Optimization of PON Planning for FTTH Deployment Based on Coverage

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***Abstract*—With the growing demand of very high bandwidth services such as high definition IP Television (IPTV), Service Providers (SPs) are moving to fiber-based solutions such as Passive Optical Networks (PONs) to meet current and future bandwidth needs. As these networks are deployed, coverage tends to directly affect Capital Expenditure (CAPEX) per subscriber served, with a minimum cost per Optical Network Unit (ONU) translating to a maximum Return on Investment (ROI). By including coverage and Economies of Scale (EOS) into the optimized planning model, a more accurate representation of deployment scenarios can be determined. In this paper, the incorporation of deployment coverage and EOS into a Mixed Integer Linear Programming (MILP) formulation is presented and solved for a number of EOS scenarios. Results suggest that stepped approximations of non-linear costs based on the number of Optical Network Units (ONUs) can be effectively included in the MILP model without sacrificing the ability to compute solutions for larger scale networks.**

***Index Terms*—MILP, Network Modelling, Optimization, PON**

I. Introduction

In accordance to the growing popularity of bandwidth intensive services such as online video streaming, high definition IPTV and video conferencing, SPs are increasingly investing in broadband access. Even though competing broadband solutions such as Digital Subscriber Line (DSL) and Long Term Evolution (LTE) exist, they are limited in range due to noise susceptibility and do not provide the necessary bandwidth required by these services. Therefore, SPs are now turning to fiber-based networks to meet the current and future needs of subscribers.

Fiber-based network solutions are typically categorised as either Point-to-Point (P2P) or Point-to-Multipoint (P2MP). With P2P solutions, the subscriber links directly to the Central Office (CO) or exchange with a dedicated fiber, while P2MP solutions share a single fiber across multiple subscribers. Even though dedicated fibers provide the best future proofing in terms of bandwidth, it comes at a prohibitive cost when large numbers of subscribers are involved. Depending on the length of the fiber loop, a dedicated infrastructure can be up to 100 percent more expensive [1] than a shared solution and therefore most SPs opt for a shared infrastructure.

With this tendency to implement fiber networks, fiber has moved from backbone to last mile deployment through Fiber to the Node (FTTN), Fiber to the Curb (FTTC), Fiber to the Building (FTTB) and finally Fiber to the Home (FTTH). This is mostly due to technology and standard advances which result in reduced fiber deployment cost and easier integration with the rest of the network. Of these deployments, the most notable are the Gigabit Passive Optical Network (GPON) standard which is based on ATM PON (APON) and Ethernet Passive Optical Network (EPON) which is a derivation of the existing IEEE 802.3 standard. GPON allows for down- and upstream traffic of up to 2.488 Gb/s and 1.244 Gb/s respectively, while the current EPON standard (IEEE 802.3ah) allows for 1 Gb/s bidirectional bandwidth [1].

Both GPON and EPON have a similar physical layer structure, consisting of an Optical Line Terminal (OLT) at an exchange or CO, serving a number of passive optical splitters, which in turn distribute the signals to a number of ONUs. Each ONU then has a specified number of service ports depending on the customer requirements. This results in a tree structure, with a single fiber from the CO serving several dozens (up to 128 in the case of GPON [1]) of ONUs.

As with any other network deployment, planning plays a fundamental role in both the overall cost of deployment and the resulting network efficiency. Planning of fiber networks is traditionally done manually by planners trying to find a sufficiently optimal solution for a given number of nodes. Even though these plans are close to optimal for smaller networks, large network plans are usually sub-optimal, time consuming and require experienced planners. With the invention of planning optimization, this process can be automated to produce optimal solutions for basic models in minutes.

For private sector SPs implementing these networks, maximizing ROI is a main concern, forcing careful determination of CAPEX for a given estimated income. Where FTTH is concerned, this income is usually fixed per ONU, resulting in the need to find the minimum CAPEX per ONU. To the best of our knowledge, no tailored models exist to address this need, motivating the development of the model in this paper.

The rest of the paper is organised as follows: Section II discusses the models and techniques used in related work to optimize network planning. Section III defines the optimi-

zation problem and objectives that should be achieved. In section IV, the network planning model is defined with section V giving the optimized results from the model. Finally, section VI concludes the paper and gives an overview of possible future work.

II. Related work

Since the model in question is usually either intractable due to it being non-linear or NP-complete and overly complex, heuristics are implemented to give a close to optimal solution in a feasible amount of time. Previous studies on optimized Passive Optical Network (PON) planning can be divided into two sections; those based on heuristics and exact techniques and those based on meta-heuristics such as genetic algorithms [2]. Due to the nature of the problem, with it having a large amount of decision or binary variables, models are usually formulated as a MILP.

A. Exact methods and heuristics

In [3], the authors provide a new heuristic called Random Allocation and Reallocation Algorithm (RARA) to speed up the optimization process of greenfield PON network planning through disintegration. The heuristic is based on randomly sampling a solution from the search space and incrementally optimizing it through a Simulated Annealing (SA)-like step in their algorithm. The network model provided takes into account different types of splitters for deployment and includes GPON and EPON standard constraints such as differential distance and maximal transmission distance. The authors also introduce maximal fiber duct sharing to further decrease the overall cost of deployment. Finally, the algorithm is compared to a basic random-cut heuristic to show its efficiency.

The authors of [4] propose a purely exact model, also based on the MILP technique, to solve a multi-hierarchy PON network. The model includes splitters as well as Cable Distribution (CD) points which link to specific tenancies. Furthermore, the authors include planning constraints such as the maximum number of tenancies per CD and maximum number of CDs per splitter. Since the model is purely exact, the placement of splitters and CDs lead to global optimal results when applied to the Medium Net (MN) and Big Net (BN) data they examine.

In [5], the author provides an algorithm based on graph theory to optimize the planning of a grid-like area such as Manhattan (New York City). The greedy algorithm transforms population density on the original grid to a new graph which Jacobian is proportional to some Population Density Function (PDF). The vertices on the new graph are then compared for minimum distance allocation. This is then repeated iteratively to find minimum cost locations for OLTs, splitters and ONUs. Finally, the algorithm is compared to another population density type algorithm, PNLA.

In [6], the authors investigate the same optimization problem of PON planning, but implements a complete CAPEX model to account for the various subdivisions of expenditure streams by minimizing for each. The paper specifically examines very large problem sizes and computation times inherent to each approach. They propose a heuristic called the Branch Contracting Algorithm (BCA) which builds a tree and then iteratively refines it through customer segmentation and splitter placement. For the final step, the algorithm builds a Steiner-tree to connect CDs with splitters. The algorithm is compared with a lower bound Integer Linear Program (ILP) to determine its efficiency. The same authors also provide a methodology in a more recent work [7] for the general planning of broadband access networks and provide four different heuristics based on the network type; including PON, Active Ethernet (AE) and Very-high-bit-rate Digital Subscriber Line (VDSL). Finally, the heuristics are shown to provide solutions in the range of 10-15 % to optimal.

The authors of [8] propose the same planning problem solution for PONs, but incorporates survivability into their model. Three models based on 99.99 % and 99.999 % service availability are given and solved with exact methods. In contrast to other works, the models are formulated to optimize for network reach, maximizing the covered area. The same authors then propose a planning heuristic in [9] to provide a survivable long-reach PON design.

In [10], the authors formulate the planning problem as a multi-level capacitated facility location problem on a tree topology but with non-linear cost for links. Due to this non-linearity, MILP models can only give upper and lower bounds for the solution through objective function relaxation. The paper goes on to propose both valid inequalities and a heuristic to improve the upper bound of the solution through two phases called upper improvement and downward refinement.

B. Meta-heuristics

The authors of [11] present a hybrid approach to solving the multi-hierarchy, single split PON problem, incorporating an algorithm utilising a Minimum Spanning Tree (MST) step to form trees, a heuristic method to cluster PONs and finally a Genetic Algorithm (GA) to identify distribution point locations. The algorithm minimizes the total number of splitters and distribution points and the total length of fiber cable connections.

In [12], the authors present an evolutionary computing-based algorithm that includes non-traversable obstacle avoidance through convex hull mapping. The problem is subdivided through the use of a K-means clustering algorithm and compared to a hand-made connection plan.

While most works address the single-hierarchy PON problem, the authors of [13] propose a GA based algorithm with a multi-hierarchy planning heuristic incorporating a Min-Max Distance Cluster (MMDC) algorithm to cluster potential splitters to ONUs. The authors of [14] also address the multi-hierarchy problem, with placement of primary and secondary nodes optimized through a GA. In addition, they include the split ratios of each splitter into their model as well as optic attenuation and apply the algorithm to a residential area in Turkey.

In [15], the authors apply GA techniques combined with graph theory to modified versions of the PON problem, including bus, tree and ring topologies. The authors of [16] use the

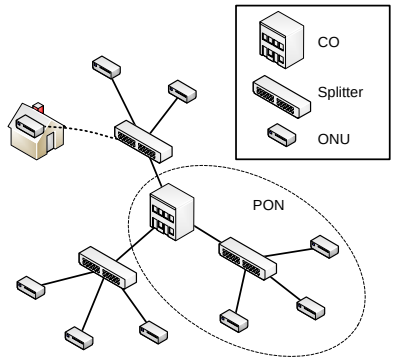

Fig. 1. A basic passive optical network topology

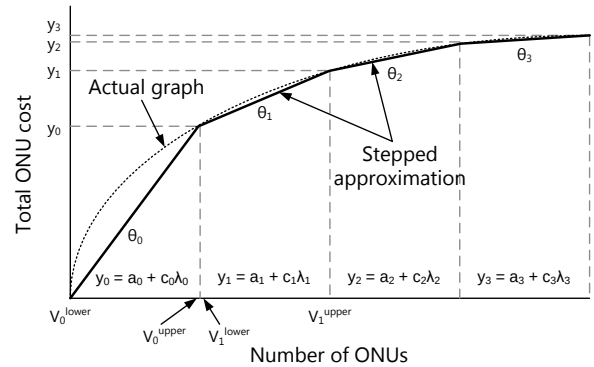

Fig. 2. Stepped approximation for economies of scale for ONUs

same meta-heuristic GA techniques, but propose an algorithm to optimize for minimum power consumption, comparing optimal MILP, heuristic and meta-heuristic solutions based on performance.

Finally, the authors of [17] introduce an interesting algorithm based on a combination of clustering techniques and ant colony optimization. It produces better global solutions than comparable heuristic algorithms since it is not as vulnerable to local optima.

Even though these studies optimize PON planning for a wide number of cases using both exact and genetic type algorithms and heuristics, none of them take coverage into account to optimize cost for a given deployment span. Thus, the authors propose a basic model to study the effects of coverage on network deployment cost.

III. Model Formulation and Objectives

A. Problem Formulation

The PON planning problem is very similar in structure to the Multifacility Location-Allocation Problem (MLAP) introduced in [18], which is defined as the problem of allocating fixed location distribution centres to warehouses for minimum cost. In this problem, the warehouse locations are variable and introduces an additional level of complexity where all locations must be exhaustively tested for optimality.

By replacing warehouses with splitters and distribution centres with ONUs, we arrive at figure 1, although the PON problem introduces an additional factor - the unknown number of splitters at onset. In essence, the problem can be broken down into three sub-problems that must be solved simultaneously, as given in [3]:

1) Determining the optimal amount of splitters.
2) Allocating ONUs to splitters through clustering.
3) Relocating splitters to minimize the overall cost.

B. Model Formulation

The proposed PON planning problem can now be defined further by specifying how the test data is manipulated. To calculate the distances between the CO, ONUs and splitters, three approaches are common. Firstly and ideally, the use of real-world Geographic Information System (GIS) data in the form of civil and planning layers to calculate the exact *civil distance* between points on a map as in [11], [19]. Secondly, the approximation through the calculation of the Euclidian distance between points on a Cartesian plane [3] and thirdly, the use of the *Manhattan* or zig-zag distance defined as $\ell_{0-1} = |x_0 - x_1| + |y_0 - y_1|$. For the purpose of this paper, the Manhattan distance is used since it provides more accurate estimations when used in an urban environment while not requiring accurate civil maps of the area.

The percentage of homes passed, or covered, is included in the model through the use of a parameter ω. The parameter can then be adjusted to connect the *best* specified number of ONUs to the optimal splitters for minimum cost. As ω is altered, groups of ONUs in a previous optimal solution might not be contained in the next solution and thus this approach introduces an additional complexity factor over just adjusting the number of input ONUs.

To account for coverage, a metric of *cost per ONU* is used. As income per ONU is fixed for a specific service, a lower CAPEX to connect ONUs will result in a higher ROI. For this paper, where the model is formulated as a MILP, coverage is not variable to avoid non-linearity. However, by solving the model for a number of different coverage factors, a rough estimated coverage for minimum *cost per ONU* can be found.

Economies of scale are also included in the model, to account for a reduction in cost of ONUs, splitters, fibers and trenching as the scale of the network increases. The number of ONUs is used as a metric for network scale, while a stepped approximation for unit cost as in figure 2 ensures model linearity.

C. Objectives

The objective of a PON planning problem formulation can be defined as the optimization, whether minimization or maximization, of a specific parameter or combination of parameters in the model. Even though some authors minimize fiber length [3], maximize PON reach [8], [9] or minimize the amount of splitters used, a cost-based objective provides a number of advantages. Rather than optimizing for a single parameter, a cost-based objective combines parameters as a weighted sum, producing a real-world accurate solution when accurate weights are used.

The mathematical model's objective in this paper is defined as the minimization of the sum of splitter, OLT, ONU and fiber

cable costs. OLT costs are implemented as a fixed start-up cost to implement the necessary infrastructure for the PON and includes all testing of feeder fibers and management systems.

IV. Mathematical Model

The basic mathematical model used to study the effects of coverage on deployment cost is now defined as follows:

A. Variables

- ψ_i - Binary variable used to indicate usage of the *i*-th splitter. The variable takes on a value of 1 if the *i*-th splitter is used and 0 if it's unused.
- π_j - Binary variable used to indicate usage of the *j*-th ONU. Like ψ_i, the variable takes on a value of 1 if the *j*-th ONU is used and 0 if it's unused.
- ϕ_{ij} - Binary variable used to define the usage of a link between the *i*-th splitter and the *j*-th ONU. If the two are connected, the variable takes on a value of 1. If unused, the variable is 0.
- $\lambda_n^S, \lambda_m^{ONU}$ - Integer variables to select the total number of splitters and ONUs to deploy for each segment *n* and *m* of the cost graph respectively.
- $\theta_n^S, \theta_m^{ONU}$ - Binary selection variables used in the stepped cost graph selection. Takes on 1 if the *n*-th or *m*-th segment is selected and 0 if it's unselected respectively.
- Ψ, Π - The total number of splitters and ONUs used respectively.

B. Parameters

- C_{OLT} - The fixed OLT cost incurred for each PON.
- γ_ω - The average cost of trenching a single meter at a coverage of ω for the deployment of subterranean optic fibers.
- κ_{ONU}^S - The maximum number of ONUs that can connect to each splitter. For this model, we assume that the splitters are of the same type.
- σ_ω^{CO-SP} - The cost of a meter of fiber between the CO and a splitter at a coverage of ω.
- σ_ω^{SP-ONU} - The cost per meter of fiber between a splitter and ONU at a coverage of ω.
- ω - The coverage factor. This parameter defines the percentage of ONUs passed and takes on a value between 0 and 1.
- ξ - A large number used to define the relationship between ψ_i and ϕ_{ij}. The value must be larger than κ_{ONU}^S. For simplicity, a value of 10^5 is used in this paper.
- ϵ - A small number to define the relationship between λ_n^S / λ_m^{ONU} and θ_n^S / θ_m^{ONU}. A value of 10^{-5} is used in this paper.
- ℓ_i^{CO} - The Manhattan distance in meters between the *i*-th splitter and the CO.
- ℓ_{ij} - The Manhattan distance in meters between the *i*-th splitter and the *j*-th ONU.
- N, M - The total number of cost segments for splitters and ONUs respectively.
- $\check{v}_n^S, \hat{v}_n^S$ - The lower and upper bounds for the *n*-th cost segment for splitters respectively.
- $\check{v}_m^{ONU}, \hat{v}_m^{ONU}$ - The lower and upper bounds for the *m*-th cost segment for ONUs respectively.
- a_n^S, a_m^{ONU} - The offset of the *n*-th and *m*-th cost line segment for splitters and ONUs respectively.
- c_n^S, c_m^{ONU} - The gradient of the *n*-th and *m*-th cost line segment for splitters and ONUs respectively.

C. Sets

- $\mathbf{U}$ - Contains a set of all possible locations for ONUs in the form of Cartesian coordinates. The index *j* is used to indicate the coordinates of the *j*-th ONU.
- $\mathbf{S}$ - The set of all possible locations for splitters in the model. For this set, the index *i* is used to indicate the *i*-th splitter coordinates.

D. Objective function

The model aims to minimize the total cost of fiber deployment given a certain coverage factor and sets $\mathbf{U}$ and $\mathbf{S}$. The objective function is given as follows:

Minimize

$$C_{total} = C_{OLT} + C_{splitter} + C_{ONU} + C_{fiber}^{CO-SP} + C_{fiber}^{SP-ONU} \quad (1)$$

with

$$C_{splitter} = \sum_{n=0}^{N-1} (a_n^S \theta_n^S + c_n^S \lambda_n^S) \quad (2)$$

$$C_{ONU} = \sum_{m=0}^{M-1} (a_m^{ONU} \theta_m^{ONU} + c_m^{ONU} \lambda_m^{ONU}) \quad (3)$$

$$C_{fiber}^{CO-SP} = (\gamma_\omega + \sigma_\omega^{CO-SP}) \times \sum_{i \in \mathbf{S}} \ell_i^{CO} \psi_i \quad (4)$$

$$C_{fiber}^{SP-ONU} = (\gamma_\omega + \sigma_\omega^{SP-ONU}) \times \sum_{i \in \mathbf{S}} \sum_{j \in \boldsymbol{U}} \phi_{ij} \ell_{ij} \quad (5)$$

The objective function in (1) consists of five terms, the first of which is the fixed OLT cost and the second, the splitter cost. The third term describes the cost of ONU deployment while the fourth and fifth terms define the cost of laying fibers between the CO and splitters, and splitters and ONUs respectively.

E. Constraints

Finally, the model's constraints are given as follows:

Subject to

$$\sum_{j \in \mathbf{U}} \pi_j = \omega |\mathbf{U}| = \Pi \quad (6)$$

$$\sum_{i \in \mathbf{S}} \psi_i = \Psi \quad (7)$$

$$\sum_{n=0}^{N-1} \lambda_n^S = \Psi, \quad \sum_{m=0}^{M-1} \lambda_m^{ONU} = \Pi \quad (8)$$

$$\sum_{n=0}^{N-1} \theta_n^S = \sum_{m=0}^{M-1} \theta_m^{ONU} = 1 \quad (9)$$

$$\sum_{j \in \mathbf{U}} \phi_{ij} \leq \xi . \psi_i \qquad \forall i \in \mathbf{S} \quad (10)$$

TABLE I
DESIGN PARAMETERS

Parameter	Symbol	Value (Rand)
Fixed OLT setup cost	C_{OLT}	10,000
Splitter unit cost	c_0^S	6,000
ONU unit cost	c_0^{ONU}	200
Max trenching cost per meter	γ_ω	300
Max fiber cost from CO to splitter per meter	σ_ω^{CO-SP}	200
Max fiber cost from splitter to ONU per meter	σ_ω^{SP-ONU}	100
Max ONUs per splitter	κ_{ONU}^S	64

TABLE II
SIMULATION COMPUTATIONAL RESULTS

Scenario	Avg. time (s) (μ)	Standard deviation (σ)
100 ONUs, $1km^2$	0.904	0.66
300 ONUs, $1km^2$	3.504	1.981
500 ONUs, $4km^2$	12.789	2.344
1000 ONUs, $100km^2$	22.434	8.415

$$\sum_{i \in \mathbf{S}} \phi_{ij} = \pi_j \qquad \forall j \in \mathbf{U} \quad (11)$$

$$\sum_{j \in \mathbf{U}} \phi_{ij} \leq \kappa_{ONU}^S \qquad \forall i \in \mathbf{S} \quad (12)$$

$$\check{v}_n^S \theta_n^S \leq \lambda_n^S \leq (1-\epsilon)\hat{v}_n^S \theta_n^S \qquad 0 \leq n < N \quad (13)$$

$$\check{v}_m^{ONU} \theta_m^{ONU} \leq \lambda_m^{ONU} \leq (1-\epsilon)\hat{v}_m^{ONU} \theta_m^{ONU} \qquad 0 \leq m < M \quad (14)$$

Constraint (6) enforces the coverage factor on the number of used ONUs while constraints (8), (9), (13) and (14) implement economies of scale into the cost structure. Constraints (10) and (11) ensures that when a link exists between a splitter and ONU, the binary variable arrays are set accordingly while (12) constrains the number of ONUs that can connect to each splitter.

V. RESULTS

The model was tested by populating a square region with random points for ONUs, splitters and the CO from a uniform distribution. This test set is termed *TestNet*. Coverage was set between 10 % and 100 % in 10 % intervals and the solution was computed through the use of IBM ILOG CPLEX on an Intel Core i7 processor running at 2.67 GHz. The design parameters were set according to table I and the number of ONUs were set between 100 and 1000. Figure 3 illustrates the four basic EOS cost scenarios used. These EOS scenarios are theoretical illustrations of how splitter and ONU unit cost can decrease with an increase in coverage (volume) - constant (no EOS), linear, exponential and inverse exponential. The computational time to solve each scenario is shown in table II.

Figure 4 shows the cost per ONU metric results for the model with ω between 10 % and 100 % for each of the types of EOS graphs. It is clear that the cost per ONU follows the same form as the costing scenarios. Also, for the constant cost case i.e. no EOS, the cost per ONU is nearly linear, which can be ascribed to two factors - the fact that a linear model with linear link cost is used and that *TestNet* is generated from a uniform distribution. If the data is not uniformly distributed, the cost per ONU will be equally non-linear.

Figures 5 and 6 show the model results at 10 % and 50 % coverage respectively, with green circles signifying used splitters and unfilled or white circles showing unused splitters. Dots and blue circles are used to represent unconnected and connected ONUs respectively while the red square represents the CO. Finally, the Manhattan distances between ONUs, splitters and the CO are shown with black and grey lines, with the horizontal component plotted first.

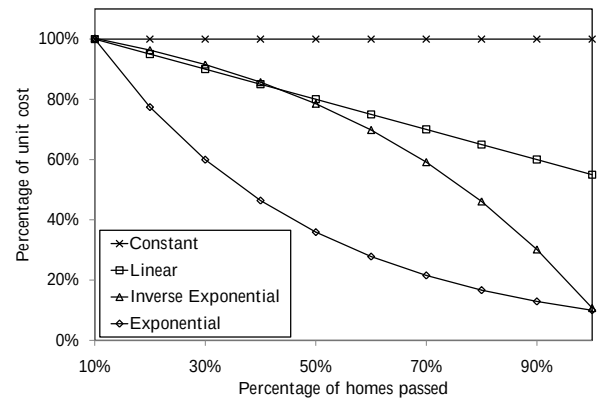

Fig. 3. EOS scenarios used to generate solutions to illustrate decreasing ONU, splitter and fiber unit costs for increasing coverage

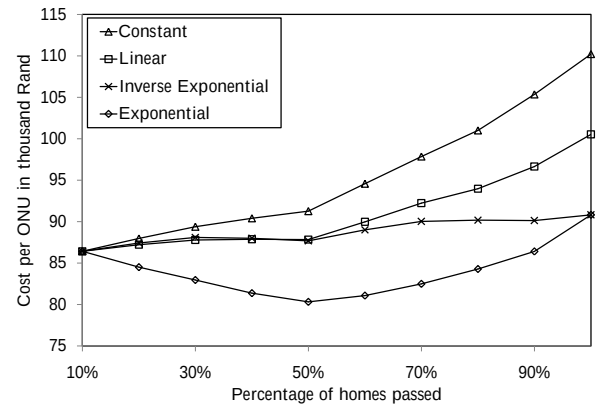

Fig. 4. Cost per ONU for coverages between 10 % and 100 % for each type of EOS graph

VI. CONCLUSION & FUTURE WORK

In this paper we have shown how the PON problem can be mathematically formulated using MILP techniques and how to incorporate coverage to optimize for minimum deployment cost. This formulation resulted in optimal results in just a few seconds for small networks, outperforming manual planning techniques by orders of magnitude.

We also show how private sector SPs can minimize their CAPEX by incorporating coverage into the PON planning problem. Linear cost results show that fixed costs and EOS largely influence the coverage point for minimum cost per ONU, which can vary extensively between real-world deployment scenarios.

The fact that a large test scenario of 1000 ONUs could be solved in under a minute attest to the fact that MILP techniques are still viable to optimize medium-sized PON plans. When moving on to larger networks in the order of 10,000 to 100,000 ONUs however, a disintegration heuristic will be required to solve the problem in a reasonable amount of time.

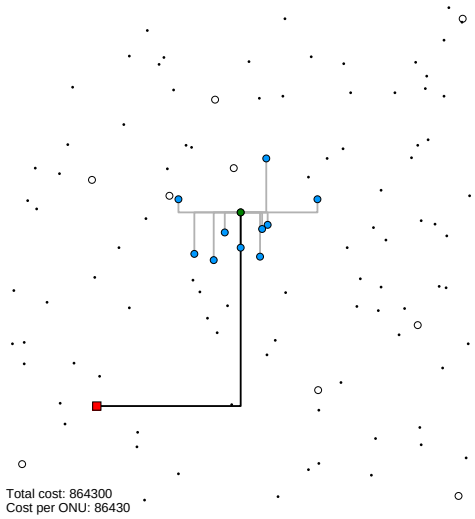

Fig. 5. *TestNet* with 100 ONUs at 10% coverage

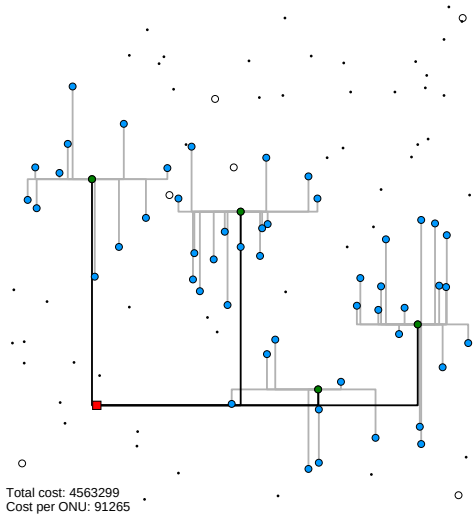

Fig. 6. *TestNet* with 100 ONUs at 50% coverage

Future work will encompass the refinement and improvement of the model in question, incorporating more detailed aspects of the PON problem, including optimizing for non-linear fiber link costs dependent on length, fiber cable conduit sharing and multi-hierarchy topologies. Since these additions will likely shift the model into non-linearity, the use of heuristics or meta-heuristics will be required to produce feasible solutions and speed up execution time. Finally, the use of non-uniform, real-world GIS data will improve the solution accuracy and will likely lead to more practically applicable conclusions.

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References

[1] F. Effenberger, D. Clearly, O. Haran, G. Kramer, R. D. Li, M. Oron, and T. Pfeiffer, "An introduction to pon technologies [topics in optical communications]," *Communications Magazine, IEEE*, vol. 45, no. 3, pp. S17 –S25, March 2007.

[2] T. Weise, *Global Optimization Algorithms - Theory and Application*. it-weise.de (self-published): Germany, 2009. [Online]. Available: http://www.it-weise.de/projects/book.pdf

[3] J. Li and G. Shen, "Cost minimization planning for greenfield passive optical networks," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 1, no. 1, pp. 17 –29, June 2009.

[4] A. Ouali and K. F. Poon, "Optimal design of gpon/ftth networks using mixed integer linear programming," in *Networks and Optical Communications (NOC), 2011 16th European Conference on*, July 2011, pp. 137 –140.

[5] S. Khan, "Heuristics-based pon deployment," *Communications Letters, IEEE*, vol. 9, no. 9, pp. 847 – 849, Sep. 2005.

[6] A. Mitcsenko, G. Paksy, and T. Cinkler, "Topology design and capex estimation for passive optical networks," in *Broadband Communications, Networks, and Systems, 2009. BROADNETS 2009. Sixth International Conference on*, Sep. 2009, pp. 1 –8.

[7] A. Mitcsenkov, G. Paksy, and T. Cinkler, "Geography- and infrastructure-aware topology design methodology for broadband access networks (fttx)," *Photonic Network Communications*, vol. 21, no. 3, pp. 253–266, 2011.

[8] B. Kantarci and H. Mouftah, "Optimization models for reliable long-reach pon deployment," in *Computers and Communications (ISCC), 2011 IEEE Symposium on*, July 2011, pp. 506 –511.

[9] B. Kantarci and H. T. Mouftah, "Availability and cost-constrained long-reach passive optical network planning," *Reliability, IEEE Transactions on*, vol. 61, no. 1, pp. 113 –124, March 2012.

[10] Y. Kim, Y. Lee, and J. Han, "A splitter location-allocation problem in designing fiber optic access networks," *European Journal of Operational Research*, vol. 210, no. 2, pp. 425–435, 2011.

[11] K. Poon, D. Mortimore, and J. Mellis, "Designing optimal ftth and pon networks using new automatic methods," in *Access Technologies, 2006. The 2nd Institution of Engineering and Technology International Conference on*, June 2006, pp. 49 – 52.

[12] B. Lakic and M. Hajduczenia, "On optimized passive optical network (pon) deployment," in *Access Networks Workshops, 2007. AccessNets '07. Second International Conference on*, Aug. 2007, pp. 1 –8.

[13] M. Lv and X. Chen, "Heuristic based multi-hierarchy passive optical network planning," in *Wireless Communications, Networking and Mobile Computing, 2009. WiCom '09. 5th International Conference on*, Sep. 2009, pp. 1 –4.

[14] A. Kokangul and A. Ari, "Optimization of passive optical network planning," *Applied Mathematical Modelling*, vol. 35, no. 7, pp. 3345 – 3354, 2011.

[15] T. y Villalba, S. Rossi, M. Mokarzel, M. Salvador, H. Neto, A. Cesar, M. Romero, and M. de L. Rocha, "Design of passive optical networks using genetic algorithm," in *Microwave and Optoelectronics Conference (IMOC), 2009 SBMO/IEEE MTT-S International*, Nov. 2009, pp. 682 – 686.

[16] A. Ahmad, A. Bianco, E. Bonetto, D. Cuda, G. Castillo, and F. Neri, "Power-aware logical topology design heuristics in wavelength-routing networks," in *Optical Network Design and Modeling (ONDM), 2011 15th International Conference on*, Feb. 2011, pp. 1 –6.

[17] W. Xiong, C. Wu, L. Wu, X. Guo, Y. Chen, and M. Xie, "Ant colony optimization for pon network design," in *Communication Software and Networks (ICCSN), 2011 IEEE 3rd International Conference on*, May 2011, pp. 380 –383.

[18] L. Cooper, "Location-allocation problems," *Operations Research*, vol. 11, no. 3, pp. pp. 331–343, 1963.

[19] K. F. Poon and A. Ouali, "A milp based design tool for ftth access networks with consideration of demand growth," in *Internet Technology and Secured Transactions (ICITST), 2011 International Conference for*, Dec. 2011, pp. 544 –549.

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