

# Cost Minimization Planning for Passive Optical Networks

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**Abstract:** We plan PON network deployment to minimize its total cost. An efficient heuristic is proposed, which can reduce 50%~70% PON network deployment costs compared to a benchmark sectoring approach.

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## 1. Introduction

Passive optical networks (PON) can be deployed in forms of Ethernet PONs, Gigabit-capable PONs (G-PON), or WDM PONs [1]. Much research on PON has focused on dynamic bandwidth allocation (DBA) among Optical Network Units (ONU) and system upgradation for wider coverage and higher bandwidth of PON [1]. Nonetheless, little research has been performed on how to efficiently plan for PON networks, which, however, is essential for an economic PON deployment. Very recently, a study on PON deployment was carried out to minimize the total deployment cost subject to the constraint that all ONUs are connected to a Central Office (CO) and the constraint that a specific power budget is met [2]. However, the study only considered several special cases under a single PON, thereby not thorough and difficult to be generalized for PON network deployment with hundreds of ONUs.

In this paper, we develop a more scalable optimization approach for PON network deployment, which is able to minimize the total PON deployment cost for the designs with hundreds of ONUs. The research shows that the proposed approach can plan much more cost-effective PON networks than a benchmark sectoring approach. Moreover, it is found that there is a saturating trend of the impact of optical split ratio on the PON deployment cost. Whenever the optical split ratio reaches a certain threshold level, a further increase of the ratio will not help much to reduce PON deployment costs.

## 2. Problem definition

As shown in Fig. 1, the problem that we are interested in is to optimally deploy PON networks to connect all disperse ONUs to a Central Office (CO). The optimization objective is to minimize the total deployment cost, which is made up of several subcosts, including (i) the hardware cost of PON, such as Optical Line Terminals (OLT) and optical splitters, (ii) the labour cost for laying fibres, and (iii) the cost of fibres. Because costs (ii) and (iii) are proportional to fibre distance, we merge them as a single cost, *fibre cost* or *cost of laying fibre*. Among all these costs, the cost of laying fibre is generally the most expensive, which overwhelms all the other costs in the whole deployment. Thus, when planning or deploying PON networks, minimizing the total distance of (laying) fibre is a key objective for the optimization.

Several PON system constraints should be considered in the optimization, including (i) a limited optical split ratio of a PON, (ii) a maximal coverage of a PON, and (iii) a maximal differential distance of a PON. The limited split ratio sets a constraint on the maximal number of ONUs that can be connected to a common optical splitter or PON. For example, a PON with a split ratio of 1:16 can maximally connect up to 16 ONUs. The maximal coverage of a PON is defined as the maximal transmission distance between an OLT and an ONU in the PON. The current standards for this distance are 20 km under EPON and 60 km under G-PON, respectively [1]. Finally, the maximal differential distance is defined as the maximal allowed distance difference between the distances from the different ONUs to an OLT within the same PON. For both EPON and G-PON, this value is up to 20 km [1].

The solution to the optimization problem includes a total number of required optical splitters, the geometric locations and the types of the splitters, and the connection relationship of each ONU to the splitters. The whole optimization problem may be decomposed into two subproblems, i.e., (i) clustering ONUs, which determines which groups of ONUs should be connected to common splitters, and (ii) determining the number and locations of splitters. We term subproblem (i) *allocation subproblem* and subproblem (ii) *location subproblem*. Both of them are hard. Subproblem (i) can be proved to be NP-complete, and subproblem (ii) is also intractable because of the difficulty in determining an optimal number of splitters required to achieve a minimal deployment cost. Thus, to solve the above optimization problem, heuristics are the most practical solutions.

## 3. Algorithms for PONs Deployment

We consider two heuristics in our study. The first one is an intuitive sectoring algorithm, which is similar to cutting a full cake. Given a set of ONUs that are distributed in a full circle or an annulus and a maximal optical split ratio  $1:S_r$ , a first cut is made on the positive vertical axis if the cake is assumed to have a coordinate. Starting from this first cut, we divide the cake into multiple slices with each slice containing  $S_r$  ONUs, except

for the last one, which may contain less than  $S_r$  ONUs if the total number of ONUs is not an integer multiple of  $S_r$ . We use this intuitive heuristic to provide a benchmark deployment to evaluate the efficiency of the second more efficient heuristic. It should be noted that the sectoring algorithm does not consider the PON system constraints including maximal transmission distance and maximal differential distance.

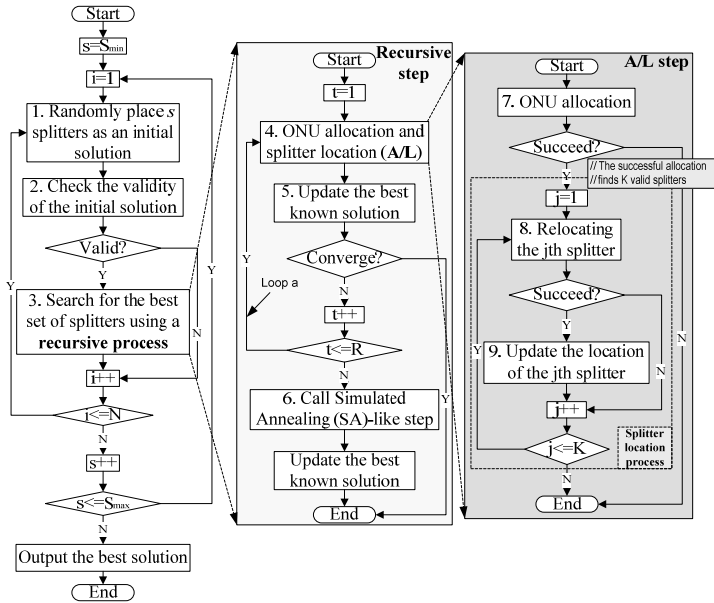


Fig. 2. Flowchart of RALA.

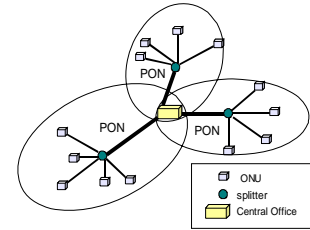


Fig. 1. Example of PONs.

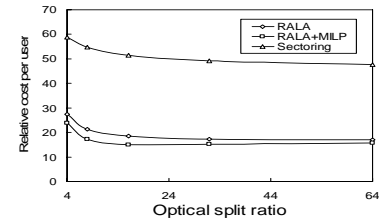


Fig. 3. Cost per user for an annulus planning.

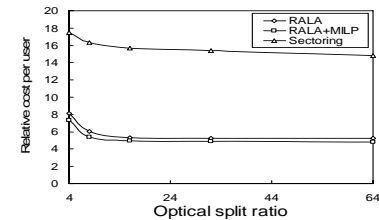


Fig. 4. Cost per user for a full-circle planning.

The second algorithm, named Recursive Allocation and Location Algorithm (RALA), is extended from Cooper's algorithm, which has been used to solve the Multi-Facilities Location Problem (MFLP) in logistics studies [3]. Fig. 2 shows a flowchart of RALA. The left column implements an outer loop, in which Step 1 randomly generates an initial set of splitters and their locations on a Euclidean plane. Step 2 validates whether this initial set of splitters are an eligible solution to meet all the PON system constraints. If so, Step 3 triggers a recursive process to find the best set of splitters and locations based on this initial set of splitters (i.e., this initial set of splitters essentially functions as a starting point of the recursive process).

The middle column in Fig. 2 shows the detail of the recursive (searching) process in Step 3. Specifically, the process first triggers an "ONU allocation and splitter location" step (i.e., Step 4), which is termed A/L step in short and whose detail is shown in the right column of Fig. 2. The A/L step can find a set of valid splitters and their corresponding locations, which are then used to update the best known solution through a convergence loop, *loop a*. Specifically, if a new solution performs better than a previous best known solution, Step 5 is executed to update the best known solution. In most cases, *loop a* can always converge within few iterations; however, occasionally, it may not converge after  $R$  iterations. If that occurs, a Simulated Annealing (SA)-like process (i.e., Step 6) is triggered to finalize a (good) solution. Due to the page limit, we do not provide detail on the SA-like step here.

The right column shows the detail for the A/L step, which is made up of two substeps, including (i) ONU allocation and (ii) splitter relocation. The step of ONU allocation (i.e., Step 7) is to connect each ONU to a set of splitters one by one. We employ the following principle for the allocation process: any unconnected ONU that has the shortest distance to an optical splitter is connected (allocated) to the splitter first, and this allocation process is repeated and stopped until all the ONUs find their associated splitters. During this allocation process, the PON system constraints are always checked to see whether the connection of a new ONU to a splitter will cause the constraints such as the maximal split ratio, the maximal transmission distance, and the maximal differential distance of a PON unsatisfied. Any ONU that makes the constraints unsatisfied should not be connected to that splitter. The above ONU allocation step eventually divides all the ONUs into several groups, of which each is connected to a common splitter. Based on these groups, we can further optimize the location of the splitter (i.e., Step 8) by employing Weiszfeld's algorithm [4], which determines a Fermat-Weber point for a polygon with a group of ONUs and an OLT as vertices. Note that the Fermat-Weber point ensures the shortest fibre distance to connect this group of ONUs to the OLT among all possible locations in a Euclidean plane. Thus, if the new found splitter location satisfies all the PON system constraints, Step 9 will record the new location for the splitter for a better solution.

The RALA algorithm can find an efficient set of splitters and the connection relationship between each ONU and the splitters. However, based on this heuristic solution, in which the set of splitter has become a given parameter, we can further optimize the connection relationship between each ONU and the splitters by employing a Mixed Integer Linear Programming (MILP) model. Here due to the page limit, we do not provide the detail of the MILP model. Interested readers can find the model on our webpage at [5]. We solved the MILP model using an AMPL/CPLEX software. Our study shows that this MILP optimization is computable and effective for a small or medium-size design with up to several hundred ONUs.

#### 4. Simulation studies

Simulation studies were carried out to find optimal solutions so as to evaluate the efficiency of the RALA algorithm. The following assumptions are made. First, five types of splitters are assumed, which include split ratios of 1:4, 1:8, 1:16, 1:32 and 1:64. We also assume a relative cost factor of laying fibre (per km),  $\alpha=2$ , a relative cost factor of each OLT,  $\beta=2$ , and a relative cost factor of each splitter output port,  $\gamma=0.01$ . Note that these relative cost factors are proportionally assigned based on real system deployment costs, and for an optical splitter with a split ratio 1: $S_r$ , its relative cost is  $0.01 \times S_r$ .

We study two deployment cases, an annulus and a full circle. For the annulus, we assume that 500 ONUs are randomly and uniformly distributed in an annulus with a radius of outer circle 50 km and a radius of inner circle 16 km, respectively. The G-PON standard is assumed for the planning, which allows a 60 km maximal transmission distance and a 20 km maximal differential distance. For the full-circle case, 500 ONUs are randomly and uniformly distributed in a circle with a radius of 16 km, and the EPON standard is assumed to allow a 20 km maximal transmission distance and a 20 km maximal differential distance. For both of the cases, the Central Office and all the OLTs are assumed to be located at the origin.

Fig. 3 shows how the PON deployment cost per user (each ONU corresponds to a user) changes with different maximal split ratios under the annulus case. Here if a design allows a maximal split ratio 1:  $S_r$ , all types of splitters whose split ratios are no greater than  $S_r$  can be used in the planning. Three planning schemes are compared, including (i) a benchmark sectoring planning, (ii) a planning based on the RALA algorithm, and (iii) a further MILP optimization for the RALA planning. Based on the results shown in Fig. 3, we can see that the RALA algorithm performs efficiently to reduce 50%~70% PON network deployment costs compared to the benchmark sectoring approach. Also, comparing the schemes (ii) and (iii), we find that a further MILP optimization can bring about 10% cost reduction compared to the pure RALA approach. This result thus verifies the effectiveness of the MILP effort as well as the efficiency of the allocation step in the pure RALA algorithm. For a medium-size design, it is useful to carry out a following-up MILP optimization for a better solution, while for a large-size design, at which the MILP optimization model may not be computable, a pure RALA design is efficient to be never 10% more expensive than an optimal MILP design.

We also evaluate the impact of the maximal split ratio on the PON deployment cost. As shown in Fig. 3, it can be found that there is a saturating trend with the increase of maximal split ratio. When the split ratio is small, its increase can significantly reduce the deployment cost per user (up to 40% from the ratio 1:4 to the ratio 1:16). However, if the split ratio has reached a certain level, its further increase would not bring much reduction of the deployment cost. As shown in Fig. 3, after the ratio 1:16, not much cost can be reduced with the increase of split ratio to 1:32 and 1:64. Finally, similar results were found for the full circle case as shown in Fig. 4, in which the RALA algorithms again significantly outperform the benchmark sectoring approach and a similar saturating trend is observed with the increase of the maximal split ratio.

#### 5. Conclusion

We plan PON network deployment to minimize its total cost. We propose an efficient algorithm to find optimal locations for optical splitters. The simulation results indicate that the RALA algorithm is effective to significantly (50%~70%) reduce PON network deployment cost compared to the benchmark sectoring approach. The results also show that there is a saturating trend for the PON deployment cost versus the increase of maximal split ratio. An increase of maximal split ratio will not reduce PON deployment cost if the ratio has exceeded a certain threshold level.

Our current 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 our current planning approaches, which will be our subsequent research.

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