On optimized Passive Optical Network (PON) deployment

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***Abstract*— Service providers emphasize the need for faster, cheaper and more reliable deployment of broadband networks, therefore making the hardware manufacturers pursue innovative solutions driving down component complexity, installation time, required skill level and, ultimately, the overall deployment cost for an access network structure. The current dramatic increase in the Fiber-to-the-Home (FTTH) deployment pace along with the general desire to eventually migrate completely to these systems, puts the Passive Optical Network (PON) deployment issues in the spotlight of current academic and system vendor research. Numerous publications [1-6] explore new technology developments leading to the reduction in the overall costs required to deploy FTTH networks today, especially in terms of the PON structure [7-9], installation time, and required craftsman skill level.**

Keywords; PON, optimization, clustering, genetic algorithm, FTTH, PSC (Passive Splitter Combiner)

I. Introduction

After 25 years of being the future technology of access networks, the FTTH infrastructure is now being deployed on a large scale in Asia [10-12] and USA [12, 13], and is beginning to pick up pace also in Europe [1, 14, 15].

The Asian broadband market is currently subject to tremendous growth in the number of FTTx lines deployed, since national carriers realized that DSL lines are short lived, suffer from high management costs, and are not completely future-proof [11]. Hybrid Fibre Coaxial (HFC) structures, typically deployed by local cable TV operators (CATV), providing support for broadcast and data services (cable TV, data, telephone), are also not a very attractive solution, mainly due to the large OPEX (Operative Expenditures) / CAPEX (Capital Expenditure) investments which have to be carried out in a continuous manner, in order to maintain the network in an operational state. Asian telecom and cable operators understood that it is essential to introduce FTTx networks, with fibre spanning between the Central Office (CO) and customer premises (FTTH) or at least local curb switches (FTTC). The DSL to FTTx transition, once complete, will provide each connected household with a broadband, fully bidirectional data link of at least 100 Mbps, delivering sufficient bandwidth for several High Definition (HD) TV channels, high-speed Internet services, as well as various video services and bundled Plain Old Telephone Service (POTS), typically deployed as Voice over IP (VoIP). Currently, the Asian market is assumed to be the largest FTTx deployment plant in the world, with approximately 5 million FTTH subscribers expected by the end of 2005 in Japan only [16], and with a monthly growth rate exceeding 2.5 million new subscribers, surpassing current DSL line deployment more than 5-fold (approximately 500 thousand new subscribers per month and decreasing [10]). The remaining large telecom and cable operators in the other large Asian countries (Korea, China, etc.) are not far behind, deploying large numbers of FTTH lines mainly in the form of Ethernet PONs (EPONs [17]), which attracted more attention when compared with GPONs [18].

The American market (including USA and Canada) is more conservative, though the last few years saw the increase in the number of FTTx deployments, mainly driven by non-traditional carriers, such as public utility companies, municipalities and home developers, as well as visionary competitive local exchange carriers (CLECs) [19]. Today, FTTH has also become the technology of choice of Incumbent Local Exchange Carriers (ILECs), both for new builds and overbuilds [20]. Canada, on the other hand, despite its low population density, remains one of the global leaders in broadband penetration, mainly due to literally hundreds of local broadband initiatives and government initiated programs such as The Broadband for Rural and Northern Development Pilot Program (BRAND), which was started in 2002 and has since funded 58 rural broadband projects for 884 communities with approximately 105 million dollars (Canadian). The largest national telecom operator, Bell Canada, is moving steadily forward with Greenfield FTTH and selected rural rehabilitation sites, mainly because its customers are asking for higher bandwidth services with inherent tri-play. Additionally, the company targets decrease in the OPEX costs and cutting down on power consumption for in-field devices (which constitutes a significant share of the DSL line operation costs).

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Europe is generally lagging behind Asia and North America in terms of FTTx deployment [1]. As for the beginning of 2005, there were merely 500 thousand FTTx line subscribers with more than 2.5 million homes passed, which is more or less comparable with the monthly increase in the subscriber number in the case of Japan. Additionally, the broadband FTTx subscribers in Europe are mostly concentrated in just 5 countries (Sweden, Italy, Denmark, Netherlands and Norway, as ordered against the number of homes passed). The current situation in Europe is mainly attributed to the existence of a high quality copper-infrastructure, allowing for deployment of ADSL/ADSL+VDSL almost at any location, providing a much more appealing alternative than trenching, fibre deployment, and creation of a new network infrastructure. Additionally, the government regulated telecommunication market in some European countries (until the late 90ties) allowed for very limited competition in the first-mile business, resulting in new cable operators entering the market only right now.

II. Research Motivation

Since FTTx deployment worldwide is picking up pace and there will be a significant growth in the number of new FTTx customers connected to the telecom network using a PON infrastructure, it is a vital issue for telecom/cable operators to deploy the PONs as economically as possible, thus avoiding any unnecessary costs. A quick analysis of the available options for PON network planning revealed a frustrating image: there are no automated tools, apart from a number of AutoCAD extension packages allowing to draw up the bill of materials for a hand made network plan and make a rudimentary power budget analysis for the given network deployment. We did not find any fully or semi automated deployment tools, providing PON deployment optimized in terms of power budget and deployment economy, allowing the network planner to select the OLT/ONUs locations in the area of interest and deploy the PON network in the most economic way. It is therefore our goal to show that hand-made PON network designs are not optimum, and that savings can be made as long as critical component location is not established based on years of experience of a network planner but rather by solving a multi-criteria optimization problem, taking such issues as power budget, PSC location, existing network resources (trenches, aerial lines, etc.), obstacles (both traversable: roads, green-field areas, etc. and non-traversable ones: houses, industrial zones, etc., which need to be bypassed in case of laying a new fibre structure), etc., into account when preparing the final network deployment plan.

The remainder of the paper is structured as follows. Section III. describes the optimization process that includes three major parts (obstacle avoidance, clustering and genetic algorithm). Section IV contains results we obtained after applying our algorithm on several maps as well as analysis of these results. Section V concludes the paper providing information on intended future work on this topic.

III. Optimization process

We are currently developing PON Builder, a semi-automated tool with the purpose of finding the optimum path distribution in terms of deployment cost, providing that path deployment along existing cable conduits is cheaper than trenching and laying fibre in a new path. The mechanism in question should also be able to determine subscriber groups of ONUs that will be connected to the OLT via single PSC in such a way that would minimize cost.

Processed maps consist of resources (represented by an ordered sequence of points), obstacles (simple polygons), ONUs, OLTs and PSCs (points).

We calculate the path price using following formula:

$$\begin{aligned} Cost(PH_l) &= UP_1 \cdot Length(PH_l) + UP_2 \cdot Length_R(PH_l) \\ &+ (UP_2 + UP_3) \cdot Length_{NR}(PH_l) + UP_4 \cdot SpliceCount(PH_l) \\ &+ (UP_2 + UP_3 + UP_5) \cdot Length_O(PH_l) \end{aligned} \quad 1$$

where:

PH_l – the path whose price we are calculating,

UP_1 – unitary price of the fibre cable

UP_2 – unitary price of deploying fibre in an already existing conduit

UP_3 – unitary price of creating a new cable conduit

UP_4 – price of realizing a fibre splice between two fibre sections

UP_5 – unitary price of deploying a fibre cable traversing a given obstacle encountered in the signal path.

$Length(PH_l)$ – length of the path PH_l

$Length_R(PH_l)$ – resource length of a path PH_l defined as the total of lengths of individual links in the said path, which reuse an already existing resource

$Length_{NR}(PH_l)$ – non-resource length of a path PH_l defined as the sum of the lengths of all individual links in the said path which can not reuse an existing resource

$Length_O(PH_l)$ – length of the path PH_l that passes through an obstacle

$SpliceCount(PH_l)$ – number of fibre splices in the path

The following subsections contain the detailed description of the optimization process

A. Obstacle avoidance

A large share of the real network deployments is carried out in densely populated areas where the shortest path connections are not always possible due to the existence of certain obstacles, which cannot be traversed at all (non-traversable obstacles) or can be traversed but at a cost which is higher when compared with a standard deployment of a new optical fibre cable. The said obstacles must therefore be taken into account when looking for an optimum path connecting two arbitrary points on a map.

First, we build a visibility map containing an ordered sequence of obstacles between every two points in the map. For that purpose, we extend the Lee's algorithm for calculation of visibility graph [22]. When connecting two points, if there are obstacles obstructing visibility between them, we get those from a visibility map and decide which will be bypassed and which will be traversed (Fig. 1). Next, we build a convex hull using Graham scan containing vertices of the obstacles we chose to bypass and the points we want to connect [23]. We then choose the shorter of the paths along the convex hull between the two points (Fig. 2). Once completed, the obstacles that are still left in the way are traversed (Fig. 3). This is a non-exhaustive description of the procedure, since there are certain cases, which require special treatment, but due to the size limitation of this paper, we will not dwell upon them in detail.

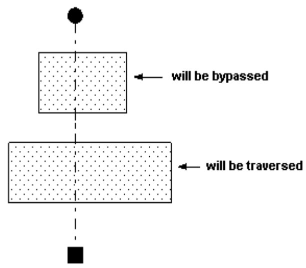

Figure 1. Choosing which obstacle will be bypassed and which traversed.

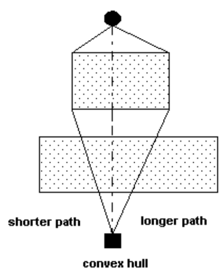

Figure 2. Convex hull.

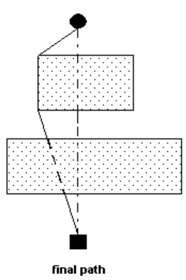

Figure 3. Final path.

B. Clustering

Clustering algorithms are used to determine the intrinsic grouping in a pre-defined set of unlabeled data. In the case of PON systems, clustering is required to find an optimum number of subscriber groups, each one to be served with a separate PON network or at least with a separate major network branch, providing that the customers are geographically remote and low in number. We have implemented K-means clustering algorithm [24].

The main idea of the K-means is to define *k* so-called *centroids* (central cluster points), one for each cluster, which should be located by any, potentially optimized way, since the examined algorithm tends to produce different results for different centroid locations. Once completed, a number of centroids are present in the input data set, and thus the next step is to take each point and associate it to the nearest centroid. Having the initial clusters for the examined data set, it is necessary to recalculate the location of all the centroids, this time defining them as the mass centers of the data points located in the individual clusters, and repeating the process of associating data points with the closest cluster, etc. This particular process is repeated until the location of the clusters becomes fixed and the data point association does not change for a number of consecutive steps.

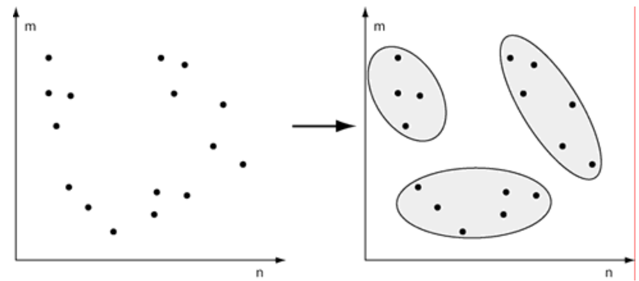

Figure 4. Graphical representation of the clustering problem (optimum solution).

The algorithm is highly sensitive to the initial selection of cluster centers, thus three different centroid selection mechanisms were examined in detail A randomized initial centroid distribution, where initial *k* (predefined value) centroids are chosen randomly, has been tested. Better convergence of the resulting clusters is achieved when the initial centroids are chosen among the points (ONUs) we want to cluster. Another approach is to choose $k^{1/2}$ initial centroids so that they cover the map area in a uniform manner. The remaining fraction of the initial cluster population size will be distributed in a random manner, resulting in the most rapidly converging clustering solution.

K-means algorithm requires an input parameter in the form of the initial, expected number of clusters and to make this step completely automatic, we apply the so-called average silhouette width [21] mechanism, in the framework of which the K-means algorithm is executed for different numbers of initial clusters, an average silhouette width is calculated for each of the solution and the cluster count achieving the largest silhouette value is selected.

C. Clustering - results

The best way to show applicability of the clustering mechanism in PON planning procedure, is to apply it on maps that represent actual areas that need a PON deployment. Here we present results we obtained by executing the clustering mechanism on such a map. We still have not adapted and tested our algorithm fully on these maps, but this step is already applicable and best represented on them.

Fig. 5 depicts an example of a real PON deployment (a section of a much larger map). For the sake of clarity of the discussion and cluster representation, the roads and green field areas were removed from the map, leaving only the building contours (non-traversable obstacles). As we can see, ONUs tend to form groups around the buildings, while the implemented clustering mechanism identified 5 different ONUs clusters. Each of the said clusters is surrounded with a light grey contour and numbered. In the following stage of the optimization process, each of the identified clusters will constitute an independent PON branch, providing that sufficient splitter capacity can be assured.

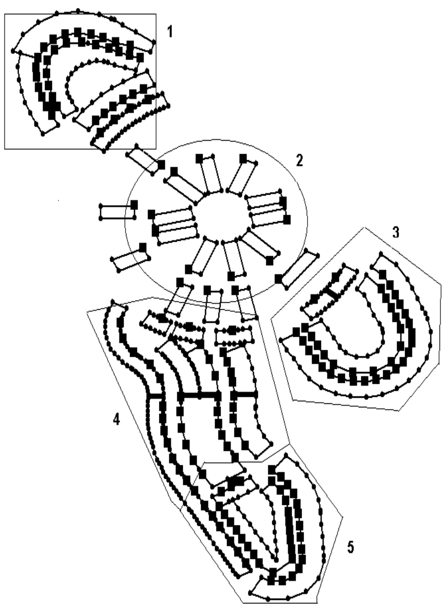

Figure 5. PON clustering process – a detailed example.

D. Genetic algorithm

Genetic algorithm encodes a potential problem solution into a chromosome-like data structure and then applies a number of recombination operators (crossing and mutation processes), in order to preserve critical evolutionary information and discard any unwanted characteristics [25].

The genetic algorithm optimization for the path deployment process is selected due to its rapid convergence. Another approach to the problem includes construction of spanning trees with description of all possible combinations of paths, which become complex when considering the number of resources, obstacles and other map elements which need to be accounted for. Once constructed, a shortest path searching algorithm would have to be applied (Dijkstra, Bellman-Ford, A* search or Floyd-Warshall algorithm), though the required processing grows exponentially with the map complexity, making any attempt to scan the whole solution space futile.

In the case of the PON optimization process, the basic data set describing the problem is limited to a single signal path connecting two pre-defined points. The said path is composed of a series of interconnected and ordered links, spanning between pairs of access points. The selection of the chromosome for a GA process is therefore straightforward. An example of a simple chromosome for PON optimization process based on a GA mechanism is depicted in Fig. 6.

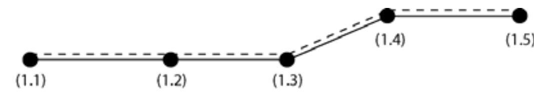

Figure 6. A simple chromosome for a GA based PON optimization process.

The said chromosome is thus a simple path representation, composed of a series of ordered spanning points (1.1) through (1.5), creating a series of links (1.1) → (1.2), (1.2) → (1.3) etc., which in turn create a complete signal path (1.1) → (1.5).

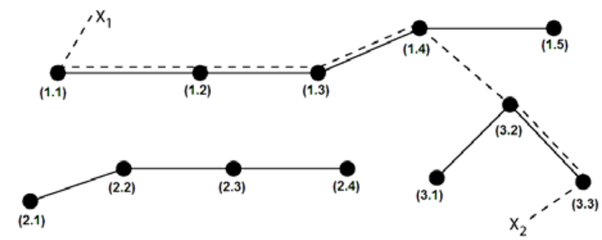

Figure 7. A selected chromosome, connecting points X_1 and X_2, spanning on 3 different resources and creating new interconnections.

Fig. 7 depicts chromosome selection for a more complex system, with several resources, interconnecting points X_1 and X_2 and creating several new connection sections, traversing in the following way: X_1 → (1.1) → (1.2) → (1.3) → (1.4) → (3.2) → (3.3) → X_2. The said PON chromosome is thus the basic data structure for the network deployment optimization process, containing genetic information in the form of an ordered list of spanning points and path fitness.. Additional information stored in the path includes traversed resources and total resource and non-resource lengths etc.

In the PON Builder framework, we optimize network one path at a time. A logical choice for the chromosome is thus a path spanning between the two points we want to connect. For each network segment, a path contains information about, whether the segment in question reuses an existing resource, traverses an obstacle or none of the above. That information enables calculation of path price using (1).

First, we create the initial set of chromosomes (termed initial population) of paths using randomized path finding procedure in order to include as much varied genetic material as possible. Each chromosome represents a potential solution of the given problem (a complete path spanning between two points on the map, traversing a number of existing and newly-created resources), the fitness of which is evaluated using a problem-specific fitness function, which describes the appropriateness of the given solution in numerical terms. The next step comprises creation of the so-called *gene pool* where the chromosomes with the highest fitness enter with higher probability. Having a gene pool, the new generation is created through crossing and optional mutation processes.

The chromosome crossing process is used to introduce variability in the genetic material of the chromosome population, mainly through exchange of sections of genetic encoding between individuals from the same or different populations. The mutation process is used to maintain high diversity of the genetic material and introduce randomness. We have developed two different crossing and three mutation processes since we did not find any already existing that could be applied directly to our problem.

Since the chromosomes with the highest fitness level can enter the gene pool many times, they are more likely to create offspring in the result of the crossing process, and thus are more likely to pass their genetic material to the next generation. Once the offspring pool is created through the crossing process, a new gene pool is created, this time picking from both offspring and parent chromosomes. The above described process is repeated until the end condition is met – the path finding process ends when the fitness function for the best chromosome in the population does not improve for a certain predetermined number of generations.

Since the whole network structure is created one path at a time, whenever a path is established, all its non-resource segments are added to the set of existing resources. That way all the resources that must be built for that path can be reused for all the subsequently calculated paths. It means that the resource map may change after establishing every new path.

IV. RESULTS

In this section, we present a few examples of the optimization schemes using custom designed maps with resources, obstacles, and PON equipment. Networks obtained by software are compared to networks we designed manually. The price-list for the PON system optimization scenarios presented in this and following sections is included in Table I.

TABLE I. UNITARY PRICES OF INDIVIDUAL OPTIMIZATION PROCESS ELEMENTS, EXPRESSED IN €.

Price component name	Unit	unitary price [€]
Fibre	M	5
SC connector - Go4 Fibre SC/APC single mode pre-assembled, zirconia / conical pre-angled APC ferrule, 125 µm fibre diameter, 0.9 mm green boot	Unit	5
Fusion splice (average price)	Unit	20
Fibre placement – existing trench (cable placement)	M	50
Fibre placement – existing aerial line (cable placement)	M	50
Resource deployment - new trench	M	1000
Resource deployment - new aerial line	M	1000
PSC price (1 to 16 split ratio)	Unit	750
Obstacle traversing	M	250

A. Single path test

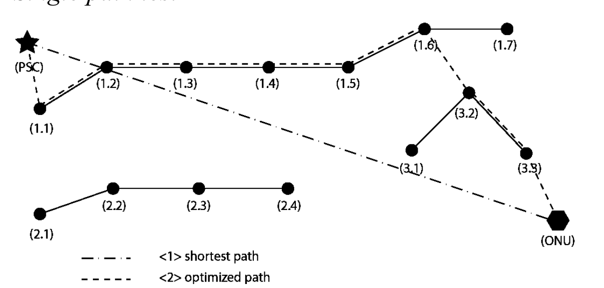

Figure 8. Demonstration of path finding procedure for a simple map.

This section contains results of genetic algorithm path finding procedure for a very simple map. On the map there is only one ONU and one PSC, thus only one path is calculated. The path we found maximizes the use of the resources and is cheaper than the shortest path (see Fig. 8).

B. Map with a dense resource base and without obstacles

The examined PON optimization scenario is comprised of a complex resource map, with several ONUs (5), an OLT and a pre-located PSC module, as depicted in Fig. 9. The available resource network has several individual branches located close to each other. The resource network allocation was selected deliberately in such a way to test the efficiency of path searching mechanisms in terms of finding cross-resource connections and re-utilize the existing resources where possible.

Table II presents the collected output parameters of the designed PON networks, namely shortest path, optimized and hand-made deployments, including total link length, network deployment cost as well as the network cost relative to the deployment cost in the optimized scenario.

In this particular case, the hand-made connection is only 1% more expensive when compared to the optimized scenario, mainly thanks to a dense resource network, allowing for deploying the fibre paths in a manner consistent with the optimization scheme. The hand-made and optimized results differ only for a single ONU, where the optimization mechanism identified a slightly different connection, resulting in a longer link but lower price since the required, new section of the light path was shorter. The difference in hand made and automatically calculated deployment is circled in Fig. 9.

The shortest path deployment (suitable in the case of green-field scenarios) proves to be more than 3.5 times more expensive than the optimized network, while the aggregated cable lengths differ only by 54.184% (747.211 m and 1152.077 m for the shortest and optimized paths, respectively).

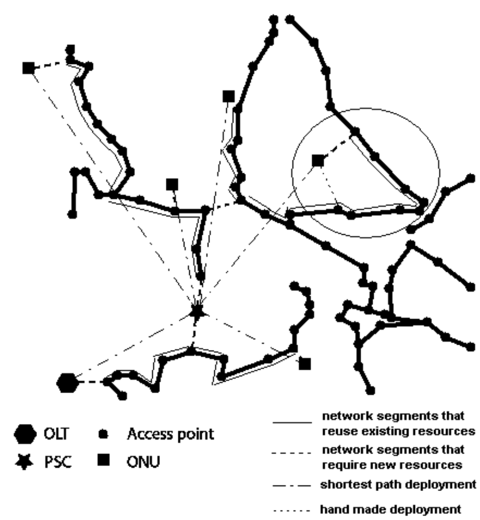

Figure 9. Complex map. Hand made and optimized paths differ significantly from the shortest possible connection.

TABLE II. COMPARISON IN TERMS OF PRICE AND PATH LENGTH BETWEEN HAND MADE AND OPTIMUM CONNECTIONS FOR A MAP DEPICTED IN FIG.9.

Path type	Path length [m]	Path cost [€]	Path cost [%]
Shortest	747.211	754682.962	350.95%
Hand-made	1025.878	217232.867	101.02%
Calculated	1152.077	215042.183	100.00%

It must be noted here that the PSC module was pre-located, thus eliminating one degree of freedom in the network design process.

C. Map with dense resource base and with non-traversable obstacles

Next, we extend the previously examined resource and PON component map with a number of non-traversable obstacles, which represent elements of the local infrastructure e.g. private houses, protected areas etc., which cannot be used to guide telecommunication cables for a variety of reasons. These obstacles must not be traversed by any of the paths that make up the network.

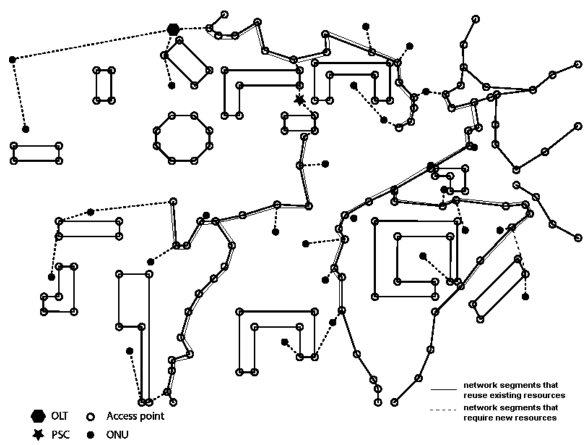

Figure 10. Dense resource map with non-traversable obstacles, hand made deployment.

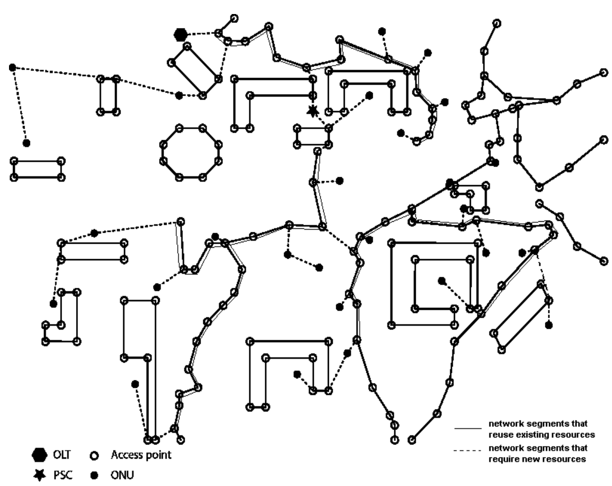

Figure 11. Dense resource map with non-traversable obstacles, deployment calculated by software.

TABLE III. COMPARISON IN TERMS OF PRICE AND PATH LENGTH BETWEEN HAND MADE AND OPTIMUM CONNECTIONS FOR MAP DEPICTED IN FIG. 10 AND 11.

Path type	Path length [m]	Scenario cost [€]	Path cost [%]
Hand-made	4661.3	784969.28	107.96%
Calculated	3422.13	727071.22	100%

D. Map with dense resource base and with mixed obstacles

Next, part of the added obstacle objects are marked as traversable, meaning that the cables can be deployed in the specific area though the cost is much higher when compared with the other regions. It is expected therefore that the optimization algorithm shall find the optimum connection path between the given pairs of points, avoiding the non-traversable and potentially running through traversable obstacles, providing that the resulting path cost is lower when compared to the scenario, when all obstacles are avoided at all costs.

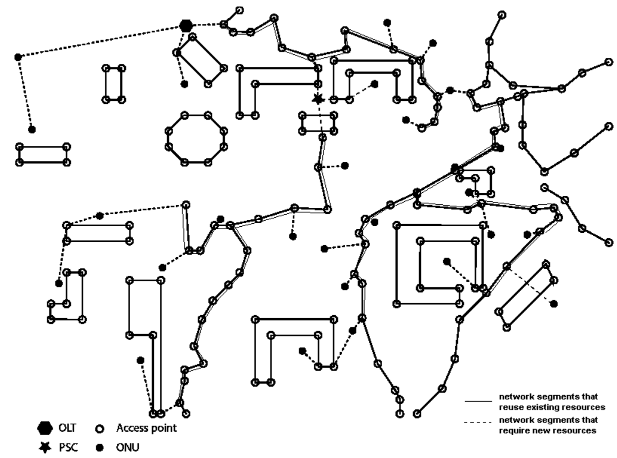

Figure 12. Dense resource map with mixed obstacles, hand made deployment

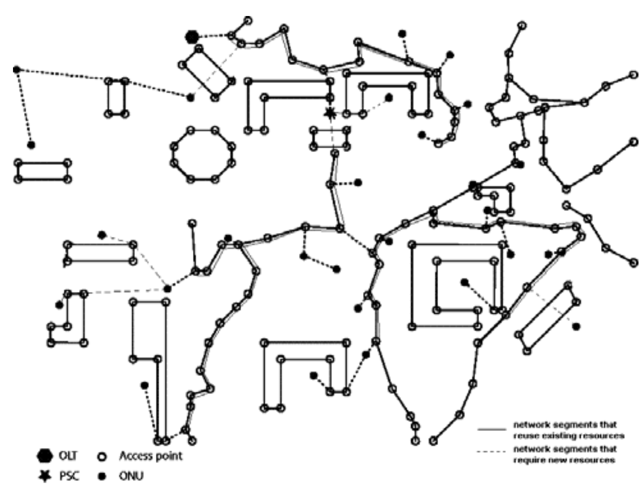

Figure 13. Dense resource map with mixed obstacles, deployment calculated by software

TABLE IV. COMPARISON IN TERMS OF PRICE AND PATH LENGTH BETWEEN HAND MADE AND OPTIMUM CONNECTIONS FOR MAP DEPICTED IN FIG. 12 AND 13.

Path type	Path length [m]	Scenario cost [€]	Path cost [%]
Hand-made	4851.72	769327.76	107.73%
Optimum	3287.53	714120.66	100%

E. *Discussion of results*

In all cases networks calculated by software turned out cheaper than the hand-made ones, though upon closer inspection of the maps, it was found that there are some parts of the hand-made deployments in Fig. 10 and Fig. 12 that are cheaper than their counterparts in the automatically calculated ones. One such pair of segments is demonstrated in Fig. 14.

TABLE V. COMPARISON IN TERMS OF PRICE OF NETWORK SEGMENTS IN FIG. 14

Path type	Scenario cost [€]
Hand-made	164520,33
Obtained by software	173415,29

This problem emerges because of the order in which paths are calculated. Since each previously calculated path is potentially a resource for the new path, ordering influences result of the network calculating process. The paths calculated are optimum for the resources that exist in the moment of their creation, but resource map may vary depending on order of connecting ONUs/OLT to the PSC. Taking into account every possible ordering increases computational complexity a lot, so different approaches for resolving this problem are needed. We are now considering some kind of preordering of ONUs based on their distance from the PSC or some other criterion.

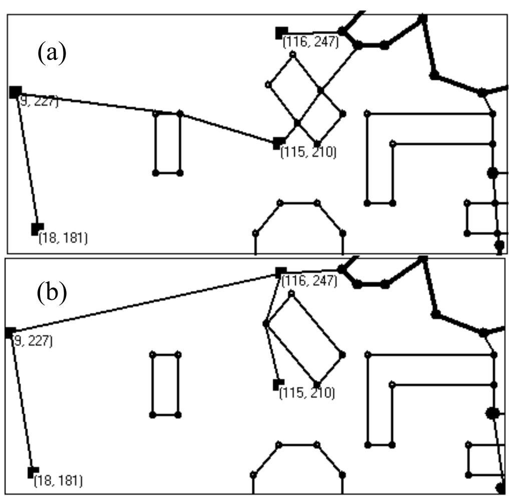

Figure 14. a) segment of the software calculated deployment from section IV.C b) segment of the hand-made deployment from section IV.C

V. CONCLUSIONS

This paper presents the initial results obtained from the PON optimization tools, which are currently under development by the authors. Several PON network deployment scenarios were examined, including hand-made and automatically calculated deployments and compared indicating that it is possible to achieve lower network cost by eliminating human factor in decision making process. The path finding GA based procedure itself works well. More research in order of connecting ONUs is needed, but overall we believe that this method has a lot of potential. We are planning to investigate obstacle avoidance more and have already developed a new method that has some advantages over the one used to produce results presented in this article. Next step in our work is to adapt and test what we have created so far on maps that represent real areas that are intended for PON deployment and to compare deployments produced by our software to those made by experienced network planners. On these maps clustering part of the procedure will play a bigger part due to the fact that ONUs, in real world, are usually concentrated around building complexes thus forming clusters. On the hand made, imaginary maps we used to test the procedure so far, ONUs were quite dispersed because our main goal was to test the genetic algorithm itself. That is why we have shown what we want to achieve by clustering on a map that represents a real area. We are now concentrated on merging clustering and path finding procedure, developing them further and testing them on real area maps.

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