European Graduate Program
Berlin - Zürich
Combinatorics

05M1 Lecture
Combinatorial Optimization and Telecommunication

Martin Grötschel

Block Course at TU Berlin
"Combinatorial Optimization at Work"
October 4 – 15, 2005

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- DFG-Forschungszentrum "Mathematik für Schlüsseltechnologien" (MATHEON)
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plus several MSc students

ZIB Partners from Industry

Bell Communications Research (now Telcordia)

Telenor (Norwegian Telecom)

E-Plus (acquired by KPN in 01/2002)

DFN-Verein

Bosch Telekom (bought by Marconi in 1999)

Siemens

Telekom Austria (Italia Telecom, ..., ÖIAG)

T-Systems Nova (T-Systems, Deutsche Telekom)

KPN

Telecel-Vodafone

Atesio (ZIB spin-off company)

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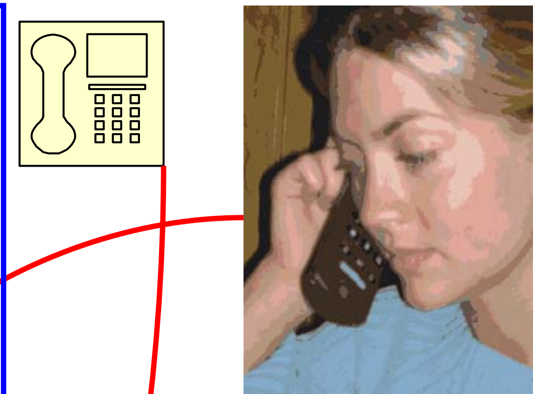
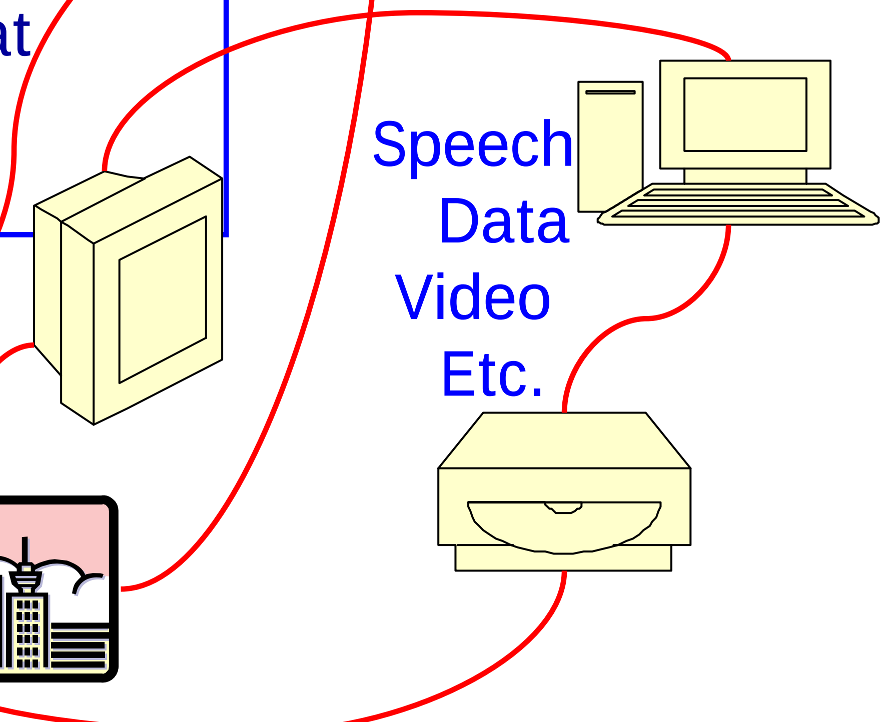
Advertisement

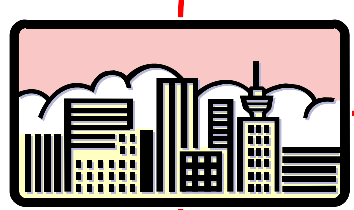
- Modern telecommunication is impossible without mathematics. Cryptography, digital signal encoding, queue management come to your mind immediately.
- But modern mathematics also supports the innovative design and the cost-efficient production of devices and equipment. Mathematics plans low-cost, high-capacity, 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 newest research. Their employment in practice is fostered by significant improvements in computing technology.

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!







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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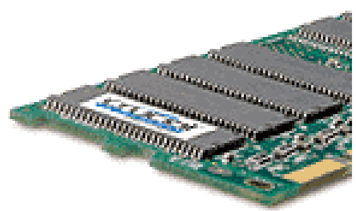
Production and Mathematics: Examples

Picture deleted

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

Mobile Phone Production Line

Picture deleted

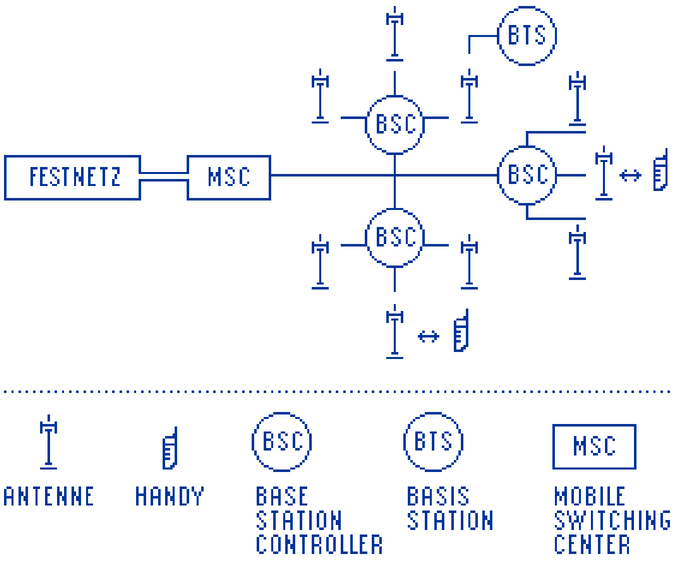
Fujitsu Nasu plant

Contents

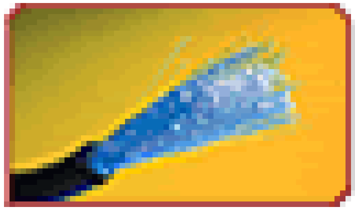
Network Components

Design, Production, Marketing, Distribution:
Similar math problems as for mobile phones

- Fiber (and other) cables
- Antennas and Transceivers
- Base stations (BTSs)
- Base Station Controllers (BSCs)
- Mobile Switching Centers (MSCs)
- and more…



Component „Cables“



Component „Antennas“

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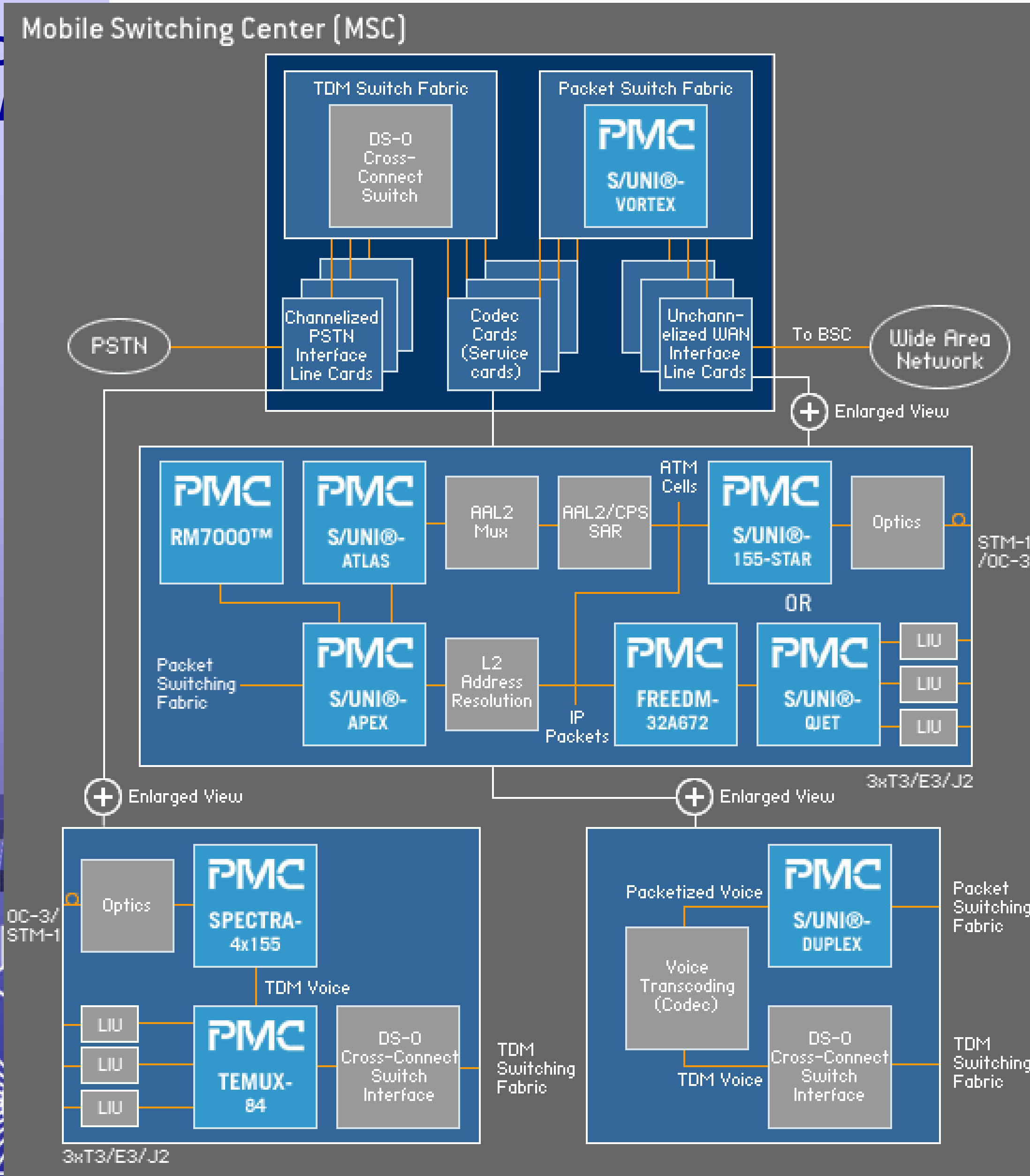
Component „Base Station“

Nokia MetroSite

Nokia UltraSite



Component „Mobile Switching Center“:

Example of an MSC Plan

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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 to antennas
- Cryptography and error correcting encoding for wireless communication
- Clustering BTSs
- Locating base station controllers (BSCs)
- Connecting BTSs to BSCs

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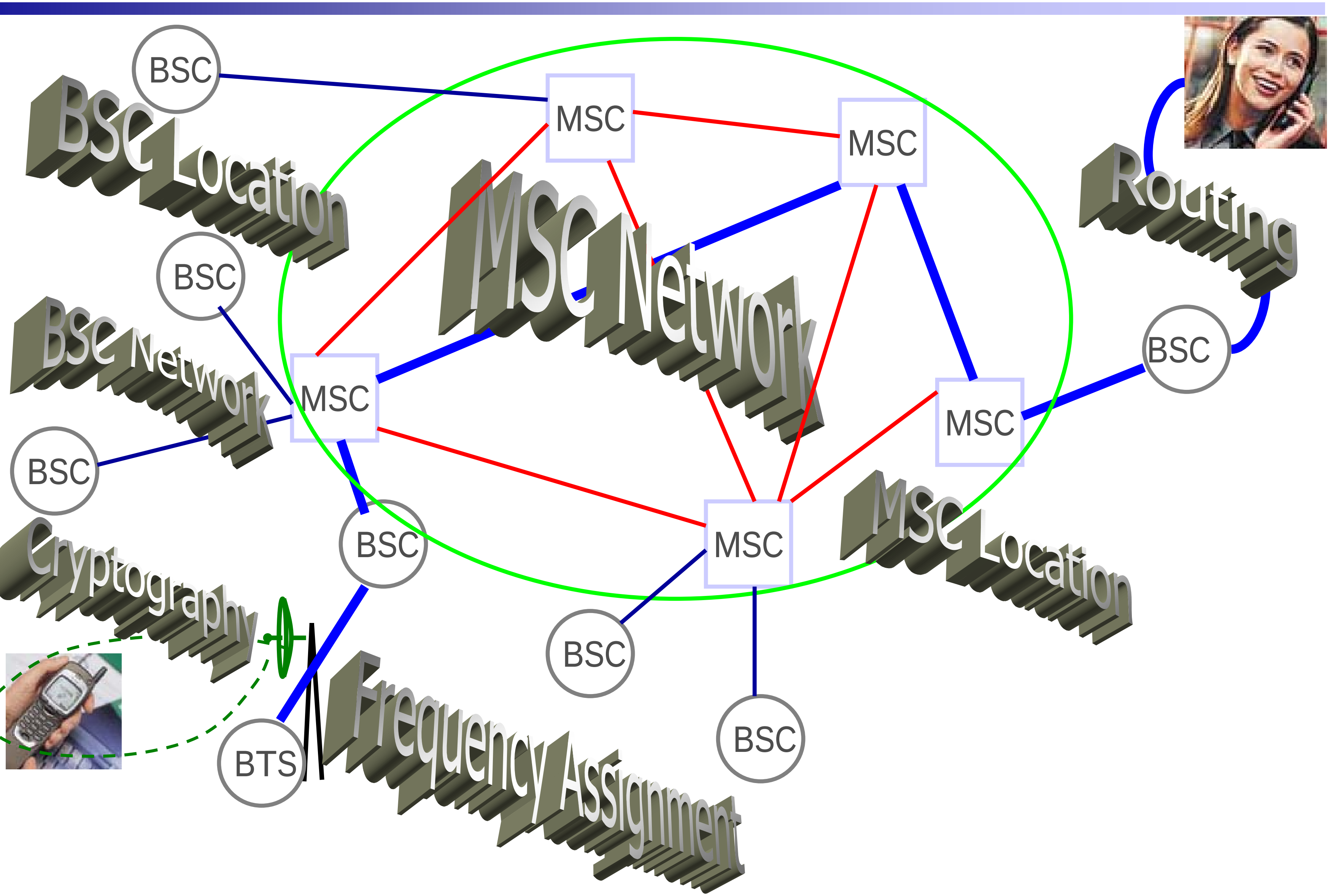
Network Design: Tasks to be solved
Some Examples (continued)

- 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

Connecting Mobiles: What´s up?



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Frequency or Channel Assignment

There will be two special lectures on this aspect, one on

- GSM technology

  (GSM = Global System for Mobile Communications)

  and one on

- UMTS

  (UMTS = Universal Mobile Telecommunications System),

  a system that is based on CDMA technology

  (CDMA = Code Division Multiple Access)

  which is currently being deployed.

Contents

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

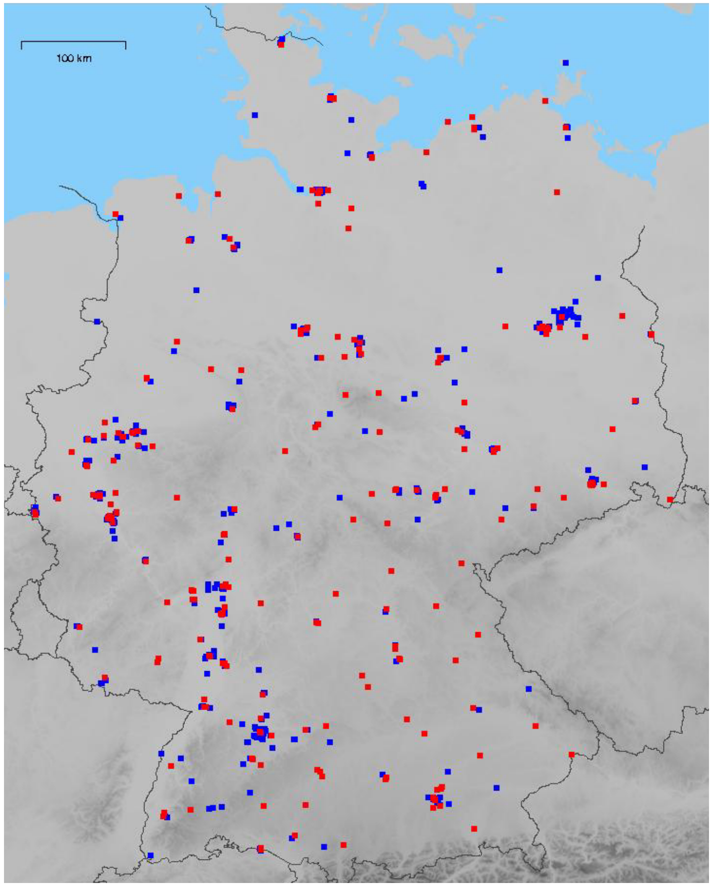
G-WiN Problem

- 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.

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



Red nodes are potential level 1 nodes

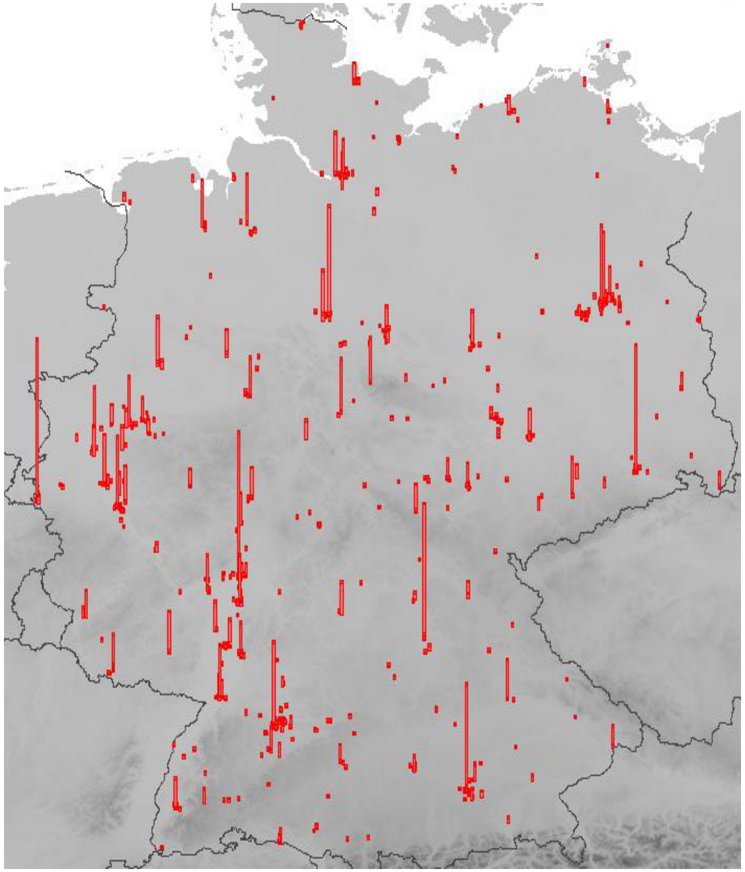
Blue nodes are all remaining nodes

Cost:

Connection between nodes

Capacity of the nodes

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)

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

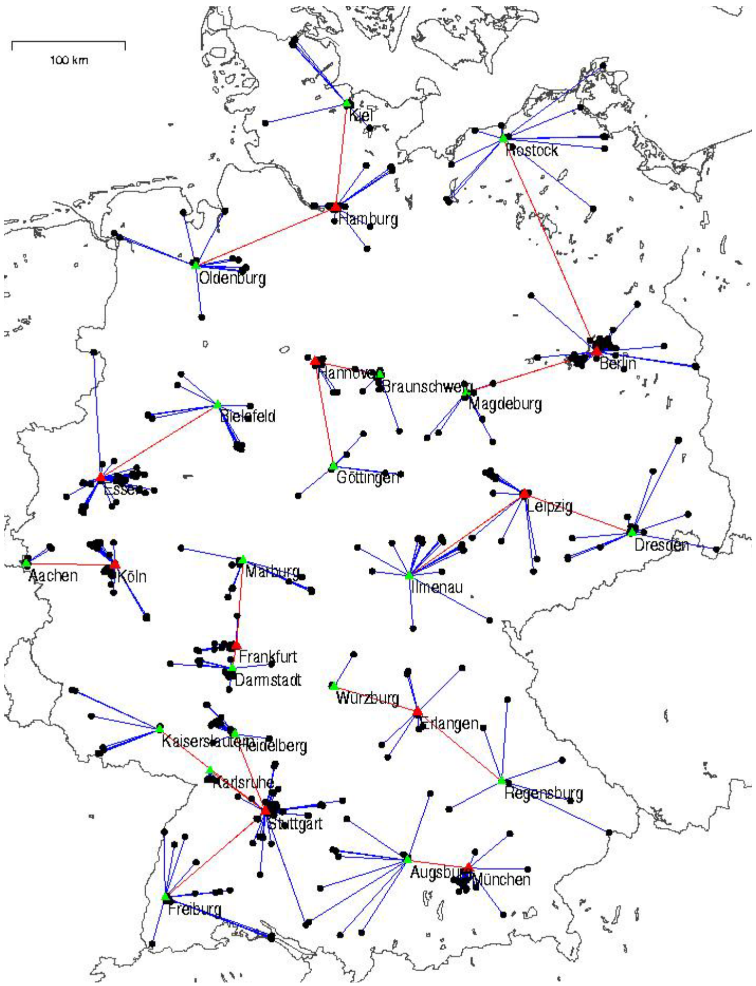
$$\sum_i d_i x_{ip} \leq \sum_k c_p^k z_p^k$$ Capacity at p must be large enough

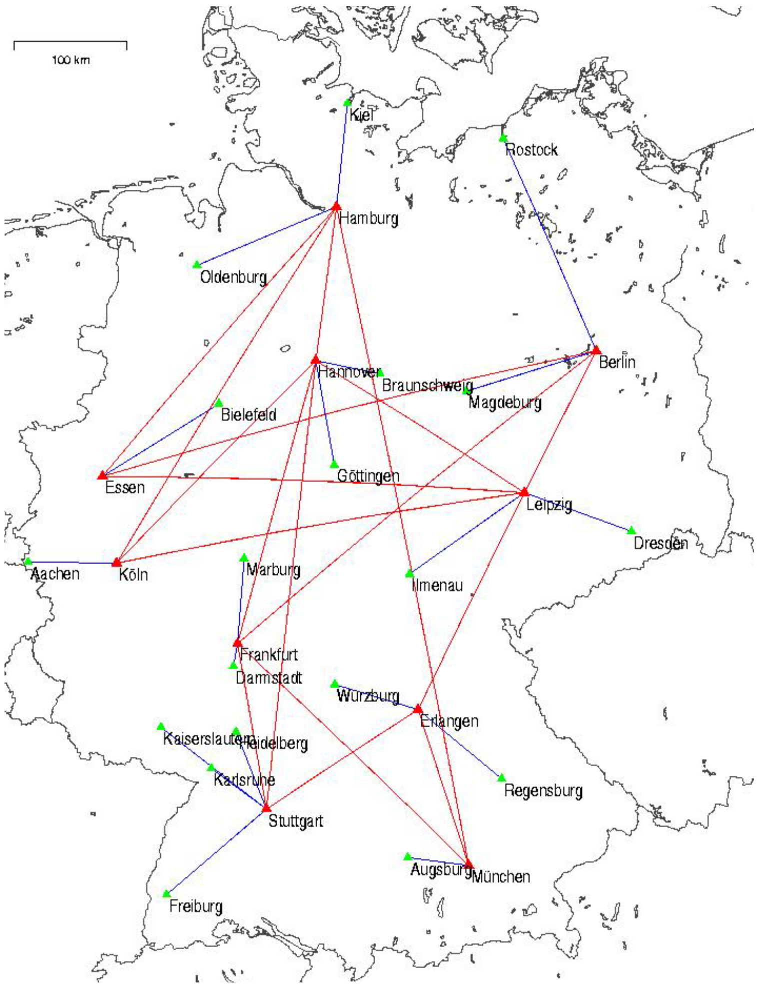
$$\sum_k z_p^k = 1$$ Only one configuration at each Location 1 node

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

All variables are 0/1.

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).

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Re-Optimization of Signaling Transfer Points

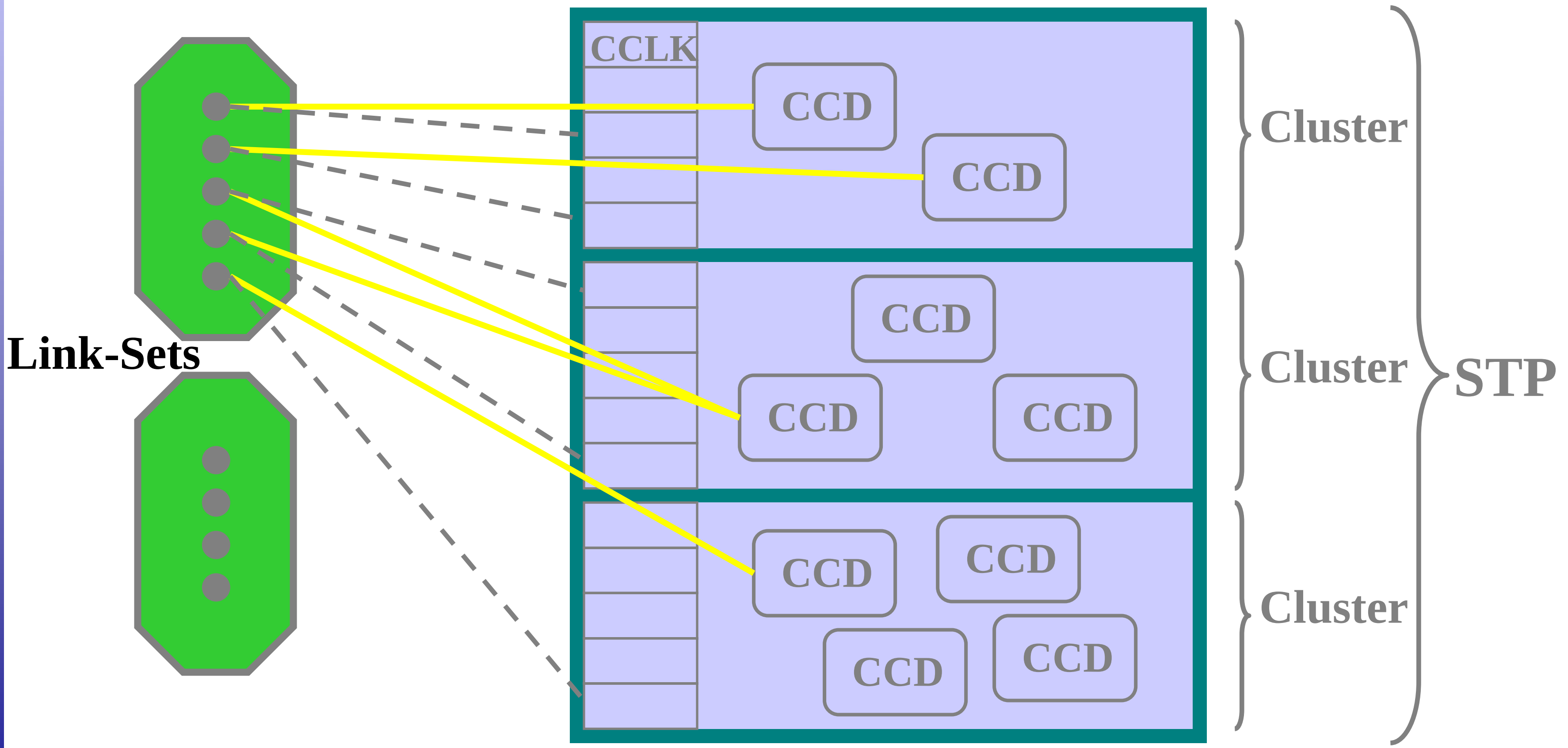
Telecommunication companies maintain a signaling network (in adition to their communication transport network). This is used for management tasks such as:

- Basic call setup or tear down
- Wireless roaming
- Mobile subscriber authentication
- Call forwarding
- Number display
- SMS messages
- Etc.

A. Eisenblätter, A. M. C. A. Koster, R. Wallbaum, R. Wessäly
Load Balancing in Signaling Transfer Points
ZIB-Report 02-50,

Signaling Transfer Point (STP)

CCD=routing unit, CCLK=interface card



CCD=Common Channel Distributors, CCLK=Common Channel Link Controllers

STP – Problem description

Target

Assign each link to a CCD/CCLK

Constraints

At most 50% of the links in a linkset can be assigned to a single cluster

Number of CCLKs in a cluster is restricted

Objective

Balance load of CCDs

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STP – Mathematical model

Data

C	set of CCDs j
L	set of links i
D_i	demand of link i
P	set of link-sets
Q	set of clusters
L_p	subset of links in link-set p
C_q	subset of CCDs in cluster q
c_q	#CCLKs in cluster q

Variables

$$x_{ij} \in \{0,1\}, i \in L, j \in C$$

$x_{ij} = 1$ if and only if link i is assigned to CCD j

STP – Mathematical model

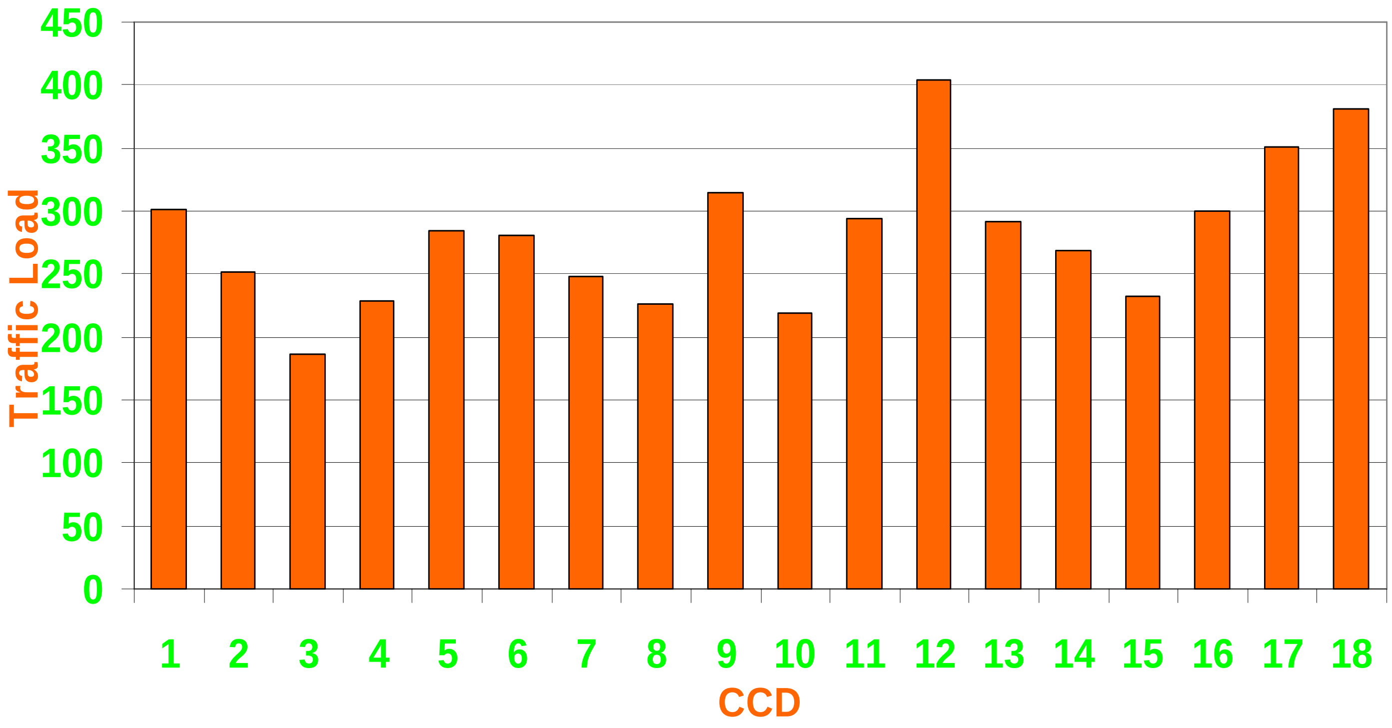
Min load difference

$$\min \; y - z$$

$\sum_{j \in C} x_{ij} = 1$	$i \in L$	Assign each link
$\sum_{i \in L} D_i x_{ij} \le y$	$j \in C$	Upper bound of CCD-load
$\sum_{i \in L} D_i x_{ij} \ge z$	$j \in C$	Lower bound of CCD-load
$\sum_{i \in L_p} \sum_{j \in C_q} x_{ij} \le \left\lceil \lvert L_p \rvert / 2 \right\rceil$	$p \in P, q \in Q$	Diversification
$\sum_{i \in L} \sum_{j \in C_q} x_{ij} \le c_q$	$q \in Q$	CCLK-bound
$x_{ij} \in \{0,1\}$		Integrality

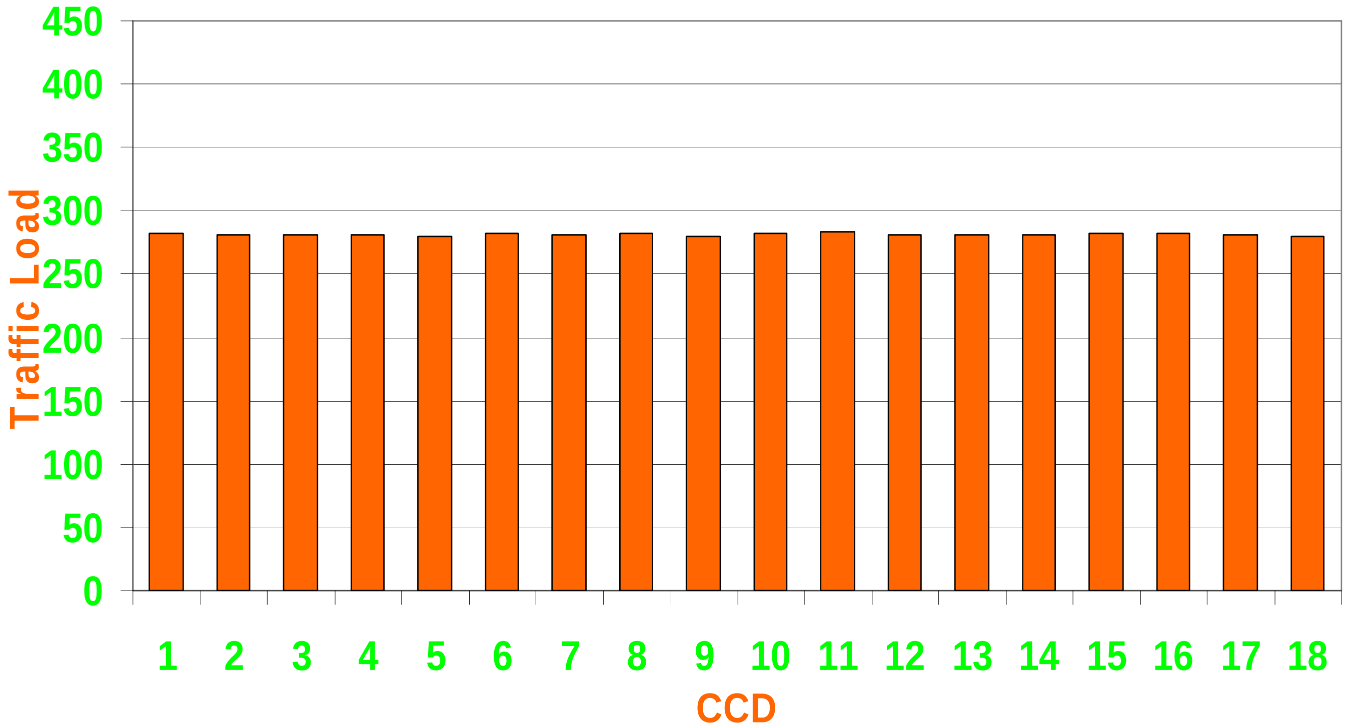
STP – former (unacceptable) solution

Minimum: 186 Maximum: 404 Load difference: 218



STP – „Optimal solution“

Minimum: 280 Maximum: 283 Load difference: 3



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STP – Practical difficulty

Problem: 311 rearrangements are necessary to migrate to the optimal solution

→ **Reformulation with new objective**

Find a best solution with a restricted number of changes

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STP – Reformulated Model

Min load difference

$$\min\ y - z$$

$\sum_{j \in C} x_{ij} = 1$	$i \in L$	Assign each link
$\sum_{i \in L} D_i x_{ij} \leq y$	$j \in C$	Upper bound of CCD-load
$\sum_{i \in L} D_i x_{ij} \geq z$	$j \in C$	Lower bound of CCD-load
$\sum_{i \in L_p} \sum_{j \in C_q} x_{ij} \leq \left\lceil \frac{\lvert L_p \rvert}{2} \right\rceil$	$p \in P, q \in Q$	Diversification
$\sum_{i \in L} \sum_{j \in C_q} x_{ij} \leq c_q$	$q \in Q$	CCLK-bound
$\sum_{i \in L} \sum_{j \in C, j \neq j^*(i)} x_{ij} \leq B$		**Restricted number of changes!**
$x_{ij} \in \{0,1\}$		Integrality

STP – Alternative Model

$$\min \sum_{i \in L} \sum_{j \in C, j \neq j^*(i)} x_{ij}$$		**Min # changes**
$$\sum_{j \in C} x_{ij} = 1$$	$i \in L$	Assign each link
$$\sum_{i \in L} D_i x_{ij} \leq y$$	$j \in C$	Upper bound of CCD-load
$$\sum_{i \in L} D_i x_{ij} \geq z$$	$j \in C$	Lower bound of CCD-load
$$\sum_{i \in L_p} \sum_{j \in C_q} x_{ij} \leq \left\lceil \frac{\lvert L_p \rvert}{2} \right\rceil$$	$p \in P, q \in Q$	Diversification
$$\sum_{i \in L} \sum_{j \in C_q} x_{ij} \leq c_q$$	$q \in Q$	CCLK-bound
$$y - z \leq D$$		Restricted load difference
$$x_{ij} \in \{0,1\}$$		Integrality

STP – New Solutions

White: D=50, (alternative)

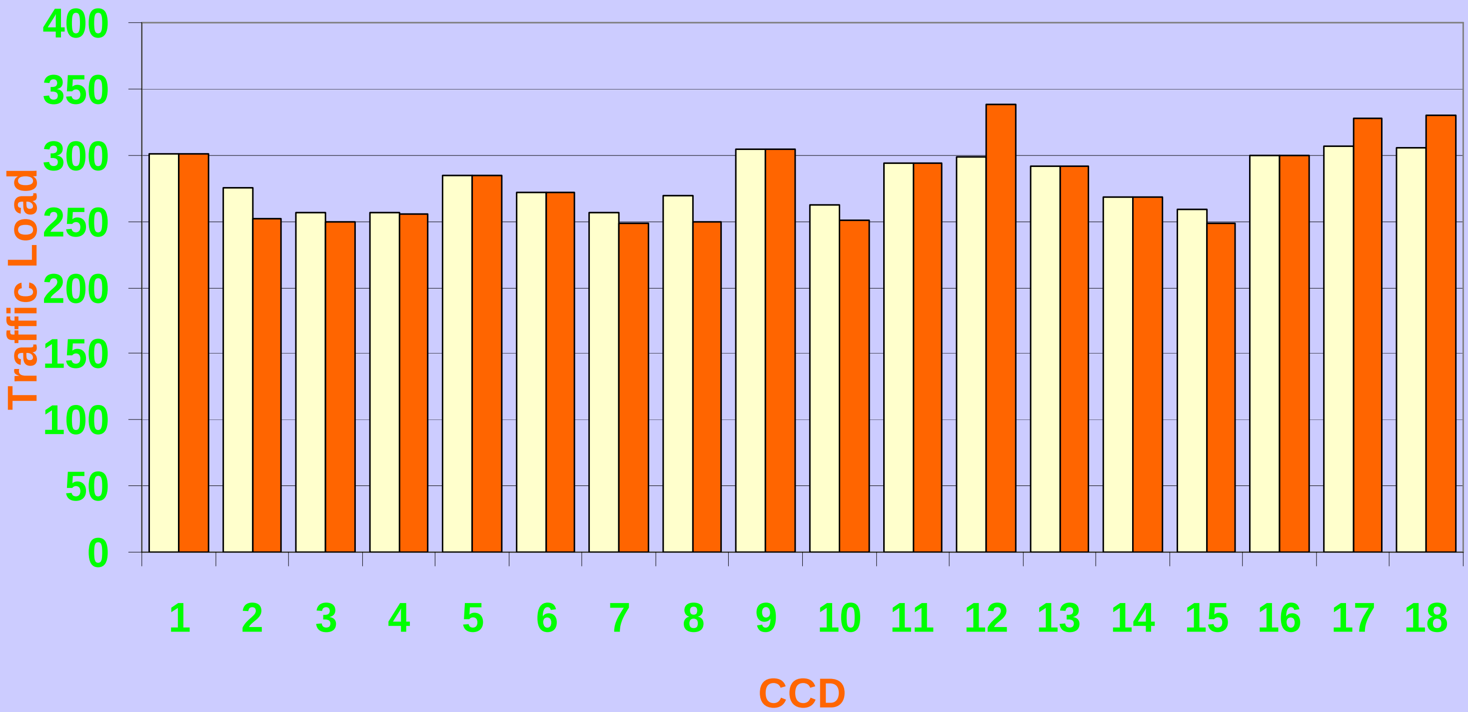
Minimum: 257 Maximum: 307

D=Load difference: 50 Number of changes: 12

Orange: B=8, (reformulated)

Minimum: 249 Maximum: 339

Load difference: 90 Number of changes : 8



STP – Experimental results

Max changes	0	5	10	15	20
Load differences	218	129	71	33	14

1 hour application of CPLEX MIP-Solver for each case

STP - Conclusions

It is possible to achieve

85%

of the optimal improvement with less than

5%

of the changes necessary to obtain a load balance optimal solution !

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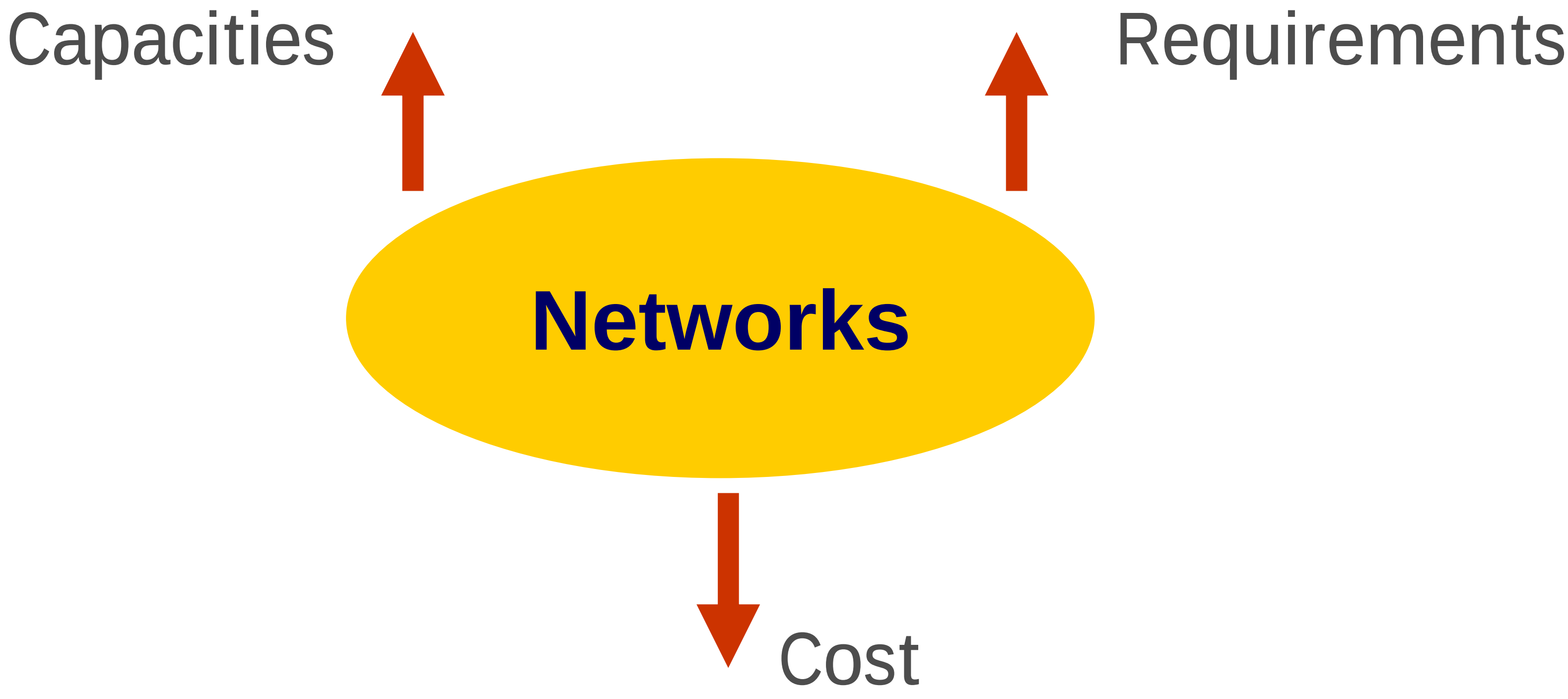
Network Optimization



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What needs to be planned?

- Topology
- Capacities
- Routing
- Failure Handling (Survivability)

} special lecture

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

DISCNET: A Network Planning Tool

(Dimensioning Survivable Capacitated NETworks)

Atesio ZIB Spin-Off

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DFN: German Research Network

Internet for German universities, scientific institutions, museums, libraries, etc.

B-WiN: Breitband WissenschaftsNetz, 1996 – 2000

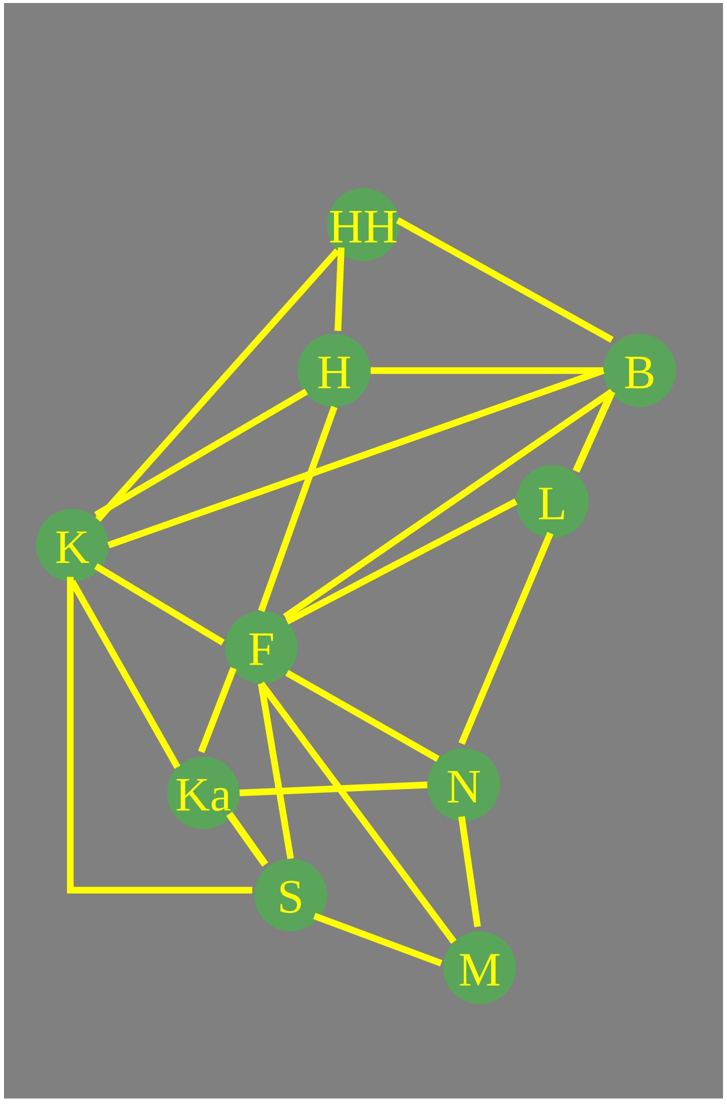
- virtual private network from DeTeSystems
- ~ 400 users
- Backbone links 35 – 155 Mbit/s

G-WiN: Gigabit WissenschaftsNetz, 2000 - ...

- virtual private SDH/WDM network from DeTeSystems
- IP over SDH/WDM
- Backbone links 155 Mbit/s – 10 Gbit/s

X-Win: ...

The network design problem



Supply Graph

Demands

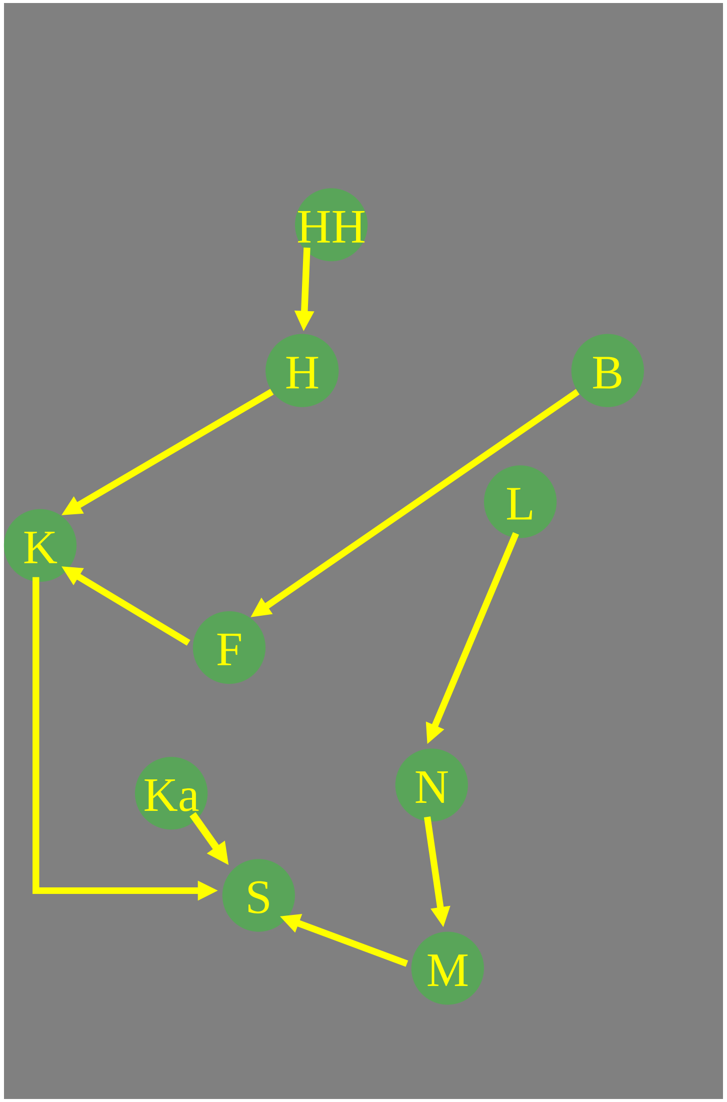
Discrete Capacities & Costs

OSPF-Routing

Survivability

Further technical constraints

OSPF-Routing: Weights



Non-bifurcated routing on shortest paths **w.r.t. non-negative** link weights

Sink-tree for each destination

Unique shortest paths necessary to guarantee feasible routing in practice!

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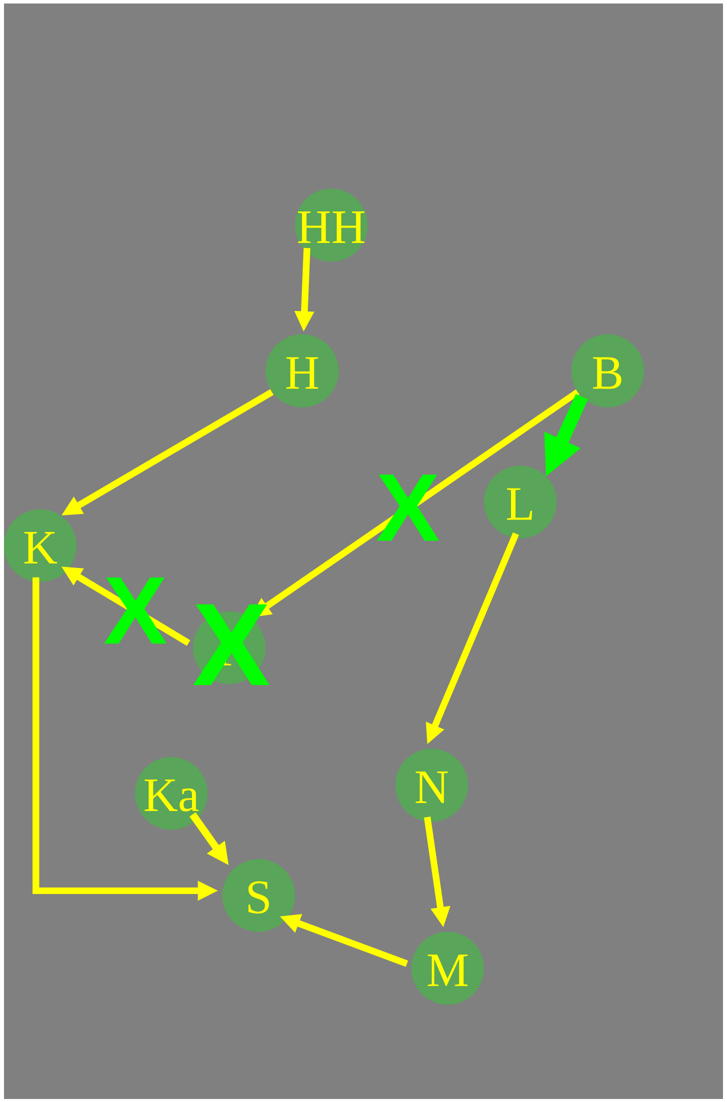
OSPF-Routing: Survivability



Survivability: Capacities must accommodate a feasible OSPF-routing in

- the normal operating state
- single edge and single node failure states

➡ **2-node-connectivity**

Model & Solution approach

Mixed-integer programming model

Solution approach (Decomposition)

- Network design
  - Cutting plane algorithm
  - Heuristics
- Weight computation
  - Linear programming

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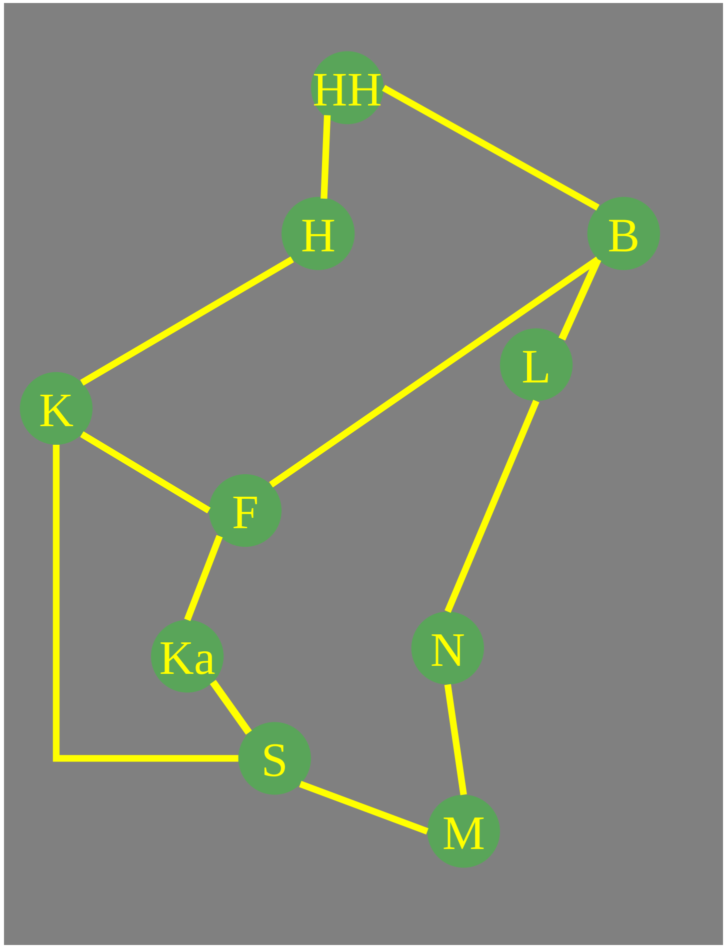
Results: Original network



Demands: Nov 1997

Routing with perturbed unit-weights

Original topology

Cost: 12.04

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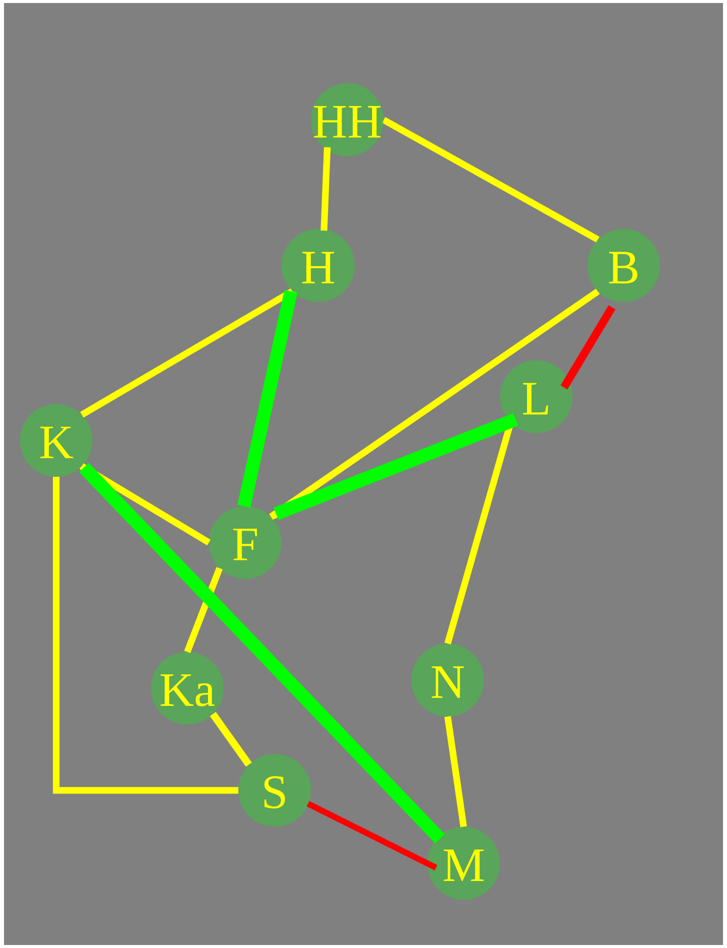
Results: New Network



Demands: Nov 1997

Routing with perturbed unit-weights

Maximal 3 topology changes

Cost: 10.71

10 % improvement on the network that has already been optimized with our algorithm

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Conclusion

OSPF-routing (weights)

and

topology & capacities

must be simultaneously optimized !

X-Win

- ZIB (Andreas Bley) is currently planning the X-Win of Deutsches Forschungsnetz (DFN) to be installed in 2006/7:
  - Locations
  - Network
  - Hub and Line Capacities

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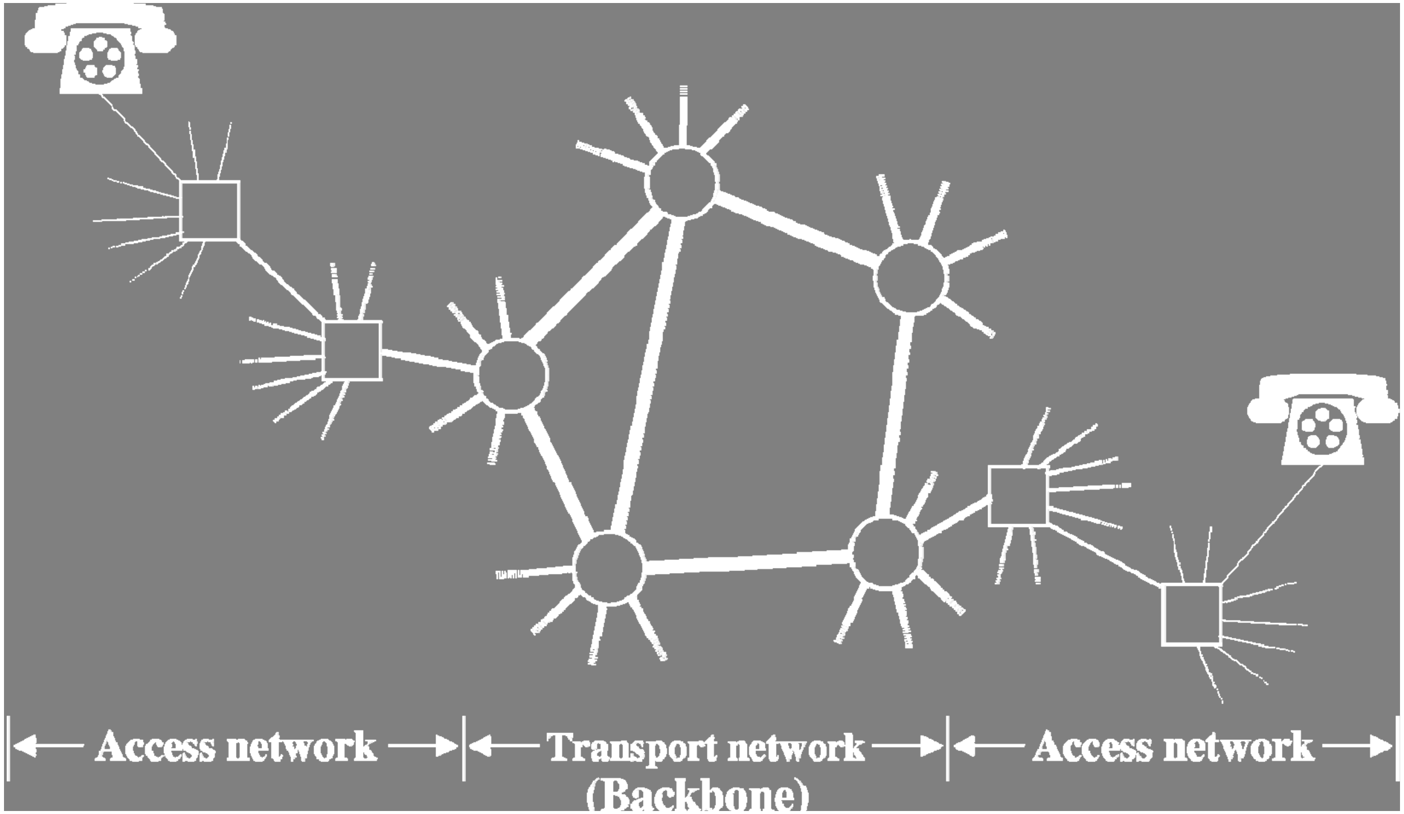
Telecommunication networks



- Focus: Backbone layer
- Planning-objective: Cost-minimal network
- Reason: New technology, new services

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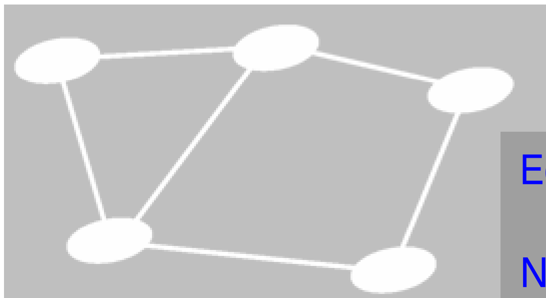
From copper to fiber...

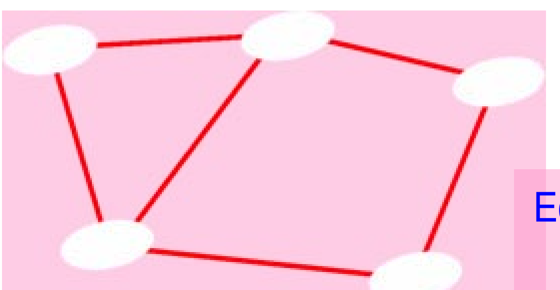
Electronic Networks



Edges:
electronic
Nodes:
electronic

Fiber

Fiber-Networks



Edges:
optic
Nodes:
electronic

- high transmission-capacity, but restricted mileage
- various types

  (uni- and bi-directional)
- various qualities

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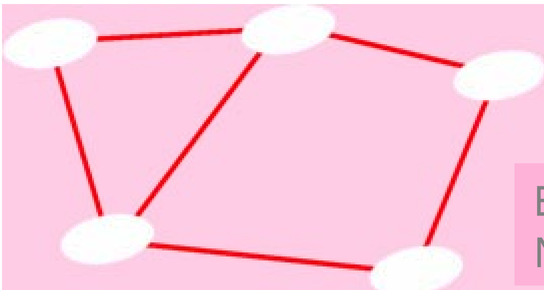
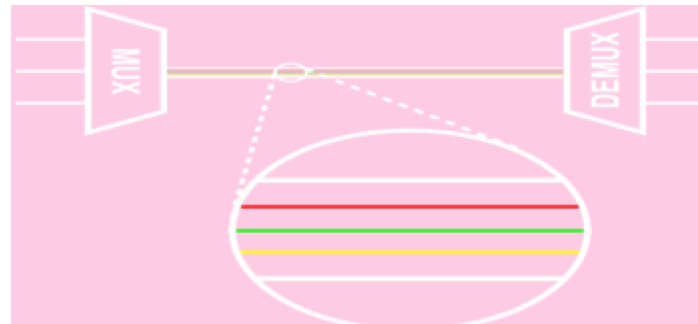
...to WDM ...

Fiber-Networks



Edges: optic
Nodes: electronic

Wavelength Division Multiplexing (WDM)



(Point-to-Point-) WDM-Networks

Edges:
optic (WDM)
Nodes:
electronic

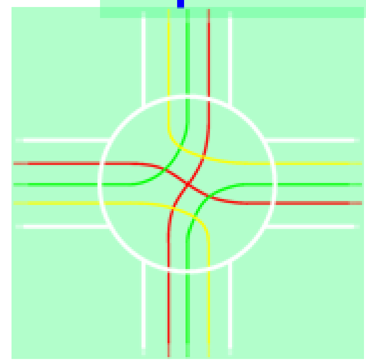
- Capacity is multiplied
- growing multiplex factors
- different systems
  (#channels and spectra)

... to all optical networks

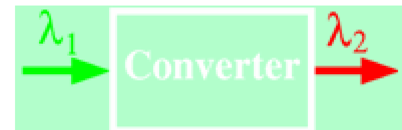
(Point-to-Point-) WDM-Networks

Edges:
optic (WDM)
Nodes:
electronic

Optical devices

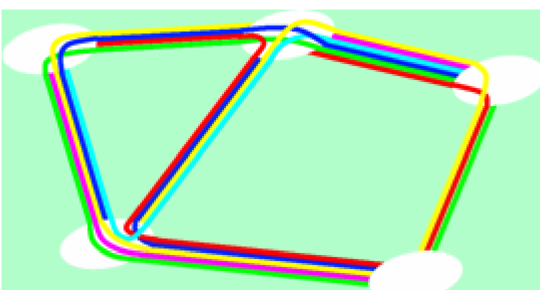


Optical Cross-connect (OXC)



Optical Wavelength Converter

Optical Networks



Edges:
optic (WDM)
Nodes:
optic

- **Switching optical channels w/o o-e-o-conversion**
- **Switching of arbitrary wavelengths**

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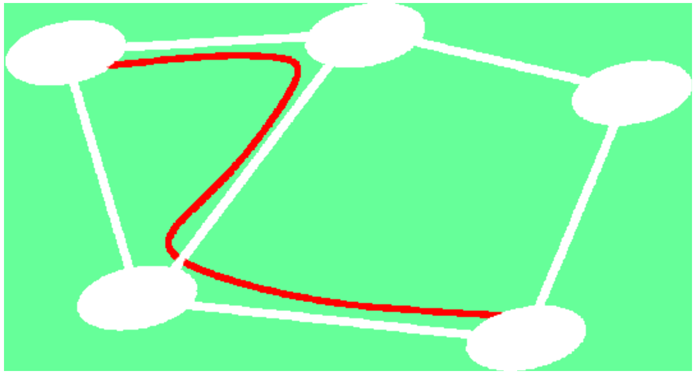
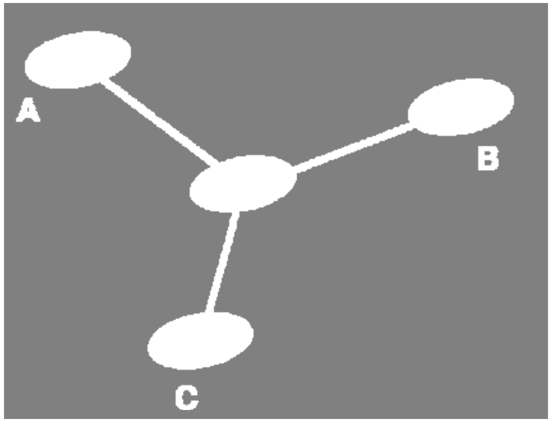
Lightpaths

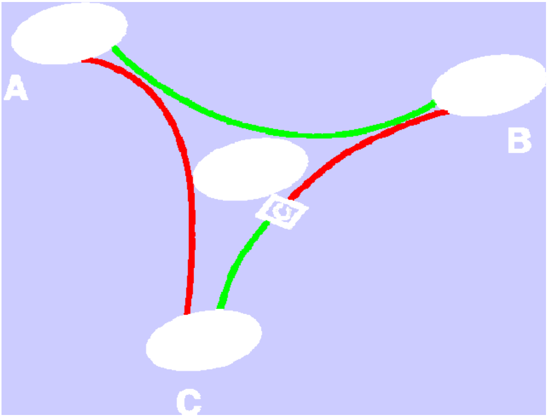
Lightpath = pure optical connection between two nodes via one or multiple fibers with optical switching in traversed nodes

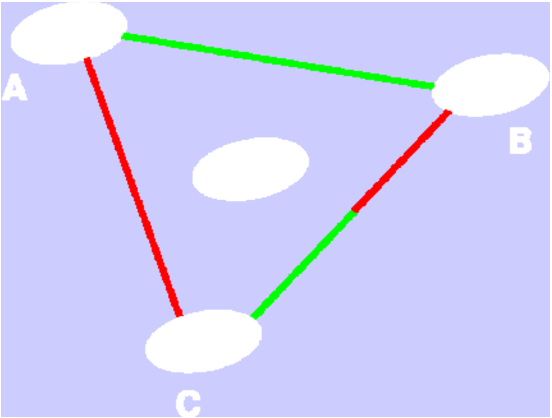


- length restriction (dispersion and attenuation)
- wavelength assignment

Optical Network Configuration







physical topology

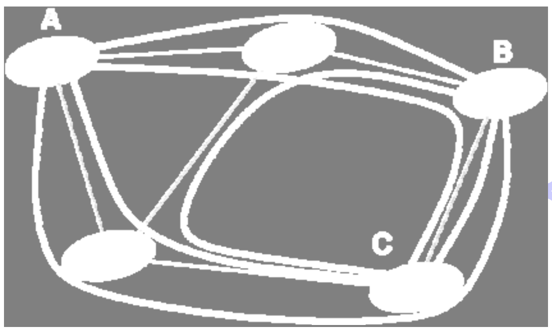
lightpath configuration

virtual topology

Planning Optical Networks

Input: Network topology and demand-matrix

Output: Cost-minimal network configuration with:



Planning present networks

Dimensioning

Edges: Transmission-capacity

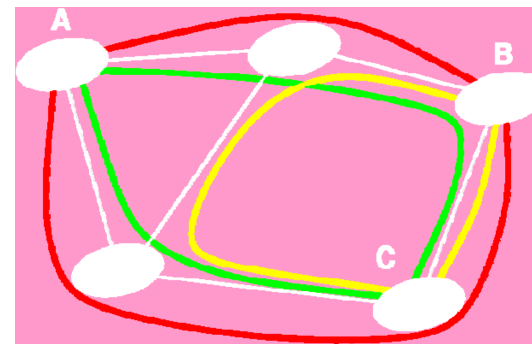
Nodes: Switching-capacity

Routing

Determination of routing (with survivability)

Coloring

Conflict-free wavelength assignment (with converters)



Planning optical networks

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Modeling Optical Networks

- Overall problem is too complex
  - extreme large mathematical model (intractable)
- Decomposition into two subproblems:
  - Dimensioning and Routing
    - connection to previous network planning
    - integer routing requirement
  - Wavelength Assignment
    - conflict-free wavelength assignment to lightpaths

Dimensioning and Routing

Present

Network Dimensioning and Routing:

- Capacity planning
  - mainly edge capacities
  - ⇒ integer capacity variables
- Routing either bifurcated (splittable)
  - ⇒ continuous flow or path variables
- or non-bifurcated (unsplittable)
  - ⇒ 0-1 flow or path variables

Optical

Network Dimensioning and Routing:

- Capacity planning
  - both edge and node related
  - ⇒ integer capacity variables
- Routing in lightpaths (integer-valued)
  - ⇒ general integer routing variables
- Lightpath length restriction
  - ⇒ only via path variables

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Integer Programming Formulation

$G = (V, E)$	Physical topology
Q	Demand set, (s^q, t^q, d^q) source, target and lightpath demand
P^q	Set of paths from s^q to t^q that are allowed to route lightpaths for commodity q
T_{mn}	Index set of available edge capacity levels (fibers + WDM systems) for edge mn
κ^0_{mn} , κ^t_{mn}	Installed edge capacity (channels), available capacity levels
c^T_{mn}	Cost of installing edge capacity level t at edge mn
Θ_m	Index set of available node capacity levels (OXCs) for node m
κ^0_m, κ^θ_m	Installed node capacity (ports), available capacity levels
c^θ_m	Cost of installing node capacity level θ at node m

Integer Programming Formulation

z_p^q # of lightpaths of commodity q routed via path p

l_{mn}^t 0-1 variable indicating whether edge capacity level t is used at edge mn

x_m^θ 0-1 variable indicating whether node capacity level θ is used at node m

Integer Programming Formulation

$$
\begin{aligned}
\min \quad & \sum_{m\in V}\sum_{\theta\in\Theta_m} c_{OXC}\, x_m^\theta + \sum_{mn\in E}\sum_{t\in T_{mn}} c_{mn}^t\, 1_{mn}^t \\
s.t. \quad & \sum_{p\in P^q} z_p^q = d^q && \forall q\in Q \\
& \sum_{q\in Q}\sum_{p\in P^q: mn\in p} z_p^q \le \kappa_{mn}^0 + \sum_{t\in T_{mn}} \kappa_{mn}^t\, 1_{mn}^t && \forall mn\in E \\
& \sum_{t\in T_{mn}} 1_{mn}^t \le 1 && \forall mn\in E \\
& \sum_{q\in Q}\sum_{p\in P^q: m\in p} z_p^q + \sum_{q\in Q: m=s^q} d^q \le \kappa_m^0 + \sum_{\theta\in\Theta_m} \kappa_m^\theta x_m^\theta && \forall m\in V \\
& \sum_{\theta\in\Theta_m} x_m^\theta \le 1 && \forall m\in V \\
& z_p^q \in Z_0^+;\ 1_{mn}^t \in \{0,1\};\ x_m^\theta \in \{0,1\}
\end{aligned}
$$

Routing

Edge Capacity

Node Capacity

Formulation Alternatives

- Depending on concrete capacity structure other variables can be used
- Every lightpath can be considered as a single commodity:
  - non-bifurcated routing of commodities, all with unit demand
  - number of variables is blown up
  - available inequalities for non-bifurcated routing are less/not effective for unit demands (with integer capacity)

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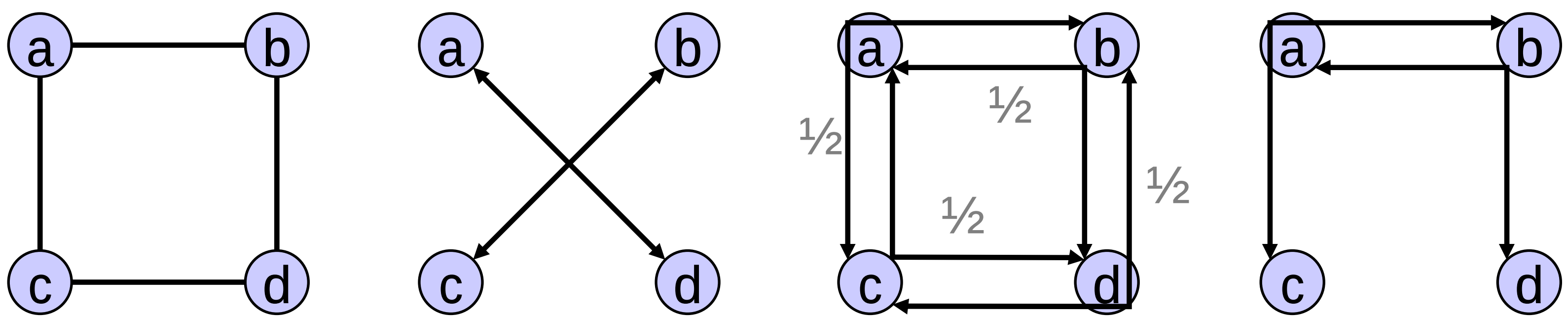
Computational Experiments

- Deleting integrality requirements yields surprisingly few non-integer routings



Remaining free capacity 1 at every edge

Lightpaths to be routed

Continuous routing

Lightpath routing

Concluding Remarks on Optical Networks

- Lightpath routing implies (general) integer routing variables
- Formulation alternative with d^q non-bifurcated commodities unattractive
- IP traffic results in assymmetric demand matrix:
  - symmetric routing not possible
  - asymmetric routing formulation
- Multi-hop networks require 2-layer formulation
- Wavelength assignment introduces a new aspect of optical network design
- Survivability concepts have to be added

Contents

Summary

Telecommunication Problems such as

- Frequency Assignment
- Locating the Nodes of a Network Optimally
- Balancing the Load of Signaling Transfer Points
- Integrated Topology, Capacity, and Routing Optimization as well as Survivability Planning
- Planning IP Networks
- 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!

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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European Graduate Program
Berlin - Zürich
Combinatorics

05M1 Lecture
Combinatorial Optimization and Telecommunication

The End

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