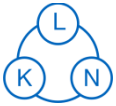


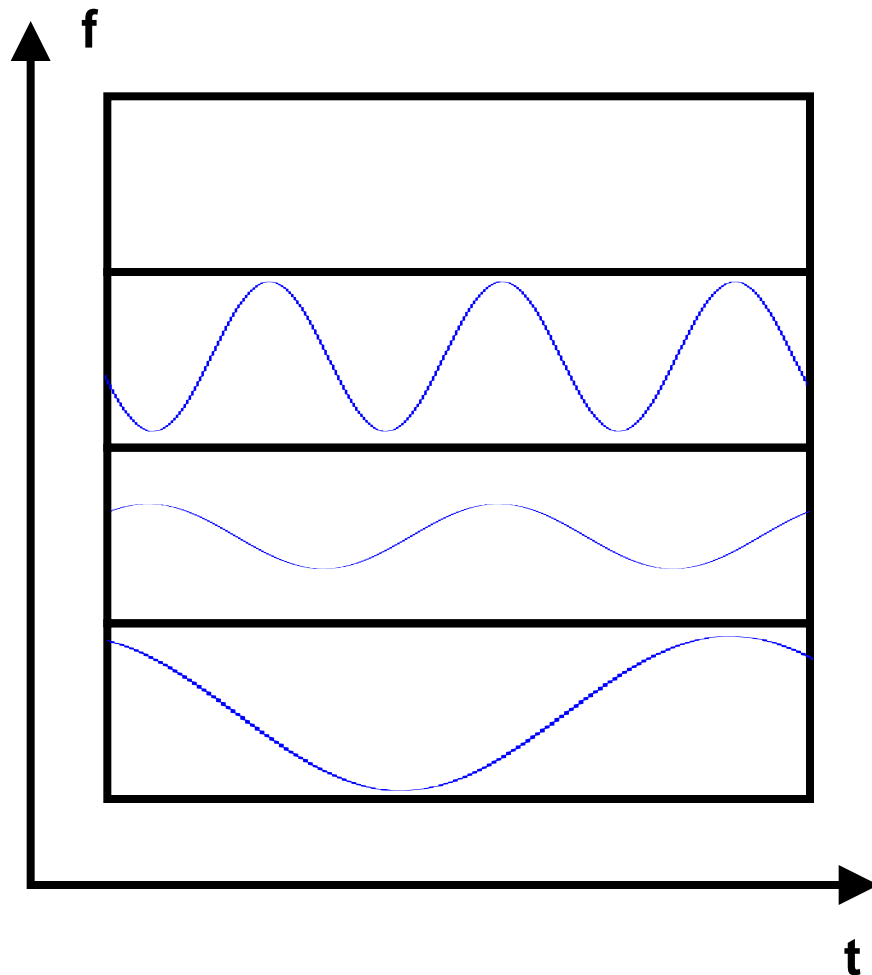
# Exploiting Transponder Performance in Optical OFDM Networks

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- Motivation: Why optical OFDM?
- Planning scenario 1: Opaque networks
- Results
  
- Planning scenario 2: Translucent networks
- Column Generation
- Results
  
- Conclusions & Outlook



Each subcarrier is a sine function with 2 degrees of freedom

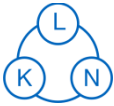
- amplitude
- phase

⇒ ***Multi-level modulation formats can be used!***

⇒ ***Multiple bits can be coded on one subcarrier***

⇒ ***Number of bits depends on signal-to-noise ratio and distance***

Can be easily adapted by software

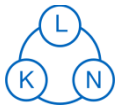


- Successful application in a vast variety of scenarios, both wired (ADSL, Powerline) and wireless (DVB-S, DVB-T, DAB, SIRIUS, IEEE 802.11a/g)
- Proposals for OFDM exist (Lowery et al. 2007, Shieh et al. 2007, Jansen et al. 2007)
- Complexity comparable to high-performance fixed-rate transponder (Spinnler et al. 2008)
- In an analogy to *Adaptive OFDM* in wireless networks (Yang et al. 2008) propose an adjustment of the relative power of the subcarriers  
⇒ quasi continuous transmission rate depending on the SNR

$$R_l = \frac{R_0}{2} \left( 1 + \text{ld} \left( \frac{2L}{L_l} \right) \right)$$

⇒ Transmission rate depending on the link length

⇒ In the following limited to the range  $\left[ \frac{R_0}{2}; 160 \text{Gb/s} \right]$

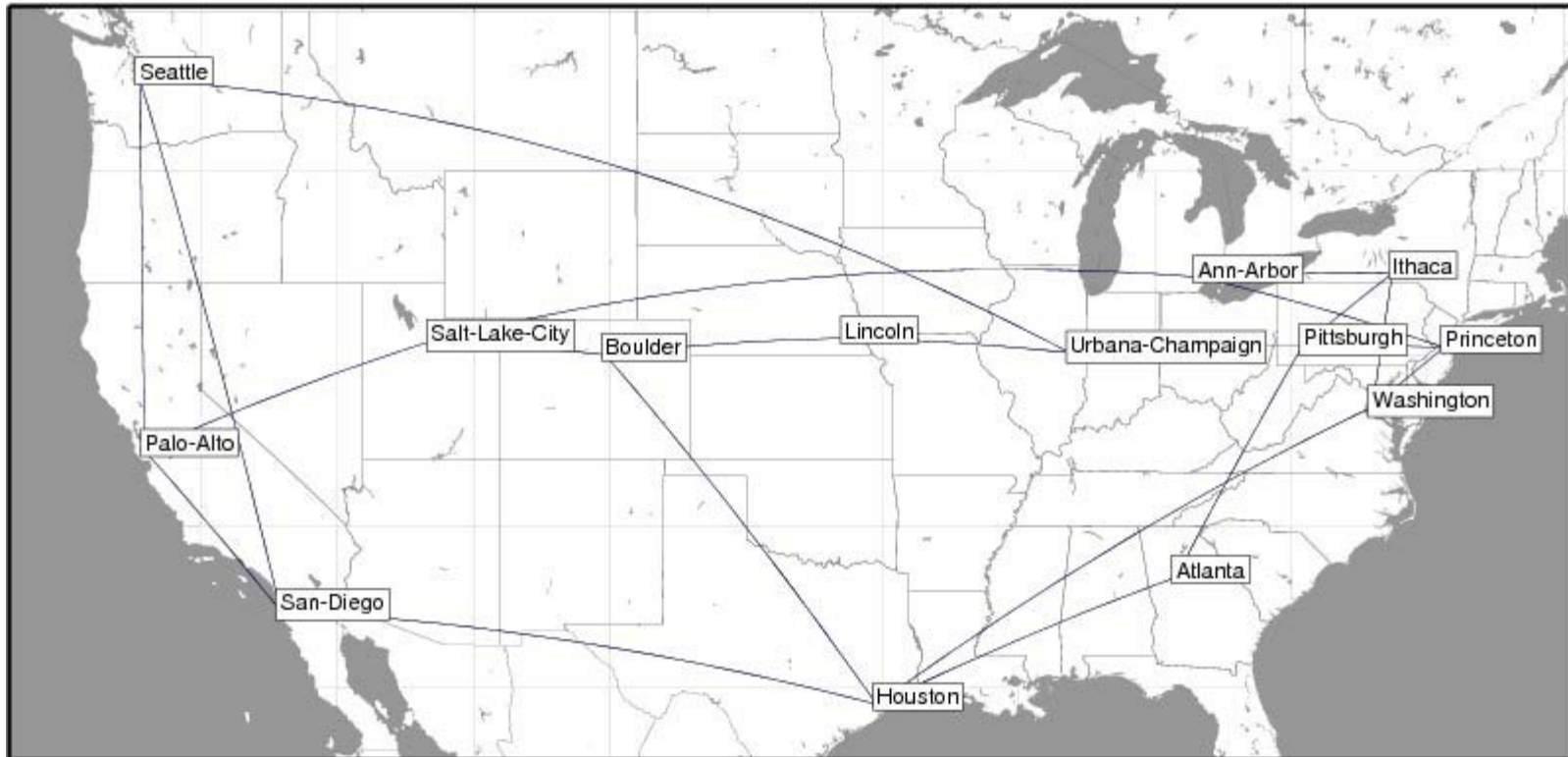


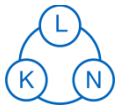
First Comparison: Opaque networks

- Realistic scenario for OFDM – no ODU Grooming possible
- Simple question – clear results

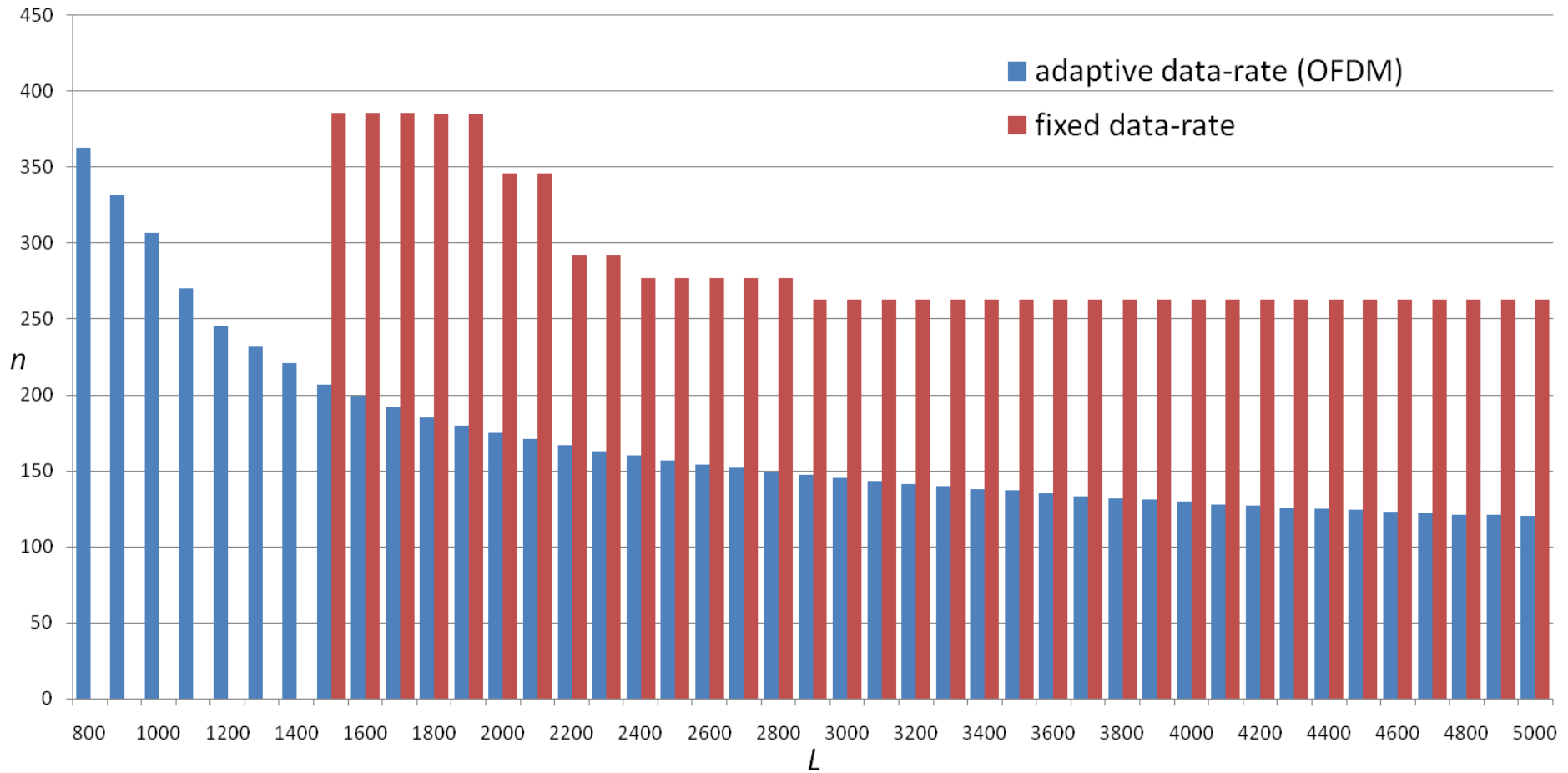
Obvious path-flow formulation:

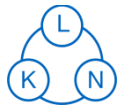
$$\begin{aligned} \min \sum_{l \in \mathcal{L}} n_l \quad & \text{subject to} \\ \sum_{p \in \mathcal{P}_d} f_{d,p} & \geq D_d \quad \forall d \in \mathcal{D} \\ \sum_{\substack{d \in \mathcal{D} \\ p \in \mathcal{P}_d: \\ l \in p}} f_{d,p} & \leq n_l \cdot R_l \quad \forall l \in \mathcal{L} \\ n_l & \leq \lambda_{\max} \quad \forall l \in \mathcal{L} \end{aligned}$$





# Results (opaque)





# Planning Aspects (opaque & 1+1)

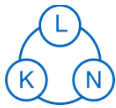
$\min \sum_{l \in \mathcal{L}} n_l$  subject to

$$\sum_{p \in \mathcal{P}_d} f_{d,p} \geq 2 \cdot D_d$$

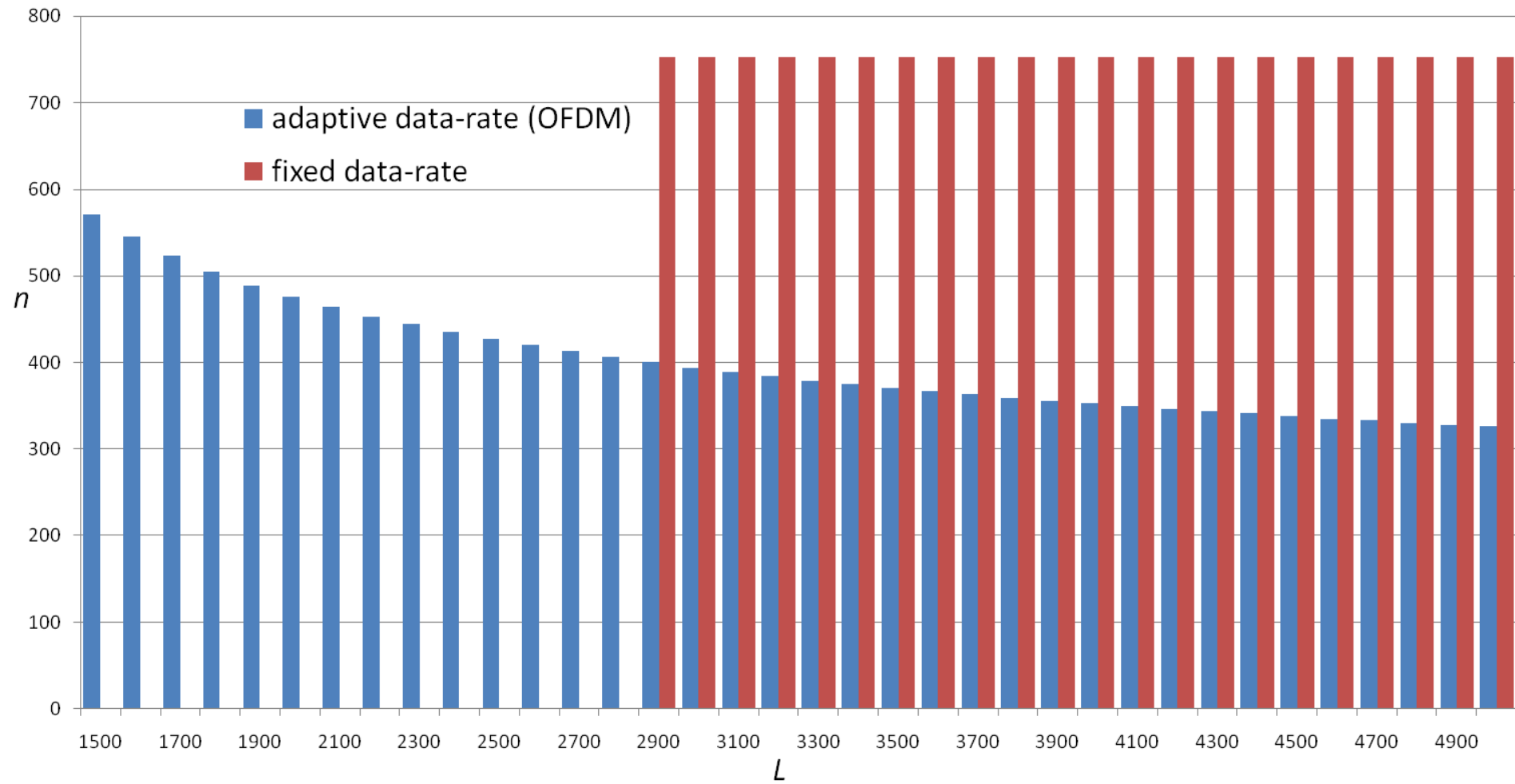
$$\sum_{d \in \mathcal{D}} \sum_{\substack{p \in \mathcal{P}_d: \\ l \in p}} f_{d,p} \leq n_l \cdot R_l \quad \forall l \in \mathcal{L}$$

$$\sum_{\substack{p \in \mathcal{P}_d: \\ l \in p}} f_{d,p} \leq D_d \quad \forall l \in \mathcal{L} \quad \forall d \in \mathcal{D}$$

$$n_l \leq \lambda_{\max} \quad \forall l \in \mathcal{L}$$



# Results (opaque & 1+1)

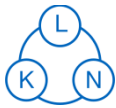


Results promising, but not the last word:

- A bit unfair for the fixed-rate system (only one transponder type)
- Expensive IP nodes (lots of traffic terminating)

New model:





# Translucent Planning: MIP (1)

$$\min \sum_{p \in \mathcal{P}} \sum_{t \in \mathcal{T}_p} C_t n_{p,t} \quad \text{subject to}$$

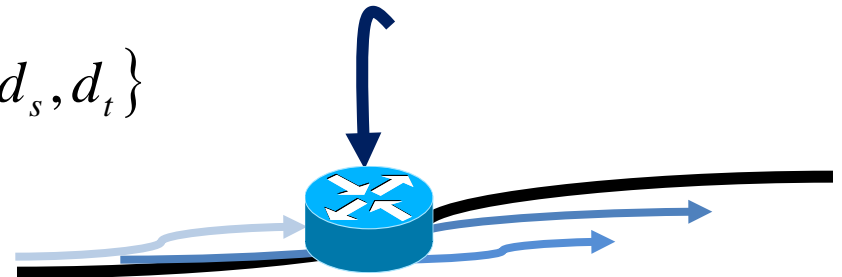
$$\sum_{d \in \mathcal{D}} f_{d,p} \leq \sum_{t \in \mathcal{T}_p} R_t n_{p,t} \quad \forall p \in \mathcal{P}$$

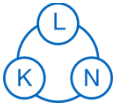
$$\sum_{\substack{p \in \mathcal{P} : t \in \mathcal{T}_p \\ l \in p}} n_{p,t} \leq \lambda_{\max} \quad \forall l \in \mathcal{L}$$

$$\sum_{p \in \mathcal{P}_{d_s}} f_{d,p} \geq D_d \quad \forall d \in \mathcal{D}$$

$$\sum_{p \in \mathcal{P}_n} f_{d,p} - \sum_{p \in \mathcal{P}^n} f_{d,p} = 0 \quad \forall d \in \mathcal{D}, \forall n \in \mathcal{N} \setminus \{d_s, d_t\}$$

$$- \sum_{p \in \mathcal{P}^{d_t}} f_{d,p} \leq -D_d \quad \forall d \in \mathcal{D}$$

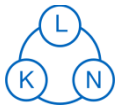




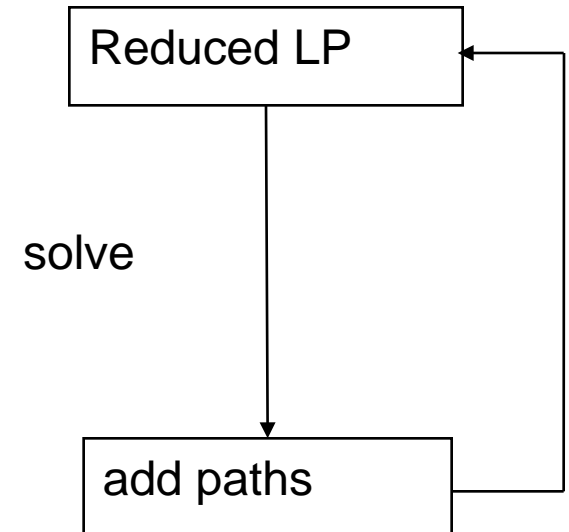
## Challenges:

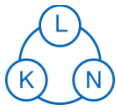
- Well-known, hard optimization problem:
    - Huge number of lightpaths
    - Huge number of flow variables
  - Standard remedies:
    - Preselection of paths (Scheffel et al. 2006)
    - (Meta-)Heuristic approaches (Kiese et al. 2007)
- Drawback: No lower bound  $\Rightarrow$  no optimality gap

$\Rightarrow$  Column Generation



- A lot of possible paths remain unused in an optimal solution
- Starting without the unused paths would still generate an optimal solution
- Problem: A priori determination of these paths





# Dual System

$$\min \sum_{p \in \mathcal{P}} \sum_{t \in \mathcal{T}_p} C_t n_{p,t} \quad \text{subject to}$$

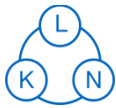
$$\sum_{d \in \mathcal{D}} f_{d,p} \leq \sum_{t \in \mathcal{T}_p} R_t n_{p,t} \quad \forall p \in \mathcal{P} \quad [\sigma_p]$$

$$\sum_{\substack{p \in \mathcal{P} : t \in \mathcal{T}_p \\ l \in p}} n_{p,t} \leq \lambda_{\max} \quad \forall l \in \mathcal{L}$$

$$\sum_{p \in \mathcal{P}_{d_s}} f_{d,p} \geq D_d \quad \forall d \in \mathcal{D}$$

$$\sum_{p \in \mathcal{P}_n} f_{d,p} - \sum_{p \in \mathcal{P}^n} f_{d,p} = 0 \quad \forall d \in \mathcal{D}, \forall n \in \mathcal{N} \setminus \{d_s, d_t\} \quad [\pi_{d,n}]$$

$$- \sum_{p \in \mathcal{P}^{d_t}} f_{d,p} \leq -D_d \quad \forall d \in \mathcal{D}$$

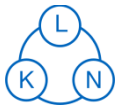


# Finding Improving Variables

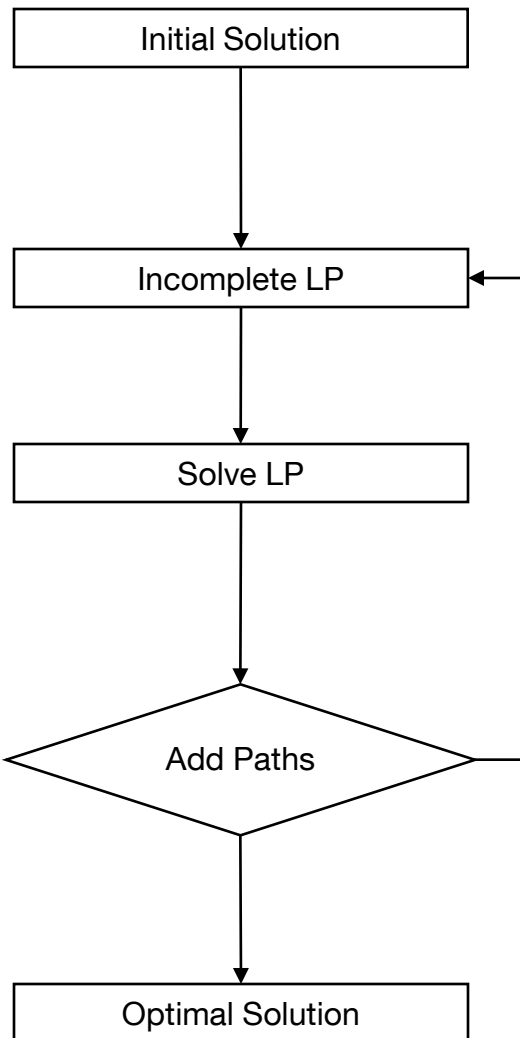
For a given path  $p$  and demand  $d$  the a path-flow variable  $f_{d,p}$  will create a dual constraint

$$\pi_{d,p_s} - \pi_{d,p_t} - \sigma_p \leq 0$$

Missing  $f_{d,p}$  will violate this constraint.

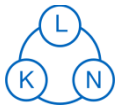


# Column Generation

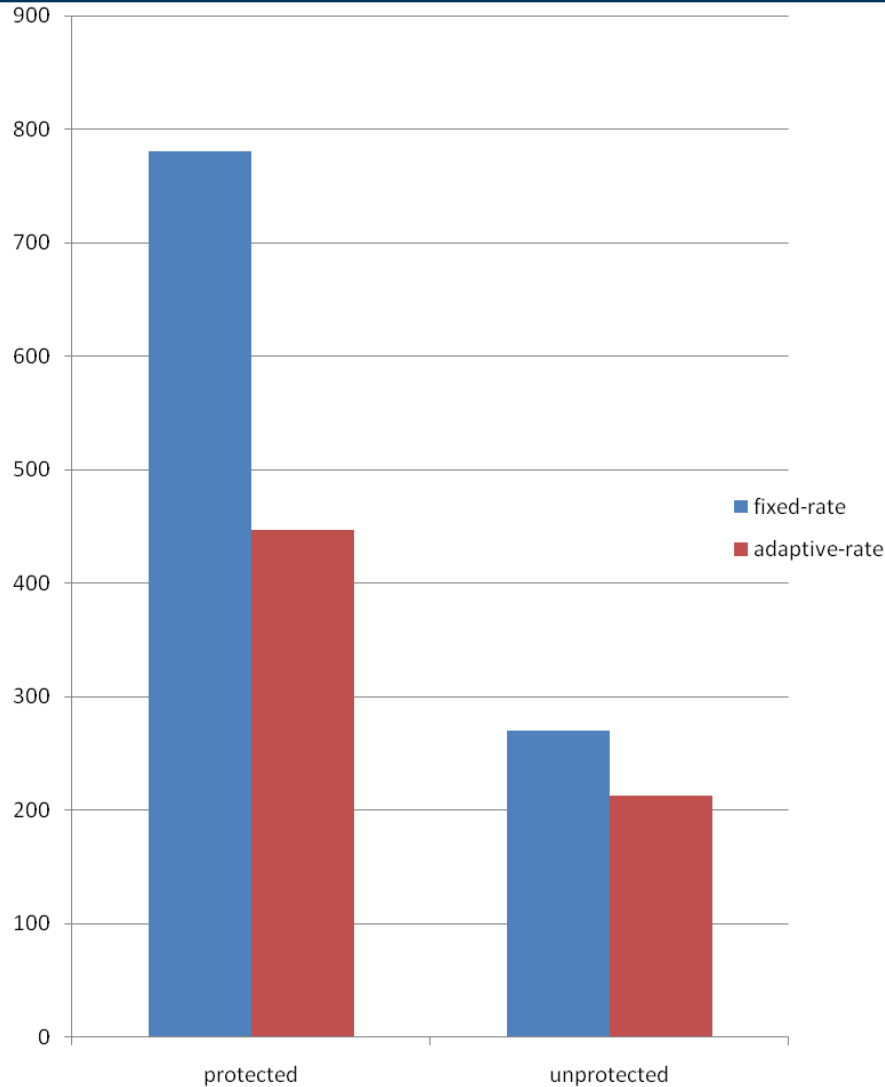


- Implemented in SCIP 1.1 with CPLEX 9.13 as LP-Solver

- Good solutions are found a lot faster
- Symmetries in the cost functions make the problem increasingly hard to solve to optimality



# Preliminary Results: Translucent Network

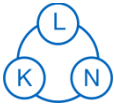


## Adaptive-rate:

- Transponder 1:
  - Range: 6000km @BPSK
  - Rate: 20Gbit/s
  - Cost: 2
- Transponder 2:
  - Range: 2000km @BPSK
  - Rate: 20Gbit/s
  - Cost: 1

## Fixed-rate:

- Transponder 1:
  - Range: 3000km
  - Rate: 40Gbit/s
  - Cost: 2
- Transponder 2:
  - Range: 3000km
  - Rate: 10Gbit/s
  - Cost: 1
- Transponder 3:
  - Range: 1000km
  - Rate: 40Gbit/s
  - Cost: 1
- Transponder 4:
  - Range: 1000km
  - Rate: 10Gbit/s
  - Cost: 0.5



- We have presented planning methodologies for opaque and translucent OFDM networks
- OFDM was able to greatly reduce the number of necessary transponders in the opaque case in (a possibly unrealistic) comparison with a fixed-rate system
- Planning for the translucent case is substantially more difficult, but can be performed via problem specific solution methods like column-generation
- Preliminary results show an even greater cost-advantage for OFDM in the translucent case.
- Still to come: More networks, cost-model variations.