Cost Optimization of Fiber Deployment for Small Cell Backhaul

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Abstract: We discuss an optimization framework for planning a cost-minimized GPON backhaul deployment for small-cell networks. Compared to typical Ethernet based point-to-point fiber backhauling approaches, this technique can save half of the deployment costs.

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1. Introduction

Ever since the introduction of mobile communications, telecommunication service providers have been investigating different solutions to cope with the increasing bandwidth demand in their cellular networks. Until recently, technology upgrades combined with the deployment of additional (macro) cell sites have enabled providers to stay ahead of demand. However, given the rapid growth of data usage due to the recent popularity of mobile data devices, such solutions are considered less effective today. The deployment of large numbers of smaller cells (microcellular network) to supplement the existing macro infrastructure has recently emerged as a means to mitigate this supply-demand battle [1]. Despite its potential to satisfy future traffic growth, the costs associated with the deployment of a small cell network, while considerably less than those associated with macro cells, are significant due to the large expenditures associated with backhaul, real estate, etc.

Some large carriers, such as AT&T, have deployed fiber-to-the-node (FTTN) access networks [2] over a significant portion of their footprint to provide residential broadband access. Spare fibers associated with these existing infrastructures can be leveraged to provide cost-effective backhaul for small cell network underlays to macro cellular networks [3]. However, even when using previously installed dark-fiber assets, care must be taken to utilize the fiber efficiently. Although AT&T's FTTN network uses a point-to-point (PTP) fiber topology, the dark fiber associated with this build is a limited and valuable resource. Thus, opting for a PTP small cell backhaul architecture, while consistent with many new macro network backhaul deployments, can consume considerable available fiber resources as it requires a pair of fibers for each connection. Furthermore, small cell underlay networks often consist of omni-directional cells which require a fraction of the bandwidth of macro cells, so a full GbE is overkill. This depletion of resources can be tempered by deploying passive optical networks (PONs) to share both fiber and central office gear.

Optimizing PON deployments in greenfield scenarios have been studied in [4,5]. However, cost-efficient deployments of PONs for small cell backhauling using existing infrastructure adds complexity because the existing resources must be taken into account. In this work, we develop an optimization framework based on integer linear programming (ILP) which can be used to plan cost-efficient PON deployments using existing fiber resources for the purpose of small cell backhauling. This is accomplished by determining the fiber routes, the best locations for splitters, and the most favorable number of PONs for a range of split ratios. We demonstrate how our model can be used to plan PON-based fiber backhaul for a small portion of AT&T's network. For this test case, the resulting cost-optimized PON can save up to 56% of the deployment cost associated with small cell backhauling, in comparison to typical Ethernet based PTP fiber backhauling approaches.

2. Optimization model

We formulate an optimization model that minimizes the total cost of the PON deployment for small cell backhauling. Let $\mathbf{C}$ denote the set of central office (CO) locations, where optical line terminals (OLTs) are placed and the access network is connected to the metro network. The set of small cell locations (existing fiber remote terminals) that need to be backhauled, and thus where the optical network terminals (ONTs) need to be installed, is denoted by $\mathbf{O}$. The set of fiber access points (FAPs), e.g. manholes or splice boxes, where splitters can be installed, is denoted by $\mathbf{M}$. Our objective is to plan PON deployments to backhaul all of the locations in $\mathbf{O}$ using existing fiber resources, by choosing a subset of $\mathbf{M}$ for splitter installations, and a subset of $\mathbf{C}$ for OLT installations, such that the total cost is minimized.

The cost contributors we consider for our ILP formulation can be broadly categorized into fiber, equipment, and labor. While the fiber is already deployed, there is still an associated cost because with the utilization of that fiber

Table 1: Parameters

Param	Description
$l^f_{c,m}$	Distance from c^{th} CO to m^{th} FAP
$l^d_{m,o}$	Distance from m^{th} FAP to o^{th} ONT
n_o	No. of ONT locations $= \lvert\mathbf{O}\rvert$
n_c	No. of CO locations $= \lvert\mathbf{C}\rvert$
n_m	No. of FAP locations $= \lvert\mathbf{M}\rvert$
n_p	Number of PONs per line card

Table 2: Variables

Variable	Definition
$f_{c,m}$:binary	1 if c^{th} CO is connected to a splitter at m^{th} FAP
$\bar{f}_{c,m}$:integer	No of connections between c^{th} CO and m^{th} FAP
$d_{m,o}$:binary	1 if a splitter at m^{th} FAP is connected to o^{th} ONU
s_m:binary	1 if at least one splitter is placed at m^{th} FAP
$\bar{s}_m$:integer	Number of splitters installed at FAP location m
$\bar{x}_c$:integer	Number of line cards in c^{th} CO location

the overall cable gets closer to exhaustion. We have thus used a standard time-value-of-money approach to determine the value of installed fiber; that price depends on the type and length used. In our model, the cost per unit length of distribution and feeder fibers are denoted by η_d and η_f respectively. The equipment costs arise from new installations of Ethernet switches, OLTs, splitters and ONTs. We denote the cost of installing an ONT in a small cell site by η_o. The cost of the OLTs depends on the number of chassis, common equipment and line cards, which in turn depends on the number of PONs connected to that CO. Typically, an OLT chassis supports several line cards with multiple PONs per card. In our formulation, η_{ch} and η_{olt} denote the cost of an OLT chassis together with common equipment and a line card, respectively. The cost involved in installing Ethernet switches at the CO is denoted by η_e. In addition, for every feeder fiber connected to the CO there are fixed costs associated with fiber jumpers and fiber distribution panels that are required to make the connection from the outside plant fiber (feeder) to the OLT shelf within the CO, and we denote this by η_k.

The cost of splitters depends on the number of enclosures plus splitters that will be installed at each of the FAPs. We denote the cost of the enclosure together with the first splitter by η_s and the cost of any additional splitters installed in this enclosure by η_a. Given the use of existing fiber infrastructure, the splitter installations account for the bulk of the labor costs. That is, there is a fixed cost associated with sending personnel to the location, η_l, plus the cost associated with the splicing procedure itself, η_i, which depends on the number of splices. In addition, the labor cost associated with the CO, η_{lc}, is also considered. The other self-explanatory parameters are listed in Table 1, while the decision variables are listed in Table 2. Our objective of minimizing the total cost of a PON deployment using existing fiber resources for backhauling small cell sites, can be represented by the following ILP:

$$\min \sum_{c\in\mathbf{C}}\sum_{m\in\mathbf{M}} l^f_{c,m}\bar{f}_{c,m}\eta_f + \sum_{m\in\mathbf{M}}\sum_{o\in\mathbf{O}} l^d_{m,o}d_{m,o}\eta_d + \sum_{c\in\mathbf{C}}\bar{x}_c\eta_{olt} + \sum_{m\in\mathbf{M}}\bar{s}_m(\eta_k+\eta_i) + \sum_{m\in\mathbf{M}}s_m(\eta_s+\eta_l) + \sum_{m\in\mathbf{M}}(\bar{s}_m - s_m)\eta_a$$
$$+ n_c(\eta_{ch}+\eta_{lc}+\eta_e) + n_o(\eta_o+\eta_i)$$

$$\text{s.t,}\ \sum_{c\in C}\bar{f}_{c,m} = \bar{s}_m,\ \forall m\in\mathbf{M} \tag{1}$$

$$\sum_{m\in M} d_{m,o} = 1,\ \forall o\in\mathbf{O} \tag{2}$$

$$\bar{f}_{c,m} \ge f_{c,m},\ \forall c\in\mathbf{C},\ m\in\mathbf{M} \tag{3}$$

$$\bar{f}_{c,m} \le f_{c,m}/n_o,\ \forall c\in\mathbf{C},\ \forall m\in\mathbf{M} \tag{4}$$

$$d_{m,o} \le s_m,\ \forall m\in\mathbf{M},\ \forall o\in\mathbf{O} \tag{5}$$

$$\sum_{o\in O} d_{m,o} \le r\bar{s}_m,\ \forall m\in\mathbf{M} \tag{6}$$

$$l^f_{c,m}f_{c,m} + l^d_{m,o}d_{m,o} \le l_{max},\ \forall c\in\mathbf{C},\ \forall m\in\mathbf{M},\ \forall o\in\mathbf{O} \tag{7}$$

$$\bar{s}_m \ge s_m,\ \forall m\in\mathbf{M} \tag{8}$$

$$\bar{s}_m \le s_m/n_o,\ \forall m\in\mathbf{M} \tag{9}$$

$$\bar{x}_c \ge (\sum_{m\in M}\bar{f}_{c,m})/n_p,\ \forall c\in\mathbf{C} \tag{10}$$

$$\bar{x}_c \ge (\sum_{m\in M}\bar{f}_{c,m}/n_p) + 1,\ \forall c\in\mathbf{C} \tag{11}$$

$$\bar{s}_m \ge 0,\ \forall m\in\mathbf{M} \tag{12}$$

$$\bar{f}_{c,m} \ge 0,\ \forall c\in\mathbf{C},\ \forall m\in\mathbf{M} \tag{13}$$

$$\bar{x}_c \ge 0,\ \forall c\in\mathbf{C} \tag{14}$$

Constraint (1) ensures that any installed splitter is always connected to exactly one CO location and the fiber connections from COs are established only with FAPs which have splitters. Constraint (2) ensures that an ONT is always connected to only one FAP, whereas constraint (5) ensures that the FAP to which the ONTs are connected contain splitters. The binary variable $f_{c,m}$ indicates the connection between COs and FAPs while $\bar{f}_{c,m}$ represents the number of connections between COs and FAPs. The relationships between these two variables are captured by (3) and (4). One of the important parameters that determines the nominal available capacity per small cell is the split ratio r. The maximum number of ONTs in a PON is bounded by the split ratio of the splitter, and constraint (6) ensures this. One important parameter that determines the span of the PON is the maximum transmission distance l_{max},which depends on the power budget of the PON and the split ratio. The total length of the feeder fibers and distribution fibers should be no more than l_{max}, and constraint (7) captures this. The binary variable s_m indicates the installation of splitters in a

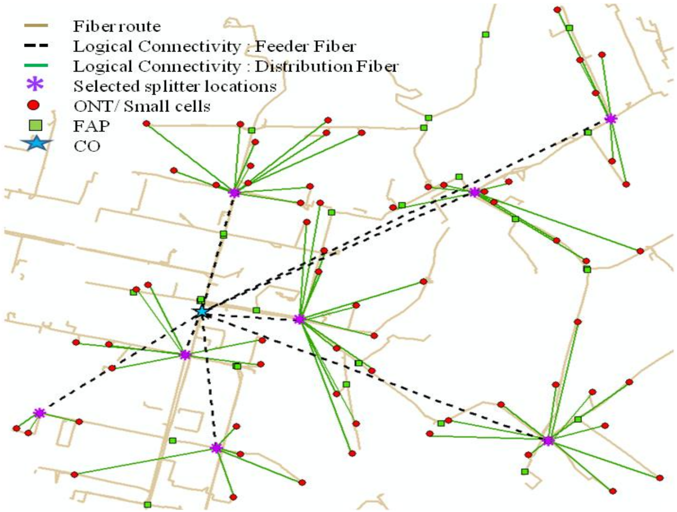

Fig. 1: ILP solution for the 1:16 split ratio scenario

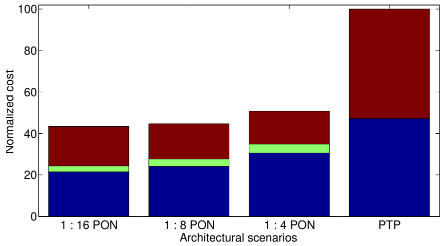

Fig. 2: Normalized costs of major cost components

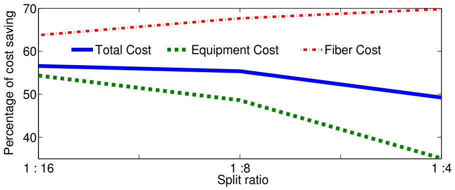

Fig. 3: Cost saving percentages compared to PTP deployment

FAP while $\bar{s}_m$ represents the number of splitters in FAPs. The relationships between these two variables are captured by constraints (8) and (9). For every n_p number of PON deployments, an additional line card is needed to be installed in the OLT chassis. This relationship between the variables $\bar{x}_c$ and $\bar{f}_{c,m}$ is represented by constraints (10) and (11). Finally, bounds on decisions variables are given by constraints (12), (13) and (14).

3. Results and Discussion

The dataset for our test case is shown in Fig. 1 and covers one CO serving area with known FTTN infrastructure. Beginning at the CO (blue star), one can follow the gold color fiber routes to a set of ONTs and FAPs which are potential splitter locations. The intended small cell locations are chosen to coincide with ONT locations. The cost-optimal PON-based backhaul solution is obtained for the range of split ratios, 1:16, 1:8 and 1:4, where we assume only one split ratio is used for each scenario. The solution given by our optimization framework when the maximum split ratio is 16, is overlaid in Fig. 1. The asterisks in Fig. 1 represent the splitter locations as determined by our framework and the black dotted lines represent the logical connectivity between the splitters and CO. The green lines represent the logical connections between the small cell sites and the splitters.

Fig. 2 shows the total cost of backhauling including the contribution of each component for both the optimized PON solution and the PTP solution. Here, the cost is normalized with respect to the cost of the PTP solution such that the total cost of the PTP deployment is 100. The main contributor to the deployment cost in the optimized PON-based solution is shown to be the equipment cost, whereas fiber cost is the main cost contributor in the PTP solution. Moreover, the equipment cost for the PON-based solutions increases when the split ratio decreases because of the increased number of splitter placements for a constant number of small cells. We limit the maximum split ratio to 1:16 due to bandwidth considerations. In Fig. 3, the cost savings that can be achieved by the PON-based solution compared to the PTP solution is plotted. Significant savings in both equipment and fiber costs can be achieved using the PON-based backhauling solution: a total saving of as much as 56 percent is demonstrated.

4. Conclusion

Leveraging existing infrastructures is one of the strategies that can be used to minimize the cost associated with small cell backhauling. To implement such a strategy, we develop an optimization framework to plan the cost-effective deployment of PONs assuming a pre-existing distribution of available dark fiber. This model considers the cost components such as fiber, equipment and labor, and minimizes the deployment cost by determining, the best fiber routes, the optimal locations for splitters and optimal number of PONs. By applying our optimization framework on a real dataset, we show that the cost of small cell backhauling can be reduced by half that of a typical PTP approach.

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