Guided Local Search for Optimal GPON/FTTP Network Design

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Abstract. Fibre optic access networks are of increased popularity among network operators. Many types of fibre network are being deployed globally to satisfy the ever increasing users bandwidth requirements. The rate of deployments of such networks is expected to increase in coming years, moreover this requires cost efficient, reliable and robust network designs. Despite the relative complex structure of these networks, designs are mostly done manually, thus design quality is not optimal. In this paper we will introduce and propose a tree based modelling scheme and will show how the metaheuristic search method Guided Local Search can be used to automate the design of FTTP/GPON networks. The design optimisation will mainly focus on reducing the deployment cost i.e finding the optimal location, type and quantity of fibre optic equipment in order to reduce the capital expenditure (CAPEX) of such deployment projects. Our proposed model builds a flexible optimisation framework, and results of the GLS algorithm compared to simple local search and Simulated Annealing show consistent optimal results.

Keywords: Guided Local Search, Fibre Networks, Network Optimisation, Network Planning

1 Introduction

With the growth of telecommunication networks and the introduction of new applications and services, the demand for higher bandwidths is increasing rapidly. With these increases of bandwidth demands fibre optic networks are becoming the preferred solution. Hybrid networks with mixed use of fibre optics and copper cables have been around for a while, however they have limited capacity. For this reason operators are moving towards FTTP(Fibre-To-The-Premises) technologies, based on the Gigabit Passive Optical Network(GPON), which enables them to provide services that are ready to meet customers demand with higher bandwidths. FTTP lines are projected to almost triple globally, from 68 million in 2011 to 198 million in 2016, driven by uptake in China, Russia, and the US and increasing deployments from Western European incumbent operators. Pyramid

Research expects FTTH broadband to generate nearly $ 116 billion in service revenue by 2016 worldwide, creating opportunities for all of the stakeholders in the value chain. [4] The United Kingdom is showcasing its broadband initiative, and FTTH deployment in most of England is growing rapidly as well.[5]

However, the deployment and further costs associated with FTTx [6] networks are comparatively greater than legacy copper access networks[1]. The competitive service-providing market motivates the network operators to design and deploy more economic networks with relativity low capital expenditure (CAPEX). Their target is to bring their FTTP costs down as close to the legacy copper telecommunication networks as possible.

One of the key aspects in reducing deployment cost is to have an efficient low cost design, meaning for a given deployment plan reducing various equipment and labour costs associated with design.

A cost efficient design depends on positioning optical components in the underlying road and duct network, so as to minimise the number of components and the length of fibre cable required. In addition to these there are several constraints that have to be satisfied in the design and the planning of the network, such as the maximum outputs any specific splitter can have. All these considerations require tools that provide efficient and robust network designs and deployment plans.

In a typical GPON deployment, an exchange area is often divided into different sections each served by an aggregation node. Each aggregation node can be seen as root to a tree of splitters, fibre distribution points(FDPs) and manifolds(see Figure 1). Once the location of this equipment is determined then the planner has to design the layout of cables from each manifold to FDPs and each FDP to a splitter respectively. These planning tasks are time consuming and the efficiency of the design and the associated costs are dependent on the planner's experience because of the simple fact that they are done manually.

In this paper we propose a tree-based model to represent the network design problem and will specifically introduce a customised Guided Local Search algorithm [2] to achieve an efficient design. The combination of the network representation model and the metaheuristic optimisation method will result in an automated tool that enables network operators to efficiently plan and design robust and efficient GPON/FTTP networks.

The automated tool will generate solutions that are considered optimal or near optimal with respect to cost and satisfying specific design constraints. The

[4] (http://www.prnewswire.com/news-releases/ftth-lines-expected-to-triple-by-2016-finds-pyramid-research-135128728.html

[5] http://www.lightwaveonline.com/business/news/Frost–Sullivan-FTTH-deployments-lend-momentum-to-European-fiber-optic-test-equipment-markets-124229344.html

[6] Fiber to the x (FTTx) is a generic term for any type of access broadband network which uses fibre optic as its main transmission medium, all starting by FTT, these variations are differentiated based on different configurations (e.g. FTTN, FTTP, FTTH, and so on, where in the above examples "N" denotes Node, "C" denotes Premises, "H" denotes Home.)

introduction of automated planning tool in context of GPON/FTTP networks results in these advantages:

- Rapid generation of network design layouts.
- Support for exploring different scenarios by changing constraints
- Minimising CAPEX
- Automatically producing bills of material
- Providing detailed implementation costs for techno-economic analysis

The rest of the paper is organised as follows: Section 3 will introduce a tree-based representation model to solve the optimisation problem followed by description of the metaheuristic algorithm for design automation in section 4. In Section 5 we describe our experimental design and results and Section 6 will provide future works and conclusion.

2 Related Work

There have been several studies on optimising various types of telecommunication networks some of which, are specifically related to fibre optic network designs.

In [3] the authors have proposed a model to optimise the design of a GPON/FTTH network, their model considers certain green field design aspects and a mixed integer linear programming solver is used to find a near optimal solution. Their solution promises a design with satisfactory degree of symmetry in addition to short computational time.

In [4] they propose an efficient heuristic called the Recursive Association and Relocation Algorithm (RARA) to solve the optimization problem. Their model also propose splitting large areas into smaller optimisation problems in order to reduce the computation time.

The other proposed model in [4] describes an algorithm that recursively assigns network elements to the design layout, their research provides a good theoretical lower bound on the deployment cost for PON networks. For more complex design cases that consider constraints such as road maps and other geographic constraints, sub-optimal solutions can be extended from their planning approaches.

3 Model Description

When installing a new network in the access area, the majority of money has to be spent on digging the cable ducts. Thus, minimizing the total cost is mainly a matter of finding the shortest street paths which interconnect all optical network units(ONUs)[7] with the optical line termination (OLT)[8] . A city map can be

[7] In our model we will call these points Exchange, Aggregation,FDP(Fibre Distribution Point) and Splitter Nodes

[8] Known as Manifolds in our model

represented by a graph where the streets are the links, and the street junctions together with the ONUs and the OLT make up the nodes. The weights of the links are set to be proportional to the length of the respective streets. In some cases, for example, if some fibre lines exist or if some streets are preferred to be used as duct lines, special weight values can be assigned to theses edges. With this map representation, the optimization problem turns into the classical minimum Steiner tree problem. This means that we want to find a tree within a given graph which spans a designated subset of nodes in such a way that the sum of the costs of the selected edges becomes minimal. There already exists a number of algorithms that solve this problem exactly . Since the minimum Steiner tree problem is NPcomplete , these algorithms have an exponential worst-case running time. Therefore, they are not applicable in the field of network planning where it is quite common to have a great number of nodes and edges [5].

Here we will discuss how we represent the tree based structure to solve the design problem. The representation has two parts. The first maps optical components to geographical locations. Each piece of equipment is represented by a variable whose domain ranges over possible locations. By restricting the domain we can constrain the equipment to a limited geographical area.

The second part of the model describes how the optical components are connected to each other. The optical tree is considered as a collection of clients and servers. For example each splitter serves many FDPs, and each FDP could be served by one of many splitters. Moving an FDP from one splitter to one another changes the connectivity of the tree. This one to many relationship is represented by including a variable for each client whose domain ranges over its possible severs. Each component may act as both client and sever for example a splitter has FDPs as its clients and an aggregation node as its server .

Figure 1 shows one possible logical configuration and Figure 2 shows how part of this network can be laid out on a physical road network. The cables will take the shortest path between connected points. All clients of the server passed en route to the most distant client will be attached to the same cable. The cost of the network is the cost of components plus the cost of the cables.

Design constraints are controlled by adding penalties to solutions that violate the constraints. Design constraints include for example the capacity of junction boxes, maximum length of cables, branch aggregation factor of splitters and so on. The total cost to be minimised by optimisation process is :

Total Cost=Componants Cost+Cabling Cost+Penalty Cost

4 Local Search

In order to find an optimal solution to this problem we will use Local Search. Local Search encompasses a class of algorithms which move from solution to solution in the search space of candidate solutions by applying local changes until no further improvements can be found or until a time limit has been exceeded. In our problem representation a move is an assignment of a different value to

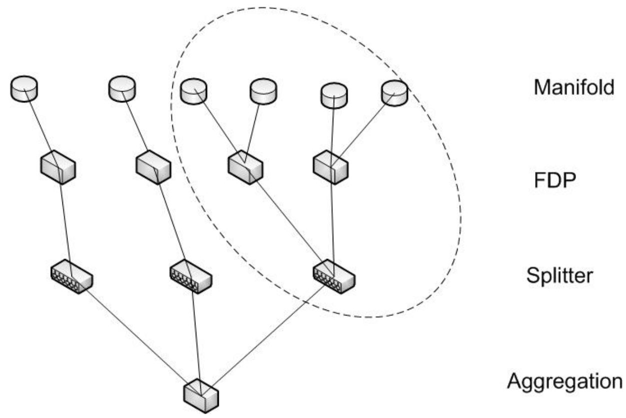

Fig. 1. Logical Configuration

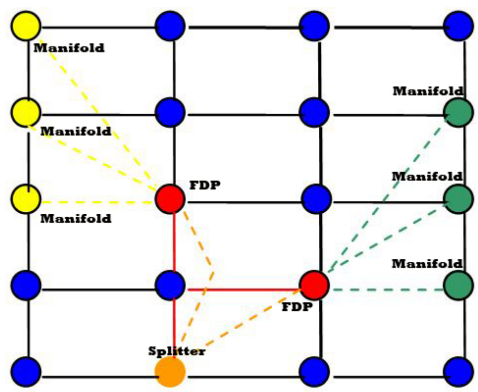

Fig. 2. Physical Layout

one or more variables. Table 1 represents the implemented moves in this local search.

Table 1. Local Search Moves

Move Types	Description
Assignment	Assign a new value to a single variable
Swap	Swap the value of two variables
Join Domains	Moves all the clients of a server to another server
Split Domain	Moves half of the clients of one server to a different server

In this section we will introduce two variants of local search; Hill Climbing and Simulated Annealing(SA), we then describe the metaheuristic, Guided Local Search(GLS).

4.1 Hill Climbing

Our proposed metaheuristic will sit on top of a tailored local search scheme designed for our proposed network optimisation model. The local search simply model solution initialization, new solution generation(neighbourhood function), and improved solution acceptance.

In Hill Climbing a move to a new solution is only accepted if it results in an improved cost. Therefore there is a monotonic improvement in cost. The disadvantage of this approach is that it is unable to scape from a local minimum.

4.2 Simulated Annealing

Simulated Annealing attempts to overcome this by allowing an "uphill" move with a probability that decreases over time. The allowance for "uphill" moves potentially saves the method from becoming stuck at local optima. In our simple configuration of SA there are 1000 iterations with the probability of move acceptance exponentially decaying with a rate of 0.9.

4.3 Guided Local Search

Local search methods suffer from two disadvantages. Firstly they easily get stuck in local minima. Secondly, in many cases we have intuition about how to guide the search but this can not be included directly in the cost function. For example, in the Travelling Salesman Problem, we know that long edges are undesirable though we can not exclude them from the beginning because they may be needed to connect remote clusters of cities in the problem. Guided Local Search(GLS) is a penalty-based approach that sits on top of local search methods which can help solve these problems. When the given local search algorithm is trapped in a local optimum, GLS dynamically changes the objective function, by penalizing some selected features that are present in this solution. This raises the cost of the solution, allowing the search to continue. The features are chosen in such a way as to guide the search towards promising areas by giving an incentive to remove unfavourable features. The novelty of GLS is mainly in the way that it selects problem dependent features to penalize, determined by two factors: the feature's cost (i.e. influence on the objective function) and the frequency with which it has been penalised in the search so far[2]. These features should simply satisfy the constraint of being non trivial, meaning that they would not appear in all solutions [6].

If S is a set of all possible solutions the presence of a feature f_i in solution $s \in S$ is represented by an indicator function

$$I_i(s) = \begin{cases} 1 & s\, has\, feature\, fi \\ \\ 0 & otherwise \end{cases}$$

Associated with each feature f_i is a cost c_i, and a penalty p_i which counts the number of times this feature has been penalised. When a local minimum is reached a feature is chosen to be penalised by a utility function which considers the cost of the feature and its current penalty. The utility function is defined by

$$util(s, f_i) = I_i(s).\frac{c_i}{1 + p_i} \tag{1}$$

Features which have already been penalised are less likely to be penalised again. This reflects the intuition that we should avoid selecting the same feature every time. Augmenting the cost function g via penalties on features gives us a new objective function h defined below:

$$h(s) = g(s) + \lambda.\sum_{i=1}^{M} p_i.I_i(s) \tag{2}$$

where M is the number of features defined over solutions and λ is a regularization parameter. Figure 3 shows the shape of the augmented function (equation 2)

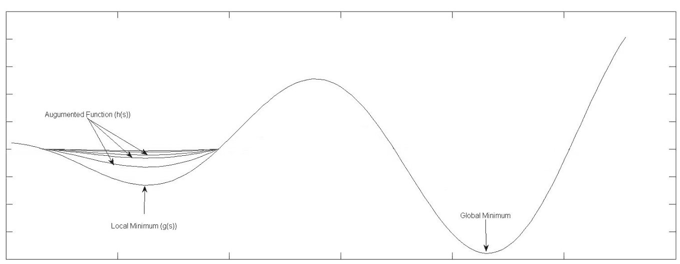

Fig. 3. Augmented Cost Function $h(s)$ v.s Cost Function $g(s)$

A number of different possible features were explored for this problem and the most effective was found to be pairs of consecutive items of equipment on a cable. The feature cost is the cost of cable linking the two items.

5 Experimental Design & Results

In this section we represent our sample experiment based on real geographical data and an actual telecommunication network and present our experimental outcome. The solver has to find a solution that connects all the manifolds to the exchange whilst satisfying all the problem constrains and minimising the cost via reducing the cabling and total equipment cost.

The selected region includes one aggregation node and one exchange, the final solution will layout cables from the single exchange point to 85 Manifolds. The constraints shown in table 2 describe the maximum number of connections that the equipment could have. The number of children in this table indicates the maximum number of clients that can be served by each item of optical equipment. Also there is a upper bound limit for the possible number of FDPs and Splitters, which are 43 and 11 respectively.

Table 2. Equipment Constraints

	Connections	Children
MANIFOLD	12	0
AGGREGATION	276	20
EXCHANGE	100000	100
SPLITTER	4	24
FDP	24	3

In order to evaluate the effectiveness of GLS two solvers were compared, the first using simulated annealing and the second using Guided Local Search with features based on cables as described earlier. Each experiment was run 50 times over the sample experimental data to find the optimal solution. In each case the search was allowed to continues until no improvement had been found for more than 6 minutes. Given equal execution time we are interested in the most optimal cost(minimised) that derives from the automated design of the network. Table 3 depicts the statistics for SA and GLS. The results simply imply more consistent performance from GLS algorithm in comparison to higher standard deviation of the SA. The average cost of the network is also smaller while using GLS. For the sake of statistical analyses we have performed a two sample t-test with the null hypothesis that data in the vectors of SA and GLS are independent random samples from normal distributions with equal means and equal but unknown variances, against the alternative that the means are not equal. The results shown in table 3 allow us to reject the null hypothesis.

For further proof of the effectiveness of our metaheuristic methods we have also tested a simple hill climbing algorithm [9], the results obtained simply shows very poor performance i.e. the solver in this case failed to satisfy many of the problems constrains failing to produce any acceptable solution. The nature of GLS algorithm enables it to scape settlements in local minima therefore results prove to be more consistent.

[9] This iterative method starts with an arbitrary solution and tries to find a better solution by using the described local search moves. If the change results in better solutions it will accept the solution until no further improvements occur

Table 3. Best Cost Statistics for 50 runs

	GLS	SA
Mean	13958.72	14263.19
Standard Deviation	297.7969	690.6522
Kurtosis	0.06251	6.583823
Skewness	1.015195	2.249336
Min	13621.93	13613.12
Max	14742.49	16977.58

Table 4 and figure 4 represent the output of the automated network design. The list of materials shows the reduction in the number of items used in comparison to the initially available optical equipment[10].

Table 4. List of Materials for a near optimal solution

Item(Equipment)	Quantity	Cost	Item(Cable)	Quantity	Cost
FDP	31	£3,038,00	MiniCable72	492.343	£413.57
SPLITTER	5	£2,000.00	MiniCable24	615.243	£301.47
AGG	1	£150.00	MiniCable48	563.964	£349.66
MANIFOLD	85	£850.00	MiniCable96	186.726	£190.46
EXCHANGE	1	£0.0	BFT12	1,839.469	£1,214.05
			BFT7	6,506.954	£3.058.27
			MiniCable12	3,491.23	£1,536.14
			Total		£13,101,61

6 Conclusion & Future Work

Designing fibre optic access networks is becoming of great interest to global telecom providers. In this paper we have presented an automated GPON/FTTP design framework based on a tree-based model utilising a guided local search algorithm to find a near optimal solution. The model structure is relatively flexible enabling production of various network designs with different constraints and requirements. The automated algorithm enables network designers and planners to quickly plan GPON networks with high flexibility and near optimal solutions. We use Guided Local Search(GLS) to eliminate the common problem of local search algorithms getting trapped in local optimum solutions. The GLS

[10] Here these results are given to give more clearer view of the application of the automated network design tool, hence at this point we are not analysing these outcomes

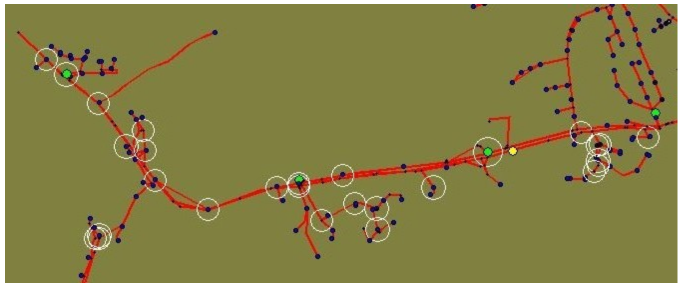

Fig. 4. Sample experiment solution

metaheuristic tends to produce robust results in many runs thus ensuring rapid solutions with high quality. The ability of GLS to escape local minima provides significantly higher quality results.

Further work could be more analyses of the generated results in relation to symmetry and other industry related design criteria in order to fine-tune the search algorithm. Moreover the current model could be incorporated within a techno-economic model in order to build a decision making tool for network operators and investors.

As this automated tool could be used by field engineers the automated algorithms could be improved to perform faster, this could be achieved by utilising techniques such as Fast Local Search algorithm.

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