Frequency Planning By Means Of High-Dimensional Optimization

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Frequency Planning Department

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Frequency Planning

- frequency planning is not pure science
- basis is communication science and electrical engineering
- both technical and economical constraints, i.e. transmitter sites, erp and costs
- political constraints, different countries have different approaches to broadcasting

Frequency Plan Generation

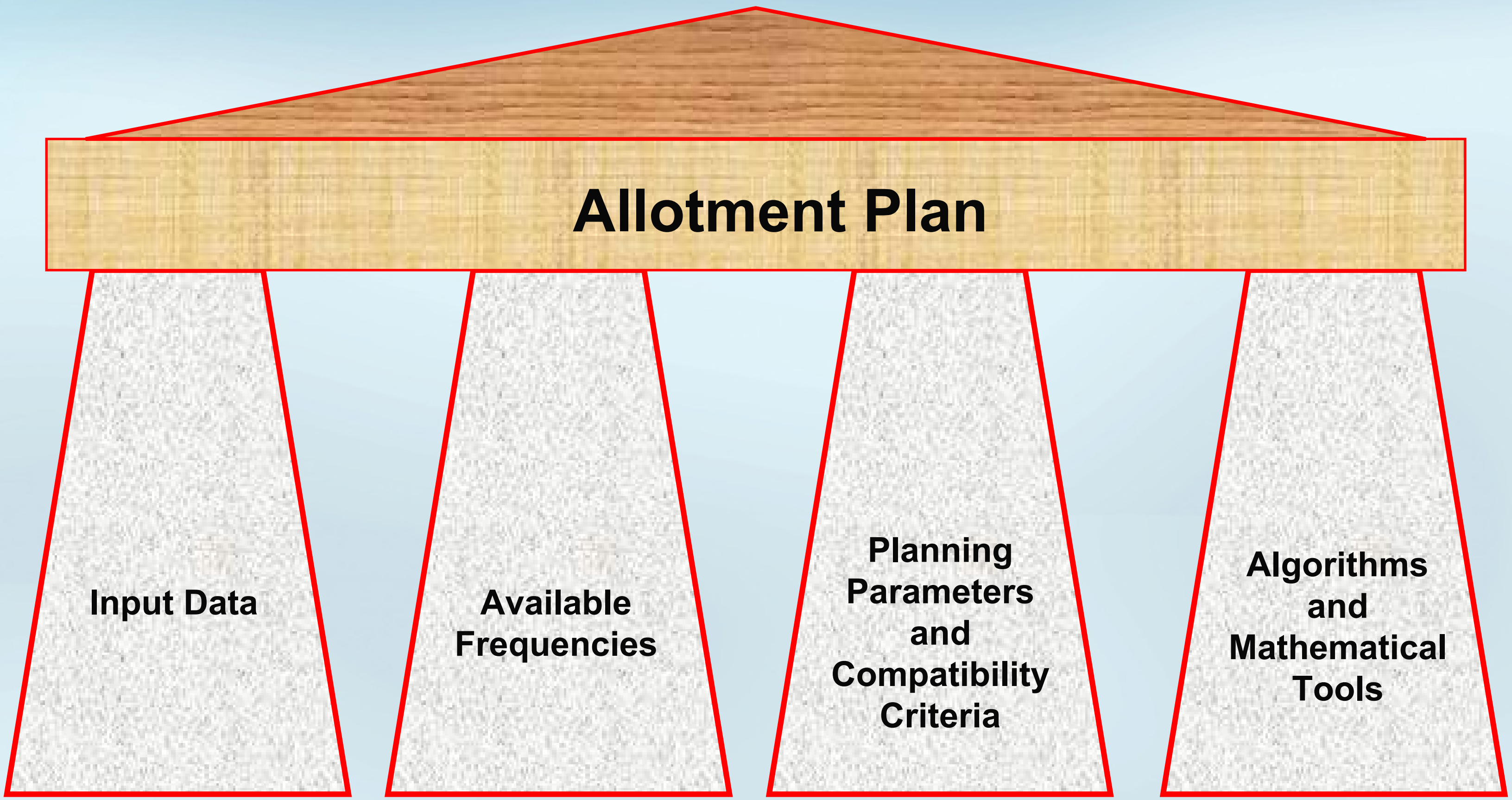
Allotment (of a radio frequency or radio frequency channel):

Entry of a designated frequency channel in an agreed plan, adopted by a competent conference, for use by one or more administrations for a terrestrial or space radiocommunication service in one or more identified countries or geographical areas and under specified conditions.

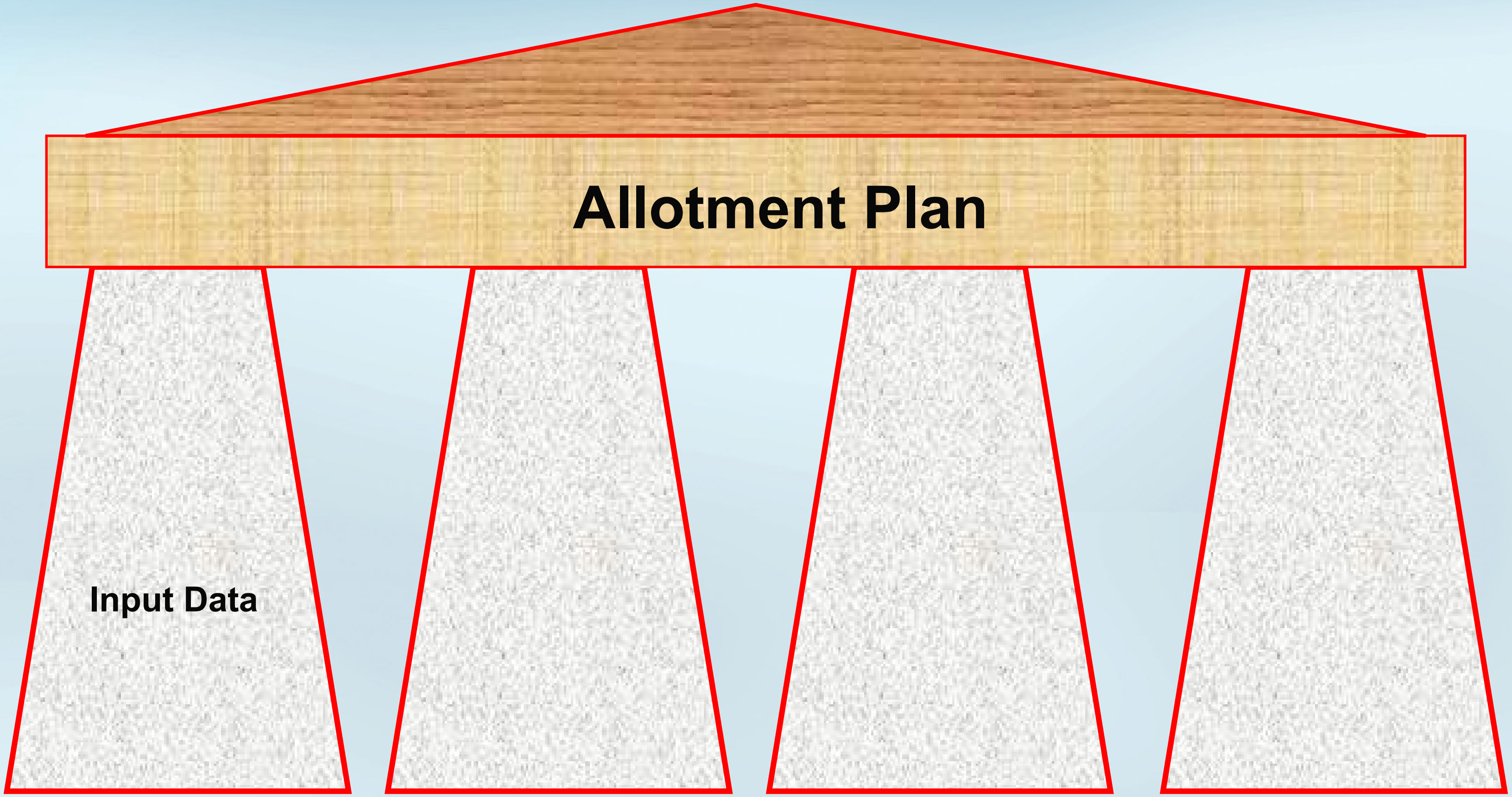
Assignment (of a radio frequency or radio frequency channel):

Authorization given by an administration for a radio station to use a radio frequency or radio frequency channel under specified conditions.

Frequency Plan Generation



Frequency Plan Generation



Input Data

Allotment Requirements:

- polygons on a sphere, i.e. a finite number of vertices connected by segments of great circles

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- interference potential: reference networks (RN)
  coverage target : reference planning configurations (RPC)

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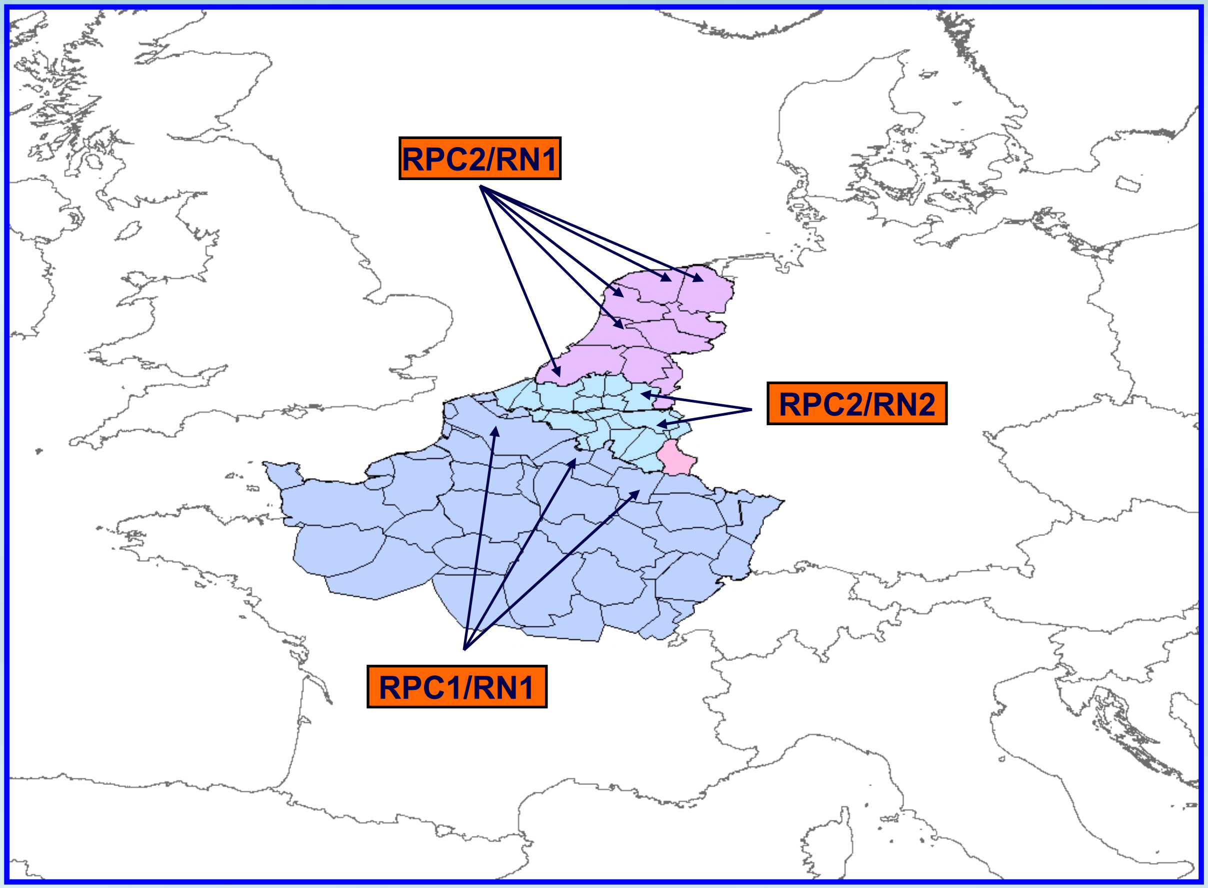


Input Data

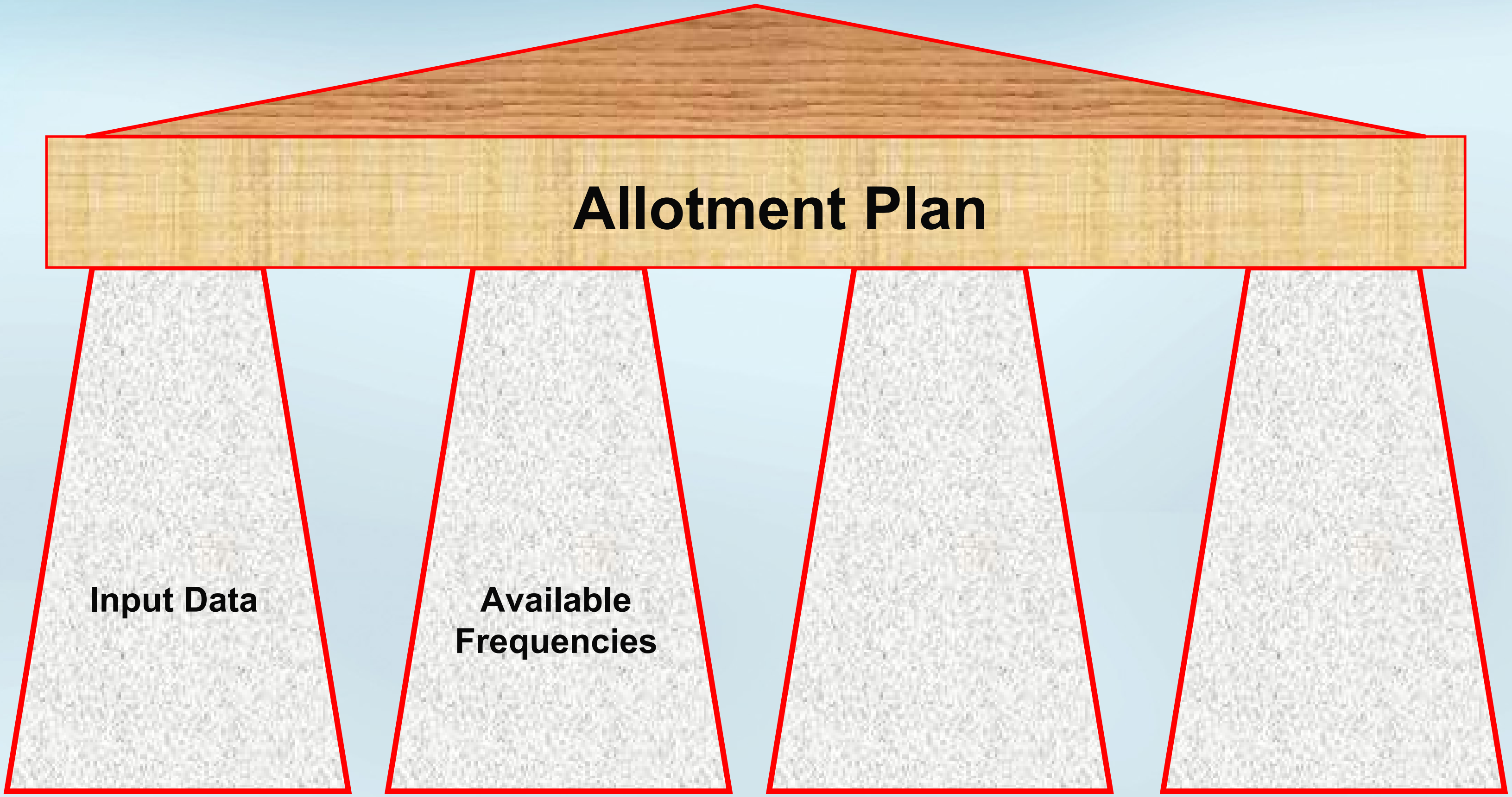
Allotment Requirements:

- **polygons on a sphere, i.e. a finite number of vertices connected by segments of great circles**

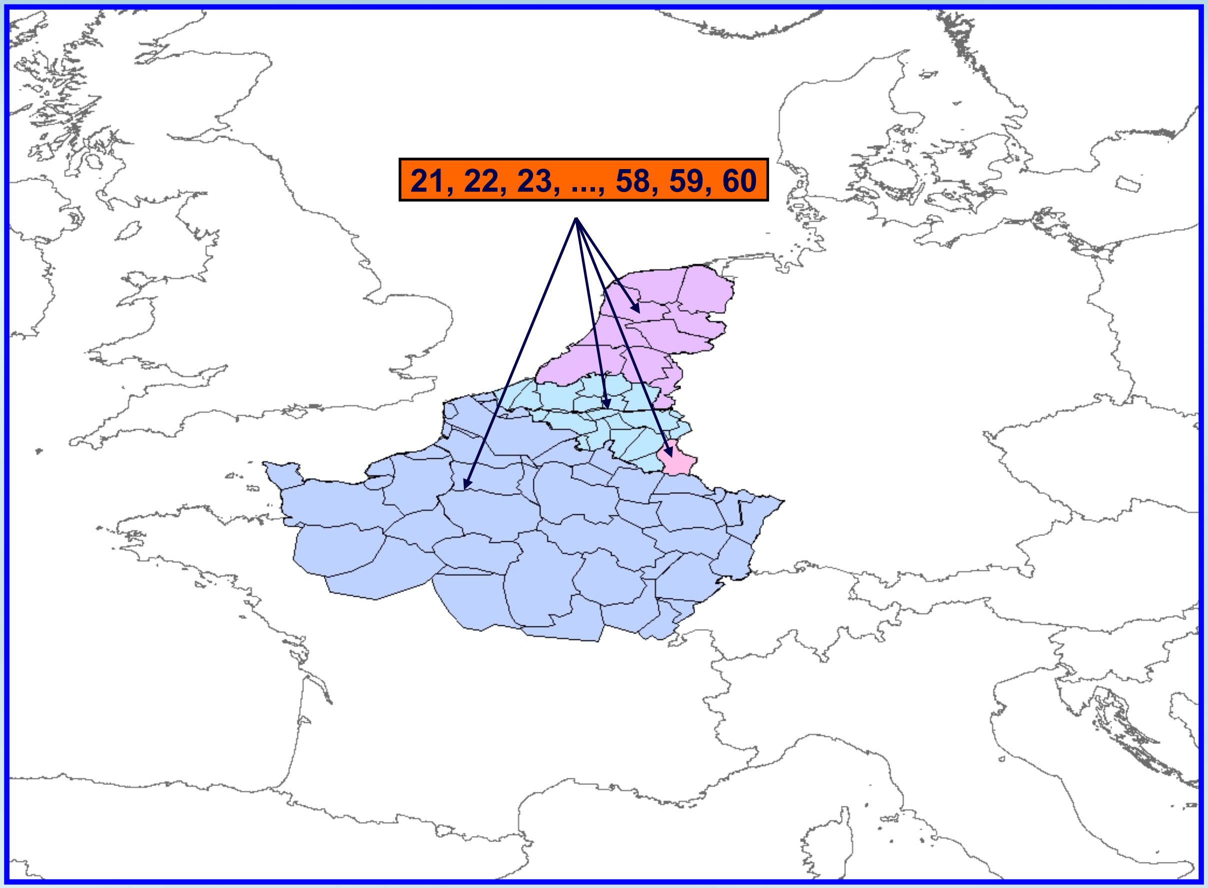
- **interference potential: reference networks (RN)**
  coverage target : reference planning configurations (RPC)

- **administrative declarations**

Frequency Plan Generation



Available Frequencies



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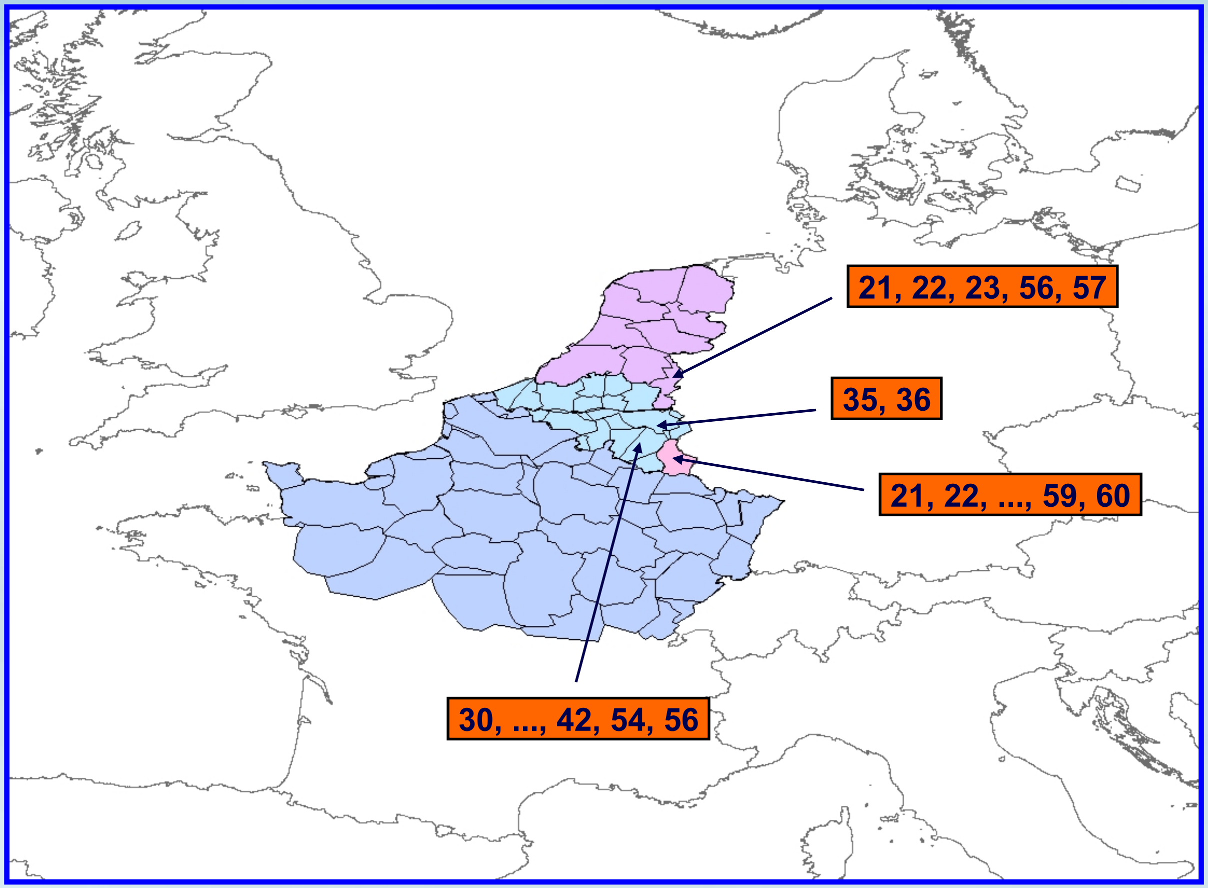
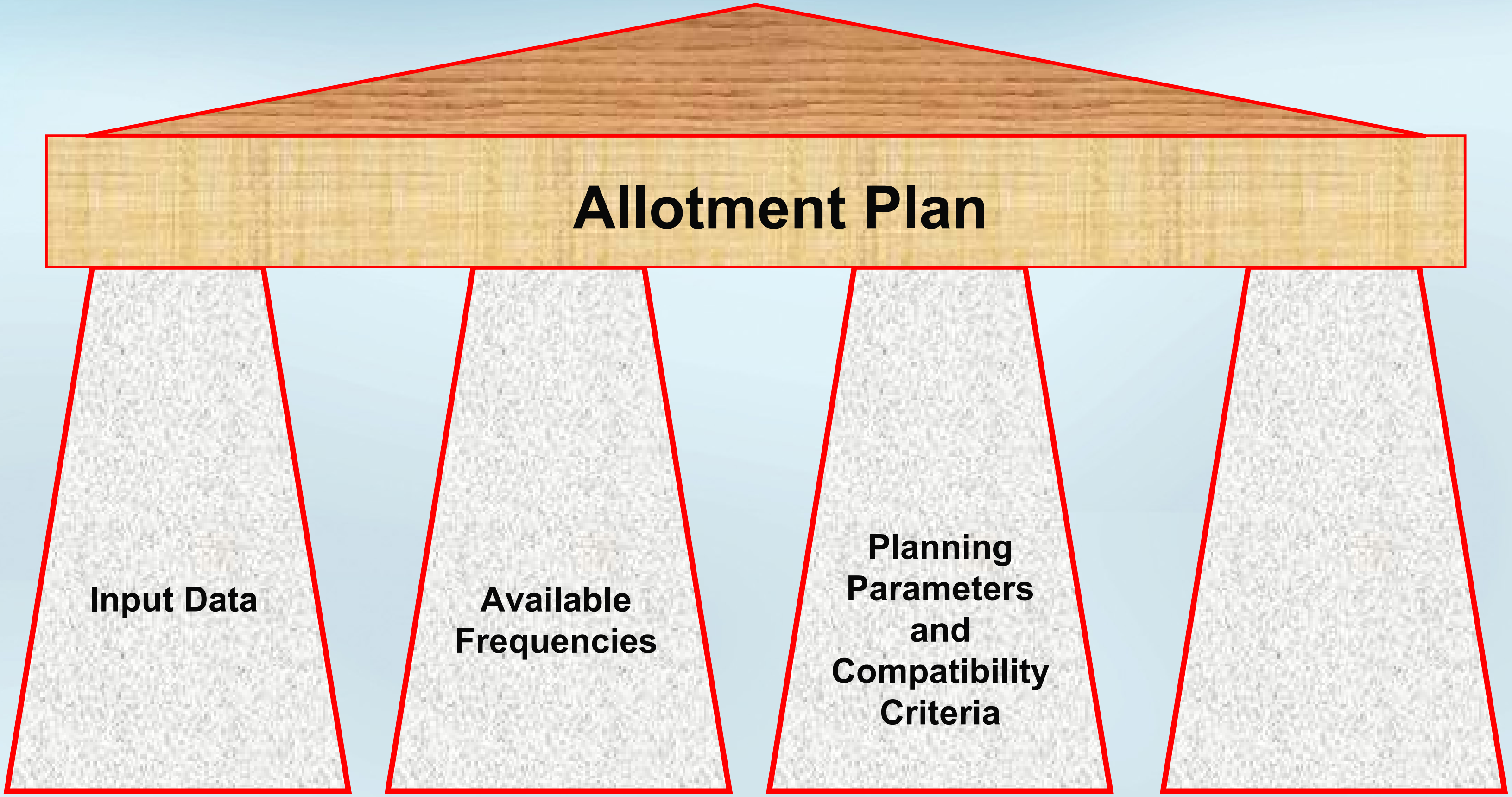


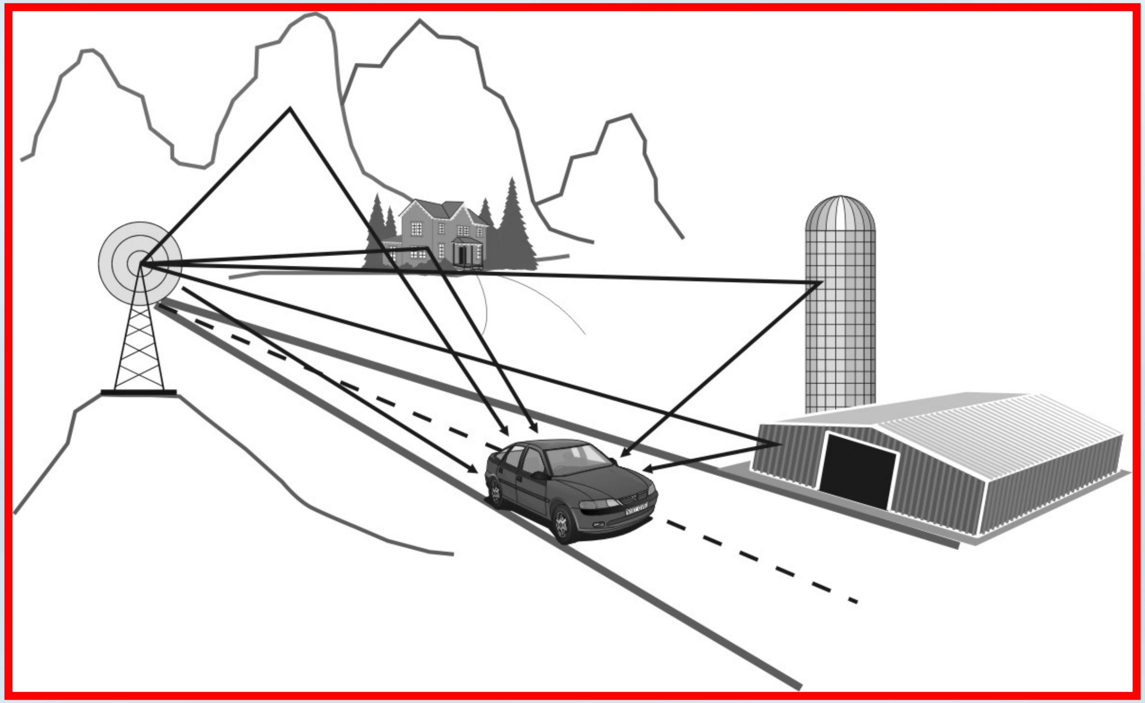
Frequency Plan Generation



Planning Parameters

Wave Propagation

Radio Channel

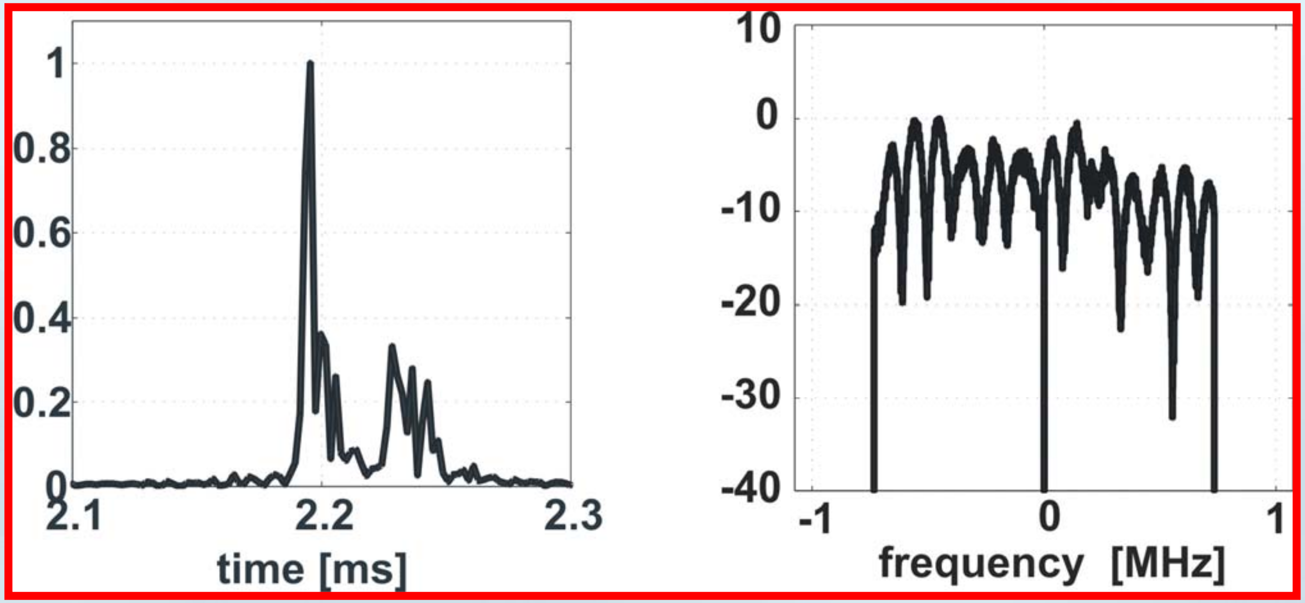


multipath environment leading to frequency selective fading

Planning Parameters

Wave Propagation

Radio Channel



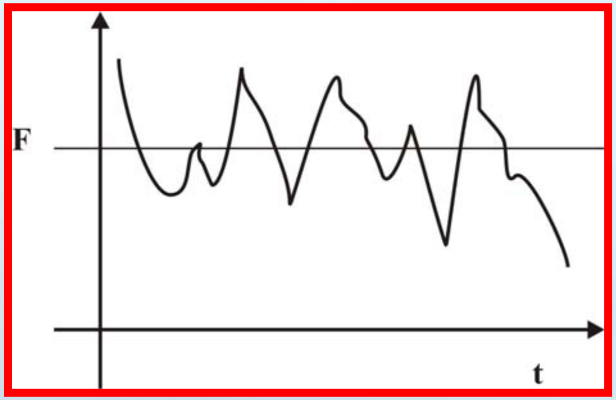
measurement of impulse response and transfer function of radio channel in DAB network near Stuttgart

Planning Parameters

Wave Propagation Model

Task: calculation of field strength at a given point

Input data: transmitter characteristics



→ temporal variation of radio channel requires statistical interpretation:

the value F corresponds to a field strength level which is exceeded in x % of time

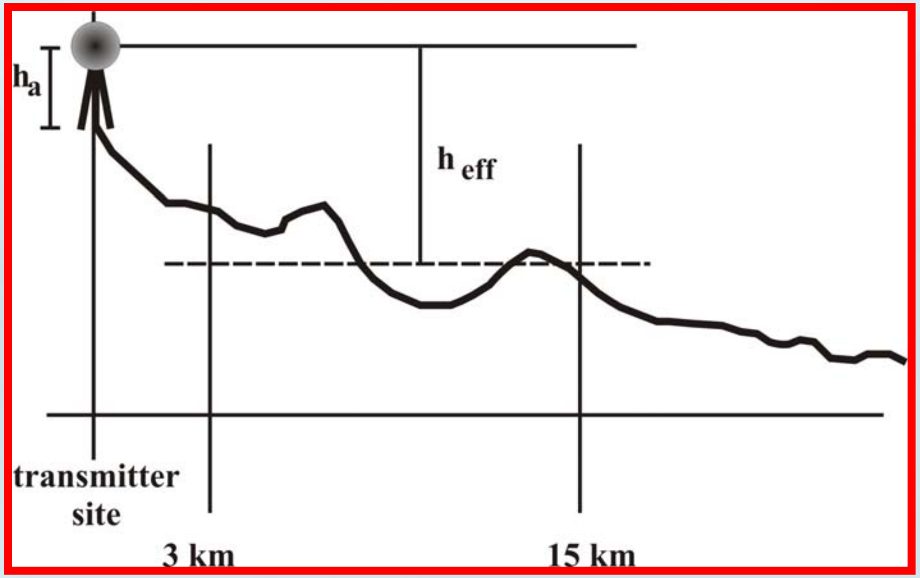
Planning Parameters

Wave Propagation Model

ITU Recommendation P-1546

ITU Rec. P-1546: statistical model, not (really) path specific

Parameters: power, antenna height, antenna pattern, effective heights



Planning Parameters

Coverage Prediction

- **assessment of coverage quality in the presence of interference:**

  required minimum field strength
  protection ratio

- **problem: field strength calculation at discrete points only**

- **limited resolution of topographic and morphologic data defines „pixel“ size (100m*100m)**

- **spatial distribution function (mean, standard deviation)**

Planning Parameters

Coverage Prediction

- calculation of probability that at x % of locations given field strength is exceeded

- coverage assessment in the presence of interference:

served:	minimum field strength and protection ratio reached	at x % of loc.
interfered:	minimum field strength reached, protection ratio not reached	
not served:	neither minimum field strength not protection ratio reached	

Planning Parameters

Reference Planning Configurations (RPC)

	RPC1 (fixed reception)	RPC2 (portable outdoor, mobile)	RPC3 (portable indoor)
system	DVB-T	DVB-T	DVB-T
location probability	95%	95%	95%
protection ratio	21 dB	19 dB	17 dB
minimum field strength at 200 MHz at 10 m	50 dB µV/m	67 dB µV/m	76 dB µV/m
minimum field strength at 650 MHz at 10 m	56 dB µV/m	78 dB µV/m	88 dB µV/m

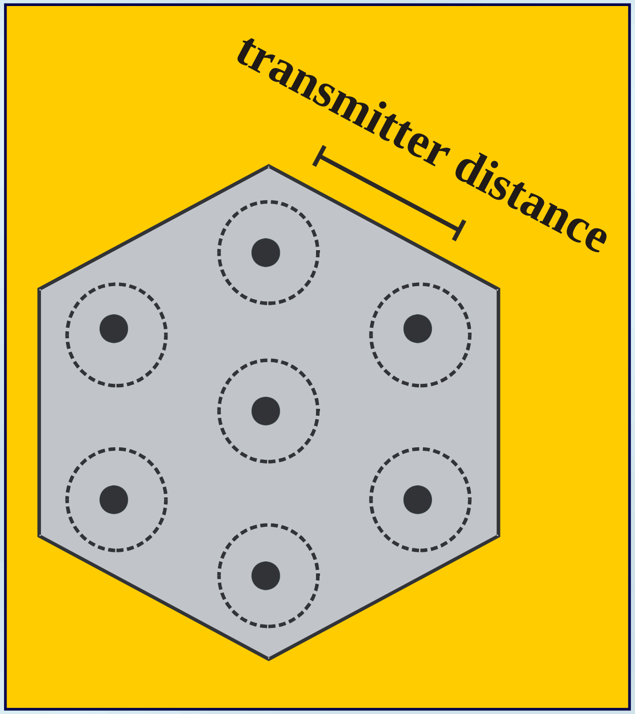
Planning Parameters

Reference Planning Configurations (RPC)

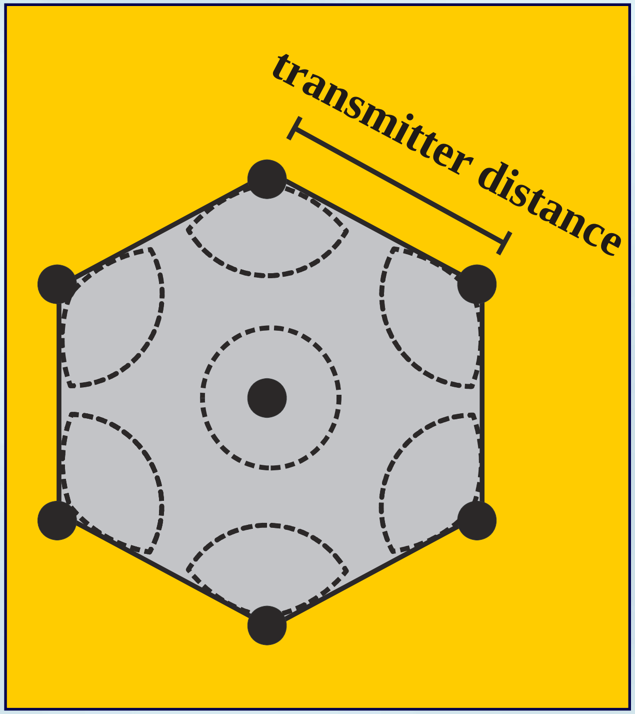
	RPC4 (mobile)	RPC5 (protable indoor)
system	T-DAB	T-DAB
location probability	99%	95%
protection ratio	15 dB	15 dB
minimum field strength at 200 MHz at 10 m	60 dB V/m	66 dB V/m

Planning Parameters

Reference Networks (RN)



open network



closed network

Planning Parameters

RN1 for DVB-T

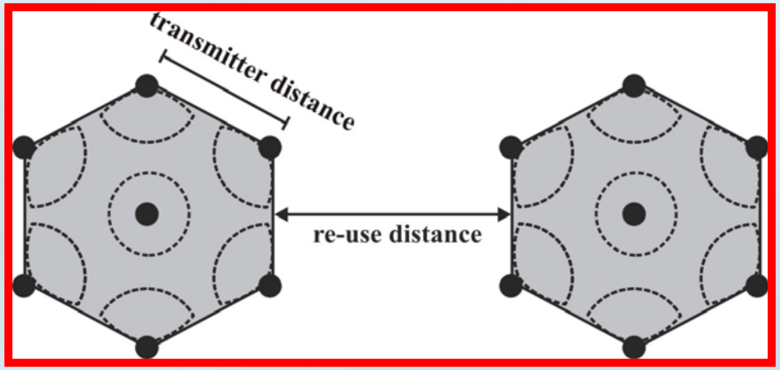
open hexagon, 7 transmitters

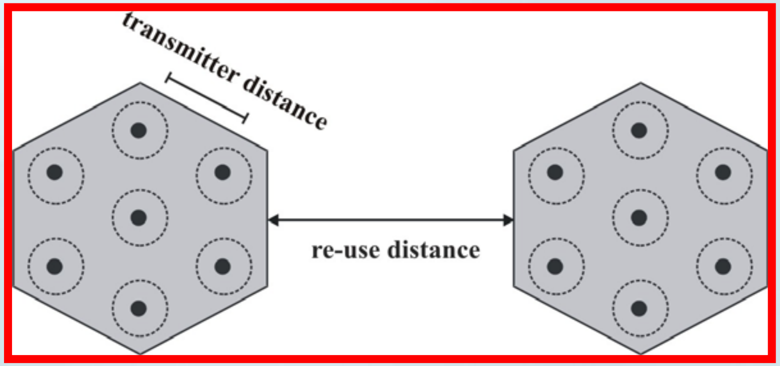
RPC and reception type	RPC 1 fixed antenna	RPC 2 portable outdoor and mobile	RPC 3 portable indoor
inter-transmitter distance	70 km	50 km	40 km
effective antenna height	150 m	150 m	150 m
ERP in Band III	4.1 dBkW (2.5 kW)	6.2 dBkW (4.2 kW)	10 dBkW (10 kW)
ERP in Band IV/V	12.8 dBkW (19 kW)	19.7 dBkW (93.3 kW)	22.4 dBkW (173.8 kW)

Planning Parameters

Re-Use Distances

re-use distance: **minimum distance required between service areas using the same frequency providing different content**





Planning Parameters

Re-Use Distances

re-use distance: **minimum distance required between service areas using the same frequency providing different content**

calculation mehods:

a) „first pixel flips“

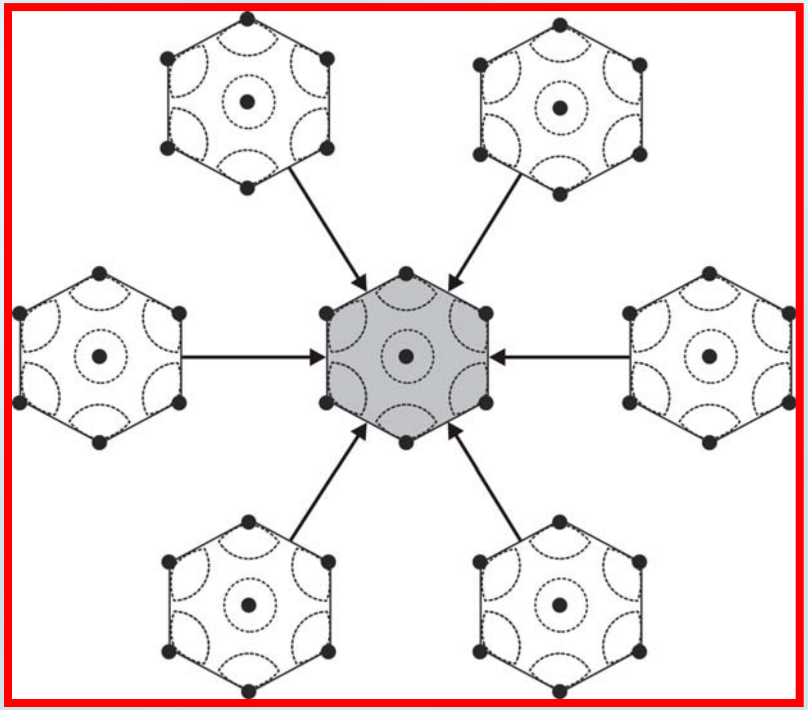
b) infinite plane

Planning Parameters

Re-Use Distances

„first pixel flips“

- wanted network in the centre
- 6 interfering networks positoned on a hexagon
- distance changed from large to small
- re-use distance reached if first pixel inside wanted service area flips from „served“ to „interfered“



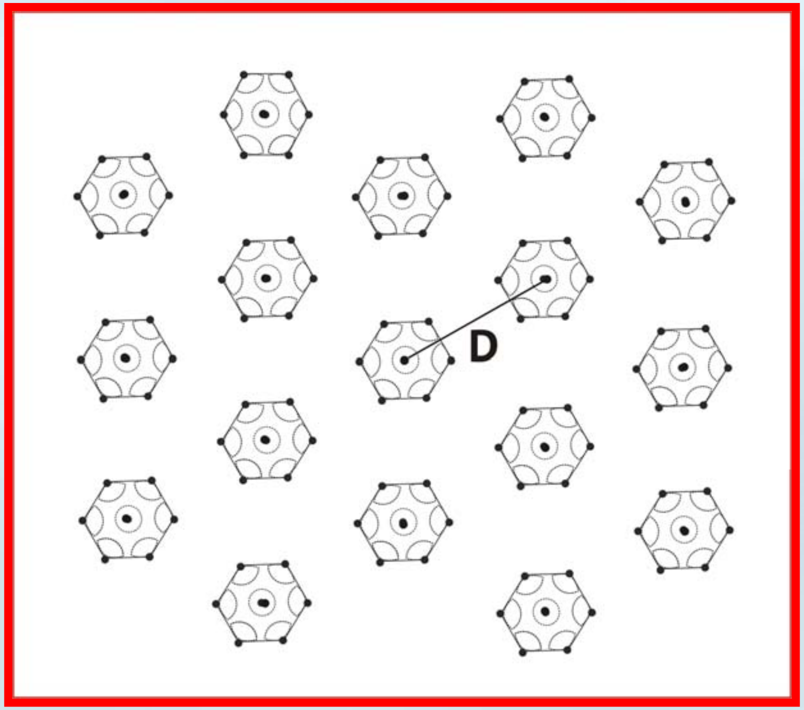
→ **calculation of re-use distance protects coverage needs**

Planning Parameters

Re-Use Distances

infinite plane

- „infinite number“ of networks on a hexagonal grid in the „infinite“ plane
- each pixel in large area is assessed and number of served pixels N is determined
- distance D is changed
- maximum of function D →N defines re-use distance



→ **calculation aims at optimal use of available spectrum**

Planning Parameters

Re-Use Distances

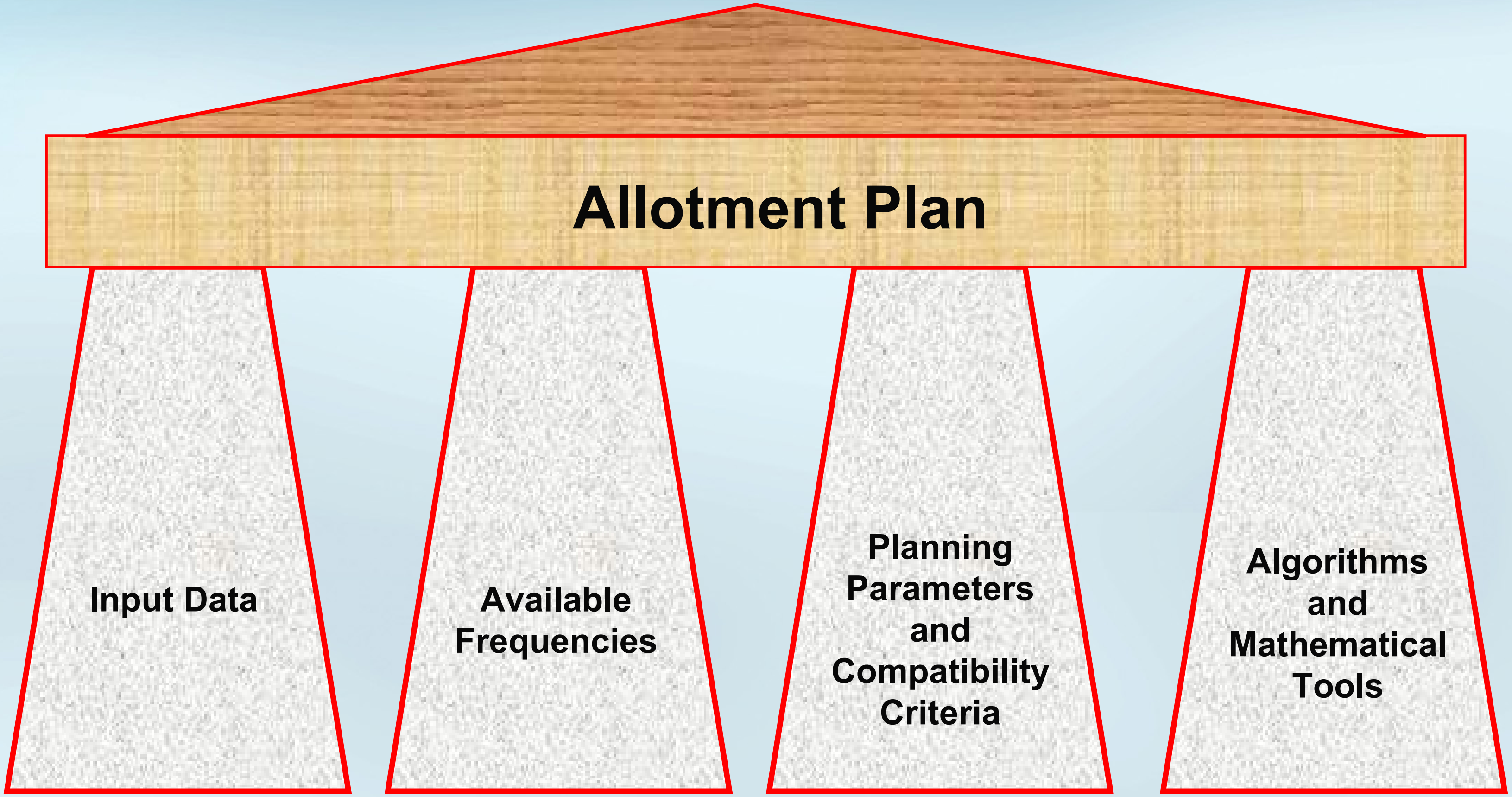
propagation conditions

- ITU Rec. P-1546 covers propagation above land, cold sea and warm sea
- Re-use distance für T-DAB (WI95)

	land	cold sea	warm sea
VHF	81 km	142 km	173 km
L-Band	61 km	348 km	485 km

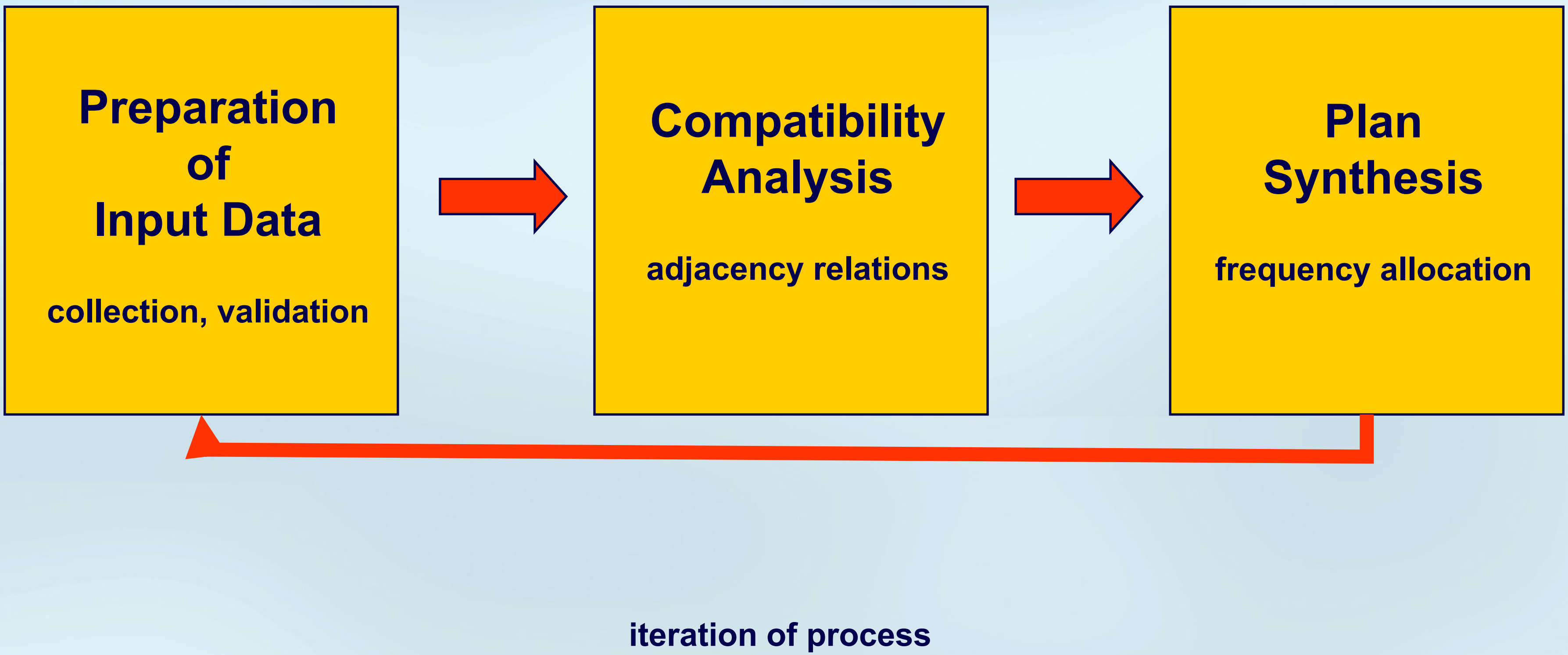
- Re-use distance für DVB-T 100 km – 140 km

Frequency Plan Generation



Mathematical Algorithms

General Approach of Frequency Planning Problems



Mathematical Algorithms

Compatibility Analysis

Compatibility Analysis

assessment of pairs of requirements to determine if they can share a frequency

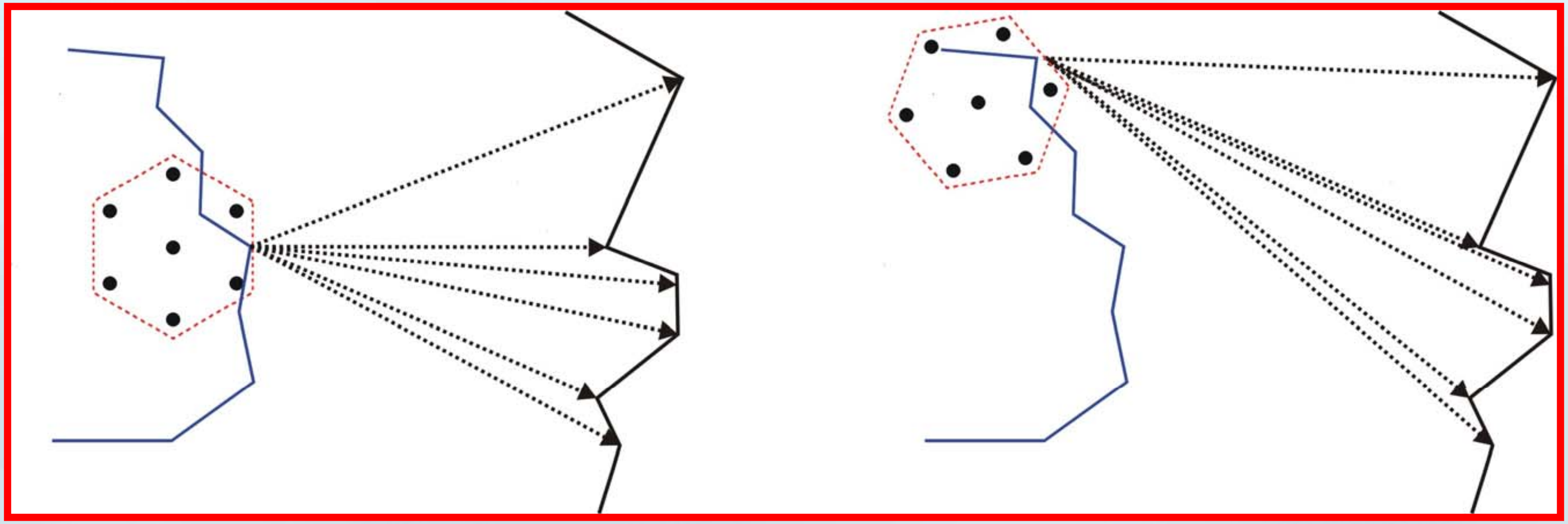
↓ **Based on Field Strength**

↓ **Based on Effective Distance**

Mathematical Algorithms

Compatibility Analysis

Field Strength Based

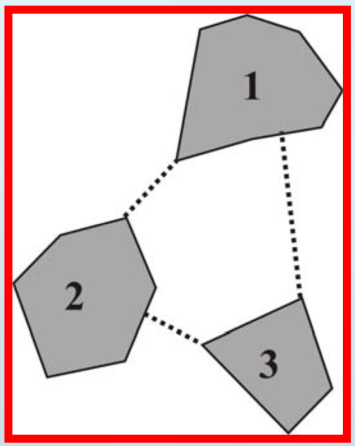


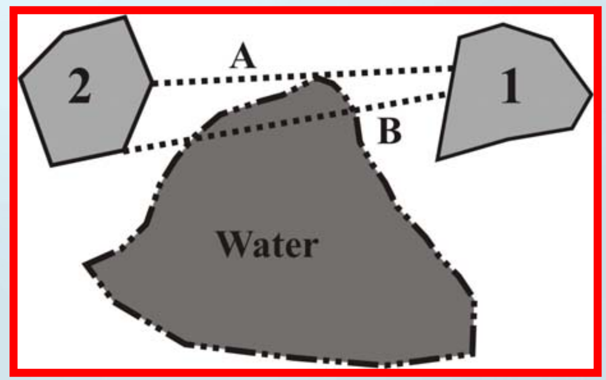
Mathematical Algorithms

Compatibility Analysis

Effective Distance

Idea: calculate distance between allotments and compare with re-use distance





minimal geometrical distance either between vertices or an edge and a vertex (also in spherical geometry!)

→ corresponds to most critical path

no longer true in the case of mixed propagation conditions !!!

Mathematical Algorithms

Compatibility Analysis

Effective Distance

Observation (VHF, T-DAB): 81 km above land have the same impact as 142 km above cold water in VHF for T-DAB

Definition of Effective Distance between two points:

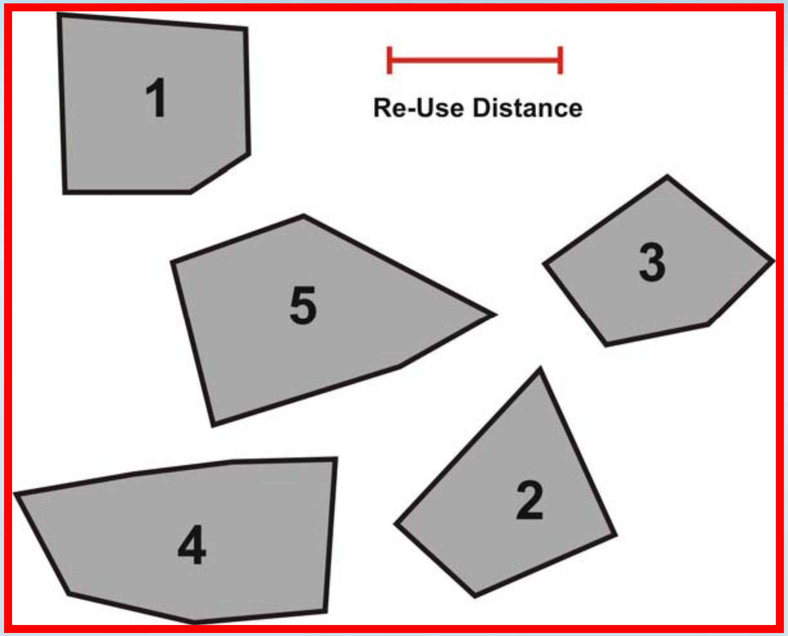
- determine fractions of land (x), cold (y) and warm sea (z) path
- add different path lengths after appropriate scaling
- compare resulting effective distance with re-use distance above land

Example (VHF, T-DAB):

$$d_{eff} = x + y * \frac{81}{142} + z * \frac{81}{173}$$

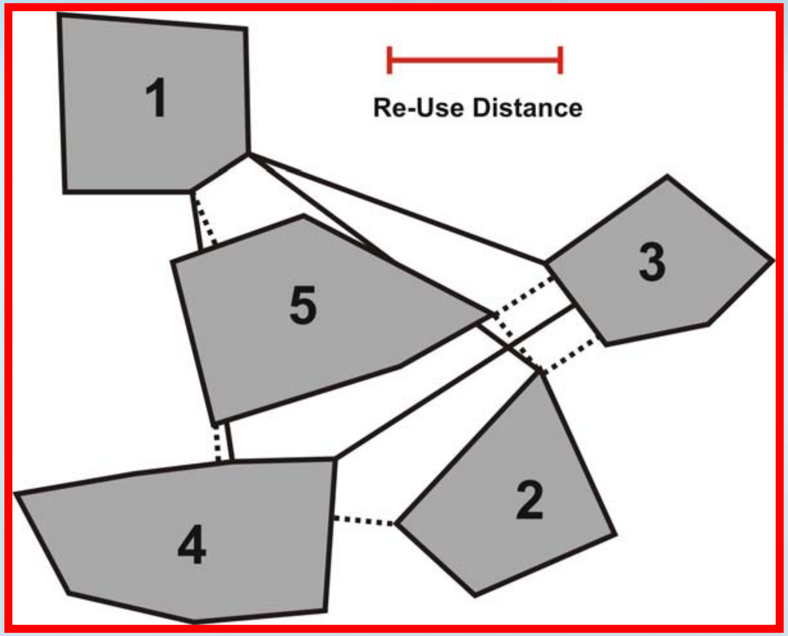
Mathematical Algorithms

Compatibility Analysis



Mathematical Algorithms

Compatibility Analysis



adjacency matrix

$$N = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{pmatrix}$$

compatibility matrix

$$C = \begin{pmatrix} 0 & 48 & 41 & 35 & 9 \\ 48 & 0 & 9 & 8 & 10 \\ 41 & 9 & 0 & 37 & 8 \\ 35 & 8 & 37 & 0 & 5 \\ 9 & 10 & 8 & 5 & 0 \end{pmatrix}$$

Mathematical Algorithms

Compatibility Analysis

elements of adjacency matrix N :

- **0 or 1**

elements of compatibility matrix C :

- **effective distance**
- **ratio of area overlap of the two considered allotment areas**

→ **N and C are required for frequency assignment algorithms**

Mathematical Algorithms

Plan Synthesis

Types of Planning Problems

Spectrum Demand Study

application: introduction of a new service

target: estimate minimum amount of spectrum needed to satisfy all requirements

method: graph coloring

Mathematical Algorithms

Plan Synthesis

Types of Planning Problems

Spectrum Demand Study

application: introduction of a new service

target: estimate minimum amount of spectrum needed to satisfy all requirements

method: graph coloring

Constrained Frequency Assignment Problems

application: planning of a service in a given spectrum range with individual access to spectrum

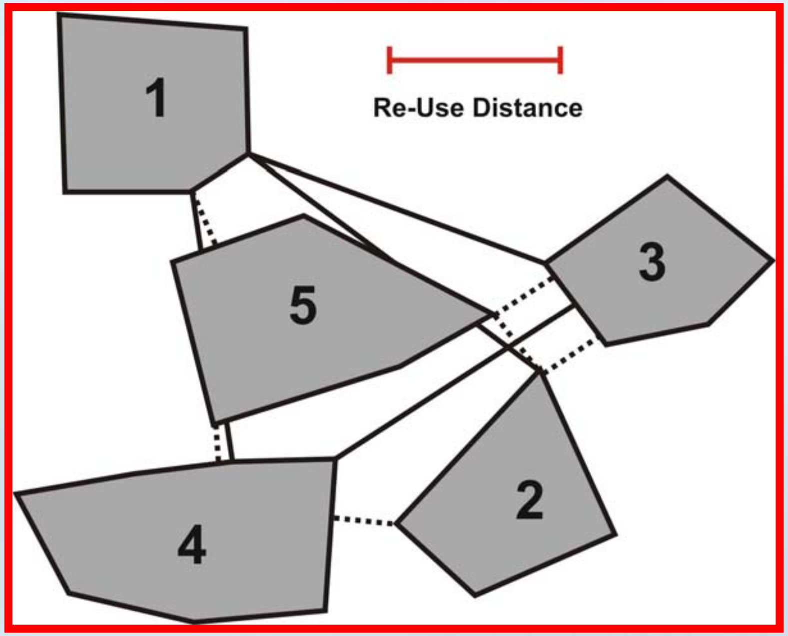
target: use available spectrum to fit in requirements such that interference is minimized

method: stochastic optimization

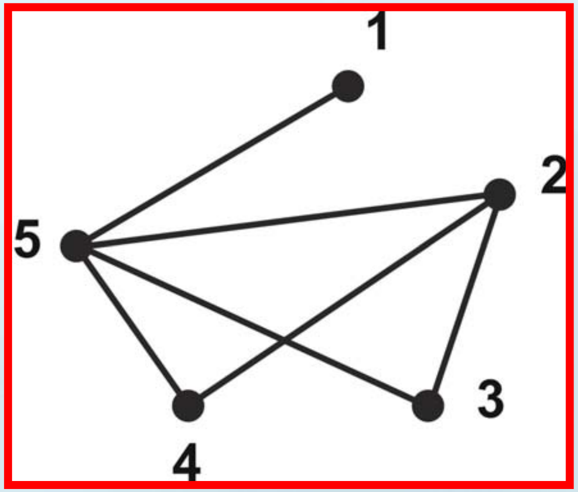
Mathematical Algorithms

Spectrum Demand Study

Graph Coloring Algorithms



mapping
to graph



Mathematical Algorithms

Spectrum Demand Study

Graph Coloring Algorithms

target: assign a color to each vertex such that vertices connected get different colors whilst minimizing the total number of required colors

complexity: high dimensional combinatorical optimization problem

N allotments, M frequencies,
e.g. N=20, M=10 results in 10^20 different possibilities !!!

brute force approach:

0.000001 s to check one → 10^14 s = 3.17*10^6 ys !!!

→ how to tackle that (NP-hard) problem ???

Mathematical Algorithms

Spectrum Demand Study

Graph Coloring Algorithms

solution: look for almost optimal solution

methodology: sequential deterministic graph coloring

- generate an ordering of vertices
  - use vertex degrees: number of edges ending in a vertex
- assign frequencies in compliance with adjacency relations

Mathematical Algorithms

Spectrum Demand Study

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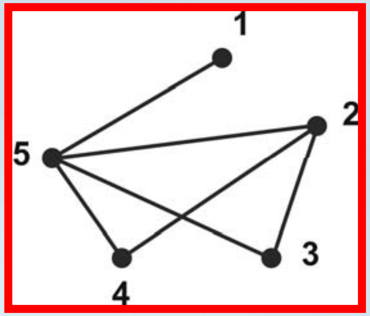

vertex	5	2	4	3	1
degree	4	3	2	2	1
color					

Mathematical Algorithms

Spectrum Demand Study

Graph Coloring Algorithms

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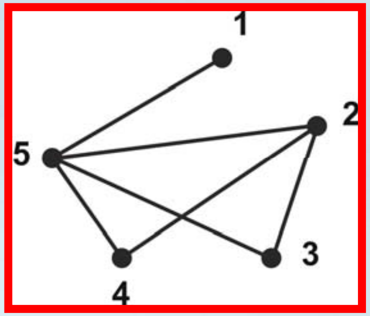

vertex	5	2	4	3	1
degree	4	3	2	2	1
color	0	1	2	2	1

→ at RRC-06 many different orderings have been employed

Mathematical Algorithms

Constrained Frequency Assignment Problems

spectrum demand study limited help for constrained problems:

- **spectrum accessibility globally restricted and invidualized**

Mathematical Algorithms

Constrained Frequency Assignment Problems

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- **individual constraints overriding the results of the compatibility analysis have to be taken into account (administrative declarations)**

Mathematical Algorithms

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- **graph coloring algorithms adapted to particular boundary conditions and constraints**

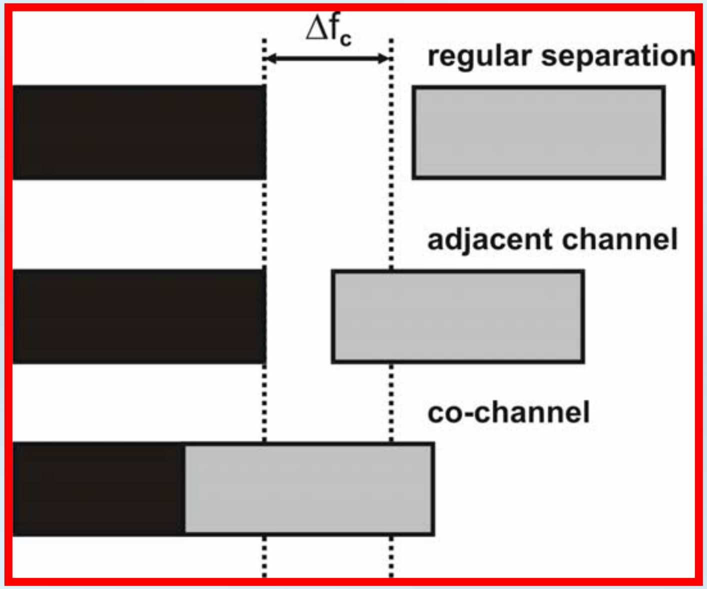
Mathematical Algorithms

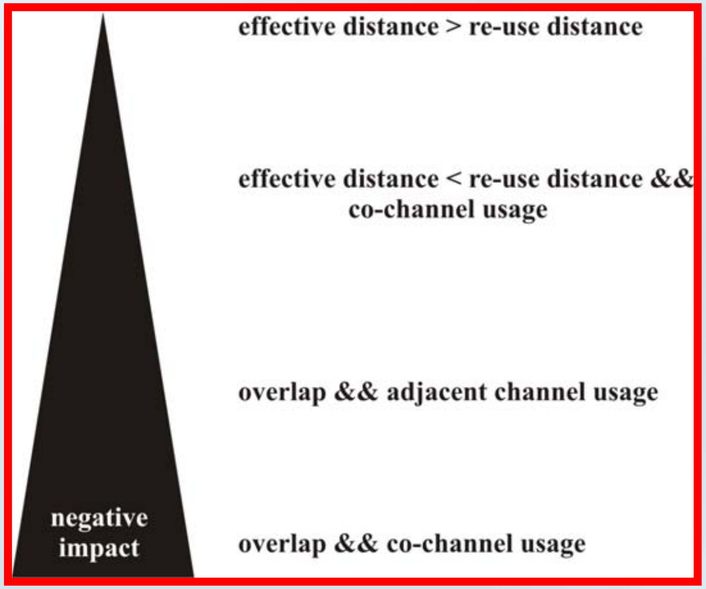
Constrained Frequency Assignment Problems

Impact in terms of Interference

several layers of allotment mean overlapping allotments

→ co-channel usage vs. adjacent channel usage





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→ **stochastic optimization strategies can help**

example : Great Deluge Algorithm

Mathematical Algorithms

Constrained Frequency Assignment Problems

Stochastic Optimization

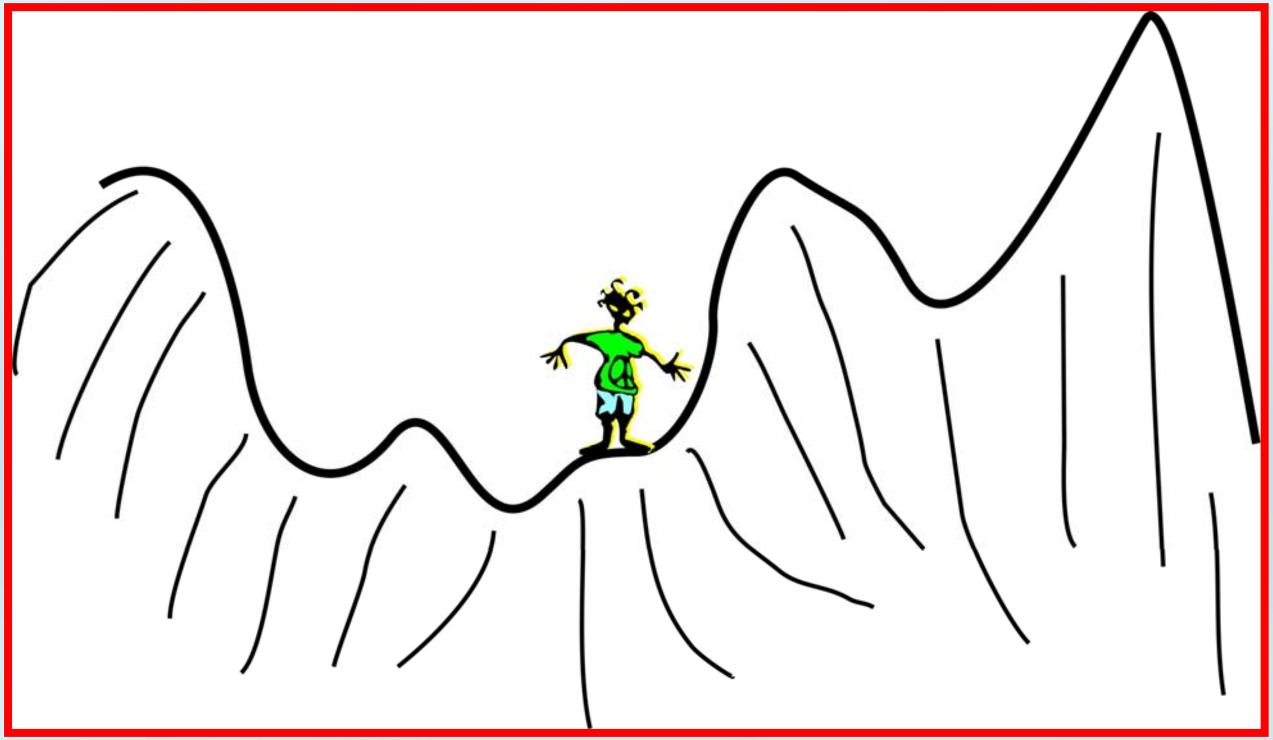
stochastic optimization can be applied if

- **state or configuration of a system can be fully described by a set of parameters**
  (here: configuration corresponds to assigning a frequency to all requirements)
- **a quality function can be defined to assess a configuration of the system**
  (here: number of used channels, conflicting frequency assignments)
- **„neighborhood“ can be defined in configuration space**
  (here: changing a single frequency results in a similar quality)
- **iterative stochastic search in configuration space can be defined**
  (here: start with one frequency assignment, generate a new one out of previous)
- **dynamically changing access to states in configuration space can be defined**

Mathematical Algorithms

Constrained Frequency Assignment

Great Deluge Algorithm



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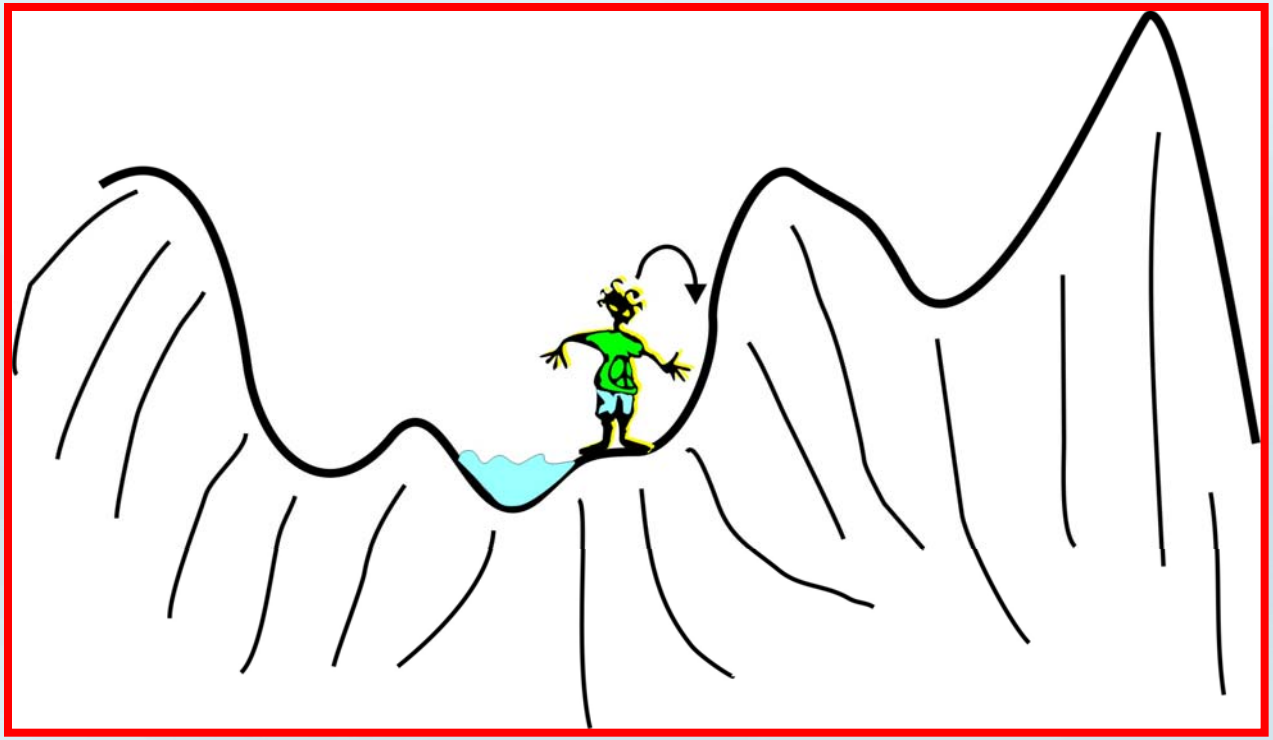
Constrained Frequency Assignment

Great Deluge Algorithm



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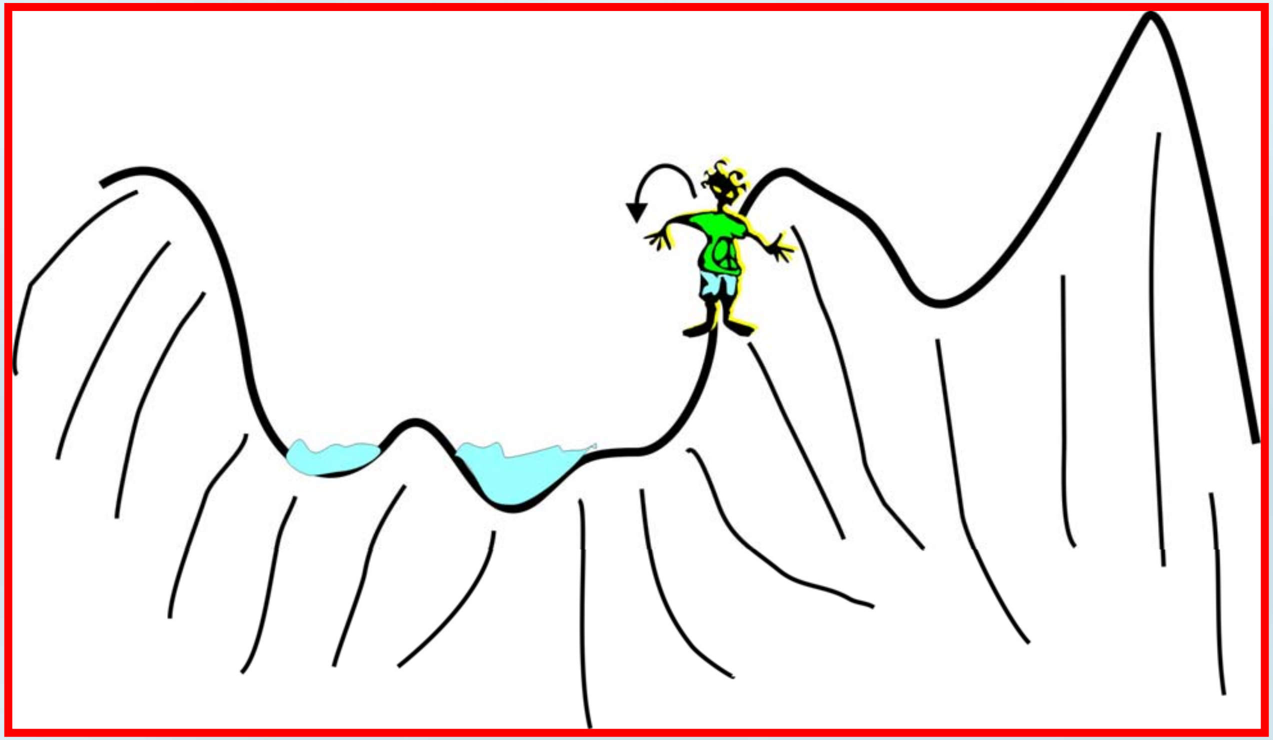
Constrained Frequency Assignment

Great Deluge Algorithm



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Constrained Frequency Assignment

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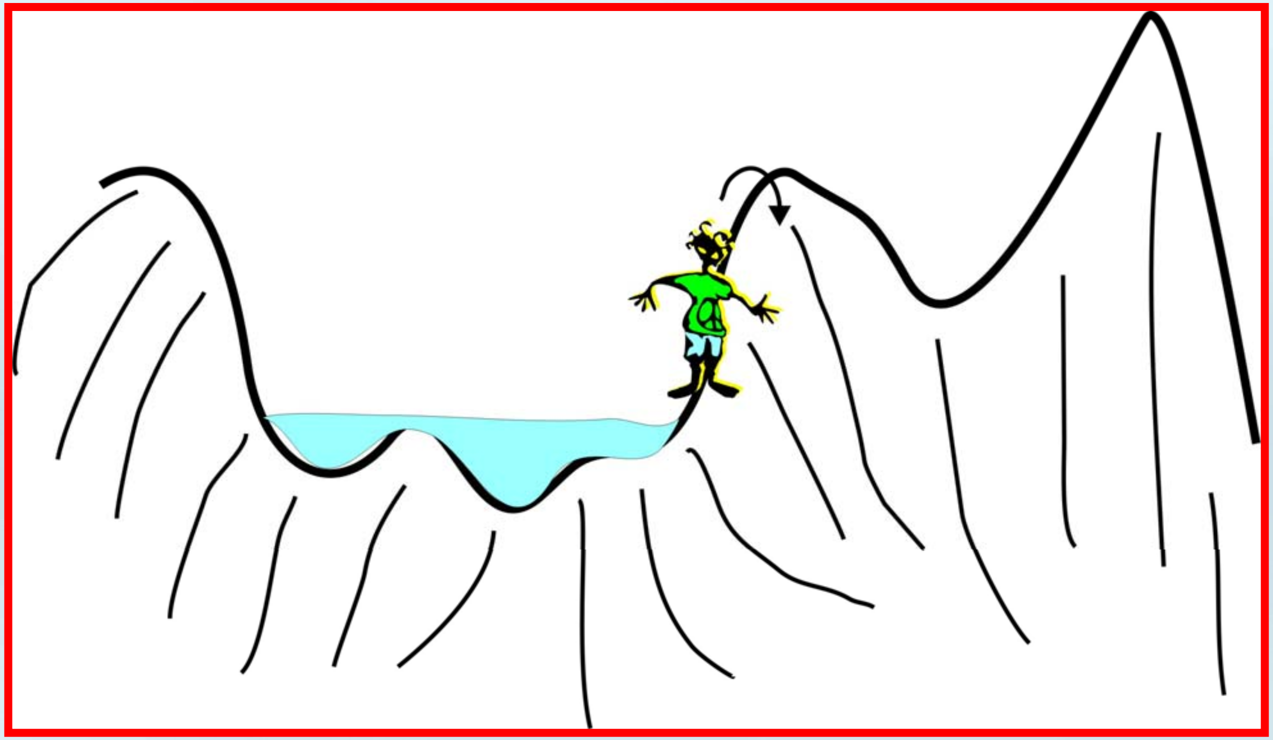

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Constrained Frequency Assignment

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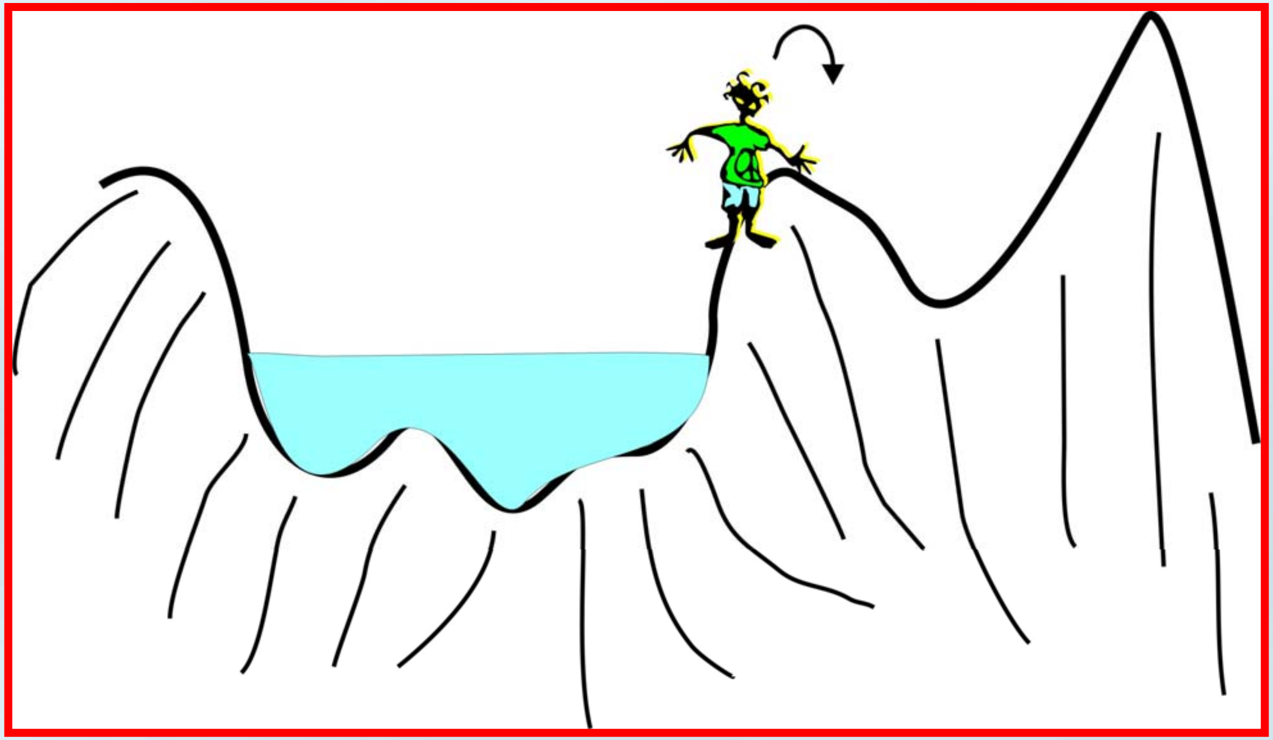

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Constrained Frequency Assignment

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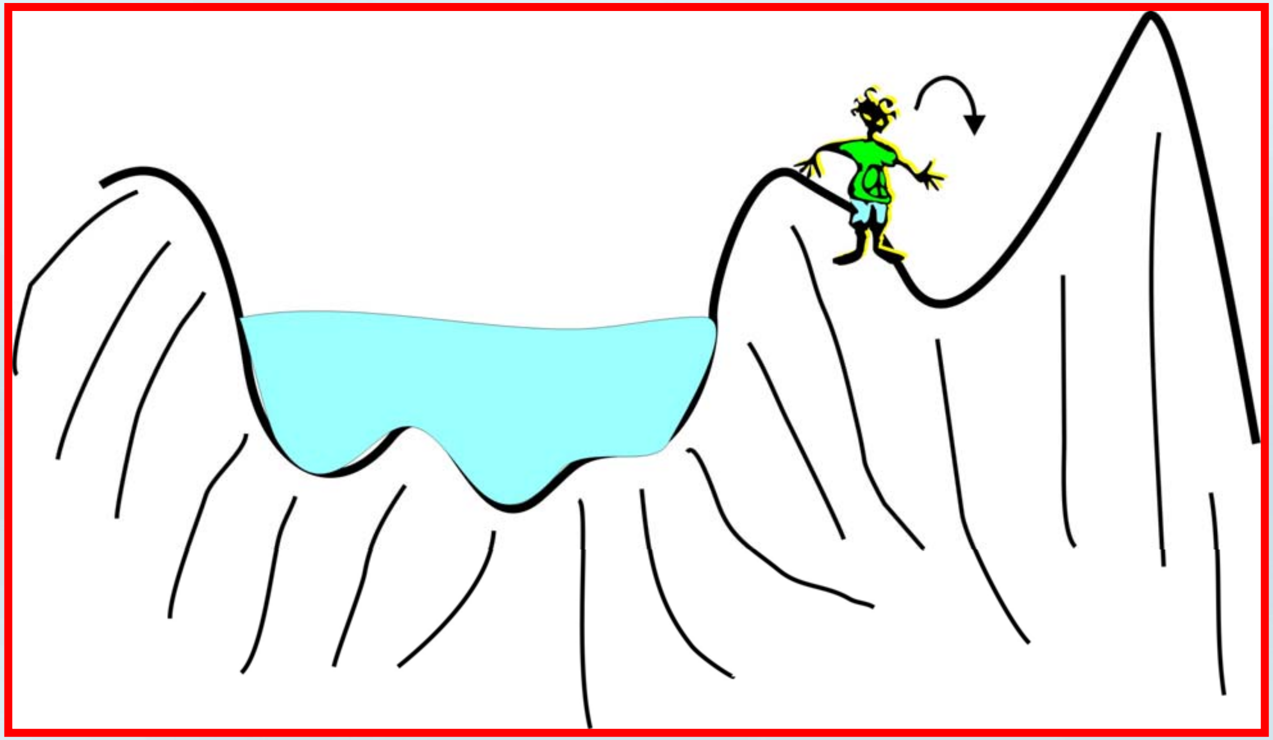

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Constrained Frequency Assignment

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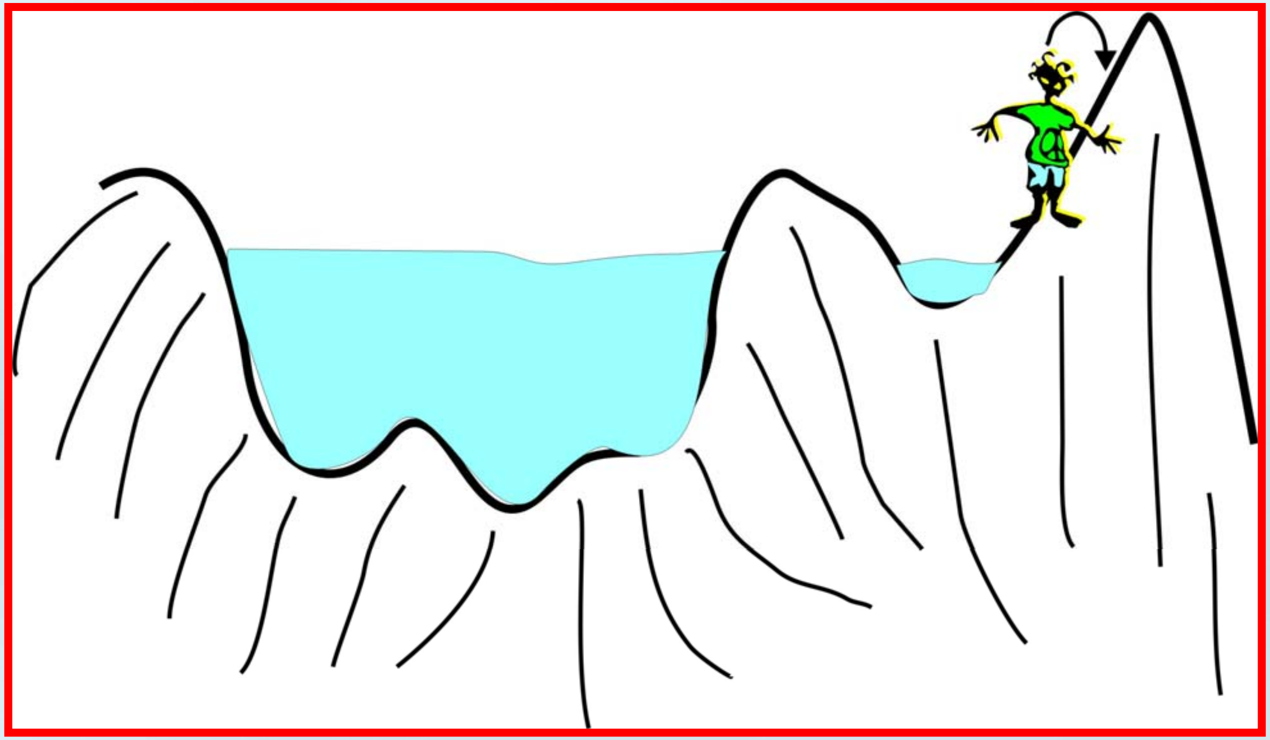

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Constrained Frequency Assignment

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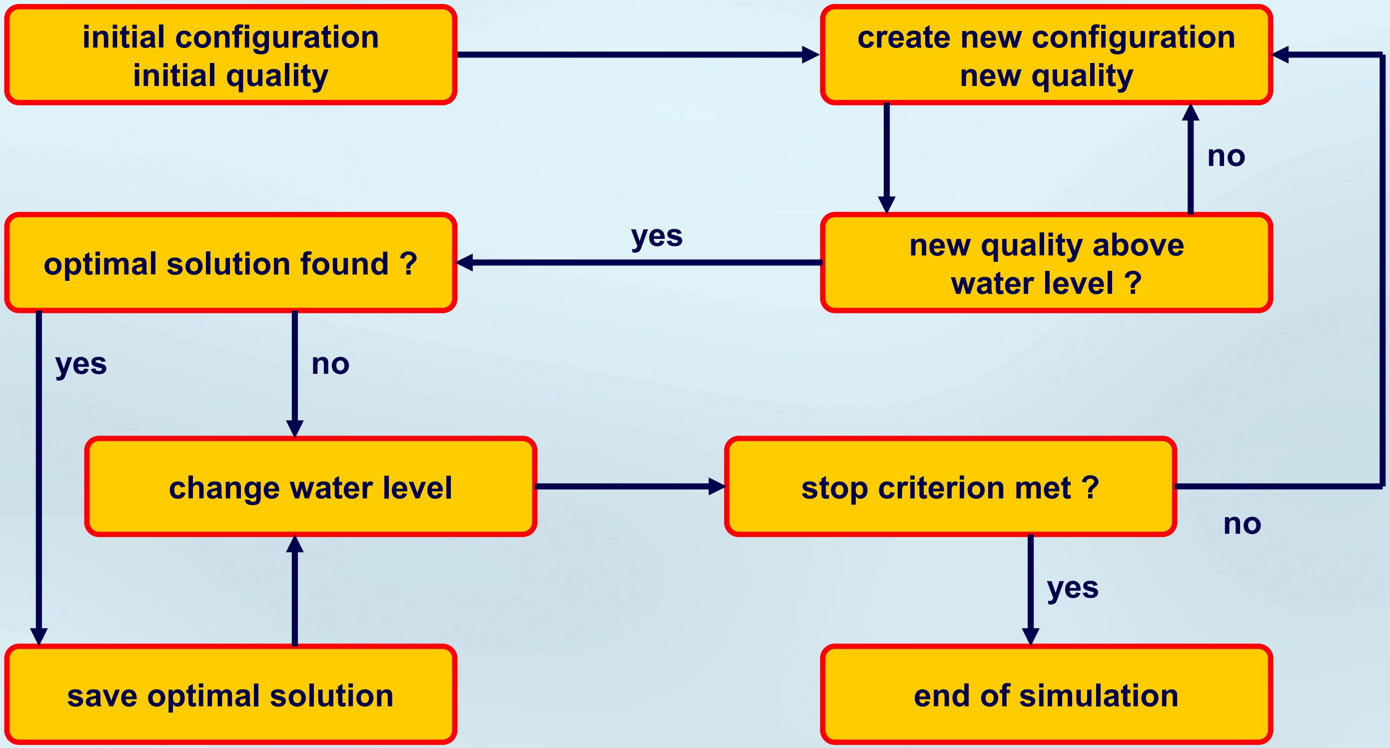


Mathematical Algorithms

Constrained Frequency Assignment

Quality Function

assessment of mutual impact of two co-channelled allotments:

$$\Delta_{ij} = RU - ED(i, j)$$

measure of overlap between allotment areas:

$$\Psi_{ij} = \frac{2 \cdot \text{size of overlapping area}}{\text{area}(i) + \text{area}(j)}$$

Mathematical Algorithms

Constrained Frequency Assignment

Quality Function

$$\Delta_{ij} = \begin{cases} 0 & , \quad RU < ED(i,j) \\ RU - ED(i,j) & , \quad RU \geq ED(i,j) \geq 0 \\ RU + 100^*\psi_{ij} & , \quad \text{for overlapping areas} \end{cases}$$

$$\Delta = \sum_{i,j} \Delta_{ij}$$

summation of pair contributions

→ **example: planning exercise submitted to ECC-TG4**

Concluding Remarks

- pair contributions: „solution globally optimal but locally a disaster“
  → cluster based quality function ?

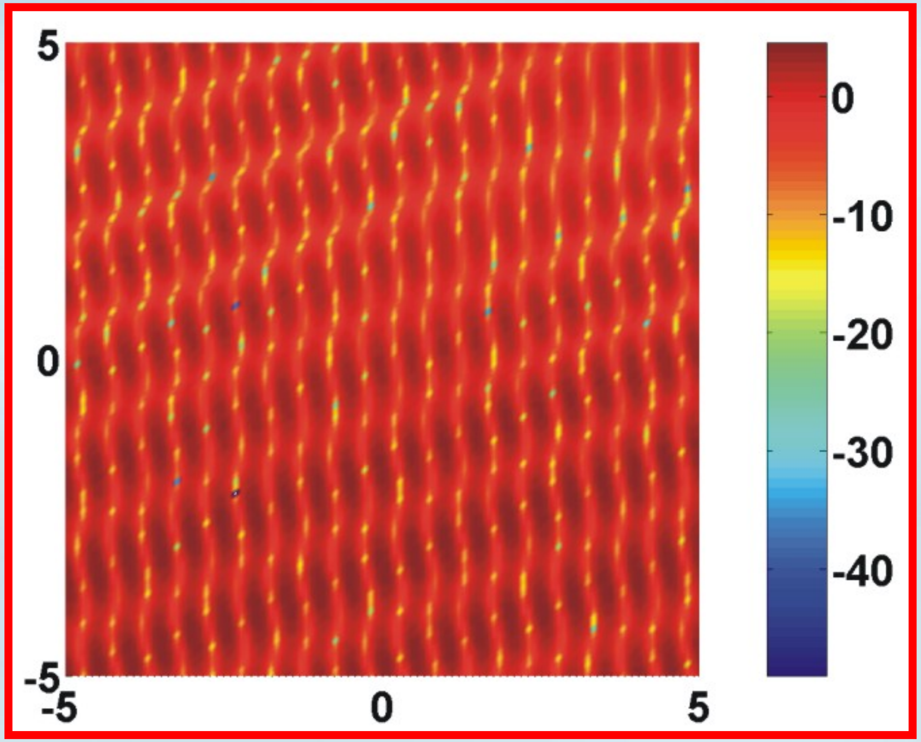
- reduction of computational times by means of parallel computing

- stochastic optimization also applicable to network planning:
  - site selection
  - optimization of erp, antenna pattern, time delay
  - area or population coverage
  - network cost optimization

Thank you very much for your attention !

Planning Parameters

Coverage Prediction

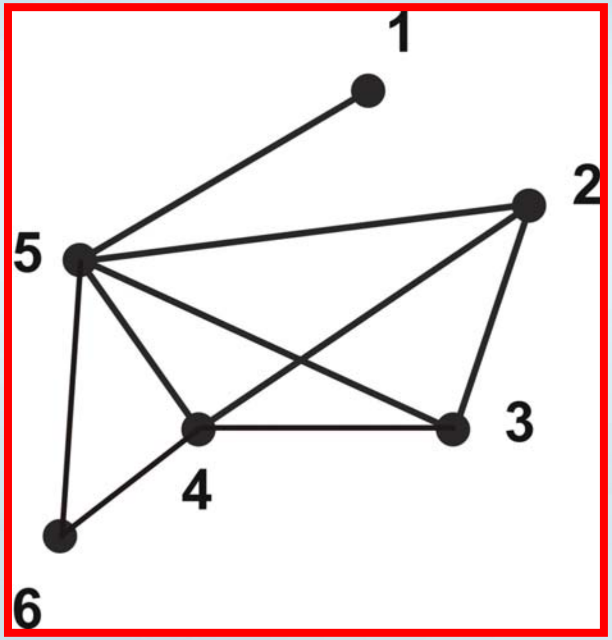


multipath environment gives rise to spatial variation of field strength

Mathematical Algorithms

Spectrum Demand Study

Clique Analysis



maximum clique: { 2, 3, 4, 5}

→ vertices are members of several cliques!

Mathematical Algorithms

Spectrum Demand Study

Clique Analysis

quality of solution: is that a good or bad result ?

idea: what is the chromatic number χ of the graph?
→ investigate the cliques of the graph

clique: other word for complete graph referring to a graph where all vertices have the same degree κ

estimate: the vertex degree of the maximum clique κ_{max} is linked to the chromatic number χ :

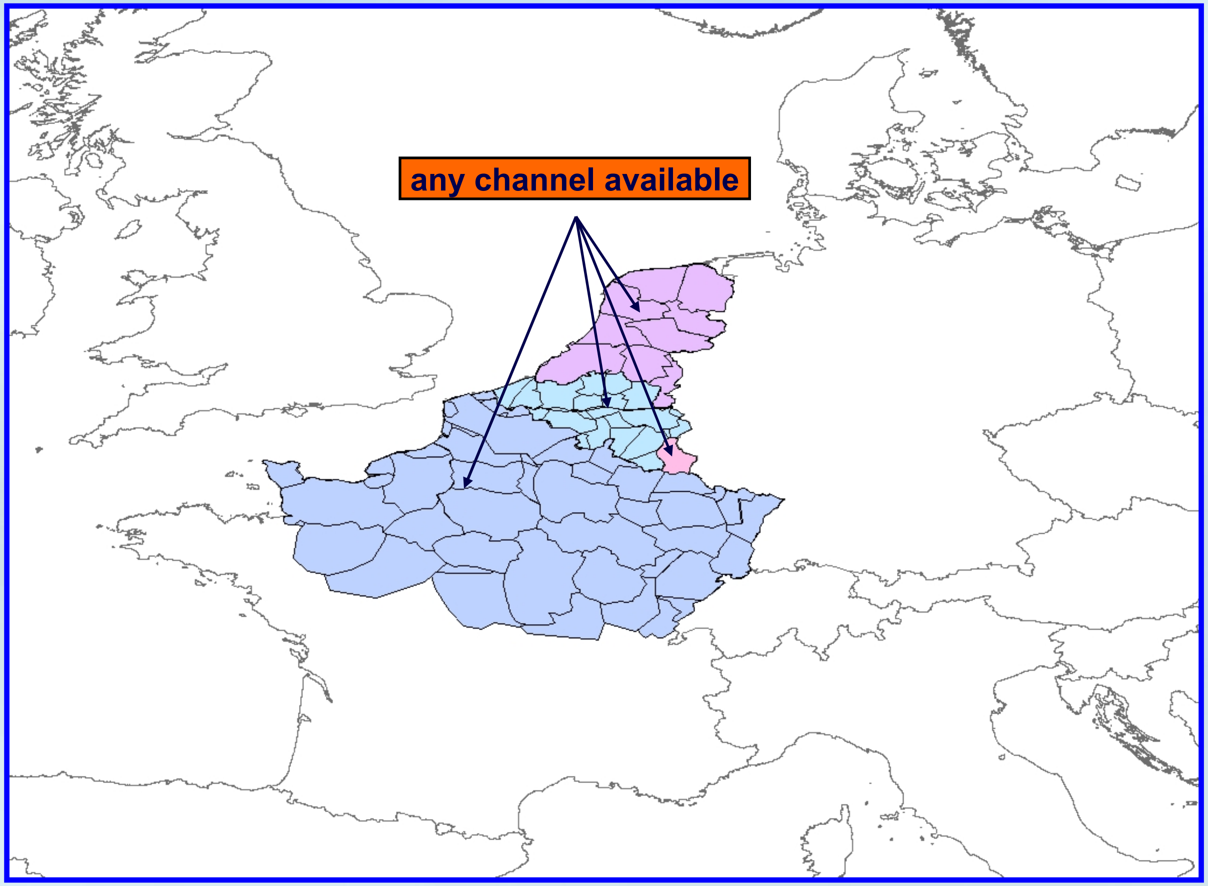
$$\chi \geq \kappa_{max} + 1$$

→ finding the maximum clique is NP-hard, too.
deterministic algorithm works for modest number of vertices

Mathematical Algorithms

Spectrum Demand Study

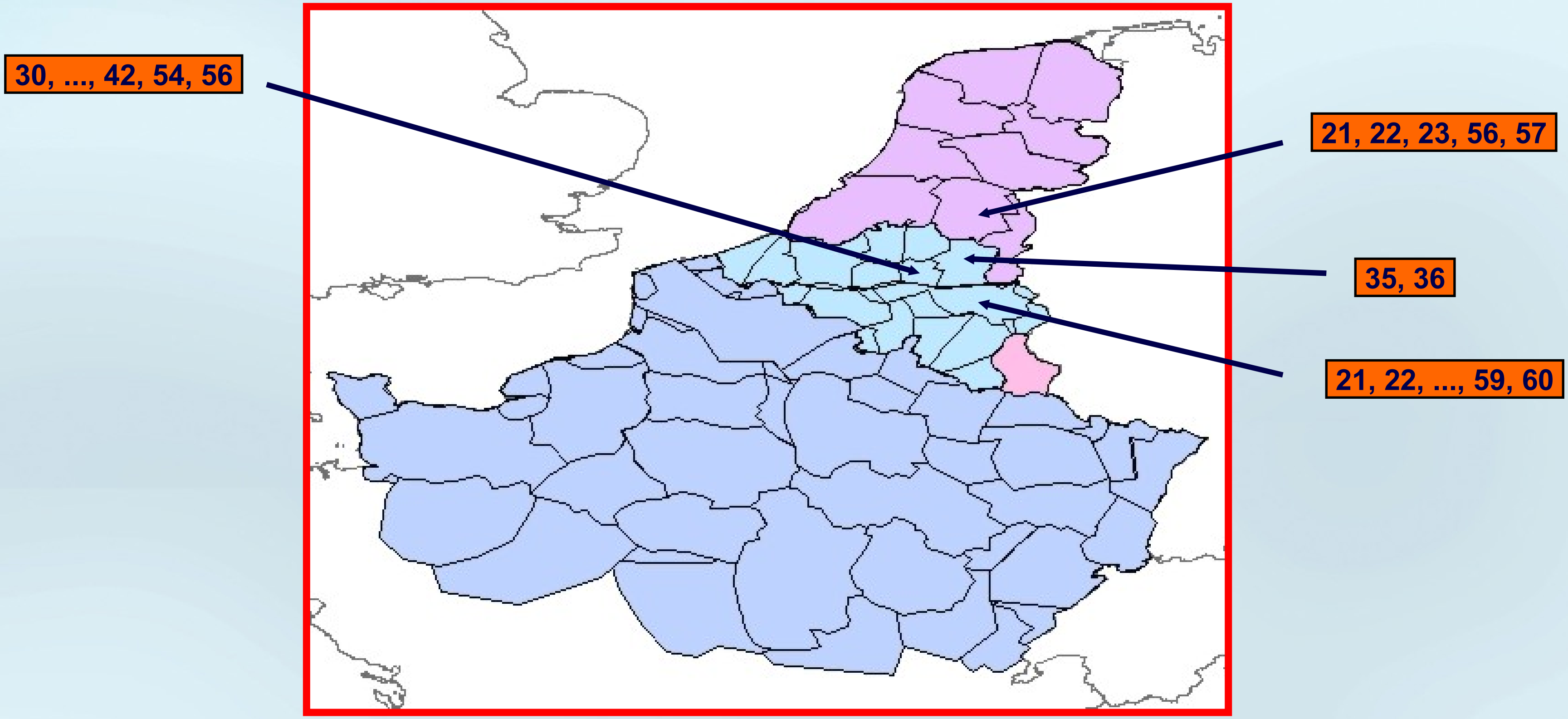
no boundary conditions



Mathematical Algorithms

Constrained Frequency Assignment

Restricted Access to Spectrum

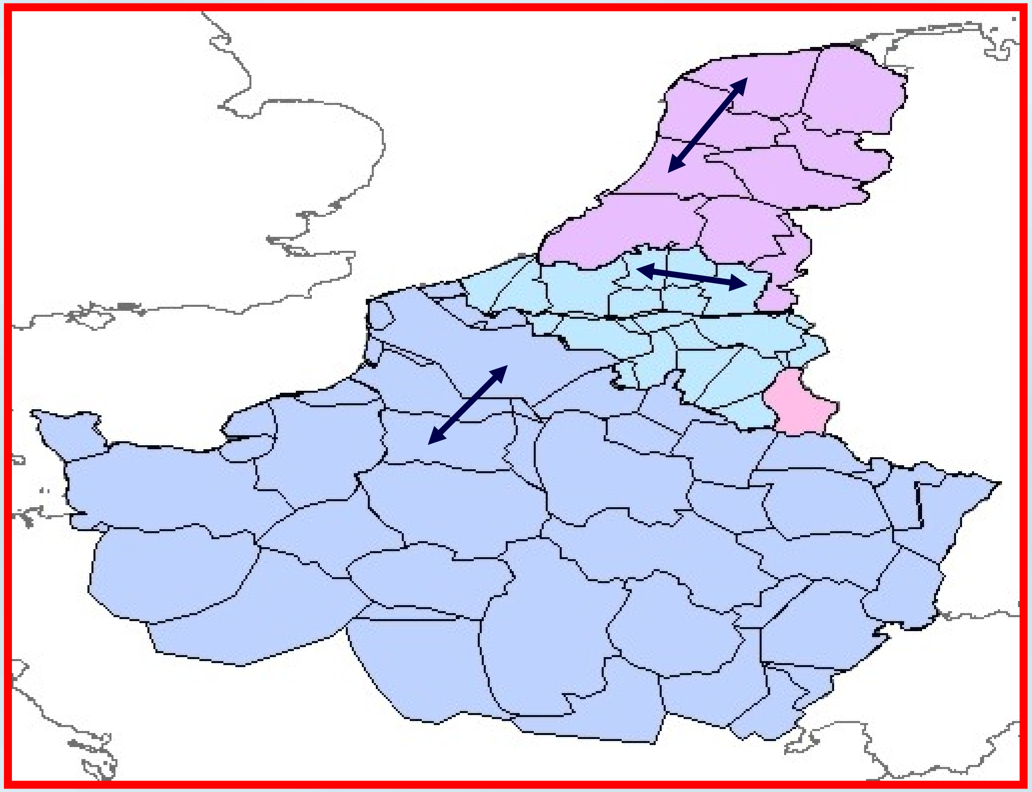


Mathematical Algorithms

Constrained Frequency Assignment

Administrative Declarations

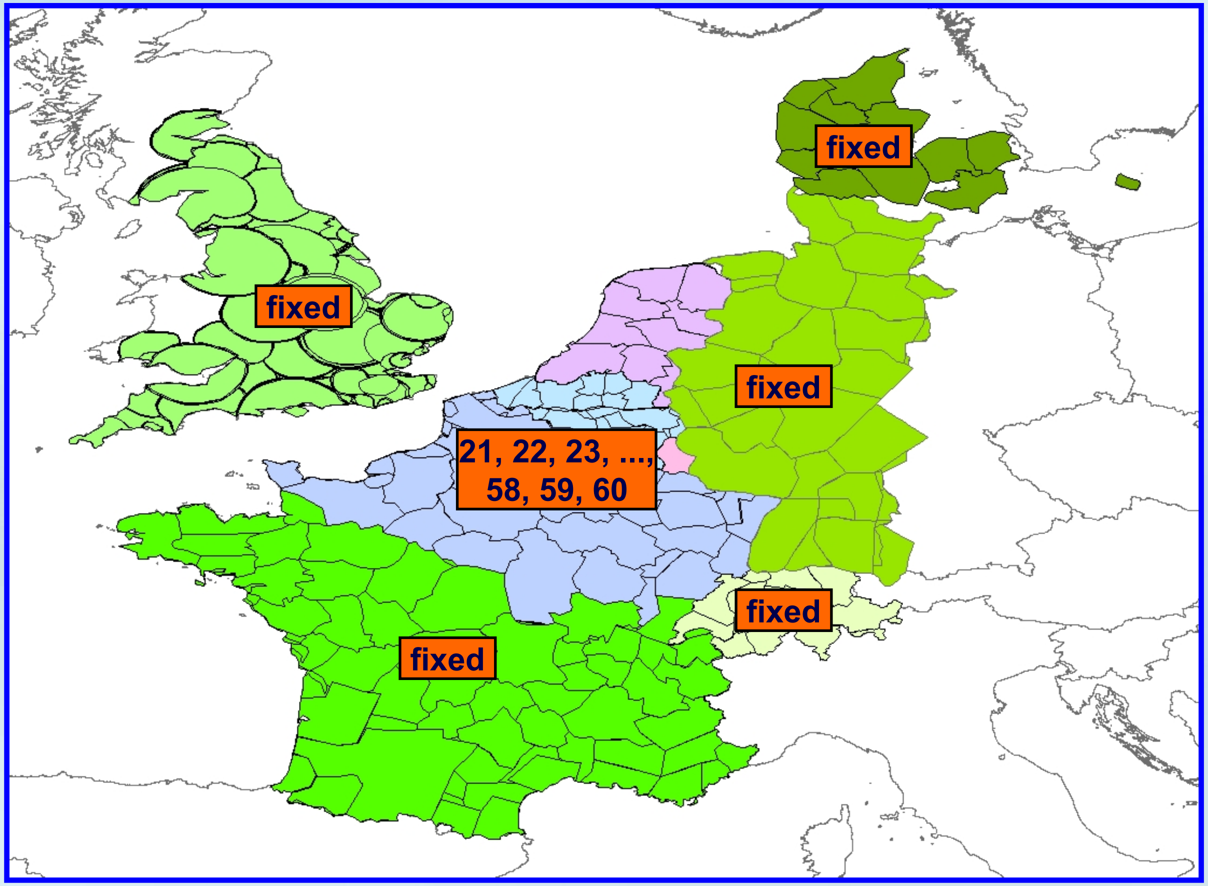
allotments are allowed to share a channel in contrast to result of compatibility analysis



Mathematical Algorithms

Constrained Frequency Assignment

Case 1 : Fixed Boundary Conditions



Mathematical Algorithms

Constrained Frequency Assignment

Case 2 : Restricted Access to Spectrum