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**22nd European Regional ITS Conference
Budapest, 18-21 September, 2011**

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Automatic Map-based FTTX Access Network Design**

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Topology design, Strategic Design, Network planning, GIS, Map, Techno-economic, Cost estimation

Abstract

Several mature and standardized optical access network technologies are available for network operators providing broadband services, being now in deployment phase; therefore cost estimation, business analysis, efficient deployment strategies, network and topology design issues for FTTx access networks play an increasingly important role regarding profitability and market success.

In a competitive environment, techno-economic evaluation supports the optimal choice among available technologies. Even the tradeoff between future proof technical superiority and short term investment minimization requires a farseeing decision. In our point of view, cost estimation and techno-economic evaluation is strongly related to strategic network design: among others the uneven population density, irregular street system or infrastructure have significant impact on the network topology, thus the deployment costs as well. In order to deal with these aspects, a high-level, strategic network design is necessary that adapts to geospatial characteristics of the services area, providing accurate and detailed network information for the techno-economic evaluation [1].

We have developed a topology designer methodology that supports the above requirements, providing (near) optimal topology of the fully or partially optical access network, based on the geospatial information about the service area: digital maps, existing infrastructure and subscriber database.

Automatic topology design for large-scale service areas, with 10.000s of subscribers is a highly complex mathematical problem. The tough algorithmic challenge is addressed by decomposition techniques and highly specialized heuristic algorithms for a near optimal, yet efficient solution. The developed algorithms were evaluated regarding their speed and accuracy.

Based on topology design results, a detailed and flexible techno-economic comparison is carried out, since the framework handles various broadband access network technologies, as presented in a case study.

Introduction

Access networks are currently moving from the legacy copper infrastructure to a new fiber infrastructure. These optical access networks provide among others notably higher bandwidth; lower latency and the potential of triple (quadruple) play services. From operator perspective, these altogether mean a future-proof solution for current and future subscriber demands and service requirements.

Optical access networks are also referred to as *Fiber to the X* (FTTX) network, where the X stands for the termination of the optical transmission, e.g. Fiber to the Home (FTTH), Fiber to the Building (FTTB), Fiber to the Curb (FTTC), Fiber to the Neighborhood (FTTN), etc. Multiple competing technologies exist that are capable to deliver optical access connectivity to customers.

Passive Optical Networks (PON) have a point-multipoint structure, having a passive optical distribution node between the Central Office of the provider and the customer premises. The EPON or GPON technologies, which are already standardized and widely deployed all across the world, belong to this group. The new WDM PON systems have also appeared on the market, offering virtual point-to-point connectivity with separate wavelengths to every subscriber.

Active Ethernet architecture provides a different approach for the point-multipoint access network, using active equipment in the distribution node. *Point-to-point optical access networks* are also applied widely, providing dedicated fiber connectivity, which makes it attractive for e.g. business customers.

The FTTC / FTTN architectures often rely on the existing copper infrastructure, replacing the feeder part of the copper network with optical fiber, except the last mile (or even shorter) segment. The *xDSL* (e.g. VDSL, VDSL2) technologies offer a reasonable trade-off between cost-savings in the cable plant, and increased network capabilities.

As we have seen, several optical access network technologies are available for network operators providing broadband services. Profitability and market success may be achieved by efficient deployment strategies. Not only high-level guidelines and rules of thumb, but strategic network design, preliminary cost estimation, decision support, feasibility studies, and the business case analysis has to be integrated in a computer-aided network designer system.

The next section summarizes the fundamental objectives of such economic and also technical analysis of various network technologies, including evaluation and comparison of the options. The section dedicated to *strategic network design* gives an overview of the methodology and some insights about the algorithmic aspects of topology design as a mathematical problem.

Description of the proposed framework and comprehensive methodology, which combines network design with preliminary cost estimation and economic analysis, follows the theoretic approach, and finally a case study completes the paper.

Techno-economic analysis

Techno-economic analysis, as the name suggests, refers to the investigation of the network from two different, but strongly connected aspects: technical performance, and economic value. Obviously, the already mentioned FTTX technologies have different strengths and weaknesses, which makes them hard to compare, and impossible to choose the “best” among them in general. On the other hand, a comparison of them for a particular service area is possible, and this is in the focus of techno-economic studies.

In a competitive environment, techno-economic evaluation supports the optimal choice among available technologies. Even the tradeoff between future proof technical superiority and short term investment minimization requires a farseeing decision. Coupled with the fact that the technologies adapt differently to various geospatial conditions, techno-economic comparison is clearly a highly complex issue, having key importance.

The fundamentals of a general techno-economic framework are presented in one of our recent papers [3], and we highlight its most important elements here.

Economic aspects

Deployment cost estimation is the first and foremost step in the comparison of competing technologies. In the current practice, geometric models are applied to acquire information about the expected network topology and characteristics for cost and further business analysis. A drawback of these geometric models lies in the fact that uneven population density, irregular street system or infrastructure are beyond scope of these models using solely average descriptors of the service area (for a deeper comparison see [2]).

In our point of view, cost estimation is strongly related to strategic network design: the above mentioned issues have significant impact on the network topology, thus the deployment costs as well, as our recent evaluations have shown [2]. In order to deal with these aspects, a high-level, strategic network design is necessary that adapts to geospatial characteristics of the services area, providing accurate and detailed network. It supports the deployment cost estimations and further economic evaluation also, as it provides the data necessary for e.g. OPEX calculations.

If these results are combined with market analysis and revenue expectations, the future Cash Flow, Return of Investment or IRR calculations become available, and significantly higher accuracy is available, in comparison to rule-of-thumb type cost per user estimations.

Technical performance

The mentioned FTTX technologies have different physical characteristics that make them attractive for a set of scenarios, but inappropriate for others. Not only the economic aspects, but also the technical performance (level of service) makes a difference between them, depending on the population density, diameter of the service area, etc.

The strategic network design, which takes the physical constraints into account, reveals these effects in the preliminary design and estimation phase. Coupled with a market analysis, the most suitable technology may be chosen, that meets the demands, requirements, and offers the highest profitability.

The strategic network design process lies in the heart of the methodology. It provides the level of detail necessary for the preliminary calculations, without the complexity and input data requirements of low-level design. This strategic network design is presented in the next section as a mathematical problem, along with the brief description of the methods for solving it.

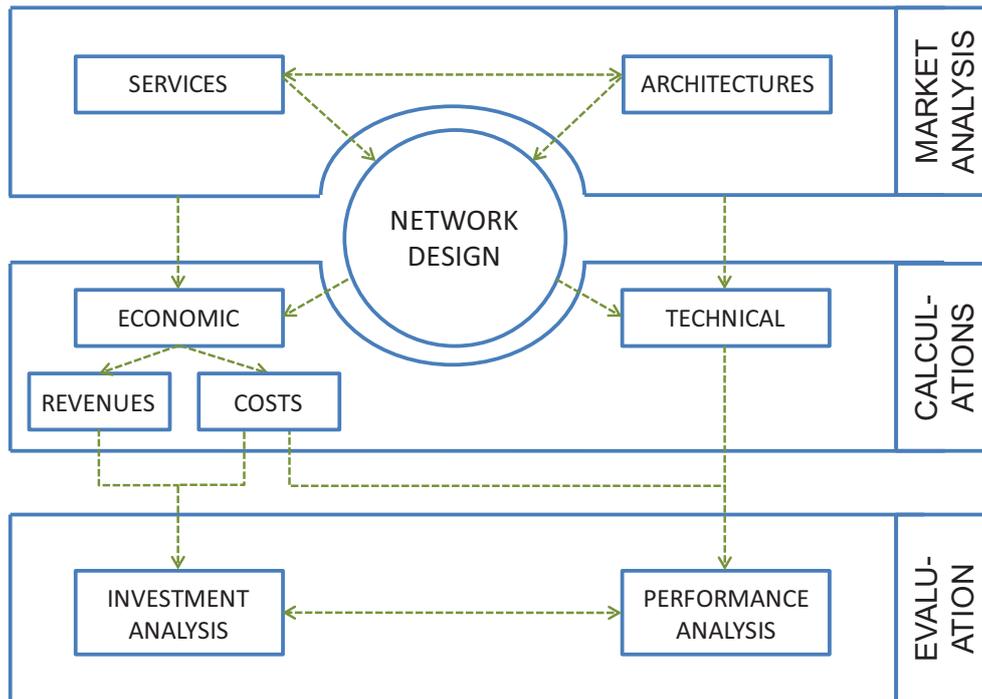


Figure 1 Techno-economic evaluation (source: [3])

Strategic network design

In order to make more accurate estimation of the investment costs, strategic network design is a clearly better choice in contrast with geometric estimation models. It is a totally different approach; geographical information of the service area are also taken into consideration. In this case, the network topology is created based on miscellaneous geospatial data e.g. street system, existing network infrastructure and location of the potential subscribers. Thus, the cost of the cable plant and network equipments will be computed as results of the network design process. Therefore, the accuracy of the cost estimation can be significantly increased, due to the higher level of detail.

The main algorithmic challenge is to develop a methodology for automatic topology design of point-to-multipoint access networks that can be used to perform calculations for the expected deployment costs. This topology optimization problem can be well formulated as a mathematical graph problem that will be presented in the following section.

Network model

In the service area of a point-to-multipoint access networks each subscriber is connected to the central office of the telecommunication provider via distribution equipments, with respect to the chosen technology, i.e. splitters in PONs. For the mathematical representation of this network topology, we are using the following graph model (Figure 2): given a graph representing a set of the possible network links; many subscriber nodes (a set of households); and finally a source node (the location of the central office).

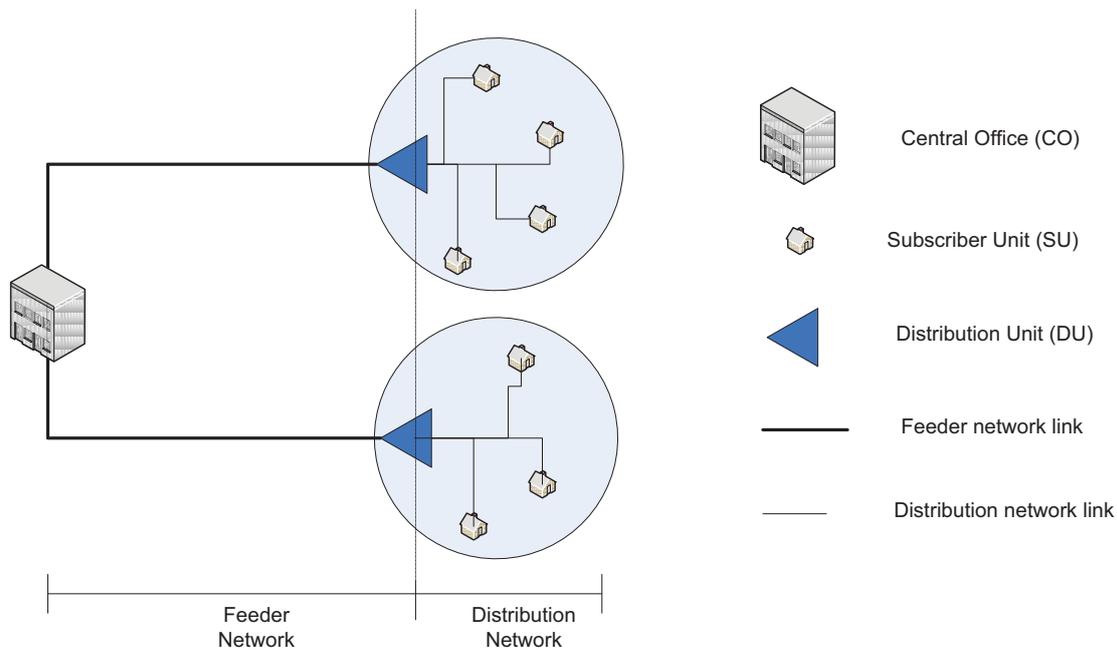


Figure 2 Point-multipoint access network architecture

Constraints

We need to define various constraints in order to meet the physical requirements of the access networks. These technological requirements are transformed to parameters in the network model. The following constraints are assigned: maximal capacity limit of distribution equipments; allowed locations for the distribution equipments (a set of nodes); length limits of the connections at the each segment of the network e.g. in active optical access networks different limits are applied to the feeder network (between CO and distribution units), and the distribution network (between subscriber nodes and distribution units), while in PON networks length limits are applied for the complete optical connection.

Cost function

According to the elaborated basic network model the optimization problem is to find a minimum-cost subgraph which corresponds with the above-mentioned constraints. Therefore, our objective is the minimization of the capital expenditures including equipments cost and cable costs (not only path length minimization). The first part of the objective function is the equipments cost (particular distribution units); calculation of that is straightforward. The second part contains the cable costs; however they can be computed with difficulty. The cost of the cable deployment contains the installation cost that depends on the existence of the cable and the fiber cost that is a capacity-dependent cost, resulting in a stepwise function.

Complexity

NP-hardness for the formulated problem is proven via linear reductions of various known hard problems [1], e.g. Steiner-tree [4] or Capacitated Plant Location Problem [5]. In addition, realistic large-scale scenarios, with 10.000s of subscribers make an extreme algorithmic challenge that needs highly efficient methods.

Methodology

The access network design problem has a general formal representation as we have seen; solution with integer linear programming is an obvious choice. This way we can get exact optimum, however computation time is significantly increased due to the exponential time complexity. Unfortunately, large-scale inputs make it impossible to use; even with high-performance computers and CPLEX ILP solver, topology planning process is intractable for inputs over a thousand subscribers.

Relaxation is a potential choice in order to handle large-scale scenarios; the simplified problem by relaxing hard constraints results in reduced complexity. Regarding our planning problem such a relaxation approach can be a predetermined parameter e.g. predefined subscribers groups, predefined equipment locations, etc. or ignore either of constraints. Applying these simplifications the complexity is considerably reduced, but on the other hand the accuracy of cost estimation and the practicability of the developed method is questionable, which is in turn a relevant part of the strategic topology design.

Thus, using approximation algorithms is the right way for finding applicable solutions. In this case, we have to make a trade-off between the accuracy of the convergence and computational time. Then we get a valid, but sub-optimal solution within a reasonable time even for large-scale scenarios. Execution time of design process is less emphasized, given the fact that network planning is typically an offline problem. Therefore the optimization process could take even up to several days, if the accuracy of solution is significantly improved.

Algorithms

The aforementioned technological solutions in the access network are different many ways; technology-dependent heuristics are needed. However the basic – point-to-multipoint – architecture is identical as shown at the abstract graph model (Figure 2) and it provides a natural decomposition (Figure 3).

- (1) Groups of subscribers are created based on their assignment to distribution units, where size of a cluster is bounded by maximal capacity, which makes it a special graph clustering problem.
- (2) In the separated groups, the respective distribution units are allocated by minimization of fiber usage.
- (3) Finally the distribution units are connected to the central office and the subscribers to their distribution units by optimizing installation needs and fiber usage.

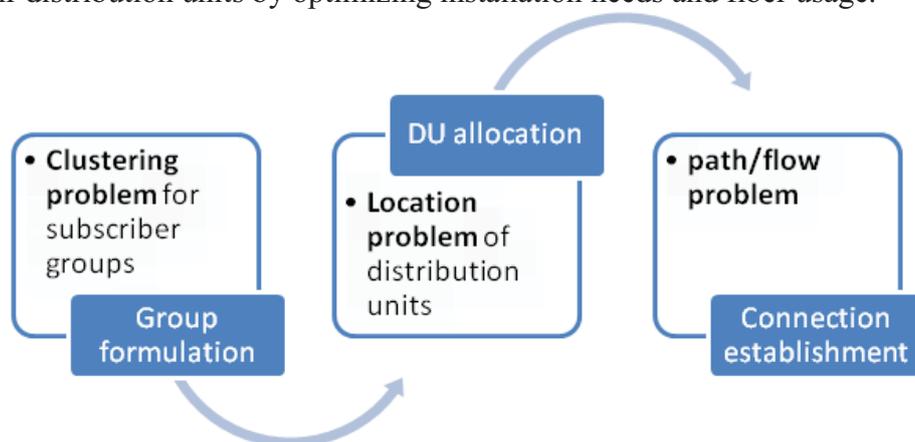


Figure 3 Decomposition technique of the point-to-multipoint access network design problem

Due to the strong interdependence of the three subproblems (e.g. low fiber usage cannot be achieved with scattered clusters), they have to be analyzed and solved carefully. The topology-dependent algorithms were developed based on the above demonstrated decomposition technique, solving each subproblem with efficient specialized heuristics, taking into account the interdependence among the phases also.

The developed algorithms were evaluated regarding their speed and accuracy. Exponential complexity was successfully avoided, that makes practical applications possible, even for large-scale scenarios, with 10.000s of households in a single service area. On the other hand, the approximation performance has proven to be acceptable, being within 10-15% of the optimum.

AccessPlan Framework

Applying the strategic design process for cost estimation requires a complete framework with various modules and subroutines. Thus, we have developed a complete topology designer framework to support the above requirements. A layered view of the main modules of AccessPlan Framework is shown on Figure 4.

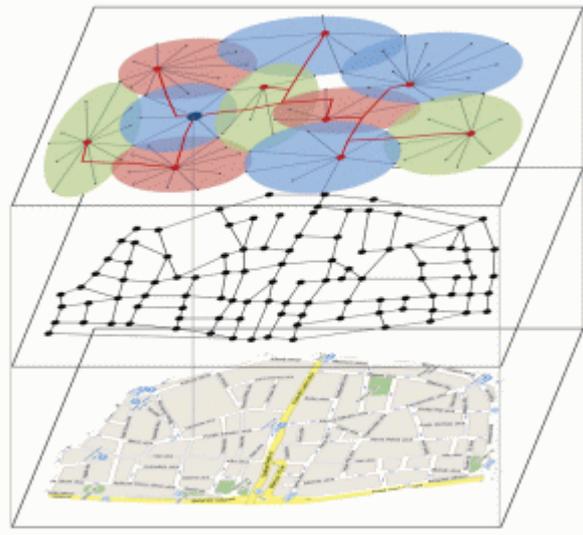


Figure 4 AccessPlan Framework [6]

The automatic topology design process provides near optimal topology of the fully or partially optical access network, based on the geospatial information about the service area. So as an initiative step, collecting and processing of GIS data are required from digital maps, existing infrastructure and subscriber database. Geospatial data analysis is also available in this phase, e.g. the population density variance.

In the second phase after the input data processing, the introduced graph model is created, representing the access network. Combined the graph model with the technology-specific constraints and type/cost values of the links, the optimization problem is defined.

In the optimization phase, a set of specialized heuristic algorithms are working on the graph model, using the decomposition technique that was discussed in the latter section. Finally the optimized strategic topology design is transformed from the graph model to the original map supporting further use with visualization.

The resulting topology offers the detailed information necessary for accurate cost calculations, e.g. equipments lists and cable plant needs (bill of material). Coupled with the specific cost models of the operator, it supports investment decision and feasibility studies.

Based on topology design results, a detailed and flexible techno-economic comparison is carried out, since the framework handles various broadband access network technologies, e.g. GPON, 10GPON, WDM PON, Point-to-Point optical access, Active Ethernet or xDSL systems. The techno-economic evaluation framework supports network design, deployment cost analysis, preliminary CAPEX/OPEX calculations, investment decision and comparison of technologies and architectures.

Case Study

In this section a case study is presented, based on real-life data about a particular service area in Budapest - the specific parameters of the selected area are found in the following table and the map is shown on Figure 5.

This section is now dedicated to the demonstration about how to apply the strategic network design for cost estimation and techno-economic evaluation, and is not about a comprehensive techno-economic analysis of FTTX technologies.

The selected scenario is the complete service area of a central office located in Budapest, the capital of Hungary. We have chosen mixed type urban-suburban area with various types of buildings and residential zones, to demonstrate the flexibility of the developed methodology and framework: in this case, the mentioned irregularity is present in the population density distribution and the street system as well.

Area [km ²]	4.7
Buildings	1079
Building density [building/km ²]	230
Households	4239
Household density [household/km ²]	902
Street system length [km]	82
Graph nodes	~8000
Graph edges	~8500

Table 1 Scenario parameters

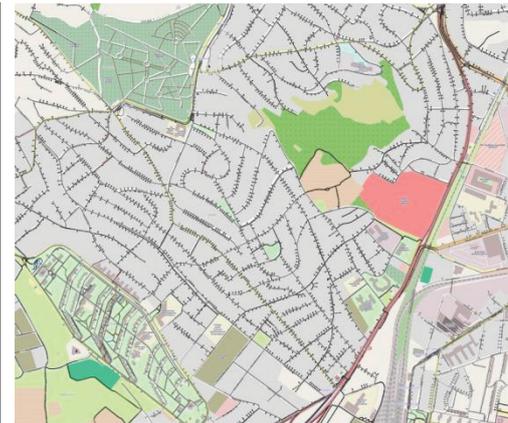


Figure 5 Scenario map

After the input GIS data and technology-specific parameters are processed, the strategic topology designs were produced for the following technologies: P2P, GPON, AETH, and VDSL. The calculations took 5-30 minutes for the different technologies, respectively, which is a remarkably low computational time for a scenario with over 4.000 households.

First of all, the result of the design process is a set of various network data, including the necessary materials and cabling activity, as presented in Table 2 for GPON.

A comparison of the cable plant dimensions is shown on Figure 6. The significantly higher fiber needs of a point-to-point network is obvious compared to a point-multipoint topology: the use of distribution nodes in the cable plant leads to approx. one order of magnitude decrease in fiber usage. Among the other point-multipoint topologies, the fiber usage is connected to the capacity of the distribution unit equipments, i.e. the cluster diameter.

For the VDSL network, the distribution (copper) network is shaded, but indicated for comparison.

Table 2 Material calculations (GPON)

Material summary	
#Splitters (1:64 GPON)	79 (at 70 different locations)
Total length of cable plant (traces)	35 910 m
Total length of optical fiber	776 278 m
Optical fiber in feeder network	212 182 m
Optical fiber in distribution network	564 096 m
Cable needs	
<i>Cable capacity (fiber count)</i>	<i>Length</i>
12	15 211 m
24	7 856 m
36	7 508 m
48	1 761
72	1 942
96	1 401
144	228
Cable capacity (fiber count)	Length
Topology average descriptors	
Optical fiber / demand point	177 m
Average splitter usage (fill-rate)	86%

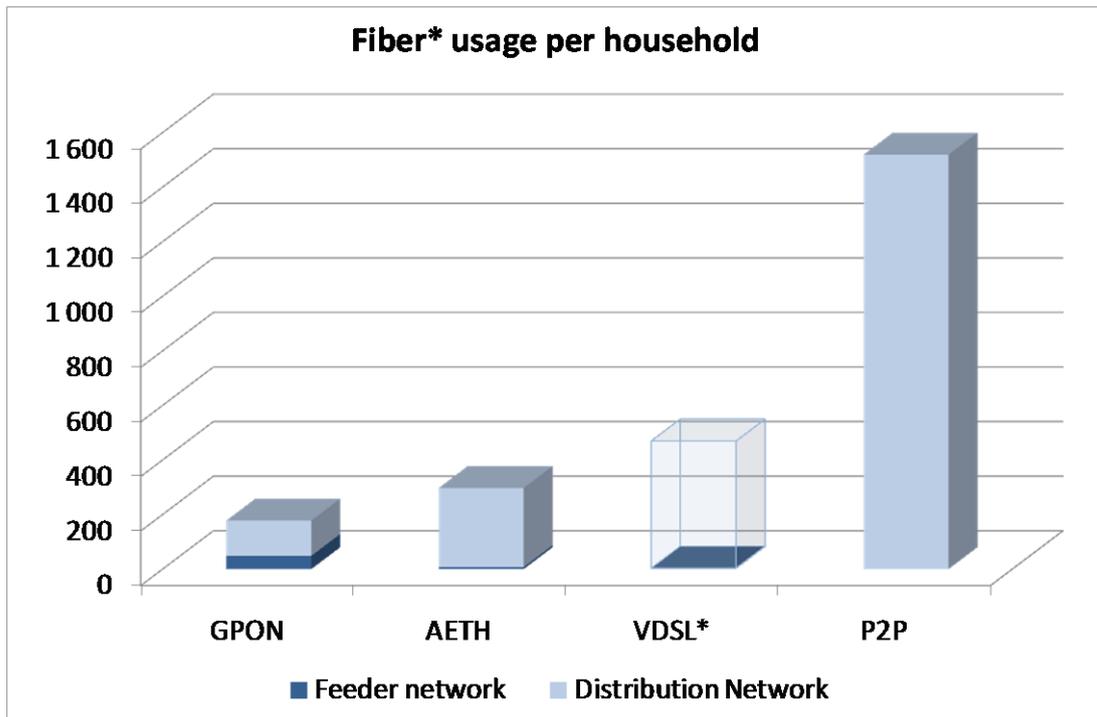


Figure 6 Fiber usage (m / per household)

The network information, coupled with a detailed cost database results in a reliable estimation of network deployment costs (CAPEX).

Figure 7 shows a comparison of the estimated CAPEX, divided into equipment and cable plant parts, according to the provided infrastructure information. Most of the area was covered by existing cable ducts or aerial poles, which could be re-used with a moderate cost.

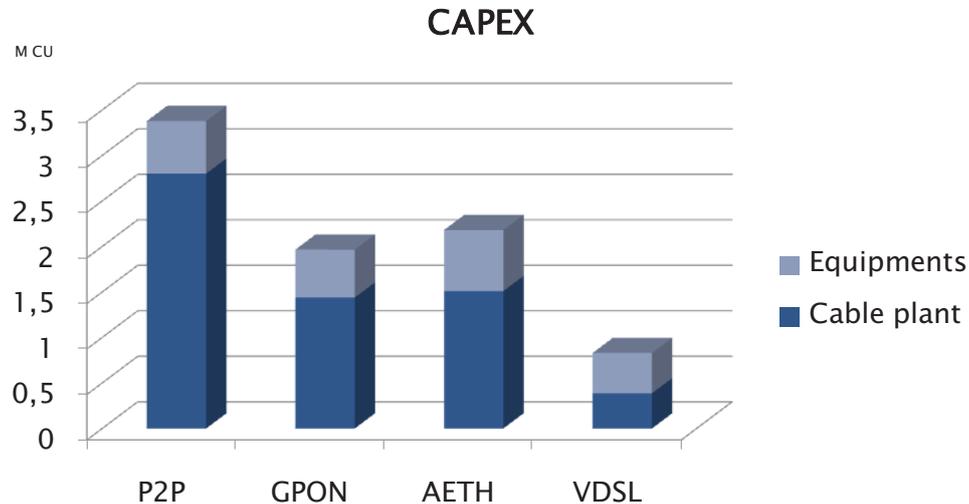


Figure 7 Comparison of deployment costs

In addition, investment calculations were also performed as seen on the next figures: annual and cumulated cash flows were evaluated, in order to be of assistance to telecommunication providers and network designers in investment decisions. In the current scenario, a VDSL and GPON network (due to its lower cable plant investment needs) leads to a profitable project with relatively long payback period (VDSL with lower investment and income rates), while the point-to-point optical access for all homes does not pay off.

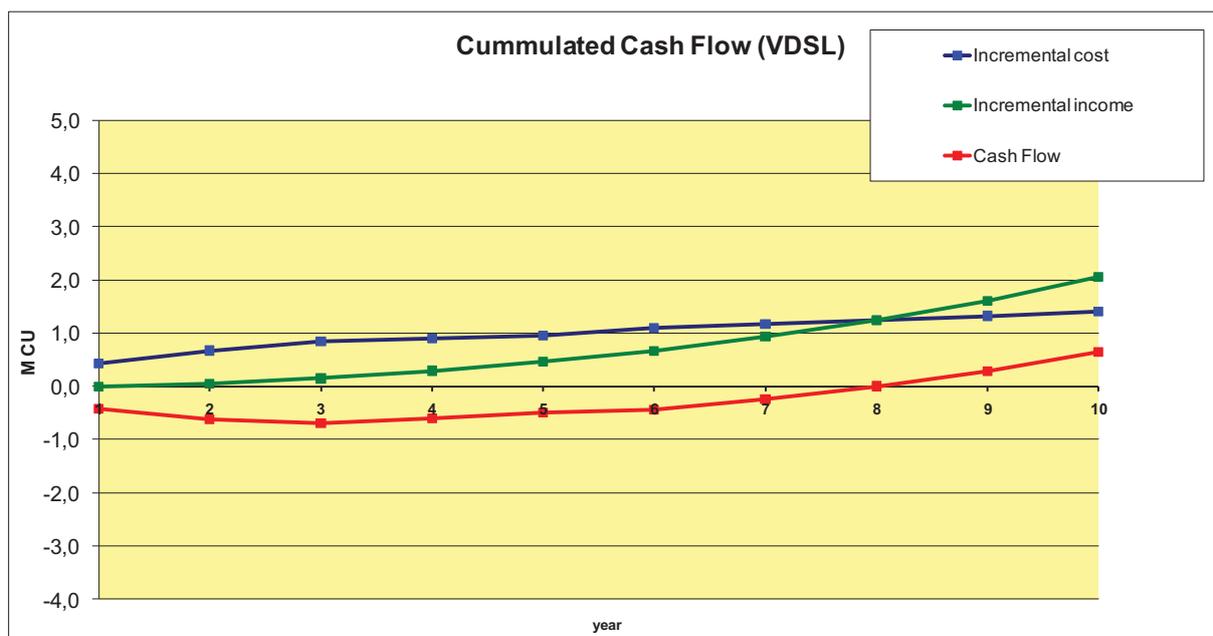


Figure 8 Cash Flow (VDSL)

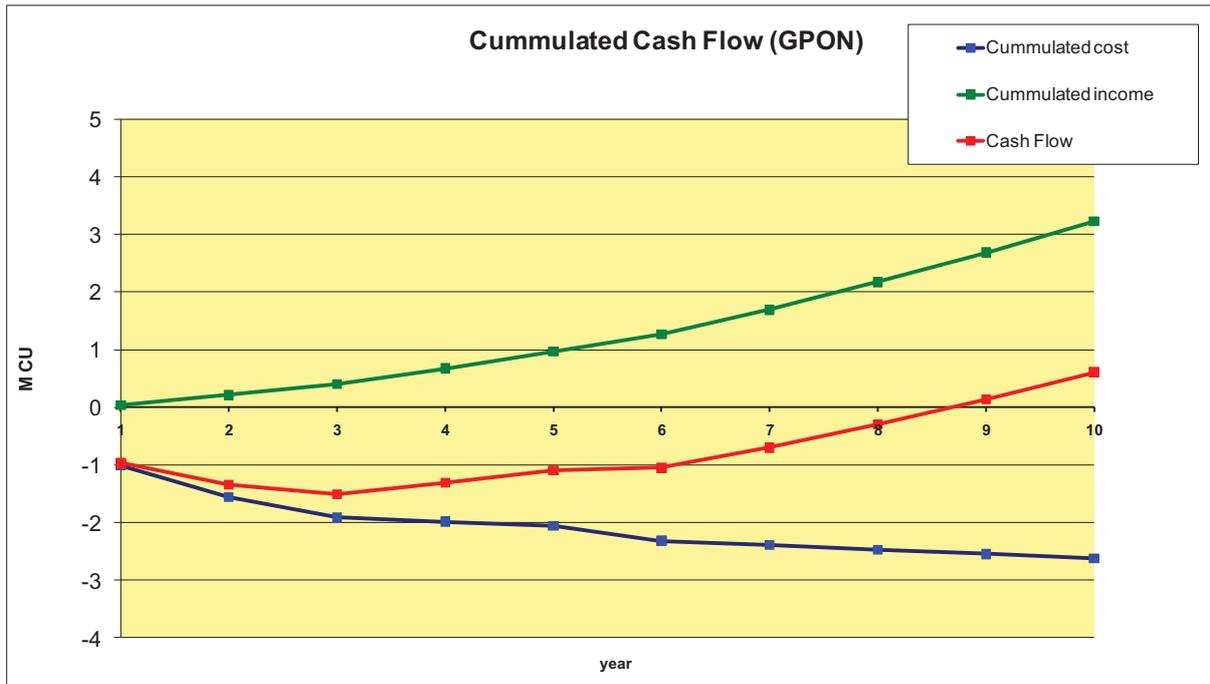


Figure 9 Cash Flow (GPON)

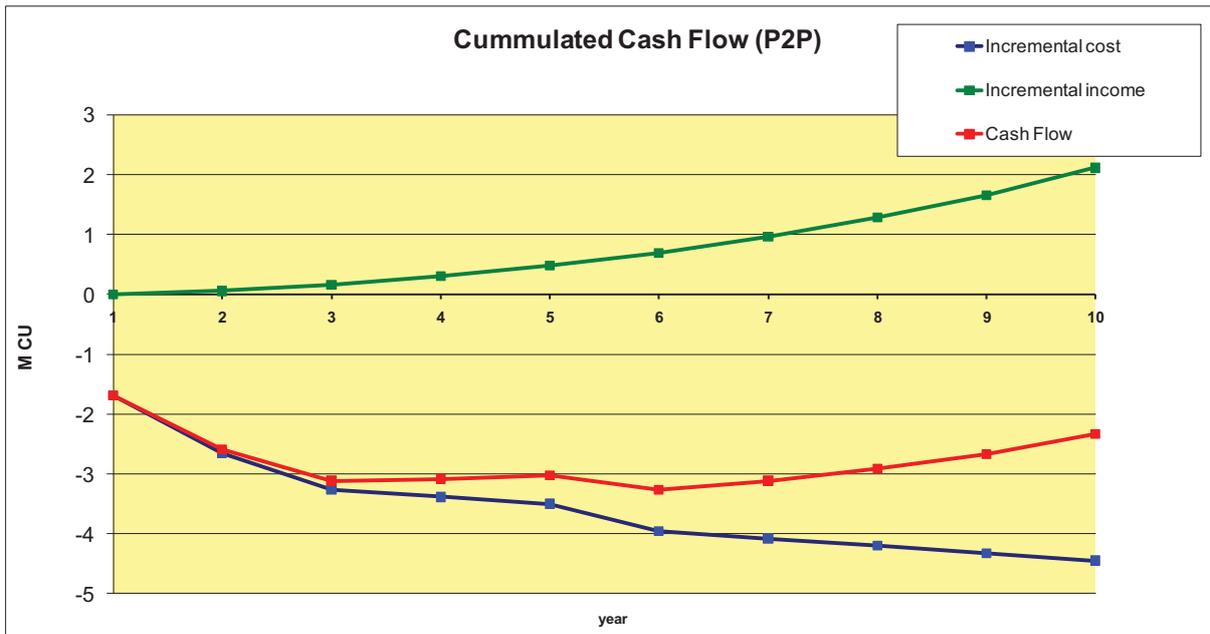


Figure 10 Cash Flow (P2P)

Summary

In this paper we have presented a GIS map-based, automatic network design methodology for optical access networks (FTTX). The elaborated methodology is capable to deliver a high-level view of the access network topology for any particular service area, based on geospatial information, considering not only the digital map, but also the infrastructural and subscribed data.

The role and application of the methodology in a complete techno-economic evaluation workflow also shown, illustrated by a case study performed by a framework for GIS data processing and strategic network design that also provides network information for economic analysis.

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