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Overall Plan for Copper-Fiber Infrastructure Switchover: Why, Where, and When

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Abstract: Nowadays, broadband plays an important role in our society. Countries around the world are pursuing initiatives to provide high-speed broadband as a universal service. Currently, digital subscriber line technologies (xDSL) dominate the broadband market, covering more than half of the subscriptions in Organisation for Economic Co-operation and Development (OECD) countries. However, these technologies are unlikely to keep up with these ambitious broadband goals; consequently, traditional copper carriers should need to undertake a costly transition in their access infrastructure sooner or later by moving from copper- to fiber-based lines. It is crucial to study, understand, and evaluate different ways of performing this transition to take advantage of the required investment. This paper presents an overall strategy for a copper-fiber switchover, transitioning from the analysis of current copper access, including its limitations, to systematic methods for planning the fiber upgrade and evaluating its economic feasibility. The following questions summarize the investigated key points of focus: Is it necessary to upgrade the copper access infrastructure? Where is it more efficient to initiate the fiber deployment? When is the investment expected to return profits? **DOI: 10.1061/(ASCE)IS.1943-555X.0000240.**

Author keywords: Fiber access planning; Economics in broadband; xDSL performance; Fast broadband as universal service; Infrastructure; Planning; Computer networks; Network analysis; Optimization models.

Introduction

Broadband has become essential in our daily lives, and its relevance is expected to keep growing in the future. All around the globe, actions are being initiated all around the world in order to improve broadband infrastructure at a global scale. For example, the Digital Agenda of the European Union (EU) sets the goal of achieving 100% access to 30 Mbps downstream connections by 2020 (European Commission 2012); and in the United States, the National Broadband Plan sets the goal of providing 100 million households access to at least 100 Mbps downstream and 50 Mbps upstream connections also by Kruger (2013).

Copper lines still dominate the broadband access market, but they are becoming obsolete due to their transmission data rate limitations, especially over the mid-range and long range. For example, a household 3 km from its access point can only subscribe to an xDSL connection with a theoretical maximum data rate of approximately 5 Mbps downstream.

The contribution of the copper infrastructure in fulfilling or keeping up with future performance-level expectations is rather limited due to its technological constraints, motivating a massive fiber upgrade of the wired broadband infrastructure. Thus, carriers owning the copper infrastructure may need to progressively start replacing the globally spread copper cables with optical fiber lines in order to reach future broadband goals, facilitate a faster development of digital services in society (i.e., tele-health), and help narrow the broadband divide (Plum Cons. 2008; Forzati and Mattson 2011).

Planning the infrastructure to support this transition is rather challenging due to its dimension in the sense of economic investment and efficiency, deployment time, and computational complexity. In this context, the problem must be thoroughly studied in order to determine whether to proceed with an infrastructure deployment of this magnitude. The arguments on this issue should address two simple questions: (1) Is it necessary to replace copper access lines? (2) If this is the case, what would be an efficient approach?

This paper considers the following tasks to provide the proper foundations to answer these two fundamental questions: (1) performance analysis of the existing copper access to identify if upgrading the infrastructure is needed; (2) determining the effect and feasibility of upgrading the copper infrastructure by increasing the number of access points (if a network upgrade is required); (3) evaluation of the necessity of replacing the copper access lines with fiber lines; (4) planning and scheduling of a global copper-fiber switchover plan (if required); and (5) economic analysis of the feasibility of the project to decide where and when to perform the upgrade.

This paper presents a complete methodology for solving the copper-fiber switchover problem from an infrastructure planning perspective based on the aforementioned aspects, including a novel systematic approach to efficiently schedule the fiber deployment. In addition, this methodology was applied to a Danish geographical area for validation and illustration purposes. The results of the study provide enough evidence to answer the two questions.

Copper infrastructure performance and fiber access deployment have been covered in the relevant literature from different perspectives. Examples related to xDSL infrastructure performance include a study of broadband accessibility (Grubesic and Murray 2002), and xDSL quality measurements (Dischinger et al. 2007). Also, a

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wide range of publications cover fiber access deployment, such as Riaz et al. (2005), about the use of geographic information systems (GIS) in automated access planning; Conner and Hanlon (2006), about deployment strategies; and Flecker et al. (2006), about fiber installation. In connection with economic analyses, some representative studies and themes are market challenges, in Shinohara (2005); fiber-to-the-home (FTTH) business models and profitability, in Verbrugge et al. (2011); FTTH rollout cost estimations in Casier et al. (2008); and economic study for global FTTH deployments in Europe (Hätönen 2011) and Germany (Jay and Plueckebaum 2011).

However, to the best of the authors' knowledge, no prior papers have focused on a systematic approach for a global copper-fiber switchover, ranging from the analysis of the current infrastructure (including its potentials and limitations) to the economic feasibility study of a fiber upgrade. Moreover, two concrete and unique contributions can be identified in this work: (1) the systematic use of individual entity-level (household-level) GIS data for thousands of users in the analysis, design, and deployment scheduling of broadband access networks, and (2) efficient fiber deployment scheduling decision methods, focusing on the profitability of the global fiber access plan, including an economic feasibility analysis.

Background

Definitions

The following list gives some important definitions for the proper understanding of this work:

- Basic broadband, fast broadband, and next-generation access (NGA): These terms are used in the document to refer to access data rates. Basic broadband covers the segment up to 30 Mbps, fast broadband between 30 and 100 Mbps, and NGA above 100 Mbps.
- Copper loop: This term refers to the part of the copper access network infrastructure between the users and an access point. This access point can be a central office or a digital subscriber line access multiplexer (DSLAM), and it is the transition point between fiber and copper in the network infrastructure.
- Broadband penetration rate: This term refers to the percentage of households in a given area that have the option of being connected to the broadband access. These households or users are referred to as *connected* in this paper. This number is independent of the number of subscribed users, and it can also be used in relation to a specific access technology.
- Broadband adoption rate: This term refers to the percentage of connected users that are subscribed via a broadband connection. These households or users are referred to as *subscribers* in this paper.
- Broadband divide: This term refers to the difference in accessible data rates by users in an defined area, mainly due to their geographic location (urban or rural). It derived from the digital divide concept, which includes the differences in information technology (IT) development between defined groups (Kandilov and Renkow 2010).
- Phase planning: In this work, the fiber deployment is divided and scheduled into phases or waves. Each phase covers a specific set of households to provide with a fiber connection. The decision of assigning households to each phase can be based on different planning parameters, such as distance, to the access point or population density.
- Preemptive fiber planning: This concept is related to the trenching tasks and deployment of fiber lines. When a road needs to be trenched, enough tubes are placed to install the current required fiber not only for that specific phase, but also for potential future phases. In this way, it is possible to blow fiber into already existing tubes without having to reopen any trenches. The calculation of how tubing is required must be based on a plan for 100% penetration, determining the maximum number of potential connections within each tube.
- Point-to-point: A type of fiber access architecture characterized by providing dedicated fiber connectivity between households and access points. Currently, this architecture may provide the highest bandwidth to end users, which is usually a 100-Mbps symmetric connection (being ready to provide 1 Gbps according to the IEEE 802.3 standard).
- Passive infrastructure: In general terms, this refers to network elements that do not require any power supply. More concretely, the passive infrastructure considered in this work is the set of tubes and fiber required for implementing the network.
- Capital expenditure (CapEx): In this work, this term means the cost of deploying the fiber access passive infrastructure. It covers the expenses of the required trenching, fiber, and tubing.

Foundations

The following list summarizes the topics and publications that serve as foundation or are part of this paper:

- xDSL performance estimation and upper-bound limitations: Initially, a method to evaluate xDSL infrastructure performance at the household level was introduced by Jensen and Gutierrez (2012), which also presented an estimation of growth limitations in copper-based broadband access. In addition, this method was applied to study the broadband divide for a very specific set of users—namely, the agricultural sector—in Jensen et al. (2013). Therefore, the method is indistinctly valid whether it involves hundreds of thousands or only a few users.
- Scheduling deployment: Gutierrez et al. (2013) gave an introduction to deployment prioritization at a global scale. The work describes how to systematically assign deployment priorities to all households in a given area. Basically, this study shows that it may be convenient to prioritize users in dense areas instead of users closer to the access point when providing fiber. This paper extends this concept by implementing a method that outperforms the density based prioritization.

Related Work

The theme covered in this paper is rather broad, and different influences, inspirations, and related work in very diverse fields contributed to the development of this study. There are mainly three categories: xDSL performance evaluation, fiber access planning, and the economics of broadband access.

There are two main groups of methods in relation to xDSL performance estimation: (1) those based on experiments; and (2) those based on infrastructure analysis. Experimentally based estimations consist of taking a number of users and measuring the relevant broadband connection parameters. This can be done actively, by sending and receiving packets from and to the user, or passively, by monitoring and collecting traffic traces from users. An example of active measurement is Dischinger et al. (2007), where cable and xDSL connections in the United States are measured in terms of latency, jitter, and packet-loss rates. An example of passive measurement is Pries et al. (2009), where wireless access traffic is

monitored to compare the throughput of different types of traffic. These kinds of studies provide a performance analysis based on existing broadband connections. They are interesting as a way of understanding the real-world behavior of the network, but they do not really consider the potentials and limitations of the infrastructure itself. Moreover, the tested users must have an active subscription, limiting the analysis to a fraction of the total number of households.

On the other hand, infrastructure analysis–based estimations study the geographic location of the broadband access infrastructure to estimate the potential of users' broadband connections. These are usually done at ZIP/postal code or county level, providing statistical results characterizing broadband possibilities in the defined areas. Therefore, the results provide the likelihood for users to be able to access a certain technology or connection data rate, but they do not distinguish between unique households to identify exactly who has access to what. Some of the most recent examples are Kandilov and Renkow (2010) and Renkow (2011), where broadband availability was studied to quantify the digital divide between different communities. However, this type of studies is rarely performed at the household level. One of the most relevant studies carrying out a broadband analysis at a household level is Grubesic and Murray (2002), where an experiment on the broadband possibilities in a county in Ohio was conducted to estimate the Euclidean distance between access points and households. Then, an optimization exercise is performed in order to provide a better broadband coverage by properly placing the access points. The method in this work differs from the aforementioned study in that it uses cable traces for the evaluation of the copper lines, making it more realistic.

In terms of fiber deployment methods, this paper is based on the fundamentals of GIS combined with automatic algorithms to simultaneously design access networks for thousands of entities. There are several studies that form the foundation or act as inspiration for this work. For example, Madsen and Riaz (2008) introduced a reference model for future access planning, ranging from a review of access technologies to long-term strategic planning processes. Riaz et al. (2005) presented a systematic approach for fiber access planning based on GIS data. Also, Conner and Hanlon (2006) showed FTTH rollout cost estimations where the deployment of a passive optical network (PON) fiber topology is based on the graph theory and optimization algorithms. Hence, this paper adds a new element to the systematic methodology for planning fiber access by developing various selection methods to organize and schedule the deployment plan.

In connection with economic feasibility analyses of global FTTH deployment, interesting contributions include Hätönen (2011), which provided an exhaustive analysis on the cost and financing possibilities of a global fiber deployment in the EU; and Jay and Plueckebaum (2011), which studied the profitable FTTH penetration in Germany. However, these studies were not based on a real-life planning of the network, but on extrapolations of assumptions on the deployment costs of fiber lines. On the contrary, real network design is the foundation for the economic analysis in this work because it involves calculating where the fiber line trenches are dug and the exact amount of fiber (loop length) required to connect each individual user.

Market analysis is not a focus of this work; however, previous studies are worth consulting to complement the economic feasibility analysis presented. Shinohara (2005) presented market challenges and opportunities for high-speed broadband in Japan, and Verbrugge et al. (2011) carried out a survey on FTTH business models and profitability.

Methodology

This section presents the methodology for each task included in this work, illustrated in Fig. 1. Each task is presented in the following format: introduction to the problem, objective, input data, output results, and procedure.

This work is solely focused on access-level infrastructure, so it covers the last few kilometers of the network connecting the user to the net. These are the main elements in the used network model graph:

- Access point (AP): APs are the transition locations between fiber and copper in the access network. APs include central offices as well as DSLAMs, and they are the last active points in the access network before reaching the network termination (NT) point, discussed next. The influence area of an AP is referred to as the set of NTs to which it provides connectivity.
- Network termination (NT): NTs are the final point in the access network infrastructure, where the users are located, and represent private households, businesses, warehouses, and other elements.
- Segment point (SP): The road network is abstracted as a graph formed by thousands of nodes connected by road segments. These points are referred to in this work as *segment points*. The weight given to the road segments is their physical length. In this way, the road network is transformed into a format that facilitates the computation of graph optimization processes. Each NT and AP is connected to the road network through only one SP. Fig. 2 illustrates an example of the road network abstraction.

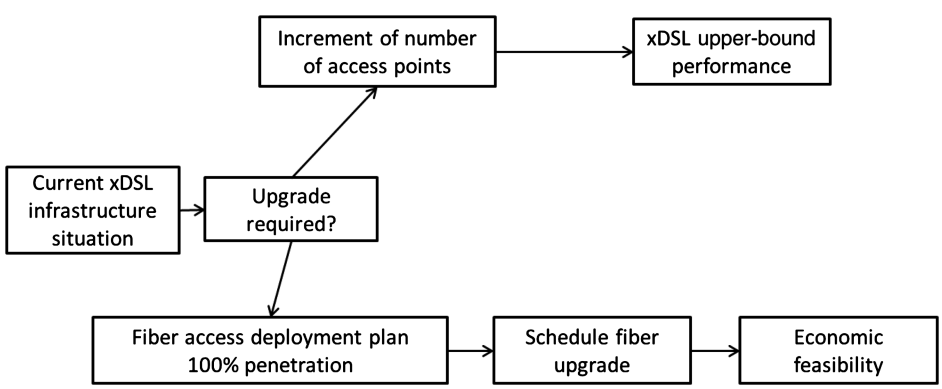

Fig. 1. Copper-fiber switchover evaluation method

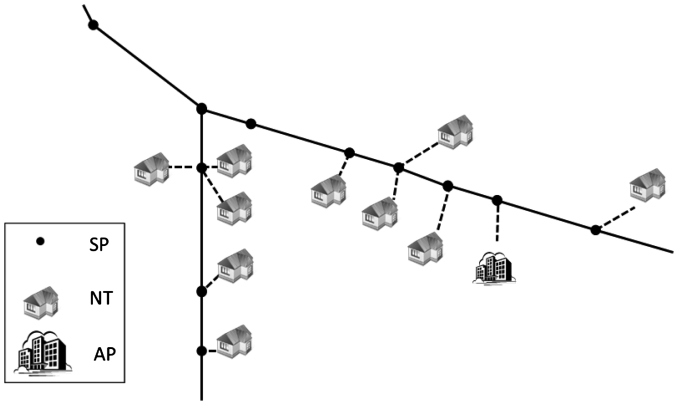

Fig. 2. Road network abstraction

Current xDSL Performance Analysis

Introduction

The following question summarizes the goal of this analysis: *Is there any need to upgrade the copper access infrastructure?*

The quantification of the current user broadband accessibility can provide an answer to this question. Consequently, the following text introduces the procedure to evaluate the performance of xDSL infrastructure at a household level. xDSL data rates are highly influenced by the length of the copper loop due to signal attenuation, degradation, and interference in the transmission medium. Jensen and Gutierrez (2012) graphically presented the relation between downstream and upstream data rates of different xDSL technologies and copper loop length.

Several initiatives are currently under development to increase the achievable data rates over a distance via copper lines. Examples are pair bonding, vectoring (Oksman et al. 2010), and future technologies such as G.Fast and Phantom (Umek 2012). Unfortunately, the effective range of these technologies is still a short distance from the access point (i.e., vectoring is claimed to provide connections up to 100 Mbps in a 300-m range) and will most likely only improve the access to customers that already had a good very-high-bit-rate digital subscriber line (VDSL) connection.

For customers farther from the access point (e.g., 3,000 m), there is no feasible copper-based solution to achieve downstream data rates anywhere close to fast broadband or NGA levels. Thus, the development of these new transmission techniques over copper access will not solve the broadband divide problem, but it could help ease it.

Objective

- Quantify the maximum accessible xDSL downstream and upstream data rates by each individual potential user (NT) in a region.

Input Data

- The geographical location of all APs and the area of influence;
- The geographical location of all NTs in the area;
- The geographical information about the road network in the area; and
- The theoretical relation between copper loop length and achievable xDSL data rates.

Output Result

- The distance from each individual NT to its associated AP.

Procedure

Usually, copper loop lines follow the street/road network as either an underground or aerial infrastructure. Consequently, in order to estimate the local loop length for each NT, the calculation of the shortest road path spanning tree (SPST) from each AP to all NTs in its respective influence area is required. In this case, the path length from each NT to its AP is equivalent to the loop length, so it is directly related to the achievable data rates presented in Jensen and Gutierrez (2012). The use of the shortest path and theoretical maximum achievable data rates generate best-case-scenario results. In reality, examples exist where copper lines do not strictly follow the shortest paths or their quality/conditions do not allow achievable data rates close to the theoretical maximum values.

The SPST is a minimization problem formulated as follows. Let $G(V, E)$ be the road network graph, with V as the nodes [or segment points (SPs)] and E as the edges (or road segments). Thus, a combination of edges $E' \subseteq E$ can be found for each AP that forms a tree $T(V', E')$, which allows the establishment of the shortest path between the AP and all NTs in its influence area, with all these NTs connected to one and only one of the elements of $V' \subseteq V$. The number of trees formed is the same as the number of APs.

Therefore, the procedure includes three basic steps:

1. Calculation of SPST from all APs to all NTs in their influence area;
2. Estimation of the copper loop length for each NT; and
3. Quantification of xDSL possibilities relating the copper loop length with achievable data rates versus distance.

xDSL Infrastructure Upper-Bound Performance Estimation

Introduction

The following question summarizes the goals of this estimation: *Could/should the xDSL access infrastructure be upgraded by increasing the number of APs?* The answer can be obtained by estimating the xDSL performance in several scenarios created by increasing the number of APs in the studied area in a distributed way. Usually, the strategy followed by copper carriers is to progressively push fiber closer to the customers, deploying fiber-to-the-cabinet (FTTC) or fiber-to-the-build (FTTB) and providing second-generation VDSL (VDSL2) connections (Alcatel-Lucent 2011). The last segment of the access infrastructure is still a copper line, but since the APs are closer to the users, the loop length is reduced and the accessible data rates increase. The main question regarding this approach is how many of theses APs are required to provide fast broadband as a universal service. Each of the APs contains active equipment that needs a power supply, implying an upper-bound quantity limit.

The basic idea of this analysis is to estimate the size of a copper access network (number of APs) necessary to provide certain services to the majority of the population. In this work, the term *majority* refers to coverage above 90% of households (NTs). The method and experiment were previously introduced by Jensen and Gutierrez (2012). In addition, an estimation of the number of APs required to provide fast broadband to the majority of the population was noted.

Objective

- Studying the feasibility of increasing the number of APs that can provide a number of common online services and fast broadband to more than 90% of the population in a region.

Input Data

- The geographical location of all NTs in the area;
- The geographical information about the road network in the area;

- The theoretical relation between copper loop length and achievable xDSL data rates; and
- Data rate requirements for the evaluated services.

Output Result

- The relation between the required number of APs and coverage for the evaluated services and fast broadband.

Procedure

In this experiment, different scenarios were created by evenly distributing a variable number of APs in the studied region. For each scenario, the achievable upstream and downstream data rates by each individual NT are calculated, and the services they have proper access to are indicated implicitly.

However, this is a nondeterministic polynomial (NP)–time-hard facility location problem, and in this specific case, solving it for a considerable variable number of APs to extract the results and combining them with road distance calculations is resource-consuming. Similar problems solved in different fields using various methods include the description of a novel approach for locating the electric vehicle infrastructure for highways applying continuous facility location models (Sathaye and Kelley 2013); and the presentation and evaluation of heuristics-based methods to reduce the search time in uncapacitated problems (Ghosh 2003). The proposed method in this paper is based on an idea introduced by Nielsen et al. (2006) showing that there is no significant difference between the final cost of deploying a FTTH network when locating APs using an Euclidean-based center of gravity method in comparison to a Lagrangian relaxation with a subgradient optimization solution. The cost is directly related to the length of the roads trenched.

The method used here consists of dividing the area under study into square cells of dimension CD. Each cell may contain an AP only when fulfilling the precondition of minimum household per cell MHC, and it is located at the center of gravity of the cell. Eq. (1) determines the location of a generic AP in a cell C [$AP(C)$], with NT_C as the set of NTs within cell C and x_{nt} and y_{nt} as the coordinates of each $nt \in NT_C$

$$AP(C) = \left(\frac{\sum_{nt \in NT_C} x_{nt}}{|NT_C|}, \frac{\sum_{nt \in NT_C} y_{nt}}{|NT_C|} \right) \tag{1}$$

Hence, the center of gravity is based on Euclidean distances between points. Alternatively, a more complex approach would be to calculate the minimum spanning tree (Cheriton and Tarjan 1976) within each cell, and the point where the average distance between itself and all NTs within the cell is minimized. This point can be calculated by solving the P-median problem, which is NP-hard (Narula et al. 1977).

The coverage of four common services and fast broadband are evaluated for each of the scenarios generated when distributing the APs. Table 1 presents the services, together with their characteristics and maximum loop length to fulfill the data rate requirements.

Table 1. Services, Requirements, and Copper Loop Length Thresholds

Service	Downstream (Mbps)	Upstream (Mbps)	Loop length (m)
3D TV broadcast	18	0	1,800
YouTube streaming HD 1080 P	8	0	3,000
HD e-health video presence	5	5	1,200
Skype HD video calling	1.5	1.5	2,000
Fast broadband	30	—	900

Note: Data from Evensen et al. (2011), Ezell et al. (2009), Krogfoss et al. (2011), and Skype (2014).

The information about the services is extracted from Krogfoss et al. (2011), Ezell et al. (2009), Evensen et al. (2011), and Skype (2014). Restrictions for video conference services usually come due to upstream limitations since most of the current xDSL connections are not symmetric, dedicating considerably more bandwidth to downstream traffic.

NT Priority Selection

Introduction

The deployment of fiber access is a process that can take several years, and its planning and scheduling are not trivial matters. The first required task is to calculate how the network must be interconnected (i.e., how NTs physically connect to APs). The copper-fiber switchover project is based on an already-existing infrastructure. It is a brownfield scenario where the APs' facilities in the copper access are maintained, converted into fiber-access APs, and used in the newly planned fiber access.

In practice, access networks do not operate in isolation, as a back-haul infrastructure is necessary to connect them to the world. To address this problem, the authors assumed that the necessary distribution network interconnecting all APs is in place and sufficient to carry all the traffic demands from the access network. Moreover, the APs are limited to the ones already in place, as involving new APs may also require restructuring the distribution network in the design process.

In this work, the interconnections are designed by determining the SPST with the APs as roots, as the fiber lines are assumed to be installed along the roads. The resulting trees provide connectivity between each of the NTs and one of the APs. Then the deployment must be planned in time following a scheduling procedure. Basically, the scheduling is the selection of households/neighborhoods to prioritize the order of fiber access deployment. The idea discussed here is simple: to provide fiber connectivity first to the NTs that indicate the lowest investment. In this way, the investment required to generate income from subscribers may be minimized.

The deployment prioritization is interesting both when 100% of the NTs are connected to the network and when only a fraction of them are provided with fiber. In the case of global coverage (100% penetration), the resulting infrastructure at the end of the project is the same regardless of the deployment scheduling: it is global FTTH penetration that provides the shortest road path between APs and NTs. The different scheduling procedures represent various ways of reaching the same goal. For this reason, the first time that a road segment is trenched, enough tube is put in place to install all the potential lines that may be required for future deployment phases. Despite the final network being the same in all cases, it might be preferable to connect the NTs implying the least expenses first. This raises up the first question in relation to deployment (or rollout) scheduling: *Is it relevant to schedule the deployment of a fiber access network at the household level when aiming for 100% fiber penetration?*

On the other hand, the benefits are clearer in the case of partial coverage, where a balance between CapEx and penetration has to be met, making the project economically feasible. This balance can be formulated in terms of return of investment (e.g., calculating the maximum final penetration without exceeding a certain payback period) or in terms of profitability (e.g., calculating the penetration to obtain the maximum profit over the lifetime of the fiber infrastructure). These two points of view lead to the following two questions:

- How can the deployment be scheduled to maximize the penetration in a profitable fiber access implementation project?

- How can the deployment be scheduled to maximize the profit in a fiber access implementation project?

The main difficulty with assigning deployment priorities is that the price of providing one NT with fiber cannot be isolated from the rest of the NTs. This cost is highly dependent on which other NTs are already connected at that time and which NTs are sharing the infrastructure costs and how. Thus, this dependency creates a complex combinatorial problem to determine the optimal deployment order, where the cost of progressively connecting thousands of NTs depends on what has been previously connected.

The problem of scheduling infrastructure deployment related to profit/CapEx optimization has been treated from many different points of view. For example, Hong et al. (2006) analytically investigated how to optimize the scheduling of water distribution infrastructure elements replacement in terms of costs. This study was based on models describing failure occurrence and expected CapEx.

Similar to this work, Hsieh and Liu (1997) proposed a two-stage method to maximize the profit of an infrastructure investment. First, an investment plan is optimized using multiobjective heuristics, and based on the outcome, the scheduling of the investment plan is optimized using linear programming techniques.

Theoretically, this scheduling problem is a combinatorial optimization problem that could be solved using binary decision variables, using as many decision variables as the number of NTs to be interconnected, and at each phase, selecting the NTs that minimize the deployment costs or maximize the profit of the project. However, there are several factors that make this problem complex to solve. The cost of providing one NT with fiber cannot be isolated from the rest of the NTs, and the cost of deploying fiber in a street segment (the edges of the graph) is variable and dependent on the final network that would be implemented. Moreover, the nonlinearity of the constraint of always forming connected trees at the conclusion of each phase makes it infeasible to use efficient optimization techniques using decision variables such as integer linear programming (ILP). For example, Zhang et al. (2013) used this technique in the context of life-cycle optimization in pavement networks.

Methods based on heuristics such as genetic algorithms or simulated annealing are potential ways to solve very complex combinatorial optimization problems with nonlinear constraints [see Cunha and Sousa (2001), which worked on optimizing hydraulic infrastructure]. However, the large size of the binary vectors that would be required (30,000 for the case study), combined with the requirement of verifying the connectivity of the resulting trees and evaluation of the objective function for each tentative solution, may also incur impractical running times. Therefore, this paper proposes a method to simplify the NT priority selection and compares it with two others that are widely used in real FTTH infrastructure design (distance- and population density-based). The novel method introduced in this work outperforms the other two.

Objective

- Evaluate different methods to schedule the fiber deployment by dividing the set of NTs to provide fiber access into groups (phases).

Input Data

- The geographical location of all NTs in the area;
- The geographical information about the road network in the area;
- SPSTs from the APs connecting all NTs (they are considered as inputs to the scheduling problem but must be calculated beforehand);
- The distance from every NT to its associated AP;
- Population density; and
- The economic cost model for CapEx calculation and cost factor selection method.

Output Results.

- Priority assignment to all covered NTs in the network applying three distinctive methods; and
- Relation between penetration and CapEx for three selection methods.

Procedure

The basic idea behind the procedure in this paper is to assign to each NT a priority value based on three different parameters: distance to the AP, population density, and cost factor. Gutierrez et al. (2013) already introduced the first two parameters in relation to scheduling the deployment of a FTTH network dividing it into three phases. Moreover, Hätönen (2011) indicated that the density-based method could be a good approach for deciding which users can be provided with fiber access more economically; however, the conclusion is based on assumptions and extrapolations rather than real-life planning designs. Also, Rokkas et al. (2010) acknowledged that the density-based procedure is followed by incumbent operators to replace their copper infrastructure.

Based on any of the proposed prioritization methods, the complete set of NTs to be connected by fiber can be subdivided into deployment phases. In this way, early deployment phases cover the NTs with the highest priority. The numerical value of the priorities assigned to the NTs is trivial so long as the order is maintained. The deployment phases can be characterized or limited by the number of NTs covered (e.g., deployment time or CapEx). The next text describes in detail the three evaluated scheduling methods, focusing on the novel contribution of this part of the study, the cost factor–based scheduling:

- Distance-based (PR_{dist}): NTs closer to their AP are given higher priority. In this way, the tree formed when deploying the fiber is progressively expanding from the APs in all possible directions. Hence, a priority PR_{dist} given to all NTs is inversely proportional to their distance to their AP.
- Density-based (PR_{dens}): NTs in areas with higher population density are given a higher priority. Each NT is associated to a population density value Pd. Thus, a priority PR_{dens} assigned to all NTs is directly proportional to their density value.
- Cost factor–based (PR_{cf}): The priority is given based on a variable cost factor; in this case, it is assigned to the SPs belonging to the SPSTs for 100% fiber penetration. The chronology of the method is the opposite of the two previous approaches. Instead of starting with assigning higher priorities to NTs, in this case the lower priorities are assigned first. Conceptually, the priorities are given based on how expensive it is to deploy parts of the network, giving higher priorities to cheaper parts. The assignment process consists of iteratively reducing the tree graphs by removing the most expensive parts to be deployed. A cost factor associated to each SP indicates which parts are the most expensive, and this dynamically varies along with the iterative process. Initially, cost factors are calculated for all SPs in the SPSTs and 100% fiber penetration. The objective is to select the SPs with the highest cost factor, remove them from the graph, and then recalculate the cost factor for the remaining SPs in the subgraph. Summarizing, a cost factor (Ct) is assigned to each SP, representing the CapEx savings obtained by removing it and its associated branch from the tree graph.

The removal of SPs from the graph is performed by a greedy iterative algorithm that selects one SP at a time—the one with the highest cost factor. This removal affects the cost factor associated with some of the remaining SPs, and these need to be updated as the graph is modified. Each removed SP and all the associated

NTs removed with it from the graph at the same time are given the same priority PR_{cf}, inversely proportional to the order of removal. The process ends when all the SPs are removed from the tree.

The following list and text formally present the methodology to assign the initial cost factor:

- Definition 1: Let a primary node be any SP in the network, denoted as p, and its associated primary link $l_{p,p'}$ (between SP p and SP p') being the first link in the path between p and its AP, with p farther from the AP than p'.
- Definition 2: Let the secondary nodes associated to a primary SP p be all the nodes that contain p in their path to their AP, and the secondary links be the existing links of the SPST interconnecting all secondary nodes between each other and p.
- Definition 3: Let a branch B^p be the subgraph formed by a primary node p, its associated primary link $l_{p,p'}$, and all the associated secondary nodes and links.

From an infrastructure point of view, a branch B^p can be defined as a combination of deployed trenches, tubes and fiber, connecting NTs to a subgraph. These parameters are used to define the cost factor, referred to as *cumulative variables* and presented in Eqs. (2)–(5). The cost model excludes the last meters of infrastructure connecting the NTs to their correspondent SP. Depending on the strategy of the carrier, this expense relays on the customer, the carrier, or both.

Eq. (2) formally defines the cumulative parameter cm^p_{nt}, which represents the number of NTs connected to the network by a generic branch B^p, NT_{sp} being the set of NTs connected to SP sp in B^p

$$cm^p_{nt} = \sum_{\forall\, sp \in B^p} |NT_{sp}| \tag{2}$$

Eq. (3) presents the cumulative variable cm^p_{tr}, which determines the required trenching for a generic branch B^p associated with a primary SP p. Each of the links $l_{s,s'}$ is characterized by a weight $\omega(l_{s,s'})$, in this case representing its length; and (s, s') are any pair of nodes that are directly connected by a link in B^p

$$cm^p_{tr} = \sum_{\forall s,s' \in B^p} \omega(l_{s,s'}) \tag{3}$$

Eq. (4) shows the calculation of the cumulative parameter cm^p_f, which represents the required fiber to serve all NTs in a branch B^p, d_{sp} being the road path distance between SP sp in the network and its associated AP, and NT_{sp} being the set of nodes connected to an SP. In a point-to-point architecture, providing an NT with fiber implies that one dedicated fiber should be deployed from the AP to the NT

$$cm^p_f = \sum_{\forall sp \in B^p} |NT_{sp}| \cdot d_{sp} \tag{4}$$

Eq. (5) describes the the cumulative parameter cm^p_{tb}, which quantifies the tubing installed in a branch B^p, fb_{tb} being the maximum number of fibers that can be installed per tube. Here, s and s' are any pair of nodes that are directly connected by a link in B^p, s being farther from the AP than s'

$$cm^p_{tb} = \sum_{\forall s,s' \in B^p} \omega(l_{s,s'}) \cdot \left\lceil \frac{cm^s_{nt}}{fb_{tb}} \right\rceil \tag{5}$$

Eq. (6) concludes by illustrating the initial cost factor Ct^p_o assigned to an SP p. P_{tr}, P_{tb}, and P_f are the prices for a meter of trenching, tube, and fiber, respectively. Conceptually, the cost factor represents the average cost per household to provide fiber to all NTs in a branch

$$Ct^p_o = \frac{cm^p_{tr} \cdot P_{tr} + cm^p_f \cdot P_f + cm^p_{tb} \cdot P_{tb}}{cm^p_{nt}} \tag{6}$$

Removal and Update

Once the initial cost factors are assigned, the iterative removal process begins. The SP with the highest Ct_o is selected, and all NTs connected to it are given the same deployment priority, which is inversely proportional to the iteration in which they are removed (i.e., the first-removed NTs would have the lowest priority, and vice versa). The corresponding branch is removed from the tree, implying that all its associated elements (NTs, SP, and links) are removed. The cumulative variables of all the affected SPs must be updated to calculate new associated cost factors. The update can be generically formulated as described next.

Let a be an SP selected to be removed and cm^a_{nt}, cm^a_{tr}, cm^a_{tb}, and cm^a_f its associated cumulative parameters. The path from a to its AP can be defined as a combination of SPs $[SP(p_a)]$ and implicitly, the only SPs affected by the removal of a are the elements in $SP(p_a)$. Eq. (7) presents the updated calculation for the cumulative parameters for all affected $b \in SP(p_a)$, with cm'^b_x as the updated parameters for b; and its associated cost factor is calculated using the newly updated parameters in Eq. (6):

$$\begin{aligned} cm'^b_{nt} &= cm^b_{nt} - cm^a_{nt} \\ cm'^b_{tr} &= cm^b_{tr} - cm^a_{tr} \\ cm'^b_{tb} &- cm^b_{tb} - cm^a_{tb} \\ cm'^b_f &= cm^b_f - cm^a_f \end{aligned} \tag{7}$$

Fig. 3 presents a simple example illustrating the cumulative parameter calculations and updates for SP b, with a being the removed SP. The weights given to the links represent their lengths.

Economic Models

The economic feasibility of any project can be evaluated from several perspectives and specific constraints, but however it is calculated, it has one characteristic goal: positive balance. More concretely related to the topic of this paper, the decisions involved in the network deployment plan, such as final penetration or deployment scheduling, should be based on additional specific economic goals. The authors evaluated two simple goals: (1) earning maximum profit after the network's lifetime and (2) achieving the maximum profitable penetration.

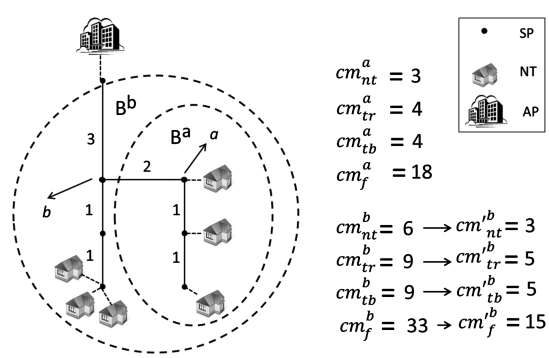

Fig. 3. Cost factor calculation and update example

The following text presents the economic model used to evaluate the feasibility of FTTH deployments in connection with the prioritization methods described previously. These methods are used to divide the deployment period into phases that each provide a number of NTs with fiber.

The basic idea is to illustrate how the decision of which users are given a fiber connection first has an effect on the cash flow, payback period, and profitable deployment coverage for a carrier. Therefore, the economic impact of the scheduling of a switchover plan is evaluated in this case by calculating the *discounted payback period (DPB)* and the *net present value (NPV)* of the project. Basically, DPB reflects the time that it takes to make a project profitable (in this case, the time to recover the CapEx involved in the deployment of the network), and NPV may be related to how profitable the project is.

Since this work focuses on the copper-fiber switchover, the considered expenses are only related to the deployment of the passive infrastructure, leaving out the cost of active equipment replacement at the APs. The considered profit is a fraction of the revenue obtained from the subscription fee (i.e., the fraction assigned to recover the deployment expenses). Thus, once the fiber is installed, there are only positive cash flows, and no further expenses are considered. The model assumes that the expenses for one year are prepaid in advance.

Objective

- Evaluate the profitability of the fiber access deployment in relation to the three introduced prioritization methods.

Input Data

- Fiber access planning for 100% penetration;
- Resulting priorities assigned to all NTs by the three selection methods: PR_{dist}, PR_{dens}, and PR_{cf};
- Economic cost model for CapEx calculation; and
- Economic feasibility model for DPB and NVP calculation.

Output Result

- CapEx, DPB, and NPV for the resulting networks based on the three selection methods and varying penetration rates.

Procedure

The idea discussed here is simple: to divide the deployment of the network into phases based on the three prioritization methods, one at a time, and to evaluate the feasibility and profitability of each one. The feasibility analysis consists of progressively evaluating which of the different phases is preferable. In other words, it figures out what penetration rate is most convenient for deploying the network, which is related to the desired investment recovery time. In addition, profitability can be evaluated by calculating the balance between the earnings and expenses over the lifetime T of the network, in this case the net present value in year T, NPV_T. The methodology and model involved in the feasibility and profitability analyses are described next.

Let NPV_n be the net present value for a fiscal year n defined by Eq. (8), r_d the discount rate representing the average interest rate for investor asset financing, and CF^i the cash flow in year i. CF^0 corresponds to start-up expenses, in this case the CapEx for the first year (CE^1). Let p be the last deployment year for the planned network and DPB be the time (in years) since the initiation of the project until NPV becomes positive after the network is deployed. Eq. (9) formally presents this concept

$$NPV_n = \sum_{i=1}^{n} \frac{CF^i}{(1+r_d)^i} + CF^0 \tag{8}$$

$$DPB = n, \quad \text{if } NPV_n > 0, \qquad NPV_{n-1} < 0 \ \& \ n \geq p \tag{9}$$

The cash flow represents the balance between expenses CE and revenue RE. The model assumes that the expenses for a fiscal year i are paid in advance at the end of the previous year $(i-1)$, and the revenue is collected at the beginning of the following year $(i+1)$. Eq. (10) generically defines the CapEx in year i, with CE^i, tr^i, tb^i, and f^i being the meters of trenching, tube, and fiber to be deployed in year i; and P_{tr}, P_{tb}, and P_f being the respective prices per meter. Eq. (11) presents the CapEx involved in the deployment of the whole network CE_{NT}. The revenue RE^i in year i is illustrated in Eq. (12), with NT^t being the total number of NTs in the final plan, pr^i and ar^i being the overall penetration and adoption rates, and sr^i being the yearly revenue from the subscription fee per customer for that year

$$CE^i = tr^i \cdot P_{tr} + f^i \cdot P_f + tb^i \cdot P_{tb} \tag{10}$$

$$CE_{NT} = \sum_{i=0}^{p} CE^i \tag{11}$$

$$RE^i = NT^t \cdot pr^i \cdot ar^i \cdot sr^i \tag{12}$$

Finally, Eq. (13) illustrates the calculation of the cash flow in year i CF^i:

$$CF^i = RE^{i-1} - CE^{i+1} \tag{13}$$

Practical Application and Case Study

The following section illustrates the application of the methods introduced previously by carrying out a number of experiments about a global copper-fiber switchover plan for a concrete geographical area. The results of the experiments provide the necessary support to answer the questions stated earlier in this paper. Validating the methodology as a useful tool to systematically deal with such problems.

Scenario

The geographical area under study is the municipality of Lolland in Denmark. The area of the region is 889 km^2, it covered around 30,000 addresses, 20 existing copper-access APs (as of October 2013), and 1,700 km of roads were used for the experiments. Three experiments were carried out in this location:

- The current xDSL situation;
- xDSL upper-bound performance estimation; and
- Fiber deployment NT priority selection and economic feasibility analysis.

Current xDSL Situation

As previously stated, this experiment consisted of estimating the distance from each individual NT to its AP. In this way, it was possible to calculate the loop length for each NT and consequently relate it to the equivalent accessible data rates, and also to determine who already had access to fast broadband, and the coverage disparities for the residual NTs. Consequently, in this case the results are divided into eight reference coverage groups (four downstream and four upstream), illustrating the current situation of the copper access in Lolland. Table 2 presents these reference groups and their associated loop lengths, from Jensen and Gutierrez (2012).

Table 2. Data Rate Reference Coverage Groups versus Loop Length Thresholds

Data rate (Mbps)	Downstream distance limit (m)	Upstream distance limit (m)
> 30	< 900	< 300
> 10	< 2,500	< 900
> 5	< 3,000	< 1,200
> 2	< 5,000	< 1,800

Note: Data from Jensen and Gutierrez (2012).

Fig. 4 illustrates the coverage results by reference group. As expected, the difference between downstream and upstream accessibility is very significant due to the high degree of asymmetry in the bandwidth allocation for each flow direction. In this particular case, current xDSL technologies provide 30% of the NTs with access to 30 Mbps downstream, as opposed to the EU goal of providing 100% coverage for this value by 2020. Moreover, xDSL currently cannot provide 2 Mbps of downstream access with 100% coverage. To conclude this experiment, return to the initial question: *Is there any need to upgrade the copper access infrastructure?* Here, it is possible to affirm that in this case, the answer is "Yes." Assuming that the 2020 goals will be achieved (or nearly achieved), and that the subscription price differences among access technologies are not significant, the copper access lines providing best-case connections below the fast broadband threshold might become obsolete, as anyone in that segment would have a better fast broadband access option.

xDSL Upper-Bound Performance Estimation

The strategy followed by many traditional copper carriers is to bring fiber closer to customers by deploying new copper APs. This upgrade improves the accessibility to fast broadband for some users, but the question is if this is feasible as a global solution. The following section presents the experiment performed to evaluate this feasibility.

The procedure was to create different scenarios with different numbers of APs, evaluating the xDSL possibilities for users in each of them. The different results may indicate the effect of upgrading copper access by increasing the number of APs over the accessible data rates by users. For this purpose, the area under study was divided into cells forming a grid, characterized by the cell dimension CD and increasing it from 1,000 to 5,000 m in 1,000-m increments. A cell was entitled to have its own AP if the minimum number of households per cell MHC was fulfilled. The value of MHC also varied from 0 to 30 NTs by 10-NT increments. A total of 20 different scenarios were created, with the number of APs ranging from 46 to 840.

Fig. 5 illustrates the results, presenting the coverage as a percentage of NTs that have access to each service and fast broadband in relation to the number of APs. Providing current existing services to the majority of the NTs (> 90%) would require an enormous number of APs (between 200 and 300), and providing fast broadband access would require more than 400 APs. Considering that the current number of existing APs in the region is 20, most likely it would not be feasible to upgrade the network with the necessary APs for at least two reasons: (1) it is not clear that enough copper cable collection points exist for the new APs, and (2) the required amount of active equipment might make the project infeasible in terms of energy consumption, equipment costs, or both.

Consequently, the obtained results provide an answer to the previously stated question: "*Could/should the xDSL access infrastructure be upgraded by increasing the number of APs?*" The answer in this case is "No." Such an upgrade can improve the broadband access in marginal cases to a limited number of users. The number of required APs for it to become a global solution is infeasible in practical terms.

Fiber Deployment NT Priority Selection and Economic Feasibility Analysis

The main goal of this exercise is to evaluate how fiber deployment scheduling affects the economic parameters of the project, such as overall profit or return of investment time. Initially, it is considered that the main contribution to the investment comes from the carrier itself; however, this may not be possible when considering 100% penetration. The was is to assign priorities to the NTs that were to be connected by fiber and, based on these priorities, distribute them as deployment phases. The NTs included in one phase were provided with a fiber connection replacing the old copper loops. The three introduced priority assignment methods were applied to the scenario, and the CapEx for each phase was calculated using Eqs. (10) and (11). The assumed average prices per meter were the following:

- For trenching: $P_{tr} = 20€$
- For tubing: $P_{tb} = 2€$
- For fiber: $P_f = 0.05€$

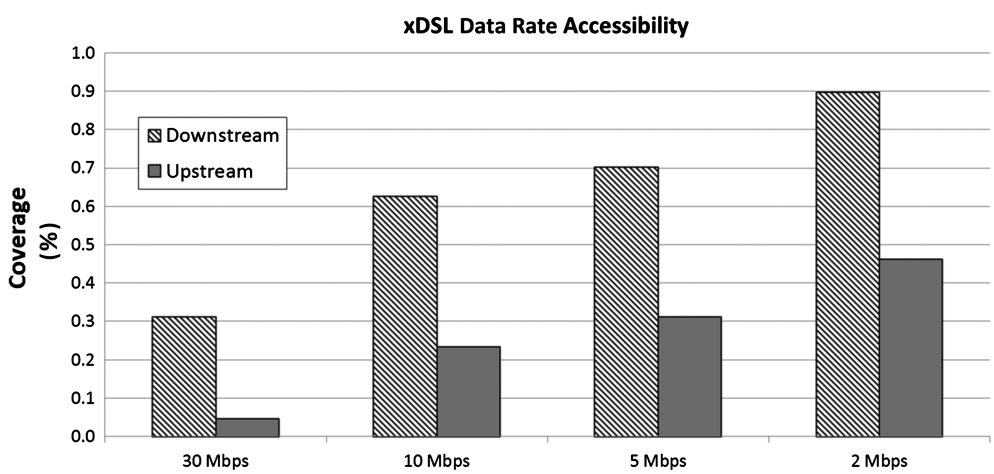

Fig. 4. xDSL accessibility in Lolland

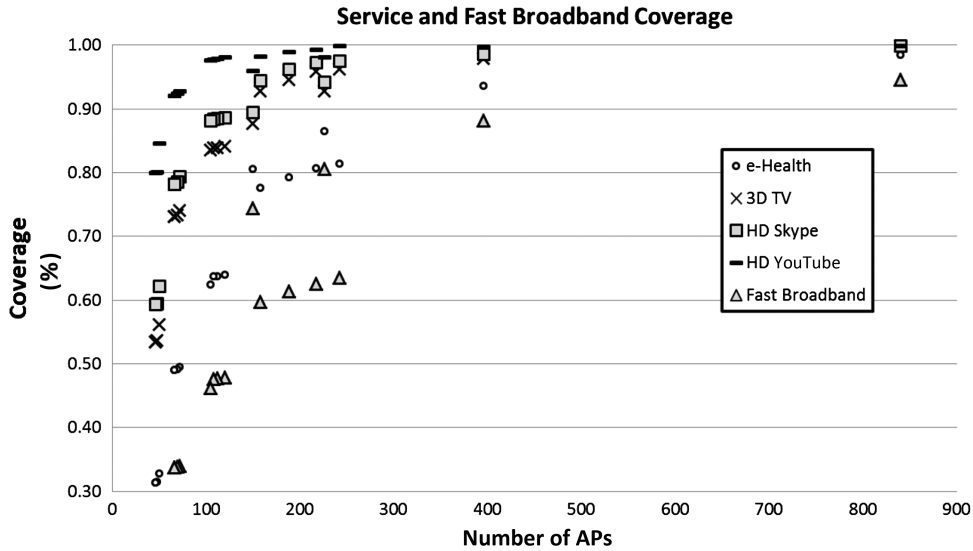

Fig. 5. Services and fast broadband access with regard to number of APs

This simplified version of the model allows a basic comparison among the prioritization methods. In this case, each of 10 deployment phases in one year was considered, each one covering the same number of NTs (10% of the total), and yielding the CapEx required to connect the NTs as a result. Another alternative could be to have a constant CapEx per phase as an input yielding the number of NTs connected as a result.

Users can subscribe to the offered services whenever the deployment of the phase that they belong to finishes. The used adoption rate (a_r) is 50%, and it is modeled as evenly distributed within the first five years after a phase is deployed. In this way, the first year after deployment, 10% of the connected NTs become subscribers, 20% in the second year, and so on, until 50% is finally reached. Following this model, Fig. 6 presents an illustrative example of how the adoption distribution is related to the penetration distribution in the case of 100% penetration. In other cases when global coverage is not achieved, adoption follows a similar distribution. The subscription rate, representing the income from customers to pay off the deployment, investment is symbolically set to $s_r =$ 20€ per month. The two infrastructures were assumed to coexist for at least the deployment period, and users may choose to switch or not. These users were assumed to be ones that will reward the investment. When more users choose to switch, the cost to serve (CTS) per customer in the copper network will increase, and that may encourage making a complete switch. Eventually, the copper network would be shut down, and the rest of the users would be switched automatically. Fig. 7 presents an illustration of the cumulative CapEx in relation to penetration (or phase) when applying the three prioritization methods.

Regardless of the procedure, the cost of building the network for 100% penetration is constant since the model did not consider inflation or interest rates for the purposes of this experiment. For any other penetration value, the most convenient option is always to prioritize based on the proposed cost factor. These results also indicate that density-based selection is more convenient than the distance-based approach.

The main challenge at this stage is to evaluate how relevant this CapEx difference is to the overall economics of the project. First, it is important to relate the project to the time that it would take to recover the investment. Fig. 8 illustrates the curves representing the net present value of the network in the three cases and 100% penetration, calculated by Eq. (8) using a discount rate of $r_d = 0.06$. The intersection points between each of the curves and the x-axis represent the value of the discounted payback periods DPB. In this case, the deployment scheduling based on the cost factor returns the lowest DPB.

However, the value of DPB is rather high (23 years) for a 100% penetration. It has been acknowledged by several reliable sources, such as Hätönen (2011), that carriers cannot entirely cover the expenses of providing 100% fiber penetration on their own. Normally,

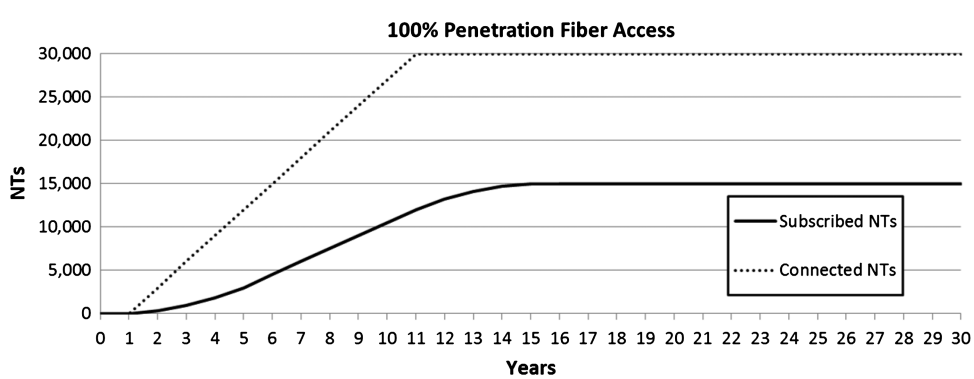

Fig. 6. Connected and subscribed NTs in the case of 100% penetration

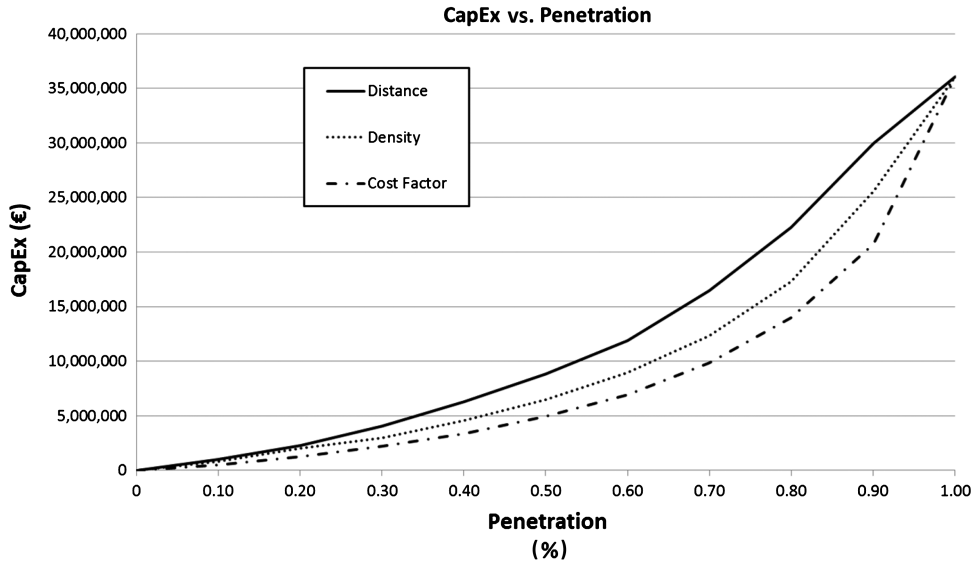

Fig. 7. Priority selection method comparison

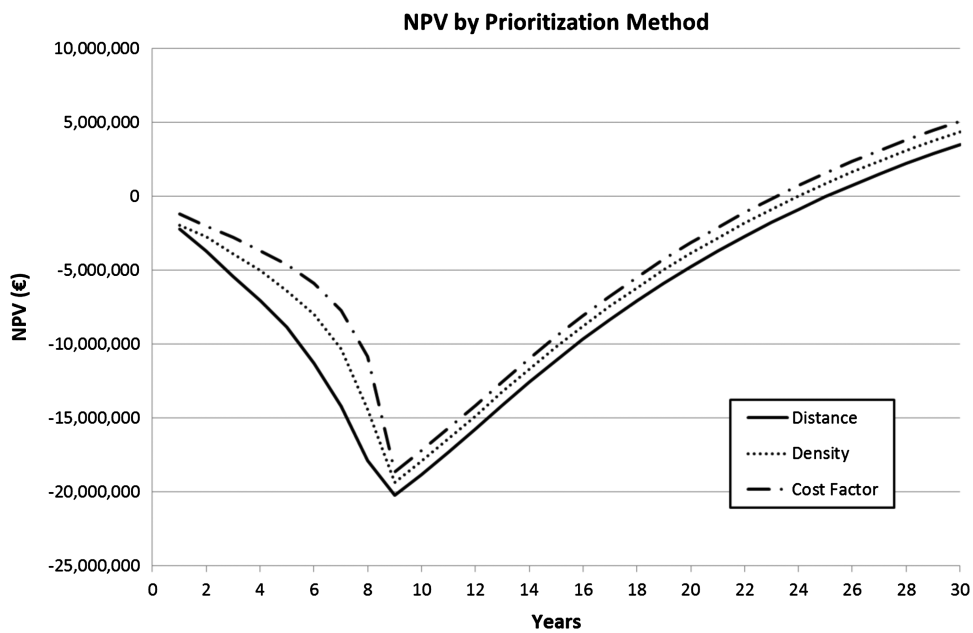

Fig. 8. NPV for 100% penetration

the last segment of users (20–30%) may require a public-private financing model or entirely public funding.

As an illustrative example, Table 3 presents the resulting penetration, NPV_{15}, and a maximum DPB of 15 years. The granularity of the penetration rate is given by the number of phases (10% in this case). The results indicate that both the density- and cost factor–based selections can cover up to 80% of the NTs, the cost factor indicating a significantly higher NPV_{15}.

Table 3. Penetration and NPV_{15} for a Maximum DPB of 15 Years

Method	Penetration (%)	NPV_{15}
Distance-based	60	1,350,269
Density-based	80	47,742
Cost factor-based	80	2,687,308

In addition, from a carrier's point of view, it is interesting to know when and how the maximum profit can be achieved. Fig. 9 illustrates the profit of the project in relation to penetration and selection method, considering a network lifetime of 30 years. Once again, the cost-based approach provides the overall maximum profit (at 70% penetration).

To verify the robustness of the proposed scheduling method, a sensitivity analysis is performed to study the influence of the adoption and subscription rates (a_r and s_r, respectively) over the maximum achievable profit measured over 20, 25, and 30 years. It is assumed that when comparing methods and fixing the values of a_r and s_r, the best option is the one with the highest profit, regardless of the penetration achieved. Fig. 10 illustrates the difference between the maximum profit obtained with the distance- and density-based methods normalized over the cost-based results. The displayed values correspond to the scenarios after 20, 25, and

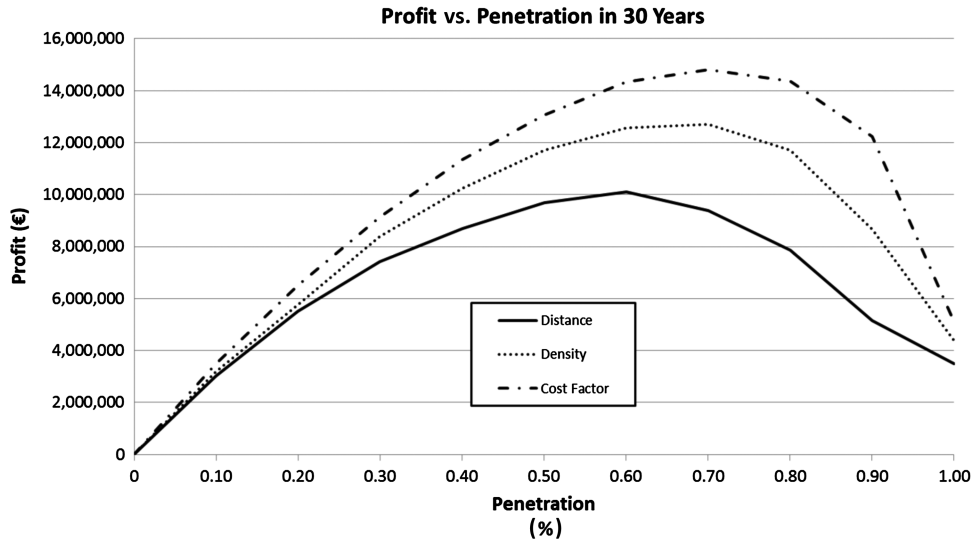

Fig. 9. Profitability by selection method and penetration. Net present value after 30 years (NPV_{30})

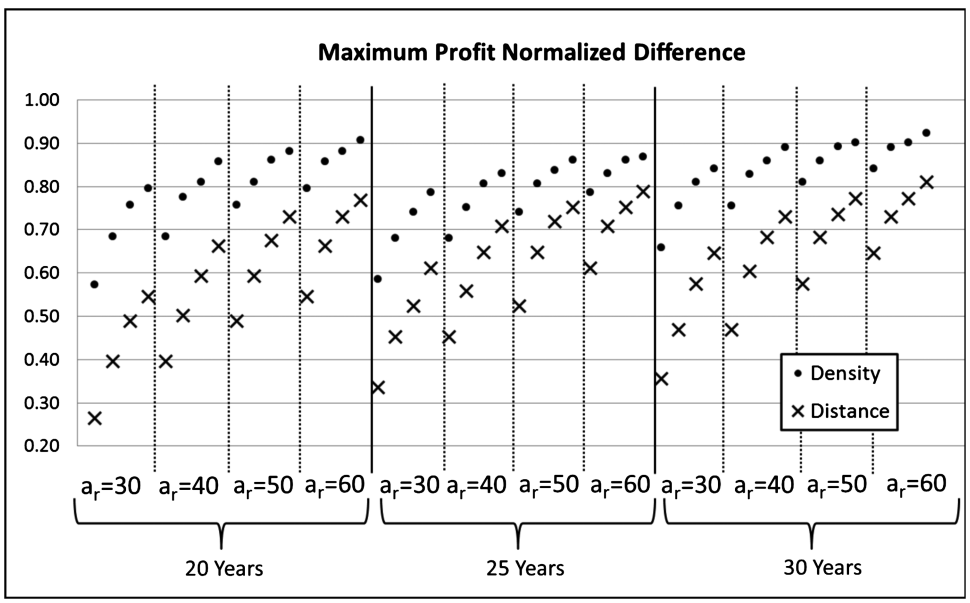

Fig. 10. Sensibility analysis for adoption and subscription rates over maximum profit

30 years. Each set representing the same values of a_r, the year, and the selection method has four samples corresponding to s_r values of 15, 20, 25, and 30€ (from left to right in Fig. 10). The cost factor approach provides the best results in all cases (with 1 being the highest value), followed by the density approach. Moreover, the difference between methods decreases in increments of a_r and s_r for the same year. There is no significant difference between the results for different years.

Fig. 11 illustrates the sensitivity analysis for the value of DPB over the maximum feasible penetration to recover the investment for the three selection methods. The same granularity constraint of 10% shown in Table 3 applies for penetration. Consequently, when two consecutive values of DPB (n and $n+1$) result in equal penetration for the same method, the difference relies on NPV, NPV_{n+1} being higher than NPV_n. The cost factor approach outperforms the other methods in all cases. There are a few cases where the resulting penetrations for the cost factor– and density-based methods are identical; however, in all these cases, the cost factor method still outperforms the density-based approach because it always has a higher NPV.

Finally, the results obtained in this experiment can be summarized by answering the three previously stated questions:

"*Is it relevant to schedule the deployment of a fiber access network at the household level when aiming for 100% fiber penetration?*" The answer is "Yes." The resulting network is always the same; however, providing fiber to customers indicating a lower investment first (cost-based factor selection) has a beneficial long-term effect on all the economic parameters studied (namely, DPB, NPV, and profitability).

"*How can the deployment be scheduled to maximize penetration in a profitable fiber access implementation project?*" and "*How can the deployment be scheduled to maximize the profit in a fiber access implementation project?*" When comparing the three proposed selection approaches, the answer to both these questions

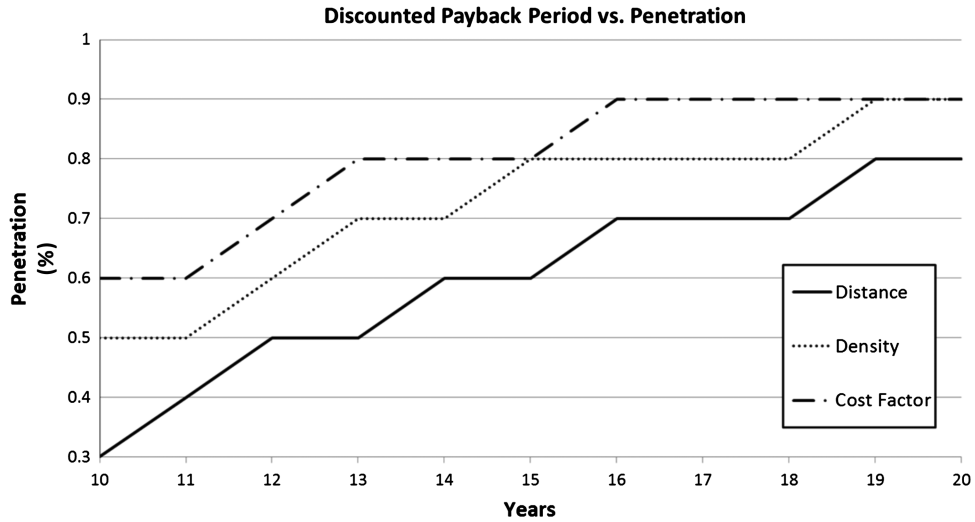

Fig. 11. Sensibility analysis for DPB

is to apply cost-based prioritization. Taking a maximum DPB value of 15 years as an example, the resulting penetration is 80% when applying density- or cost-based selections (the cost-based selection indicating a higher NPV_{15}). In addition, the largest benefit when applying the cost-based approach can be identified in relation to maximum overall profit. For example, the maximum profit after 30 years is estimated to be around 14.8 million euros for the cost-based selection and 12.7 million euros for the density-based selection (more than a 16% increase), with 70% penetration for both.

In these partially covered scenarios, the challenge for carriers would be to connect the most potential users given their investment and economic goals. When the feasible penetration thresholds are reached, the coverage of the leftover users should be planned according to collaborative public-private schemes or public funding. However, this is not the scope of this work, so it is left out of the economic analysis.

The balance between penetration and investment, including the economic contribution of third parties, should be further investigated. Results indicate that after a certain penetration level, the profit is inversely proportional to the penetration. Hence, it would be interesting to evaluate how different solutions based on multiobjective optimizations (such as a pareto front) fit the constraints of the third-party funding authorities. An interesting study related to multiobjective optimization evaluation is Lidicker et al. (2013), which presents an exhaustive study in pavement management decision making based on the minimization of both costs and CO_2 emissions. In addition, the way this alternative funding is distributed or when it is available are key issues that need to be investigated further to be able to integrate them into the optimization processes, as they may have a significant impact on the profitability of the project over time.

Conclusion

Worldwide broadband development initiatives are setting up very ambitious goals for 2020. Theoretically, copper access lines may achieve the required/estimated data rates that these initiatives are considering, at least over short distances. However, the distance-dependent performance of copper access technologies make them an unlikely broadband option in the future outside of the most densely populated areas. Hence, traditional copper carriers might be facing a massive replacement of their copper lines in the near future. This paper discussed a complete methodology to address the copper-fiber transition problem. The methodology ranges from current copper access analysis to economic feasibility for a copper-fiber switchover on a global scale. These are the main covered focus points, all systematically performed at the household level:

- The performance of current copper access;
- The potential of upgrading the network by increasing the number of access points;
- The planning and scheduling of an overall copper-fiber switchover plan; and
- The economic feasibility analysis of the switchover project.

This methodology is applied to a case study in the municipality of Lolland in Denmark. The most relevant obtained conclusions worth highlighting are the following:

- Current copper access performance in the area under study would fulfill the 2020 EU broadband goals (30 Mbps downstream data rates) for only 30% of the households.
- Upgrading the copper access by increasing the number of APs may not be a global solution as it would require an extensive number of new APs. Moreover, this type of upgrade is very unlikely to reach most rural populations, where broadband possibilities are usually below average.
- If copper access lines are to be replaced by fiber lines, the proper time plan or scheduling may have economic benefits in the long term. The application of the proposed cost factor priority selection method has shown to be beneficial in terms of general economic parameters, such as the DPB and NPV, compared to the other studied options.
- Carriers may increase their profitable penetration or revenue by properly scheduling the fiber deployment. However, results show that in this case study, that the most convenient penetration from a business perspective would be 70%–80%. To achieve 100% penetration, some alternative public-private funding schemes may be required.

In the future, an improvement on the proposed cost factor approach could be to assign an individual likelihood of adoption probability to each household. This probability may be influenced by coexisting access technologies, social parameters such as household income or level of education, or demographic parameters, such as the number of household inhabitants. However, for the moment, this improvement can be accomplished only theoretically

due to the lack of important aspects, such as detailed broadband mapping or studies relating the aforementioned parameters with the likelihood of adoption probability.

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