Designing telecommunication networks by integer programming

TU Berlin
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Remark

- These are the slides of the lecture held on May 3. For copyright reasons some slides, in particular slides with pictures/photos, had to be removed.

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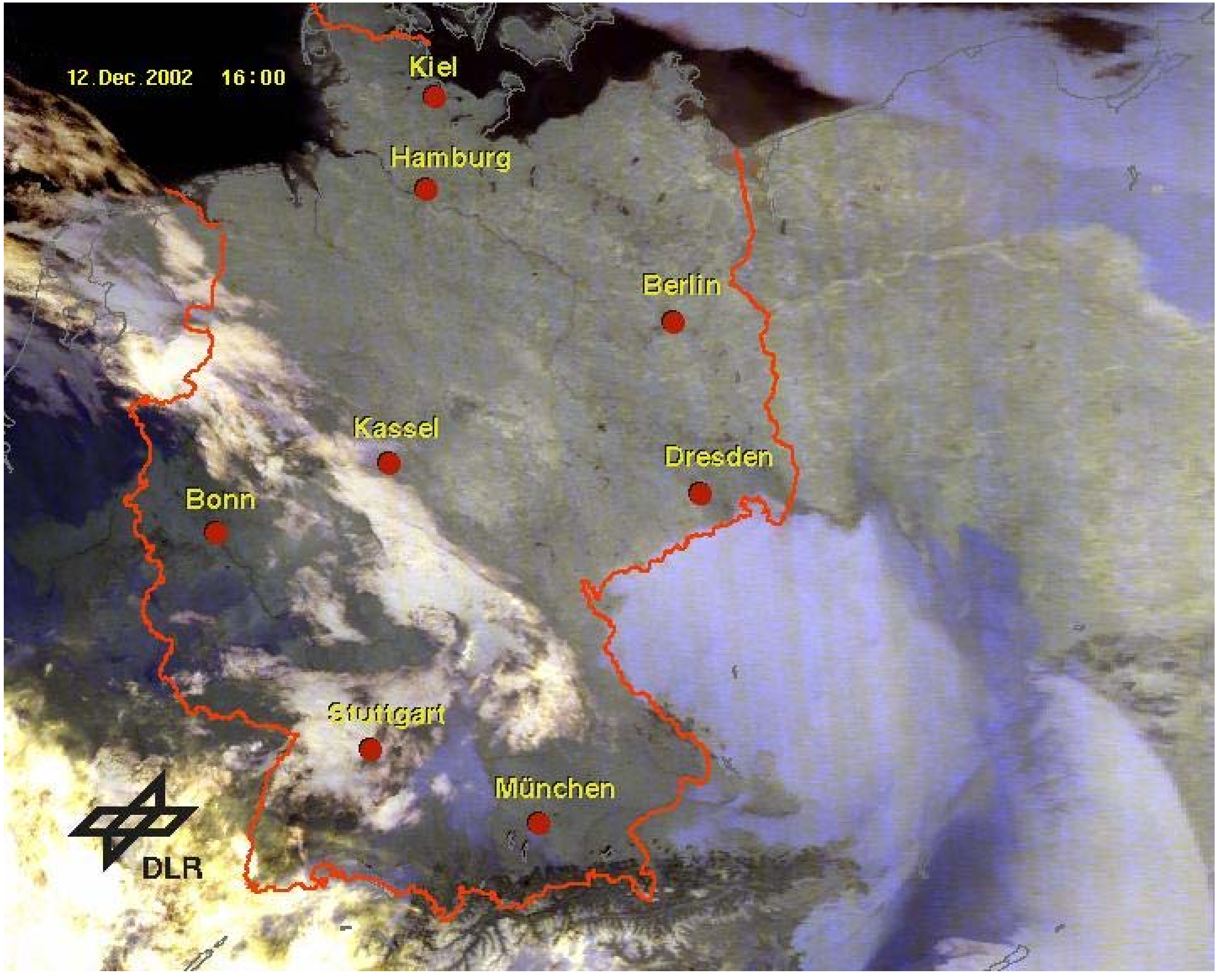
Germany: Satellite-Picture of DLR



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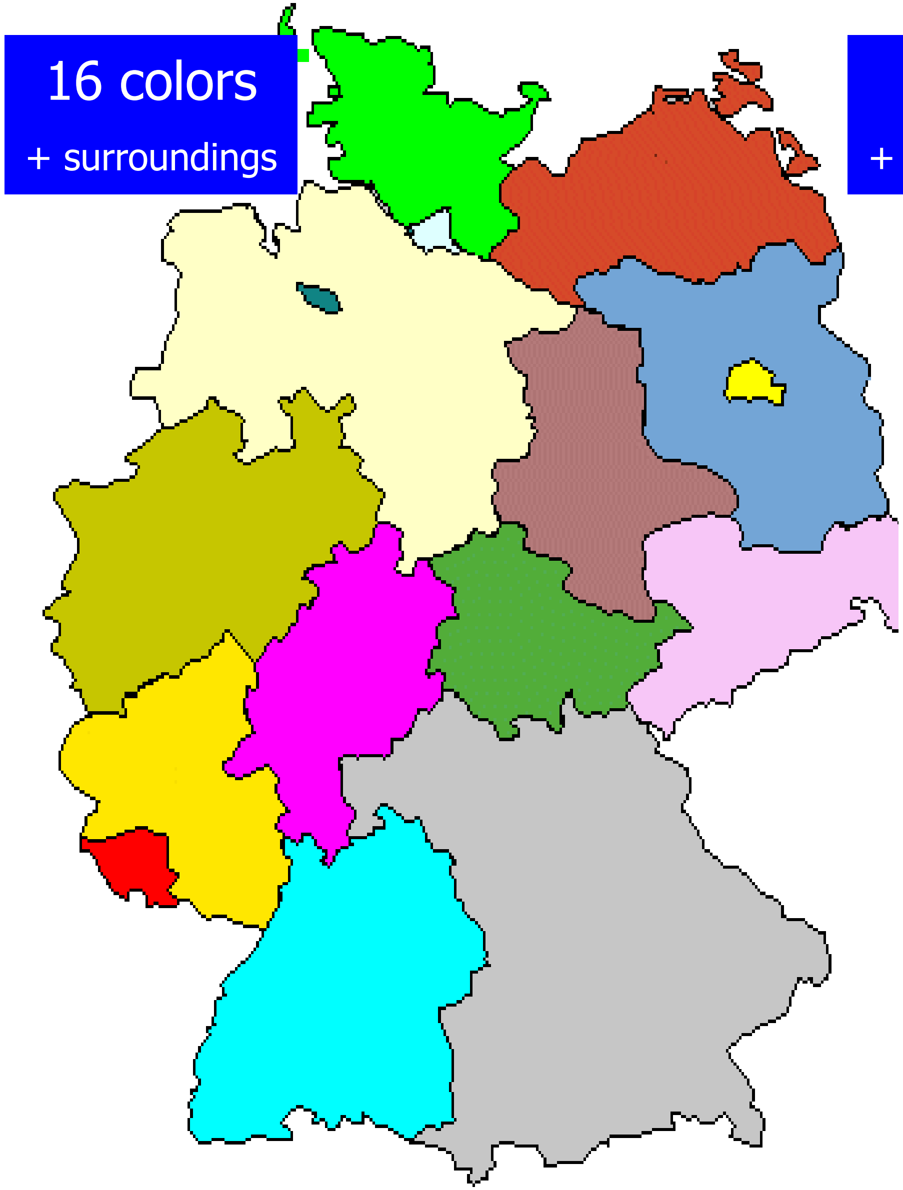
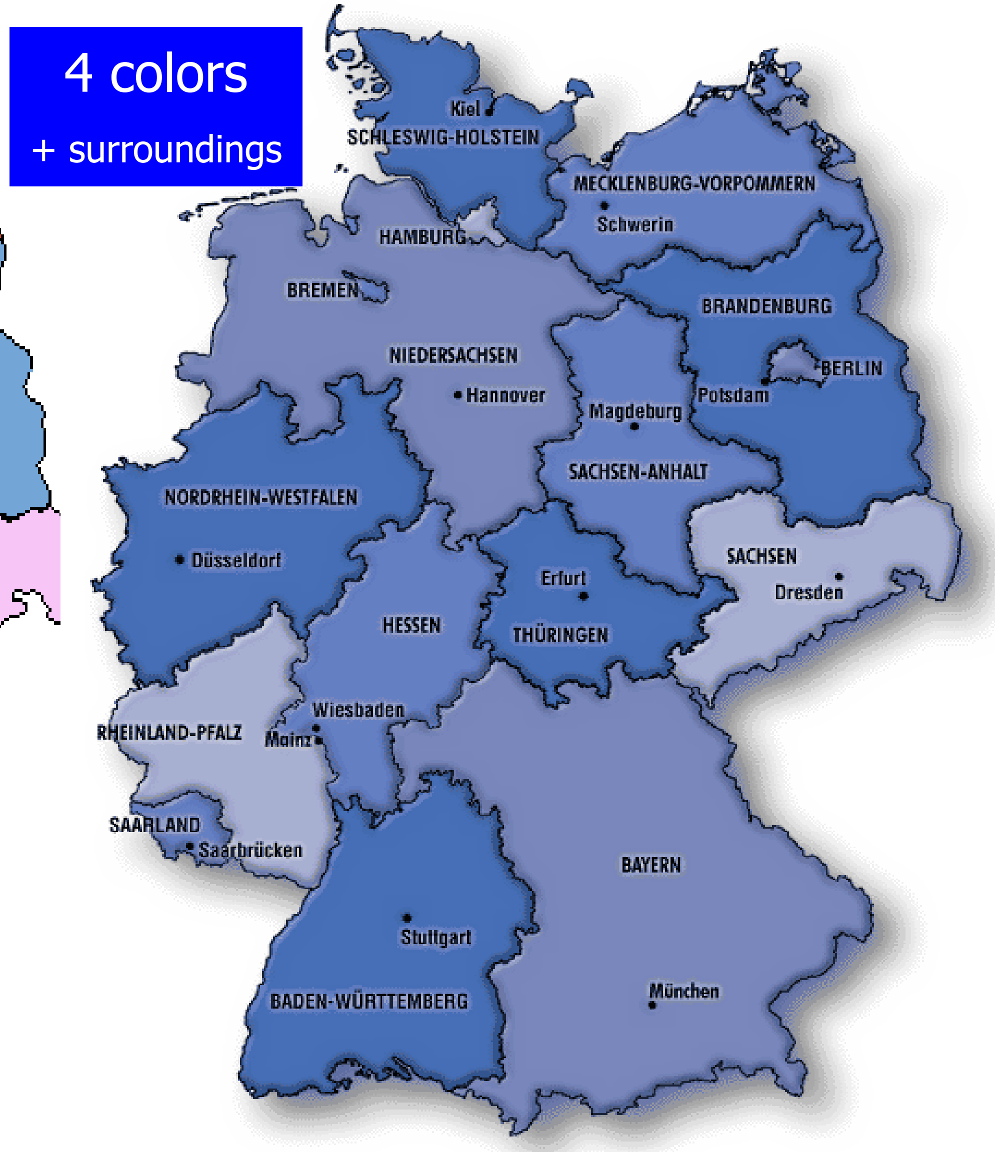
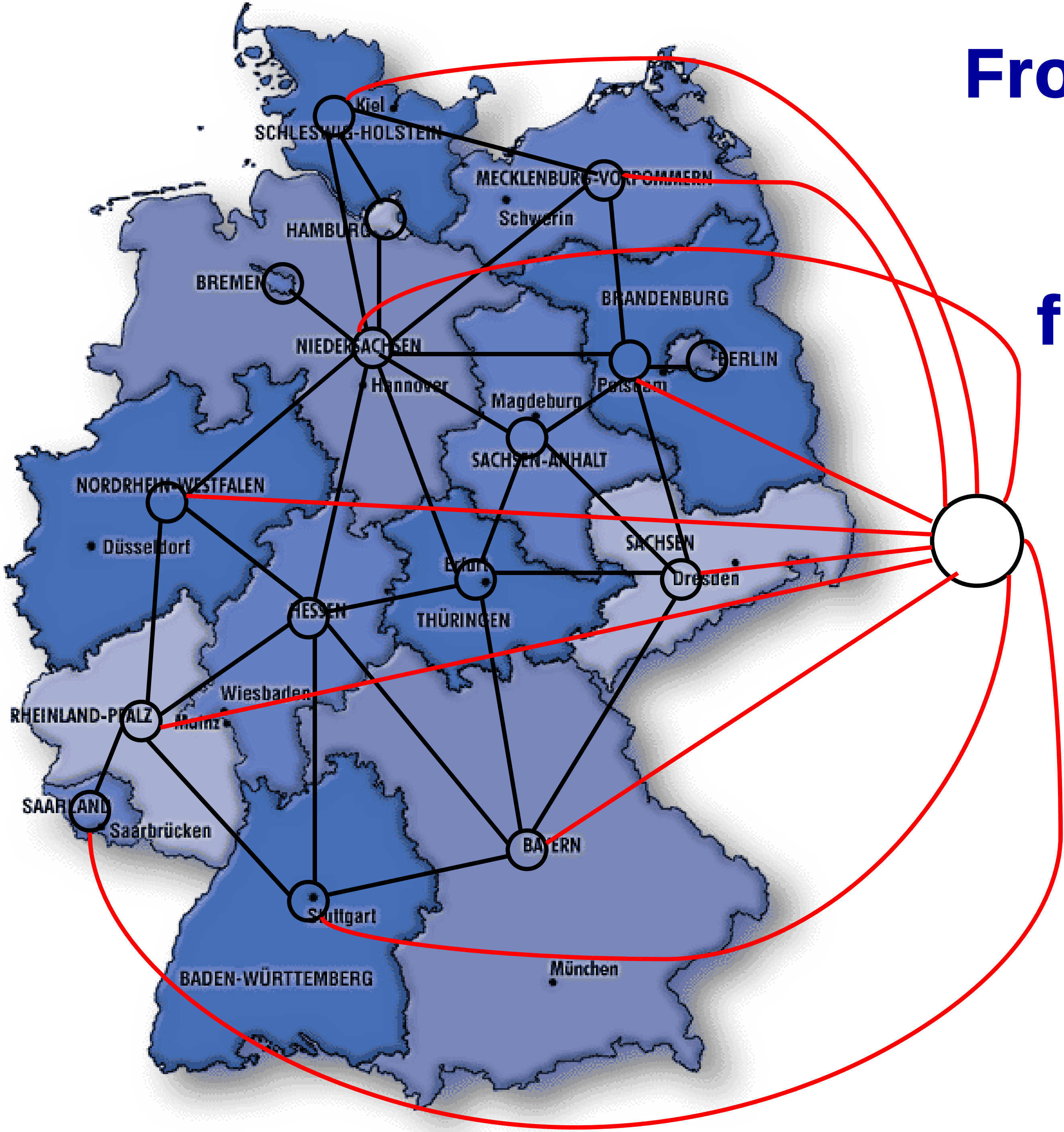
Two Germany Maps



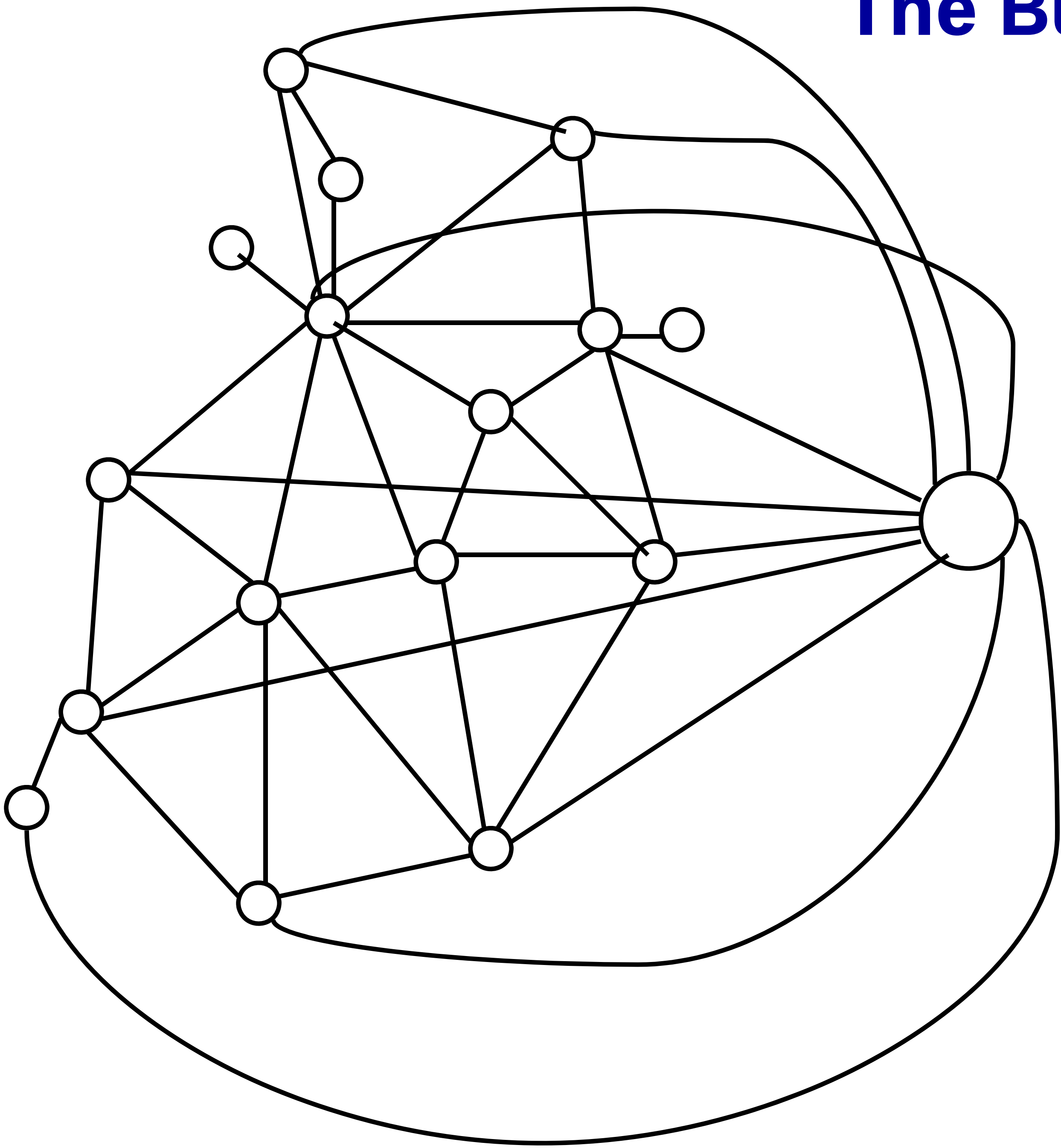




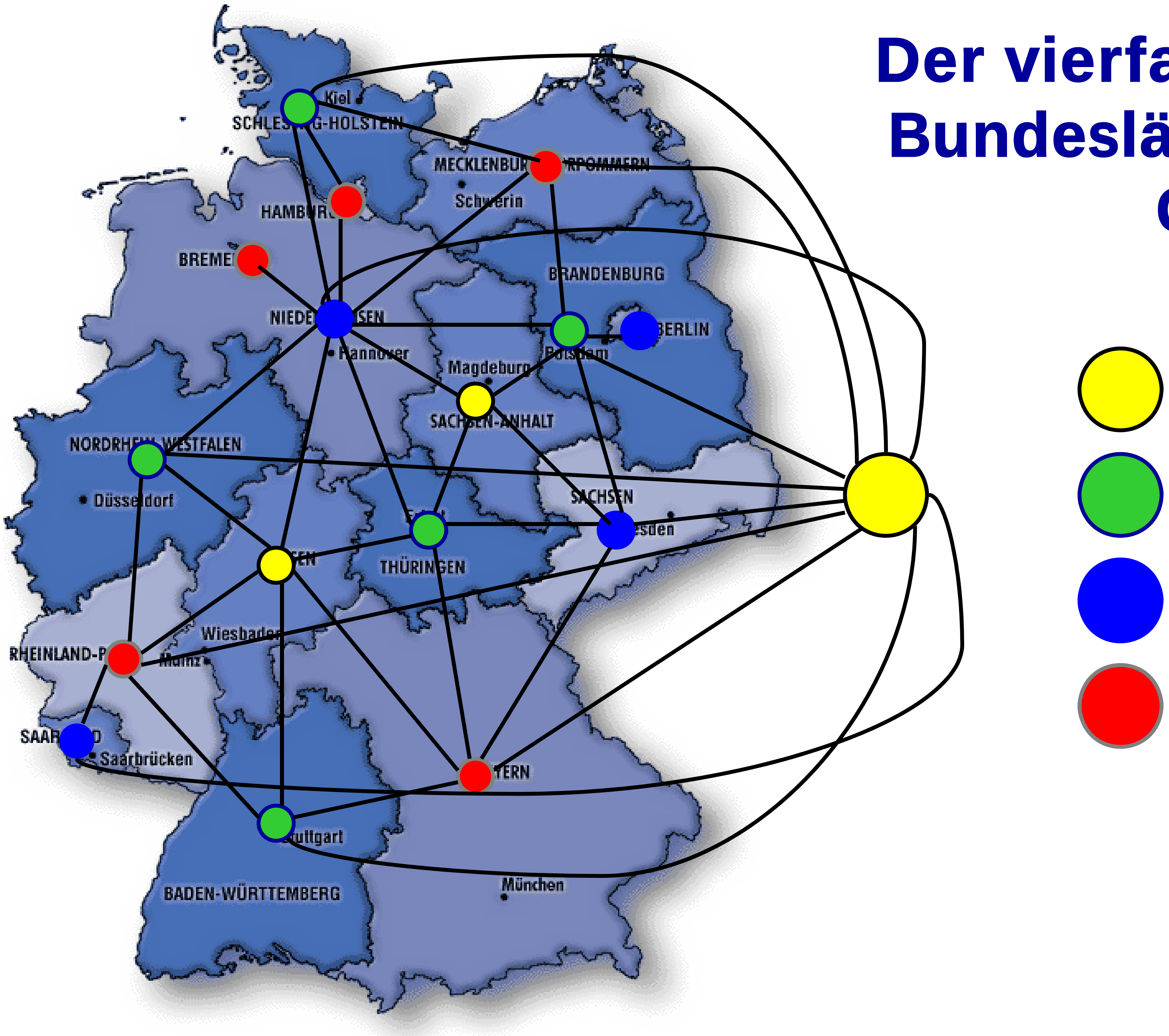
From countries to nodes,

from borders to edges

The Bundesländer-Graph



Der vierfarbige Bundesländer-Graph



Four colors suffice

The Four Color Problem (1852 – 1976)

1. K. Appel and W. Haken, Every planar map is four colorable. Part I. Discharging, Illinois J. Math. 21 (1977), 429-490.
2. K. Appel, W. Haken and J. Koch, Every planar map is four colorable. Part II. Reducibility, Illinois J. Math. 21 (1977), 491--567.
3. K. Appel and W. Haken, Every planar map is four colorable, Contemporary Math. 98 (1989).

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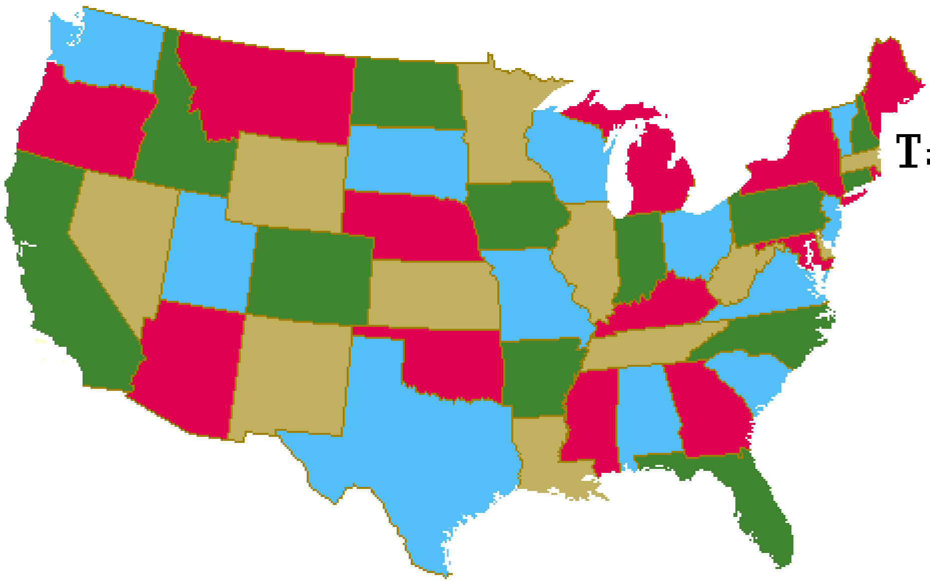
A new proof of the four color theorem

The Four Color Theorem

This page gives a brief summary of a new proof of the Four Color Theorem and a four-coloring algorithm found by Neil Robertson, Daniel P. Sanders, Paul Seymour and Robin Thomas.



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History of the 4-color-problems

History.

The Four Color Problem dates back to 1852 when Francis Guthrie, while trying to color the map of counties of England noticed that four colors sufficed. He asked his brother Frederick if it was true that **any** map can be colored using four colors in such a way that adjacent regions (i.e. those sharing a common boundary segment, not just a point) receive different colors. Frederick Guthrie then communicated the conjecture to DeMorgan. The first printed reference is due to Cayley in 1878.

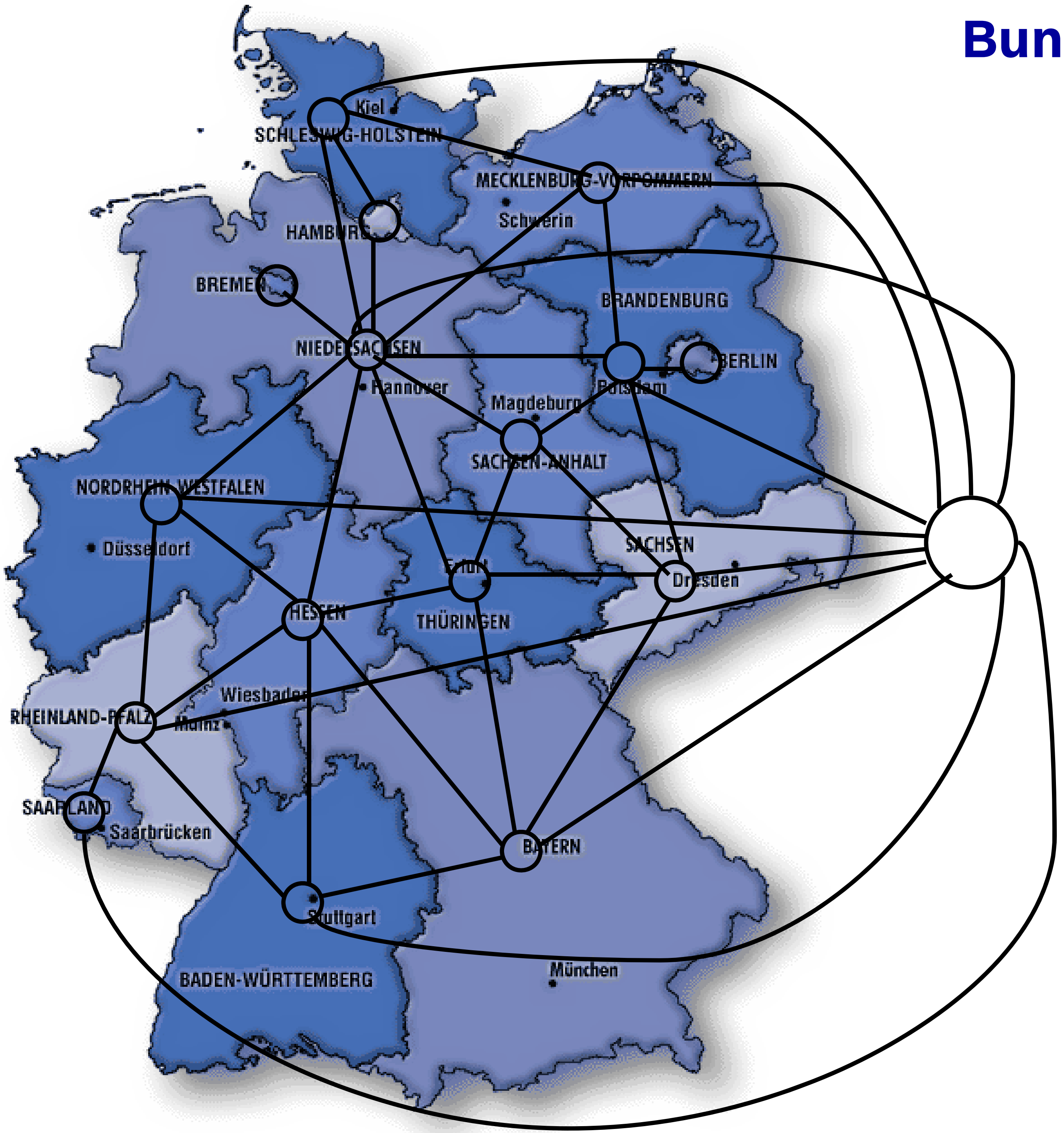
A year later the first `proof' by Kempe appeared; its incorrectness was pointed out by Heawood 11 years later. Another failed proof is due to Tait in 1880; a gap in the argument was pointed out by Petersen in 1891. Both failed proofs did have some value, though. Kempe discovered what became known as Kempe chains, and Tait found an equivalent formulation of the Four Color Theorem in terms of 3-edge-coloring.

The next major contribution came from Birkhoff whose work allowed Franklin in 1922 to prove that the four color conjecture is true for maps with at most 25 regions. It was also used by other mathematicians to make various forms of progress on the four color problem. We should specifically mention Heesch who developed the two main ingredients needed for the ultimate proof - reducibility and discharging. While the concept of reducibility was studied by other researchers as well, it appears that the idea of discharging, crucial for the unavoidability part of the proof, is due to Heesch, and that it was he who conjectured that a suitable development of this method would solve the Four Color Problem.

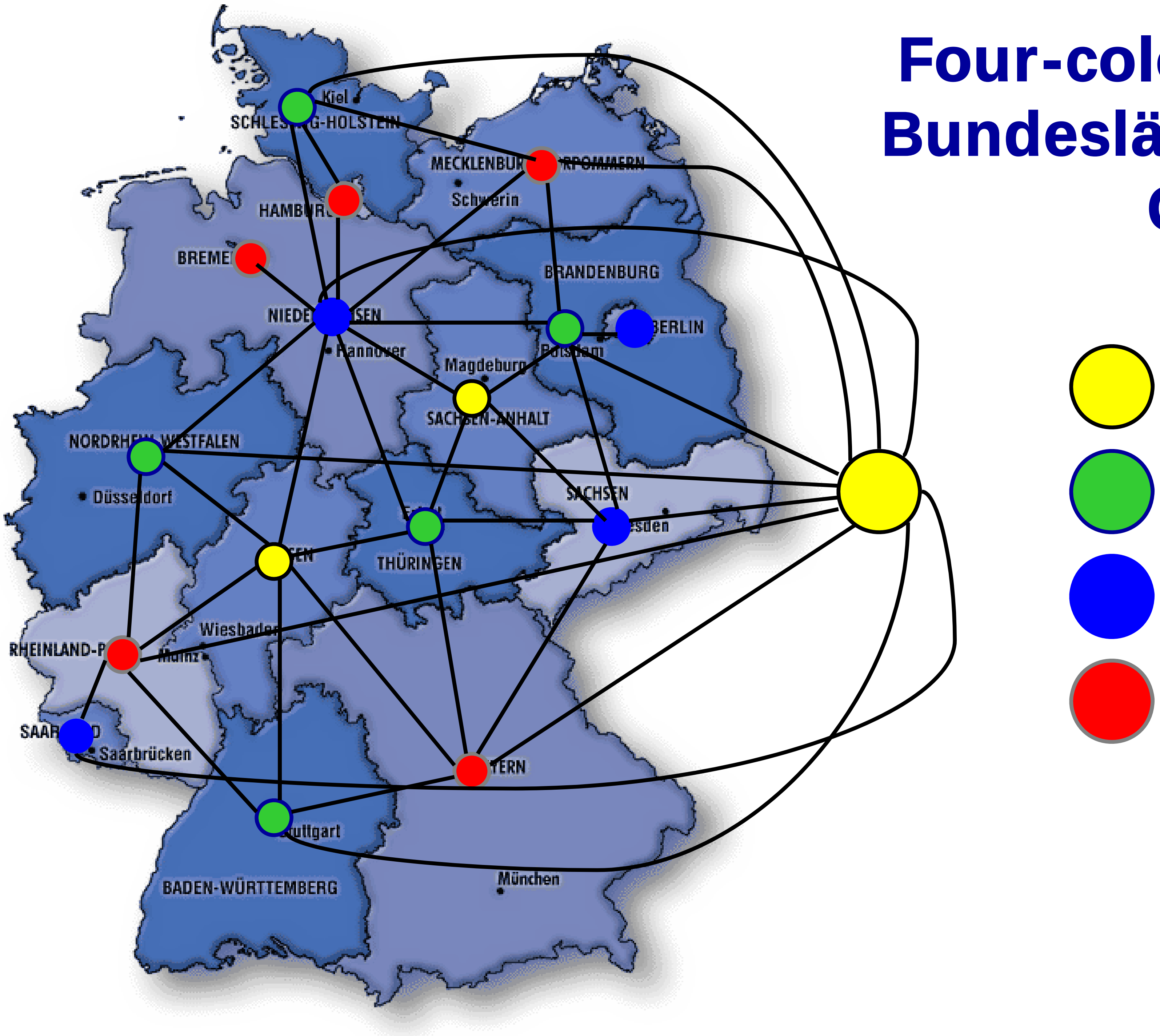
This was confirmed by Appel and Haken in 1976, when they published their proof of the Four Color Theorem [1,2].

Bundesländer-Graph

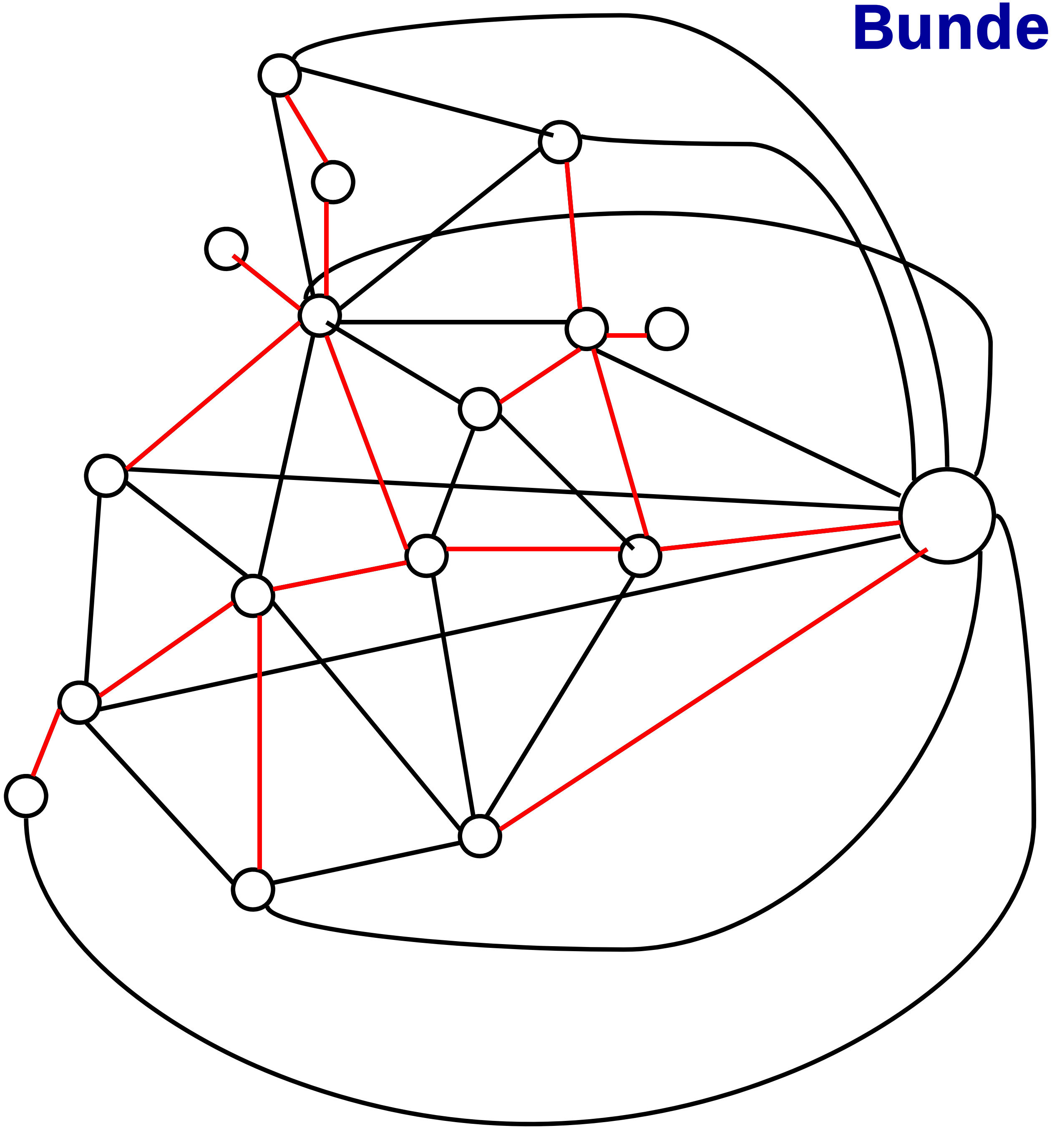
A Graph



Four-coloured Bundesländer-Graph

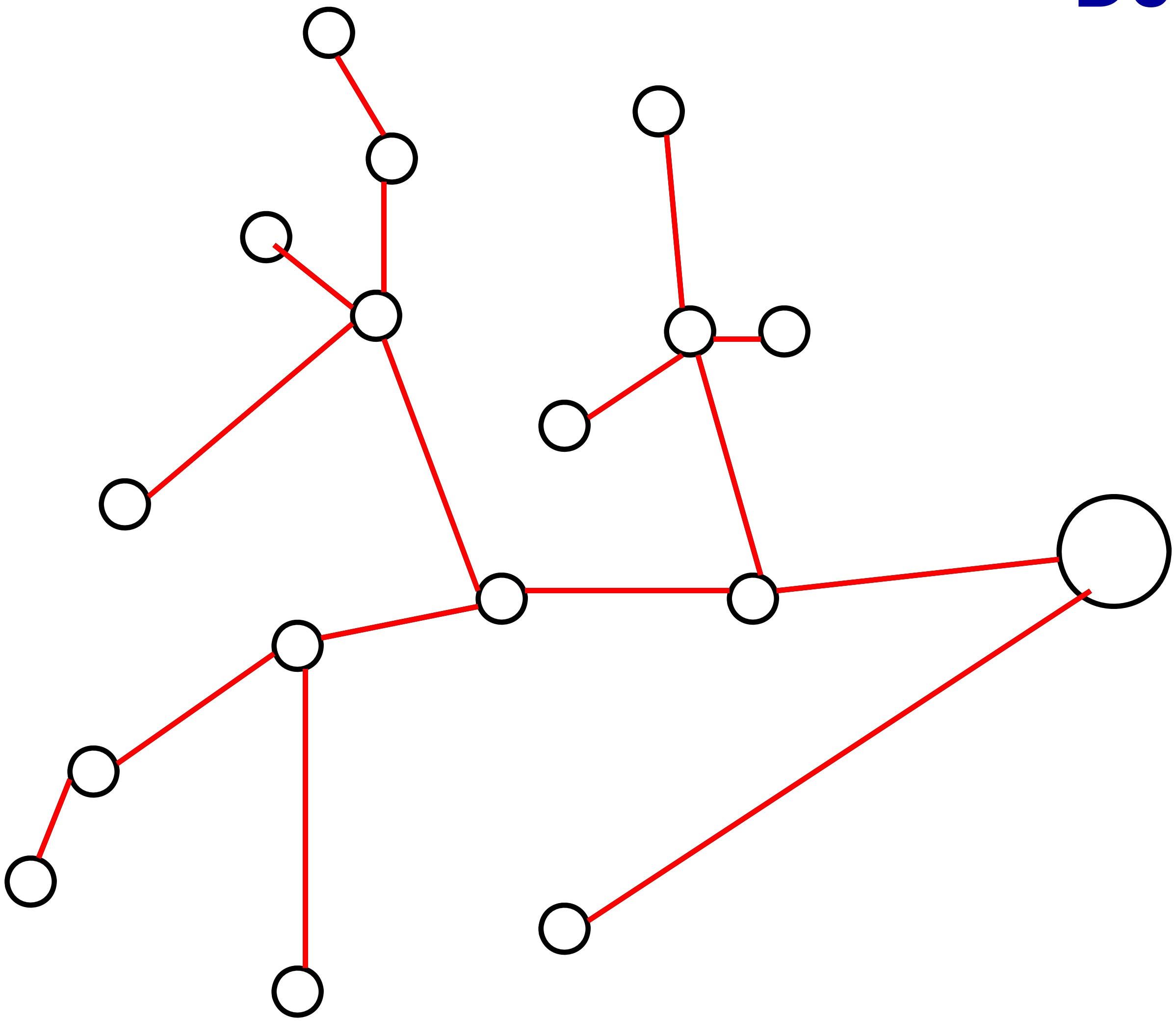


Bundesländer-Graph



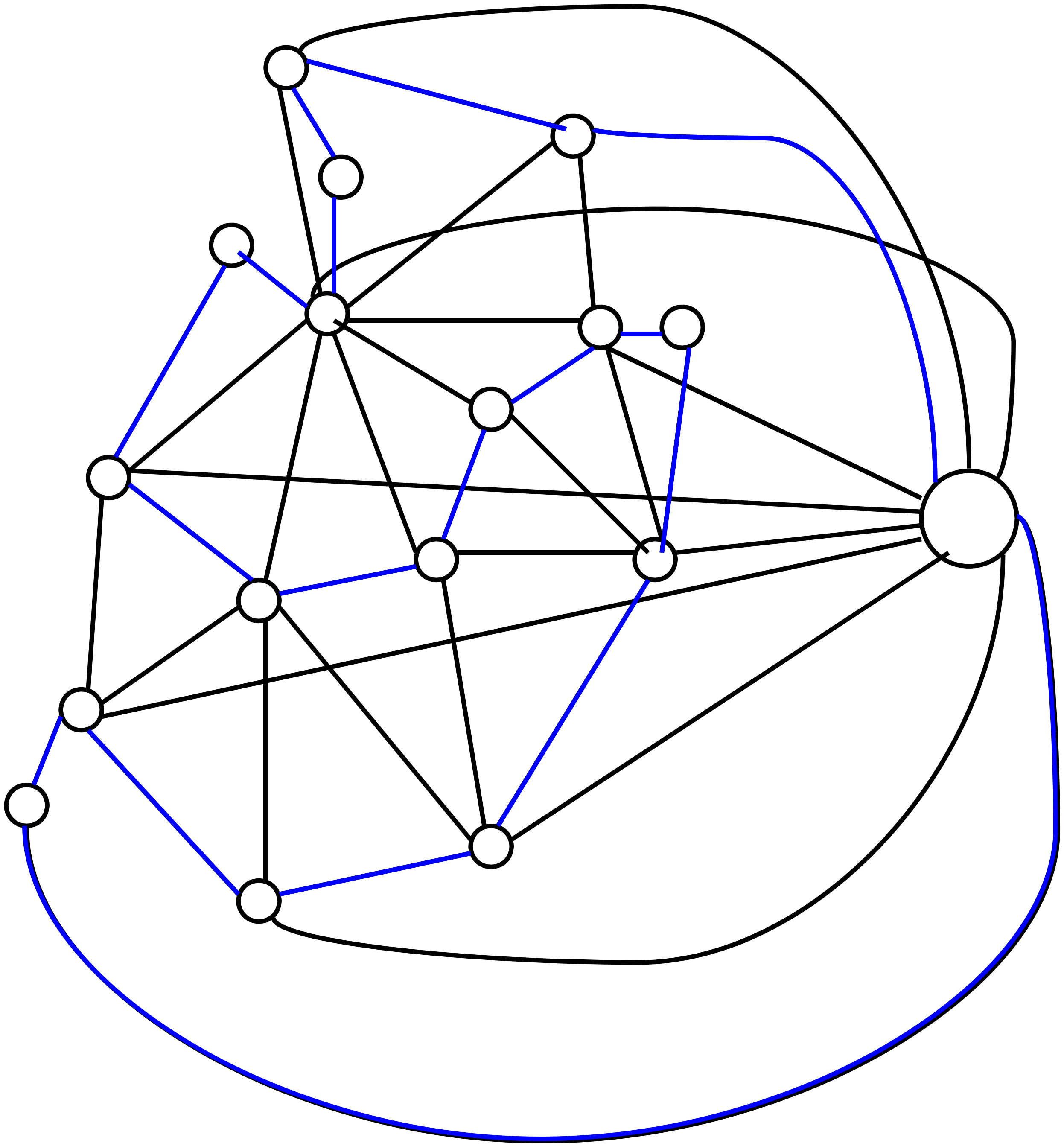
A spanning tree

Der Bundesländer-Graph



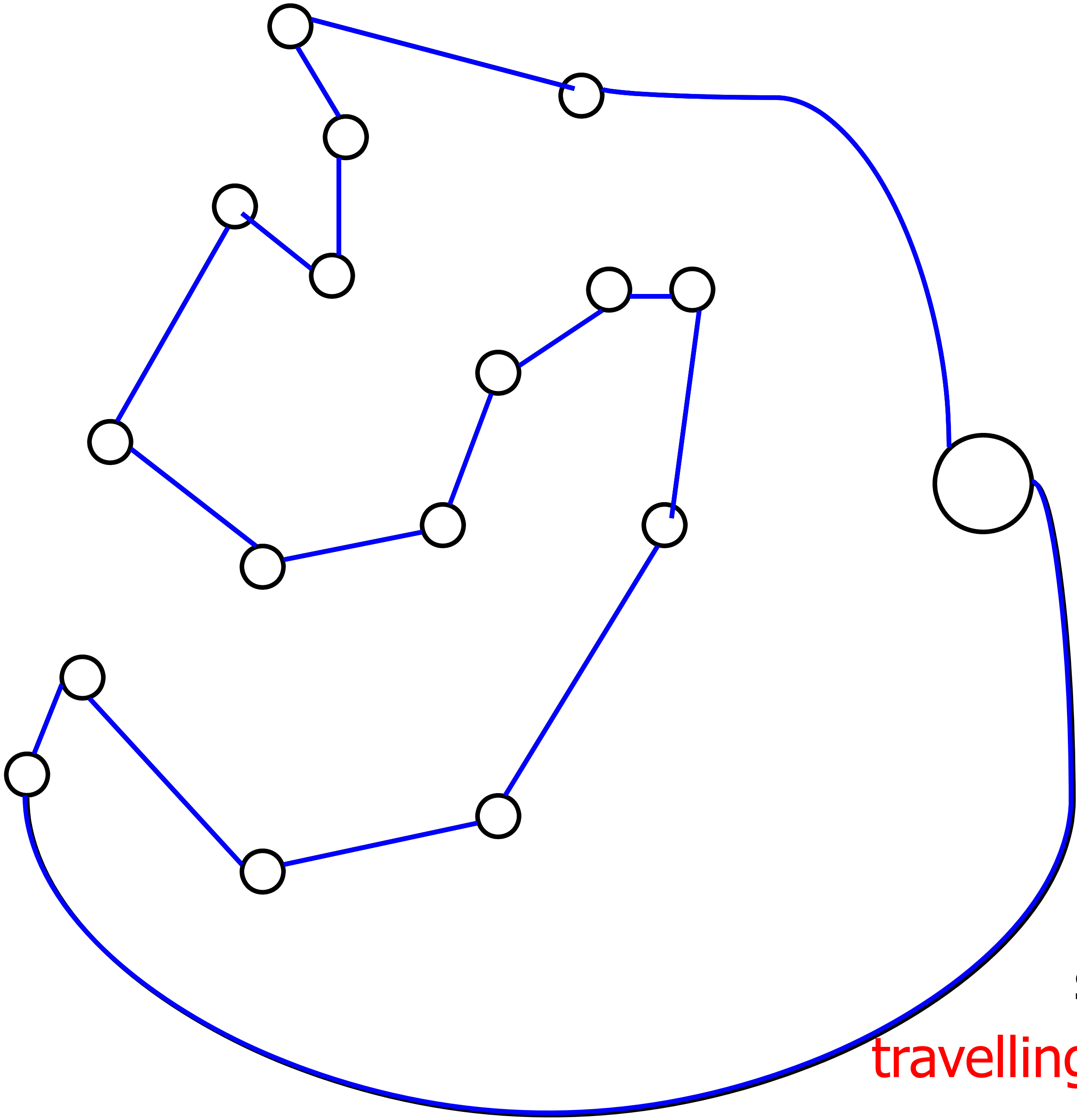
A spanning tree
(not a shortest)

Some Graph



A tour or hamiltonian circuit

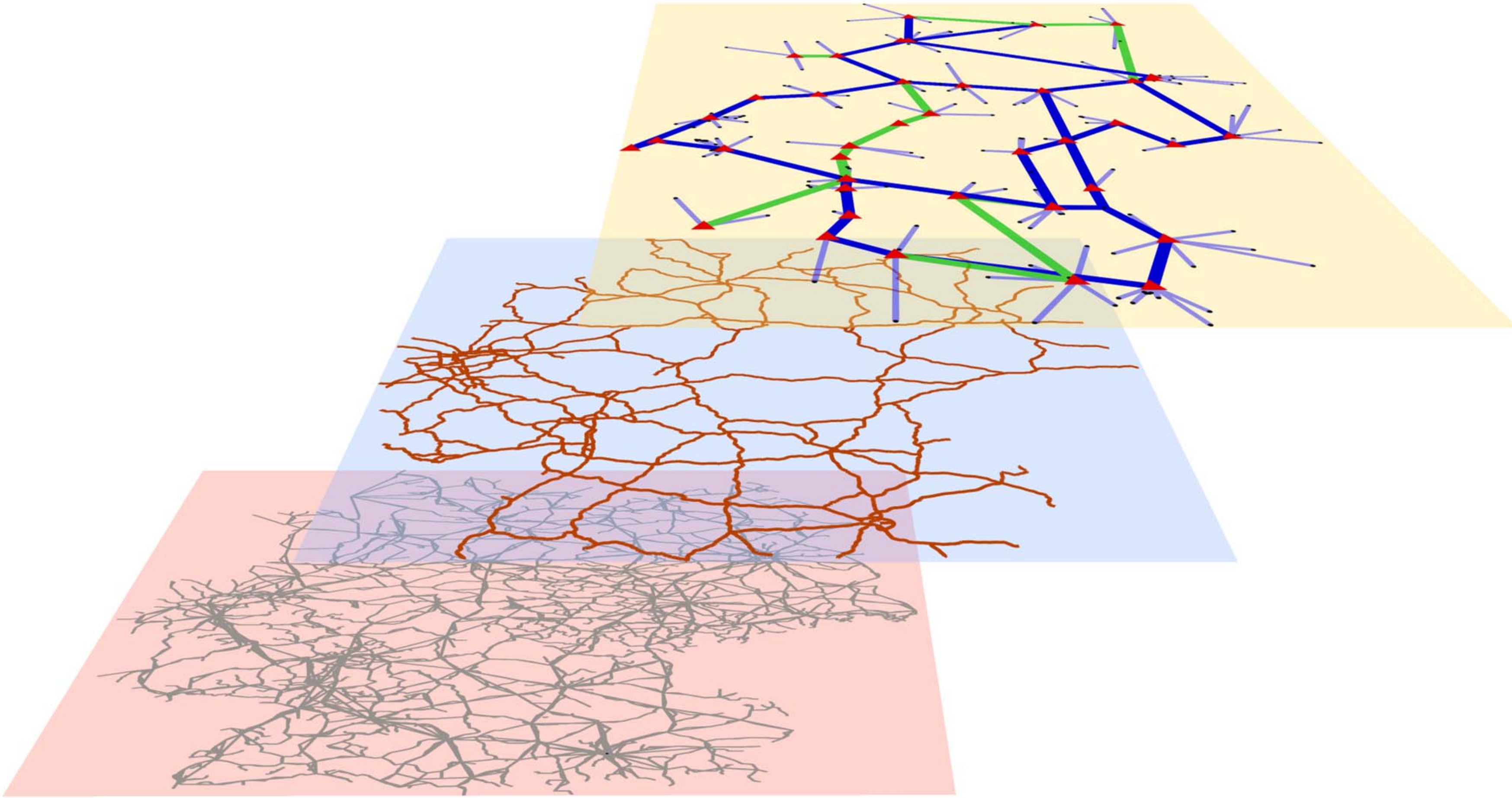
Some Graph



A
tour
or
hamiltonian
circuit

Finding a shortest tour is the travelling salesman problem

Networks in Germany



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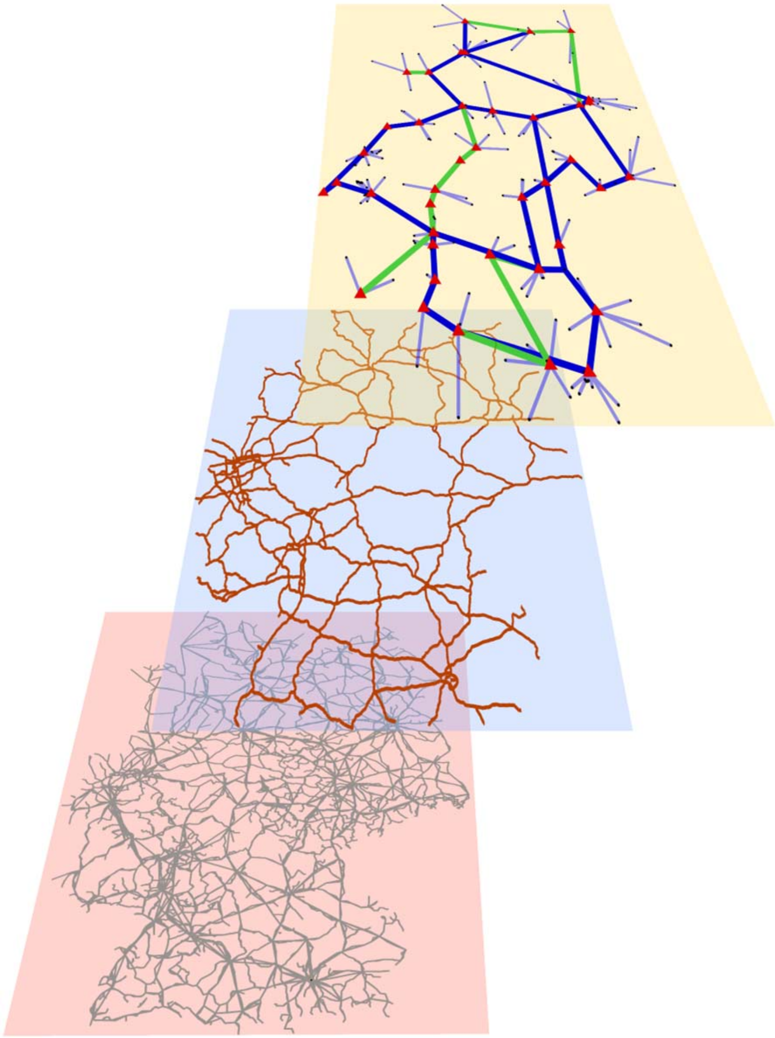
A MATHEON Vision



- The role of networks
  - Networks are omnipresent
  - Rapidly growing in size and importance
  - Their design and operation poses new challenges
- What constitutes a good network?
  - Study common mathematical properties of network applications
  - Develop theory, algorithms, and software for an advanced level of network analysis
  - Address network planning problems as a whole

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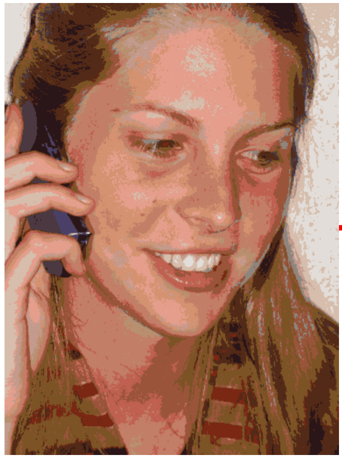
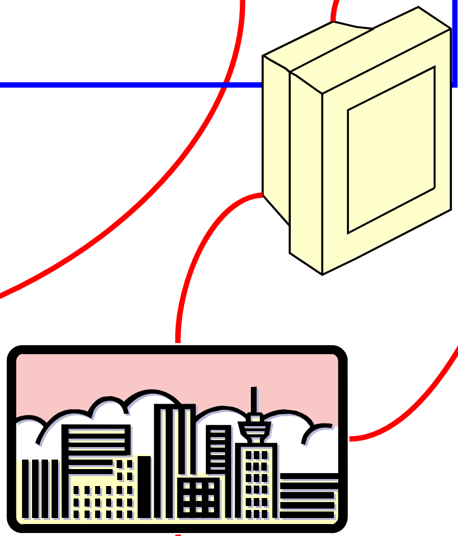
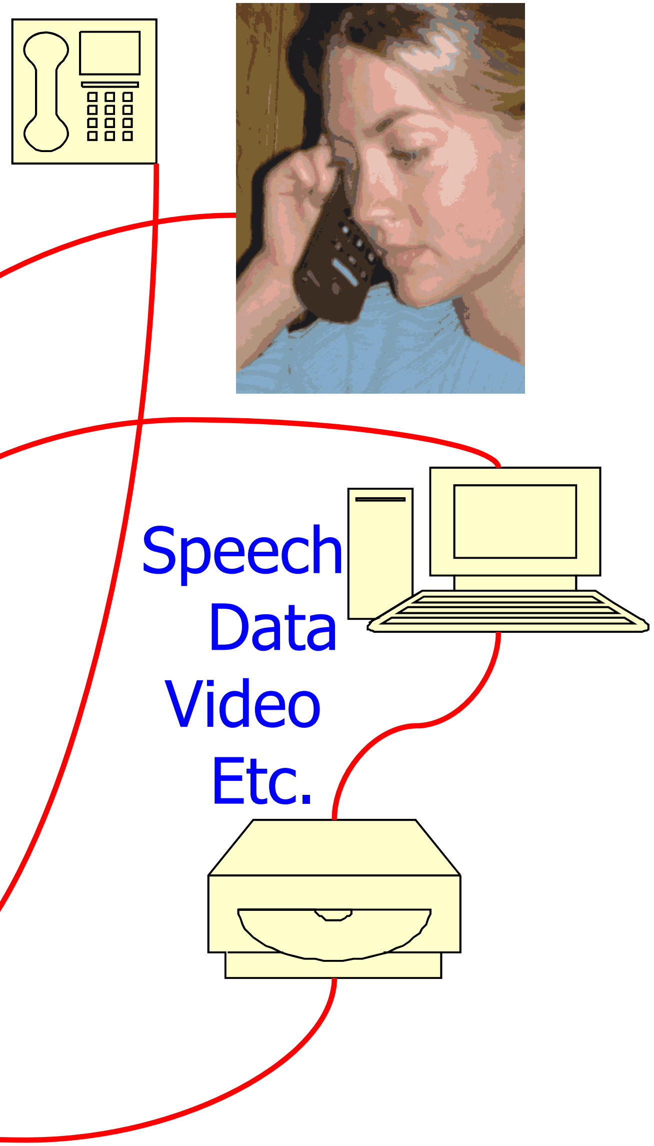
What is the Telecom Problem?

Design excellent technical devices and a robust network that survives all kinds of failures and organize the traffic such that high quality telecommunication between very many individual units at many locations is feasible at low cost!







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What is the Telecom Problem?

Design excellent technical devices and a robust network that survives all kinds of failures and organize the traffic such that high quality telecommunication between very many individual units at many locations is feasible at low cost!

This problem is too general to be solved in one step.

Approach in Practice:

- Decompose whenever possible.
- Look at a hierarchy of problems.
- Address the individual problems one by one.
- Recompose to find a good global solution.

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Cell Phones and Mathematics

Designing mobile phones

- Task partitioning
- Chip design (VLSI)
- Component design

- Computational logic
- Combinatorial optimization
- Differential algebraic equations

Producing Mobile Phones

- Production facility layout
- Control of CNC machines
- Control of robots
- Lot sizing
- Scheduling
- Logistics

- Operations research
- Linear and integer programming
- Combinatorial optimization
- Ordinary differential equations

Marketing and Distributing Mobiles

- Financial mathematics
- Transportation optimization

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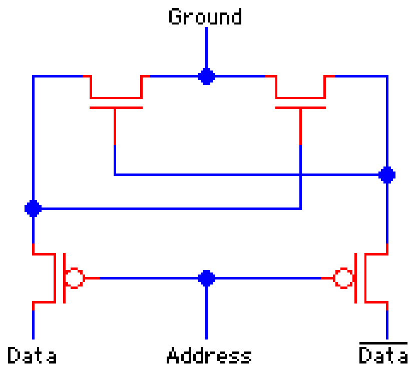
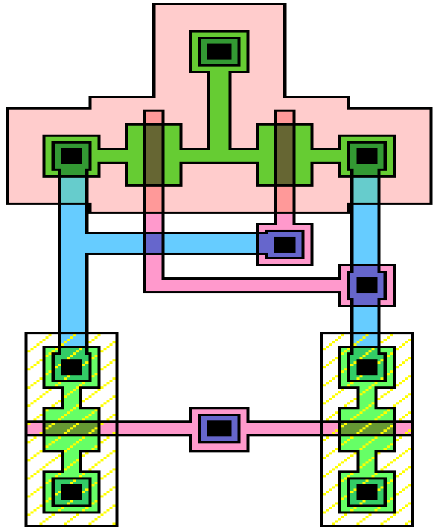
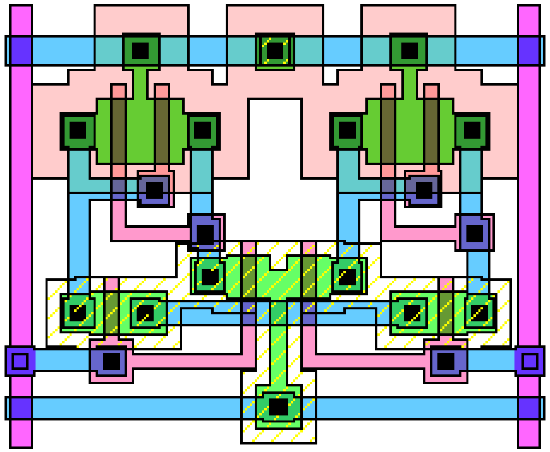
Chip Design



Schematic for four-transistor static-memory cell

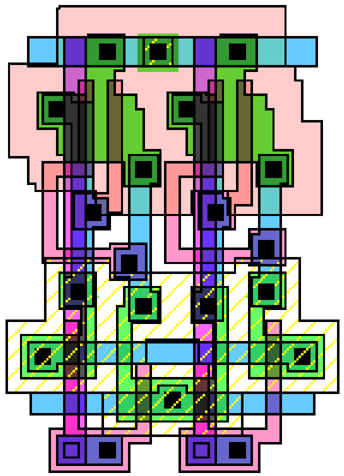


CMOS layout for four-transistor static-memory cell



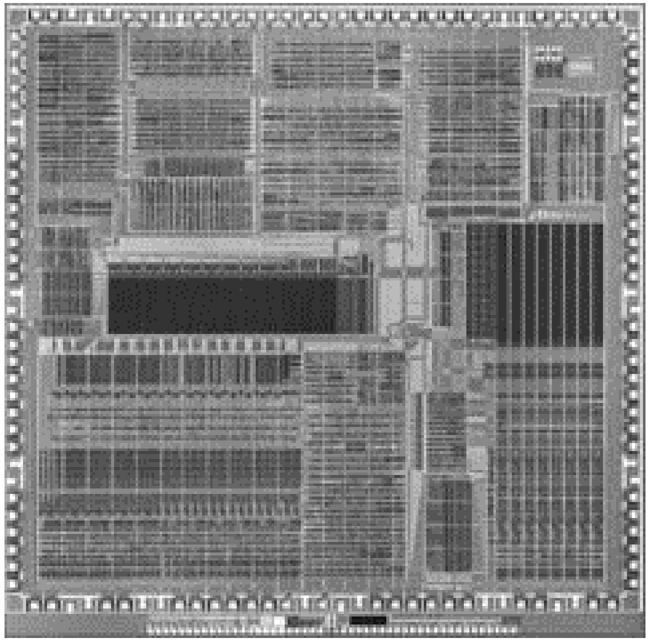
CMOS layout for two four-transistor static-memory cells.

Placement
Routing
Compactification

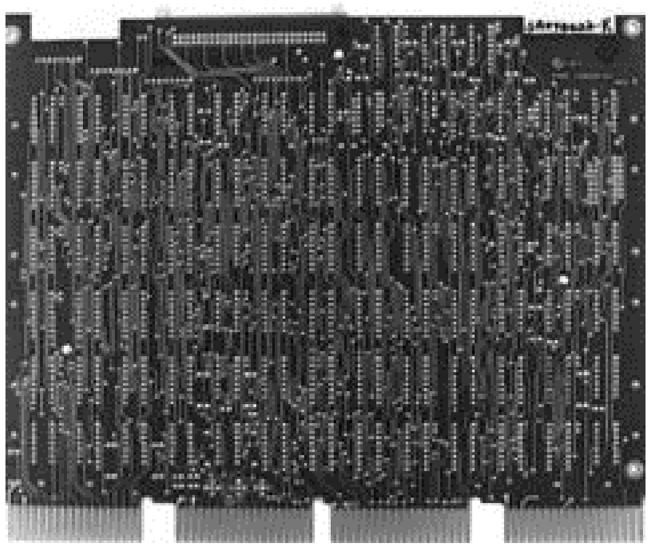


Compacted CMOS layout for two four-transistor static-memory cells.

Design and Production of ICs and PCBs



Integrated Circuit (IC)



Printed Circuit Board (PCB)

Problems: Logic Design, Physical Design

Correctness, Simulation, Placement of Components, Routing, Drilling,...

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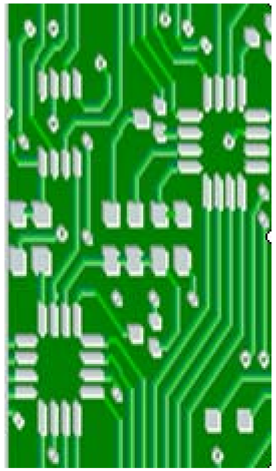
Production and Mathematics: Examples

CNC Machine for 2D and 3D cutting and welding (IXION ULM 804)

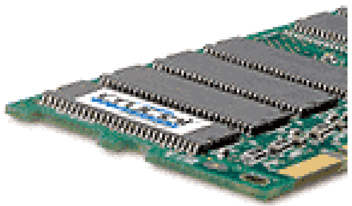
Sequencing of Tasks and Optimization of Moves

Mounting Devices

Minimizing Production Time via TSP or IP



SMD



Printed Circuit Boards

Optimization of Manufacturing

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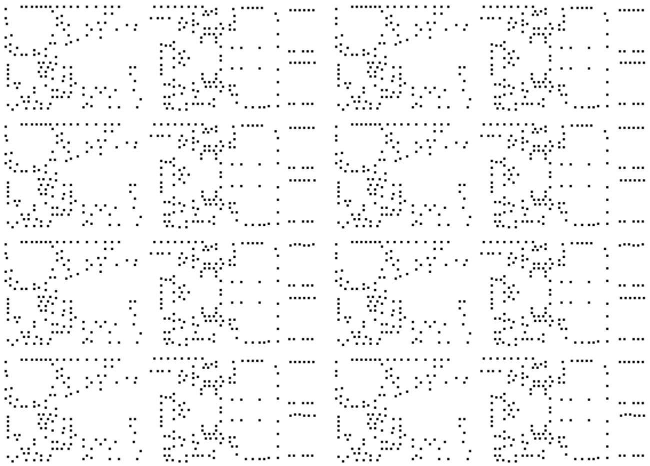
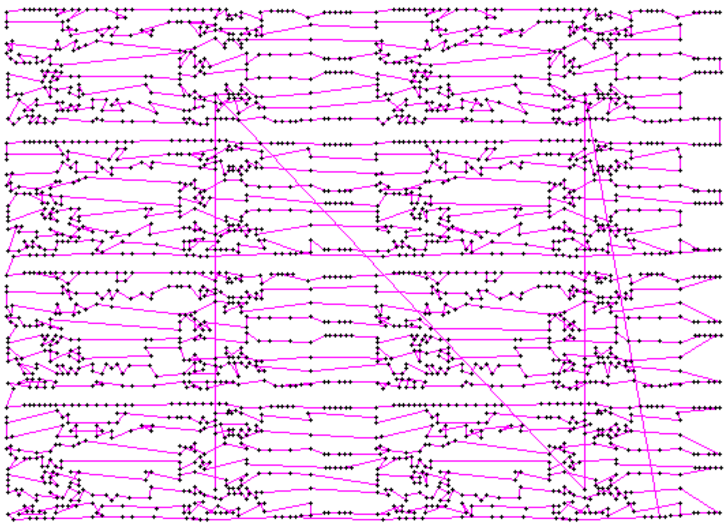
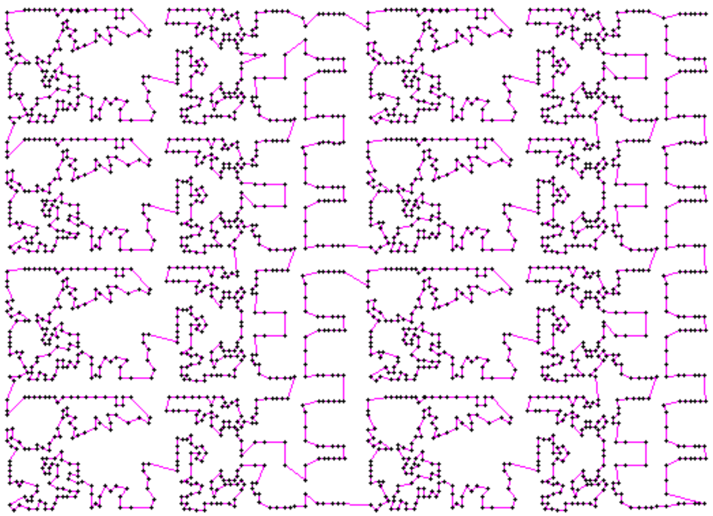
Drilling 2103 holes into a PCB



Significant Improvements
via solving the
travelling salesman problem

Padberg & Rinaldi





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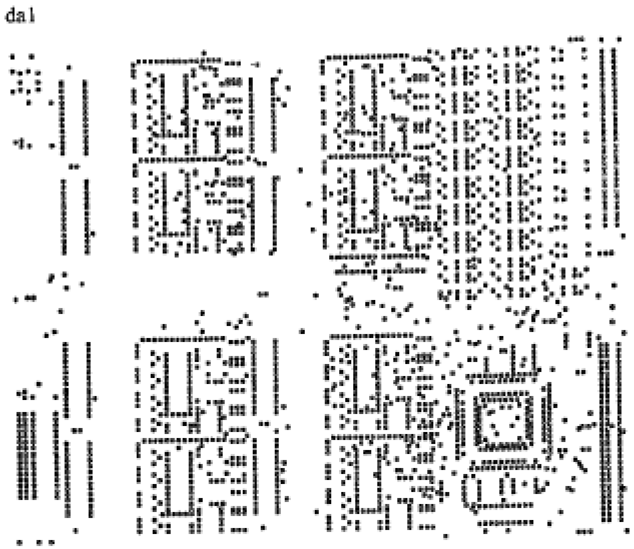
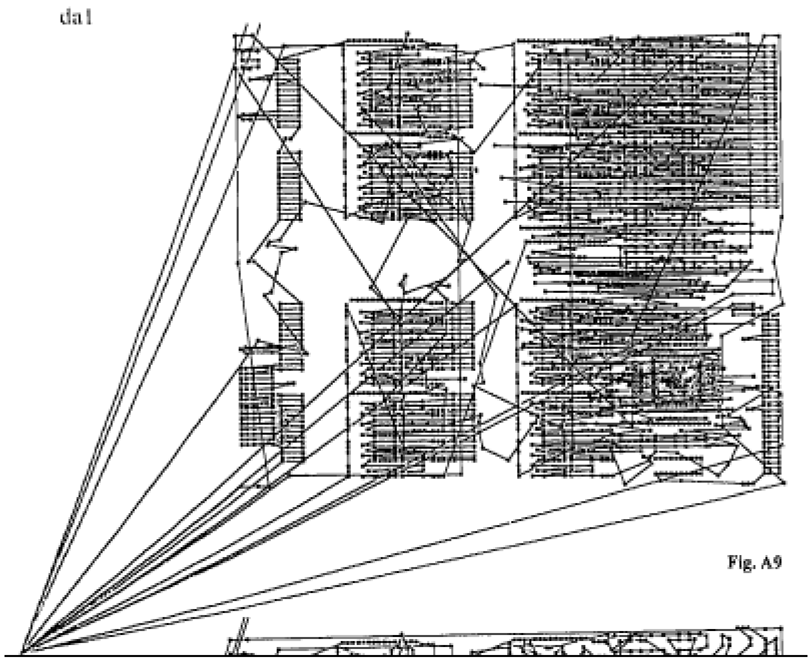


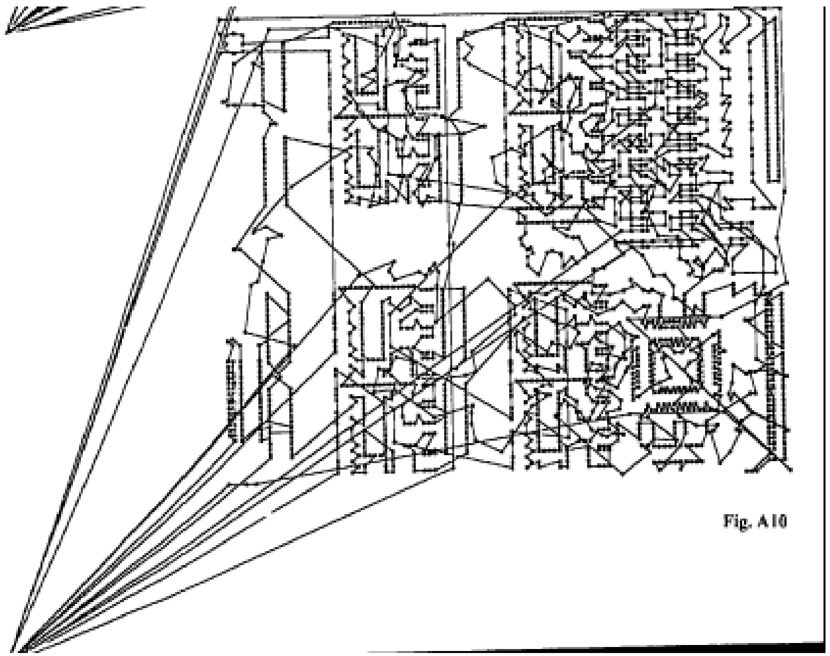
Fig. A7

Siemens Problem

printed circuit board da1

Grötschel, Jünger, Reinelt





before

after

Fig. A8

Siemens Problem

printed circuit board da4

Grötschel, Jünger, Reinelt

da4

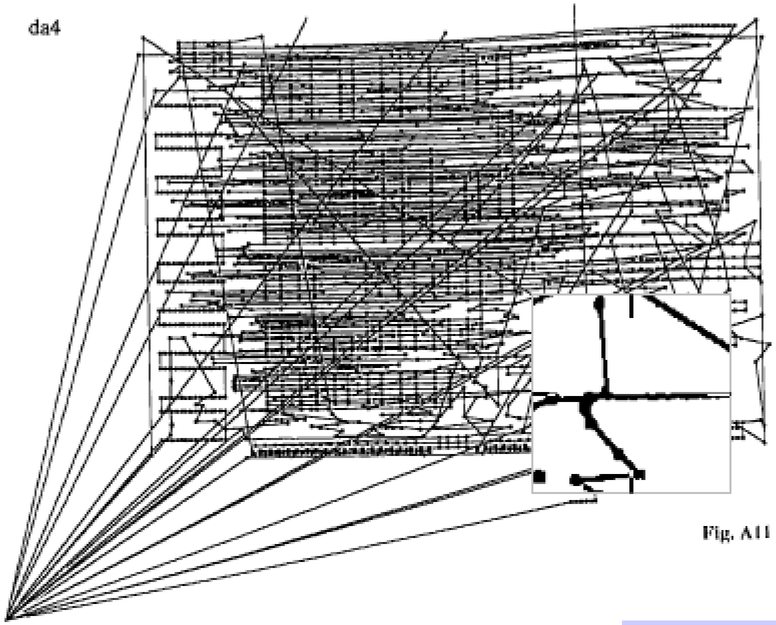


Fig. A11

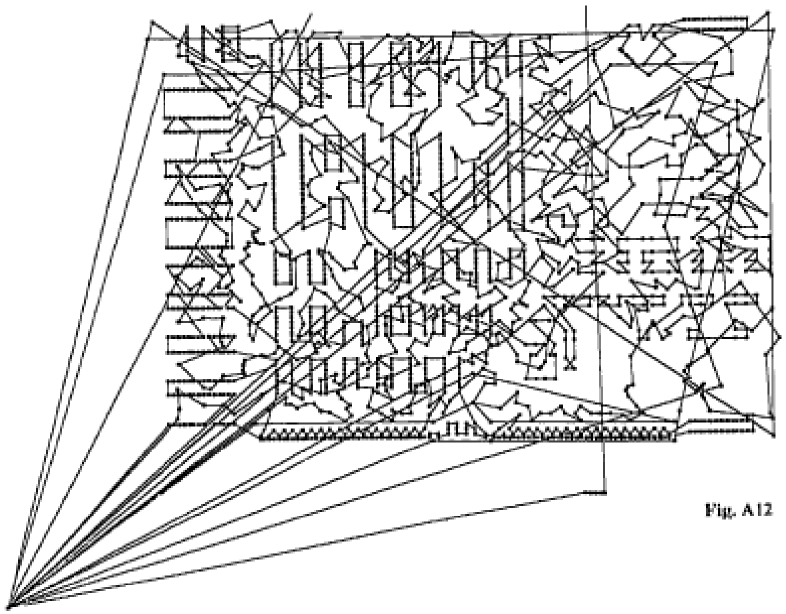


Fig. A12

before

54% shorter

after

Locating antennas

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Locating base stations

Nokia MetroSite

Nokia UltraSite

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Network Design: Tasks to be solved Some Examples

- Locating the sites for antennas (TRXs) and base transceiver stations (BTSs)
- Assignment of frequencies/channels to antennas (GSM)
- Capacity and coverage planing (UMTS)
- Cryptography and error correcting encoding for wireless communication
- Clustering BTSs
- Locating base station controllers (BSCs)
- Connecting BTSs to BSCs

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Network Design: Tasks to be solved Some Examples (continued)

- Locating Mobile Switching Centers (MSCs)
- Clustering BSCs and Connecting BSCs to MSCs
- Designing the BSC network (BSS) and the MSC network (NSS or core network)
  - Topology of the network
  - Capacity of the links and components
  - Routing of the demand
  - Survivability in failure situations

Most of these problems turn out to be Combinatorial Optimization or Mixed Integer Programming Problems

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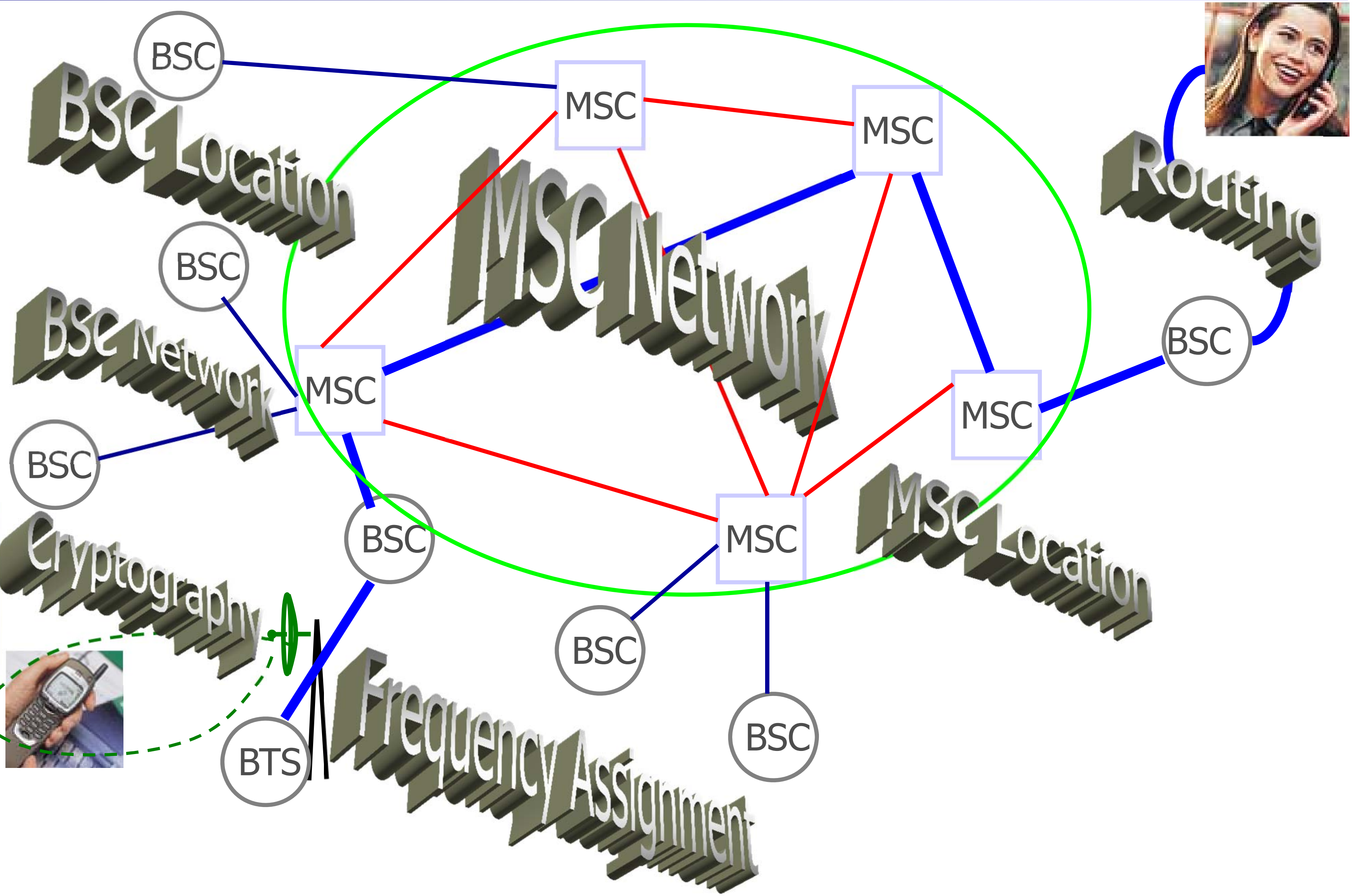
Connecting Mobiles: What´s up?



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Frequency or Channel Assignment

- The story to be told now is based on
  GSM technology
  (GSM = Global System for Mobile Communications), see
  http://en.wikipedia.org/wiki/GSM
- There are other mobile communication technologies such as UMTS
  (UMTS = Universal Mobile Telecommunications System),
  a system that is based on CDMA technology
  (CDMA = Code Division Multiple Access) where the „story" is different,
  see, e.g., http://en.wikipedia.org/wiki/Universal_Mobile_Telecommunications_System

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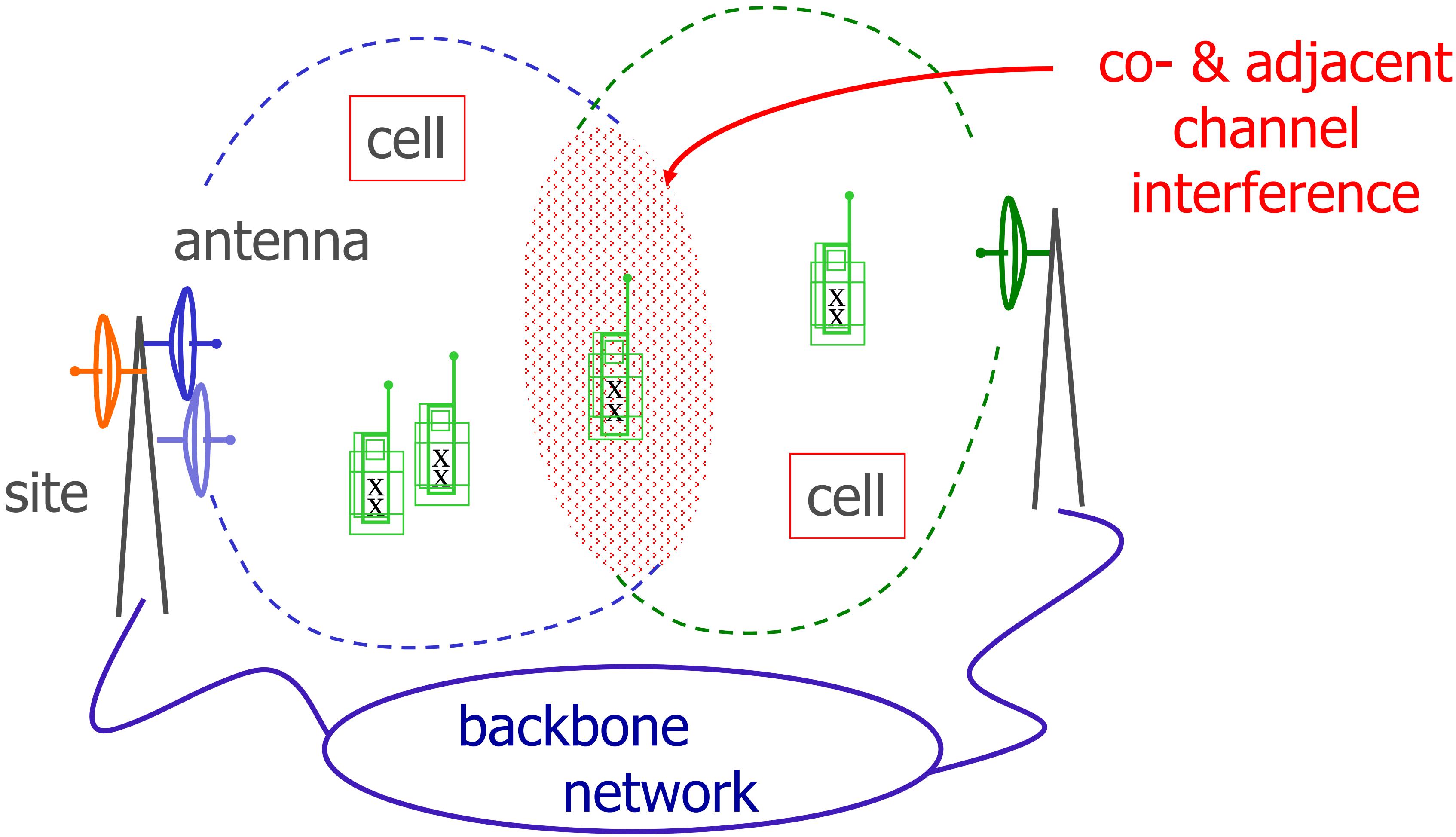
Antennas & Interference



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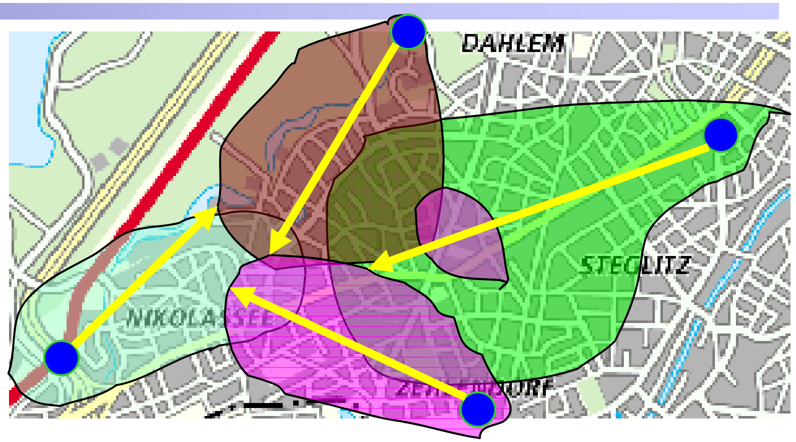
Interference



Level of interference depends on

- distance between transmitters
- geographical position
- power of the signals
- direction in which signals are transmitted
- weather conditions
- assigned frequencies
  - co-channel interference
  - adjacent-channel interference

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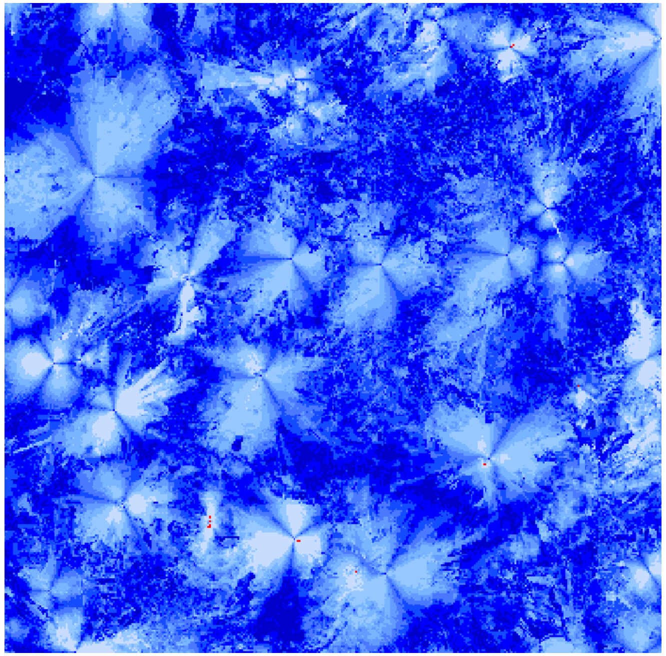
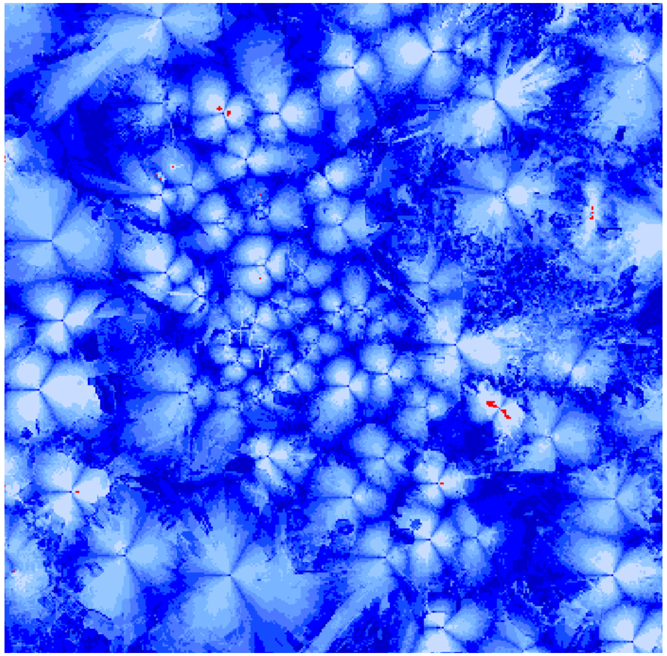
GSM Cell Diagrams



Rural
Terrain Data



Metropolitan
Buildings 3D

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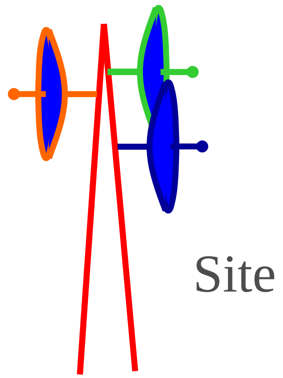
Separation

Frequencies assigned to the same location (site) have to be separated

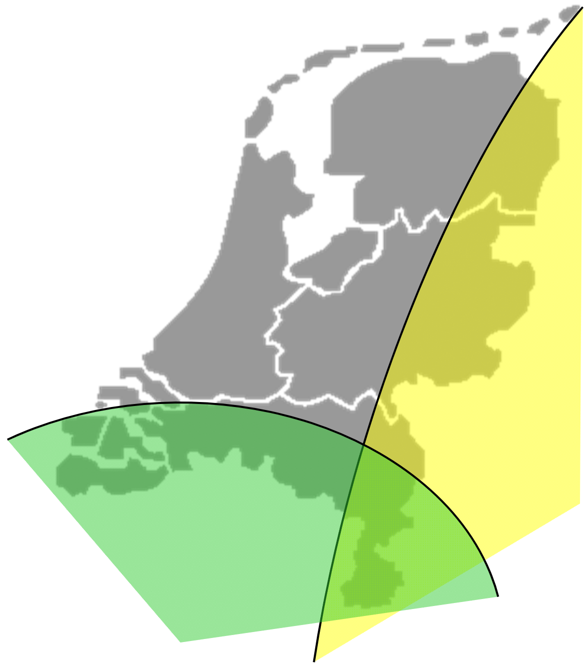


Blocked channels

Parts of the spectrum forbidden

at some locations:

- government regulations,
- agreements with operators in neighboring regions,
- requirements military forces, etc.



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FAP:
Frequency Assignment Problem

Find an assignment of frequencies to transmitters that satisfies

- all separation constraints
- all blocked channels requirements

and either

- avoids interference at all

or

- minimizes the (total/maximum) interference level

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Minimum Interference Frequency Assignment Problem (FAP)

FAP is an Integer Linear Program:

$$
\begin{aligned}
\min \quad & \sum_{vw \in E^{co}} c^{co}_{vw} z^{co}_{vw} + \sum_{vw \in E^{ad}} c^{ad}_{vw} z^{ad}_{vw} & \\
s.t. \quad & \sum_{f \in F_v} x_{vf} = 1 & \forall v \in V \\
& x_{vf} + x_{wg} \le 1 & \forall vw \in E^d, |f-g| < d(vw) \\
& x_{vf} + x_{wf} \le 1 + z^{co}_{vw} & \forall vw \in E^{co}, f \in F_v \cap F_w \\
& x_{vf} + x_{wg} \le 1 + z^{ad}_{vw} & \forall vw \in E^{ad}, |f-g| = 1 \\
& x_{vf}, z^{co}_{vw}, z^{ad}_{vw} \in \{0,1\} &
\end{aligned}
$$

that is very difficult to solve.

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A Glance at some Instances

Instance	|V|	density [%]	minimum degree	average degree	maximum degree	diameter	clique number
k	267	56,8	2	151,0	238	3	69
B-0-E-20	1876	13,7	40	257,7	779	5	81
f	2786	4,5	3	135,0	453	12	69
h	4240	5,9	11	249,0	561	10	130

E-Plus Project

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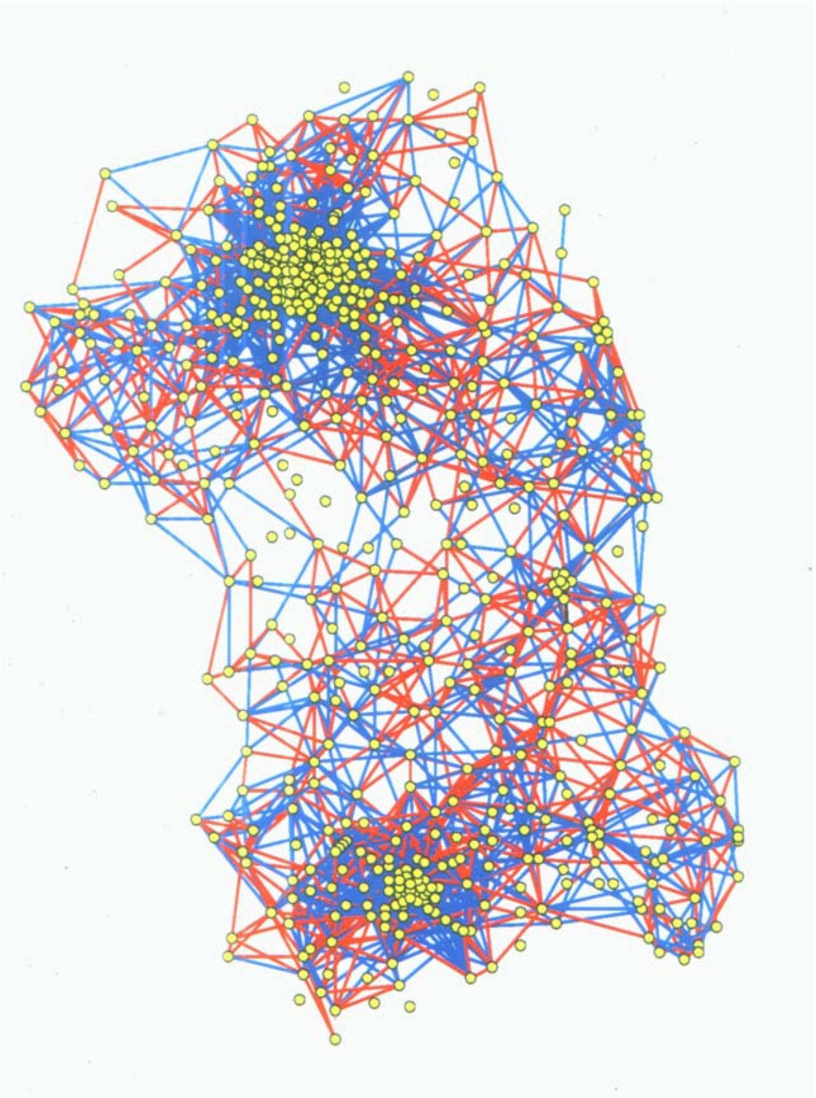
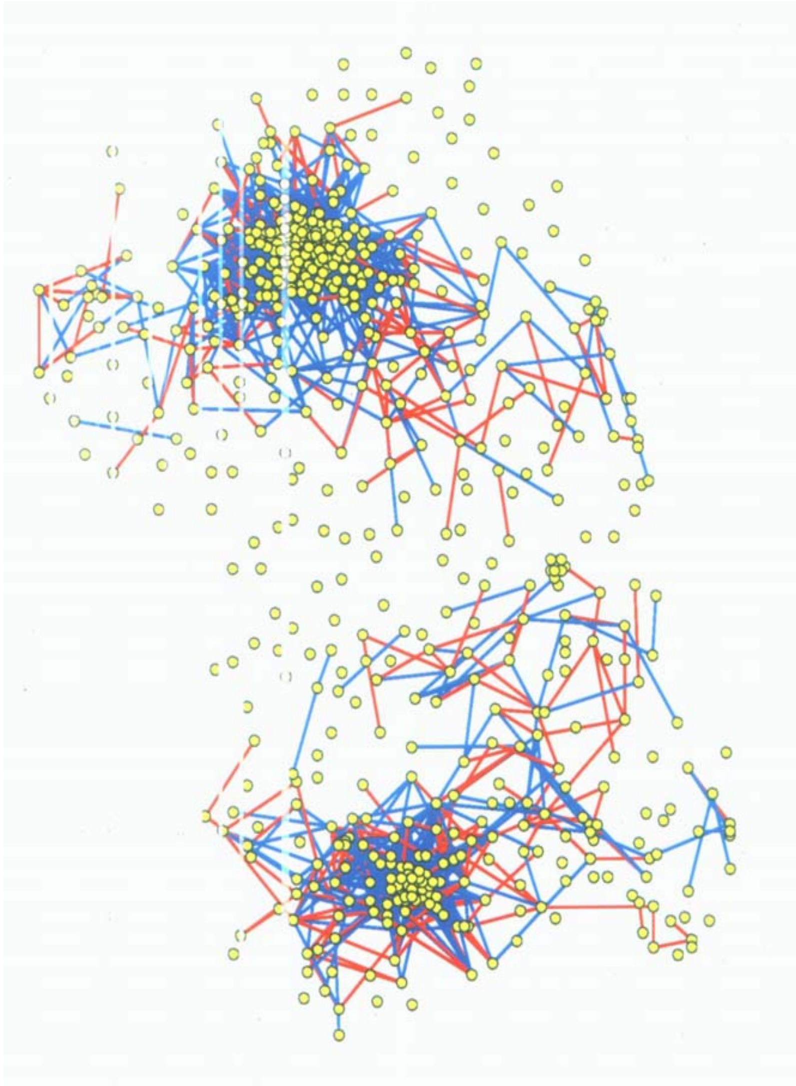
Region Berlin - Dresden



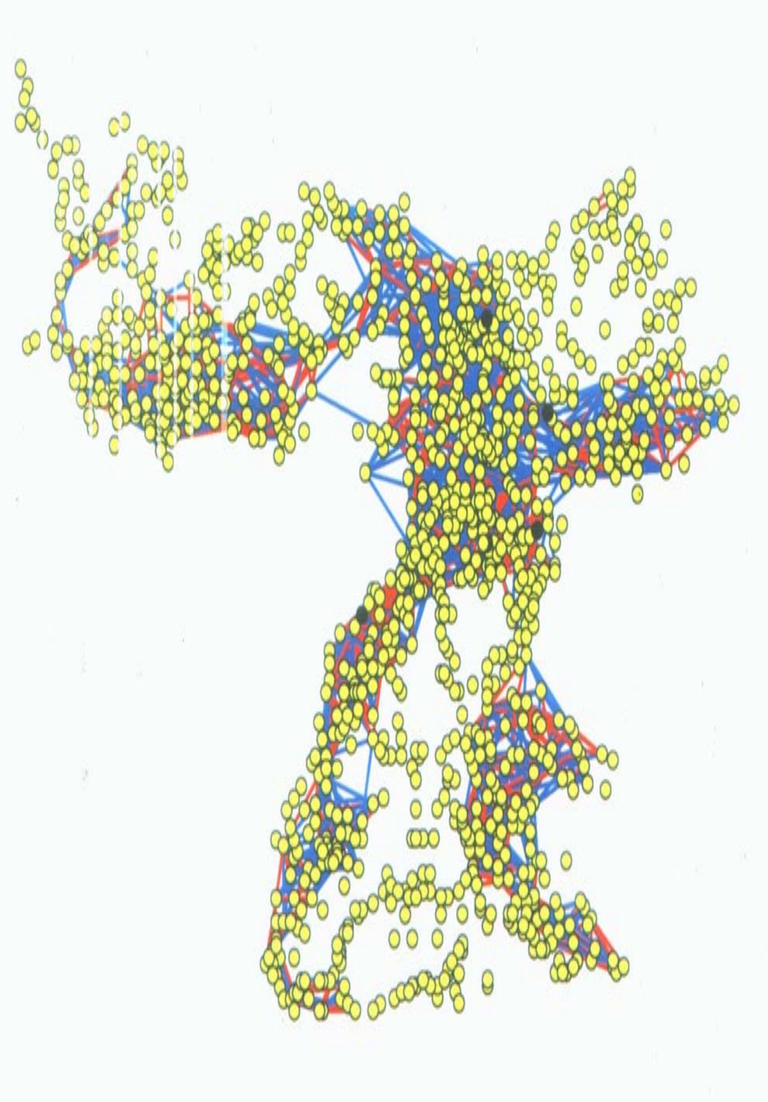


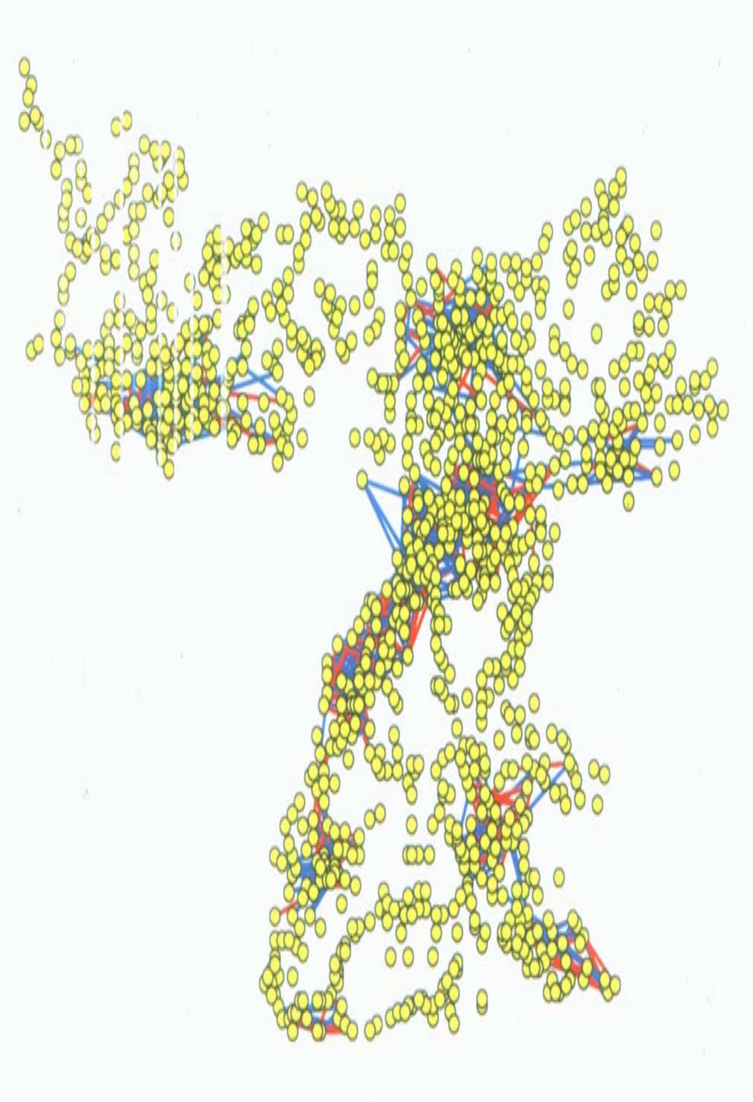
2877
carriers

50 channels

Interference
reduction:
83.6%

Region Karlsruhe



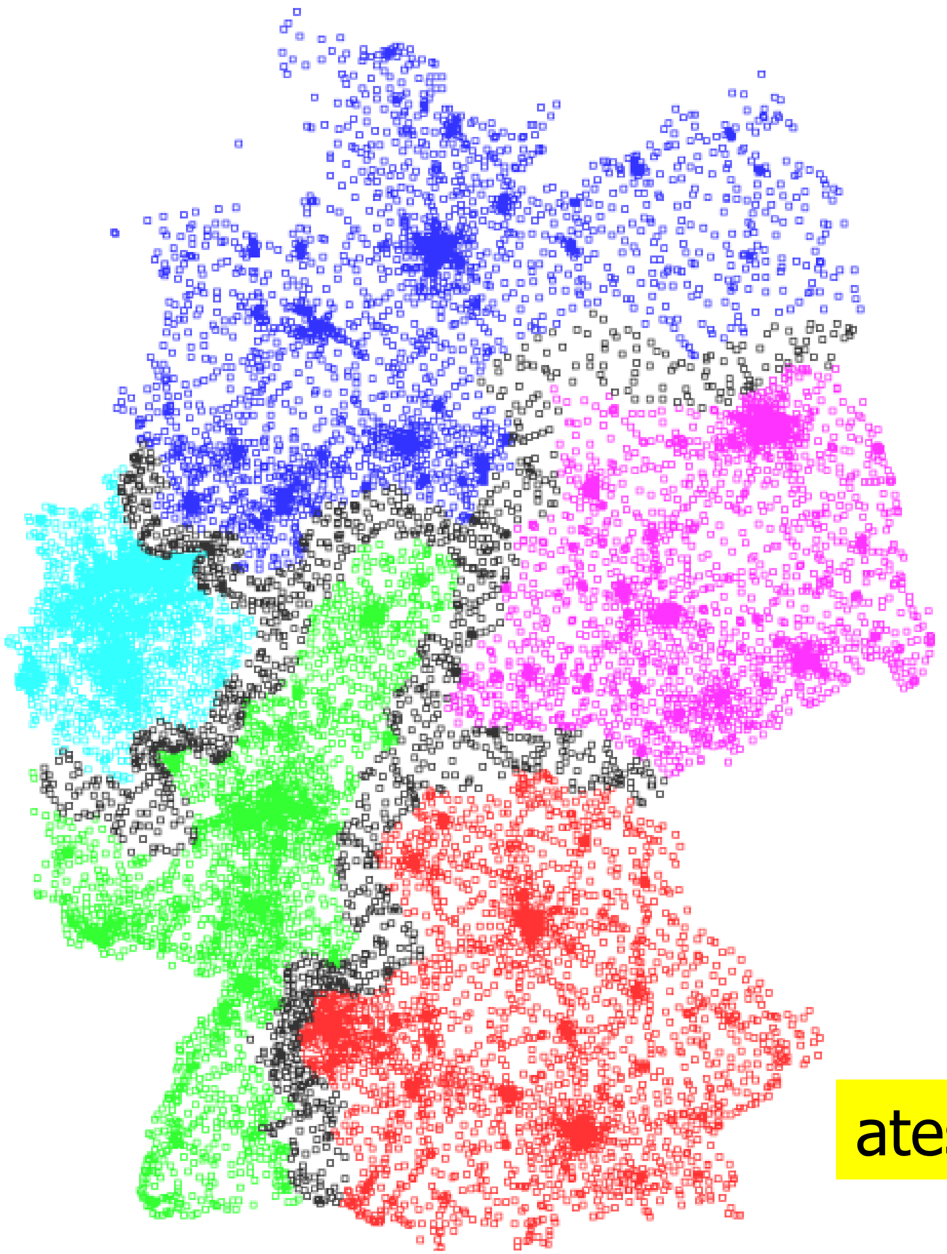


2877
Carriers

75 channels

Interference
Reduction:
83.9 %

GSM 900-Optimization in Germany



1. Optimierung je Region aller
   - Standorte
   - Sektoren
   - Bänder
2. Zusammenführung der Ergebnisse aller Regionen
3. Optimierung eines Streifens entlang der Regionsgrenzen
4. Optimierung des 1800 MHz-Anteils von Dualband-Sektoren

FAP Solvability

- Although we can find feasible solutions that are a lot better than what has been done in practice (in former times) we are far away from being able to solve the FAP integer program to optimality. Even provable near optimality is very hard to reach.

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G-WiN Data

G-WiN = Gigabit-Wissenschafts-Netz of the DFN-Verein
Internet access of all German universities
and research institutions

- Locations to be connected: 750
- Data volume in summer 2000: 220 Terabytes/month
- Expected data volume in 2004: 10.000 Terabytes/month

Clustering (to design a hierarchical network):

- 10 nodes in Level 1a
- 20 nodes in Level 1b
- All other nodes in Level 2

261 nodes eligible for Level 1

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G-WiN Problem

- Select the 10 nodes of Level 1a.
- Select the 20 nodes of Level 1b.

- Each Level 1a node has to be linked to two Level 1b nodes.
- Link every Level 2 node to one Level 1 node.

- Design a Level 1a Network such that
  - Topology is survivable (2-node connected)
  - Edge capacities are sufficient (also in failure situations)
  - Shortest path routing (OSPF) leads to balanced capacity use (objective in network update)
- The whole network should be „stable for the future".
- The overall cost should be as low as possible.

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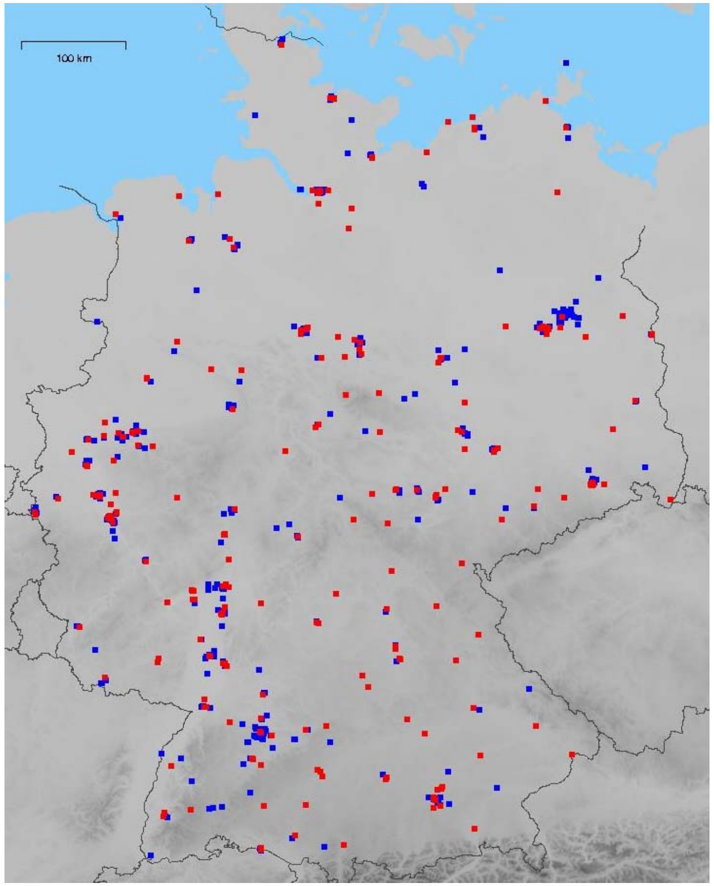
Potential node locations for the 3-Level Network of the G-WIN



Red nodes are potential level 1 nodes

Blue nodes are all remaining nodes

Cost:
Connection between nodes
Capacity of the nodes

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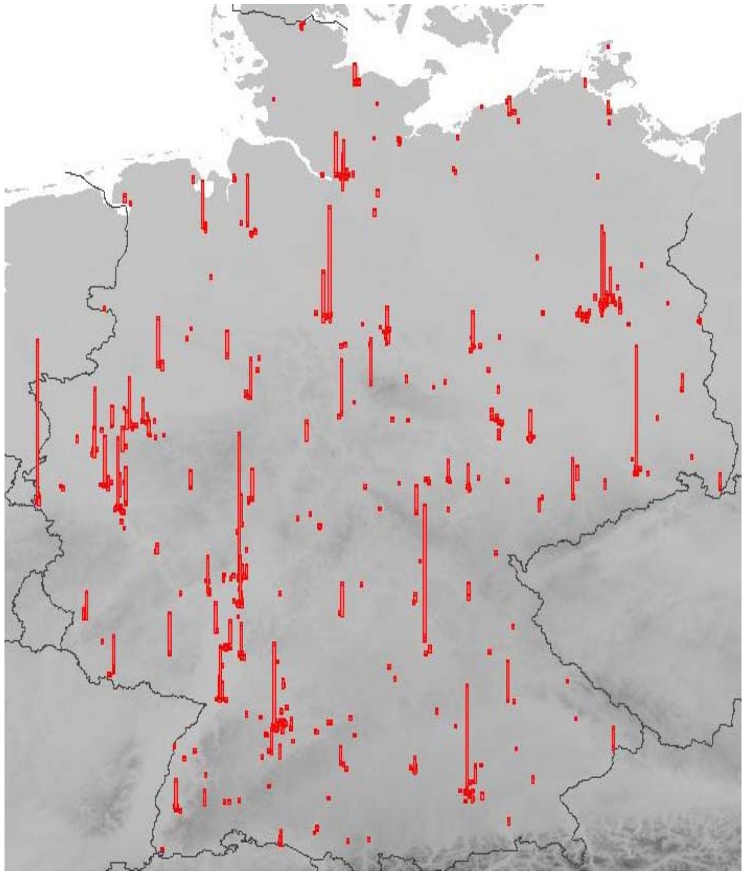
Demand distribution



The demand scales with the height of each red line

Aim

Select backbone nodes and connect all non-backbone nodes to a backbone node such that the overall network cost is minimal (access+backbone cost)

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G-WiN Location Problem: Data

V = set of locations

Z = set of potential Level 1a locations (subset of V)

K_p = set of possible configurations at location p in Level 1a

For $i \in V$, $p \in Z$ and $k \in K_p$:

w_{ip} = connection costs from i to p

d_i = traffic demand at location i

c_p^k = capacity of location p in configuration k

w_p^k = costs at location p in configuration k

x_{ip} = 1 if location i is connected to p (else 0)

z_p^k = 1 if configuration k is used at location p (else 0)

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G-WiN Location/Clustering Problem

$$\min \sum_{p \in Z} \sum_{i \in V} w_{ip} x_{ip} + \sum_{p \in Z} \sum_{k \in K_p} w_p^k z_p^k$$

$$\sum_p x_{ip} = 1$$ Each location i must be connected to a Level 1 node

$$\sum_i d_i x_{ip} \leq \sum_k c_p^k z_p^k$$ Capacity at p must be large enough

$$\sum_k z_p^k = 1$$ Only one configuration at each Location 1 node

$$\sum_p z_p^k = const$$ # of Level 1a nodes

All variables are 0/1.

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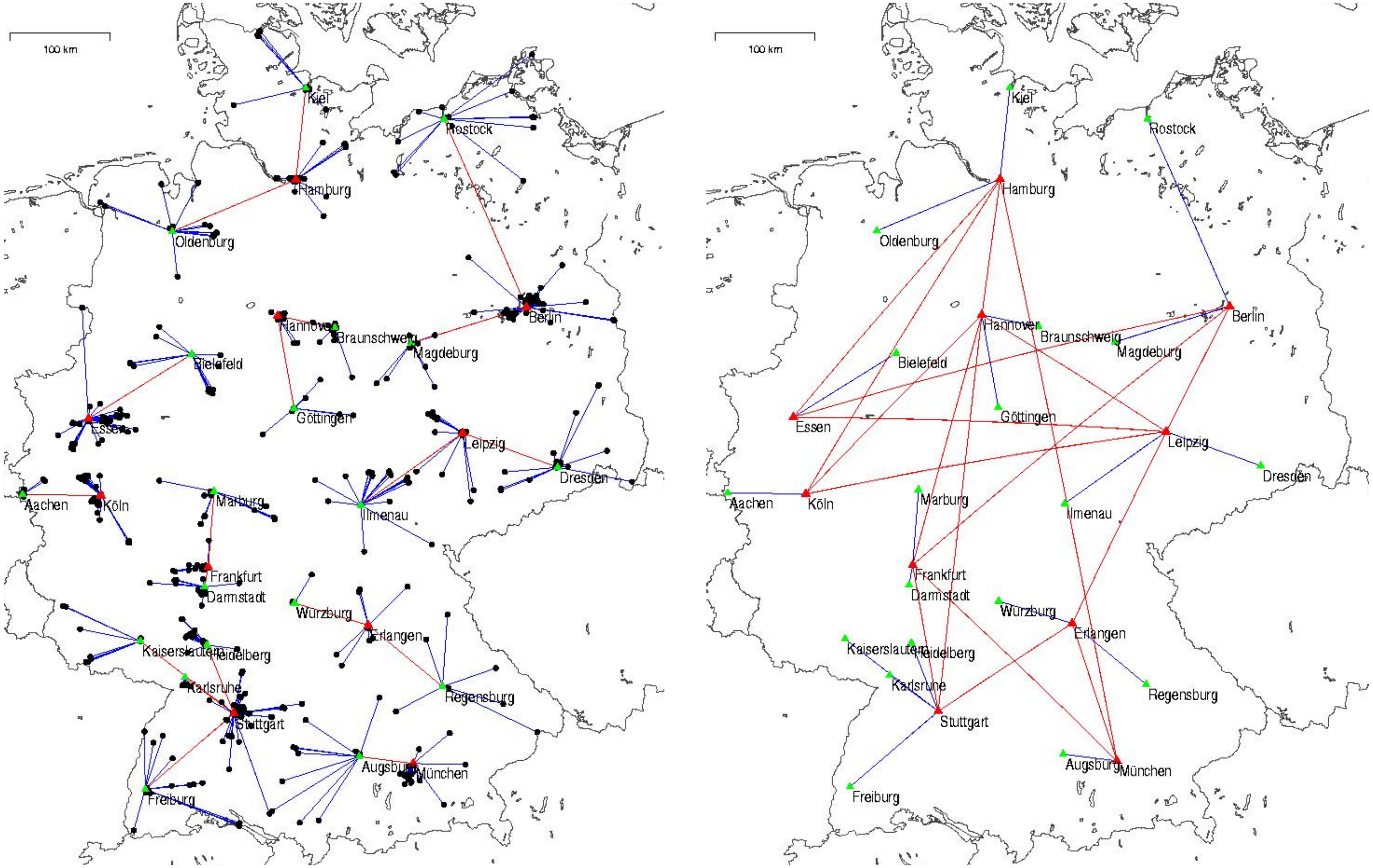
Solution: Hierarchy & Backbone



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G-WiN Location Problem: Solution Statistics

The DFN problem leads to ~100.000 0/1-variables.
Typical computational experience:
Optimal solution via CPLEX in a few seconds!

A very related problem at Telekom Austria has ~300.000 0/1-variables plus some continuous variables and capacity constraints.
Computational experience (before problem specific fine tuning):

10% gap after 6 h of CPLEX computation,
60% gap after „simplification"
(dropping certain capacities).

Contents

Martin Grötschel

X-WIN

- G-WIN served the ~750 scientific institutions from 2000 to 2006.
- G-WIN was reconfigured about every two months to meet changes in demand. Three modifications were allowed at each update at most.
- With new transport, hub, and switching technologies new design possibilities arise. We have designed the new German science network, called X-WIN. It is currently in the implementation phase with modifications coming along every other day.

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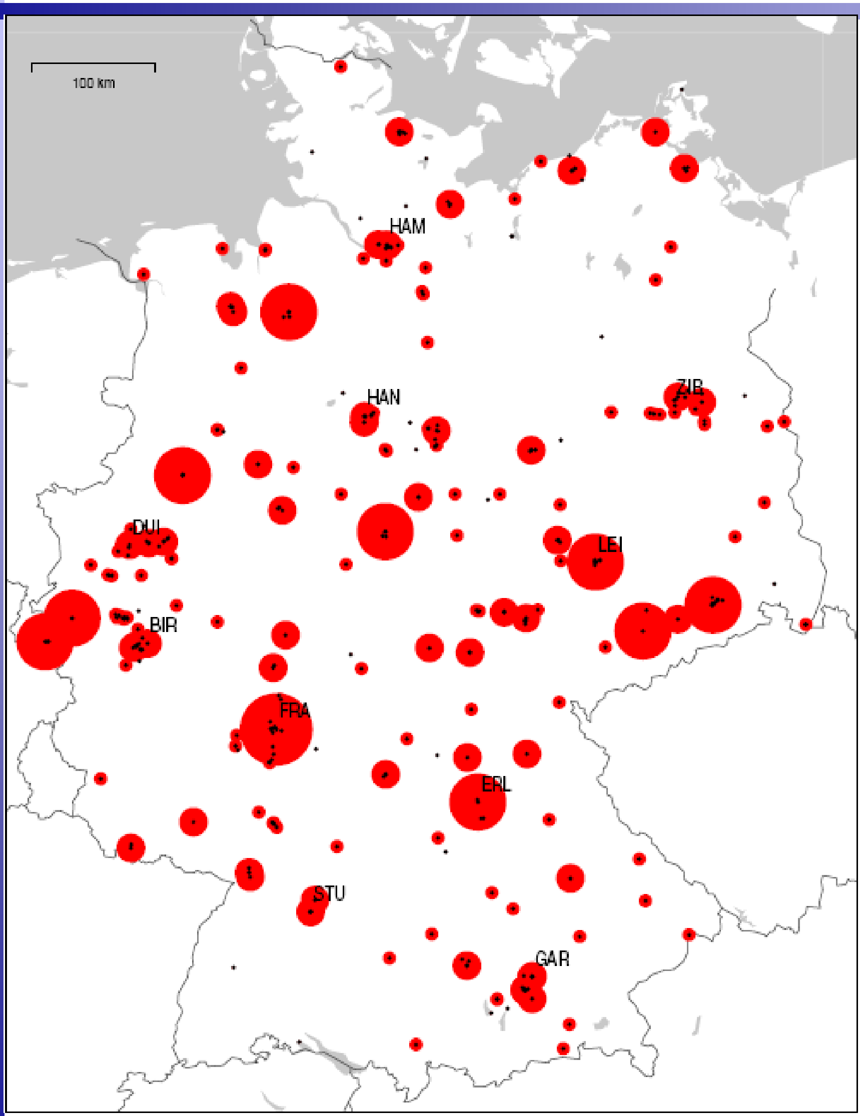
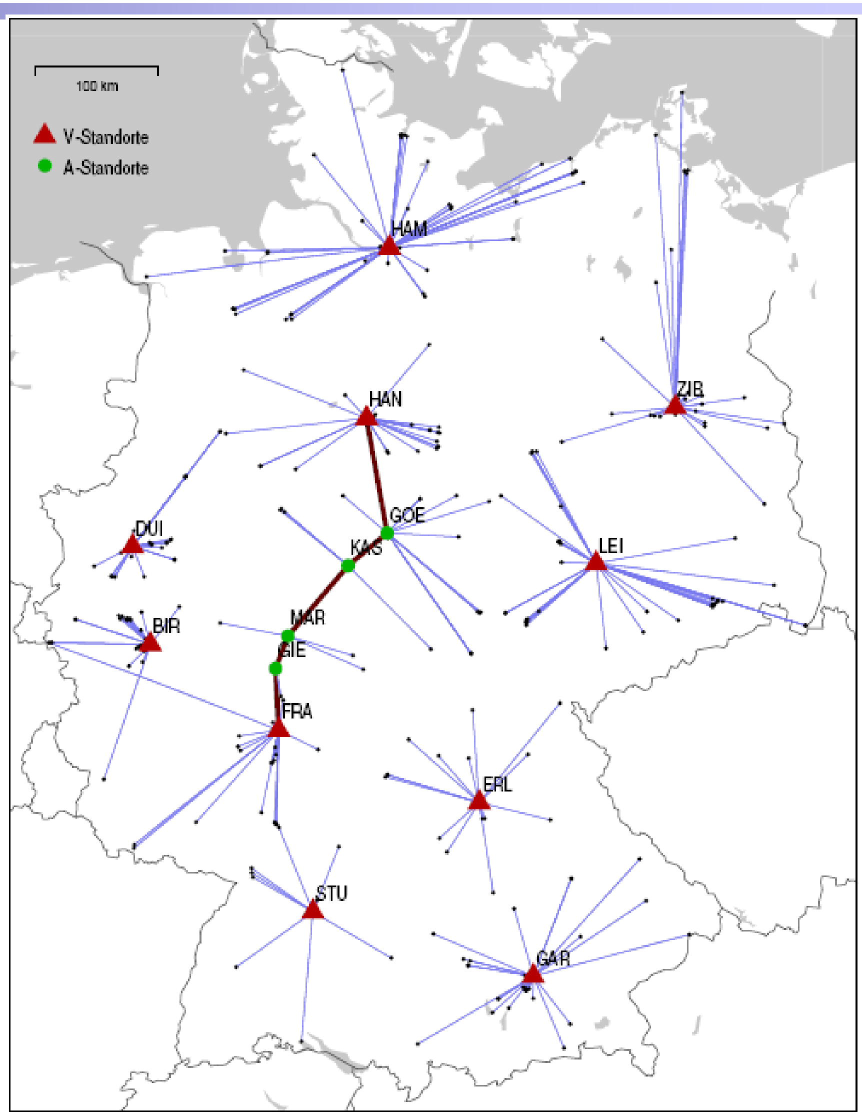
X-WIN Andreas Bley und Marcus Pattloch



Node Bandwidths



Level 1a and some 1b Nodes

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Data and a glimpse at the model

Gegebene Parameter

- V — Menge der V-Standorte.
- A — Menge der möglichen A-Standorte. Sie werden entweder A-Standort oder Anwenderstandort.
- N — Menge der Anwenderstandorte
- L — Menge aller möglichen Verbindungen zwischen Anwenderstandort und V- oder A-Standort. Für jede Anbindung wird jeweils nur die billigste Verbindung berücksichtigt, deren Kapazität mindestens so groß ist wie die Anschlussbandbreite des Anwenders.
- P — Menge aller möglichen Ketten zur Anbindung von A-Standorten an die V-Standorte. Jede Kette hat die Form $(v_1, a_1, \ldots, a_m, v_2)$, d.h. sie bindet die A-Standorte $a_1, \ldots, a_m$ ausfallsicher an die beiden V-Standorte v_1 und v_2 an. Für jede Kombination von Kapazitäten auf den einzelnen Verbindungen gibt es eine eigene Kette p.
- k_a^A — Kosten für das Einrichten des A-Standortes $a \in A$.
- k_{ij}^L — Kosten der (billigsten) Zugangsleitung $ij \in L$ von Anwenderstandort i zu A- oder V-Standort j.
- k_p^P — Kosten der Kette $p = (v_1, a_1, \ldots, a_m, v_2) \in P$ zur Anbindung der A-Standorte $a_1, \ldots, a_m$ an die V-Standorte v_1, v_2. Die Kosten einer Kette sind die Summe aller Einzelverbindungskosten.
- c_p — Kapazität der Kette p. Sie ist die kleinste Kapazität aller Einzelverbindungen.

Entscheidungsvariablen

- y_a — 1 genau dann, wenn a zum A-Standort wird, 0 sonst.
- x_{ij} — 1 genau dann, wenn i ein Anwenderstandort ist oder wird und i an den A- oder V-Standort j angebunden wird, 0 sonst.
- z_p — 1 genau dann, wenn $a_1, \ldots, a_m$ zu A-Standorten werden und diese über die Kette $p = (v_1, a_1, \ldots, a_m, v_2)$ an die V-Standorte v_1, v_2 angebunden werden, 0 sonst.

Zielfunktion

Ziel ist die Minimierung der Gesamtkosten für das Einrichten der gewählten A-Standorte, für die Ketten zur Anbindung dieser A-Standorte an das V-Netz, sowie für die Zugangsleitungen zu den übrigen Anwenderstandorten:

$$\min \sum_{a \in A} k_a^A y_a + \sum_{p \in P} k_p^P z_p + \sum_{ij \in L} k_{ij}^L x_{ij}$$

Nebenbedingungen

Jeder Anwenderstandort wird an genau einen A- oder V-Standort angebunden:

$$\sum_{ij \in L} x_{ij} = 1 \quad \text{für alle } i \in N.$$

Wird ein möglicher A-Standort nicht eingerichtet, so wird dieser Standort als Anwenderstandort an einen anderen A- oder V-Standort angebunden:

$$\sum_{aj \in L} x_{aj} = 1 - y_a \quad \text{für alle } a \in A.$$

Ein Anwenderstandort kann nur dann an einen möglichen A-Standort angebunden werden, wenn dieser auch tatsächlich eingerichtet wird:

$$x_{ia} \le y_a \quad \text{für alle } a \in A \text{ und } ia \in L.$$

Jeder eingerichtete A-Standort wird über genau eine Kette doppelt an das V-Netz angebunden:

$$\sum_{p \in P \text{ mit } a \in p} z_p = y_a \quad \text{für alle } a \in A.$$

Die Kapazität einer Kette muss mindestens so groß sein wie die Anschlussbandbreiten aller über sie angebundenen Standorte zusammen:

$$\sum_{a \in p} \left(b_a + \sum_{ia \in L} b_i x_{ia} \right) \le c_p + \left(\sum_{i \in A \cup N} b_i \right) (1 - z_p) \quad \text{für alle } p \in P.$$

initial model:

- 1 million variables

after reduction

- ~100.000 variables
- ~100.000 constraints

solved by ZIMPL/CPLEX

in a few minutes.

- 81 scenarios have been considered and solved – after lots of trials – for each choice of reasonable number of core nodes.

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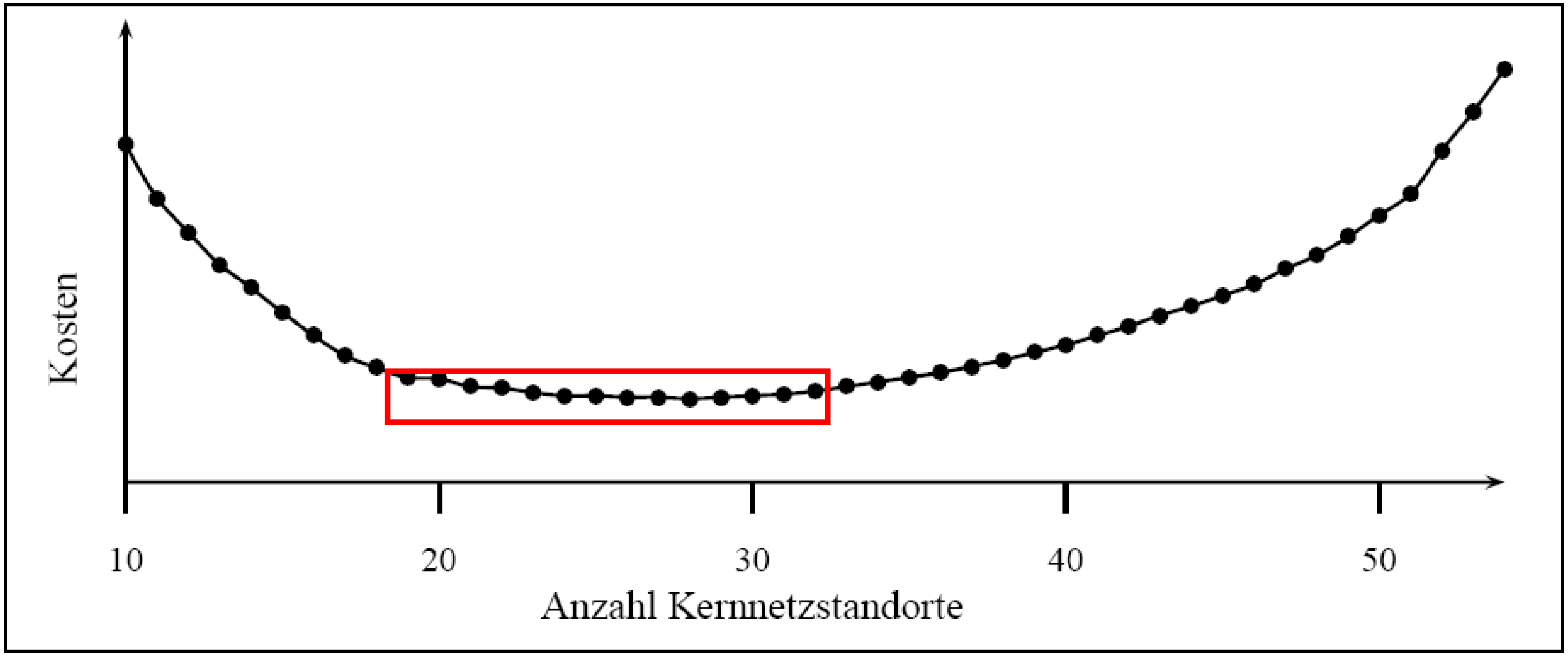
Number of Nodes in the Core Network



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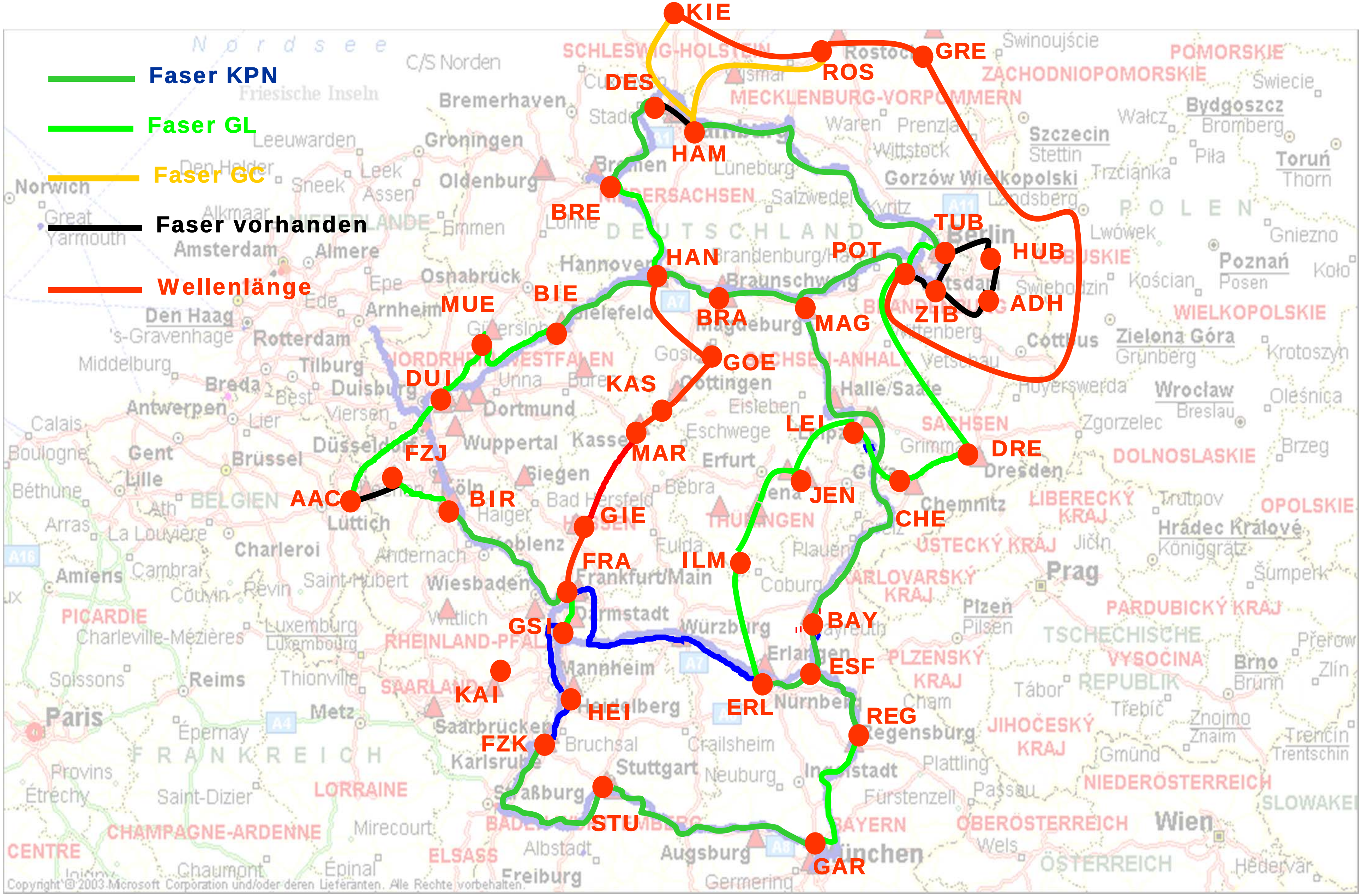
Location- and Network Topology Planing: solvable to optimality in practice



Contents

Martin Grötschel

IP Routing

- The slides of the section 8 of this presentation have been prepared by Andreas Bley when he was working at ZIB. (Andreas is now at TU Berlin.)
- Andreas has written several papers on this subject (just go to his homepage for further information). A comprehensive treatment with all the details can be found in his dissertation "Routing and Capacity Optimization for IP Networks " (TU Berlin 2007) which can be downloaded from
- http://opus4.kobv.de/opus4-zib/frontdoor/index/index/docId/1019

Traffic Routing in IP Networks

- Distributed routing of traffic
- Congestion is a significant problem
- How to control congestion?

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Overview

- **Practice**
  - Internet routing = Shortest path routing
- **Theory**
  - $\Omega(V^2)$ worse than UFP and other routing schemes
  - Hard to approximate
  - Feasible routing patterns form independence system
- **Solution approaches**
  - Lagrangian decomposition
  - MILP for end-to-end paths + LP for routing weights

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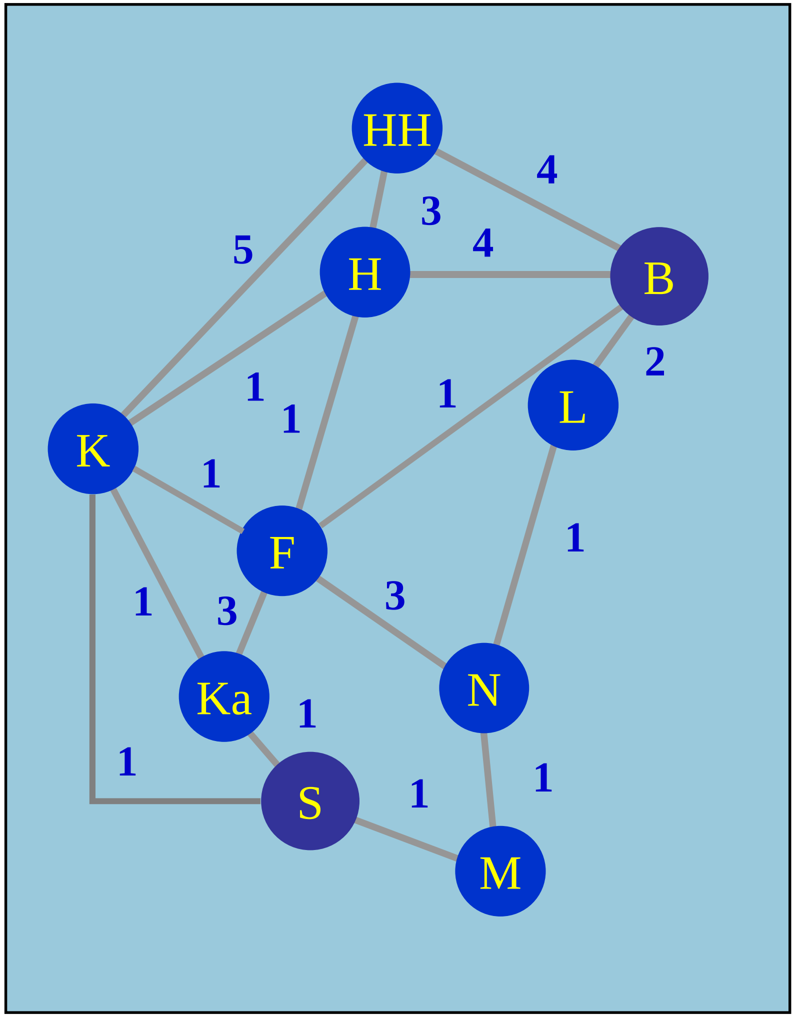
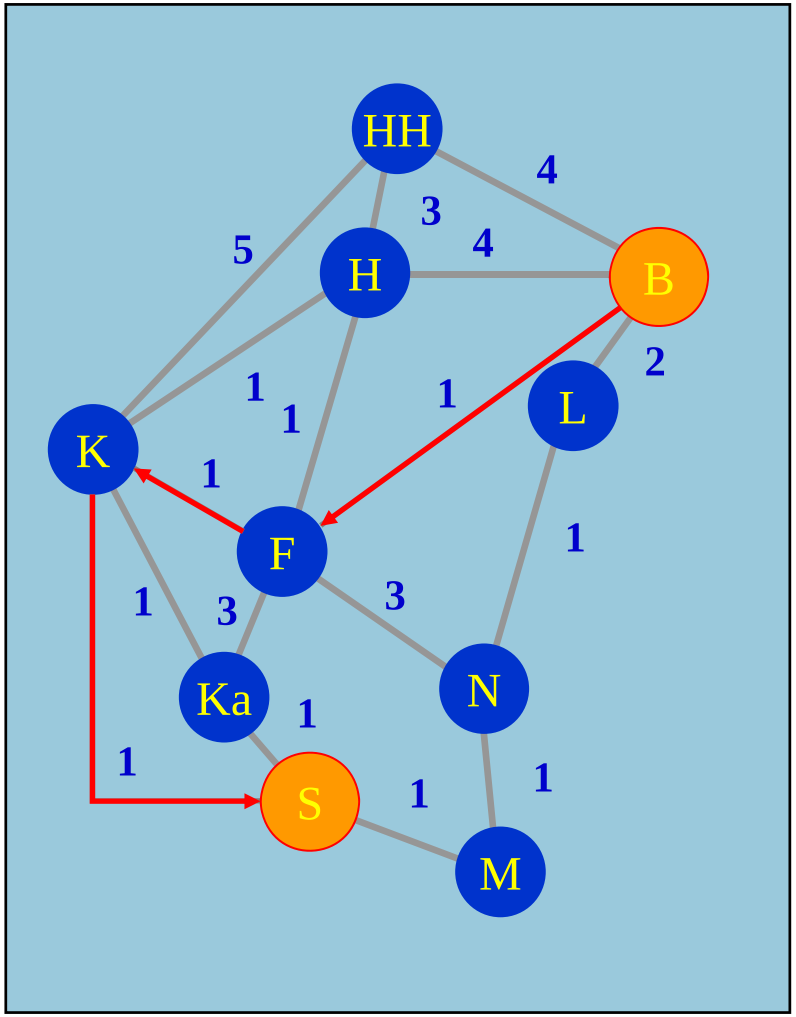


Internet: Shortest path routing

(1) **Set routing weights**
(Network administrator)

Practice

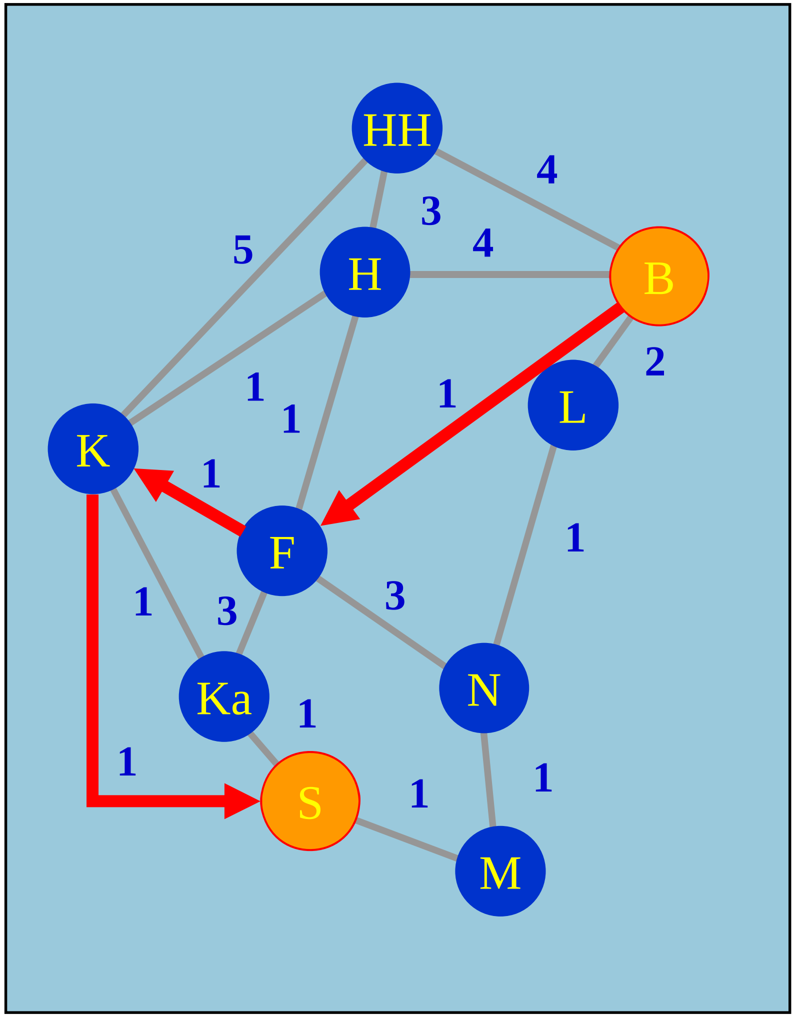


Internet: Shortest path routing

(1) **Set routing weights**
(Network administrator)

(2) **Compute shortest paths**
(Autonomously by routers)

Practice



Internet: Shortest path routing

(1) **Set routing weights**
(Network administrator)

(2) **Compute shortest paths**
(Autonomously by routers)

(3) **Send data packets on these paths**
(Local forwarding table lookups)

Administrative routing control

- **only indirectly** via routing weights
- **only jointly** for all paths

Variants

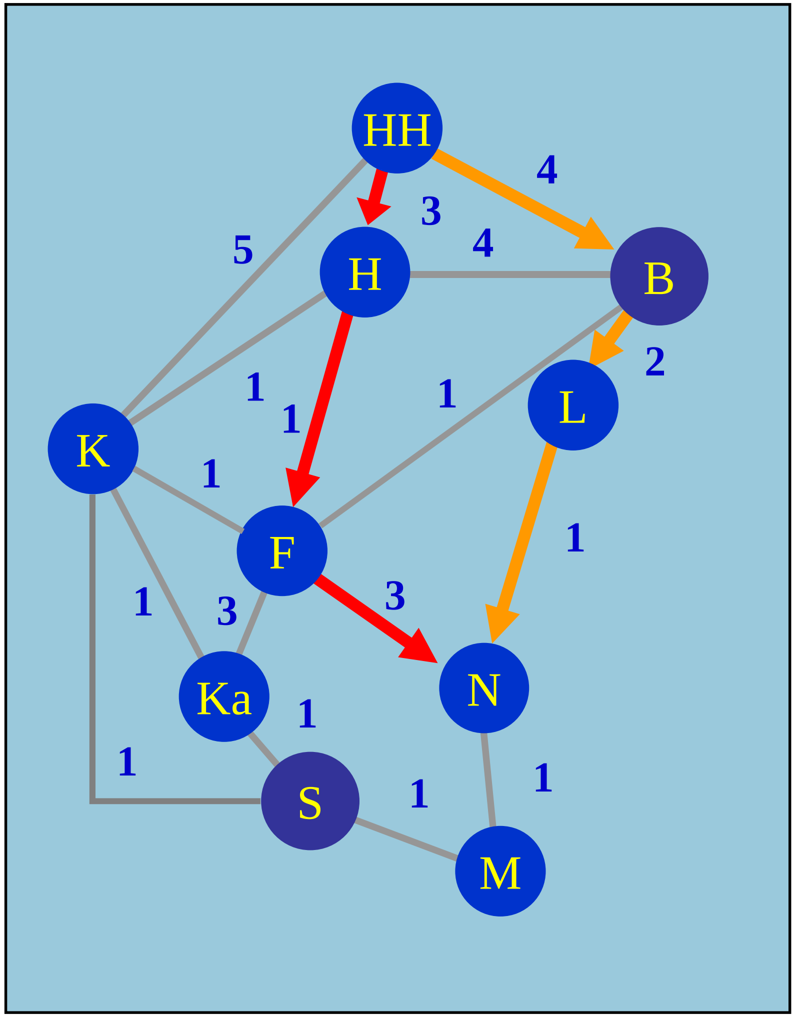
- Distance vector vs. Link state
- **Single path** vs. Multi-path

Unsplittable Shortest Path Routing

We are given

- an undirected simple graph G=(V,E)
- integral edge capacities c(e)>0 for all edges e
- a set K contained in VxV, called commodities
- integral demands $d_{(s,t)}$ >0 for each commodity (s,t) ε K

An unsplittable shortest path routing (USPR) of the commodities K is a set of flow paths f(s,t), (s,t) ε K, such that each f(s,t) is the unique shortest (s,t)-path for commodity (s,t) with respect to a common integral length function l(e)>0.



Unsplittable shortest path routing

(1) ...

(2) Compute **some** shortest path

- autonomously by routers
- arbitrary tie-breaking

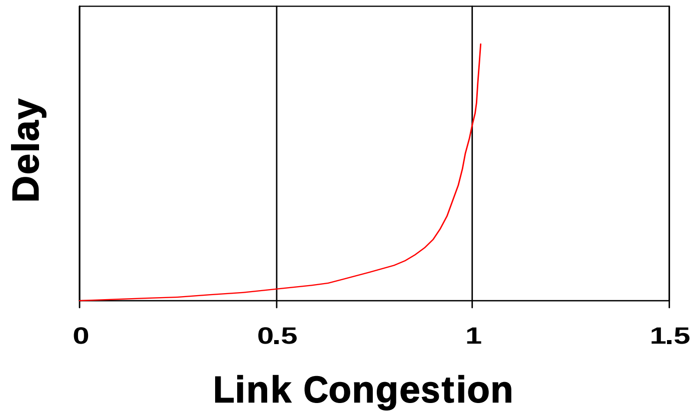
(3) ...

To have full control over routing all shortest paths must be **unique**!

Practice

Link congestion affects

- package loss rate
- avg. package delay
- jitter
- …



Traffic engineering (short-term planning):

– keep network hardware configuration fixed

– **change routing weights**

in order to

– **minimize congestion**

Problem

MinConUSPR: Minimum Congestion Unsplittable Shortest Path Routing

Instance	Digraph D=(V,A) with capacities c_a>0, a ε A Commodities K in VxV with demands $d_{(s,t)}$>0, (s,t) ε K

Def: Lengths λ : A ! Z_+ define an **unsplittable shortest path routing** if there is a **unique** shortest (s,t)-path $P^*_{s,t}(\lambda)$ for each (s,t) ε K.

Induced arc flows $f_a(\lambda) := \sum_{(s,t)\in K: a\in P^*_{s,t}(\lambda)} d_{s,t}$

Solution	Lengths λ : A ! Z_+ that define an USPR for K.
Objective	min L , s.t. $f_a(\lambda)$·Lc_a for all a2 A

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Complexity

Trivial

- (weakly) NP-hard even if D is a bidirected ring (Partition)
- Inapproximable within $2-\varepsilon$ (Disjoint Paths)

Currently best known

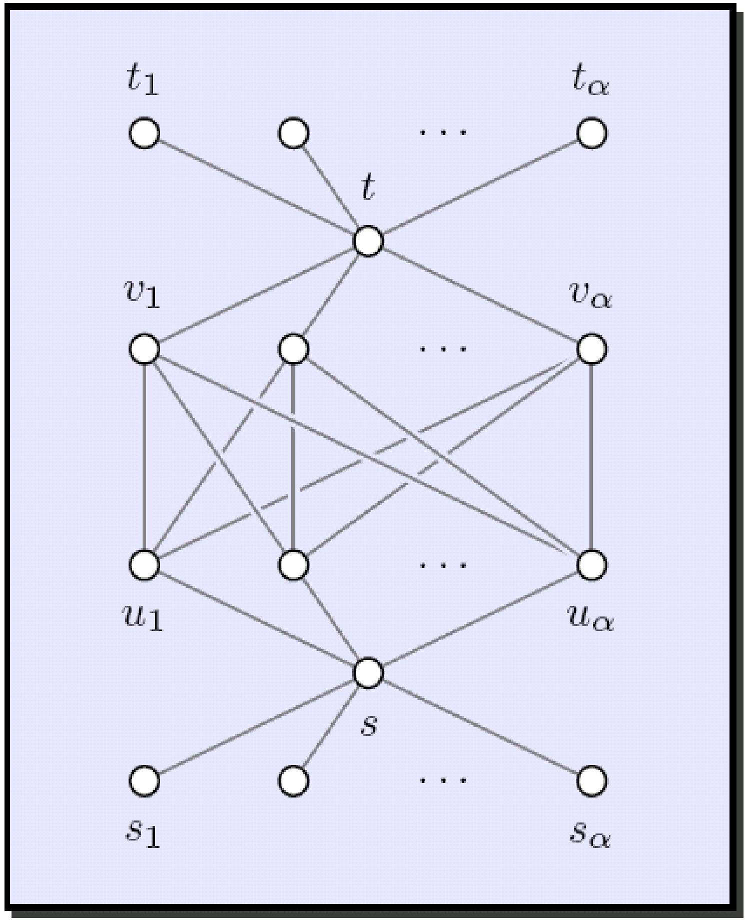
- Inapproximable within $\Omega(|V|^{1-\varepsilon})$ [B05]
- Approximable within

min{|A|,|V|}	General
3	Bidirected ring
2	Undirected cycle

Related

- Shortest multi-path version inapproximable within $3/2-\varepsilon$ [FortzThorup00]
- **$\Omega(|V|^2)$ worse than unsplittable flow** or shortest multi-path [B05]
- Same complexity with or without $d_{max} \cdot c_{min}$ [B05]

Related Routings



Multicommodity flow

Fractional flow for each (s_i, t_i).

All commodities independent.

Unsplittable flow

Single path for each (s_i, t_i).

All commodities independent.

Unsplittable shortest path routing

Unique shortest path for each (s_i, t_i).

Interdependencies among all (s_i, t_i).

Shortest Multi-Path routing

All shortest paths for each (s_i, t_i).

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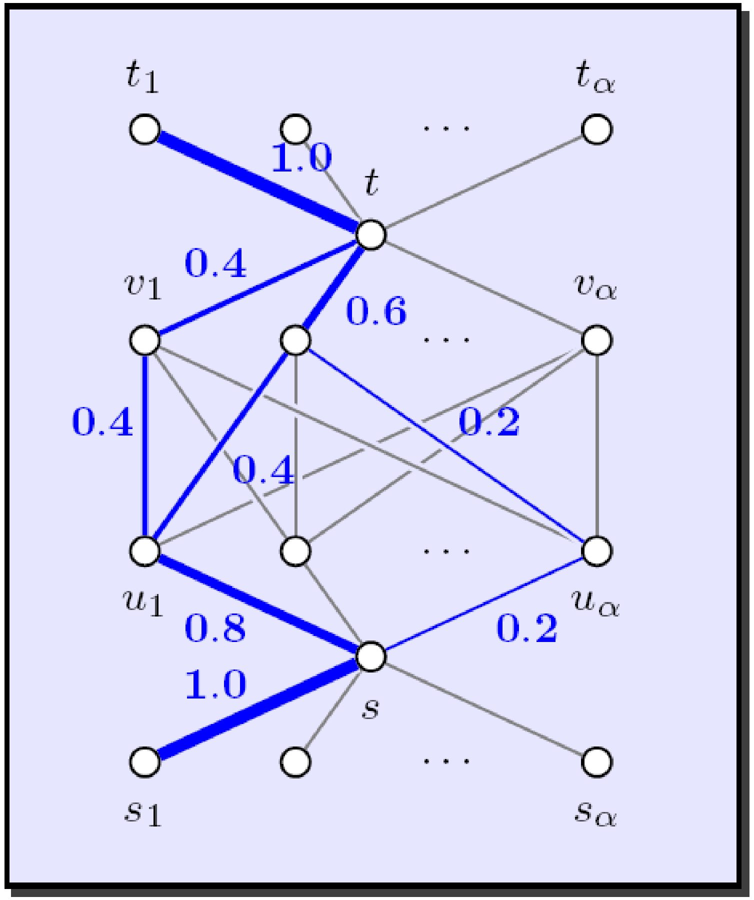

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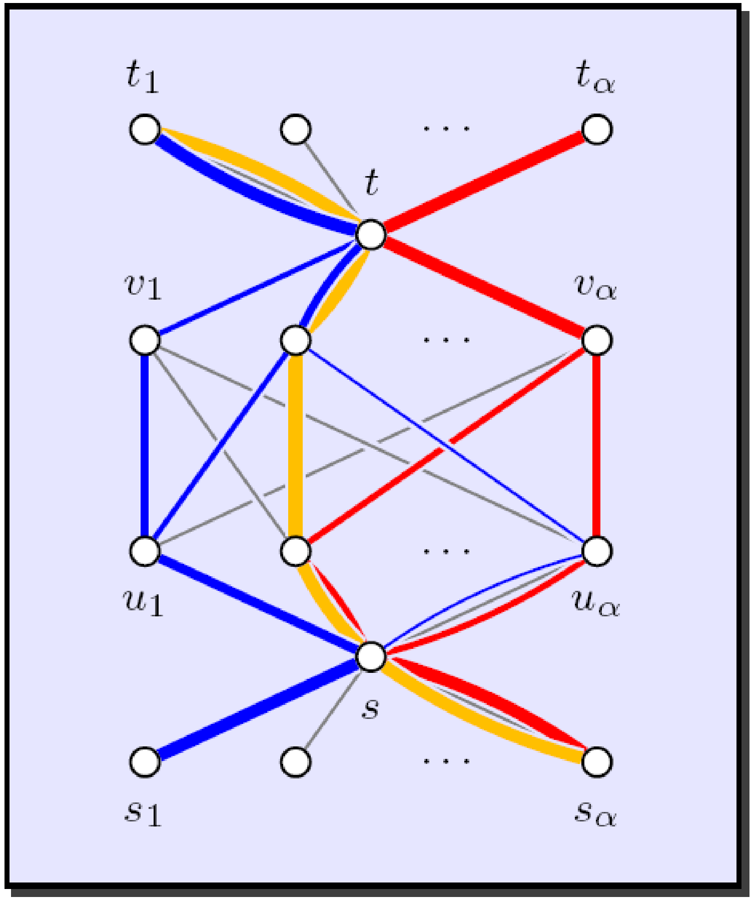

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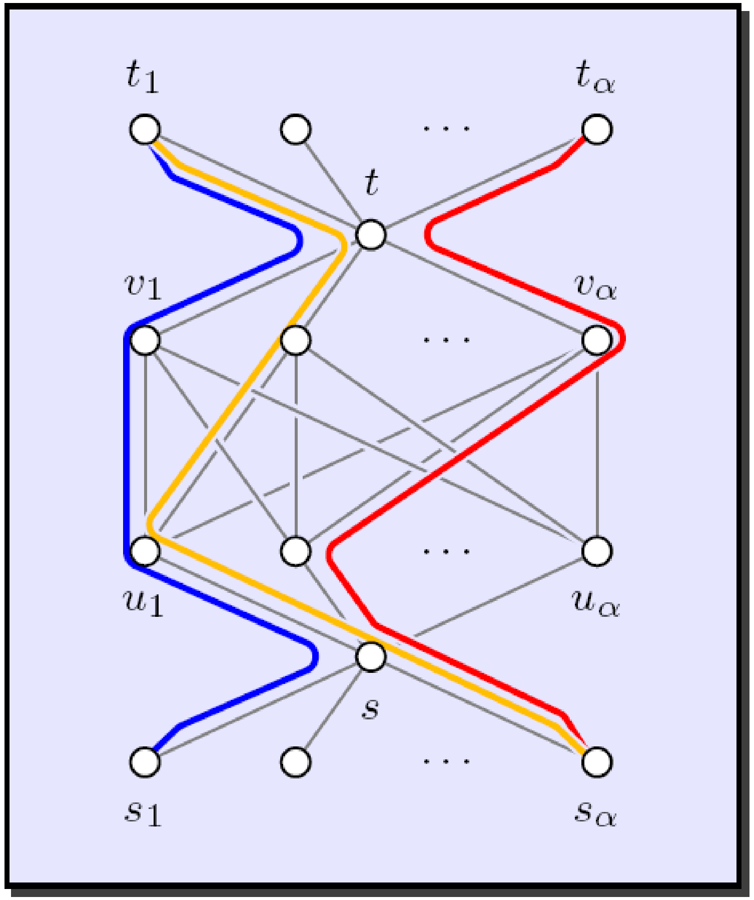

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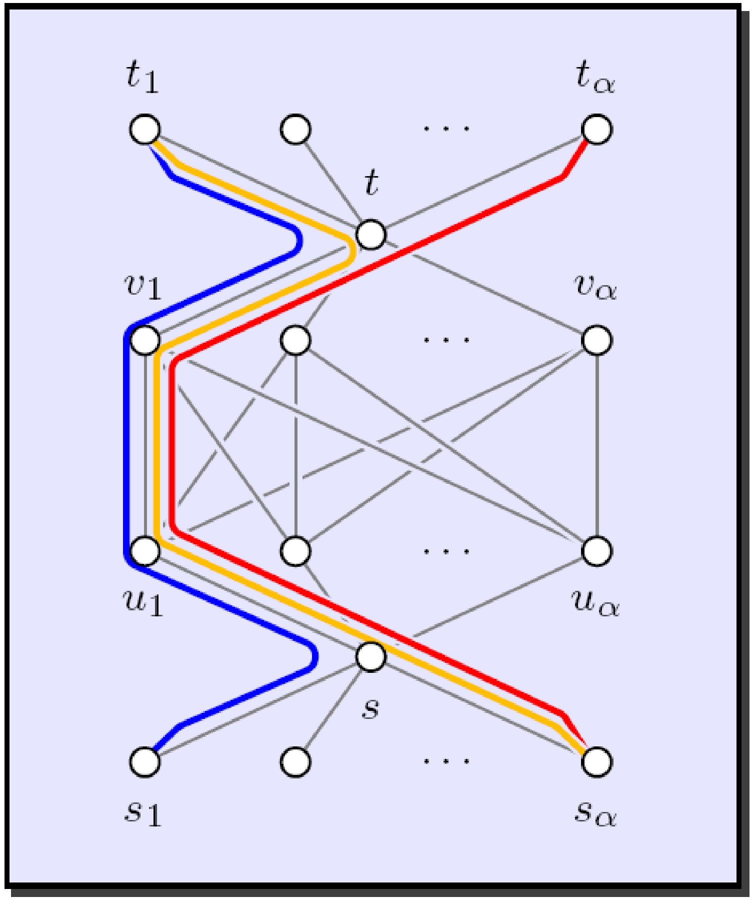

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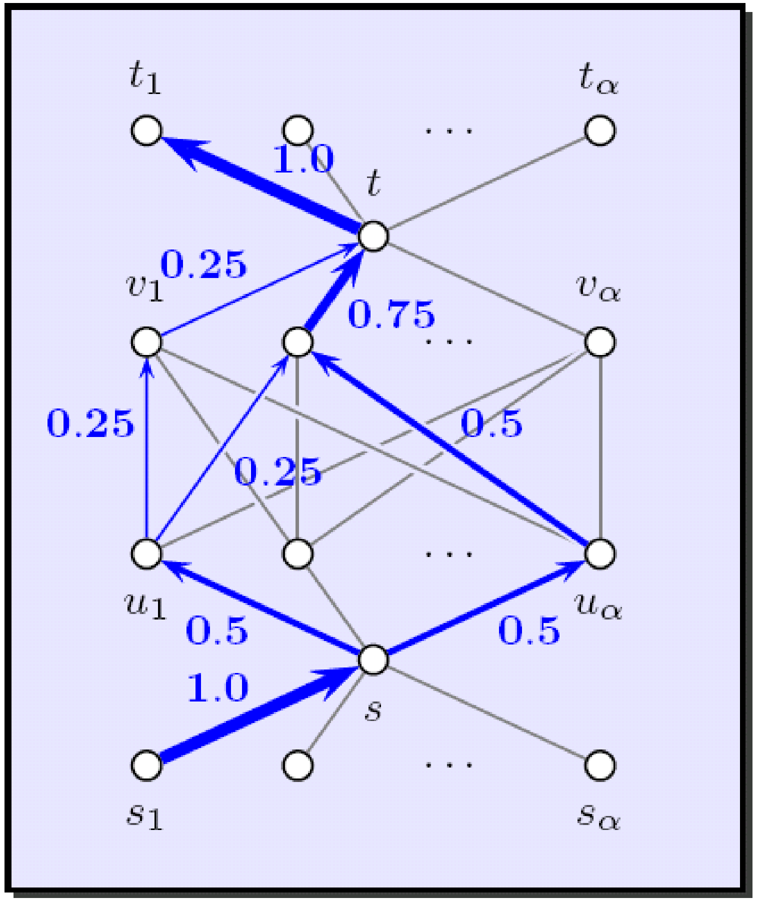

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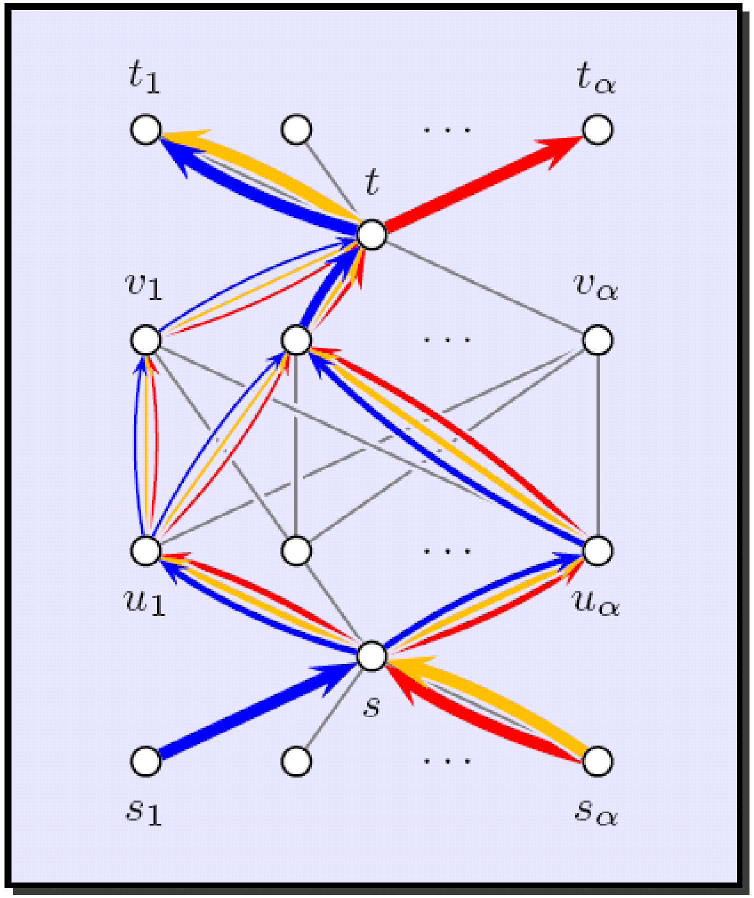

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Obs: (1) $L^{USPR} \in \Omega(V^2)$ { L^{MCF}, L^{UFP}, L^{ECMP} } where $L := \min \max_a f_a/c_a$
(2) no-bottleneck constraint is irrelevant

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    (feasible routing patterns form independence system)

Previous Work

Structure of path sets of (undirected) USPR

[BenAmeurGourdin00,BrostroemHolmberg05,Farago+98]

Weight-based optimization approaches

Modify lengths ⇨ **Evaluate effects on routing**

- **Local Search, Genetic Algorithms, ...**
  [BleyGrötschelWessäly98, FaragoSzentesiSzvitatovszki98, FortzThorup00, EricssonResendePardalos01, BuriolResendeRibeiroThorup03, ...]
- **Lagrangian Approaches** [LinWang93, Bley03, ...]

Flow-based optimization approaches

Optimize end-to-end flows ⇔ **Find compatible weights**

- **Integer linear programming** [BleyKoch02, HolmbergYuan01, Prytz02, ...]

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Optimize end-to-end flows ⇔ **Find compatible weights**

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Lagrange

min L

s.t. $f_{(u,v)} \leq L \cdot c_{(u,v)} \quad \forall (u,v) \in A$

$L \in [0, L_{max}]$

$(f, w) \in \mathbf{USPR}$

$\mu_{(u,v)} \geq 0$

Dual variables = penalty costs

Relax capacity constraints
Penalize capacity violation

Lagrange

$$Lag(\mu) := \min \; L - \sum_{(u,v)\in A} L \cdot \mu_{(u,v)} \cdot c_{(u,v)} + \sum_{(u,v)\in A} \mu_{(u,v)} f_{(u,v)}$$

s.t. $L \in [0, L_{max}]$

$(f, w) \in \mathbf{USPR}$

$$= \left(\min \; L - \sum_{(u,v)\in A} L\, \mu_{(u,v)}\, c_{(u,v)}, \quad L \in [0, L_{max}] \right) + \left(\min \sum_{(u,v)\in A} \mu_{(u,v)} f_{uv}, \quad (f, w) \in \mathbf{USPR} \right)$$

$$= Lag^{\mathbf{L}}(\mu) + Lag^{\mathbf{USPR}}(\mu)$$

Best penalties provide lower bound $\max_{\mu \geq 0} Lag(\mu) =: Lag^* \leq L^{opt}$

Lagrange

Congestion subproblem $Lag^{\mathbf{L}}(\mu)$

- Trivial
- Remark: Min cost network design without routing for network design problem

$$\min \; L - \sum_{(u,v)\in A} L\,\mu_{(u,v)}\,c_{(u,v)}$$
$$L \in [0, L_{max}]$$

- **Trivial:** L = 0 or L = L_{max}

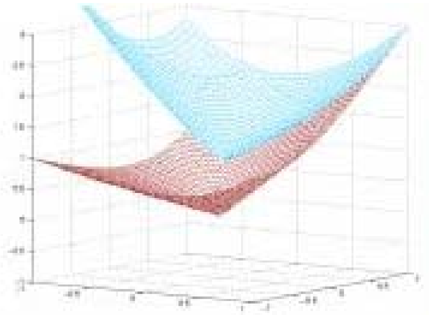
Routing Problem $Lag^{\mathbf{USPR}}(\mu)$

- **all pairs shortest path** problem
- optimal solution $w_{(uv)} := \mu_{(u,v)}$
- uniqueness by perturbation

$$\min \sum_{(u,v)\in A} \mu_{(u,v)} f_{uv}$$
$$(f, w) \in \mathbf{USPR}$$

- Dijkstra variant
- uniqueness by using link numbering as tie-breaker
- weights in [0,...,65535] in postprocessing

Dual maximization problem $\max_{\mu \geq 0} Lag(\mu)$



- convex optimization problem
- solvable by subgradient algorithms:

  descent methods,

  cutting plane methods,

  bundle methods, …

- **ConicBundle** algorithm [Helmberg]
- independent bundles for $Lag^{\mathbf{L}}(\mu)$ and $Lag^{\mathbf{USPR}}(\mu)$
- large bundle size (2|E|) to have small # evaluations

Lagrange

Heuristics are easy to integrate

- interpretation of **duals** as **routing weights** $w_{(uv)} := \mu_{(u,v)}$
- call heuristic after dual descent steps

- **Heuristic 1** (Min con or network design with few topology restrictions)
  1. **shortest paths** and **flows** f for $w := \mu$ by $Lag^{\text{USPR}}(\mu)$
  2. **min cost hardware** installation sufficient for f

- **Heuristic 2** (network design with tight topology restrictions)
  1. min cost **feasible hardware** installation by $Lag^{\text{Design}}(\mu)$
  2. **shortest paths** and **flows** f for $w := \mu$ on **restricted network**
  3. **min cost hardware** installation sufficient for f

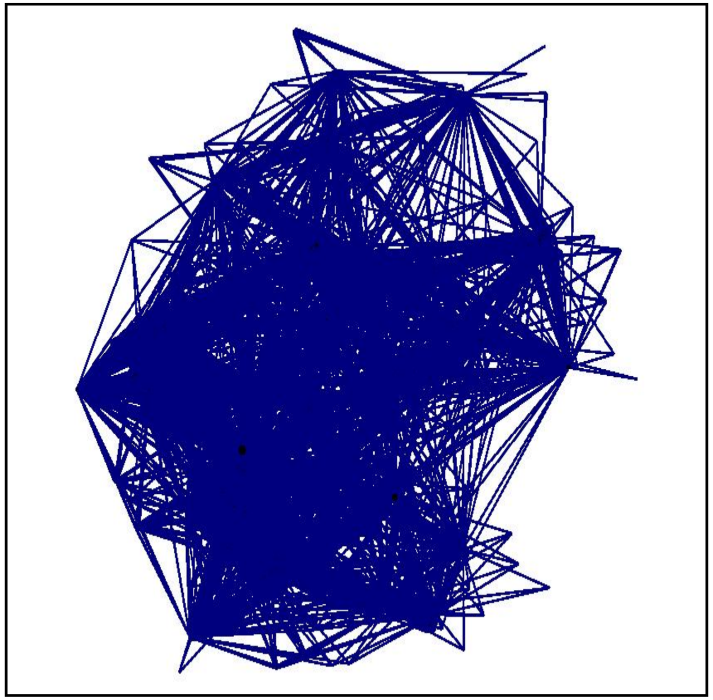
Results Lagrange

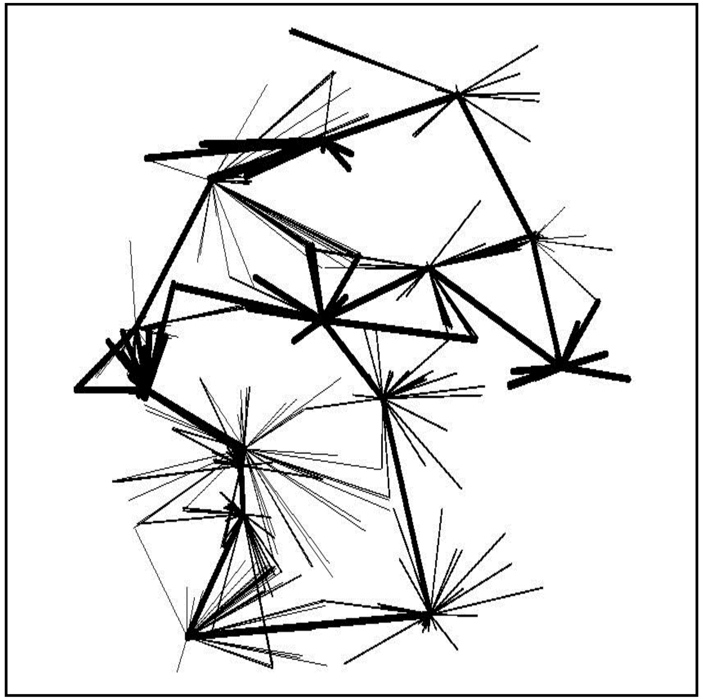
Problem	V	E	K	LB	UB	Gap(%)	Gap MIP (%)	Time (sec)
B-WiN	10	16	90	78	160	105.0	0.0	110
G-WiN uni	11	20	110	508	511	0.6	0.0	3
X-WiN	42	63	250	269	342	27.2	25.7	55
Atlanta	15	22	210	920	957	4.0	0.0	23
DiYuan	11	42	22	1000	1000	0.0	0.0	3
PDH	11	34	24	867	956	10.3	0.0	3
TA1	24	55	391	430	530	23.3	12.5	7
Nobel-EU uni	28	41	378	632	675	6.8	6.8	14
Nobel-US uni	14	21	91	46	52	10.8	0.0	261
Nobel-GER	17	26	121	631	762	20.8	0.0	32
Nobel-GER uni	17	28	121	354	458	29.4	14.5	8
Polska	12	17	66	937	1254	33.8	26.9	10
Polska uni	12	18	66	700	767	9.6	9.6	2
France	25	45	300	822	960	16.8	16.8	40
France uni	25	45	300	528	734	39.0	14.2	15
Norway	27	47	702	352	464	31.8	31.8	19
Norway uni	27	51	702	273	324	18.7	18.7	31
Newyork	16	46	240	141	147	4.3	2.1	7
Newyork uni	16	49	240	45	64	45.5	14.5	16

Symmetric routing, Values: 1000 * maximum congestion
Gap = Lagrange solution / Lagrange bound
Gap MIP = Lagrange solution / MIP bound
Primal: After each dual step try current duals for 5 random perturbations
Original instances available at sndlib.zib.de, MinConUSPR versions at cmw.zib.de

Results Lagrange

Lagrangian Approach: simple & robust & fast





Example: real-world two-layer network design problem (G-WiN)

757 nodes, 6.407 links, 122.180 non-zero demands

0.3% proven optimality gap **in <30 minutes** on P4 1.7GHz

Approaches

Structure of path sets of (undirected) USPR

[BenAmeurGourdin00,BrostroemHolmberg05,Farago+98]

Weight-based optimization approaches

Modify lengths ⇨ Evaluate effects on routing

- **Local Search, Genetic Algorithms, ...**
  [BleyGrötschelWessäly98, FaragoSzentesiSzvitatovszki98, FortzThorup00, EricssonResendePardalos01, BuriolResendeRibeiroThorup03, ...]
- **Lagrangian Approaches** [LinWang93, Bley03, ...]

Flow-based optimization approaches

Optimize end-to-end flows ⇔ **Find compatible weights**

- **Integer linear programming** [BleyKoch02, HolmbergYuan01, Prytz02, ...]

Inverse USP

Inverse Unique Shortest Path Problem

Given: Directed graph $D = (V, A)$ and **path set** $Q \subseteq \mathcal{P}$.

Task: **Find weights** $\lambda \in \mathbb{R}^A$ such that each (s,t)-path $P \in Q$ is the unique shortest (s,t)-path with respect to λ (or prove non-exist.).

IUSP is equivalent to solving **linear system** [BenAmeurGourdin00,...]:

$$\sum_{a \in P'} \lambda_a - \sum_{a \in P} \lambda_a \geq 1 \;\; \forall \; P \in Q, \;\; P' \in \mathcal{P}(s_P, t_P) \setminus \{P\} \quad (1)$$

$$\lambda_a > 0 \;\; \forall \; a \in A$$

Inequalities (1) polynomially separable via 2-shortest path algorithm.

Thm:

(1) IUSP is **polynomially solvable**.

(2) Above LP feasible) λ_a are compatible weights for Q.
Above **LP infeasible**) dual Farkas ray / IIS of rows yields **irreducible non-unique shortest path system**

Inverse USP

Inverse Unique Shortest Path Problem

Given: Directed graph $D=(V,A)$ and **path set** $Q \subseteq \mathcal{P}$.

Task: **Find weights** $\lambda \in \mathbb{R}^A$ such that each (s,t)-path $P \in Q$ is the unique shortest (s,t)-path with respect to λ (or prove non-exist.).

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$$\lambda_a > 0 \;\; \forall \; a \in A$$

Inequalities (1) polynomially separable via 2-shortest path algorithm.

Remark: Only **small integer lengths** admissible in practice.

Thm [B'04]: Finding min integer λ is APX-hard.

Thm [BenAmeurGourdin00]: min integer λ is approximable within a factor of min($|V|/2$, $\max_{P\in Q}|P|$).

Approaches

Structure of path sets of (undirected) USPR

[BenAmeurGourdin00,BrostroemHolmberg05,Farago+98]

Weight-based optimization approaches

Modify lengths ⇨ Evaluate effects on routing

- **Local Search, Genetic Algorithms, ...**

  [BleyGrötschelWessäly98, FaragoSzentesiSzvitatovszki98, FortzThorup00, EricssonResendePardalos01, BuriolResendeRibeiroThorup03, ...]

- **Lagrangian Approaches** [LinWang93, Bley03, ...]

Flow-based optimization approaches

Optimize end-to-end flows ⇔ Find compatible weights

- **Integer linear programming** [BleyKoch02, HolmbergYuan01, Prytz02, ...]

MILP Approach

Idea

(1) Use your favorite UFP formulation
(2) Add inequalities characterizing USPRs

$$\min \; L$$

$$\sum_{P \in \mathcal{P}(s,t)} x_P = 1 \qquad \forall\; (s,t) \in K$$

$$\sum_{P:\; a \in P} d_{(s_P, t_P)} x_P \leq L \cdot c_a \qquad \forall\; a \in A$$

$$x \in \text{USPR} \qquad (*)$$

$$x_P \in \{0,1\} \qquad \forall\; P(K) \in \mathcal{P}$$

$$L \geq 0$$

Question: What are these USPR inequalities?

MILP Model

) **Independence system polytope yields complete characterization of all valid USPRs.**

$$\min \; L$$

$$\sum_{P \in \mathcal{P}(s,t)} x_P = 1 \qquad \forall \; (s,t) \in K$$

$$\sum_{P:\; a \in P} d_{(s_P,t_P)} x_P \leq L \cdot c_a \qquad \forall \; a \in A$$

$$\boxed{x \in IND(\mathcal{I}_{USPR})} \qquad (*)$$

$$x_P \in \{0,1\} \qquad \forall \; P(K) \in \mathcal{P}$$

$$L \geq 0$$

Valid and sufficient inequalities for USPR:

$$\sum_{P \in Q} x_p \leq rank(Q) \quad \forall \; Q \subseteq \mathcal{P}$$ (rank inequalities for $\mathcal{I}_{SPS}$)

Separation

Separation of **rank** inequalities $\Longleftrightarrow$ **min weight** (irreducible) **non-SPS**

Good news:

Given a path set $Q \subseteq \mathcal{P}$, we **can find some** irreducible non-SPS $C \subseteq Q$ **in polynomial time.**

We can cut-off of infeasible integer routings in polynomial time.

$$\sum_{P \in C} x_p \leq |C| - 1 \quad \forall\ C \in \mathcal{C}_{SPS}$$

Bad news:

Thm [B'04]: **Min cardinality** and **min weight non-SPS** are **NP-hard to approximate** within $7/6 - \epsilon$.

- Computing the rank of an arbitrary path set is NP-hard.
- Separation of rank inequalities is NP-hard (even for only irreducible non-SPS).

MILP Approach

MILP model

- **Variables**
  - Path or Arc-flow variables
  - Congestion
- **Constraints**
  - Capacity constraints
  - Flow conservation and integrality
  - Shortest path routing (easy)
  - Shortest path routing (hard)

Algorithms

Opt end-to-end routing

- Cutting plane algorithm
- Branch & Cut (& Price)
- Heuristics

Rank-Cuts

Find compatible weights

Linear programming (+rounding)

Remarks:

- **Pricing** of path variables is **NP-hard**.
- Indepence system characterization of USPR **arc-flows analogously.**

Results MILP

Problem	V	E	K	Initial LP	LB	UB	Gap(%)	Time (sec)	BB-Nodes
B-WiN	10	16	90	79	160	160	0.0	14	540
G-WiN uni	11	20	110	508	510	510	0.0	6	110
X-WiN	42	63	250	269	269	272	1.4	3600	962
Atlanta	15	22	210	920	957	957	0.0	62	56
DiYuan	11	42	22	1000	1000	1000	0.0	0	1
PDH	11	34	24	867	956	956	0.0	0	4
TA1	24	55	391	447	530	530	0.0	13	6
Nobel-EU uni	28	41	378	632	632	633	0.2	3600	436
Nodel-US	14	21	91	922	922	925	0.4	3600	6894
Nobel-GER	17	26	121	631	733	733	0.0	160	26
Nobel-GER uni	17	28	121	354	400	400	0.0	313	80
Polska	12	17	66	938	988	988	0.0	35	74
Polska uni	12	18	66	701	707	707	0.0	211	691
France	25	45	300	822	960	960	16.8	3600	43
France uni	25	45	300	529	643	669	4.0	3600	38
Norway	27	47	702	352	352	436	23.8	3600	192
Norway uni	27	51	702	273	273	318	16.4	3600	126
Newyork	16	46	240	141	144	144	0.0	9	14
Newyork uni	16	49	240	45	56	62	10.9	3600	79

Values: 1000 * maximum congestion, Arc-flow formulation
Original instances available at sndlib.zib.de, MinConUSPR versions at cmw.zib.de

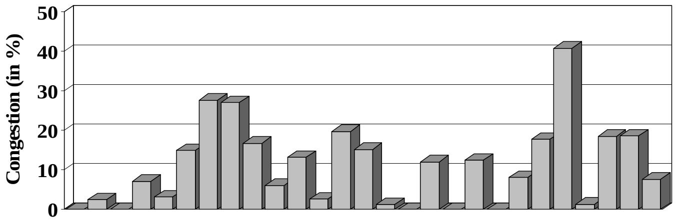
Relevance

Little efford & big QoS improvement in practice by optimizing routing weights!

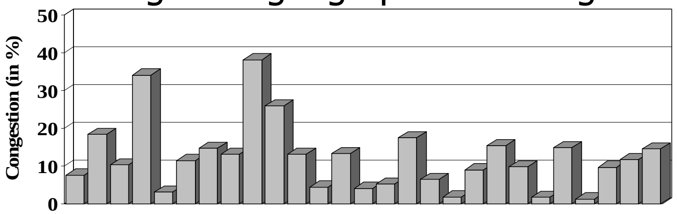
Default settings: L_{max} > 38 %

Optimized weights: L_{max} = 17 %

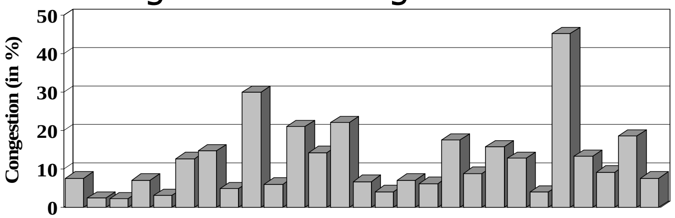
Weights = inverse capacities

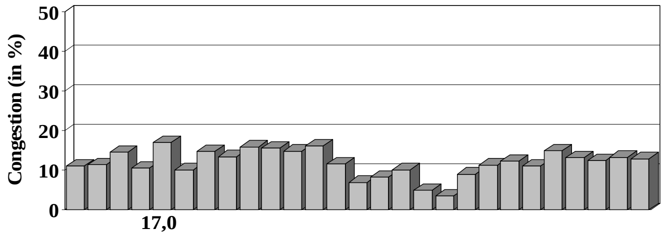


Weights = geographic link lengths

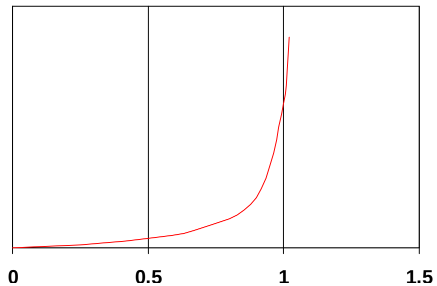


Weights = unit lengths





Packet loss rate / Congestion



High congestion = poor QoS

Conclusions

Unsplittable shortest path routing

- very complex from routing planning perspective

Lagrangian approach

- simple, fast, good scaling properties
- reasonably good bounds and solutions
- easy in include further side constraints

  (hop/delay-limits, hardware reuse, reconfiguration restrictions,…)

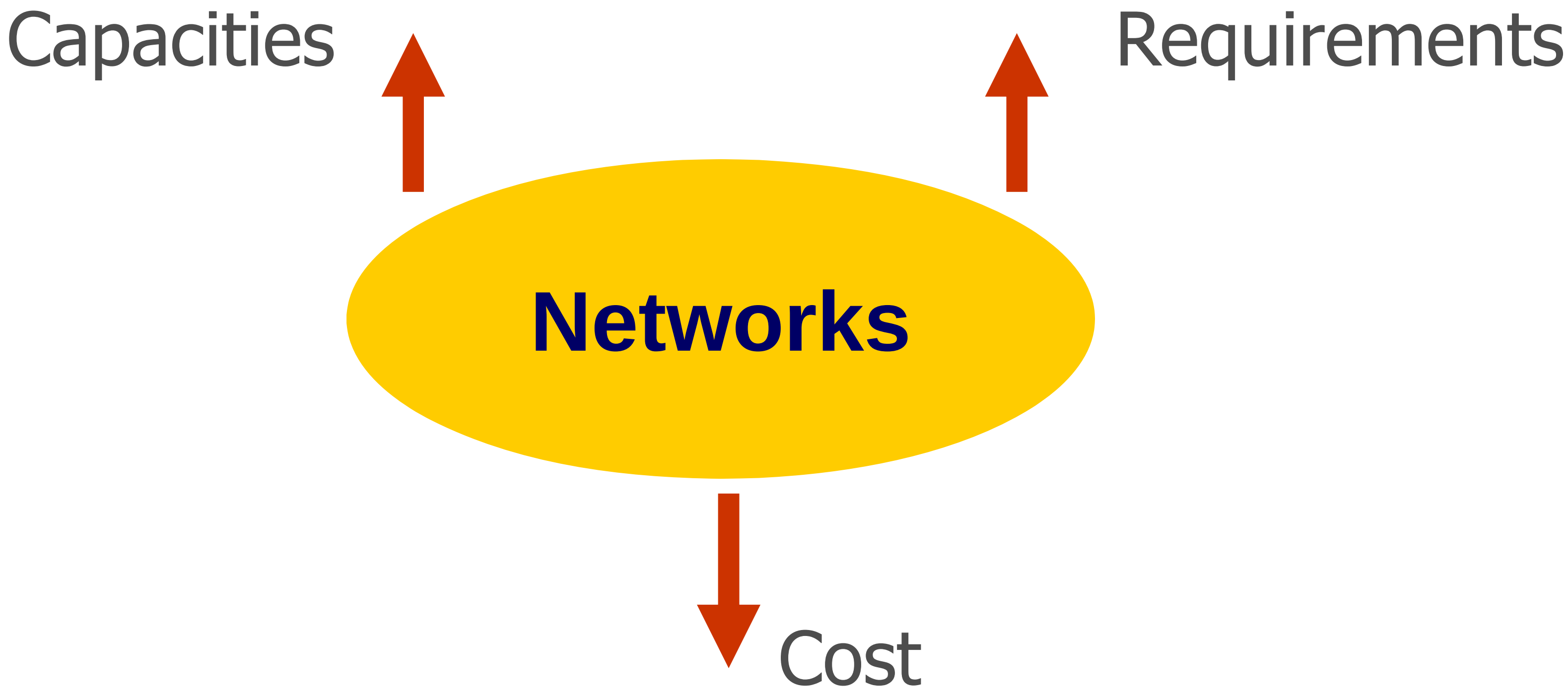
MILP appraoch

- often better solutions than Lagrange or heuristics
- best known lower bounds, often even optimality
- bad scalability
- works only for **unsplittable** shortest path routing
- difficult to implement efficiently

Contents

Martin Grötschel

Network Optimization



Martin Grötschel

What needs to be planned?

- Topology (telecom jargon for graph = routing network)
- Capacities
- Routing
- Failure Handling (Survivability)

- IP Routing
- Node Equipment Planning
- Optimizing Optical Links and Switches

DISCNET: A Network Planning Tool

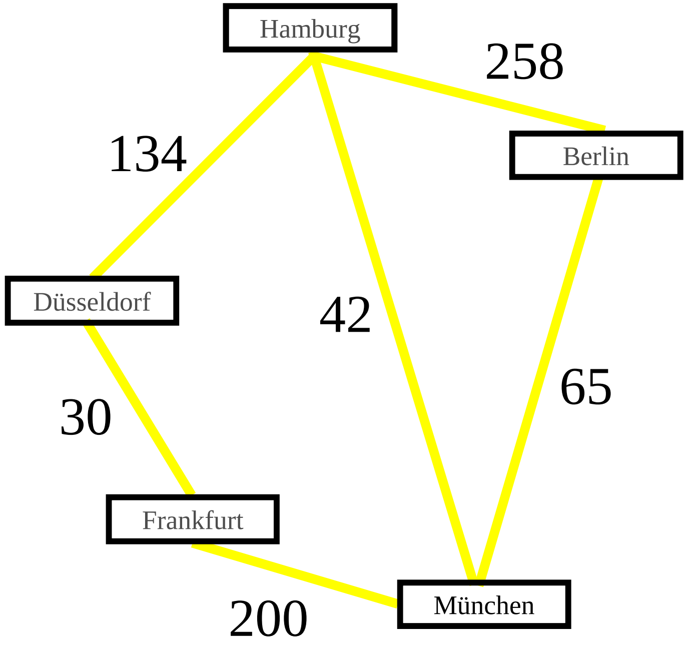
(Dimensioning Survivable Capacitated NETworks)

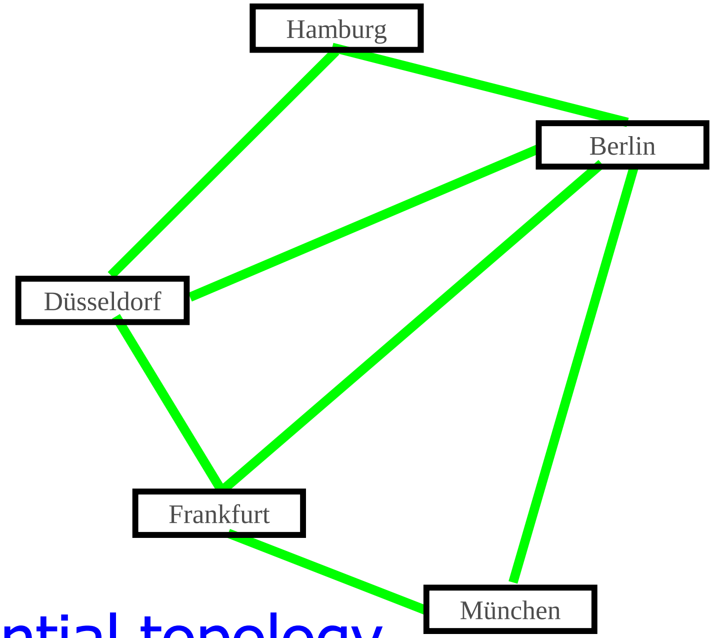
atesio ZIB Spin-Off

Martin Grötschel

The Network Design Problem

Communication Demands





Potential topology
&
Capacities

Martin Grötschel

Capacities

(P)SDH=(poly)synchronous digital hierarchy

PDH	SDH
2 Mbit/s	155 Mbit/s
34 Mbit/s	622 Mbit/s
140 Mbit/s	2,4 Gbit/s
	... WDM (n x STM-N)

Two capacity models : Discrete Finite Capacities
Divisible Capacities

WDM=Wavelength Division Multiplexer
STM-N=Synchronous Transport Modul with N STM-1 Frames

Martin Grötschel

Survivability

- What does this mean?
- Does anyone care?
- How much?

Martin
Grötschel

USA 1987-1988

PUBLICATION: TE&M

June 15, 1988

THE NIGHTMARE ON LINCOLN ST.

Illinois Bell experiences its worst service disaster in history as an extra-alarm fire silences phones for nearly two weeks

Severed line snags calls long-distance

The loss of a major fiber optic telecommunications cable caused significant problems on Wednesday, August 12th, with long-distance calls out of the 201 calling area

The Star Ledger

Date: September 22, 1987

Damage to fiber cable hinders phone service

By TED SHERMAN

Telephone service was disrupted throughout the Northeast yesterday, after a major fiber optics cable was severed north of Trenton.

The problem briefly knocked out all voice and data circuits on American Telephone & Telegraph Co.'s main East Coast fiber cable, which runs from Cambridge, Mass., to Arlington, Va.

USA 1987-1988

PUBLICATION: Star-Ledger

DATE: February 26, 1988

Cable snaps, snags area phone calls

American Telephone & Telegraph Co. (AT&T) service along the East Coast was disrupted yesterday when a telephone cable snapped about 15 miles southwest of Newark.

Saturday, November 19, 1988

Phone snafu isolates New Jersey

Long-distance cable severed

By J.D. SOLOMON,
MARY ROMANO
and ROBIN SIDEL
Courier-News Staff Writers

American Telephone & Telegraph Co.'s long-distance telephone service throughout the East Coast was disrupted for about 10 hours yesterday when a major transmission cable was severed by a construction crew working in a Sayreville train yard, AT&T officials said.

Problems were especially severe in portions of Central Jersey, and customers closest to Sayreville were expected to be among the last to have their service fully restored, an AT&T spokesman said.

The break in the 3-inch fiber optic cable occurred at 12:15 p.m. Service was restored gradually as computers rerouted calls through other points. Almost all service was restored by about 7 p.m., AT&T said.

"It's almost like a highway in that you have to go along it to get from, say, New York to Florida. This is a major blockage affecting the whole East Coast."

Jim Nelson, AT&T district manager

In addition to affecting phone service, private customers whose computer networks use AT&T phone line transmissions experienced service problems, Nelson said.

Harry Baumgartner, a spokesman for AT&T in the Basking Ridge section of Bernards, said calls between area codes on the East Coast

Martin Grötschel

Special Report by IEEE Spectrum

0018-9235/89/0600-0032$1.00©1989 IEEE

IEEE SPECTRUM JUNE 1989

SPECIAL REPORT:

Keeping the phone lines open

The telephone network's moment-by-moment reconfigurations to meet emergencies real and simulated add up to de facto *risk management*

necessary, Joe
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tiple repeaters
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Martin Grötschel

Sometime after 4:00 p.m. on Sunday, May 8, 1988, on the first floor of a telephone switching center in the Chicago suburb of Hinsdale, a metal cable sheath came into contact with a damaged, energized power cable and touched off an electrical fire. Thus began one of the worst disasters in the history of U.S. telephony.

By the time the smoke had cleared, 35 000 residential and business customers had no service at all, and others served by some 120 000 trunk lines lacked long-distance service. A facility that had relayed 3.5 million telephone calls a day was a messy mix of destroyed and damaged equipment, much of it fast corroding from the caustic combination of water and vapors released by burning paneling.

The community soon found out just how much it depended on telephony. Chicago's busy O'Hare Airport came to a standstill while technicians jury-rigged some telephone lines for the Federal Aviation Administration to use for air-traffic control. Emergency 911 service was no more. Cellular telephones were also out because Hinsdale had housed a key installation in the local system. Automatic teller machines in the Chicago area, which transmit transaction details over telephone lines, were down. Pizza makers, florists, real estate agents, stockbrokers, "mom-and-pop" proprietors, boyfriends and girlfriends—all lost a vital link.

Some areas had no service for a month, and dollar estimates of lost business ranged from the hundreds of millions to the tens of billions.

Special Report

IEEE Spectrum June 1988

Martin Grötschel

Berlin 1994 & Köln 1994

Graue Mattscheiben und stille Telefone

Totalausfall in Charlottenburg und Spandau bringt Tausende in Rage / Panne bei Bauarbeiten

24.12.94

VON BERNHARD KOCH

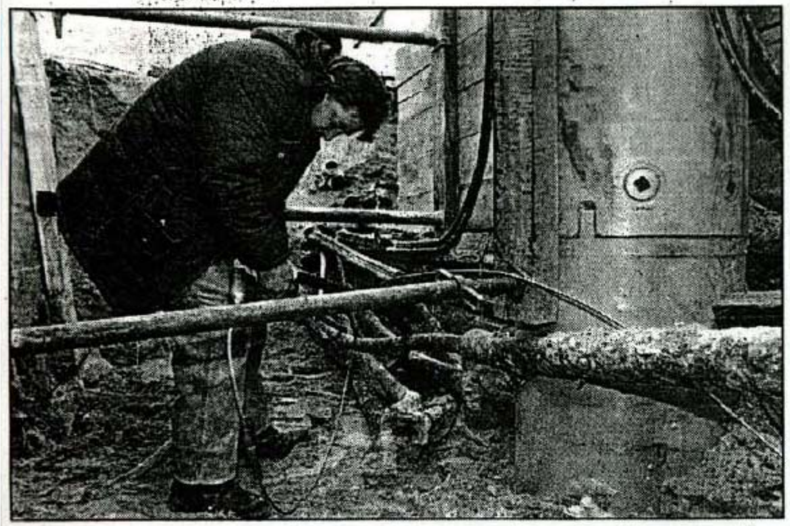
BERLIN. Unverantwortliche Schlamperei einer Baufirma, so Telekom-Sprecher Bernhard Krüger, führte am Donnerstag zum Totalausfall von Kabelfernsehen und -rundfunk in rund 160 000 Haushalten in Charlottenburg und den Spandauer Ortsteilen Siemensstadt, Gatow und Kladow. Infolge eines bei Tiefbauarbeiten nahe dem S-Bahnhof Heerstraße in Charlottenburg zerstörten Kabelpakets wurden zudem 3000 Telefonkunden vom Netz vollständig abgeschnitten. Weiter war die Zahl der Leitungen auf der Strecke zwischen den betroffenen Bezirken erheblich eingeschränkt. Die Telekom sprach von der größten Panne, die es bislang in Berlin gegeben habe. Die Kabelstränge für Fernsehen und Radio konnten bis Freitag abend schrittweise repariert werden, der Schaden an den Telefonleitungen werde jedoch frühestens im Laufe des heutigen Heiligen Abends behoben sein. 25 Männer seien ohne Pause im Einsatz: „Am ersten Weihnachtstag ist die Lage im Griff."

Ein sogenannter Fundamentbohrer hatte am Donnerstag gegen 15 Uhr ein Loch von 60 Zentimeter Durchmesser in die Telekom-Kabelstränge an der Heerstraße gerissen. Die Baufirmen, die dort mit Straßen- und Brückenbauarbeiten beschäftigt sind, „hatten exakte Pläne über unsere Versorgungsleitungen", betonte Bernhard Krüger. Welche Firma die Schuld treffe – die Bauunternehmen Kemmer und Holzmann sind dort tätig – sei noch nicht ermittelt. Die Reparatur dauere deshalb so lange, weil mehrere jeweils 250 Meter lange Kabel komplett ausgetauscht und Rohre als Schutzmantel neu verlegt werden müßten.

Unterdessen war bei der Störungsannahme und den Servicestellen der Telekom nach der Panne „die Hölle los". Tausende erboste Kunden hätten ihrem Unmut über schwarze Mattscheiben und schweigende Telefone Luft gemacht. „Wir werden den ganzen Tag beschimpft, einige drohen uns sogar", sagte eine spürbar genervte Frau beim Telekom-Störungsdienst. Pausenlos klingelten auch die Telefone beim SFB und bei anderen Fernsehanstalten, hieß es auf Nachfrage. Weil sie keine Auskünfte über die Störung bekamen, fragten einige Bürger gar bei der Polizei nach. Auch beim Tagesspiegel gingen zahlreiche Beschwerden über die Telekom ein, eine Spandauerin forderte zum Beispiel, sämtliche ausgefallene Sendungen sollten wiederholt werden.

Telekom-Sprecher Krüger bat hingegen um Verständnis, schließlich sei man nicht Verursacher des Schadens: „Ich habe so etwas noch nicht erlebt. Die Droge Fernsehen macht offenbar derart süchtig, daß die Leute so in Rage geraten." Über die Ausfälle und Störungen beim Telefon hätten vergleichsweise wenige Kunden geklagt.

Die Höhe der Reparaturkosten, mögliche Regreßforderungen von Geschädigten sowie die Summe der Gebührenausfälle aufgrund des gestörten Telefonverkehrs seien noch nicht abzusehen, sagte Krüger. Privatkunden, so der Telekomsprecher, bekämen grundsätzlich nur dann Vergütungen, wenn das Telefon länger als fünf Tage ausfalle.



FEHLBOHRUNG MIT ERHEBLICHEN FOLGEN. Ein Fundamentbohrer riß auf dieser Baustelle an der Charlottenburger Heerstraße ein Loch in die Telekom-Kabeltrasse. Foto: Mike Minehan

EXPRESS Köln

23 000 Kölner ohne Anschluß

exp Köln - Fünf Stunden lang waren gestern die Telefonleitungen von 23000 Kölnern in Flittard und Höhenhaus tot. Bei der Verlegung einer Gasleitung hatten Arbeiter mehrere Telekom-Kabel zerstört. 3000 Kunden blieben die ganze Nacht über ohne Anschluß.

Martin Grötschel

High-Tech Terrorism 1995

DEUTSCHLAND

kommt, dann tut sich endlich was in diesem Nest", hofft der Elektromeister Jürgen Moritz. Mehr als 30 Jahre lebt er schon in dem tristen Ort; nun, im Jahre sechs nach der Wende, „muß doch mal was passieren".

„Der hat Ideen und viele Kontakte", sagt Moritz bewundernd, „von Marktwirtschaft versteht er was."

Mangels Schloß und Pachtzins verdingt sich der Adelsmann zur Zeit in einem bürgerlichen Beruf: als Inneneinrichter ostdeutscher Friseurgeschäfte. Von Wiesenburg bei Potsdam aus beaufsichtigt von Ribbeck acht Angestellte, die Barbieren Spezialstühle, Spiegel und Trockenhauben anbieten.

Ratsmitglied Böttcher ist davon nicht beeindruckt: „So schlau wie der von Ribbeck sind wir auch." Vor der Wende war Böttcher Vorsitzender der LPG, heute ist er der Chef der örtlichen Agrar GmbH. Die Pacht für Wiesen, Weiden und Stallungsgrund kassiert bislang noch die Treuhand.

Ein „Investitionshemmnis" nennt Böttcher den Junker: Längst hätten neue Traktoren angeschafft werden müssen, „aber wovon denn?" Wegen der Ribbeck-Ansprüche auf Rückgabe „gibt uns keine Bank Kredit".

Solche Klagelieder kann der emsige Protestant Moritz, der mit Freunden in der Freizeit die Dorfkirche renoviert, nicht mehr hören. Die Leninstraße hätten die Gemeindeväter nach der Wende in Theodor-Fontane-Straße umbenannt, „viel mehr ist nicht passiert".

Moritz träumt davon, daß die Rückkehr derer von Ribbeck Touristen in den Ort bringt, der außer dem berühmten Namen nichts weiter zu bieten hat.

Allerhand hat der Erbe schon vorgeschlagen, um das brandenburgische Nest auf Trab zu bringen, und auch, um den Dörflern zu gefallen. Eine „Managementschule für Ökologie" möchte von Ribbeck in Ribbeck errichten, eine Käserei, einen Reiterhof. Oder eine Pizzeria, ein Sägewerk, eine Rinderzuchtfarm. Neueste Idee aus der Ribbeckschen Denkfabrik: eine Brennerei, für Birnenschnaps natürlich.

„Eine Schnapsidee", kontert Böttcher, „wir bekommen doch gar keine Brennrechte."

Geld, räumt von Ribbeck ein, habe er nicht, „aber es gibt doch Banken". Und solange er in Deutschland keine Brennrechte bekommt, will er den hofedlen Birnenschnaps derer von und zu Ribbeck eben in Italien destillieren lassen, „mit ein paar Anstandsbirnen aus dem Havelland drin".

Auf einem Acker an der Schnellstraße hat von Ribbeck bereits 1000 Birnbäume pflanzen lassen. Doch auch das hat Bauer Böttcher nicht besänftigt. „Die jungen Bäume", spottet er, „stehen doch viel zu eng beieinander." ❑

Anschläge

Stummer Rebell

Erstmals in Deutschland schlugen in Frankfurt High-Tech-Terroristen gegen die Kommunikationsgesellschaft zu.

Die Täter kamen in der Nacht, irgendwann nach drei Uhr früh. An drei Orten nördlich und östlich des Frankfurter Flughafens, Kilometer voneinander entfernt, wuchteten sie zentnerschwere Betondeckel hoch und kletterten in den Orkus der verkabelten Gesellschaft.

In den Gruben kreuzen sich Telekom-Kabel für Computer- und Datenleitungen mit Kabeln für Telefon- und Fax-Verkehr wie Nervenstränge.

„Vermutlich mit Sägen", so die Polizei, durchtrennten die kundigen Kabel-Killer Kupferstränge und Bündel armdicker Glasfaserleitungen. Insgesamt schnitten sie 4,5 Meter Kabel heraus.

Um fünf Uhr dann am vergangenen Mittwoch, als im Flughafen die Computer angeschaltet wurden, zeigte sich, was die Säger angerichtet hatten: Bildschirme flimmerten nur noch, 13 000 Telefone im Süden Frankfurts, darunter alle Leitungen der Universitätsklinik, waren tot; stumm waren auch viele Außenleitungen der Frankfurter Flughafen AG und jene Glasfaseradern, die den Lufthansa-Buchungscomputer in Kelsterbach mit dem benachbarten Airport verbinden.

„Ein einmaliger Anschlag", stöhnte Telekom-Sprecher Michael Hartmann; die Tat verrate Systemkenntnis und „massive kriminelle Energie".

In einem Schreiben an die *Frankfurter Rundschau* bekannte sich eine bislang unbekannte Gruppe namens „Keine Verbindung e.V." zu der Untat. Mit der „Aktion", so die vermutlich linksterroristischen Bekenner, hätten sie den Flughafen lahmlegen wollen. Denn der habe eine Funktion „im Rahmen der imperialistischen Weltwirtschaftsordnung".

Mit dem Blackout im Airport trafen die Terroristen die High-Tech-Gesellschaft, wo sie am verwundbarsten ist: Sie demolierten drei von insgesamt mehreren tausend Kabel-Knotenpunkten der Republik, deren exakte Lage und Bedeutung nur wenigen Experten bekannt ist.

Buchungsschalter im Frankfurter Flughafen: Chaos durch Kabel-GAU

Fachkundige Attentäter, warnt der Darmstädter Staatsrechtler Alexander Roßnagel, könnten zentrale Informations- und Kommunikationssysteme lähmen sowie ganze Wirtschaftszweige ins Chaos stürzen – und damit „Katastrophen nationalen Ausmaßes" auslösen.

Kraftwerke und Chemiefabriken, Militär, Polizei und Nachrichtendienste, Banken und Versicherungen, Krankenhäuser und Verwaltungen hängen am Computer. Tausende von Milliarden Mark werden täglich via Datenelektronik umgeschlagen, lebenswichtige Informationen per Kabel lichtschnell durch die Republik und um die Welt geschickt.

Die gigantischen Datenmengen der Wirtschaft lassen sich nach Angaben der

Martin Grötschel

Berlin 1997 & Wien

SEITE 10 / DER TAGESSPIEGEL Nr. 15 945 / DIENSTAG, 8. APRIL 1997

Glasfaserkabel beschädigt Tausende ohne Anschluß

BERLIN (ADN). Durch die Beschädigung eines Glasfaserkabels kam es gestern in Charlottenburg zu erheblichen Störungen im Telefon-Verkehr. Tausende Kunden mit Rufnummern der Anfangsziffern 321 und 301 konnten bis 18 Uhr 30 in Richtung Spandau, Kreuzberg und Reinickendorf nur eingeschränkt telefonieren. Ein Bagger hatte das Kabel nach Auskunft der Telekom gegen 9 Uhr vormittags bei Tiefbauarbeiten in der Schlüterstraße gekappt.

Tir. Tgztg. 5.3. (15)

Telefon lahmgelegt

Die Telefonleitung von Wien nach Tirol war gestern fast gänzlich lahmgelegt. Der Grund: Ein Bagger hatte ein wichtiges Kabel beschädigt. Seite 22

Zwei Drittel der Kapazität stand still

Telefon nach Tirol war unterbrochen

Keine Telefonverbindung nach Westösterreich gab's gestern für Kunden, die von Wien aus über St. Pölten nach Tirol, Salzburg, Vorarlberg telefonieren wollten. Ein Kabelschaden verhinderte den Kontakt.

ST. PÖLTEN (APA). „Es ist ein schwerer Kabelschaden im Bereich Prinzersdorf zwischen St. Pölten und Melk

Der ziemlich fatale Telefonkabel-Schaden bei Prinzersdorf wurde bei den Bauarbeiten für den viergleisigen Ausbau der Westbahnstrecke verursacht. „Der Bagger einer von uns beauftragten Firma hat nicht nur ein Lichtquellen-, sondern auch ein Koaxialkabel durchtrennt. Das erfolgte bei Erdarbeiten bei einer Böschung", erklärte Ing. Günter Novak, Projektmana-

Presse 6.3. (16)

Türkei: Ericsson baut GSM-Netz

WIEN (red.). Der türkische

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Austria

Kurier 5.3. (26)

Telefonleitung durch Bagger lahmgelegt

Ein Bagger hat am Donnerstag eine Haupttelefonleitung zerstört: Zwischen Wien, den westlichen Bundesländern und dem Ausland gab's „Funkstille". **Seite 13**

„Funkstille" zwischen Wien und Salzburg

Bagger kappte Telefonleitung, stundenlang herrschte Chaos im Äther, Kabel wurde wieder geflickt

Die Nachricht über die Senkung der Telefontarife war für viele Fernsprechteilnehmer am Donnerstag nur ein schwacher Trost. Zwischen Wien und den westlichen Bundesländern herrschte „Funkstille".

Im Festnetz strapazierte das permanente Besetztzeichen die Nerven von Anrufern. Und auch die Mobiltelefone im Netzbereich von A 1 funktionierten nur zeitweise. Grund für die Störung war ein Kabelschaden in der Gegend von Sankt Pölten.

„Der Bagger einer Baufirma hat die Leitung durchtrennt, jetzt ist leider eine größere Reparatur notwendig", sagte Emil Burka von der Telekom. Das Kommunikations-Unternehmen habe zur Entschärfung der Situation mehrere Ersatzleitungen freigeschaltet. „Leider reicht die Kapazität nicht für einen störungsfreien Fernsprechverkehr", bedauert Burka.

Obwohl sie keine Schuld an dem Zwischenfall traf, bekam die Telekom den Zorn von Kunden zu spüren. Die Leitungen zu den Störstellen waren überlastet. Viele Anrufer wunderten sich, daß auch Handys von dem Kabelschaden betroffen waren. „Ein Teil des Mobilfunks läuft über das Festnetz", meint Burka. „Unsere Techniker arbeiten mit Hochdruck an der Behebung des Schadens."

Am Nachmittag war das Kabel zu 90 Prozent wieder geflickt.

Presse 5.3. (27)

Bagger kappte Telephon-Hauptkabel

Bei Bauarbeiten an der Westbahnstrecke wurde am Donnerstag ein Hauptverkehrskabel der Telekom beschädigt. Die Verbindungen nach Westösterreich waren bis am Nachmittag zu zwei Drittel gestört.

WIEN (apa/red.). Durch einen schweren Kabelschaden der Telekom Austria im Bereich von Prinzersdorf in Niederösterreich waren am Donnerstag die Telephonleitungen nach Westösterreich weitgehend unterbrochen. Auch Auslandsgespräche konnten nur eingeschränkt durchgeführt werden.

Bei Bauarbeiten an der Westbahnstrecke durchtrennte Donnerstag früh ein Bagger die Hauptleitung der Telekom in Richtung Westen. Ein Lichtquellen- und ein Coaxialkabel wurden dabei schwer in Mitleidenschaft gezogen.

Die Reparaturarbeiten an dem Kabel erwiesen sich als kompliziert. „Ein solcher Hochleistungsstrang besteht aus einer riesigen Anzahl von Strängen, die nur mit einem aufwendigen Verfahren repariert werden können", berichtet ein Telekom-Sprecher. Die Post stand mit mehreren Reparatur-Trupps im Einsatz. Erst um 15 Uhr war der Schaden behoben.

Die Unglücksstelle liegt zwischen St. Pölten und Melk. Dort wird derzeit von der Hochleistungs-AG (HL-AG) die Westbahnstrecke viergleisig ausgebaut. Der Bagger „knabberte" das Kabel während Erdarbeiten an einer Böschung an, erklärte ein Projektmanager der HL-AG.

Slzg. Nachr. 5.3. (28)

Glasfaserkabel gekappt

Bagger legte Telefonverbindung in den Westen lahm

WIEN, ST. PÖLTEN (SN, APA). Die Telefonverbindung zwischen Ost- und Westösterreich war am Donnerstag großteils lahmgelegt. „Es ist ein schwerer Kabelschaden im Bereich Prinzersdorf zwischen St. Pölten und Melk aufgetreten. Ein Glasfaserkabel wurde durchtrennt", erklärte Walter Zeiner von der Abteilung „Customer Care" der Telekom Austria.

Zeiner: „Der Schaden betrifft leider unsere Hauptverkehrsstrecke in Richtung Westen. Die Kapazität ist um zwei Drittel eingeschränkt." Die Verbindungen nach Salzburg, Tirol und Vorarlberg waren erheblich gestört, weiters natürlich auch Auslandsgespräche.

Das Problem: Der durchtrennte Hochleistungsstrang bestand aus einer riesigen Anzahl von Strängen, die erst wieder mit einem aufwendigen Verfahren (mikro-elektro-optisch) repariert werden mußten. Erst im Verlauf des Tages bestätigte sich die Vermutung, daß die Bauarbeiten bei der Westbahn-Hochleistungsstrecke der HL-AG bei Prinzersdorf zu dem Schaden geführt haben.

Dort wird am viergleisigen Ausbau der Westbahnstrecke gearbeitet. „Der Bagger einer von uns beauftragten Firma hat bei Erdarbeiten nicht nur ein Lichtquellen- sondern auch ein Coaxialkabel (herkömmliches Telefonkabel, Anm.) durchtrennt", erklärte Günter Novak, Projektmanager der HL-AG in diesem Bereich, Donnerstag. Am späten Nachmittag konnte der Schaden behoben werden.

Kl. Ztg. 5.3. (29)

Störung. Kein Telefonieren in Richtung Westen gab es gestern für die Bewohner des Großraums Wien über die Hauptverbindung über St. Pölten. Bei Bauarbeiten im Bereich Prinzersdorf (NÖ) war versehentlich ein Glasfaserkabel gekappt worden, eine riesige Anzahl von Strängen mußte in einem aufwendigen Verfahren (mikro-elektro-optisch) erst wieder repariert werden.

Wr. Ztg. 5.3. (30)

Telefonstörung

Bagger trennte Verbindung nach Westen

Westösterreich war Donnerstag für den Rest Österreichs telefonisch nicht zu sprechen. Bei Bauarbeiten für den viergleisigen Ausbau der Westbahnstrecke im Bereich Prinzersdorf zwischen St. Pölten und Melk durchtrennte ein Bagger die Glasfaserkabel für das Telefon. Walter Zeiner von der Abteilung „Customer Care" der Telekom Austria: „Der Schaden betrifft leider unsere ‚Hauptverkehrsstrecke' in Richtung Westen. Die Kapazität ist um zwei Drittel eingeschränkt." Der ab 8.19 Uhr gestörte Betrieb konnte um 15 Uhr wieder aufgenommen werden. Die Verbindungen nach Salzburg, Tirol und Vorarlberg sowie Auslandsgespräche waren erheblich gestört.

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Survivability

A first attempt:

- A network is survivable if the underlying graph is k-node or k-edge connected for some integer k>0.

A second attempt:

- For each pair of nodes (s,t) let k(s,t)>0 be the number of disjoint paths required. A network is survivable if it contains for each pair (s,t) at least k(s,t) node or edge disjoint paths.

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Reduction

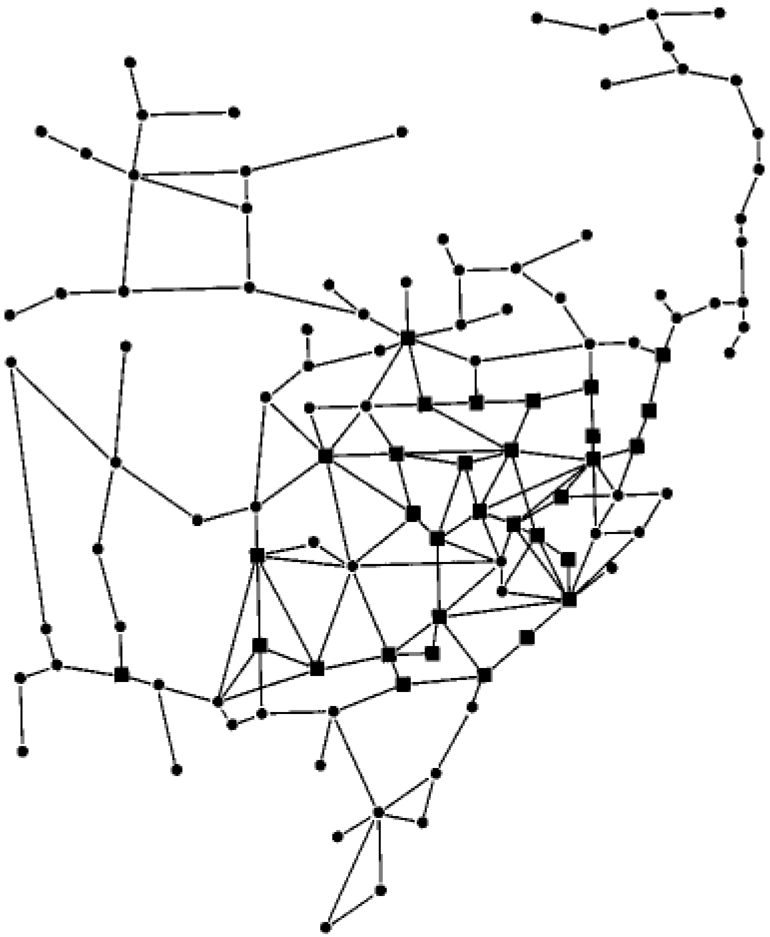

Fig. 4. Original graph of LATADL-problem.

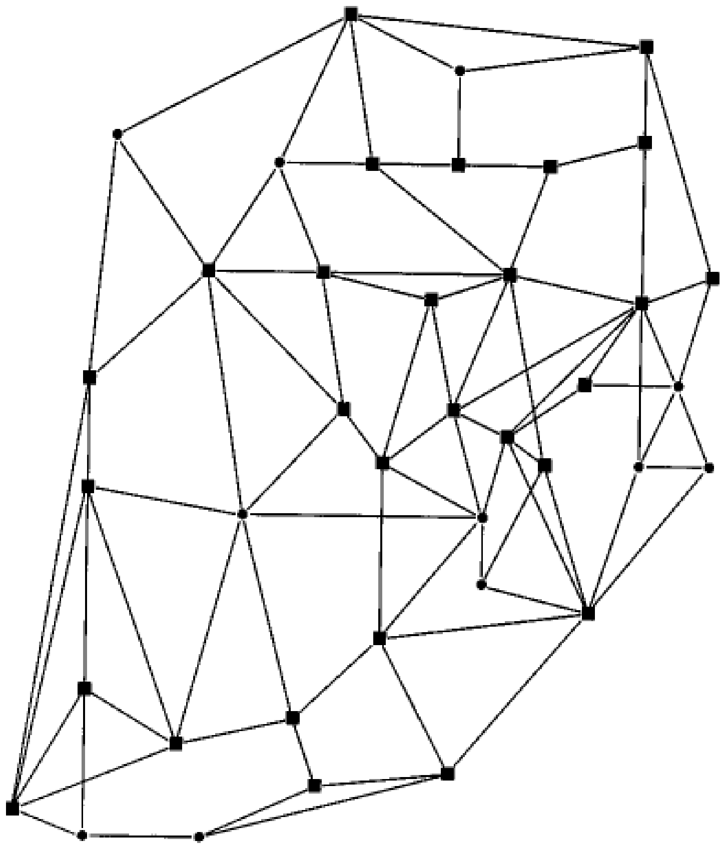

Fig. 5. Reduced graph of LATADL-problem.

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LATA DL: optimum solution

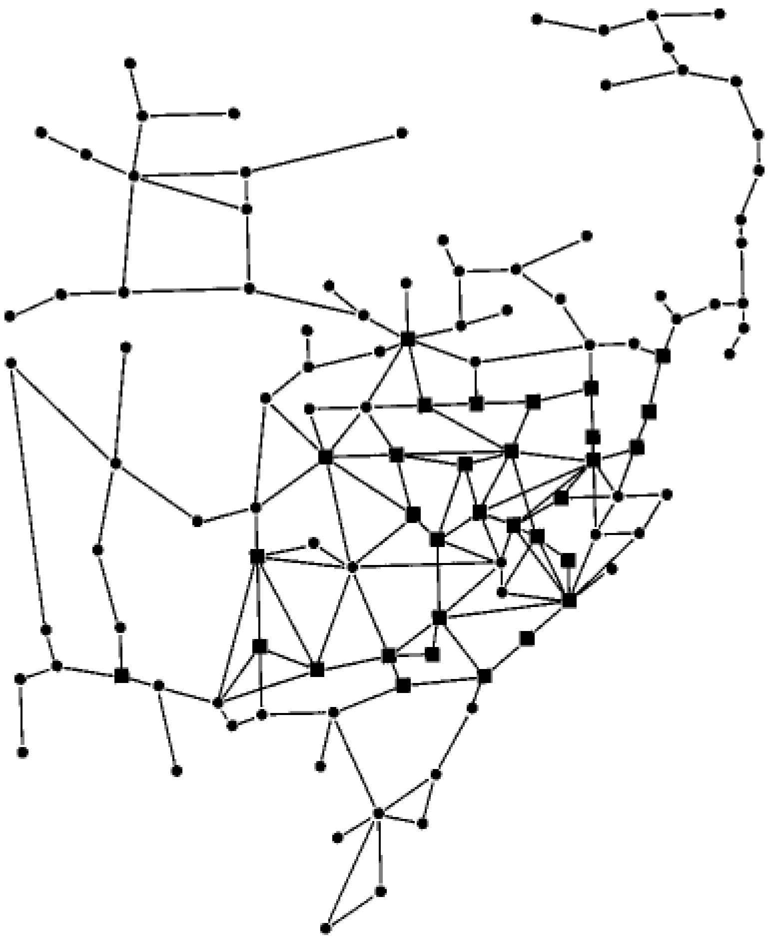

Fig. 4. Original graph of LATADL-problem.

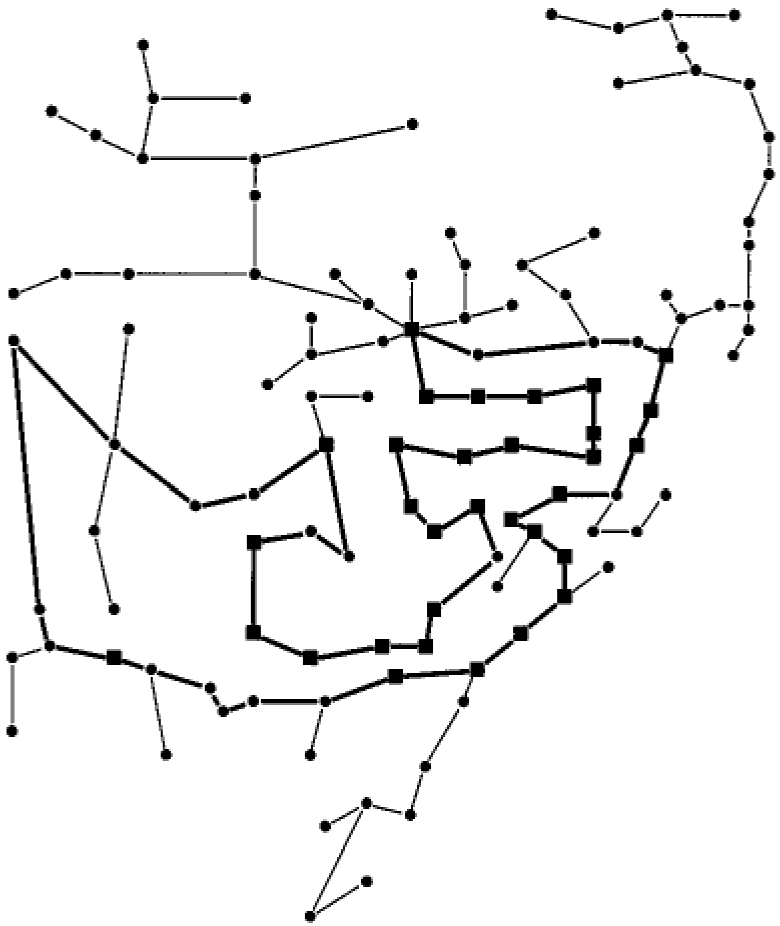

Fig. 6. Solution of LATADL-problem.

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The Ship Problem: higher connectivity

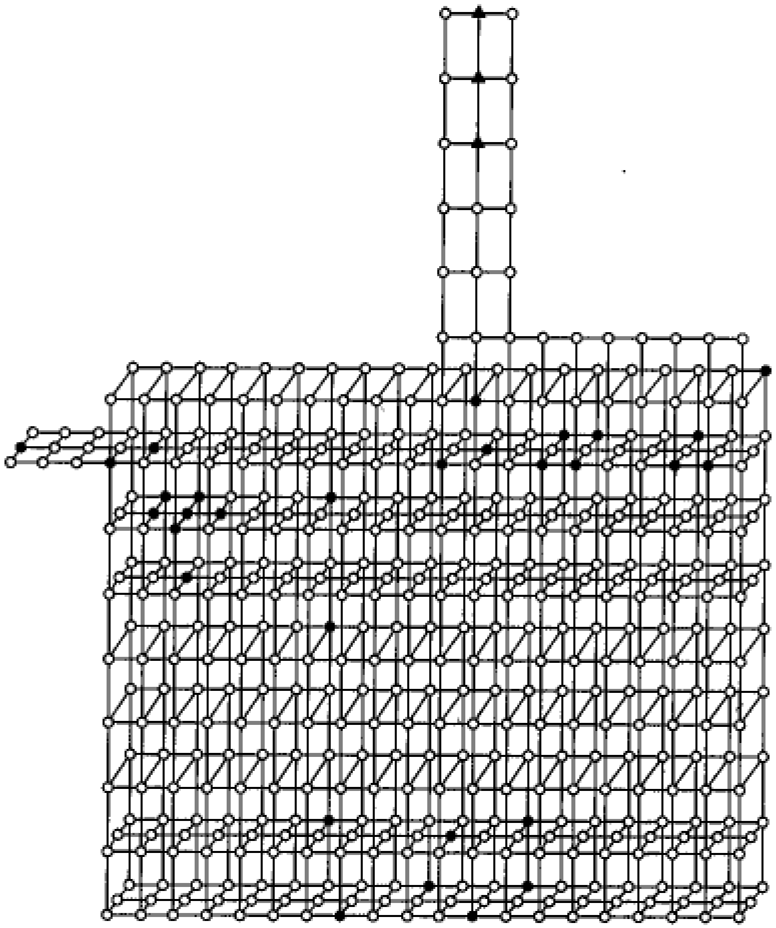

Fig. 7. Grid graph of the ship problem.

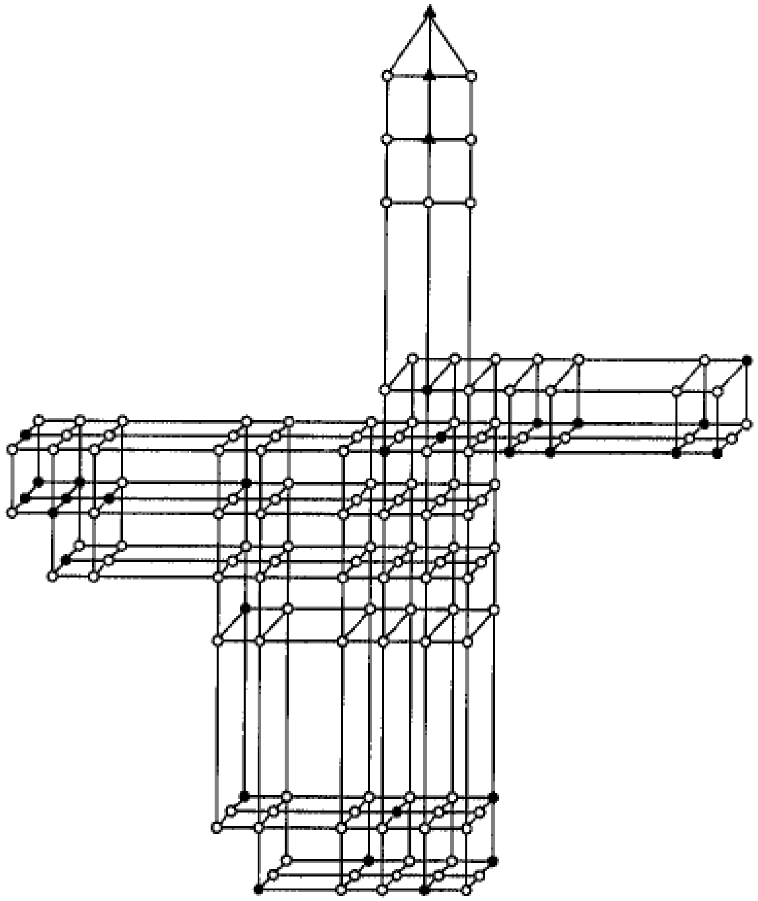

Fig. 8. Reduced grid graph of the 'ship13' problem.

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The Ship Problem: higher connectivity

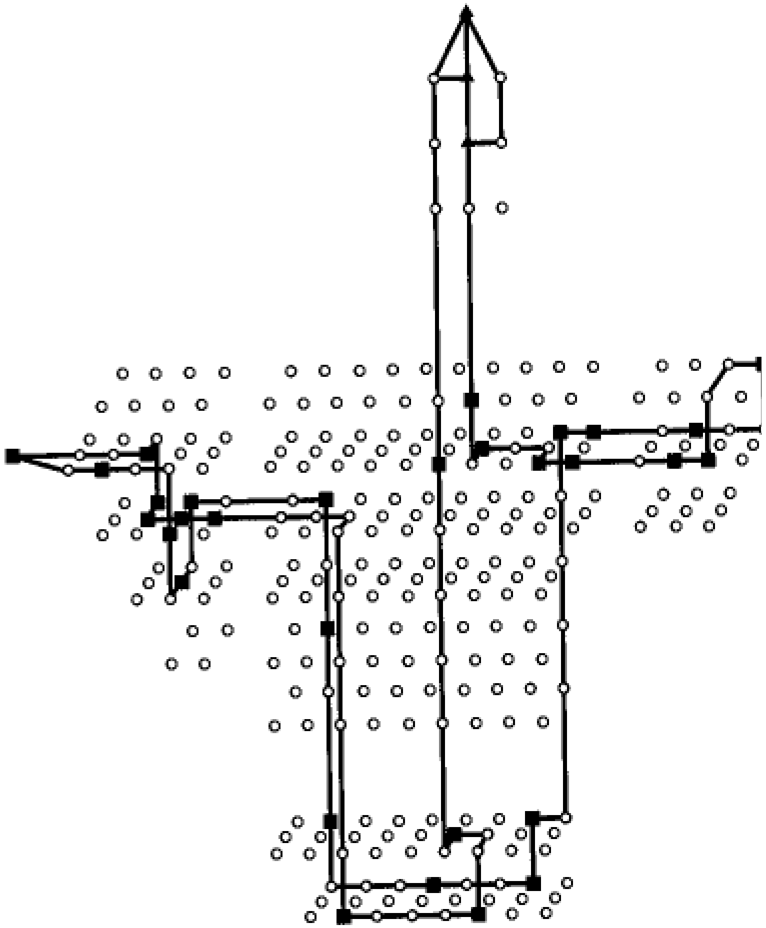

Fig. 9. Optimum solution of reduced 'ship23' proble

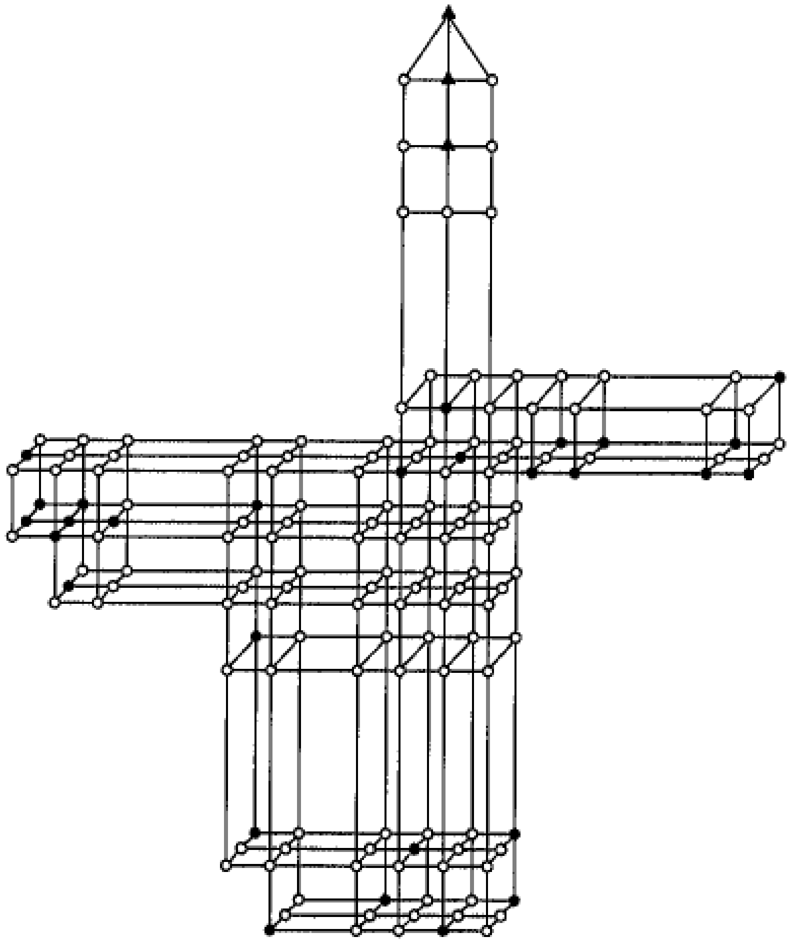

Fig. 8. Reduced grid graph of the 'ship13' problem.

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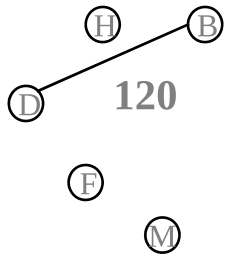
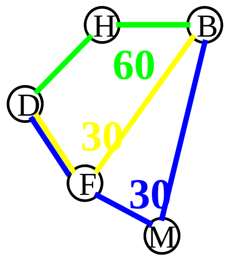
Survivability

Diversification

„route node-disjoint“

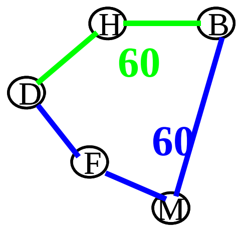


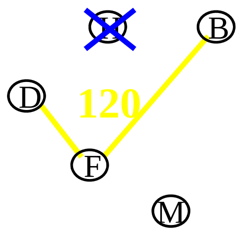


Reservation

„reroute all demands“

(or p% of all demands)

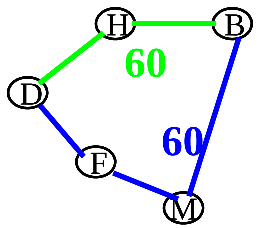


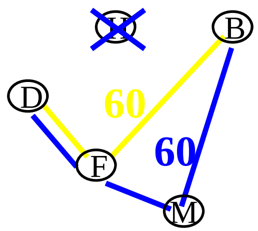


Path restoration

„reroute affected demands“

(or p% of all affected demands)





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Model: Capacities

Capacity variables : **e ∈ E, t = 1, ..., Te**

$$x_e^t \in \{0,1\}$$

Cost function :

$$\min \sum_{e \in E} \sum_{t=1}^{T_e} k_e^t x_e^t$$

Capacity constraints : **e ∈ E**

$$1 = x_e^0 \geq x_e^1 \geq \cdots \geq x_e^{T_e} \geq 0$$

$$y_e = \sum_{t=0}^{T_e} c_e^t x_e^t$$

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Model: Routings

Path variables : $s \in S, uv \in D_s, P \in \mathcal{P}_{uv}^s$

$$f_{uv}^s(P) \geq 0$$

Path length restriction

Capacity constraints : $e \in E$

$$y_e \geq \sum_{uv \in D} \sum_{P \in \mathcal{P}_{uv}^0 : e \in P} f_{uv}^0(P)$$

Demand constraints : $uv \in D$

$$d_{uv} = \sum_{P \in \mathcal{P}_{uv}^0} f_{uv}^0(P)$$

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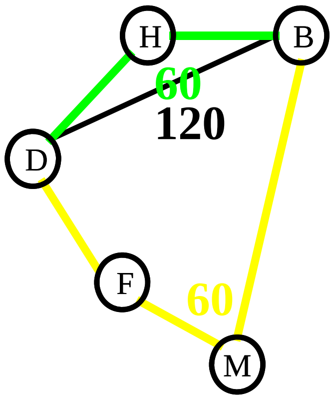
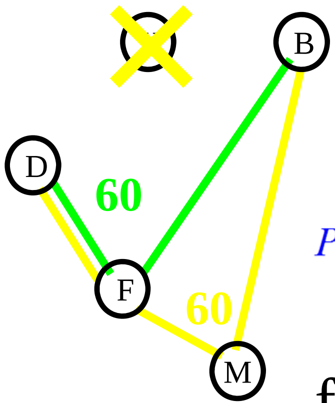
Model: Survivability (one example)

Path restoration „reroute affected demands"





for all s∈S, uv∈Ds

$$\sum_{P \in P^s_{uv} \cap P^0_{uv}} f^0_{uv}(P) + \sum_{P \in P^s_{uv} : e \in P} f^s_{uv}(P) \geq \sigma_{uv} d_{uv}$$

for all s∈S, e∈Es

$$\sum_{uv \in D_s} \Big(\sum_{P \in P^s_{uv} \cap P^0_{uv} : e \in P} f^0_{uv}(P) + \sum_{P \in P^s_{uv} : e \in P} f^s_{uv}(P) \Big) \leq y_e$$

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Mathematical Model

$$\min \sum_{e \in E} \sum_{t=1}^{T_e} k_e^t x_e^t$$

$$x_e^t \in \{0,1\} \quad e \in E, t = 1,\dots,T_e$$

$$x_e^{t-1} \geq x_e^t \quad e \in E, t = 1,\dots,T_e$$

$$y_e = \sum_{t=0}^{T_e} c_e^t x_e^t \quad e \in E$$

$$y_e \geq \sum_{uv \in D} \sum_{P \in \mathrm{P}_{uv}^0 : e \in P} f_{uv}^0(P) \quad e \in E$$

$$d_{uv} = \sum_{P \in \mathrm{P}_{uv}^0} f_{uv}^0(P) \quad uv \in D$$

$$f_{uv}^s(P) \geq 0 \quad s \in S, uv \in D_s, P \in \mathrm{P}_{uv}^s$$

- ✓ topology decisison
- ✓ capacity decisions
- ✓ normal operation routing
- ✓ component failure routing

$$\sum_{P \in P_{uv}^s \cap P_{uv}^0} f_{uv}^0(P) + \sum_{P \in P_{uv}^s : e \in P} f_{uv}^s(P) \geq \sigma_{uv} d_{uv} \quad s \in S, uv \in D_s$$

$$\sum_{uv \in D_s} \Big(\sum_{P \in P_{uv}^s \cap P_{uv}^0 : e \in P} f_{uv}^0(P) + \sum_{P \in P_{uv}^s : e \in P} f_{uv}^s(P) \Big) \leq y_e \quad s \in S, e \in E_s$$

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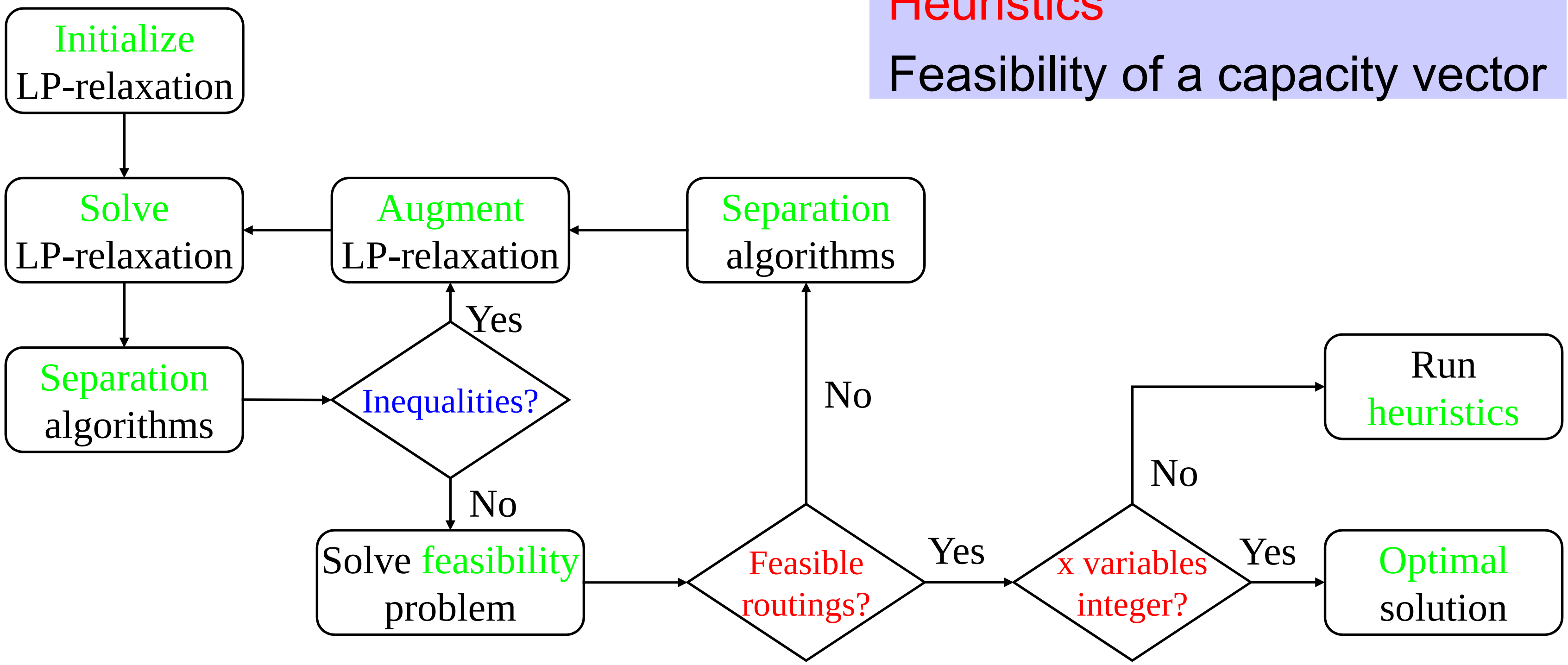
Flow chart

LP-based approach:

Polyhedral combinatorics
Valid inequalities (facets)
Separation algorithms
Heuristics
Feasibility of a capacity vector



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Finding a Feasible Solution?

Heuristics

- Local search
- Simulated Annealing
- Genetic algorithms
- ...

Manipulation of

– Routings
– Topology
– Capacities

Problem Sizes

Nodes	Edges	Demands	Routing-Paths
15	46	78	> 150 x 10e6
36	107	79	> 500 x 10e9
36	123	123	> 2 x 10e12

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How much to save?

Real scenario

- 163 nodes
- 227 edges
- 561 demands

PhD Thesis:

wessaely@atesio.de

34% potential savings!

==

> hundred million dollars

Contents

1. What is Network Design?
2. Telecommunication: The General Problem
3. Some Problems in the Problem Hierarchy:
   - Cell Phone Design and Mathematics
   - Chip and Printed Circuit Board Design
   - Antenna and Base Station Location
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5. Frequency/Channel Assignment in GSM Networks
6. Locating the Nodes of a Network: The G-WIN case
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9. Telecommunication Network Planning
10. Summary

Summary

Telecommunication Problems such as

- Frequency assignment
- Locating the nodes of a network optimally
- IP Routing to minimize congestion
- Planning IP networks
- Integrated topology, capacity, and routing optimization as well as survivability planning

- Balancing the poad of signaling transfer points
- Optical network design
- and many others

can be succesfully attacked with optimization techniques.

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Summary

The mathematical programming approach

- Helps understanding the problems arising
- Makes much faster and more reliable planning possible
- Allows considering variations and scenario analysis
- Allows the comparison of different technologies
- Yields feasible solutions
- Produces much cheaper solutions than traditional planning techniques
- Helps evaluating the quality of a network.

There is still a lot to be done, e.g.,
for the really important problems,
optimal solutions are way out of reach!

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The Mathematical Challenges

- Finding the right ballance between flexibility and controlability of future networks
- Controlling such a flexible network
- Handling the huge complexity
- Integrating new services easily
- Guaranteeing quality

- Finding appropriate Mathematical Models
- Finding appropriate solution techniques (exact, approximate , interactive, quality guaranteed)

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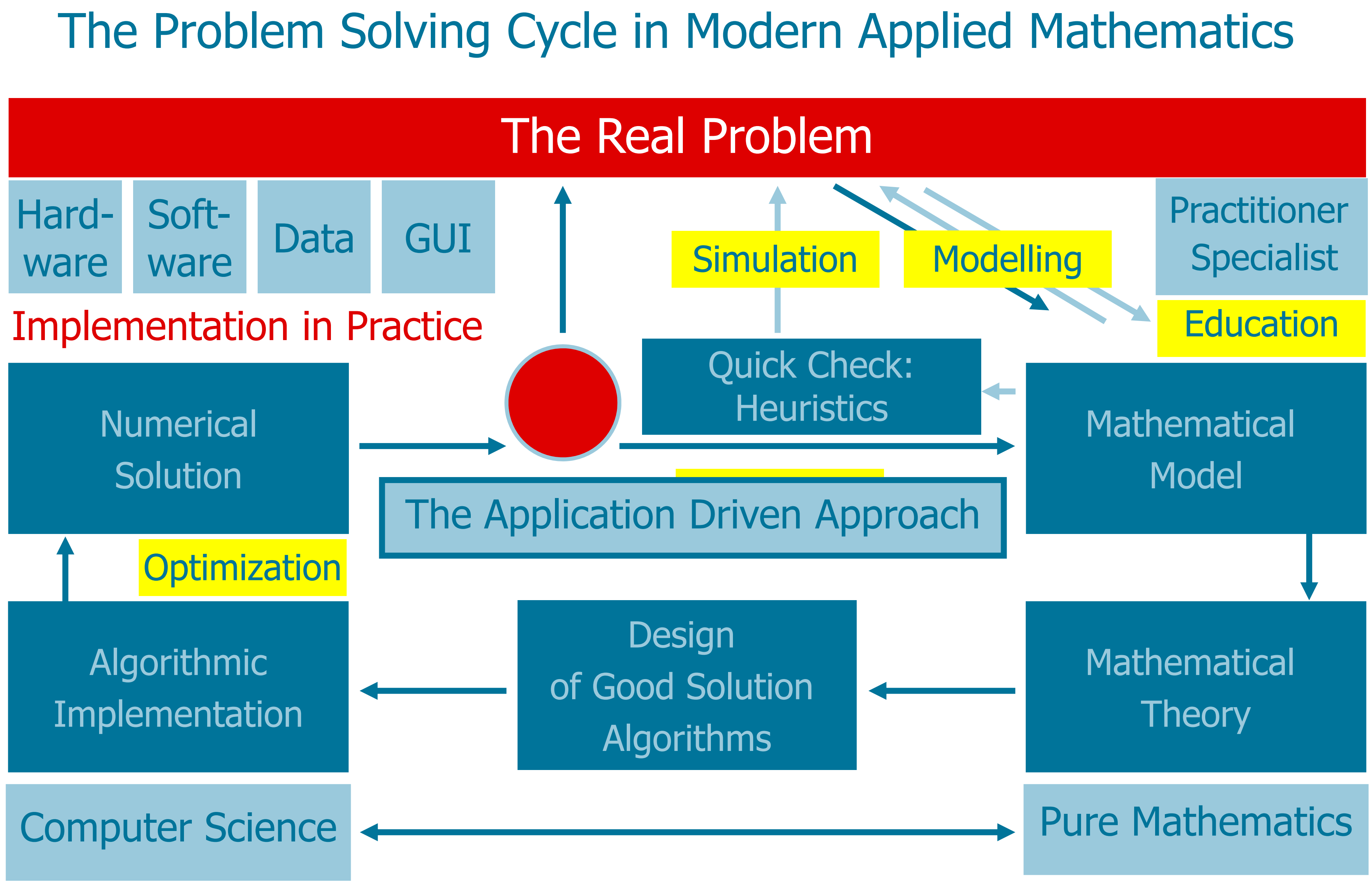
The Problem Solving Cycle in Modern Applied Mathematics
The Real Problem
Hard-
ware
Soft-
ware
Data
GUI
Simulation
Modelling
Practitioner
Specialist
Education
Implementation in Practice
Quick Check:
Heuristics
Numerical
Solution
Mathematical
Model
The Application Driven Approach
Optimization
Algorithmic
Implementation
Design
of Good Solution
Algorithms
Mathematical
Theory
Computer Science
Pure Mathematics

Advertisement

- Modern telecommunication is impossible without mathematics. Cryptography, digital signal encoding, queue management come to your mind immediately.
- But modern mathematics also supports the innovative design and the cost-efficient production of devices and equipment. Mathematics plans low-cost, high-capacity, survivable networks and optimizes their operation.
- Briefly: no efficient use of scarce resources without mathematics – not only in telecommunication.
- Many of these achievements are results of recent research. Their employment in practice is fostered by significant improvements in computing technology.

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Designing telecommunication networks by integer programming

The End

Ralf Borndörer & Martin Grötschel

ZIB, TU, and MATHEON, Berlin