Topology Design and Capex Estimation for Passive Optical Networks

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Abstract—**Several optical access network technologies are available for network operators providing broadband services (FTTx: Fiber-to-the-X solutions). These technologies are now in deployment phase, therefore network and topology design issues play an increasingly important role.**

In this paper we address broadband optical access network design minimizing deployment costs, taking operation issues into account, using detailed cost and network models of the above listed FTTx technologies that suit best to actual networks due to detailed cost metrics used instead of just minimizing fiber lengths. We present a heuristic solution that works fast even for large problem instances, providing results with a difference less than approximately 10-20% from the computed ILP (Integer Linear Programming) optimum for smaller cases where ILP could be used.

Along with these algorithms we present case studies of real-life network and service requirement instances (number of customers ranging from 400 to 20.000).

Keywords – Passive Optical Network; Network deployment; Topology planning; Optical access network; Broadband access; PON; FTTx; CAPEX

I. INTRODUCTION

Access network technologies being deployed in the near future have to face high bandwidth requirements and growing needs for real-time traffic or reliability. Network operators can decrease administrative, maintenance and management expenses by offering triple-play service in a single network, giving the potential to replace the separate networks for voice, data and video traffic, and use a single converged network with common control plane and management resources.

Promising technologies fulfilling these requirements use optics even in the last mile access, as close to the customers as possible, e.g. passive optical networks (PON), active Ethernet or VDSL networks. These are referred to as Fiber-to-the-X (X stands for Home, Building, etc.) network architectures [1].

These are mature and standardized technologies, being deployed currently or in the near future [2]. However, details of topology and implementation often determine success and profitability of a given network technology. Therefore, theory has to be put into practice, and high performance topology optimization methods are needed to ensure low deployment costs as well as working on actual geography (map) data and service requirements [3].

In this paper we address Passive Optical Network (PON) topology planning, paying regard to deployment cost minimization, along with trivial operational aspects. The presented algorithm uses geography data or existing access network topologies as input. Results are obtained within seconds or a few minutes, depending on the network size even for 10.000s of customers. The presented heuristic algorithm provides topologies with an overall cost of approximately 10% over the optimal solution achieved by an Integer Linear Program (ILP) – at least for smaller problem instances where ILP works.

A. Related work

Several papers have been published addressing technical issues, e.g. traffic distribution or upstream fiber access mechanisms for Passive Optical Networks; however topology design and network deployment had lower interest. Several solutions still exist in the literature for the PON network planning problem with different performance and speed characteristics. A polynomial time 2-approximation algorithm was presented in [4] – it offers fast operation in the expense of rough approximation of the optimum. In [5] and [6] the authors investigated Simulated Annealing, Tabu Search and evolutionary algorithms for fiber-VDSL network planning.

The problem addressed in [7] is slightly similar to that presented in this paper, based on a different and slightly simpler cost function. It gives an ILP optimal solution and a heuristic approach for PON network planning, providing 10% higher cost than the optimum. Finally [8] compares a Genetic Algorithm-based semi-automatic optimization tool with networks designed manually, reporting approximately 8% gap between them.

Comparison of these methods is somewhat difficult, due to the different cost functions and reference methods used. For that very reason, the cost function used in this paper is designed to reflect total practical deployment costs, including the equipments and the cable plant as well. As a reference, an ILP-based lower bound was used, being really close to the optimum.

The work described in this paper was carried out with the support of the BONE-project ("Building the Future Optical Network in Europe"), a Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme

Digital Object Identifier: 10.4108/ICST.BROADNETS2009.7245
http://dx.doi.org/10.4108/ICST.BROADNETS2009.7245

II. PROBLEM FORMULATION

In essence, the problem addressed in this paper is cost minimization topology planning for PON networks, considering technology specific constraints.

A brief description of the technology and the derived network and cost models are presented in this section. The related optimization problem and its investigation can be found in the next section.

A. Technology Options

Passive optical networks (PON) provide high bandwidth connectivity based on optical fiber connections. Customers are organized into groups connected via the same *splitter* unit forming a PON. Such a PON is served by one *optical line terminal* (OLT) placed at the *central office* (CO) of the network operator.

Customers of the same PON are connected to the OLT through a common distribution point, the *splitter*. It splits and merges the optical signal: a PON requires a single connection between the splitter and the OLT, and obviously separate connections between the splitter and each of the customers.

At the customer premises, an *optical network unit* (ONU) is placed to serve as the interface between the optical access network and the customer equipments for data, video and audio traffic.

Several PON standards are known, the first deployed passive optical networks were based on the APON (ATM PON) and BPON (Broadband PON) standards. Nowadays mostly EPON (Ethernet PON) and GPON (Gigabit PON) networks are adopted, and future standards include 10G EPON, long-reach PON, WDM PON technologies [9].

The PON standard that we have used during our recent work was Gigabit PON (GPON), providing 2.5 Gbps downstream and 1.25 Gbps upstream traffic, reach of 8-20 km, and a splitting ratio up to 64, however, the findings and results presented in this paper are not restricted to this configuration, but may be used for any PON standards. Among others, GPON is already used by Verizon, British Telecom or AT&T.

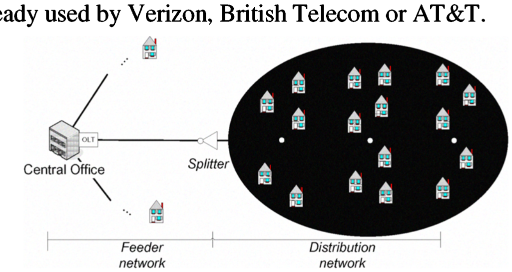

Figure 1 PON network architecture

B. Network model

For network design and topology planning problems, usually graphs are used as formal representations. We will follow this practice as follows:

Access networks are typically built in urban environment, where the road system and other geographic information, such as railway lines or rivers determine the set of potential network links. Similarly, a set of nodes is identified by location of the central office, allowed places for splitters, road crossings and customer premises. These links and nodes form a graph, representing the "map".

The desired access network topology is an overlaying graph that connects customer premises to the central office, satisfying a set of technology-specific restrictions. A set of splitter nodes exists in the network, each of them connecting at most 64 customers and the central office. The term "feeder network" will be used for the network part between the CO and the splitters, while the outside region between splitters and customers is referred to as the "distributive" network part.

C. Cost model

The cost function determines the optimization problem itself, and as described above, our goal was to address all the significant cost factors for PON network deployment, not restricting the optimization problem to path length minimization.

Therefore the cost model we use will reflect cost of the equipment, cable plant and fiber lengths simultaneously:

C [redacted].

Calculation of equipment costs is straightforward, the amount of different types of equipment used, and the unit price of them has to be known:

$C_{Equipments}$ [redacted].

It can be easily seen that price of the OLT and the splitter has to be handled together, as both mean a fixed cost for any single PON. The joint cost will be denoted by C_{SP}.

Cost of the cable plant is more complicated, since typically a bunch of connections will be deployed in parallel, and these will be joined within the same cable, typically containing 12, 24, etc. fibers. The per fiber cost of such a cable is not in direct proportion with its capacity, but it also has an additional cost as seen on Figure 2. Considering this characteristic in the cost model gives the major difference if compared to [7].

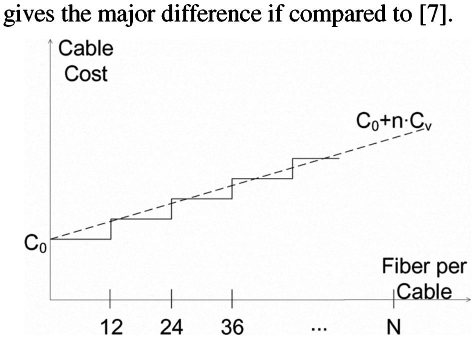

Figure 2 Cost function

Therefore the cost model for a used network link consists of two parts, C_0 that has to be paid once, regardless of the amount of connections over the specified link, and C_v as a per connection cost, C [redacted].

Moreover, we can differentiate between the "feeder" and "distributive" part of the network, as different type of cables can be used for these, as well as different techniques are used

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http://dx.doi.org/10.4108/ICST.BROADNETS2009.7245

for cable deployment, e.g. for the last, customer-related segment, aerial cables can be used. Therefore the detailed cable plant cost is described as follows:

$C_{Cableplant}$ [redacted]

C_{feed} [redacted]

C_{dist} [redacted]

III. Objectives

A. Optimization Goals

Our overall goal was to minimize CAPEX, the total cost of installing the network. As we have seen in the previous section, this overall cost may be broken into two main parts: equipment and cable plant costs.

Clearly, these are not independent. More splitters may result in less fiber needed, although raises equipment costs, while less but fully saturated splitters mean longer customer-splitter paths and higher cable costs. Obviously the optimal setup, this "equilibrium" point depends on the price of cables and splitters.

Therefore the optimization problem addresses all open questions regarding the PON network topology:

- How to form groups of customers belonging to the same PON?
- How many splitters (PONs) shall be used for the minimal cost coverage of customers?
- How to find the best path from a customer to its splitter unit?
- How to connect splitters to the central office?

Moreover, purely minimizing the cost function might lead to mathematically correct minimal solutions – sometimes with remarkable flaws in practice. Therefore some other needs of telecom operators were taken into account, e.g. an effort to use parallel, joint cables wherever it is possible, or not to cut circles just to save a little by leaving out a redundant short link from the resulting topology.

B. Solution space

The resulting topology has to fulfill a set of requirements regarding connectivity and technology specifications:

- all customer premises have to be covered and reached from the CO
- any splitter has a maximal degree equal to the actual split ratio (e.g. 64)
- every CO-splitter-customer path has to be shorter than the maximal reach of the (G)PON standard (e.g. 20 km)

Considering the solution space for the topology optimization problem, the C_0^{dist} values may be skipped from the cost function. The reason is that all network links has to be involved in the solution, since all customers have to be reached by the access network, meaning all the streets (graph edges) have to be followed. Therefore the C_0^{dist} values are a constant part of the cost, independent from the established connection and topology.

Moreover, in the feeder network segment, typically one separate, 64 fiber cable will be used for every PON, and it allows us to use a single linear C_v value for these connections including all costs.

This implies that for the cable plant, the following cost function will be used:

$C_{Cableplant}$ [redacted].

In addition, having a given map instance and a given number of customers, the amount of ONUs is determined: exactly one unit is needed for every customer. Cost of the ONUs serve as a constant part, therefore these will be eliminated from the optimization process.

C. Complexity

The topology optimization problem itself is NP-hard [10]. Even if just the amount and position of splitters, and the customer-splitter connections have to be determined, regardless of other costs, the resulting problem proved to be NP-complete: the *multiple knapsack problem* [11] can be easily reduced to it.

This fact implies that if a practically useful method is sought, a well constructed heuristic approximation is needed – as it will be presented in the next section.

D. Relaxations

Two interesting relaxations of the complete network planning process may be constructed by assuming part of the solution given in advance.

In the case when the splitters are already located, and the optimal customer-splitter assignment and connection establishment is sought jointly, polynomial complexity of the problem can be seen, through equivalence with the minimal weight perfect matching problem [12].

Similarly, if the customer groups are given in advance, and the splitter locations and connection establishment has to be optimized, the problem still has polynomial completeness. The latter problem needs *logN* executions of the Bellman-Ford algorithm.

Unfortunately, the connection between the customer segmentation, splitter placement and connection establishment makes the complete problem intractable.

IV. Heuristic solution

Due to the fact that the complete network planning problem is NP-hard, no efficient fast algorithm can be developed providing optimal solutions for all possible input data. However, typical real-life input parameters do not take all of the mathematically possible values, e.g. the given cost values are within some practical range of splitter prices or fiber costs. An effective heuristic method can be designed for such a restricted set of network parameters and service requirements. However, regarding the well known no free lunch theorem about optimization, these methods may be ineffective with a completely different range of input values [13].

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The proposed algorithm splits the problem into a set of subproblems, provides a fast algorithmic solution for them, which jointly lead to an approximation of the optimal solution. Clearly, due to the strong interconnection between these subproblems, solving them independently leads to a sub-optimal solution. However, the previous findings regarding the solution space imply, and the presented case studies demonstrate the power of this approach.

A. Subproblems

The network planning process can be split into subproblems in multiple ways. Even though, the degrees of freedom are given. The location and number of splitters, the customer-splitter assignment and the connection routes can be altered, determined during the network design phase – the map, the CO location, service requirements and the customer data is given in advance.

The subproblems identified and solved by the presented algorithm are listed in the following paragraphs, while a slightly different approach can be found in [7].

a) Forming groups of customers

Customers are organized into groups regarding the actual splitting ratio, as these customers share the same splitter unit. Benefit of using splitters instead of direct customer-CO connections consist in the lower fiber need on the feeder network segment. Therefore a good clustering maximizes this gain by covering as high percentage of the connection paths jointly as possible.

The customer segmentation is a clustering problem of geographical locations with some complementary conditions. The distances are measured on a graph, not by means of Euclidean distance and the group size is bounded from above.

Customers "close" to each other are desired to form a single group. Distance in this sense is measured as difference of their shortest paths to CO: the longer common segment means the closer nodes.

The method works as follows: the customer nodes, the central office, and shortest paths from every customer node to the CO form a tree in the initial graph G. Let us denote the set of links and nodes of this tree by *T*. L_T denotes the set of leaf nodes (customers) in the tree, *V* denotes the set of all nodes, *P(v)* denotes the parent node of *v*, i.e. the next node on the path towards the root node, *CO* denotes the central office, considered as the root node. The nodes already contained in a group are denoted by V^+, as well as the uncovered nodes by V^-. *Sub(v)* denotes customers on the sub-tree of node *v* that are not yet covered, i.e. $Sub(v) \cap V^+=\emptyset$.

At initial state none of the customer nodes are assigned to groups, during later steps the set of covered nodes will be increased, and the algorithm finishes once all the nodes are assigned to a group.

Step 0: (INIT) $V^-=L_T, V^+=\emptyset$.

Step 1: (LEAF) Find an uncovered leaf node, $v\in V^-$.

Step 2: (MOVE) $v\rightarrow P(v)$ until $|Sub(v)|\geq N$ or $v\equiv CO$. Briefly said the algorithm will move upwards in the tree until it has found a node with a sub-tree containing more uncovered customers then the maximal allowed group size.

Step 3: (GROUP) A subset of the sub-tree nodes, *Sub(v)*, containing at most *N* nodes of the sub-tree forms a new group: $G_i\subseteq Sub(v)$. Nodes of the new group are considered as covered nodes: $V^+=V^+ \cup G_i$, $V^- = V^-\backslash G_i$. If $v\neq CO$, go to Step 1, otherwise STOP.

Step 4: (STOP) If $v\equiv CO$, the last group is formed and all customer nodes are covered: $V^+=L_G$.

b) Splitter placement

Once a group of customers has been formed, finding the optimal place for the corresponding splitter is straightforward: it has to be virtually in the center of the group, minimizing the overall fiber length within the group.

Splitters cannot be placed wherever desired – but a limited set of allowed splitter locations (cabinets, manholes, poles, splicing boxes, etc) is given, where the network operator can put these units. Due to the bounded segment size, only a limited amount of allowed splitter places can be found within reach of such a group – therefore choosing the best of these places means a simple comparison of them.

For a group $G=\{v_1,v_2,...,v_n\}$ and a set of allowed splitter locations $L=\{l_1,l_2,...,l_k\}$, the selected place will be the one with the minimal sum of customer-splitter distances:

l_j [redacted].

c) Connection establishment

According to Section III.B, all links of the distributive network segment are to be used, a smaller subset of links does not promise reduced costs, thus all customer nodes should be connected to their splitters on their shortest paths.

Conversely, parallel connections play an important role in the feeder network segment, within the splitters and the central office. Parallel fibers connecting neighbouring splitters to the central office may be bundled in a single cable, altering the per-fiber cost of a single connection. For these feeder network connections different cable technologies may be used, e.g. substructures instead of air wires, and it also affects costs. These altogether explain necessity of the C_0+C_v cost model presented in Section II.C.

Fortunately this network part does not have to cover all customer nodes, just connect the splitters to the CO, and it gives the possibility of cost minimization through avoiding the C_0 costs on links not used. Since for typical cost values C_0 may be 2-3 magnitudes higher than the per-fiber C_v costs, a minimal cost spanning tree of the feeder network part closely approximates the optimal topology.

The related mathematical problem is the so-called Steiner-tree problem: a minimal weight tree, covering a given subset of nodes – in our case, the splitters and the central office. This problem is proven to be NP-complete, therefore a well known 2-approximation heuristic, the Distance Network Heuristic [14] was used in order to find the minimal weight tree, connecting the splitters and the CO.

Digital Object Identifier: 10.4108/ICST.BROADNETS2009.7245
http://dx.doi.org/10.4108/ICST.BROADNETS2009.7245

B. *Branch Contracting Algorithm (BCA)*

The complete algorithm consists of the above described elements, as shown in the flowchart (Figure 3). The name refers to the mechanism: it handles the customer nodes in the network as tree leaves. These leaves are segmented into groups by pruning those branches that are thick enough. Leaves of this branch are finally contracted around a central point, the splitter.

At the first step, customer groups are formed based on the shortest path tree on the graph *G*, then splitters are placed in the center of the groups, and finally the splitter to central office connections are established on the Steiner-tree.

The resulting topology may be slightly improved further with an iterative step similar to the K-means [16] algorithm for clustering: after forming the groups and placing the centers (splitters), the group memberships may be iteratively revised, and then the splitters re-located. This way the group-borders will converge towards more even circles (clusters) around the splitters. However, our tests have shown that the iterative improvement has just little effect on the overall costs at the expense of dramatic increase of the computation time.

Performance of the devised solution regarding connection establishment costs strongly depends on the input values, particularly on the ratio of the C_0 and C_v values. However, this specialization is inevitable in order to construct an efficient heuristic for a difficult problem – and the results support this approach for real-life case studies and actual parameter values.

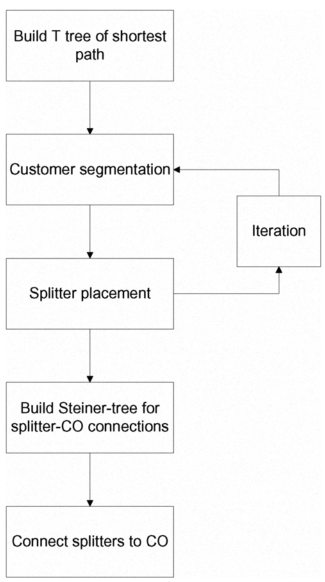

Figure 3 Flowchart of the BCA-algorithm

V. INTEGER PROGRAMMING SOLUTION

An Integer Linear Program (ILP) is a widely used tool for achieving optimal solutions for a basically linear problem. However, it can be easily seen that due to amount of its variables and constraints, it is not applicable for practical network sizes with thousands of customers.

Even though, a proper ILP formulation could serve as a reference. The performance of any given heuristic may be evaluated by comparing it to the achieved optimal solution by ILP. However, obtaining fully detailed results with all connection paths and customer-splitter assignments needs $O(|V|^2)$ variables and constraints, as presented in [7]. The required computing time unfortunately makes the ILP useless, even for considerably small problem instances.

In turn, an accurate lower bound on the optimal cost value is obtainable with significantly less variables. Recognizing this fact led to the flow problem interpretation of the problem: such a flow is needed that covers all customers, fulfills the flow conservation requirements, but allows the splitters to split an incoming flow to a set of outbound flows allowed by the actual split ratio.

This flow-based formulation uses $O(|V|)$ variables and constraints instead of $O(|V|^2)$, allowing to handle larger network sizes.

The ILP formulation is as follows:

$\min C$ [redacted] (1)

C^{feed} [redacted] (2)

C^{dist} [redacted] (3)

C^{SP} [redacted] (4)

Subject to:

$|V|$ [redacted] (5)

[redacted] (6)

N [redacted] (7)

[redacted] (8)

x_e, y_e, N, SP_v [redacted]

I_e [redacted] (9)

Variables x_e,y_e stand for the total traffic (flow) on link *e* for the feeder (CO-splitter) and distribution (splitter-customer) segments respectively. The binary I_e indicator variables denote links used for the feeder traffic – the C_0 costs apply for those links. SP_v denotes the number of splitters at node *v*, and *N* denotes the total number of splitters in the network. C_{SP} stands for the splitter cost, the splitting ratio is denoted by D_{max} and *S* identifies the set of subscriber nodes.

Equations (1)-(4) define the cost function, used as a minimization objective function in the ILP as described in Section II.C.

Equation (5) gives the binary I_e indicator values for all links, (6) holds the flow conservation constraints: splitter nodes may split the flow, while amount of total flows originated at the CO is equal to the amount of splitters, given by (7). Finally, (8) enforces the distribution flows to connect all customers to a

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given splitter, respecting the splitting ratios: splitter nodes originate SP_v flows, subscriber nodes absorb one unit flow. Intermediate nodes, without splitters and subscribers fulfill the flow conservation requirements.

This ILP formulation using merged flows instead of unique paths and connections includes the original problem, as its solution space fully contains the path problem described in [7]. Therefore the achieved minimum must be not higher than the optimal solution, and it ensures that the ILP presented here provides a strong lower bound.

VI. CASE STUDY

A. FTTx Designer Framework

As a result of our recent work, a complete FTTx topology designer was developed, that allows processing of map information and transforms it to an equivalent graph, does the topology optimization and interprets the results, analyses the resulting costs and the designed topology.

This framework allows the use of the existing (copper) network topology instead of digital maps as well. For an incumbent network operator it may substitute the expensive digital map if it is nonexistent.

This FTTx designer framework was used to provide the results presented in the next section, in cooperation with a leading network operator, based on network, service, cost and parameter data provided by the industrial partner Table 2.

B. Problem instances

Two different maps are presented here, the smaller one for a small town, the other one for a city area of Budapest. Both are served by a single central office (CO). Customer premises as well as subscriber data are given.

Figure 4 and Figure 5 shows the road system topology (graph *G*), Table 1 shows the network and service parameters, e.g. the covered area, amount of customer premises and subscribers.

Two different subscriber per building distributions were used, one realistic, with a mixture of houses and blocks (Town-N, City-N), and another one, with exactly one subscriber per location. The latter one was used to examine sparsely populated areas – as it has the same effect as increasing diameter of the map without changing the customer population.

Cost values for the case studies are presented in Table 2.

TABLE 1 NETWORK AND SERVICE PARAMETERS

Network	Town-1	Town-N	City-1	City-N
Diameter (km)	1	1	6	6
Area (km2)	0,54	0,54	14,9	14,9
Customer nodes	367	367	1100	1100
Nodes / km2	679,6	679,6	73,8	73,8
Subscribers	367,0	6950	1100	19832
Subs/km2	679,6	12870,4	73,8	1331,0
Subs/node	1,0	18,9	1,0	18,0

TABLE 2 COST VALUES

Cost values	Fiber / Cable Costs			Splitter + OLT cost (€)
	C_0^{feed}(€/m)	C_v^{feed}(€/m)	C_v^{dist} (€ / m)	
Value	5	0,03	0,03	600

C. Results

In the following section, performance of the presented heuristic network planning method will be evaluated, mostly by comparison with the achieved lower bound Integer Linear Program (ILP) solved by CPLEX.

The main advantage of the heuristic is its simplicity and short running time that allows handling of even large inputs, like the City-N input data set. Therefore the first graph presents a brief comparison of running times on these inputs, showing speed superiority of the heuristic approach. The steep time consumption growth of the BCA-algorithm shows its limits as well, however, the optimization process has taken 10 minutes for approximately 20.000 customers, and it takes around 1-2 hours for an extremely large service area of 250.000 customers; however that population is usually served by multiple central offices, resulting in a set of smaller problems. The BCA-

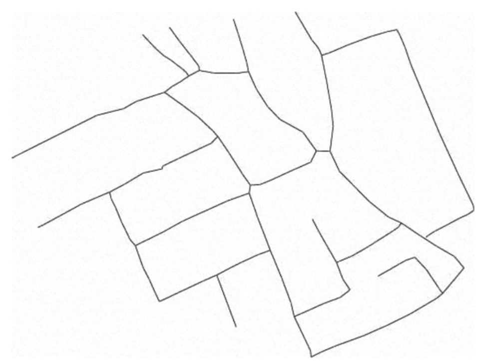

Figure 4 Town Graph

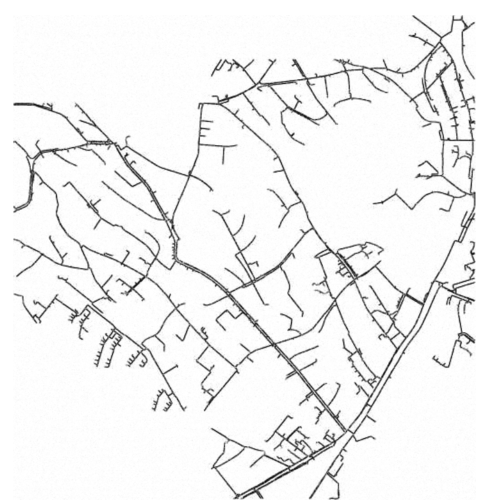

Figure 5 City Graph

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algorithm has proven to be fast enough for all practical problem sizes.

In addition, for the two more complex problem instances, the running time measured for the ILP is not the whole optimization process, since the ILP solver exited during execution due to insufficient memory, even with 4 GB of memory – and the running time was measured until this exit was triggered.

As the optimization goal was CAPEX minimization, network deployment cost serves as the main performance metric. Figure 8 shows a comparison of the total optimized cost achieved by the heuristic and the lower bound provided by the ILP-based network planning process. The difference is around 10% to 20% for the variable cost components. We note that not all expenses are involved here, just the splitter and cable plant costs (see Section III.B), since several cost factors are acting as constants: e.g. the price of ONUs used in total is determined by the amount of subscribers, and these fixed costs were not taken into account when evaluating the heuristic. If we deal with the absolute CapEx, involving the constant components, the difference falls below 5-10%.

However, all these performance evaluations mean a tough challenge: calculating the optimum (minimal cost) is impossible for realistic, large scale scenarios due to problem complexity. The ILP formulation we used does not lead to an optimal solution, but a lower bound by relaxing some constraints, in order to maintain reasonable computation times, and to achieve valid integral solutions even for large network instances. Therefore the difference between the heuristic and the theoretical optimum may be even smaller.

The following diagrams show details about the heuristic method. Figure 7 shows the execution time for each step of the algorithm: clearly, the "clustering" phase has the highest

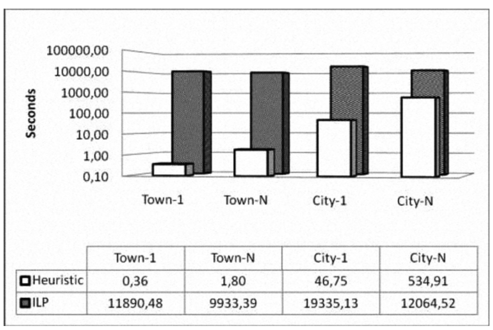

Figure 6 Running time comparison

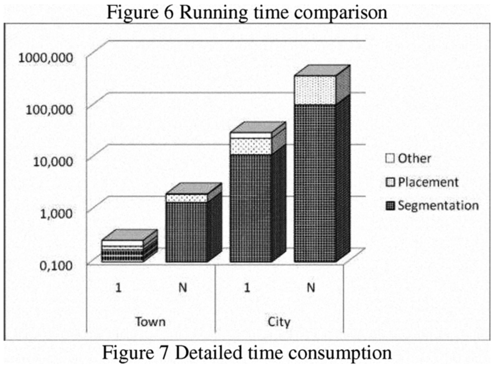

Figure 7 Detailed time consumption

complexity. The splitter placement and connection establishment problems are depicted together, due to implementation details and the strong mutual dependence of these problems.

Detailed cost breakdown of the heuristic method and the ILP shows the reason of the difference between cost results. This difference strongly depends on the cost parameters used. With the actual values, the ILP solution first of all minimizes the amount of splitters used, whilst the heuristic method minimizes the fiber length outside splitters – see Figure 9 and Figure 10. The presented algorithm leads to lower fiber costs minimizing the summarized fiber lengths, as Figure 11 shows – this way compensating the higher equipment costs.

If we try to compare the BCA-algorithm to different solutions existing in the literature for the PON network planning problem, methods with different performance and speed characteristics will be found, but none of them could outperform the presented method in terms of both. A heuristic algorithm was published in [7] that shows similarities both in performance (compared to the ILP optimum) and in speed. A fast, polynomial time 2-approximation was presented in [4],

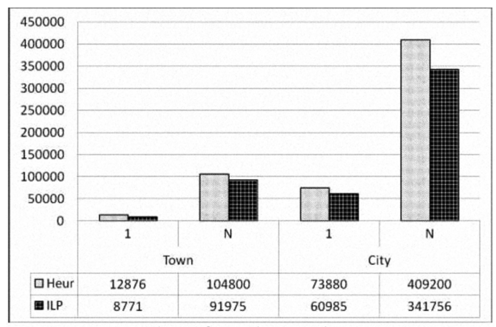

Figure 8 Total cost values

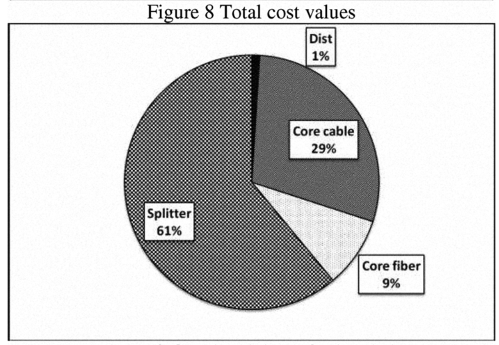

Figure 9 Cost breakdown for heuristic

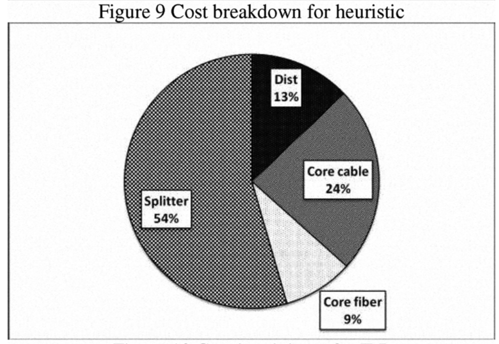

Figure 10 Cost breakdown for ILP

Digital Object Identifier: 10.4108/ICST.BROADNETS2009.7245
http://dx.doi.org/10.4108/ICST.BROADNETS2009.7245

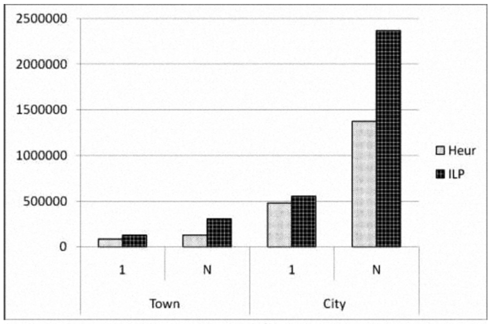

Figure 11 Total fiber lengths

however, the latter one was used only for grid networks, and with lower performance, and as the results show, the time consumption of the presented algorithm remains tolerable even for real-life problem instances.

D. *Applications*

First of all, the devised algorithm can be used for designing optimal PON network topology for a given territory and a set of service requirements.

Further applications are cost estimation and technology comparison: the presented BCA-algorithm, with minor further modifications can be applied for Active Ethernet and VDSL network planning, providing rough estimation of deployment costs for those as well. Due to its high speed operation, the algorithm may be applied even for large, real-life problem instances.

This allows preliminary deployment cost estimation for different FTTx technologies and supports the choice of the most profitable broadband access network technology.

VII. Conclusion

A fast and effective heuristic algorithm was presented for the addressed PON topology design problem. The overall optimization goal was to reduce deployment costs. A network and cost model was designed that allows calculation of total network deployment costs, and the relevant optimization problem was solved and analyzed.

Besides an ILP-based lower bound a heuristic approximation was presented, the Branch Contracting Algorithm (BCA), providing roughly 10% approximation within a few minutes of computation even for a service area with 10.000s of customers as the case studies have shown.

A framework based on the introduced topology design method was developed that allows optimal PON topology planning and FTTx network deployment cost estimation for any given practical geographic and service data.

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