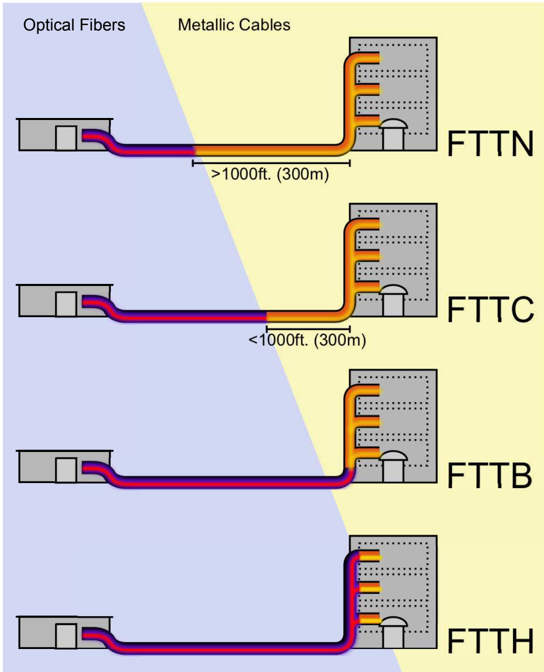
FTTx network planning

Mathematics of Infrastructure Planning (ADM III)

14 May 2012

- Fiber To The x
  - ➡ Telecommunication access networks: “last mile” of connection between customer homes (or business units) and telecommunication central offices
  - ➡ Fiber optic technology: much higher transmission rates, lower energy consumption
- Multitude of choices in the planning of FTTx networks

Roll-out strategy:



Fiber To The Node

Fiber To The Cabinet (∼ VDSL)

Fiber To The Building

Fiber To The Home

- Fiber To The x
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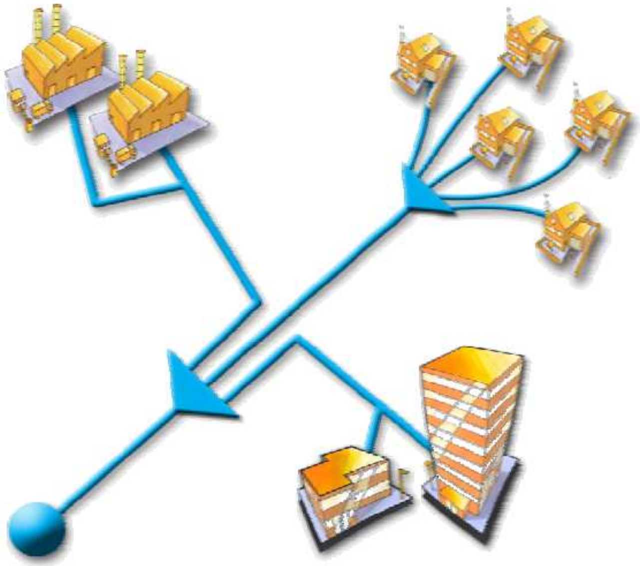
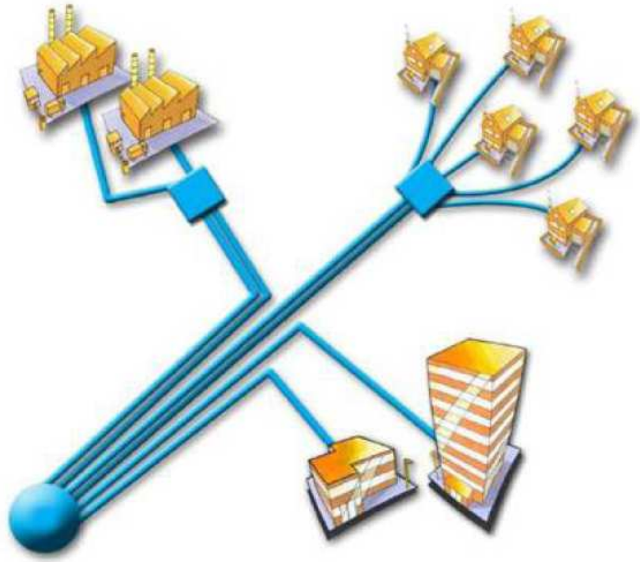
Architecture:



PON



Point-to-point

- Fiber To The x
  - ➡ Telecommunication access networks: "last mile" of connection between customer homes (or business units) and telecommunication central offices
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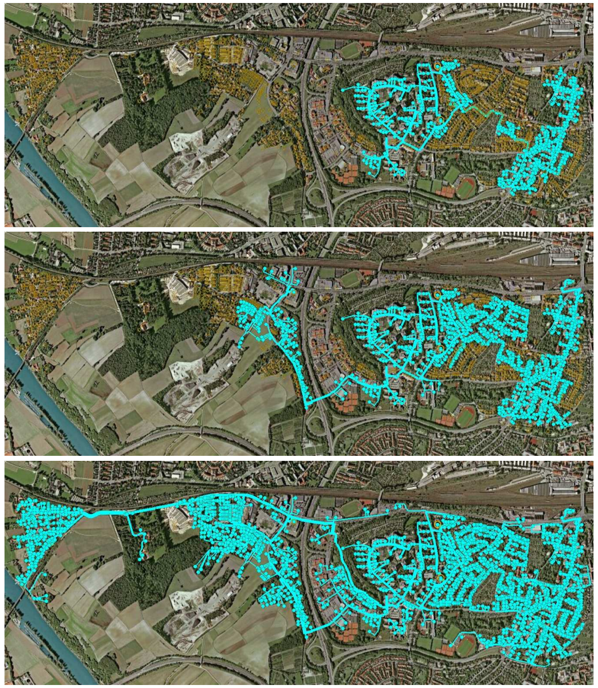
- Multitude of choices in the planning of FTTx networks

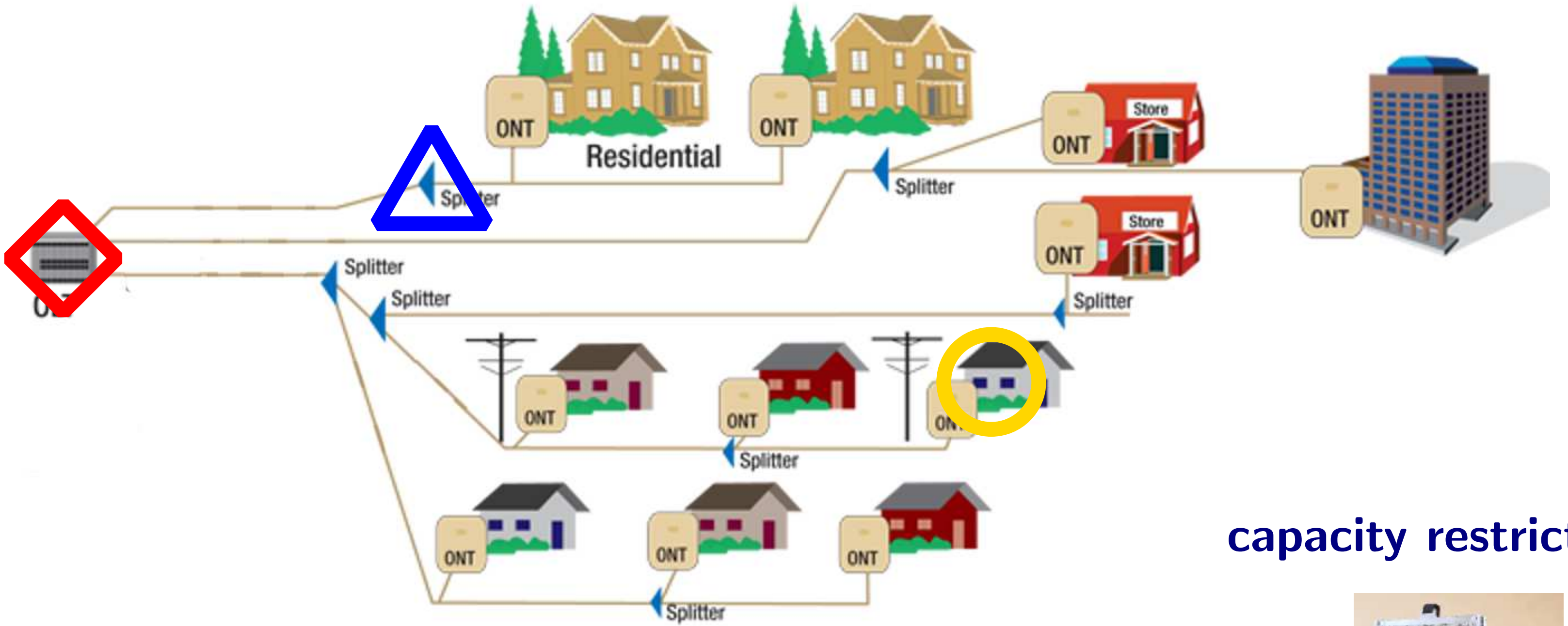
Target coverage rate:

60%

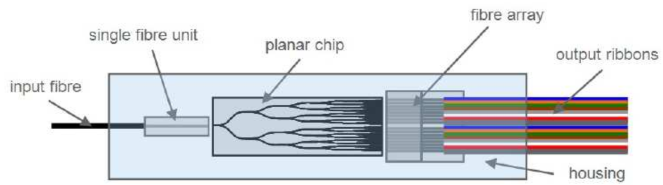
80%

100%



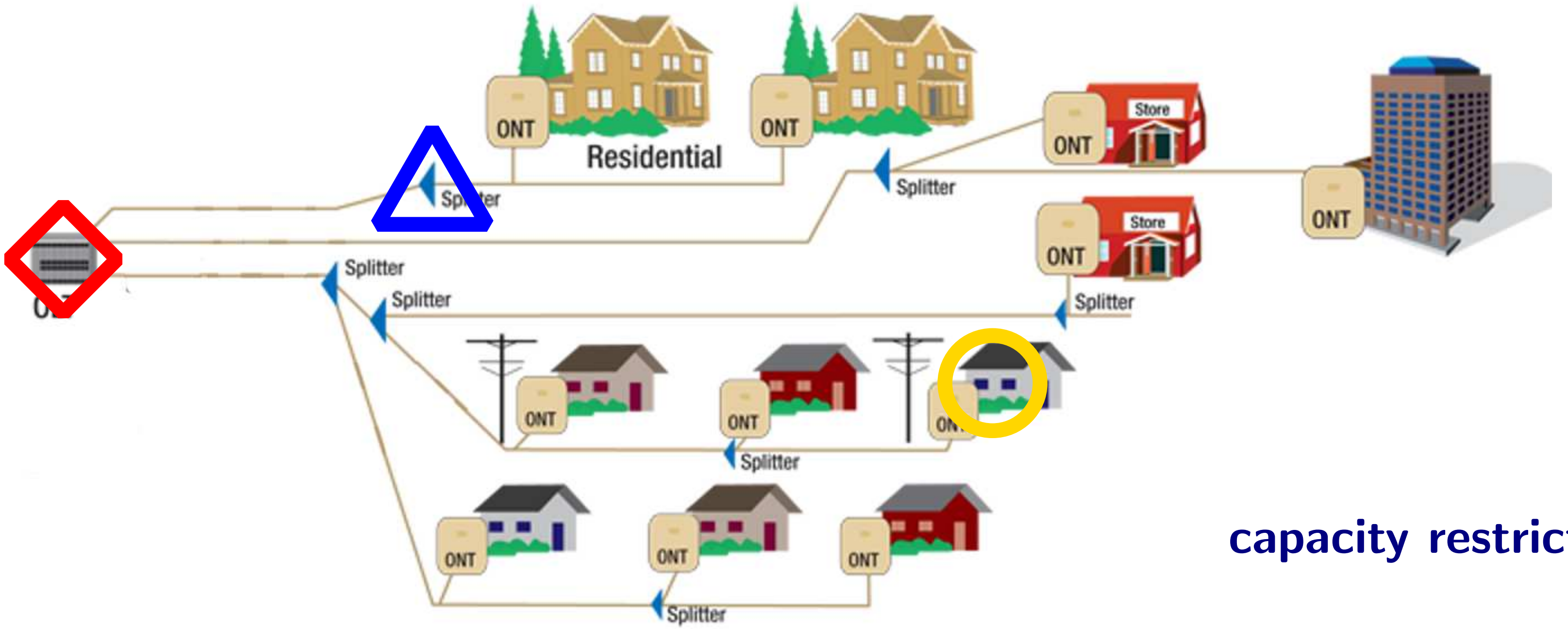


capacity restrictions!



- CO (central office): connection to backbone network
- BTP ("customer" location): target point of a connection
- DP (distribution point): passive optical switching elements
  - ➡ splitters, closures with capacities

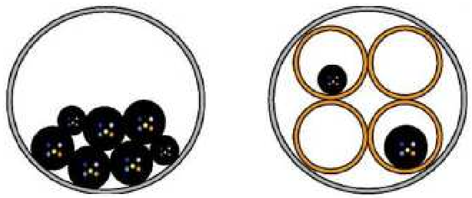
FTTx terminology

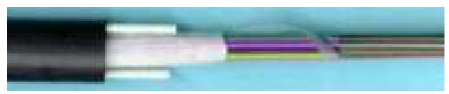


capacity restrictions!

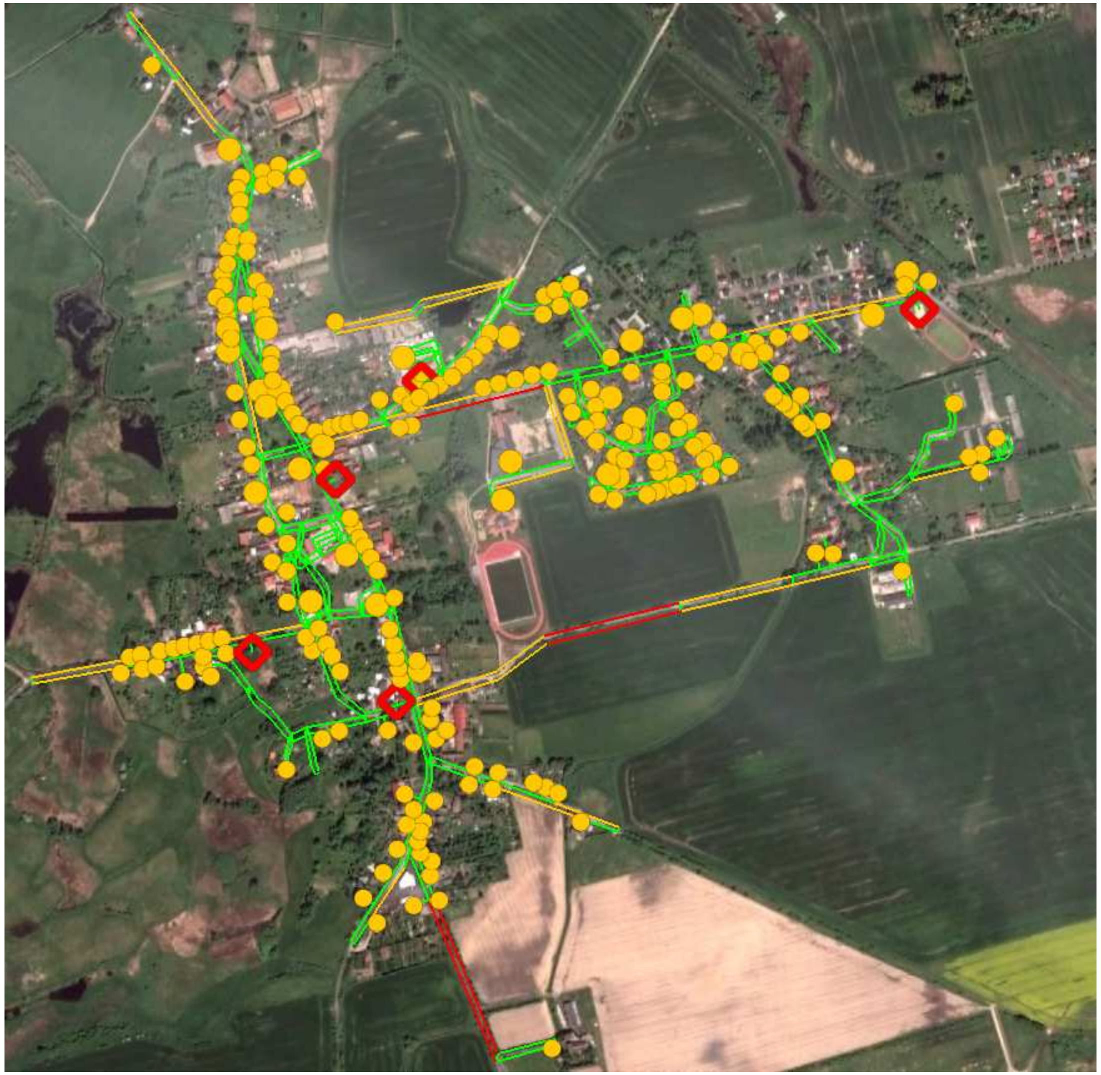
length restrictions!

- CO (central office): connection to backbone network
- BTP ("customer" location): target point of a connection
- DP (distribution point): passive optical switching elements
  - ➡ splitters, closures with capacities
- Links: fibers in cables (in micro-ducts) (in ducts) in the ground





- Given a trail network with
  - special locations: potential COs, DPs, and BTPs,
  - trails with trenching costs, possibly with existing infrastructure (empty ducts, dark fibers)
  - catalogue of installable components with cost values
  - further planning parameters (target coverage rate, max. number of residents/fibers per CO/DP, etc)



➡ Find a valid, cost-optimal FTTx network!

- BMBF funded project 2009–2011

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➡ Partners:

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➡ Industry Partners: R·KOM — Draka — Breitband Kompetenz Zentrum Niedersachsen

- Compute FTTx network in several steps:

1. step: network topology
   a) connect BTPs to DPs
   b) connect DPs to COs
   ➡ integer linear program: concentrator-location
2. step: cable & component installation
3. step: duct installation
   ➡ integer linear program: cable-duct-installation

- ▷ Given: undirected graph with
  - client nodes: fiber demand, number of residents, revenue (for optional clients)
  - concentrator nodes: capacities for components, fibers, cables, ..., cost values
  - edges: capacity in fibers or cables (possibly 0), cost values for trenching
- ▷ Task: compute a cost-optimal network such that
  - each mandatory client is connected to one concentrator
  - various capacities at concentrators and edges are respected

➡ Integer program:

- select paths that connect clients
- capacity constraints on edges
- capacity constraints for fibers, cables, closures, (cassette trays), (splitter) ports at concentrators
- constraints for coverage rate, limit on the number of concentrators

minimize
$$\sum_{i\in V_D} c_i x_i + \sum_{t\in T} c_t y_t + \sum_{e\in E} c_e w_e + \sum_{p\in P\cup\hat{P}} c_p f_p - \sum_{v\in V_B} r_v q_v$$

s.t.
$$\sum_{p\in P_v} f_p = 1 \quad \forall v\in V_A$$
$$\sum_{p\in P_v} f_p = q_v \quad \forall v\in V_B$$
$$f_p \le f_{p'} \quad \forall p\in P'$$
$$\sum_{p\in P_e\cup\hat{P}_e} f_p \le |P_e\cup\hat{P}_e|\, w_e \quad \forall e\in E_0$$
$$\sum_{p\in P_e\cup\hat{P}_e} d_p^e f_p \le u_e + u'_e w_e \quad \forall e\in E_{>0}$$
$$x_i \le \sum_{p\in\hat{P}_i} f_p \le 1 \quad \forall i\in\hat{V}_D$$
$$\sum_{t\in T_i} y_t = x_i \quad \forall i\in V_D$$
$$\sum_{v\in V_B\cap V_k} n_{k,v} q_v \ge \lceil \chi_k n_k \rceil - n_k^A \quad \forall k\in C$$
$$\sum_{i\in V_D} x_i \le m$$
$$\sum_{p\in P_i} d_p^f f_p \le \sum_{t\in T_i} u_t^f y_t \quad \forall i\in V_D$$
$$\sum_{p\in P_i} d_p^c f_p \le \sum_{t\in T_i} u_t^c y_t \quad \forall i\in V_D$$
$$\sum_{p\in P_i} d_p^r f_p \le \sum_{t\in T_i} u_t^r y_t \quad \forall i\in V_D$$
$$\sum_{p\in P_e} d_p^f f_p \le \sum_{l\in L_e} u_l^f z_l \quad \forall e\in E_D$$
$$\sum_{l\in L_i} d_l^c z_l \le \sum_{t\in T_i} u_t^c y_t \quad \forall i\in V_D$$
$$\sum_{l\in L_i} d_l^r z_l \le \sum_{t\in T_i} u_t^r y_t \quad \forall i\in V_D$$
$$\sum_{p\in P_i} d_p^s f_p \le \sum_{t\in T_i} u_t^s y_t \quad \forall i\in V_D$$
$$\sum_{p\in P_i} n_p f_p \le n_i x_i \quad \forall i\in V_D$$

Solution – FTTx network

CATEGORY	COMPONENT	COUNT	METER	COST	PERCENT
Served residents					
	BUSINESS	60			
	HOUSEHOLDS	803			
Setup cost					
	BTP	225		0,00	0,00
	DP	9		10800,00	0,87
	CO	1		470447,00	37,90
	Total	1		481247,00	38,77
BTP terminations					
	.	.	.	.	.
BTP splitters					
	.	.	.	.	.
BTP transceivers					
	TRX-GPON-ClassC+-2488-1244-ONU	280		44800	3,61
BTP ONUs					
	ONU-ALU-GPON-ONT-1	280		44800	3,61
DP closures					
	MUFFE-TY-GCO2-64	7		13666	1,10
	MUFFE-TY-GCO2-96	2		4036	0,33
	Total cost	9		17701	1,43
DP splitters					
	SP-FOC-FIC-32	19		17480	1,41
CO ODF					
	TY-FIST-GR2	1		300	0,02
CO switches					
	OLTSW-ALU-7342-ISAM-FTTU-250GB	1		6025	0,49
CO cards					
	CARD-ALU-OLT-4	3		7560	0,61
CO ports					
	PORT-GPON-2488-1244	11		0	0,00
CO transceivers					
	TRX-GPON-ClassC+-2488-1244-OLT	11		110	0,01
Cables					
	CABLE-DRA-Nano-6x12-12	3	360	334	0,03
	CABLE-DRA-Nano-6x12-24	1	675	738	0,06
	CABLE-DRA-Nano-6x12-48	1	1082	1473	0,12
	CABLE-DRA-Nano-6x12-60	1	2324	3484	0,28
	CABLE-DRA-URX-10	2	168	177	0,01
	CABLE-DRA-URX-12	2	572	651	0,05
	CABLE-DRA-URX-2	198	34192	35218	2,84
	CABLE-DRA-URX-4	18	3184	3347	0,27
	CABLE-DRA-URX-6	6	1049	1126	0,09
	CABLE-DRA-URX-8	2	317	347	0,03
	Total	232	43903	46896	3,78
Ducts					
	DUCT-110	1	53	106	0,01
	DUCT-50	262	4925	8218	0,66
	DUCT-MFR-2x40-2x32	1	53	106	0,01
	DUCT-SPG-1x10x10	18	266	1197	0,10
	DUCT-SPG-1x10x10-1x6x10	10	172	1118	0,09
	DUCT-SPG-1x18x10	7	103	773	0,06
	DUCT-SPG-1x18x10-1x10x10	4	34	374	0,03
	DUCT-SPG-1x1x10	429	6723	8404	0,68
	DUCT-SPG-1x24x10	7	94	846	0,07
	DUCT-SPG-1x2x10	219	3939	5909	0,48
	DUCT-SPG-1x6x10	71	1376	4128	0,33
	DUCT-SPG-2x10x10	9	80	640	0,05
	DUCT-SPG-2x6x10	20	477	2386	0,19
	Total	1068	17696	34204	2,76
Fibers					
	FIBER-COR-LWP	579	128208	9264	0,75
Trails					
	Digging		11236	530780	42,76
	Digging Drop-Area		5267	[illegible]	[illegible]
	Digging Non-Drop-Area		5968	325160	26,20
	Digging DP-Area exclusively		3048	166540	13,42
	Digging CO-Area exclusively		360	17460	1,41
	Digging DP- and CO-Area intersecting		2560	141160	11,37
	Existing ducts		0	0	0,00
Total				1241166	100,00
Cost per resident				1439	
Cost per building				5517	

▷ How much trenching cost is unavoidable?

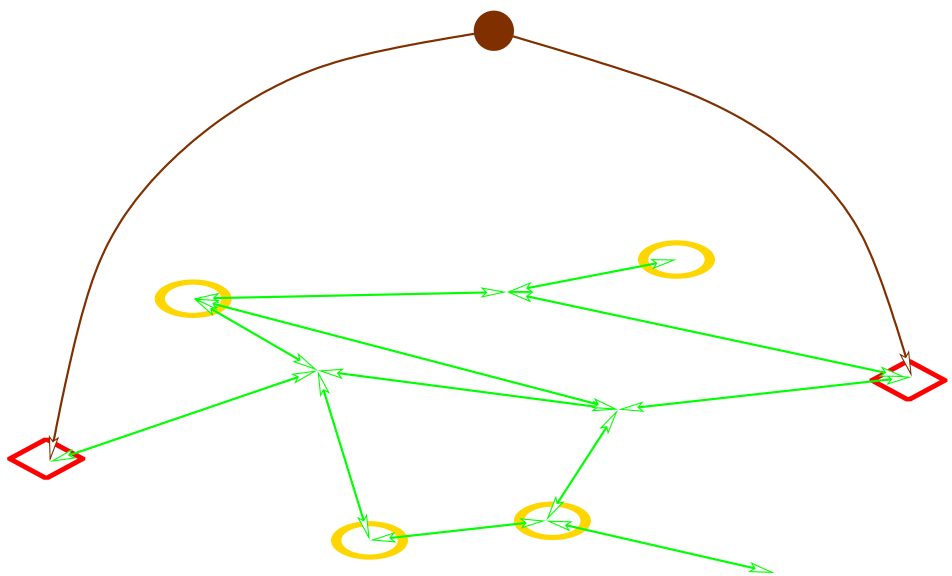
➡ All (mandatory) customer locations have to be connected to a CO

➡ More COs have to be opened if the capacities are exceeded

▷ Steiner tree approach:

➡ Construct a directed graph G with:

- all trail network locations, BTPs and COs, plus an artificial root node, as node set
- forward- and backward-arcs for each trail, plus capacitated artificial arcs connecting the root to each CO



➡ Compute a Steiner tree in G with:

- all BTPs, plus the artificial root node, as terminals
- capacity restrictions on the artificial arcs

Extended Steiner tree model

$$
\begin{array}{lll}
\text{minimize} & \displaystyle\sum_{e\in E} c_e w_e + \sum_{a\in A_0} c_a x_a & \\
\text{s.t.} & \displaystyle\sum_{a\in\delta^-(v)} f_a - \sum_{a\in\delta^+(v)} f_a = \begin{cases} N_v & \text{if } v\in V_B \\ 0 & \text{otherwise} \end{cases} & \forall v\in V \\
& f_a \le |N_B| x_a & \forall a\in A \\
& x_{e^+} + x_{e^-} = w_e & \forall e\in E \\
& \displaystyle\sum_{a\in\delta^-(v)} x_a = 1 & \forall v\in V_B \\
& \displaystyle\sum_{a\in\delta^-(v)} x_a \le 1 & \forall v\in V\setminus V_B \\
& \displaystyle\sum_{a\in\delta^-(v)} x_a \le \sum_{a\in\delta^+(v)} x_a & \forall v\in V\setminus V_B \\
& \displaystyle\sum_{a\in\delta^-(v)} x_a \ge x_{a'} & \forall v\in V\setminus V_B\,,\ a'\in\delta^+(v) \\
& f_a \le k_a x_a & \forall a\in A_0 \\
& \displaystyle\sum_{a\in A_0} x_a \le N_C & \\
& f_a \ge 0\,,\ x_a\in\{0,1\} & \forall a\in A \\
& w_e\in\{0,1\} & \forall e\in E
\end{array}
$$

▷ Instances:

- `a*`: artificially generated, based on GIS information from `www.openstreetmap.org`
- `c*`: real-world studies, based on information from industry partners

Instance:	a1	a2	a3	c1	c2	c3	c4
# nodes	637	1229	4110	1051	1151	2264	6532
# edges	826	1356	4350	1079	1199	2380	7350
# BTPs	39	238	1670	345	315	475	1947
# potential COs	4	5	6	4	5	1	1
network trenching cost	235640	598750	2114690	322252	1073784	2788439	4408460
lower bound	224750	575110	2066190	312399	1063896	2743952	4323196
relative gap	4.8%	4.1%	2.3%	3.2%	0.9%	1.6%	2.0%

➡ Trenching costs in the computed FTTx networks are quite close to the lower bound

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  2. step: cable & component installation
  3. step: duct installation

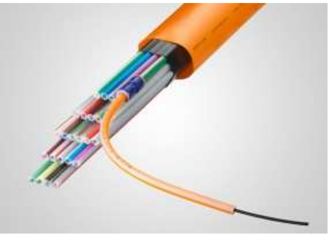
  ➡ integer linear program: cable-duct-installation

▷ Given

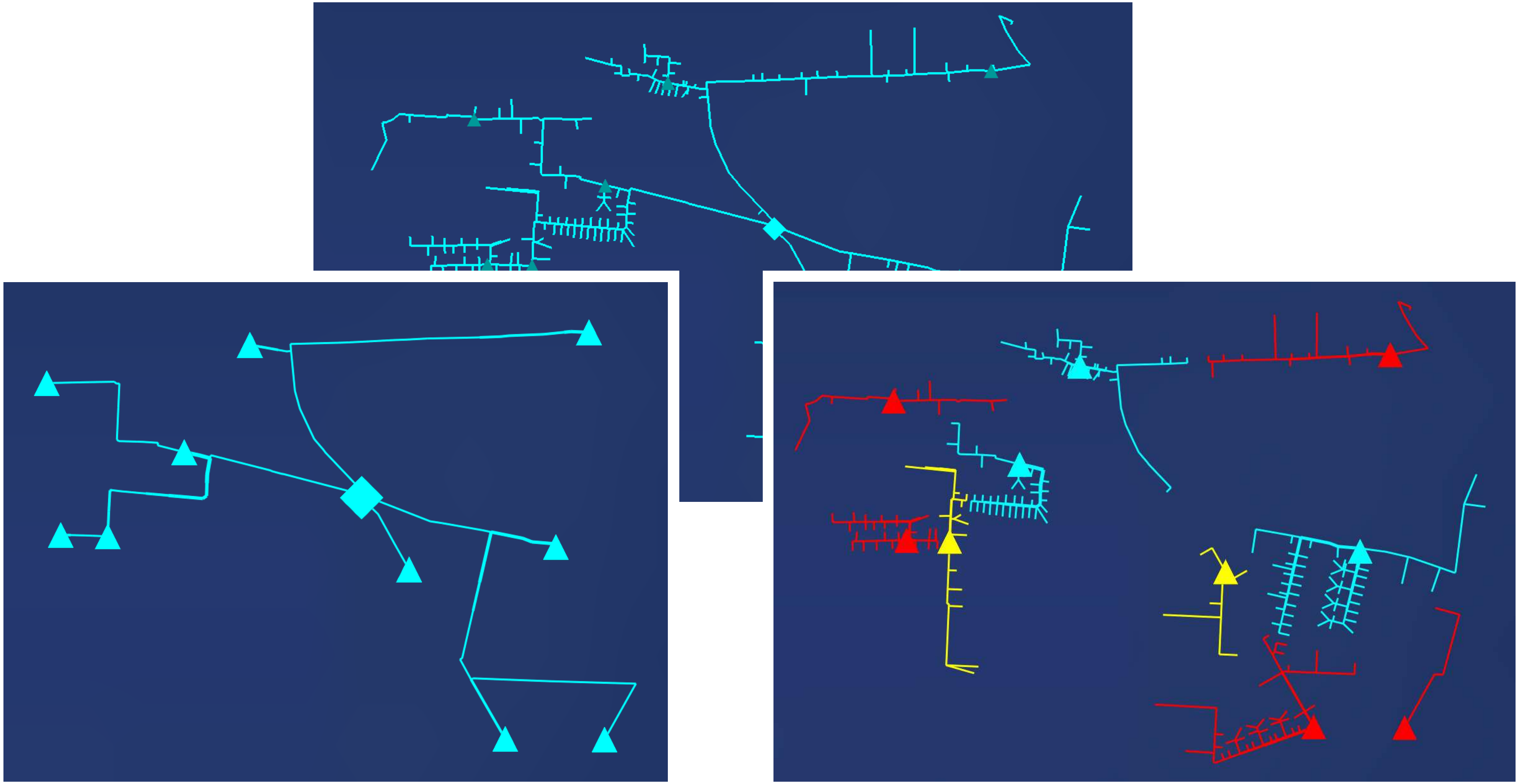
- network topology
- a fiber demand at every connected BTP
- restrictions on cable and duct installations:

  Example: Micro-ducts

  Every customer gets their own cable(s), each in a separate micro-duct within a micro-duct bundle



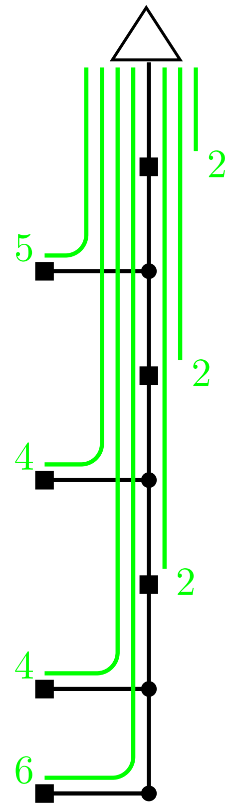
▷ Task: compute cost-optimal cable and duct installations that meet the restrictions such that all fiber demands at customer locations are met



➡ DPs and COs are roots of undirected trees

▷ Given

- an undirected rooted tree with
  - one concentrator (root)
  - client locations and
  - other locations
- set C of cable installations to embed with
  - path in the tree
  - number of cables



▷ Task: compute cost-optimal duct installations, such that every cable is embedded in a micro-duct on every edge of its path cost of duct installation d

minimize $$\sum_{d \in D} c_d x_d$$

s.t.

pipes of type p provided by duct installation d

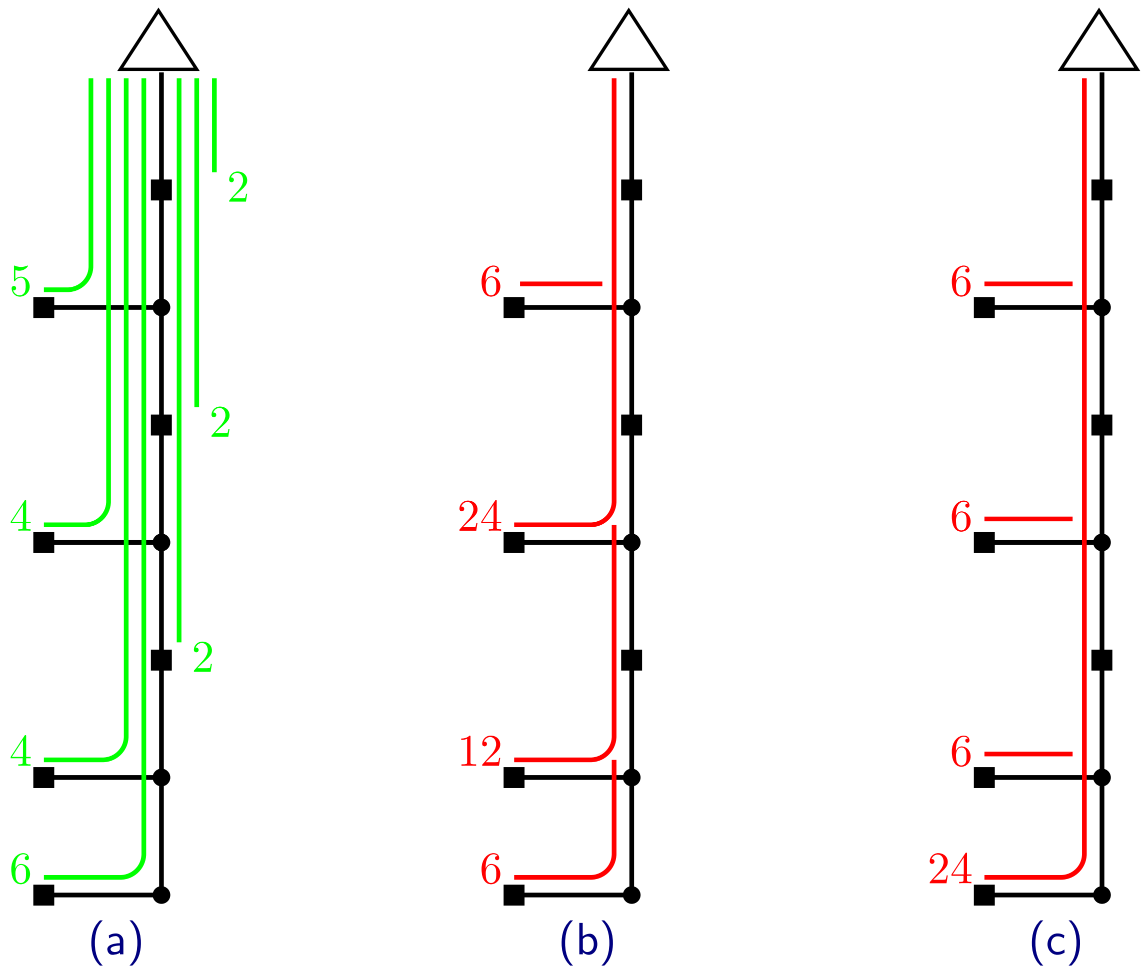
$$k_p^d x_d \geq \sum_{c \in C} x_{c,d}^p \qquad \forall\, d \in D, p \in P^d$$

cables in installation c

$$k_c = \sum_{p \in P_c^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x_{c,d}^p \qquad \forall\, c \in C, e \in q_c$$

$$x_d \in \mathbb{Z}_{\geq 0}$$ # ducts of duct installation d used

$$x_{c,d}^p \in \mathbb{Z}_{\geq 0}$$ # cables for c embedded in pipes of type p provided by duct installation d



Possible duct sizes 6, 12 and 24

- — Trail network
- ■ Client
- — Cable installation
- — Duct installation
- 1 Number of cables/ducts used in installation

maximal direction:
downward direction at an intersection with maximal number of cables on it

(a) Given cable installations

(b) Cost optimal installations with downgrading at intersections

(c) Installations used in practice (downgrading in maximal direction not allowed) minimize $$\sum_{d \in D} c_d x_d + \sum_{e \in E} c_e z_e$$

s.t.

$$k_p^d x_d \geq \sum_{\tilde{d} \in D} x^p_{\tilde{d},d} + \sum_{c \in C} x^p_{c,d} \qquad \forall\, d \in D, p \in P^d$$

$$k_c \leq \sum_{p \in P_c^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{c,d} + z_e k_c \qquad \forall\, c \in C_G, e \in q_c v$$

$$k_c = \sum_{p \in P_c^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{c,d} \qquad \forall\, c \in C \setminus C_G, e \in q_c$$

$$x_{\tilde{d}} \leq \sum_{p \in P_{\tilde{d}}^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{\tilde{d},d} + z_e M_{\tilde{d}} \qquad \forall\, \tilde{d} \in D_G, e \in q_{\tilde{d}}$$

$$x_{\tilde{d}} = \sum_{p \in P_{\tilde{d}}^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{\tilde{d},d} \qquad \forall\, \tilde{d} \in D \setminus D_G, e \in q_{\tilde{d}}$$

either embed or trench

$$k_c \geq \sum_{p \in P_c^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{c,d} \qquad \forall\, c \in C_G, e \in q_c$$

$$x_{\tilde{d}} \geq \sum_{p \in P_{\tilde{d}}^O} \sum_{\substack{d \in D_p: \\ e \in q_d}} x^p_{\tilde{d},d} \qquad \forall\, \tilde{d} \in D_G, e \in q_{\tilde{d}}$$

one cable/duct embedded in at most one duct

$$z_e \in \{0,1\}$$ ← trenching trail e (or not)