FTTH Network Design Under Power Budget Constraints

Anis Ouali*, Kin Fai Poon† and Andrej Chu‡
Etisalat British Telecom Innovation Centre,
Khalifa University of Science, Technology And Research
Abu Dhabi, UAE
* Email: anis.ouali@kustar.ac.ae
† Email: kin.poon@kustar.ac.ae
‡ Email: andrej.chu@kustar.ac.ae

***Abstract*—Fiber To The Home networks represent an interesting solution to provide a high bandwidth access to customers. To minimize the investment costs, telcos need to efficiently design their networks based on the given criteria such as power budget constraints, network equipment capacities and associated costs. Usually, a network planner starts with a large area within the reach of a central office and divides it into sub-areas to be planned individually. This manual division process is time-consuming and non-optimized which very often leads to a high design cost. This paper proposes a tool based on a Mixed Integer Linear Programming (MILP) method that can optimally decide sub-areas while still satisfying given constraints. Each sub-area is served by one fiber cabinet containing the optical splitters. Depending on the distances from customers to the central office and the splitter types being used, the model is capable of identifying customers violating the power budget and assigning them to a splitter with a smaller splitting ratio and longer reach.**

I. INTRODUCTION

The proliferation of bandwidth-intensive network services such as high definition television (HDTV) over IP and video on demand (VOD) causes a huge data traffic and a high stress on access networks. To stay competitive and to satisfy bandwidth demand, telecom operators are permanently improving their network infrastructure with new technologies. Fiber To The x (FTTx) access networks based on Gigabit Passive Optical Network (GPON) technology represent a major solution that can provide triple play services at a reasonable cost.

A PON is made up of an OLT at a central office connected to Optical Network Units/ Optical Network Terminals (ONU/ONT) in customer premises through an Optical Distribution Network (ODN) comprised of fiber cables and passive optical splitters.

Designing an efficient GPON/FTTH requires the consideration of several factors including optical splitter dimensioning and positioning. In addition, it involves satisfying several planning rules such as the maximum allowable signal power loss between an OLT and an ONU/ONT.

The power budget, in decibels (dB), is defined as the difference between the maximum transmitting power of the OLT and the minimum receiver sensitivity at the ONU located in a customer premise. Signal loss is caused by fiber connections and attenuation, splices, optical signal splitting, etc.

For a greenfield FTTH network design, a planner is typically given a new area to be served by one OLT connecting a few thousands customers. Very often, the entire area is divided into sub-areas each of which will be served by a Fiber Cabinet (FC). Customers within each sub-area are connected to optical splitters grouped into the corresponding FC. Deciding the boundaries of each FC catchment area is a difficult and time-consuming task. Indeed, each sub-area would contain hundreds of customers and the planner should ensure that each customer is satisfying the power budget constraints to maintain the quality of service. In addition, the division of the areas may not be cost-effective which will ultimately increase the deployment cost of the network.

In this paper, we propose a software tool to help the planner to decide the locations of FCs as well as their catchment areas within a big network. Thus, given the locations of customer premises and the possible locations of optical splitter cabinets, a Mixed Integer Linear Programming (MILP) model has been formulated to decide the division with the minimum deployment cost while identifying the premises that do not satisfy the power budget constraints. In addition, the tool is able to re-assign those invalid customers to a smaller splitting ratio splitter in order to increase the connecting distance.

This paper is organized as follows: Section II provides a brief description of related work. Section III describes the proposed MILP model. A case study with corresponding results is given in Section IV whilst the conclusion is provided in Section V.

II. RELATED WORK

A lot of research has been carried out in the areas of GPON network analysis and optimization. In [1], the author provided an analysis of a FTTH system in order to come up with a cost effective network supporting triple play. The proposed solution minimizes optical path loss of ODN to provide maximum reach of 20Km and 1:32 splitting ratio to the premises through a properly engineered and designed system.

For the network optimization, some of the research focus on Dynamic bandwidth allocation (DBA) algorithms [2], [3] between an OLT and ONUs while others concentrate on the physical layer design for GPON deployment. The latter can be evident by the work found in [4]. A tabu search algorithm was

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proposed to minimize the costs of the devices deployed in four types of network architectures: digital subscriber line (xDSL) from the central office, Fiber To The Premise (FTTP), Fiber To The Node (FTTN) and Fiber To The Micro Node (FTTn). The author concluded that good feasible solutions were obtained in reasonable amount of time based on this approach.

Other meta-heuristic based approaches such as ant colony optimization (ACO), genetic algorithms and simulated annealing can be found in [5], [6], [7]. In [5], the authors proposed a network assignment algorithm based on ACO with the focus on cost minimization. The algorithm simultaneously assigned customer premises to cable distribution points as well as distribution points to splitters. For this multi-level assignment problem and the size of the testing networks, the algorithm showed good results.

Both papers found in [7], [8] proposed a hybrid approach based on the combination of heuristic and meta heuristic methods. The first one employed a heuristic method to form clusters of PONs and then applied the GA to identify the locations of network elements. The second one produced a FTTH design in three steps. The first step was to avoid paths which could not be used to lay fibers, and then grouped the customer premises based on the K-means clustering algorithm. Finally, a GA was applied to identify the fiber optimal paths.

For the non-metaheuristic approaches, authors in [9] applied the MILP technique to simultaneously identify the location of splitters and provide routing information among premises and optical splitters leading to global optimal results. This kind of approach is particularly useful to handle small and medium size networks as it can produce an optimal result in a very short period of time.

III. PROBLEM STATEMENT WITH NETWORK MODEL

In this section, we propose a MILP model for the physical layer optimization of a greenfield area. The objective is to minimize the cost of deploying a GPON-FTTH network. The model optimally divides a large network area into several areas. Each area is served by a fiber cabinet. Customers in each FC catchment area will be connected to a splitter within that FC provided that they satisfy the power budget constraints.

Two scenarios have been considered. First, only one type of splitters is used. If a customer exceeds the power budget, it will still be connected to one of the fiber cabinets provided that all the remaining constraints are satisfied.

The second scenario considers two types of splitters: *1:32* (SP32) and *1:16* (SP16). SP16 allows to reduce the signal loss by around $3dB$ which provides enough power for all invalid customers of the first scenario. However, when using SP16 instead of SP32, the total cost of the corresponding PON will be shared by 16 customers instead of 32. An additional cost is needed to connect the rest of the 16 customers. It is a common practice that the total cost of connecting a customer should be kept in around hundreds of US dollars.

Prior to executing the MILP-based design tool, we assume that the following information is available:

- Location of an entry point of the network E.
- Locations of customer premises.
- Possible locations of fiber cabinets.
- A civils layer network specifying the connectivity among different network elements.

Currently, the trenching cost is not considered. We are assuming that the civils network is given. Therefore cable path sharing is already considered. It is realistic as such layer may be created manually by the planner or may already exist because it was used for a legacy network.

The details of the MILP model in terms of variables and parameters, objective and planning constraints are given below.

Variables and Parameters: Let $\mathcal{C}$ be the set of possible fiber cabinets FC and $\mathcal{P}$ be the set of customer premises. A boolean variable matrix $PlotToFC$ is defined in $\mathcal{P} \times \mathcal{C}$ to model the links from premises to FCs:

$$PlotToFC[p][c] = 1 \Leftrightarrow \ p \ is \ assigned \ to \ c \qquad (1)$$

In addition, a boolean variable array $UsedFC$ is introduced to denote whether the corresponding FC is being used. $MaxConnectionsPerFC$ specifies the maximum number of tenancies that can be connected to a single FC. The $Dist$ matrix stores the shortest distance between any two given nodes as computed by the Dijkstra's algorithm.

With respect to the power budget, let M be the maximum allowed signal loss between the OLT and the customer ONU/ONT. A variable array $PowerLoss$ that holds the signal loss of each customer is also defined below.

$$\begin{aligned} PowerLoss[p] &= commonLoss + SplitterLoss[p] \\ &+ AttenuationPerMeter \times Dist(p, E), \forall p \in \mathcal{P} \qquad (2) \end{aligned}$$

where $commonLoss$ is the signal loss incurred between the OLT and the entry point E. A variable array $SplitterLoss$ denotes the signal loss experienced by each customer due to the type of splitter being used.

$$\begin{aligned} SplitterLoss[p] &= SP16[p] \times SP16Loss \\ &+ SP32[p] \times SP32Loss \qquad (3) \end{aligned}$$

where $SP16[p]$ and $SP32[p]$ are mutually exclusive boolean variables determining the type of splitter p is connected to.

Variable arrays $SP16in$ and $SP32in$, both defined in $\mathcal{C}$, denote the number of 1:16 splitters and 1:32 splitters for each fiber cabinet respectively. The values of the elements of those arrays are obtained through a set of constraints using the arrays $SP16$, $SP32$ and $PlotToFC$.

Another array of boolean variables, $Invalid$, is defined in order to test whether a customer exceeds the power budget.

$$invalid[p] = 0 \Leftrightarrow PowerLoss[p] \leq M, p \in \mathcal{P} \qquad (4)$$

Optimization Criteria: The objective is to minimize the number of invalid customers and the global cost:

$$\min(invalidCustomers + \alpha \times GlobalCost) \qquad (5)$$

$invalidCustomers$ is the total number of premises exceeding the power budget:

$$invalidCustomers = \sum_{p \in \mathcal{P}} invalid[p] \tag{6}$$

α is a weighting factor such that the cost minimization does not interfere with the minimization of the number of invalid customers:

$$0 < \alpha \times GlobalCost < 1 \tag{7}$$

Thus, the model gives priority to minimizing the number of invalid nodes over cost minimization. For that number, it will produce the related minimum cost solution. The correct value range for α can be obtained by having an indicative planning cost of a given network.

The cost is computed as follows:

$$GlobalCost = SpCost + CabinetCost + CableCost \tag{8}$$

$CabinetCost$ is based on the total number of cabinets being used. $SpCost$ is based on the type and the number of splitters being used. In addition, there is a penalty associated with the use of a smaller splitter as it serves less customers.

$$SpCost = \sum_{c \in \mathcal{C}} (SP16Cost + penalty) \times SP16in[c] + \sum_{c \in \mathcal{C}} SP32Cost \times SP32in[c] \tag{9}$$

$CableCost$ includes the cost of all the cables from the premises to FCs and from FCs to the entry point E:

$$CableCost = FeederCableCost \times \sum_{c \in \mathcal{C}} Dist(c, E) + DropCableCost \times \sum_{p \in \mathcal{P}} \sum_{c \in \mathcal{C}} PlotToFC[p][c] \times Dist(p, c) \tag{10}$$

Planning Constraints: Different constraints used in the model will be described in this section. Most of them are derived from the planning rules commonly used in practice. For example, an FC cannot connect more than $MaxCustPerFC$ premises.

$$\sum_{p \in \mathcal{P}} PlotToFC[p][c] \leq MaxCustPerFC, \forall c \in \mathcal{C} \tag{11}$$

Each customer should be connected to exactly one FC:

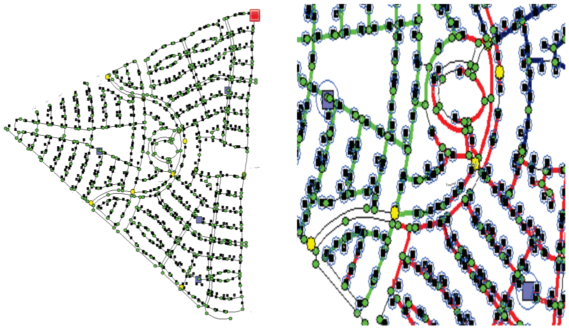
$$\sum_{c \in \mathcal{C}} PlotToFC[p][c] = 1, \forall p \in \mathcal{P} \tag{12}$$

Each cabinet cannot have more than $MaxSPsPerFC$ splitters independently of their types:

$$SP16in[c] + SP32in[c] \leq MaxSPsPerFC, c \in \mathcal{C} \tag{13}$$

The following determines whether the customer p is within the power budget:

$$\frac{1}{M} \times PowerLoss[p] - 1 \leq invalid[p] \leq \frac{1}{M} \times PowerLoss[p], \forall p \in \mathcal{P} \tag{14}$$



(a) Input Network

(b) An Optimal Assignment Solution (partial view)

Fig. 1. An Input Network and its Assignment Solution

TABLE I. RESULTS FOR PLANNING WITH 1 SPLITTER

Power Budget	**27.25**	**27.3**	**27.35**	**27.39**
Cost	2332044	2408662	2309984	2305642
Invalid Cust.	246	102	26	0
SP32	27	27	27	27

TABLE II. RESULTS FOR PLANNING WITH TWO SPLITTER TYPES

Power Budget	**27.25**	**27.3**	**27.35**	**27.39**
Cost	2566311	2430742	2340025	2305642
Cust. to SP16	271	128	48	0
SP16	17	8	3	0
SP32	19	22	25	27

TABLE III. EXAMPLES OF PLANNING PARAMETERS

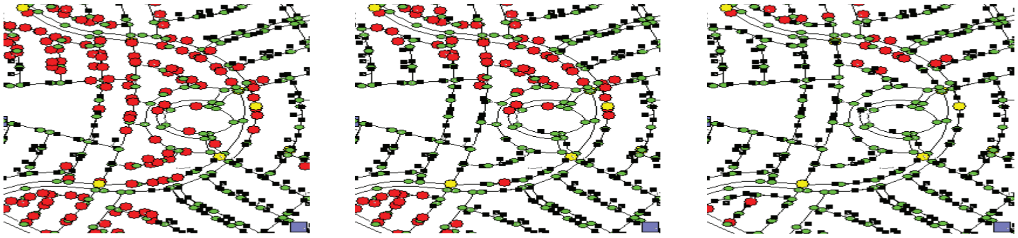
$MaxConnectionsPerFC$	240
$MaxSPsPerFC$	20
$FiberAttenuation/Kilometer$	$0.35dB$
$SP32Attenuation$	$18dB$
$SP16Attenuation$	$15dB$

IV. RESULTS

The objective of this section is to show how the proposed model can help a planner in designing a FTTH network with power budget considerations. We tested our algorithm on a realistic network with 800 customer plots. Figure 1a depicts an input civils network (black lines) containing the possible locations of fiber cabinets (4 blue squares), the location of customer premises (800 black squares) and the entry point of the network (red square).

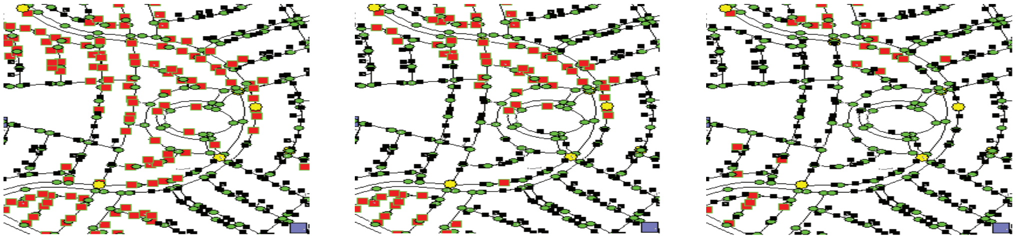
The proposed MILP model is solved by the IBM ILOG CPLEX MILP Solver 12.2 [10] which takes a few seconds only. Figure 1b shows an example of a solution with each fiber cabinet catchment area highlighted in a different color. It is an important feature of the tool because it assists the planner in identifying boundaries for each FC, which is not an easy task when he has several FCs within the same big area. In addition, the model allows the planner to define more FC locations and also to specify the number of FCs which must be used. It will then generate a solution with the minimum cost.

Figure 2 depicts the optimal results obtained with the first scenario based on given different power budget limits (Class B+ optics of the ITU-T G.984.2 standard have a budget of $28db$). Customers exceeding the power budget are highlighted with red color. Table I presents the number of invalid customers and the planning costs along with the number of splitters being used. The cabling cost makes up around 90% of the total cost.



(a) *M=27.25dB*, invalid 246 (b) *M=27.3dB*, invalid 102 (c) *M=27.35dB*, invalid 26

Fig. 2. *1SP* Planning (partial view)



(a) *M=27.25dB, 271 to SP16* (b) *M=27.3dB*, 128 to SP16 (c) *M=27.35dB*, 48 to SP16

Fig. 3. *2SP* Planning (partial view)

It can be observed that the cost of planning with power budget $27.3dB$ is higher than with $27.25dB$. The reason lies in the fact that the nearest FC does not always offer a shorter or a valid path to the entry point. If an FC other than the nearest one provides a connection to the customer within the power budget, the cost will be higher due to the longer path.

Figure 2 also shows that some customers that are relatively close to the entry point of the network, exceed the power budget. It is due to the fact that those customers must be routed through an FC. Hence, the path to the entry point is longer than the available shortest path. As a longer path leads to a higher signal attenuation, the power budget becomes insufficient. Those customers are the ones usually located close to the boundaries of the FC catchment areas.

To overcome this issue, two types of splitters are introduced. The invalid customers can be connected to a longer reach splitter which has less power splitting loss. The corresponding optimal results are presented in Figure 3. Premises connected to SP16 splitters are highlighted with the orange color. In this case, no more invalid customers can be found.

As depicted in Table II, the costs are higher than in the first scenario because of the use of more splitters and of the penalty (see Section III). Using two splitter ratios should be avoided because it is more expensive. However, it is a necessity when some customers exceed the power budget.

V. CONCLUSION

Based on the mixed integer linear programming approach, this paper presents a tool that partially automates the design of FTTH access networks. The tool can assist the planner in identifying and minimizing the number of extreme cases, in which the power budget constraints are not satisfied. Such cases are due to the fact that fiber cables from customer premises to central offices are routed through fiber cabinets and thus the paths are likely to be longer than the shortest ones. Using the proposed tool will reduce the time needed to identify the fiber cabinets boundaries and also lead to optimal sub-division of a given area. Hence, the overall cost for the network planning would be lowered. In addition, the short computational time to solve typical networks provides a significant advantage of applying MILP to automate the FTTH network problem with the consideration of power budget.

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