *I* of potential antenna installations and their propagation properties

Problem

Find a subset of *I* that "covers" the area

Hans-F. Geerdes

Radio Signal Propagation



Pixel-grid dataset for each potential antenna

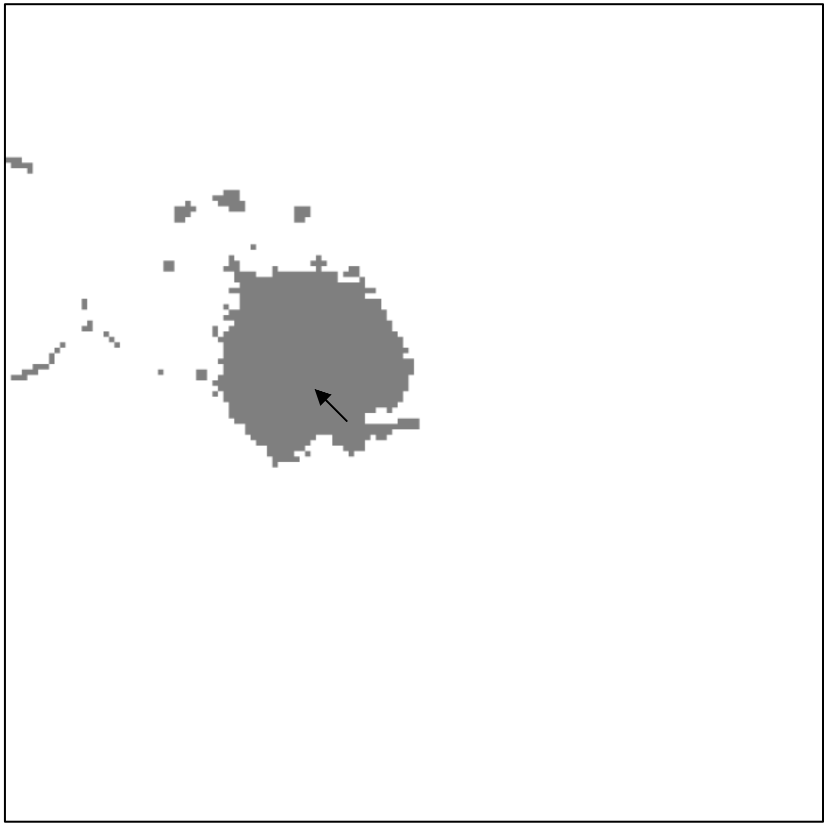
Signal attenuation

Hans-F. Geerdes

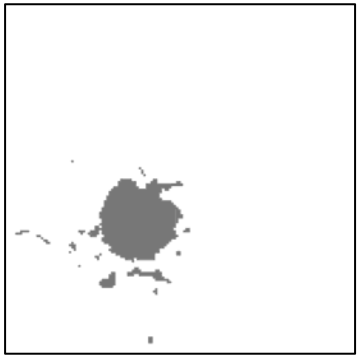
Covered Pixels

Define set of pixels covered by antenna *i:*

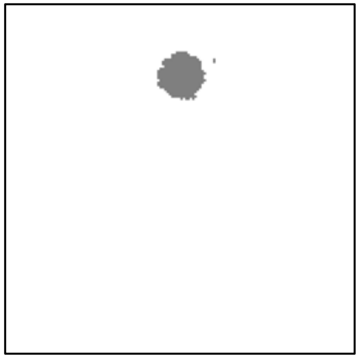
$$C_i := \{p \in A \ : \gamma_{ip} \geq \gamma^{\min}\}$$



C_1



C_2



$C_3 \ldots$

Hans-F. Geerdes

Set Covering Model

$$\min \sum_{i \in \mathcal{I}} z_i$$

$$\text{s.t.} \sum_{C_i \ni p} z_i \geq 1 \qquad \forall\, p \in A$$

$$z_i \in \{0, 1\} \qquad \forall\, i \in \mathcal{I}$$

- Simple model
- Well tractable
- But: too restrictive
  No control of individual pixels

Hans-F. Geerdes

Set Covering Model: Variants & Extensions

Coverage Variables

$$y_p \qquad \forall\ p \in A$$

$$\text{s.t.} \quad \sum_{C_i \ni p} z_i \geq y_p \qquad \forall\ p \in A$$

- Possibility to leave some pixels uncovered
- Objective function with weighted pixels

Assignment Variables

$$y_{ip} \qquad \forall\ (p,i) \in A \times \mathcal{I}$$

$$\text{s.t.} \quad z_i \geq y_{ip}$$

- Decide which pixel is served by what antenna

→ Additional modeling of technical details,
e.g. overlap area

Hans-F. Geerdes

Overview

- Introduction
- Coverage Planning
  - Set Covering + Variants
- Capacity Planning
  - “Soft Capacity” in UMTS
  - Link-Power Based Models
  - Coupling Based Models

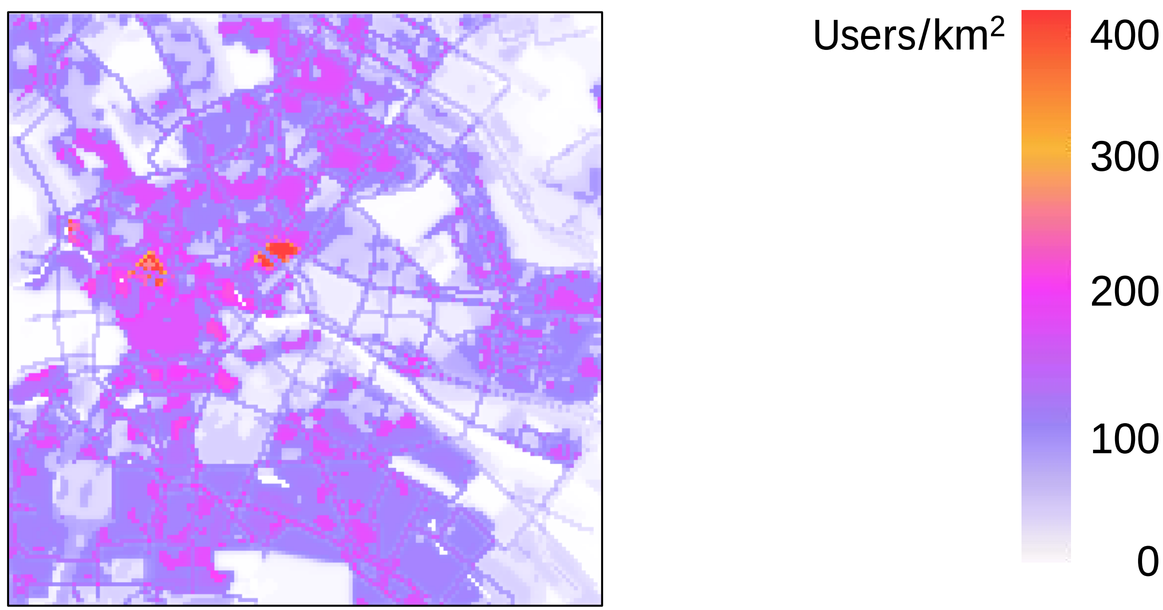
Hans-F. Geerdes

Capacity Planning

Goal Provide sufficient amount of radio resources for all users to be served.

- Input: user distribution
- Number of users and their positions is a random variable
- Target: small blocking rates (· 2%)

Average User Density

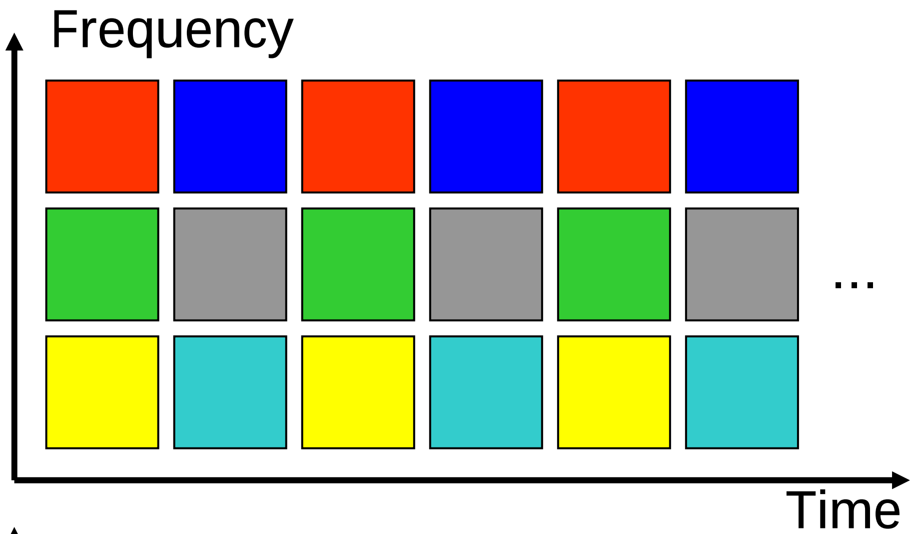


Hans-F. Geerdes

Radio Technology: WCDMA

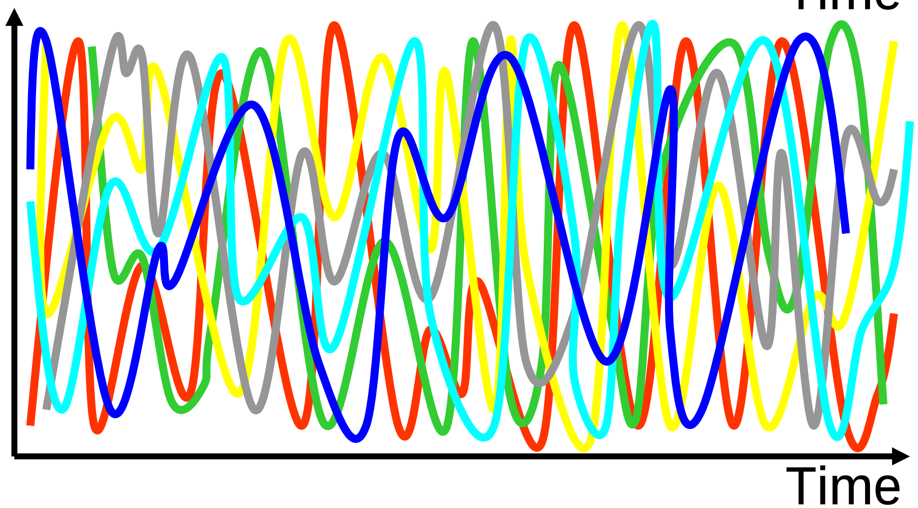
Old Technology (GSM)

- Time/Frequency Disvision Multiple Access (TDMA/FDMA)
- Divide frequency/time domain to separate users



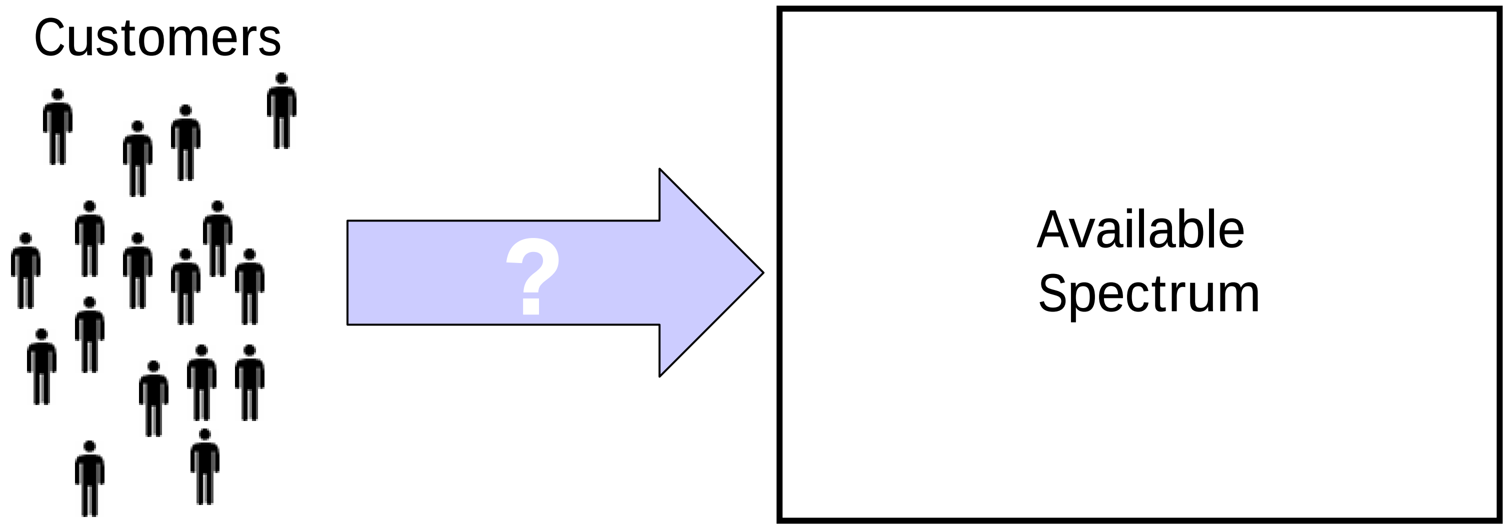
New Technology (UMTS)

- Everyone uses entire frequency band all the time
- Users separable due to different codes



Hans-F. Geerdes

Spectrum Efficiency



Hans-F. Geerdes

Spectrum Use in GSM

Subdivide into Frequency „Cubicles“

...Timetable for each cubicle

No 213:
9-10h: Smith/Miller
10-11h: Johnson/XYZ
...

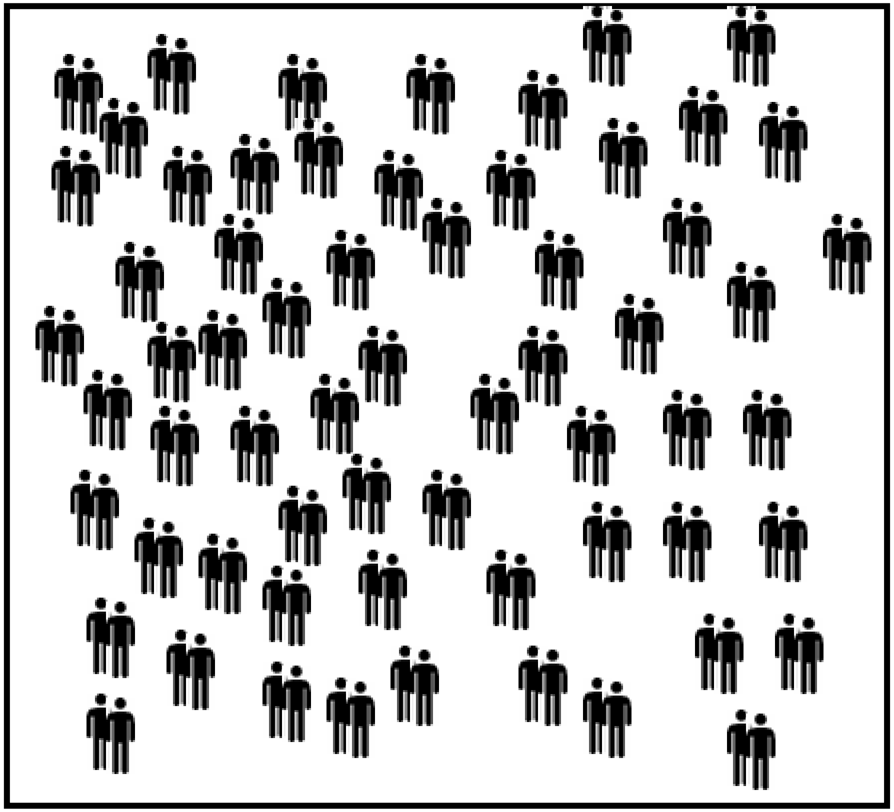
→ **FDMA**

→ **TDMA**

Radio Resource: Time/Frequency Slots

Hans-F. Geerdes

Spectrum Use in UMTS

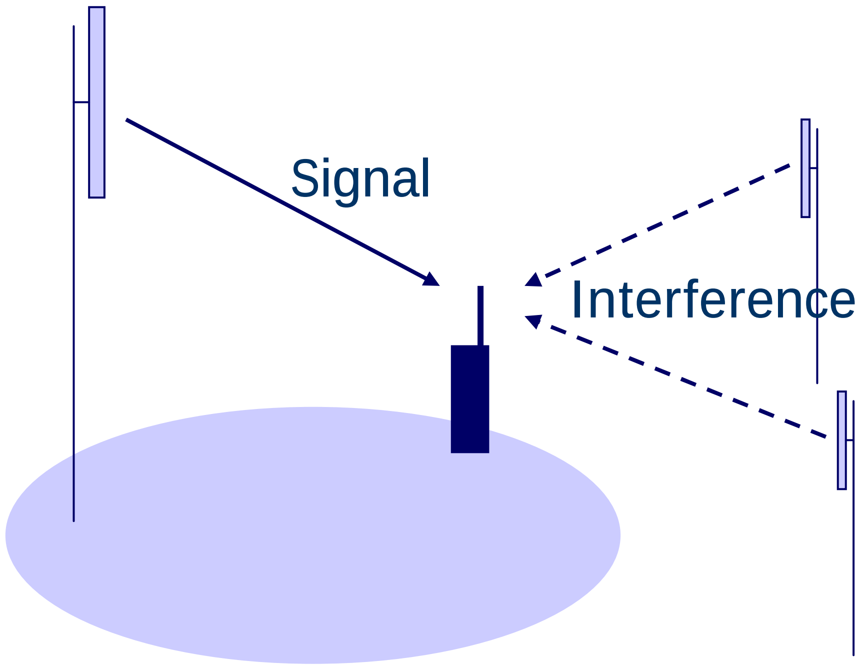


- All are in the same room
- Desired content is filtered by recipient (→ **CDMA**)
- Volume is adapted to corcumstances (→ **Power Control**)

Radio Resource???

Principle of Code Division

Controlling Interference in WCDMA



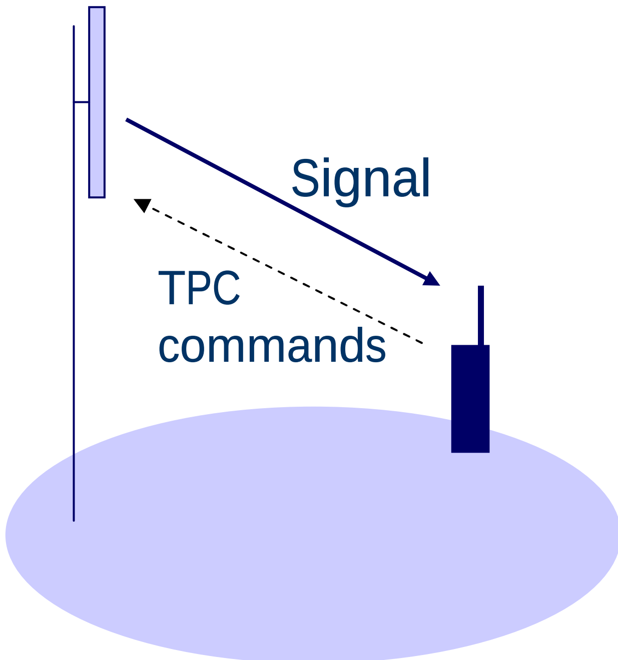
$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} \geq \text{Threshold}$$

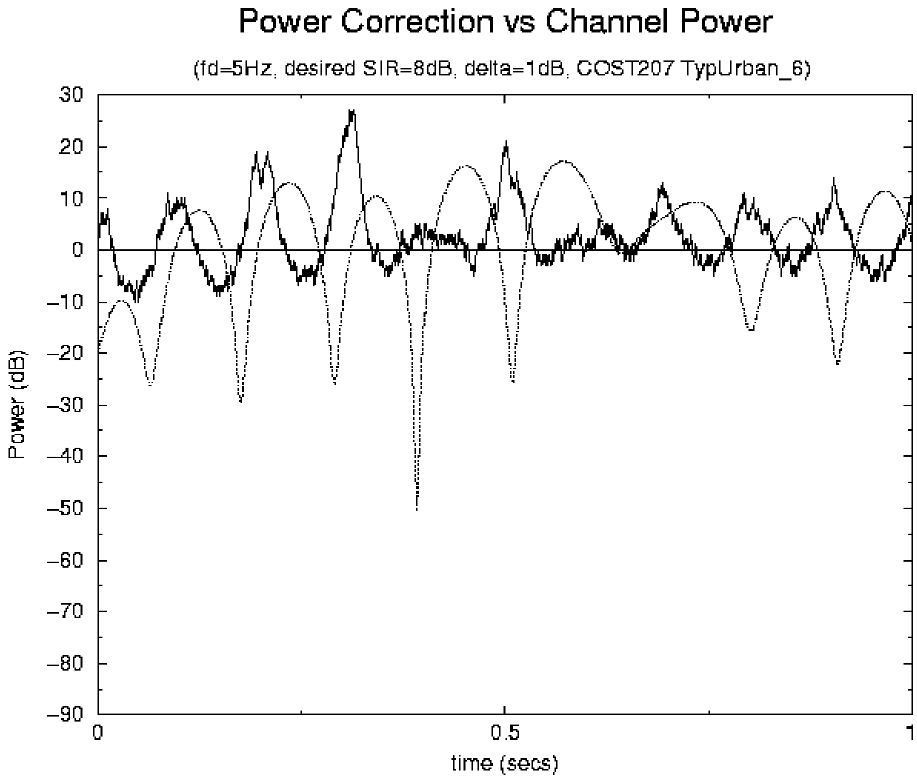
Carrier-to-Interference Ratio (CIR)

Carrier-to-Interference Ratio

Hans-F. Geerdes

Power Control in WCDMA



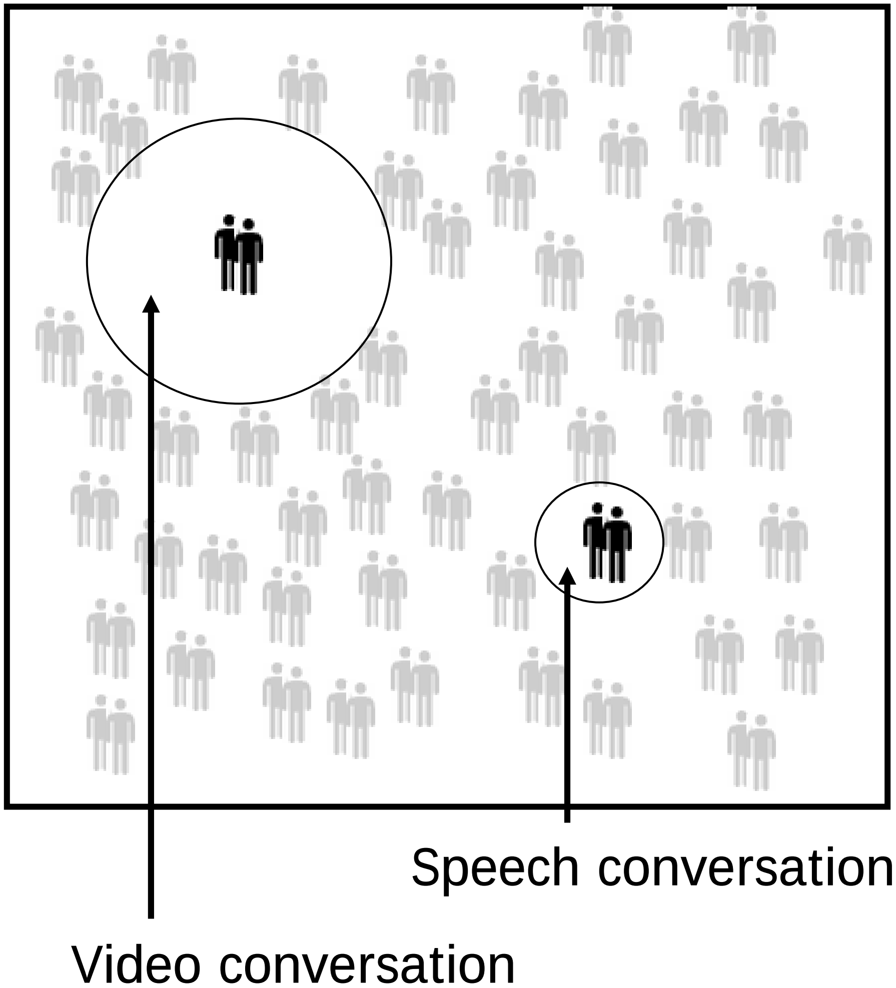


$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} = \text{Threshold}$$

Carrier-to-Interference Ratio

Hans-F. Geerdes

Flexibility in UMTS

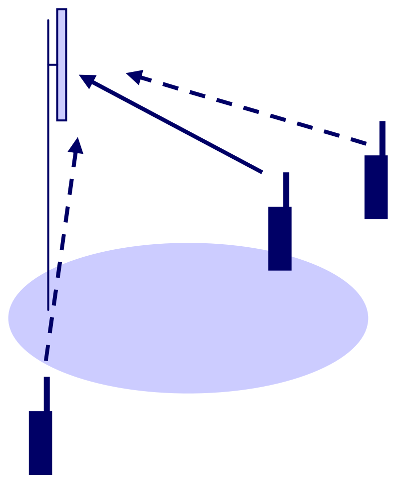


- Resource use can be freely divided between users
- Corresponds to different CIR thresholds

Hans-F. Geerdes

CIR Equality (UL)

$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} = \text{Threshold}$$



p_m	Transmit power
γ_{mi}	Attenuation
α_m	Activity Factor
η_i	Noise
μ_m	CIR Threshold

$$\frac{\gamma_{mi} p_m}{\eta_i + \sum_{n \neq m} \alpha_n \gamma_{ni} p_n} = \mu_m$$

Soft Capacity in UMTS (1)

Radio Resource:

Transmitted/received power at base station:

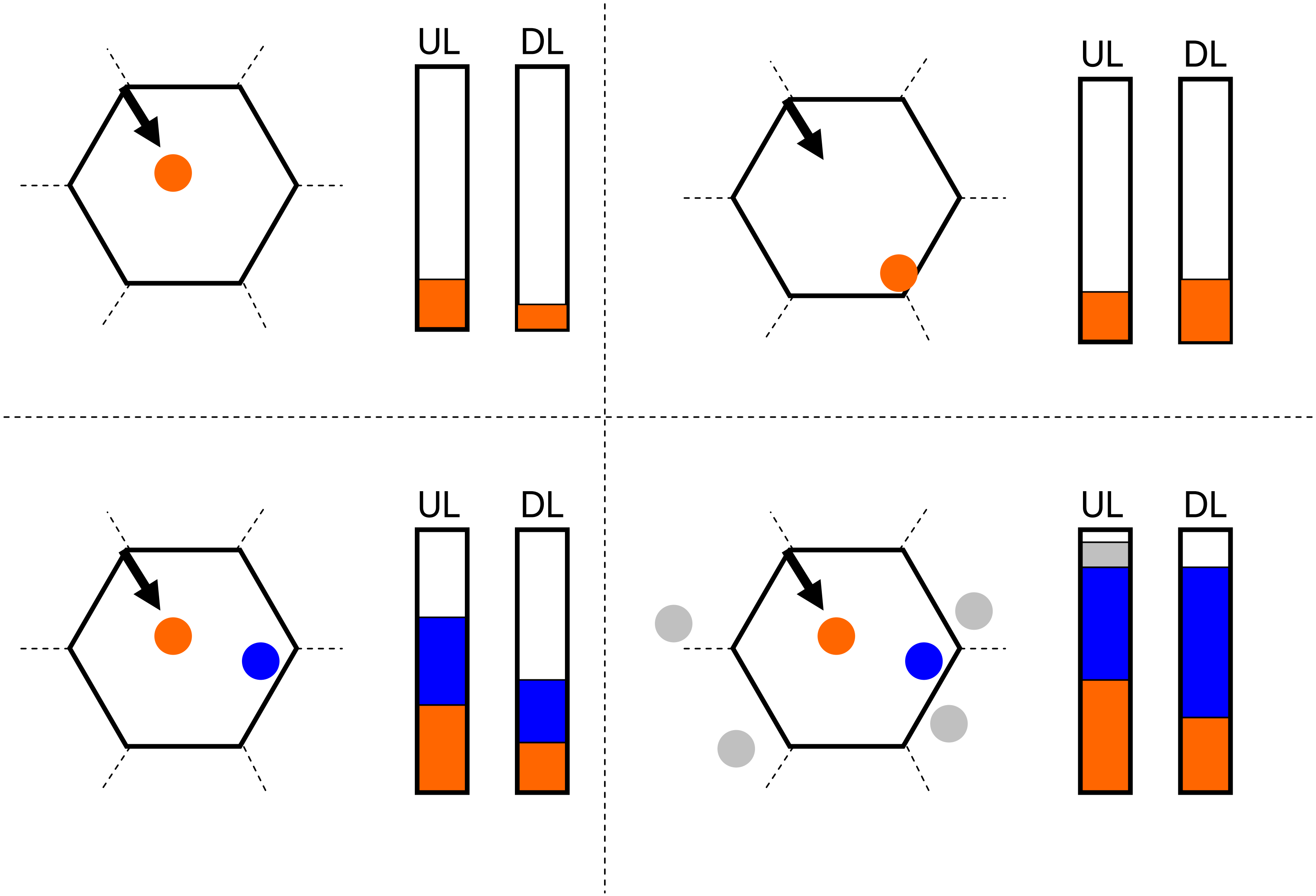
$$\sum_{m \in \text{cell } i} \gamma_{mi} p_m \leq \bar{p}^{\uparrow} \qquad \text{(UL)}$$

$$\sum_{m \in \text{cell } i} p_{im} \leq \bar{p}^{\downarrow} \qquad \text{(DL)}$$

→ Number of users per cell depends on interference (soft capacity)

Hans-F. Geerdes

Soft Capacity in UMTS (2)



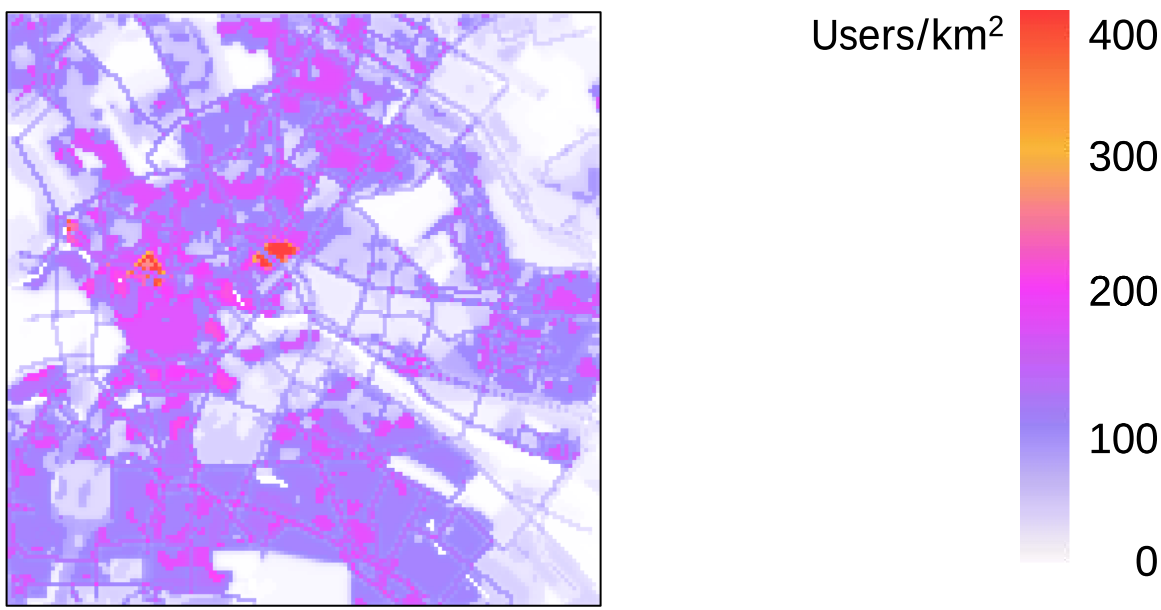
Hans-F. Geerdes

Capacity Planning

Goal	Provide sufficient amount of radio resources for all users to be served.

- Input: user distribution
- Number of users and their positions is a random variable
- Target: small blocking rates (· 2%)

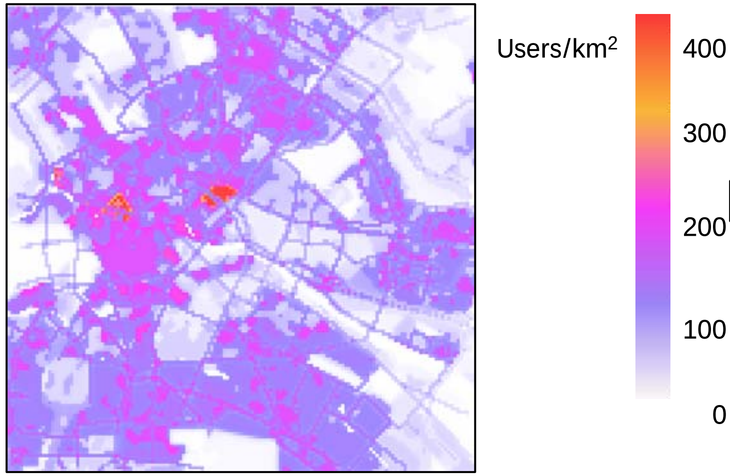
Average User Density



Hans-F. Geerdes

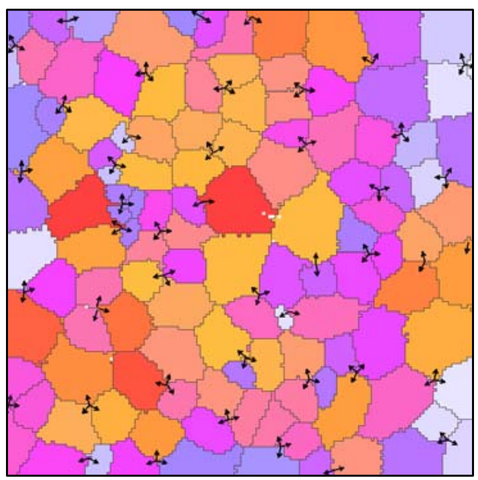
Capacity Planning in GSM

User Distribution



User Distribution (typically Poisson)

Distibution of Users per Cell



→Use 98% Quantile for dimensioning number of TRX (Erlang B formula)

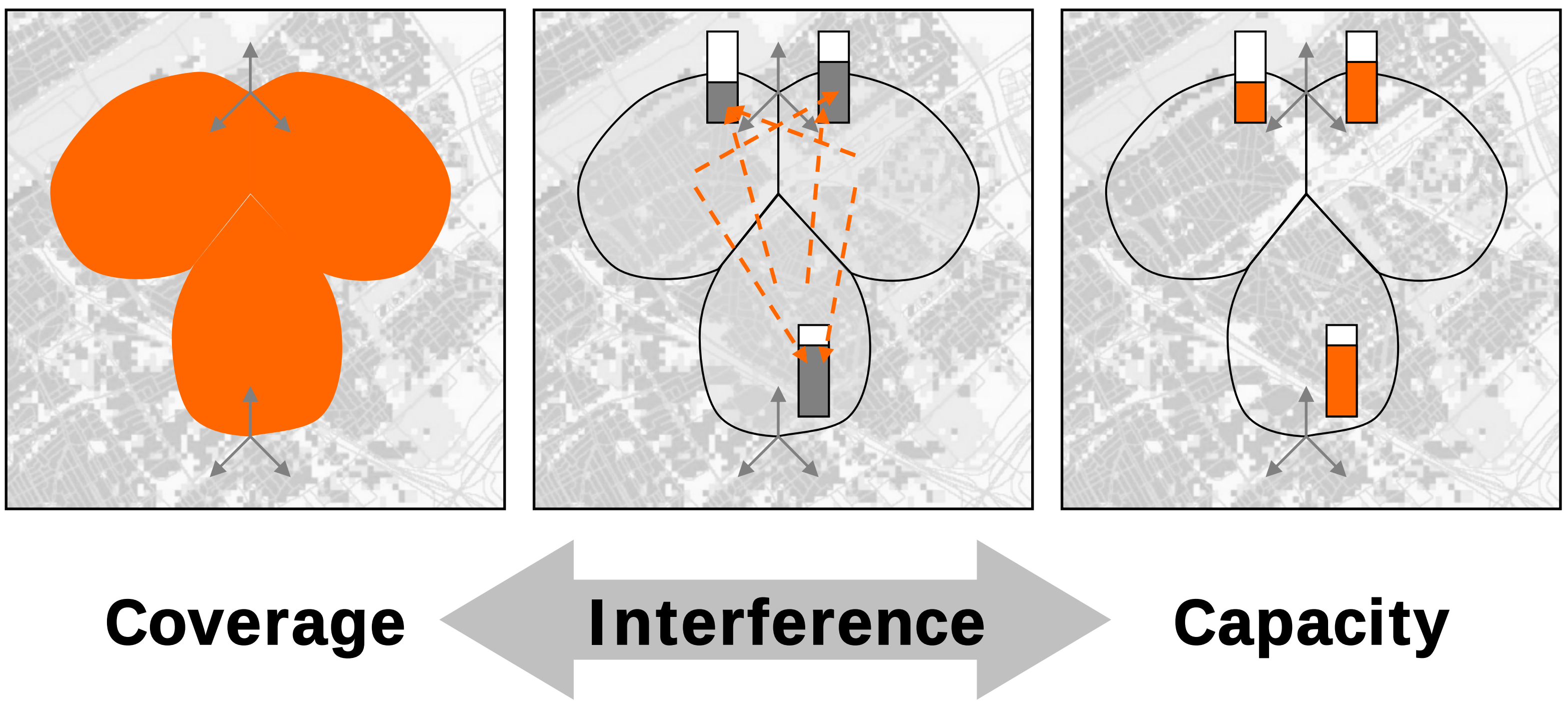
Prerequesite: Frequency Planning

Hans-F. Geerdes

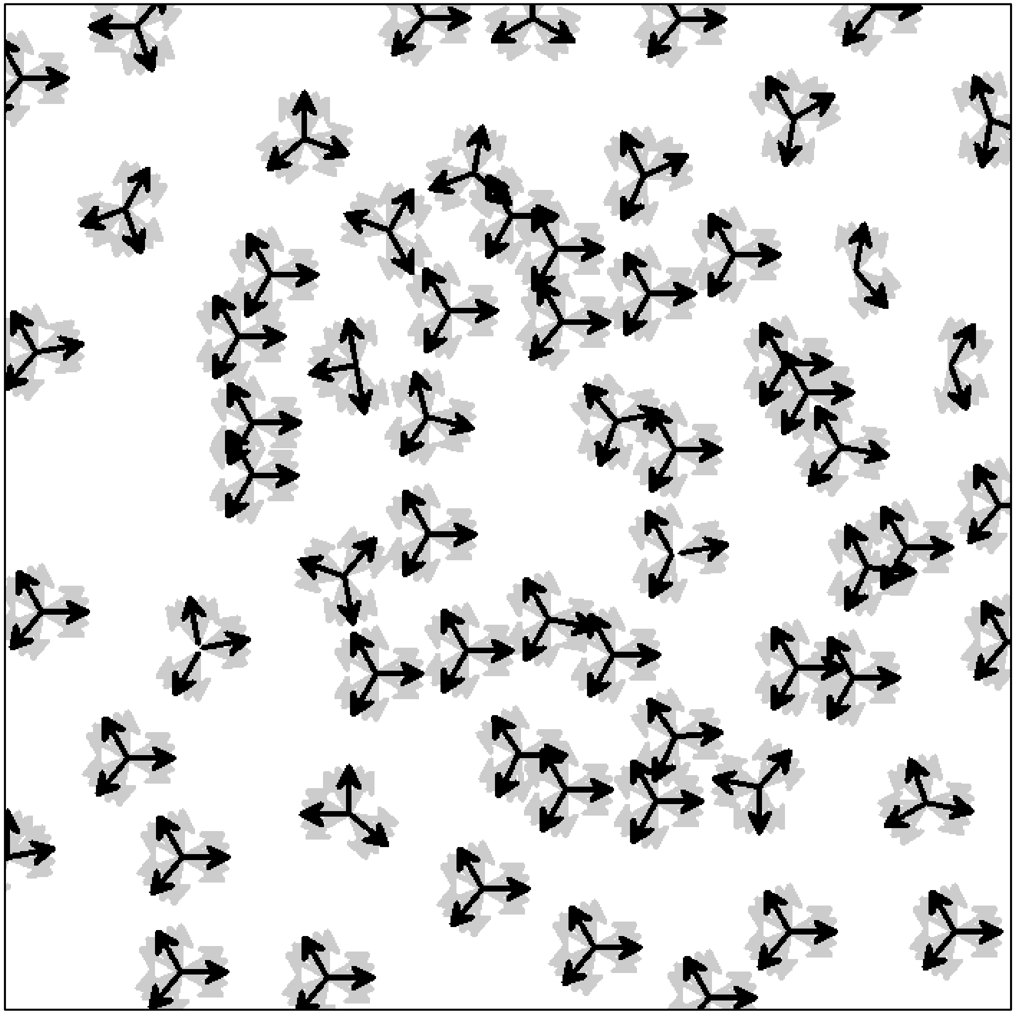
UMTS: Coverage & Capacity

Inherent to UMTS *CDMA* radio technology, coverage and capacity are coupled through **radio interference**

➔ Have to be considered *simultaneously*



A Capacity Planning Problem



Input

A set *I* of potential antenna configurations and their propagation properties

Problem

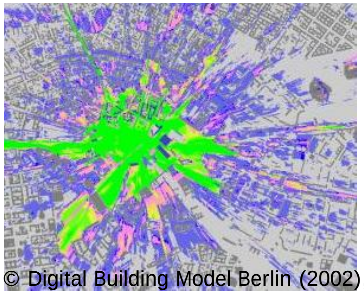
Find a subset of *I* that serves the users with minimum resource usage

Hans-F. Geerdes

Antenna Configuration

Isotropic Prediction

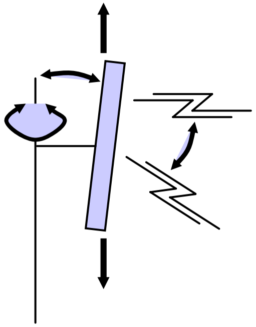
- Available for each potential antenna location



\+

Antenna Configuration

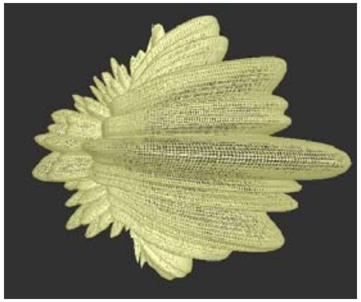
- Azimuth
- Tilt
- Height



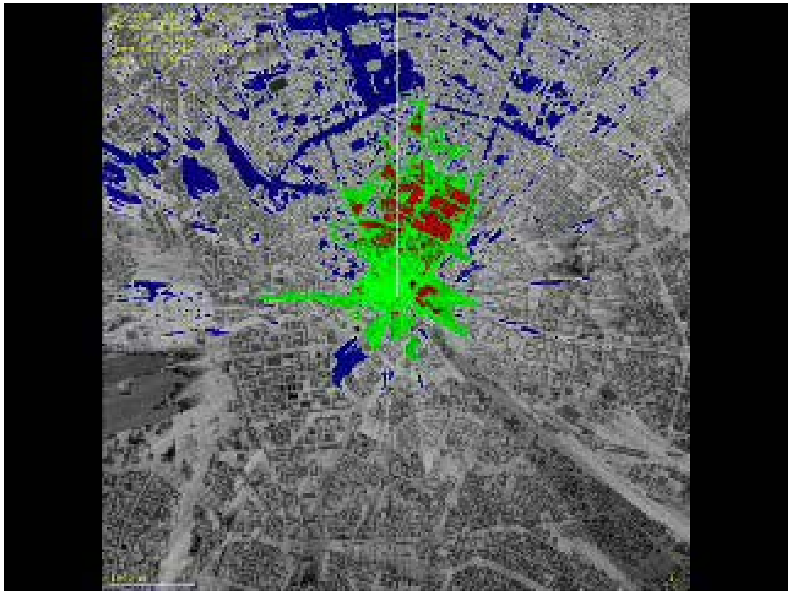
\+

Antenna Diagram

- Signal propagation in different directions



Antenna Prediction



height: 41m, electrical tilt: 0-8°, azimuth 0-120°

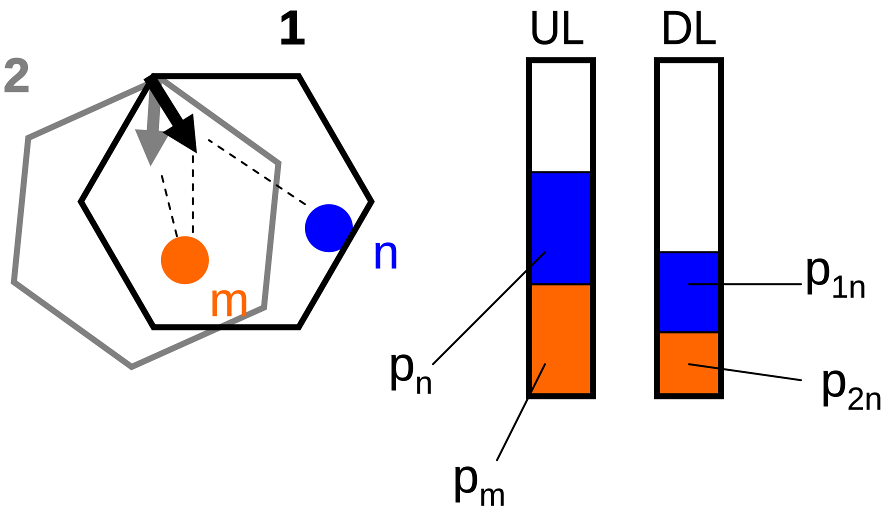
Hans-F. Geerdes

Overview

- Introduction
- Coverage Planning
  - Set Covering + Variants
- Capacity Planning
  - "Soft Capacity" in UMTS
  - Link-Power Based Models
  - Coupling Based Models

Hans-F. Geerdes

Modeling Capacity Planning



Principle

Have the optimization model calculate the effects of configuration changes on capacity

- Configuration selection variables $\mathbf{z_1}$, z_2
- Cell assignment variables x_{m2}, x_{m1}, x_{n1}
- Power variables p_m, p_n (UL), p_{1m}, p_{2m}, p_{1n}
- Include all potential CIR inequalities, but use only the ones for selected configuration

Hans-F. Geerdes

Link-Power Based MIP

$$\min \quad w \sum_m p_m + \sum_i c_i z_i$$

$$\text{s.t.} \quad \frac{\gamma_{mi} p_m}{\eta_i + \sum_{n \neq m} \alpha_n \gamma_{ni} p_n} \geq x_{mi} \mu_m$$

$$\sum_{i \in \mathcal{I}(c)} z_i \leq 1$$

$$x_{mi} \leq z_i$$

$$0 \leq p_m \leq P_{\max}$$

$$x, z \in \{0, 1\}$$

Hans-F. Geerdes

Link-Power Based MIP

$$\min \quad w \sum_m p_m + \sum_i c_i z_i$$

$$\text{s.t.} \quad \gamma_{mi} p_m + (1 - M) x_{mi} \geq \mu_m (\eta_i + \sum_{n \neq m} \alpha_n \gamma_{ni} p_n)$$

$$\sum_{i \in \mathcal{I}(c)} z_i \leq 1$$

$$x_{mi} \leq z_i$$

$$0 \leq p_m \leq P_{\mathsf{max}}$$

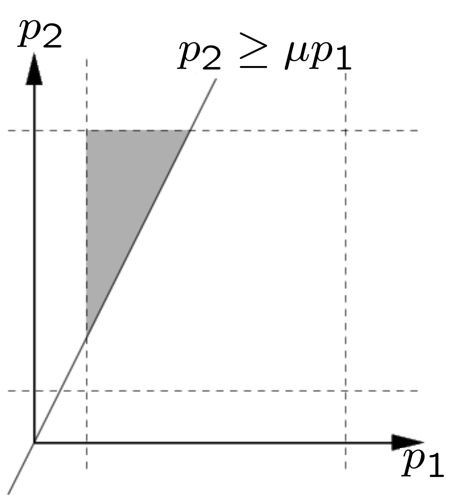
$$x, z \in \{0, 1\}$$

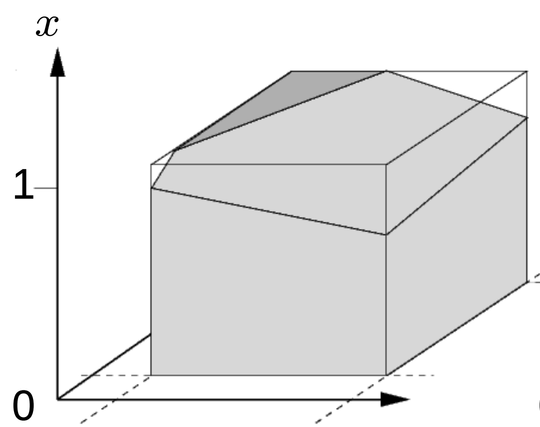
+

- DL CIR inequalities
- Coverage constraints
- ...

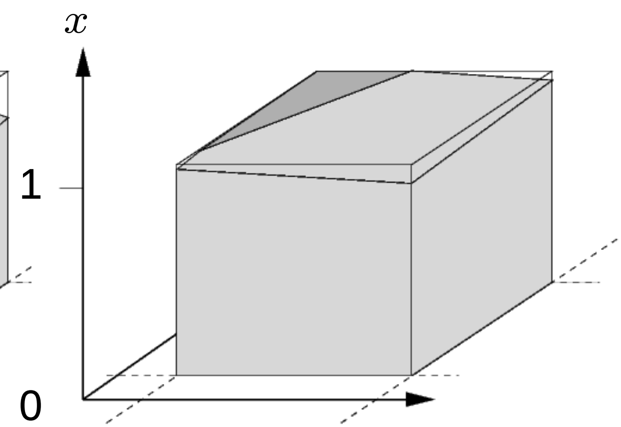
Hans-F. Geerdes

Big-M Linearization





Good bound



Bound too small

$$p_2 \geq x \cdot \mu p_1$$
$$P_{\text{min}} \leq p_1 \leq P_{\text{max}}$$
$$P_{\text{min}} \leq p_2 \leq P_{\text{max}}$$

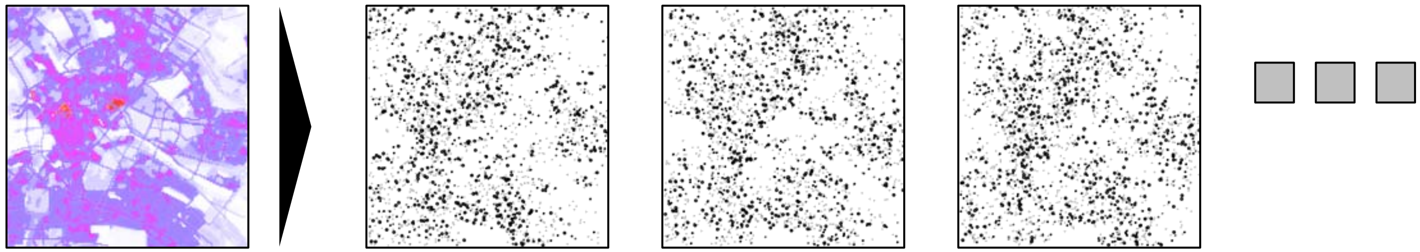
$$p_2 + M(1 - x) \geq \mu p_1$$
$$P_{\text{min}} \leq p_1 \leq P_{\text{max}}$$
$$P_{\text{min}} \leq p_2 \leq P_{\text{max}}$$

Hans-F. Geerdes

Link-Power Models

Problem Which users should be included for optimization to produce a reliable result?

1. Traffic Snapshots



2. „Average“ Snapshot
(each pixel is user with reduced activity)

However, model hardly tractable as MIP for instances of interesting size, because of

- Huge dimension
- Big-M linearization
- Dynamic Range of coefficients γ

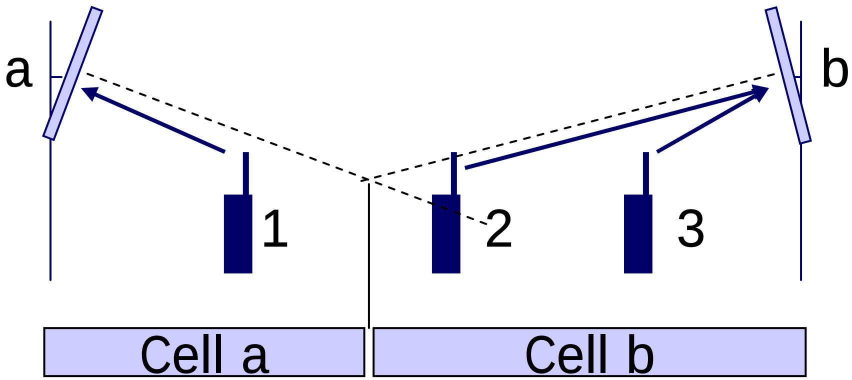
Hans-F. Geerdes

Overview

- Introduction
- Coverage Planning
  - Set Covering + Variants
- Capacity Planning
  - "Soft Capacity" in UMTS
  - Link-Power Based Models
  - Coupling Based Models

Hans-F. Geerdes

Load Evaluation: A Small Example



$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} \geq \text{Threshold}$$

Variables

- Transmit Powers p_1, p_2, p_3
- Received Powers p_a, p_b

Parameters

- Attenuation $\gamma_{1a}, \gamma_{1b}, \gamma_{2a}, \gamma_{2b}, \gamma_{3a}, \gamma_{3b}$
- Noise η_a, η_b
- Threshold μ_1, μ_2, μ_3

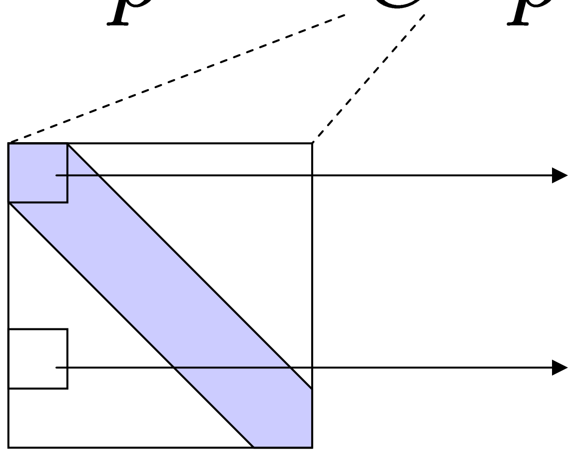
$$l_i = \frac{\mu_i}{1+\mu_i}, \qquad \begin{pmatrix} p_a \\ p_b \end{pmatrix} = \begin{pmatrix} l_1 & \frac{\gamma_{2a}}{\gamma_{2b}} l_2 + \frac{\gamma_{3a}}{\gamma_{3b}} l_3 \\ \frac{\gamma_{1b}}{\gamma_{1a}} l_1 & l_2 + l_3 \end{pmatrix} \begin{pmatrix} p_a \\ p_b \end{pmatrix} + \begin{pmatrix} \eta_a \\ \eta_b \end{pmatrix}$$

Coupling Matrix

Hans-F. Geerdes

Equation System (UL)

$$\bar{p}^{\uparrow} = C^{\uparrow}\,\bar{p}^{\uparrow} + \eta$$



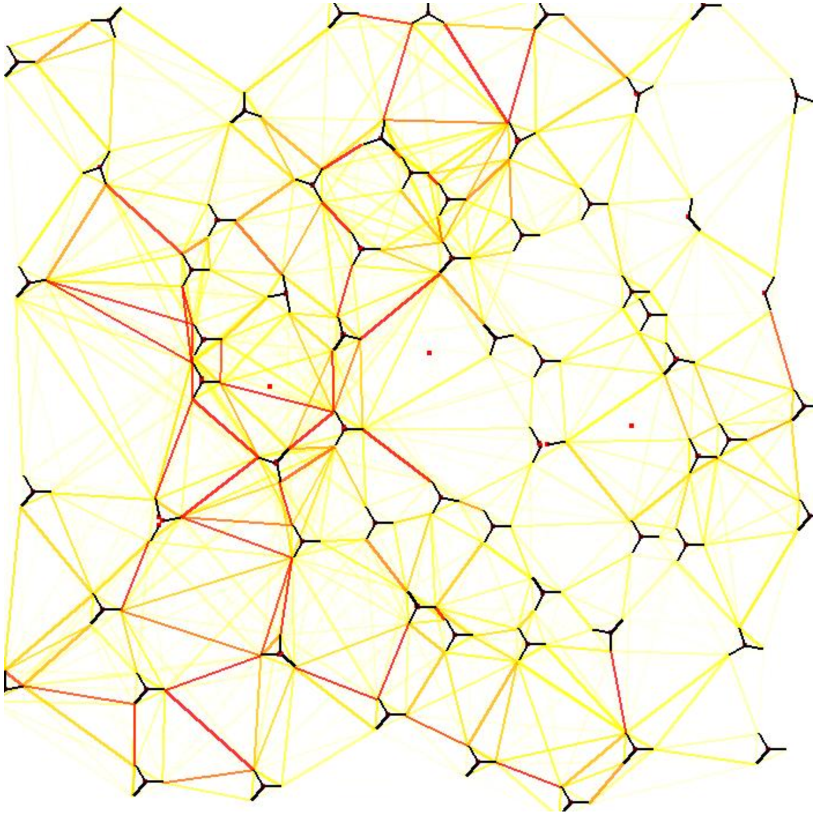
$$C^{\uparrow}_{ii} = \sum_{m \text{ in Cell } i} l_m$$

$$C^{\uparrow}_{ji} = \sum_{m \text{ in Cell } i} \frac{\gamma_{jm}}{\gamma_{im}}\, l_m$$

- Reduction from users £ users → cells £ cells
- Coupling matrices *C* are positive, (*I*-*C*) are M-matrices
- Perron-Frobenius Theory characterizes existence of positive solutions

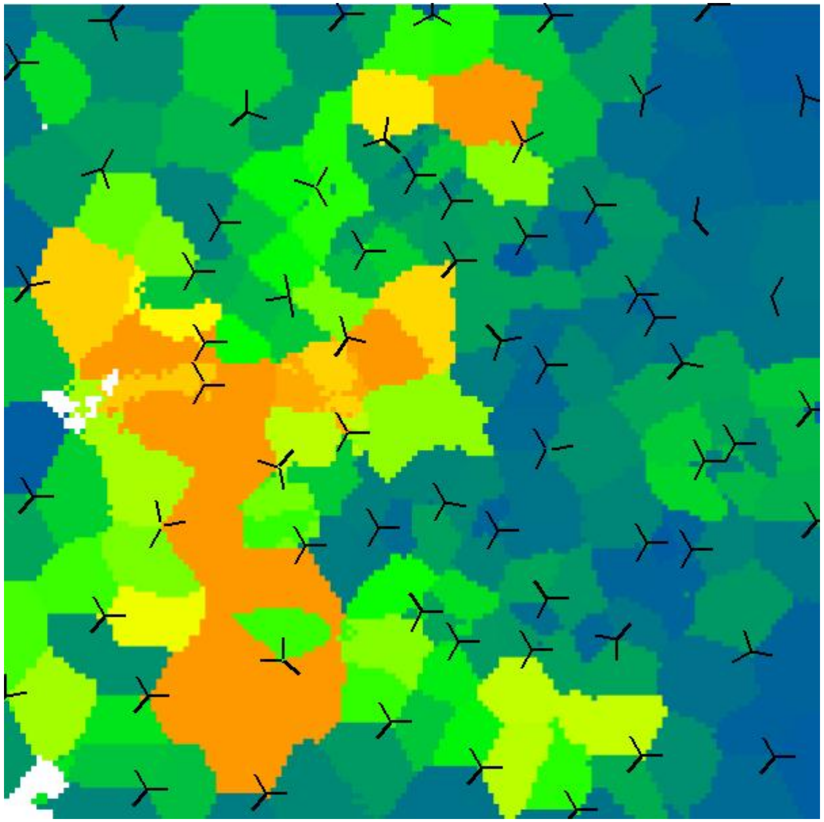
Hans-F. Geerdes

Matrix and Solution



$$C^{\uparrow}$$

Coupling diagram

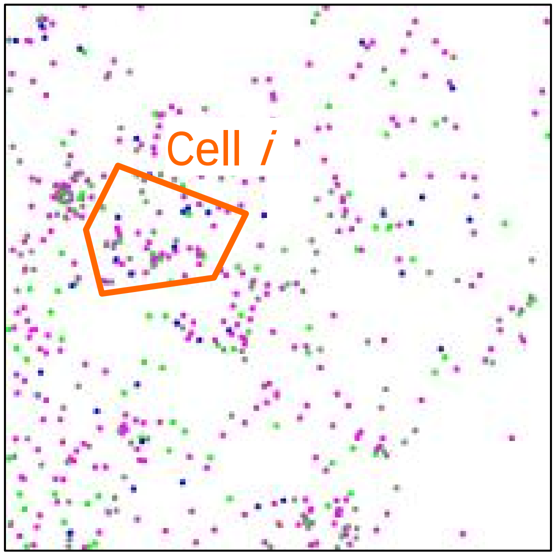


$$\bar{p}^{\uparrow} = C^{\uparrow}\,\bar{p}^{\uparrow} + \eta$$

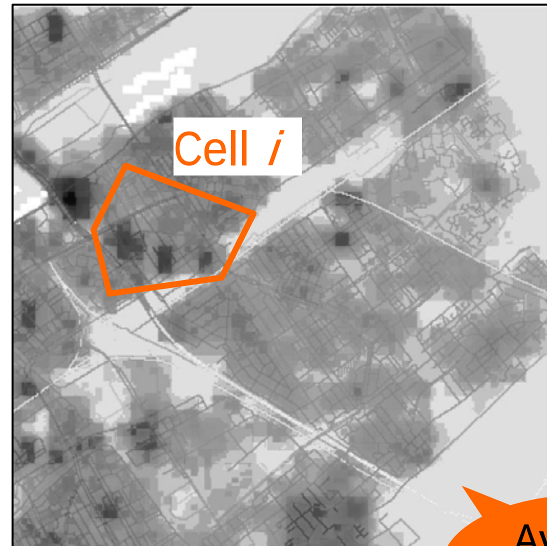
Load map

Hans-F. Geerdes

Expected Coupling



$$C^{\uparrow}_{ii} = \sum_{m \text{ in Cell } i} l_m$$



$$C^{\uparrow}_{ii} = \int_{p \text{ in Cell } i} l_p \, T(p) \, dp$$

+ Quick evaluation: just one single snapshot

+ Enables fast **local search**

– Stochastical errors (rare events averaged out)

Hans-F. Geerdes

Matrix Design

First Order Approximation

$$
\begin{aligned}
p &= C \cdot p + \eta \\
\Leftrightarrow p &= (I - C)^{-1} \cdot \eta \\
&= \sum_{k=0}^{\infty} C^k \cdot \eta \\
&\geq (I + C) \cdot \eta
\end{aligned}
$$

Network design

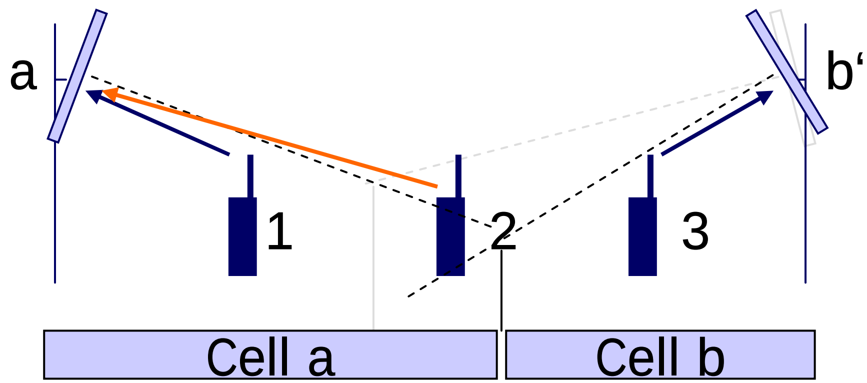
vs.

Load Balancing

$$\sum_{i,j} |C_{ii} - C_{jj}|$$

Hans-F. Geerdes

Configuration Changes



Parameters

- Attenuation $\gamma_{1a}, \gamma_{1b}, \gamma_{2a}, \gamma_{2b}, \gamma_{3a}, \gamma_{3b}$
- Noise η_a, η_b
- Threshold μ_1, μ_2, μ_3

Before

$$\begin{pmatrix} p_a \\ p_b \end{pmatrix} = \begin{pmatrix} l_1 & \frac{\gamma_{2a}}{\gamma_{2b}} l_2 + \frac{\gamma_{3a}}{\gamma_{3b}} l_3 \\ \frac{\gamma_{1b}}{\gamma_{1a}} l_1 & l_2 + l_3 \end{pmatrix} \begin{pmatrix} p_a \\ p_b \end{pmatrix} + \begin{pmatrix} \eta_a \\ \eta_b \end{pmatrix}$$

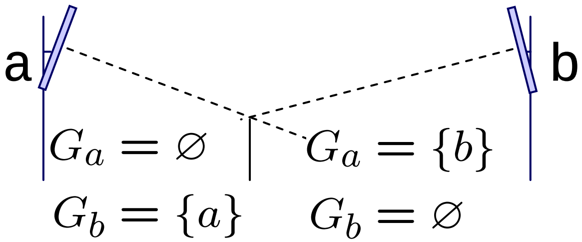
After

$$\begin{pmatrix} p_a \\ p_b \end{pmatrix} = \begin{pmatrix} l_1 + l_2 & \frac{\gamma_{3a}}{\gamma_{3b}} l_3 \\ \frac{\gamma_{1b}}{\gamma_{1a}} l_1 + \frac{\gamma_{2b}}{\gamma_{2a}} l_2 & l_3 \end{pmatrix} \begin{pmatrix} p_a \\ p_b \end{pmatrix} + \begin{pmatrix} \eta_a \\ \eta_b \end{pmatrix}$$

Hans-F. Geerdes

Matrix Design Model: Idea and Variables

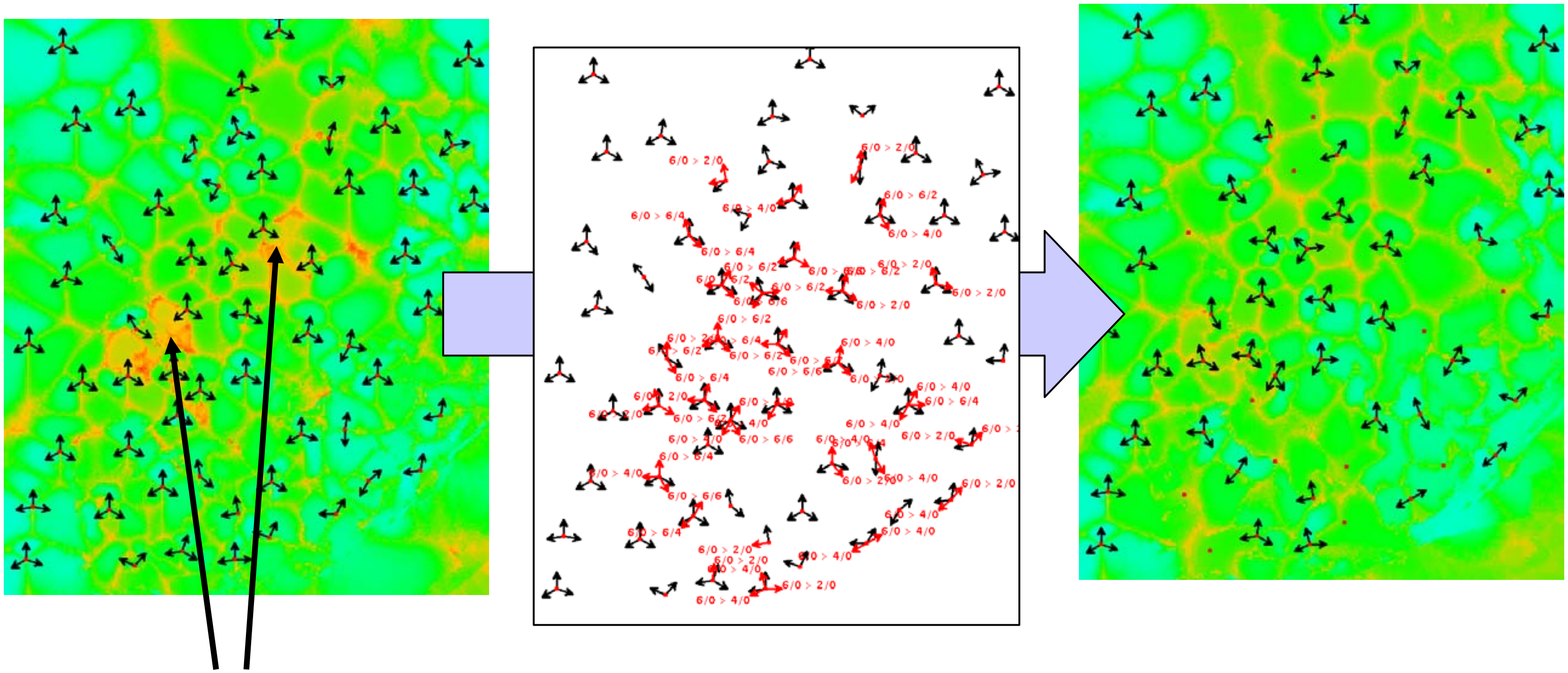
- All potential installations as input
- Binary installation selection variables z_i
- For each installation *j*, partition whole area according to the set *G* of antenna installations that dominate *j* at any location



- Parameter: potential matrix contribution **provided that no antenna in *G* is selected** $\kappa_{ij}(G)$
- Continuous variable takes on potential value or zero, according to the current network design $c_{ij}(G)$

Hans-F. Geerdes

Network Optimisation (Lisbon): Reducing Interference



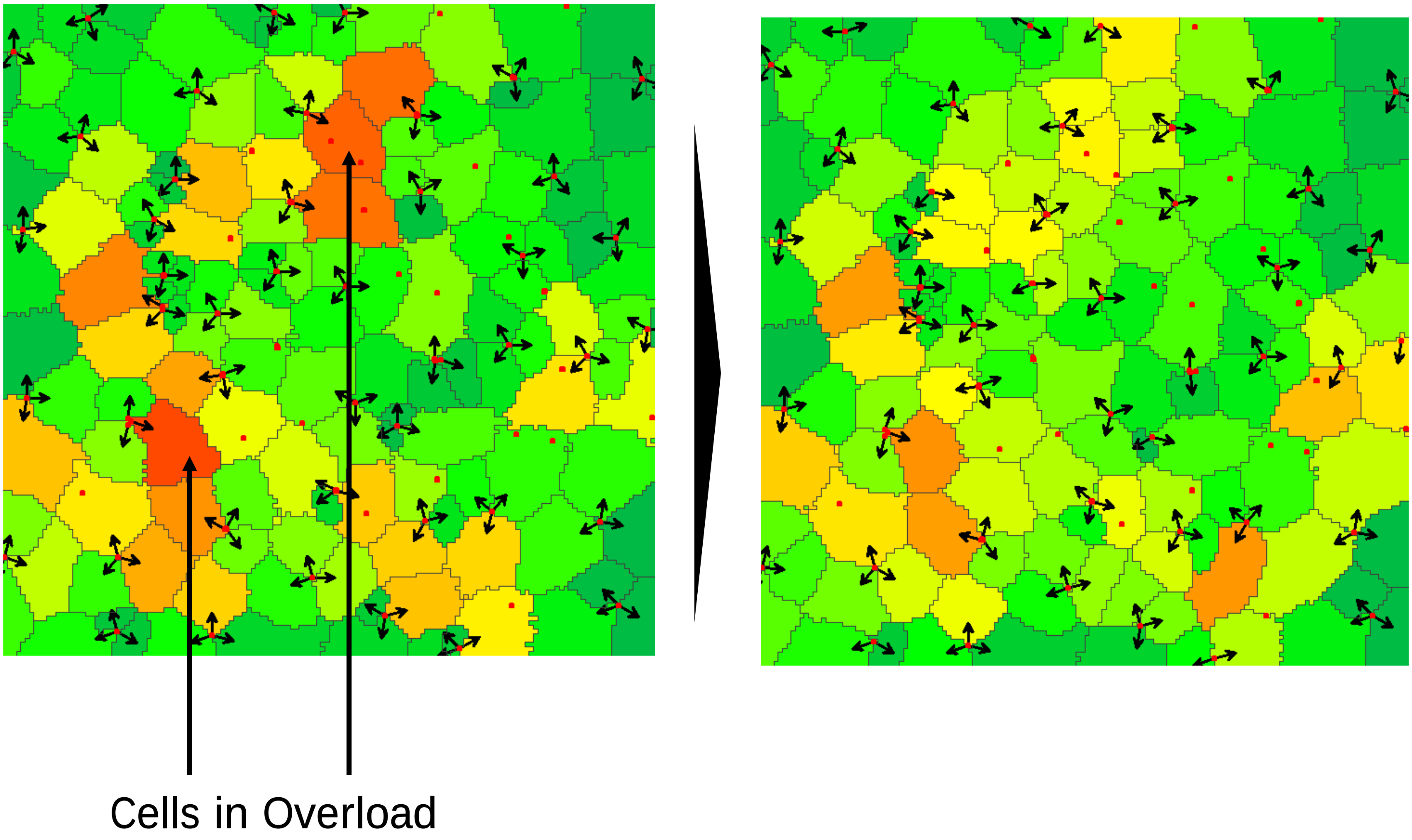
Areas with high interference

Change Antenna Configuration

OK

Hans-F. Geerdes

Network Optimisation in Berlin: Balancing Load

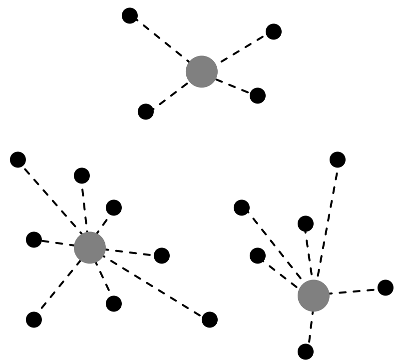


Hans-F. Geerdes

Hans-F.
Geerdes

Compact Formulation

Power Control at Link Level

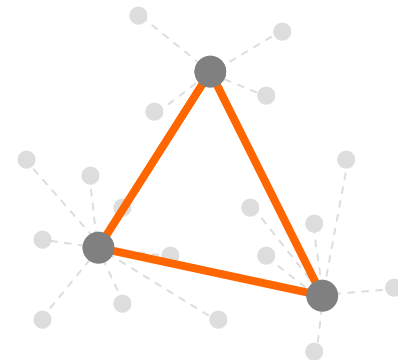


- CIR inequalities
- Individual power assignment

$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} \geq \text{Threshold}$$

Users x Users

Power Control at Cell Level



- Assume CIR met at *equality*
- Link powers deduced

$$\frac{\text{Signal}}{\text{Noise} + \sum \text{Interference}} = \text{Threshold}$$

Cells x Cells

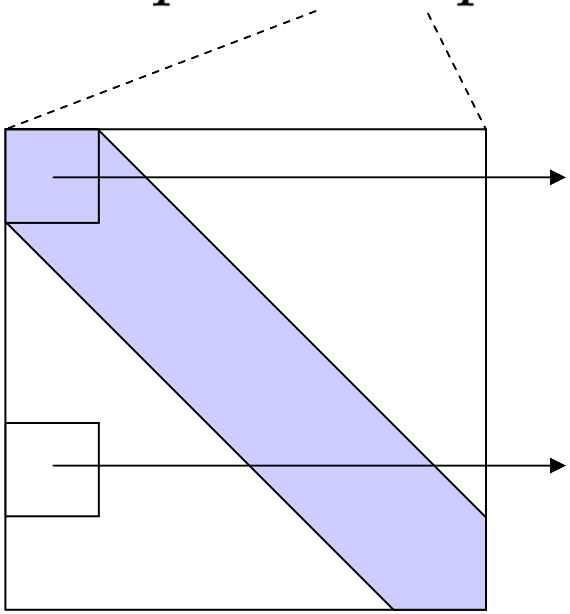
Hans-F. Geerdes

Coupling Matrices

Load is descibed as fix-point solution of linear equation system:

$$\bar{p}^{\downarrow} = C^{\downarrow}\,\bar{p}^{\downarrow} + p^{(\eta)} + p^{\text{fix}} \qquad \text{(DL)}$$

$$\bar{p}^{\uparrow} = C^{\uparrow}\,\bar{p}^{\uparrow} + \eta \qquad \text{(UL)}$$



Main Diagonal
Load collected in cell

$$C^{\uparrow}_{ii} = \sum_{m \text{ in Cell } i} l_m$$

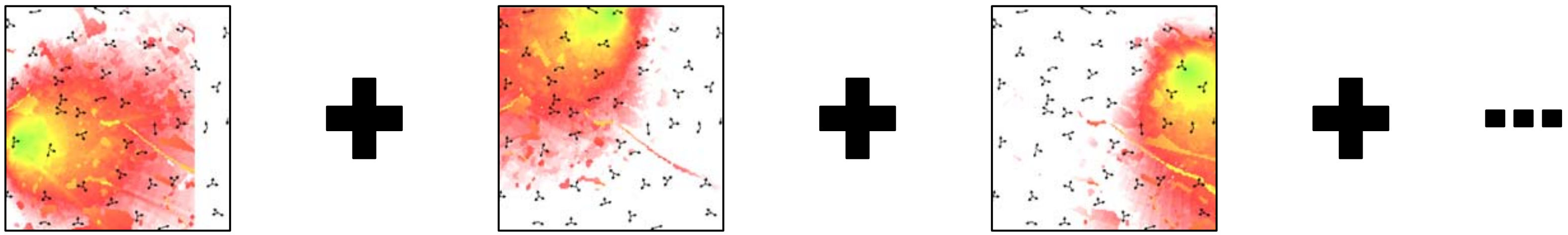
Off Diagonal
Coupling/ interference

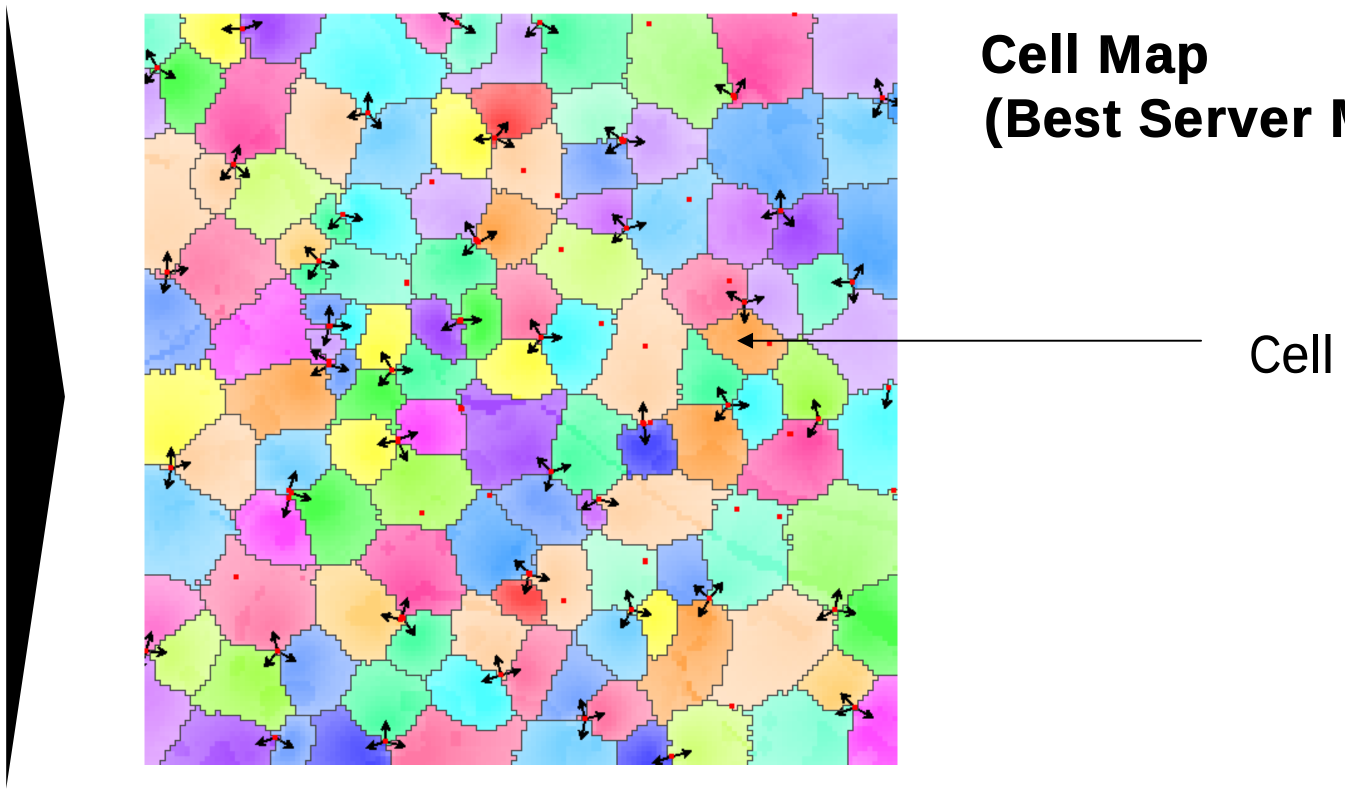
Numerical problems avoided

$$C^{\uparrow}_{ij} = \sum_{m \text{ in Cell } j} \frac{\gamma_{im}}{\gamma_{jm}}\, l_m$$

Hans-F. Geerdes

Radio Network Analysis: Cell Areas

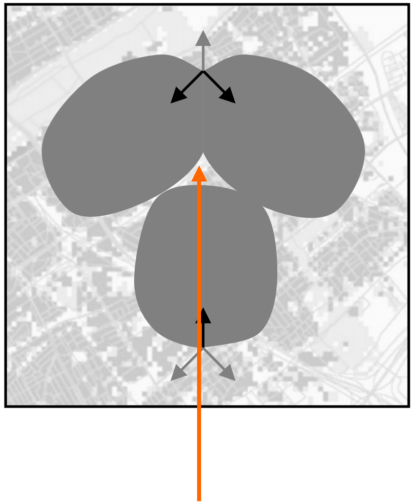




Cell Map (Best Server Map)

Hans-F. Geerdes

Coverage in UMTS



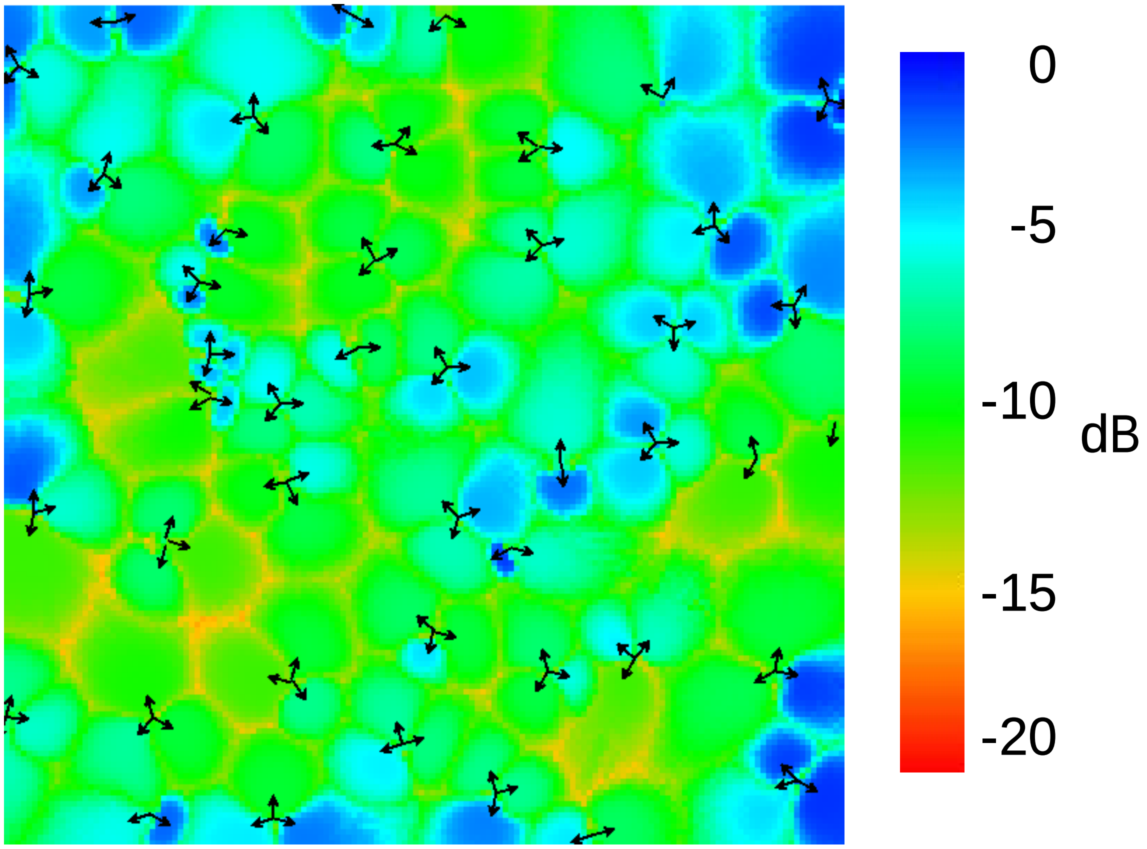
Coverage “hole”

- Users need to receive *pilot signal* to register with cells
- Pilot signal needs to
  - be strong enough to be detected by mobiles (E_c coverage)
  - have sufficient quality (not too much interference) to be decoded (E_c/I_0 coverage)
- High coverage probability is usually a constraint

Hans-F. Geerdes

Coverage Example

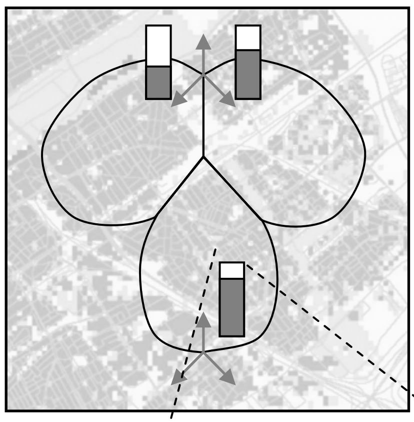
Quality of pilot signal

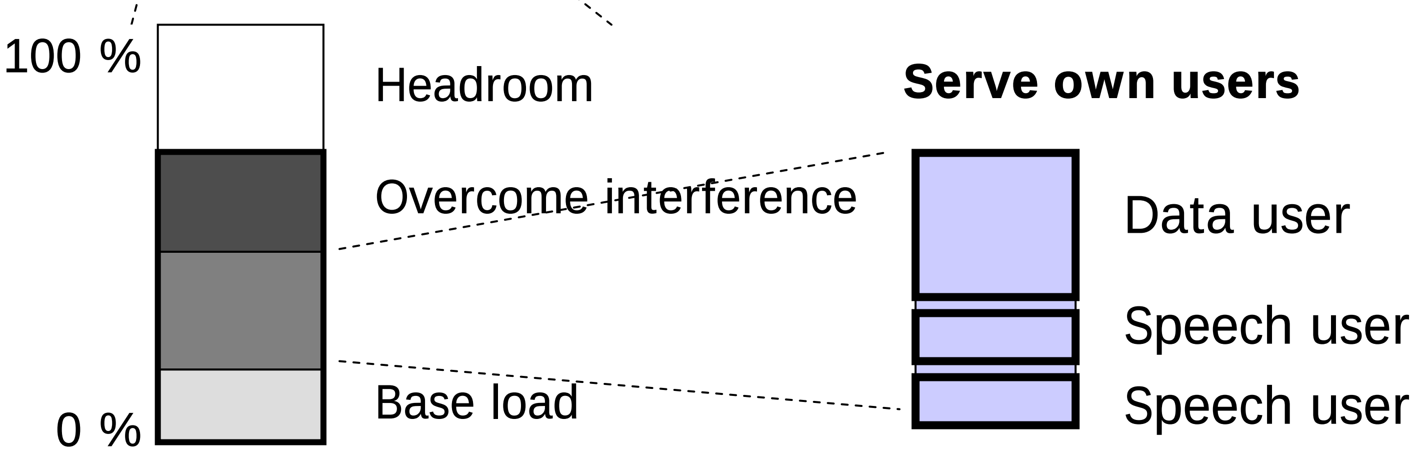


Hans-F.
Geerdes

Capacity in UMTS

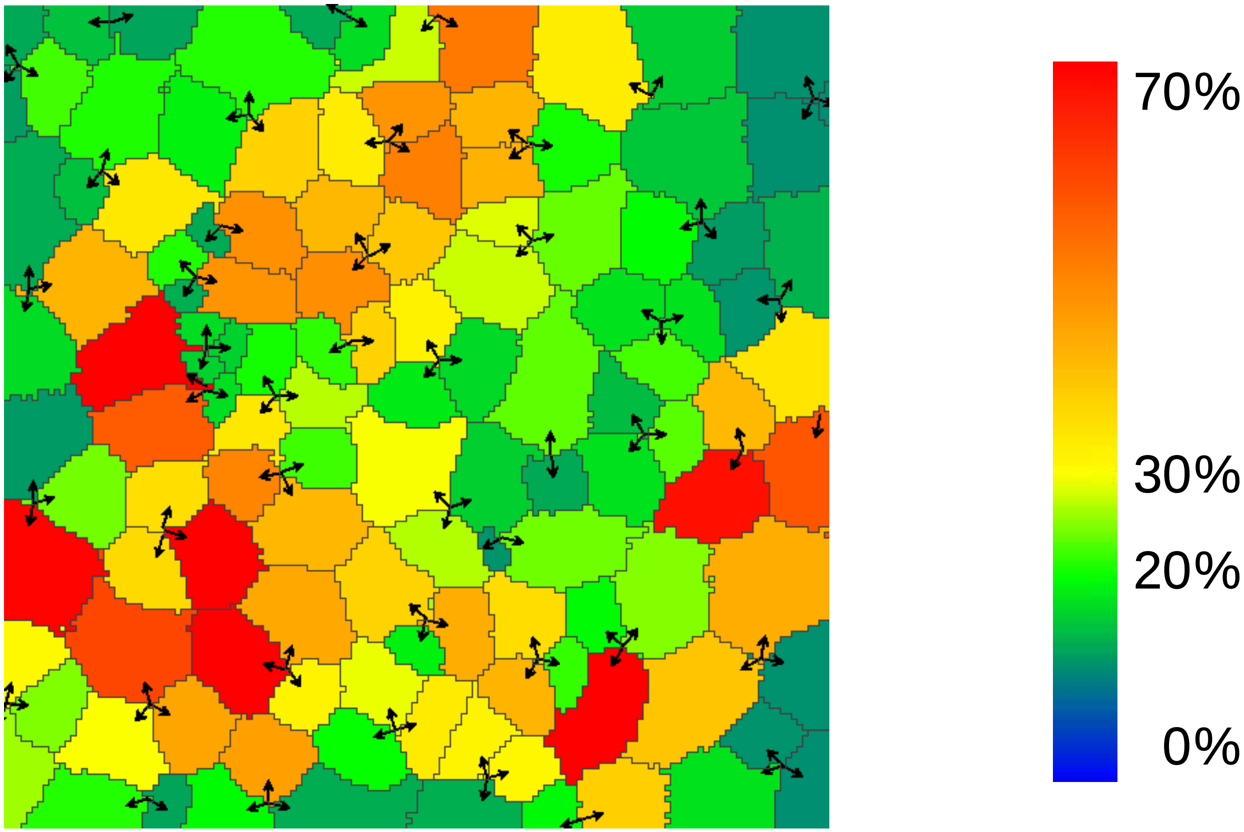
- Each cell has a limited amount of radio resources (power budget)
- Number of users that can be served depends on interference
- Users have different “weight”, according to service





Capacity: Load

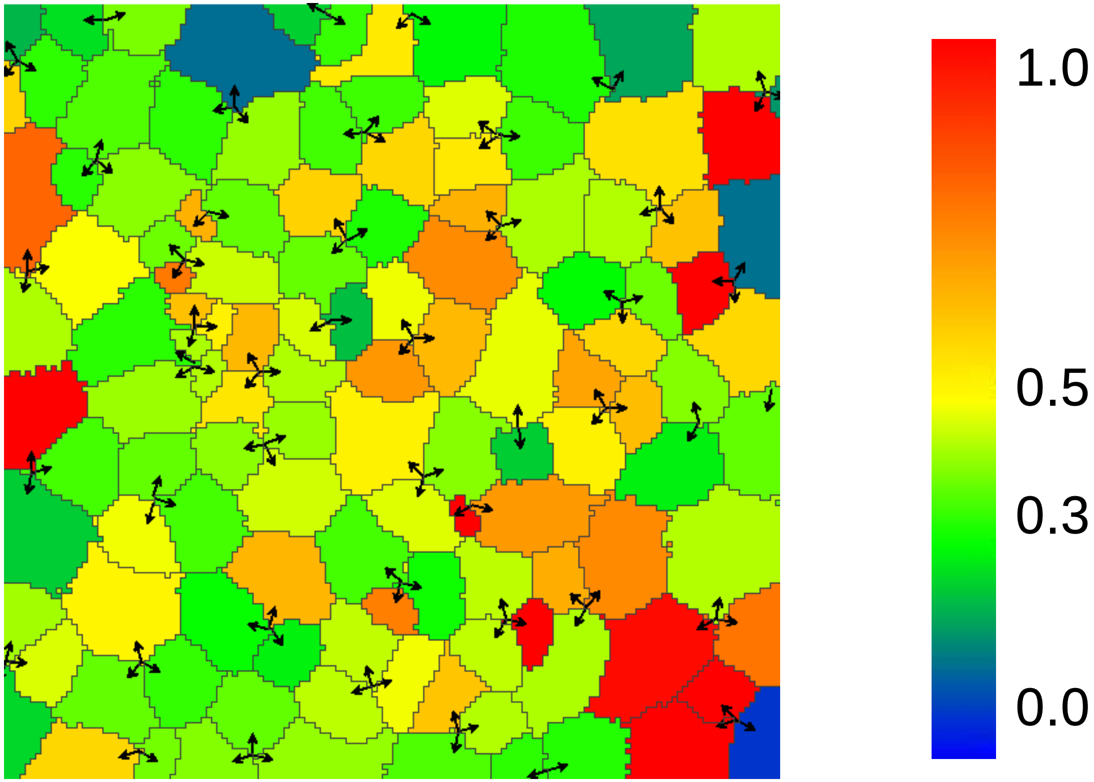
Resource usage in radio cells



Hans-F. Geerdes

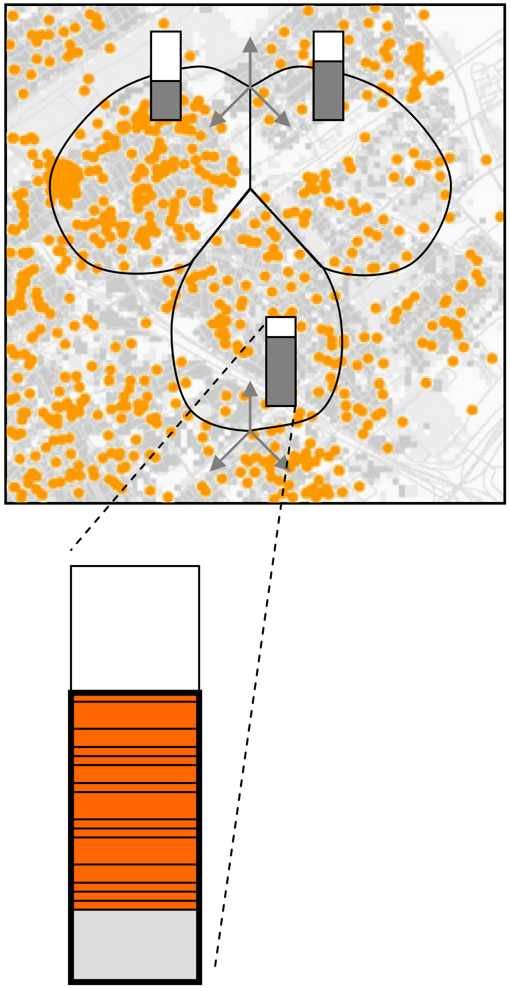
Interference

Ratio of capacity spent on interference
over capacity spent on serving own users



Hans-F.
Geerdes

Monte Carlo: Snapshot Models



Method

- Consider "snapshot" of users drawn from traffic distribution
- Assign link powers for each user

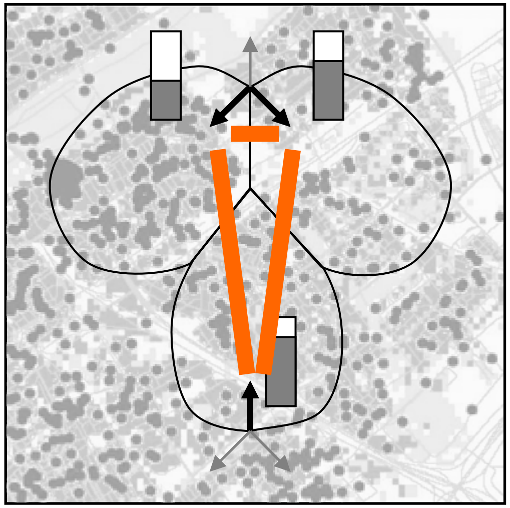
➔ Coverage and capacity are determined per user

Evaluation

- Analysis/simulation for "many" snapshots

Hans-F. Geerdes

Monte Carlo: Compact Evaluation



- Calculate cell powers
- Handle users in snapshot implicitly (can be done under mild assumptions)
- Network's performance on snapshot characterized by **coupling matrix** (cells £ cells)

➔ Network **capacity** (load vector) for the snapshot is solution of a linear equation system:

$$\bar{p}^{\downarrow} = C^{\downarrow}\,\bar{p}^{\downarrow} + p^{(\eta)} + p^{\text{fix}}$$

$$\bar{p}^{\uparrow} = C^{\uparrow}\,\bar{p}^{\uparrow} + \eta$$

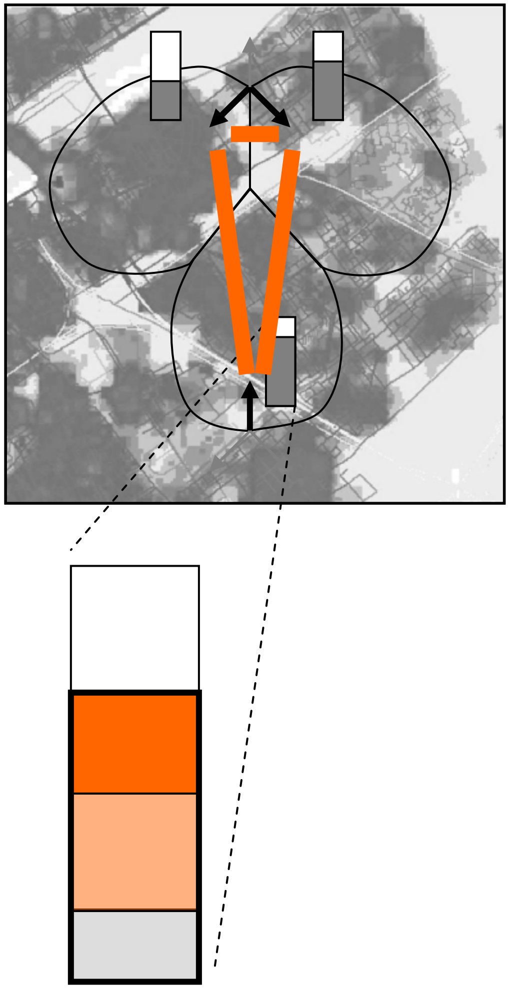
Coupling Matrix

Coverage main diagonal/trace

Interference off-diagonal elements

Hans-F. Geerdes

Average Load



Method

- Consider *average* coupling matrix based on mean values of distributions

➔ Stochastical errors (systematical), but indicates system's "real" behavior

Evaluation

- Analysis/solution of **one** equation system

Optimization

- Local search
- Analytical heuristics
- Design coupling matrix (e.g. minimize off-diagonal elements)

Hans-F. Geerdes

Hans-F. Geerdes