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A MIP-based approach to solve the prize-collecting local access network design problem ☆

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ABSTRACT

This paper presents a new combinatorial optimization problem that can be used to model the deployment of broadband telecommunications systems in which optical fiber cables are installed between a *central office* and a number of *end-customers*. In this capacitated network design problem the installation of optical fiber cables with sufficient capacity is required to carry the traffic from the central office to the end-customers at minimum cost. In the situation motivating this research the network does not necessarily need to connect all customers (or at least not with the best available technology). Instead, some nodes are *potential* customers. The aim is to select the customers to be connected to the central server and to choose the cable capacities to establish these connections. The telecom company takes the strategic decision of fixing a percentage of customers that should be served, and aims for minimizing the total cost of the network providing this minimum service. For that reason the underlying problem is called the *Prize-Collecting Local Access Network Design* problem (PC-LAN).

We propose a branch-and-cut approach for solving small instances. For large instances of practical importance, our approach turns into a mixed integer programming (MIP) based heuristic procedure which combines the cutting-plane algorithm with a multi-start heuristic algorithm. The multi-start heuristic algorithm starts with fractional values of the LP-solutions and creates feasible solutions that are later improved using a local improvement strategy.

Computational experiments are conducted on small instances from the literature. In addition, we introduce a new benchmark set of real-world instances with up to 86,000 nodes, 116,000 edges and 1500 potential customers. Using our MIP-based approach we are able to solve most of the small instances to proven optimality. For more difficult instances, we are not only able to provide high-quality feasible solutions, but also to provide certificate on their quality by calculating lower bounds to the optimal solution values.

1. Introduction

Providing future-proof broadband Internet connections is currently a major infrastructural issue worldwide. More and more information is shared across the Internet and demand for higher data rates increases with new services. The *Digital Agenda for Europe*[1] of the European Commission stresses the importance of information and communications technologies and states that "Half of European productivity growth over the past 15 years was already driven by information and communications technologies [...] and this trend is likely to accelerate." It issues the goal of achieving "internet speeds of 30 megabit per second or above for all European citizens, with half European households subscribing to connections of 100 megabit per second or higher" by the year 2020. The German government decided to place strong emphasis on the expansion of broadband communications in one of its latest economic stimulus packages.[2] The rather challenging aim, formulated in 2009, is to provide 75% of all households nationwide with 50 megabit per second connections by the end of 2014. Reaching this goal is only possible by rolling-out the fiber-optic access networks on a broad scale.

In telecommunication network planning, *customer nodes* are associated to physical locations representing buildings, business

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[1] *Digital Agenda* (May 2010), http://europa.eu/rapid/pressReleasesAction.do?reference=IP/10/581.

[2] *Breitbandstrategie der Bundesregierung* (February 2009), http://www.zukunft-breitband.de/BBA/Navigation/Service/publikationen,sdid=290026.html.

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locations or single households. The following strategies (known under a common name *FTTx*) are used for the development of access networks:

- *Fiber-To-The-Curb* (FTTC) (or *Fiber-To-The-Node*, FTTN): Part of the connection from central offices to customers consists of optical fibers, but end-transmission lines are still made of copper. Besides the fiber-optic connections that need to be established, also *multiplexing* devices have to be installed. These devices receive signals from multiple customers via copper connections and aggregate them on a high-speed fiber-optic line.
- *Fiber-To-The-Building* (FTTB): Optical fiber runs all the way to a building. Multiplexing devices (usually installed in the basement) aggregate signals from short-distance copper lines to the subscribers within the building onto a fiber-optic line.
- *Fiber-To-The-Home* (FTTH): Connection between subscribers and central offices runs completely over an optical fiber.

Which strategy is employed in a particular case depends on various prerequisites. For instance, it depends on how densely the planning areas are populated (e.g., urban vs. rural areas).

Many local telecommunication carriers are realizing FTTH or FTTB projects. Deutsche Telekom AG announced plans for the connection of thousands of households in ten German cities with FTTH. Simultaneously, FTTC solutions are realized by extending VDSL connections. The largest Austrian telecommunication provider, Telekom Austria Group, is going to invest one billion Euro in the modernization of the fixed net infrastructure.[3]

The planning of such access networks is a highly complex task. Manual planning does not allow for finding provably close-to-optimal solutions. In the last years various uncapacitated optimization problems have been proposed in the context of FTTx planning (see, e.g. Arulselvan, Bley, Gollowitzer, Ljubić, & Maurer (2011), Leitner & Raidl (2011), Gollowitzer & Ljubić (2011), Gollowitzer, Gouveia, & Ljubić (2011)). These optimization problems are mainly concerned with the design of the underlying network topology, ignoring many hardware parameters. On a more detailed level, the following aspects have to be considered in addition: There are cost/capacity relations for various active and passive components, such as transponders, splitters, fibers and cables. There are overhead cost for trenching. Also existing infrastructure has to be taken into account. There are two possibilities to deploy fiber-optic access networks: customers might be connected via *passive optical networks* (PON) or via *Point-to-point*. In the first case, signals for up to 64 customers are transmitted on a single fiber and are split on the optical level somewhere between the central office and the customer. In the second case a unique fiber starting at the central office is dedicated to each customer.

This paper deals with the detailed planning of point-to-point FTTH/FTTB telecommunication networks with a given *coverage rate* α, $(0 < \alpha \leqslant 1)$. This coverage rate is usually determined by a network carrier and represents the minimal fraction of potential customers that should be offered the service. Fig. 1 shows two deployment scenarios for a real world instance with coverage rates of 0.6 and 0.9, respectively. Square nodes denote customers. The circle node denotes the *central office r*. The served customers are depicted with dark squares. Lines denote the denote installed connections in the solution.

In the context of FTTH/FTTB the potential customers are particular physical locations. Three important features are associated to each potential customer. Firstly, the number of subscribers (e.g., apartments and/or offices) in the building. This

[3] *Press release* (July 3, 2009), http://www.telekomaustria.com/presse/news/2009/0703-telecommunication-infrastructure-en1.php.

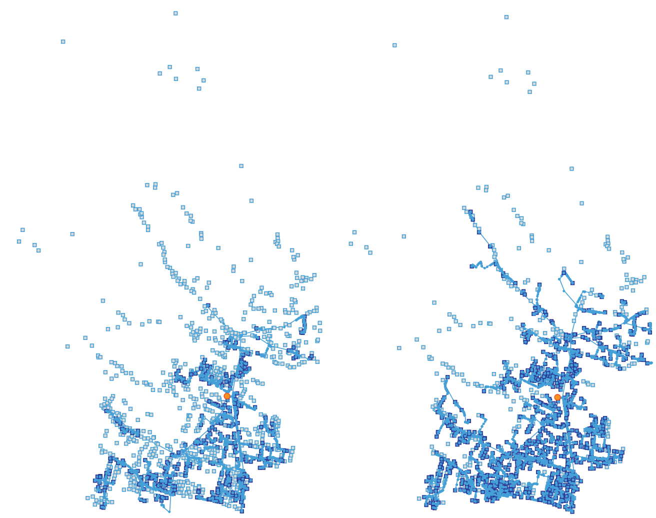

Fig. 1. Realistic planning scenario with coverage rates of 0.6 up to 0.9.

is denoted as the customers *prize*. Secondly, the number of optical fibers required to connect this potential customer is called its *demand*. Thirdly, there is a setup *cost* of installing a suitable device at the customer location. The available hardware (e.g., splitter devices in case of FTTB) determines the demand and cost for each customer.

For each customer selected for being served, there must be a fiber-optic line running to the central office. The company provides different types of cables. Each type of cable is characterized by two features. One is its capacity and represents the number of optical fibers. The other is its cost. For connecting two sites one may need several cables. Each combination of cables leads to a *module* with a given *capacity* and *cost*. The capacity of a module is simply the sum of the fibers included in the cables. The cost of a module is the sum of the cable costs plus the installation on the roads taking into account the length. The goal is to decide:

- which subset of customers to connect so that at least a fraction of α of the overall customers' prizes is covered, and
- which modules should be installed along the edges so that the total demand for selected customers can be routed through the network at minimum cost.

The fiber-optic lines that are necessary to connect a certain customer need not to run along the same single path through the network.

In this work we study exact and heuristic approaches to this problem of practical relevance. We first propose a branch-and-cut approach that is capable of solving small instances. However, due to the complexity of the problem and size of the instances in real applications, it is difficult to establish algorithmic approaches that ensure global cost-minimal solutions. In this work we also propose a new MIP-based approach that is based on an interplay between the cutting plane approach and a multi-start heuristic. The multi-start heuristic starts with fractional values of the LP-solutions and creates feasible solutions that are improved using a local improvement strategy. We introduce a new benchmark set of real-world instances with up to 86,000 nodes, 116,000 edges and 1500 potential customers. For these instances our computational experiments show that the MIP-based approach outperforms the alternative approach of only using the multi-start heuristic without MIP information.

A preliminary version of this paper was presented in the *International Network Optimization Conference 2011* (Ljubić, Putz, & Salazar-González, 2011).