Techno-economic Evaluation of FTTC/VDSL and FTTH Roll-Out Scenarios: Discounted Cash Flows and Real Option Valuation

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***Abstract*—Due to the increasing demand in data rates telecom operators are faced with the question of when to upgrade their access network infrastructure toward fiber-to-the-home (FTTH). In this paper a techno-economic study of fiber-to-the-cabinet/very high bit rate digital subscriber line (FTTC/VDSL) and FTTH deployments is performed. The economics and risks associated with the incumbent's decision to invest in dense urban and urban areas are analyzed using both discount cash flow (DCF) analysis and real options analysis (ROA). The results revealed that in the case of investment subsidization, the option value to expand in a later phase can significantly improve the financial metrics of the business cases. The analysis made is based on the ECOSYS techno-economic methodology and tool.**

***Index Terms*—Communication systems economics; Optical networks; Technology assessment; Technology forecasting; Communication system operations and management; Communication system planning**.

I. Introduction

Demand for higher bandwidth is rapidly increasing, fueled by content distribution, file sharing/downloading, and social networking. Existing copper-based (xDSL) and wireless/mobile (mainly WiFi, WiMAX and 3G, HSPA) technologies are already at a mature level, but fiber-based deployments and especially fiber to the home (FTTH) are under way with the aim to offer a future-proof solution for real sustainable high bandwidths in access networking [1,2].

However, many telecom operators are skeptical in introducing fiber to the home (FTTH) due to the high investment costs associated with civil works, especially in urban and rural areas [3]. Therefore, their current strategy is to exploit at the highest possible level their existing copper-based networks as long as possible. This strategy leads to fiber-to-the-cabinet (FTTC) and fiber-to-the-node (FTTN) deployments with very high bit rate digital subscriber line (VDSL) Ethernet access. A number of research and policy questions have arisen as different architectures and technologies are discussed, such as the upgrade possibilities from FTTC to FTTH [4]. Although 50% of the initial FTTC investment could be reused in an FTTH upgrade, if multiple operators invest in active equipment at the street cabinet, the situation could still lead to market failures [4]. To deal with the pertinent issues of FTTH deployment, regulatory and policy actions aiming to provide incentives for FTTH as a commodity are also ongoing. The most important action in this direction is the deployment of fiber-based networks from municipalities, utility companies, and housing companies [5], which aim mostly to get indirect revenues from these deployments (e.g., city attractiveness), but direct revenues could also be foreseen.

Nevertheless, the private initiatives for the deployment of future-proof networks as well as the public ones, especially from national and local governments to offer subsidies in order to boost deployments, have brought up critical questions regarding the costs and risks, mostly associated with the technology, market, and regulation of these networks. Since the financial figures of these deployments will determine the level of subsidization or the cost allocation between the different actors and stakeholders, a detailed techno-economic approach is more than important today.

During recent years, an increasing number of research papers besides the consultancy reports have been developed within national and international collaborative projects aiming to contribute to this broadband debate. Most of these works deal with the instal-

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lation first cost (IFC) of the infrastructure or a part of it [2,6–9] and they usually deal only with an analysis of techno-economic benefits of technological solutions. In [10–12] a techno-economic analysis of municipal networks and the associated costs are also presented, whereas in [13] the migration path from FTTC to FTTH is analyzed and discussed. An interesting approach based on game theory dealing with the competition in small-scale networks can also be found in [10]. In [14], an algorithm for minimizing the cost for a passive optical network is discussed, in [15] an analysis for a WDM network is presented, and [16] studies the impact of fiber deployments in the access network to the regulatory framework in Europe. In the near past, similar research has been undertaken within the European-funded projects IST-TONIC [17] and CELTIC-ECOSYS [18], which studied various upgrade or deployment scenarios for both fixed and wireless mostly mobile telecommunication networks. These projects are precursors in the investigation of the economic side of telecommunications networks and services deployments [3,19–22].

However, a complete analysis related to the FTTH deployment scenarios aiming to offer quantitative results and to analyze the associated attitude from incumbent operators is still absent, to the best of authors' knowledge. This paper aims to offer these quantitative results by incorporating both "traditional" discounted cash flow (DCF) analysis and real options analysis (ROA).

The rest of the paper is organized as follows. Section II describes the techno-economic methodology and the tool exploited for the analysis presented and discussed. Section III includes the description of the cases analyzed and the assumptions and parameters incorporated. Section IV presents the results related to the base cases, namely, the FTTC/VDSL and FTTH deployments in dense urban and urban areas. Sections V and VI introduce the real options methodology and the results based on this theory, and Section VII concludes the analysis.

II. Techno-economic Methodology and Tool

A. TONIC–ECOSYS Methodology and Tool

The techno-economic methodology adopted for the evaluation of FTTC and FTTH deployments is based on the TONIC tool developed within the IST-TONIC [17] and the CELTIC-ECOSYS [18] European projects. The TONIC tool and its enrichment, the ECOSYS tool, have been used for several studies among European telecom operators and universities for many years [3,19–21,23].

The model's operation is based on its database, where the cost figures of the various network components are kept and constantly updated from data gathered from the biggest European telecommunication companies and vendors as well as from the telecom market [3,19].

The study period is best adapted to the case at hand. For a fixed network deployment case an 8–10-year period is reasonable, considering the time a fixed network or service takes to reach market maturity and to pay back the investments. The services offered are specified as well as their market penetration over the study period. In addition, the service tariffs are defined taking into account both econometric and price forecast models, and the part of the tariff that is attributed to each network under study can also be modeled. From the combination of yearly market penetration and tariff evolution, with the ECOSYS tool the revenue side of network deployments for each year given the selected service set can be calculated.

For the expenditures side, the architecture scenarios that provide the selected service set are selected from the candidates. This kind of modeling needs network planning expertise and is mostly outside of the framework of the ECOSYS methodology. However, many network architectures can be accounted for, such as tree, mesh, or ring architectures, incorporated within the tool, which includes a set of geometric models that assist in the network planning by automatically calculating lengths for cables and ducting. These geometric models [24] are optional parts of the methodology and the ECOSYS tool can be used without them, as in the techno-economic case of radio access technologies. Network data from other planning tools can also be used. The output of the architecture scenario definition is the so-called shopping list, which is calculated for each year of the study period and shows the volumes of all network cost elements (equipment, cables, cabinets, ducting, installation, etc.) and the distribution of these network components over different network levels and layers.

To estimate the number of network components required throughout the study period, the necessary forecasts (both demand and price forecast) are carried out according to existing methodologies (e.g., [25,26]) or market studies and are incorporated in the techno-economic model. The operation, administration, and maintenance (OA&M) cost for each network element is estimated from the price of each of its constitutive parts. For example, in the case of an Ethernet switch, the model includes the switch basic equipment (switching fabric, power supply, rack and line interface cards) taking into account list price information of several vendors. The price evolution of the network components is estimated using the extended learning curve model as in [24]. As far as the cost of repair parts is concerned, it is calculated by the model as a fixed percentage of the total investments in network elements, whereas the cost of repair work is calculated based on mean time between failures (MTBF) and the mean time to repair (MTTR).

By combining the revenues and expenditures sides, namely, service revenues, investments, operating costs, and general economic inputs (e.g., discount rate, tax rate), the tool calculates the results necessary for DCF analysis such as cash flows, net present values (NPVs), internal rate of return (IRR), payback period, and other economic figures of merit (see Fig. 1). More details on the methodology are presented in [24], but they can also be found in [3,19]. For the cases presented hereafter, the dimensioning rules and the geometric models are presented in Section III.

B. Discounted Cash Flow Analysis

DCF analysis takes into account the time value of money and the risks of investing in a project and estimates and discounts the investment's future cash flows in order to calculate the present value (PV). The main advantages of DCF analysis are that it is a simple quantitative method to implement, is widely accepted, and provides clear and consistent metrics (e.g., NPV, IRR, payback period) for all kinds of projects.

It should be noted that the models used in DCF are deterministic and static and the results and decisions are fixed, as modeled. That would be valid in a world without changes in the economic environment, but in the real world conditions change rapidly. Therefore, the decision maker of a project has the flexibility to make changes when the conditions require it. This fact necessitates the analysis of uncertainty in various ways. A first step to model the uncertainty is to build a basic DCF model, taking into account as many factors as possible, especially in complex projects such as telecom projects and then to perform sensitivity and risk analysis in order to include the (un)expected developments.

III. Case Study and Assumptions

A. Architecture and Area Description

FTTH and FTTC architectures with a combination of gigabit Ethernet and Ethernet over VDSL for the last mile are investigated from the incumbent operators' point of view. Two area types in an average European country, namely, dense urban (DU) and urban (U) are studied. These areas share the same network topology but differ in several characteristics such as area dimensions, population density, and average cable and duct lengths; these characteristics are presented at Table I. One common assumption is that one central exchange (CEx) connected to four local exchanges (LEx) serves each area. Furthermore each LEx is located in the center of the service area and has a number of cabinets connected to it. Finally all the customers are connected through their nearest cabinet. The fiber lengths have been calculated with the use of a geometric model as described in the following section. In order to model an entire European-type city, the appropriate number and pattern of dense urban and urban areas matching the city's characteristics should be assembled and added.

In the case of FTTC/VDSL, the costs are significantly lower since it is not required to make new installations in the last-mile network. The incumbent operator can benefit from the high levels of available copper lines already deployed in the access network and thus avoid costly civil works [23]. The problem of VDSL implementation is the distance, since it affects dramatically the performance. Thus the 50 Mbit/s range is limited to around 400 m. This is extremely critical when IPTV is offered, which consumes a major part of the download bandwidth. On the other hand, FTTH has the advantage of dedicated bandwidth offered to the users, allowing continuous streaming applications without the interference caused from other users.

In the FTTH scenario customers are connected via Ethernet by point-to-point (PtoP) optical connections between the subscriber location and the associated LEx in a way similar to the one presented in [27]. Each customer is connected with two fibers to the LEx; one is used for Internet access and the other can be used for TV/video services. The costs of fiber cable

TABLE I
AREA CHARACTERISTICS

Area Type	Dense Urban	Urban
Duct distance between central and local exchange (L_1) (km)	4.7	7.7
Duct distance between local exchange and building L_2 (km)	0.9	1.4
Number of central exchanges	1	1
Number of local exchanges	4	4
Cabinets	256	256
Number of buildings	1024	2048
Subscribers per building	64	32
Total population per area (N)	65,536	65,536
Business customers	1638	1147
Total service area (A) (km^2)	12	32
Density (D) (houses/km^2)	5641	2048
Duct availability between LEx and cabinet	95%	55%
Duct availability between cabinet and buildings	65%	30%

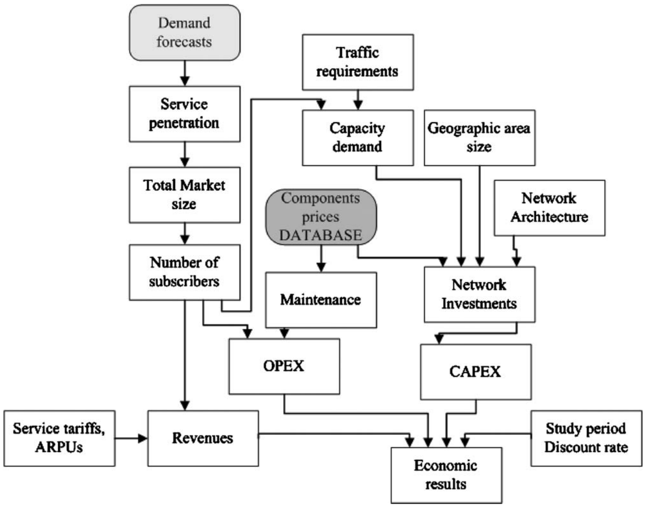

Fig. 1. Techno-economic methodology and tool [17,18].

and branching boxes, including installation costs and the pulling costs into the ducts, have also been estimated.

B. Geometric Model

A geometric model is usually used to estimate the amount of cable, ducts, and civil works (trenches) required in the network. The model takes several inputs such as subscriber density, network topology, duct availability, etc. and calculates trench length, duct length, and cable length [24]. The model follows the layered structure of the network, in which each layer uses the same basic geometric model, but with different parameters. In the model incorporated in this study, the total area covered is modeled as a square and the network follows a star topology at each layer.

The first layer, represented as flexible point (FP) #7, is a large CEx and serves a square area with side length L6. The splitting ratio of this point is equal to 1 as shown in Fig. 2. This means that there is only one point of the next lower level point (FP6), representing a branching box, which is now connected with the four LExs, numbered as FP5. Figure 3 illustrates these flexible points and layers. In all calculations, the flexibility points are always placed in the center of the next layer. The total cable and duct length is calculated by aggregation of the appropriate lengths. For example, the length of level 6 is given by

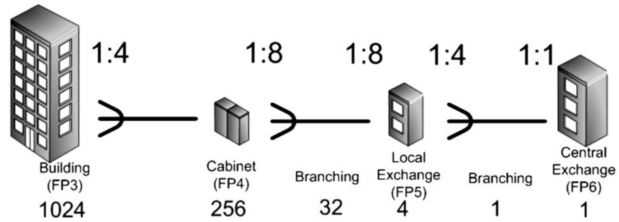

Fig. 2. Architecture of dense urban areas.

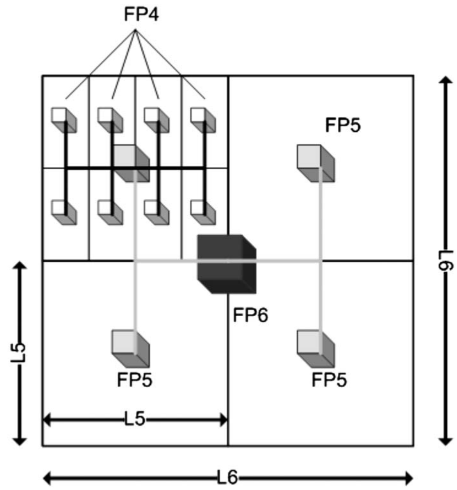

Fig. 3. Geometric model description.

$$\mathrm{L6} = \sqrt{A} = \sqrt{\frac{N}{D}}, \tag{1}$$

where A is the total service area, N is the population of the area, and D is the subscriber density.

The total duct length of Layer 6 illustrated by the H-shaped gray line ducting system in Fig. 3 is given by

$$\mathrm{DUCT}_{\mathrm{L6}} = 1.5 \cdot \mathrm{L6}. \tag{2}$$

The total cable length at one layer can easily be found by adding up cable lengths from the center FP to each of the next-level FPs. The total cable length of Layer 6 is given by

$$C_{\mathrm{L6}} = 2 \cdot \mathrm{L6}. \tag{3}$$

Following the same algorithm, the length and ducts for all layers down to layer 0, which represent customer premises, can be easily calculated.

C. Services Offered

For the analysis of the selected business cases, a set of services bundled in four service baskets has been selected, as illustrated in Table II.

These service baskets include the fees for both the service and network operator and provide unlimited national phone calls and unlimited broadband access to the Internet. The difference between the cases of FTTC and FTTH is that the latter can offer higher and symmetric data rates. TV and video services are not included in these baskets and in the following analysis since there is variety in these services across several European countries. The above tariff values have been adopted based on a survey among major European operators in several countries. A yearly

TABLE II
SERVICES OFFERED

Name	Download FTTC/VDSL (MB)	Download/Upload FTTH (MB)	Contention Ratio	Initial Monthly Price (€) FTTC (2009)	Initial Monthly Price (€) FTTH (2009)
Residential Service Basket					
Basic	6	100	1:20	20	34
Premium	12	300	1:20	28	46
Silver	24	500	1:20	33	54
Gold	50	1000	1:20	38	64
Business Service Basket					
Basic	6	100	1:5	97	100
Premium	12	200	1:5	135	169
Silver	24	500	1:5	178	223
Gold	50	1000	1:5	231	290

price erosion of 2% has been adopted in order to model the current situation of price competition worldwide.

D. Demand Forecasts

Telecommunications demand forecasting has attracted the interest of many researchers worldwide, not only due to the long period of innovations during the past several years, but also due to the unique characteristics associated with telecommunications, such as the strong substitution effects between different technology generations [28]. Related research activities focus on the study of the diffusion process dynamics aiming to develop and apply methods toward comprehensive analyses of telecommunications products, services, and technology. Usually the interest includes the study and development of demand models, the associated mathematical methods for the estimation of the models' parameters, and the evaluation of the results over specific cases [29–31].

In this analysis, a logistic model is used to perform the demand forecasts for the selected services. This model is recommended for long-term forecasts and for new services both for fixed and mobile networks [25,26]. To achieve a good fit, a four-parameter model including the saturation level is used. The model is defined by the following expression:

$$Y_t = \frac{M}{(1+e^{a+bt})^c}, \tag{4}$$

where Y_t is the actual or forecasted demand at time t as a population percentage; M is the demand saturation level as a population percentage; t is the time in years; and a, b, and c are diffusion parameters that can be estimated based on existing market data, related to broadband penetration across Europe.

Since the model is a nonlinear function of the related parameters, a typical regression analysis, e.g., ordinary least-squares regression, can lead to significant errors. Therefore, a stepwise procedure is used to find the optimal parameter estimation. More information about this topic can be found in [28–30].

Market demand considers both business and residential market segments in order to evaluate the number of subscribers belonging to each segment. The operator will provide services at both residential and business customers with the characteristics presented in Table II. The requirements of business and residential customers are obviously different, with the former often demanding a more symmetric bit rate with a higher quality of service (QoS) and increased security and in most of the cases higher data rates than the latter, especially when HDTV has not been considered.

The penetration for each packet is modeled using the previous equations with the following assumptions. During the first years that the service is introduced, the preferred packet will be the basic packet, but as the years pass, finally the silver and gold packets will prevail and attract more and more subscribers. Due to new innovative applications that will be available only to these packets, customers will be willing to pay the extra money (Fig. 4).

E. Deployment Scenarios

For the case of FTTC, the incumbent operator makes a strategic decision during the first year of the project (in this model year 2009 has been used as the first year) to invest in a VDSL upgrade on the network in the dense urban areas. On the other hand, if the FTTH scenario is chosen, all the copper lines are replaced with fiber ones reaching the customer premises.

The decision that should be made by an incumbent operator is whether it should also invest in the urban

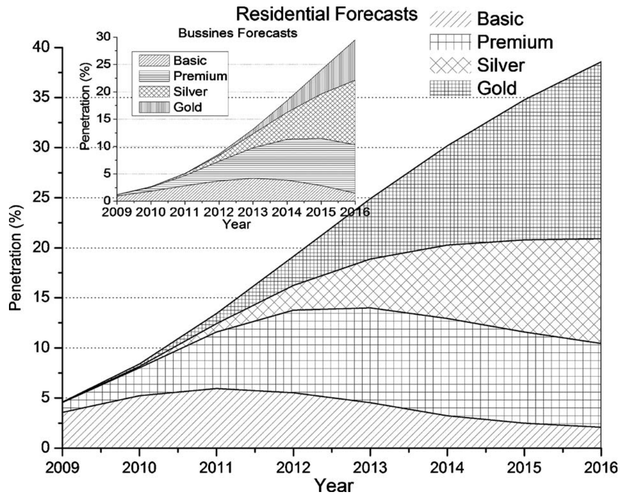

Fig. 4. Penetration forecasts for residential and business services.

areas and, if yes, when in the following years is the optimum time to do it. To answer these questions, initially the case of building these new networks simultaneously in both dense urban and urban areas will be examined, and then the impact of the delay of expanding the network to the urban areas as a function of time (e.g., if the operator delays the expansion at urban areas for $T=1,\ldots,6$ years after the initial deployment in dense urban areas at $T=0$) will be studied. The analysis will be performed both with the traditional DCF analysis but also with the application of real options analysis that will be introduced and analyzed in Section V.

IV. DCF Analysis Results

A. Base Case Results

The selected study period is set to 8 years beginning in 2009 and ending in 2016; the discount rate is assumed to be 10% and no taxes are applied. Table III presents the calculated NPV for both scenarios for the base case; the incumbent upgrades the network in both dense urban and urban areas during the initial year ($T=0$) of the project. To better understand the results, a breakdown of the NPV for the two areas is also presented. Both cases have negative values for the NPV with the remark that the FTTC/VDSL solution has a total value (both areas covered) that is better than the case of deploying FTTH only in the dense

TABLE III
Economic Results

NPV	Total (M€)	Dense Urban (M€)	Urban (M€)
FTTC/VDSL	−2.3	4.4	−6.7
FTTH	−24.1	−4.4	−19.7

urban areas. Thus from first reading one would conclude that it is better to choose the FTTC solution from the first year and for both areas.

In Fig. 5, the basic economic indices for both scenarios are presented. The cash flow depicts the balance of the economics per each year and the cumulated discounted cash flow widely known as the cash balance summarizes the total economics and gives the total financial evolution of the business case. The first observation is that both projects start with high negative values. This originates from the fact that the major part of the investments are made in the first year of the deployment, which represents a typical rule in telecommunications. The observation is used in the later sections to justify the use of the real options analysis. In both cases these costs are associated with the costly fiber roll-out in order to achieve coverage requirements, and thus these high front-end investments affect the NPV greatly as will be presented in Section V.

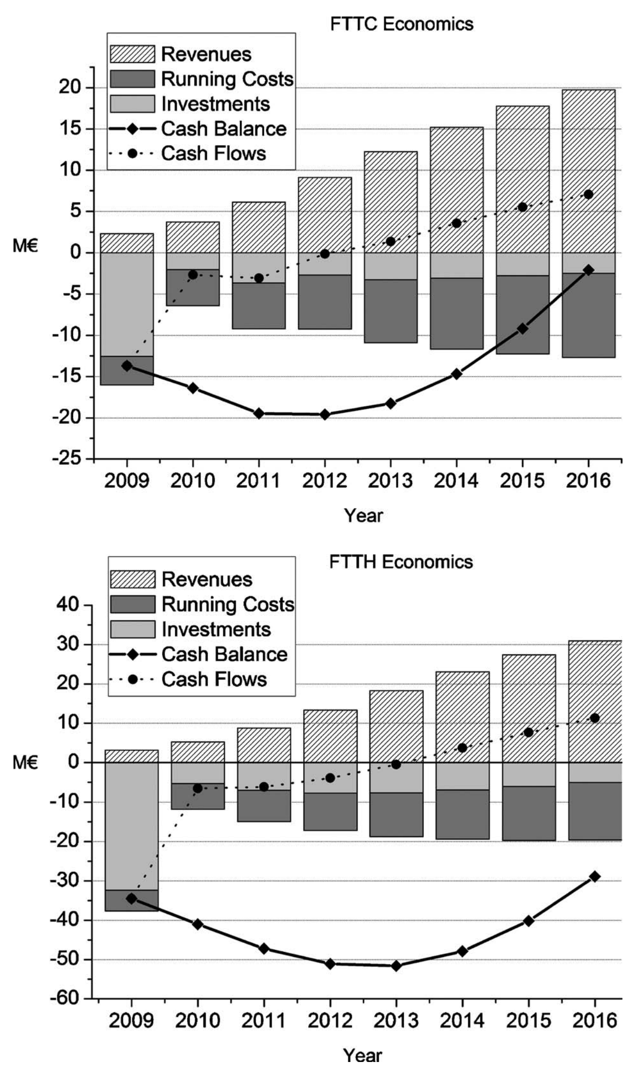

Fig. 5. Economics of the project (both areas).

To highlight the role of the initial investments in Fig. 6, a breakdown of the revenues, running costs, and investments for the whole project, for both the dense urban and the urban areas, is presented for the FTTC/VDSL case. It should be denoted that the running costs include sales and marketing expenditures, employee costs, and operations and administration (OA) and maintenance-related costs. The investments are broken down into equipment- and infrastructure-related expenditures. The major portion (74%) of investments in the case of FTTC is for equipment since there are no civil works due to the already-installed copper lines in the last mile. In the case of FTTH the infrastructure-related investments are 65% of the total investment costs. In the FTTC case, the costs related to the OA are 65% of all the running costs, followed by employee costs (15%) and maintenance (13%). The same analysis in the FTTH case reveals 73% to be the OA costs, 10% for the employee costs, and 9% for maintenance costs.

It can be observed that for the urban areas, the investments and the running costs are almost 50% higher than those in the dense urban areas, whereas the revenues are only 5% higher (since the total subscribers are almost the same). Therefore, if the investments in the urban areas could be delayed for a specific period of time, then a clear benefit can result. This is actually the strategy of the main telecom operators in Europe, and the results presented hereafter will justify, at least financially, this strategy.

Following the previous remark, the next step of the analysis is to calculate the NPV for the urban areas independently for both the scenarios as a function of time. The project is broken into two phases: the first is the upgrade to the dense urban areas at year $T=0$, and the second is the network upgrade at the urban areas at a later year in the future. The calculations are made for a delay of $T=1$–6 years in the deployment, and the results are presented in Tables IV and V.

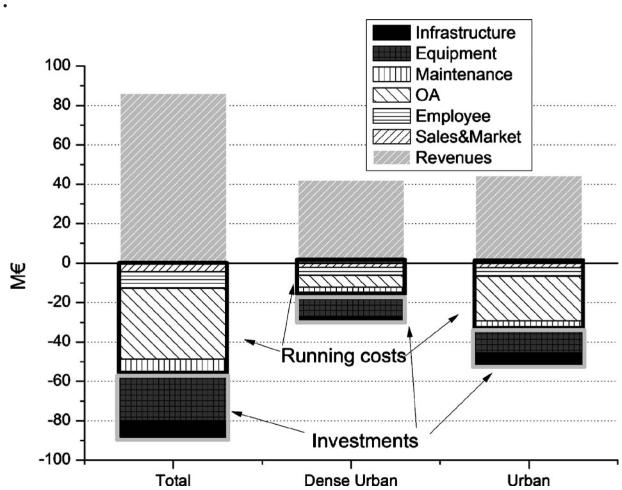

Fig. 6. Breakdown economics of the project for FTTC/VDSL.

TABLE IV
NPV SPLIT CALCULATIONS FOR THE FTTC/VDSL CASE

Upgrade Year	Phase 1 DU	Phase 2 U	Total
1	4.40	−4.08	0.32
2		−1.84	2.56
3		−0.09	4.32
4		1.06	5.46
5		1.61	6.01
6		1.48	5.88

By examining these results, it can be deduced that the optimum strategy for the FTTC/VDSL scenario is to wait for 5 years and then decide to expand to the urban areas. It can also be observed that the difference per year after the fourth year is in the range of 2M€, and thus even a 1 year delay in the installations can give positive values. As far as the decrease in project value after a 6 year delay, this is because tariff erosion cannot justify the benefits from lower prices in equipment costs and the associated running costs. For the FTTH case, the related values remain negative even if the decision to expand is postponed for 6 years. But it is obvious that the delay is in favor of the FTTH deployment case as the negative values are improved. This is of paramount importance in the case of state aid or subsidies from local governments, since any obligations applied in these cases should take into account the time of deployment.

B. Sensitivity Analysis

Since the traditional approach presented is often unable to capture the uncertainties in the telecom market, sensitivity and risk analysis have to be incorporated for the improvement of the analysis subject to adopted assumptions. Sensitivity analysis consists of studying the impact of a single parameter without any correlation to other parameters. In the analysis that follows, the parameters used for the sensitivity analysis were the duct availability between the cabinet and the customer (which is an additional parameter used in the FTTH scenarios), the tariff, the penetration, the

TABLE V
NPV SPLIT CALCULATIONS FOR THE FTTH CASE

Upgrade Year	Phase 1 DU	Phase 2 U	Total
1	−4.38	−14.60	−18.98
2		−10.00	−14.38
3		−6.37	−10.74
4		−3.41	−7.79
5		−1.55	−5.93
6		−0.72	−5.10

sales and marketing, as well as the network operations. The effect each of these has on the total NPV is presented in Fig. 7. The values of all these parameters are modified between 50% and 150% of the initial value.

The sensitivity analysis revealed that the most crucial parameter for both scenarios is the tariff level. If the tariffs collected are 50% over the price initially assumed (Table II), the FTTH case turns positive. However, it is not expected to make a major difference on this parameter from the initial assumption due to the increased competition in the broadband market. Network operation as a percentage of the total investments is the second most critical parameter. For both cases, penetration followed by duct availability and sales and marketing costs make a minor contribution. For the FTTC case, existing duct availability can make the difference between negative and positive values and is also a crucial parameter for the FTTH scenario.

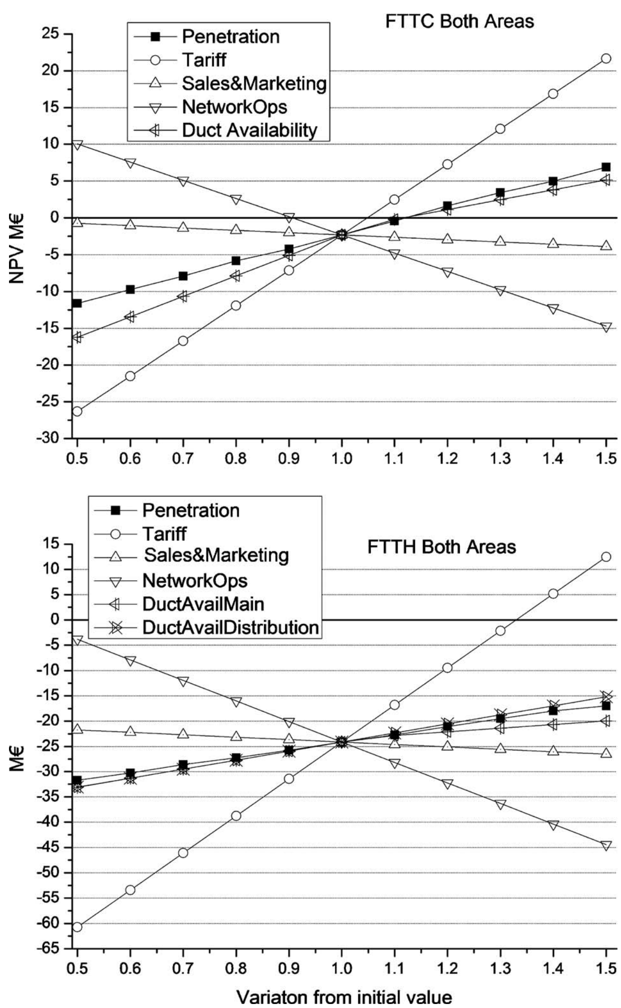

Fig. 7. Sensitivity results.

C. Risk Analysis

As a next step in the analysis, a risk analysis is performed over the same parameters used in the sensitivity analysis except of the sales and marketing costs, which have only a minor contribution as stated before. In the risk analysis, a suitable probability density function is associated with each of these most critical variables, in order to shape the risk associated with each parameter. In similar business cases usually beta and lognormal distributions are used to model the probability of each parameter to change values over a predefined space. In the analysis presented in this paper, each of the variables was modeled by beta distribution.

The beta distribution is a special case of the Dirichlet continuous probability distribution that is defined in the space [0,1] and characterized by only two positive parameters α (alpha) and β (beta), also named the shape parameters. The probability function is given by

$$P(x) = \frac{(1-x)^{\beta-1}x^{\alpha-1}}{B(\alpha,\beta)}, \tag{5}$$

where B is the beta function.

The beta distribution has a number of characteristics that make it useful for most studies: it is confined to a specified interval; it can be bounded to positive-only values, which is the case of the majority of parameters used in this analysis; and it has sufficient degrees of freedom, since it can be symmetric and bell shaped or asymmetric and peaked according to the selection of the shape parameters, α and β.

For each of the selected variables, namely, the duct availability, the tariff, the network operations, and the penetration, the default value, the upper and lower limits, the optimistic and pessimistic values, and the confidence interval were determined in order to calculate the parameters α and β of the beta distribution as presented at Table VI. The shape of the beta functions for the total penetration is presented as a representative in Fig. 8.

These distribution parameters are the input for a Monte Carlo simulation with 1000 random samples, and the NPV is selected as the output variable in order to evaluate the financial risk of the project. The simulation output values of NPV can be compared with the unique deterministic value already calculated. Thus, extensive statistical information on the result is generated, i.e., mean value, percentiles, and standard deviation. In addition, the input variables are ranked according to their significance to the outcomes, the measure can be either the contribution to the variance of the output variables or the rank corre-

TABLE VI
BETA PARAMETERS

Parameter	Min	Max	Alpha (α)	Beta (β)	Logical Explanation
Duct availability	0%	100%	10	3	There is a large percentage of ducts (70%–80%) available for fiber deployments in European countries.
Tariff erosion	95%	120%	2	3	The strong competition bounds the upper value in tariff erosion.
Network operations	18%	22%	2	3	No significant change is expected.
Penetration	0.98	1.02	2	3	No significant change is expected.

lation. It is often observed that some variables have very little significance after all and could therefore be removed in future simulations. This will increase clarity as well as reduce the time it takes to complete a simulation.

Risk analysis results for the FTTC/VDSL scenario (Fig. 9) produced a mean value of −5.3 M€, with 4.0M€ standard deviation with 23.1% of the samples to be above the base case, which was valued at −2.3 M€.

From the statistics of the risk analysis, the value of the standard deviation will further be used, in order to calculate the volatility, by dividing it with the mean value, resulting in $\sigma^2=76\%$. The results for the FTTH case are presented at Table VII. It can be observed that both projects exhibit more or less the same values as far as the percentages above the initial case are concerned. However, the FTTH case seems to be less risky, having less volatility, but still there is no possibility for a positive NPV. On the other hand, the FTTC/VDSL case has a 9% probability for positive values.

V. Real Options Analysis

A. Real Options Theory

As explained before, the traditional DCF approach does not take into account the possibility to differ with the initial decisions made at the project's beginning when additional information that lowers the uncertainty will be available. On the contrary, real options analysis has the advantage of incorporating the flexibility to alter decisions and make strategic moves and corrections during the lifetime of the project when additional information will be available [32].

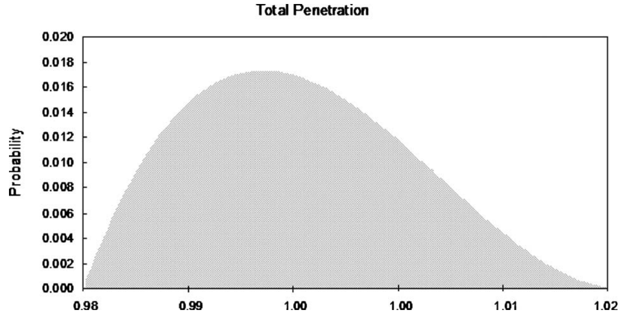

Fig. 8. Beta distribution for the total penetration.

Financial options refer to the right but not the obligation to buy/sell an asset within a predetermined period of time at a predefined value. With financial options the initial investment is treated as an option meaning that the buyer has the opportunity to benefit from positive cash flows when future prices change in favor but does not have the burden of negative cash flows if bad conditions prevail [33]. This flexibility adds value to the financial options especially in cases where the uncertainty about the future is high.

A real option is an option about a real asset and ROA is an alternative methodology to evaluate invest-

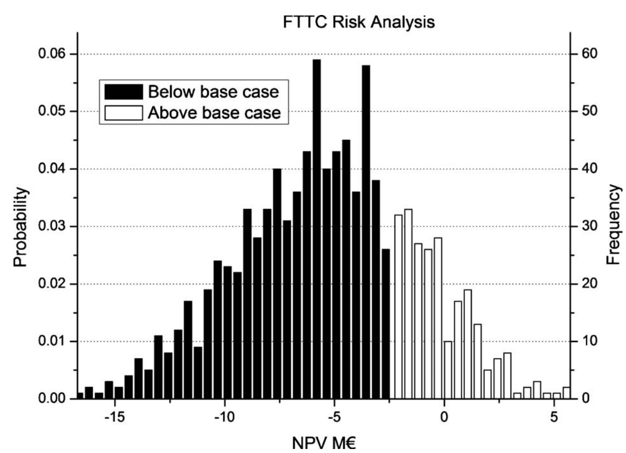

Fig. 9. Risk results for FTTC/VDSL scenario.

TABLE VII
RISK RESULTS

	FTTC/VDSL	FTTH
Mean value	−5.30 M€	−27.83 M€
Standard deviation	4.02 M€	5.62 M€
Percentage positive	9%	0%
Percentage above base case	23.1%	25.9%
Volatility	76%	20%

ment decisions and in antithesis with DCF handles the investment decision as either a single option or a sequence of options as time evolves. With this methodology, the value of investment opportunities that contain real options can be determined. For the current analysis, a European option has been used to model the investment decisions and it has been calculated. A European option is an option that can only be exercised on a specific date: its expiration date. On the other hand, an American option can be exercised at any time before its expiration.

Although certainly not necessary, additional information about real options theory and real options pricing rules can be found in [34,35].

B. Real Options Methodology

For the ROA pricing, the well-known Black–Scholes option pricing model will be used. This model assumes that the underlying price follows a geometric Brownian motion (or Wiener process) with constant volatility. This assumption is debatable in many cases, taking into account the underlying correlations between the project and financial uncertainties. However, it can be used as a building block to model an extremely broad range of investment cases such as the cases analyzed hereafter [32]. Under this assumption the current option value W is given by [36]

$$W = SN(d_1) - Xe^{r_f T}N(d_2), \tag{6}$$

where S is the current asset value (in monetary units, e.g., euros), X is the exercise price (in monetary units, e.g., euros), T is the time to exercise the option (in years), r_f is the risk-free discount rate (in percent), and $N(x)$ is the cumulative normal distribution with mean zero and standard deviation equal to 1. The parameters d_1, d_2 are given from the following equations:

$$d_1 = \frac{\ln\left(\dfrac{S}{X}\right) + \left(r_f + \dfrac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}, \tag{7}$$

$$d_2 = \frac{\ln\left(\dfrac{S}{X}\right) + \left(r_f - \dfrac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{\mathrm{T}}, \tag{8}$$

where σ^2 is the volatility measure in percent.

Equation (6) can be used to calculate the option value of the project, which in the current investment analysis is as follows, according to the framework introduced in [33,37]: S is the present value of a project's operating assets to be acquired (the PV of all estimated future cash flows if the project is implemented), X is the cost related to the acquisition of the assets or the initial investment if $T=0$ (the PV of all the investments that are made in the whole study period of the project), T is the time period when an investment decision may be taken (in years), r_f is the risk-free rate of return, and σ^2 is the risk (volatility) of the project (the measure of the uncertainty of the cash flows associated with the investment).

According to this model, if S, T, r_f, and σ^2 increase, then the value of the option increases also, but, if X increases, the value of the option decreases. The volatility factor is the only data required for real option valuation that is not required in DCF. It is a key driver in the calculated value and is positively related to that. In the DCF analysis high volatility means high risk, which translates to higher discount rates and thus lower values. On the contrary, in ROA greater volatility translates into a wider range of values. Because the option is exercised if the values exceed the exercise price, the lower side is not of concern, but higher uncertainty in the upper side (value over exercise price) gives greater option values.

C. Real Options Application in the FTTC and FTTH Cases

To apply ROA in the aforementioned cases, each project is split into two individual phases: the first phase is the deployment in dense urban areas and the second in urban areas. The first phase includes the initial investments made in the dense urban area at the beginning of the project; these expenditures are made in order to gain a foothold in the market while learning more about its potential. Thus, phase two can be described as a call option on future cash flows where the exercise price is the investments made in the urban area. This expenditure will be made only if the results from the first phase (dense urban) are sufficiently promising. The option of making the additional investment after 1 year is an example of a call option on a real asset. Thus it is a real option.

As explained, with the use of standard DCF, the first phase can be properly evaluated, but the flexibility that is inherent in the second phase will be missed. Thus, it is more appropriate to use ROA to evaluate it. From the analysis of the second phase performed previously, all the economic results (e.g., investments, running costs, revenues, etc.) necessary for the application of ROA methodology is available. If $I_{t=T}$ is denoted as the investments (of phase two) made at year $t=T$, PV_i, the present value, can be calculated for phase i results as follows:

$$X = I_{t=T}, \tag{9}$$

$$V = \sum_{t=T+1}^{\mathrm{end}} \mathrm{PV}_1, \tag{10}$$

$$S = \sum_{t=T+1}^{\text{end}} \mathrm{PV}_2, \tag{11}$$

$$\mathrm{NPV}_{\text{phase }1} = \sum_{t=0}^{T} \mathrm{PV}_1. \tag{12}$$

For the rest of the calculation, the modified Black–Scholes formula is used as follows:

$$\mathrm{NPV}_{\mathrm{RO}} = e^{-r_f T}(SN(d_1)e^{r_f T} - XN(d_2)) + V(1 - N(d_2)), \tag{13}$$

$$d_1 = \frac{\ln\left(\frac{S}{X''}\right) + \left(r_f + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}, \tag{14}$$

$$d_2 = \frac{\ln\left(\frac{S}{X''}\right) + \left(r_f - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}, \tag{15}$$

$$X'' = X + (1 + r_d)^T V. \tag{16}$$

VI. Real Options Analysis Results

In this section, the results of the previously defined ROA are presented in order to identify the effect of waiting instead of investing during the initial year for the expansion at the urban areas for both FTTC/VDSL and FTTH scenarios. The aim is to identify the optimal decision over time, e.g., how many years the incumbent must wait to carry out the expansion of phase 2. By applying the ROA equations, the parameters d_1, d_2, S, X can be calculated. Table VIII summarizes the new calculated $\mathrm{NPV}_{\mathrm{ro}}$ of the second phase (deployment in urban areas) with the use of ROA, along with previous results from the DCF analysis ($\mathrm{NPV}_{\mathrm{dcf}}$) for the FTTC/VDSL case.

It can be noted that the new total values with ROA are significantly improved compared with those with the DCF analysis. The results in this case reveal that the best deal for the incumbent is to wait for 3 years before proceeding in investing in urban areas with the remark that the differences between the results for $T = 1, \ldots, 5$ are minor compared with the total value of the project, so even expansion in the first or second year can be justified. For the FTTH case, the results based on the same methodology are depicted in Table IX.

The results are financially improved and there are cases in which the NPV turns positive. According to ROA, the optimal strategy is to wait for 4 years, but the difference between the NPV values between the second and fourth year are marginal, and thus, if the decision is made 1 or 2 years sooner, it can be justified. This is mainly the explanation of the incumbent's current attitude, especially in Europe. Most of the incumbent operators did not invest in FTTH in urban areas and are waiting for either state-aid subsidizations via national funds or significant economic developments.

TABLE VIII
ROA Results for the FTTC/VDSL Case

Upgrade Year T	d_1	d_2	Phase 2 $\mathrm{NPV}_{\mathrm{dcf}}$	Phase 2 $\mathrm{NPV}_{\mathrm{ro}}$	Total DCF	Total ROA
1	−2.46	−3.26	−4.08	5.82	0.32	10.22
2	−0.87	−2.00	−1.84	6.89	2.56	11.29
3	−0.37	−1.76	−0.09	6.96	4.32	11.36
4	−0.10	−1.70	1.06	6.30	5.46	10.70
5	−0.04	−1.83	1.61	4.84	6.01	9.24
6	−0.11	−2.07	1.48	2.46	5.88	6.86

TABLE IX
ROA Results for the FTTH Case

Upgrade Year T	d_1	d_2	Phase 2 $\mathrm{NPV}_{\mathrm{dcf}}$	Phase 2 $\mathrm{NPV}_{\mathrm{ro}}$	Total DCF	Total ROA
1	−5.63	−6.03	−14.60	1.57	−18.98	−2.81
2	−2.75	−3.32	−10.00	3.81	−14.38	−0.56
3	−1.89	−2.58	−6.37	5.23	−10.74	0.86
4	−1.56	−2.37	−3.41	5.52	−7.79	1.15
5	−1.54	−2.44	−1.55	4.57	−5.93	0.19
6	−1.85	−2.83	−0.72	2.61	−5.10	−1.77

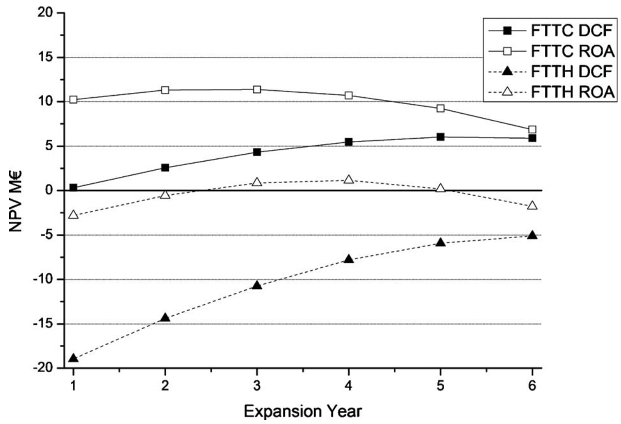

Fig. 10. ROA and DCF analysis results.

For both cases the incumbent before making the decision must also take into account the presence of the competitors in these areas and can further benefit from an earlier investment by taking over the potential market share and have accessional economical advantages that have not been captured in the analysis. All the results for both DCF and ROA are valid if no competitor enters the market during the study period. But it was learned from similar cases that the incumbent is the one that controls the situation and usually makes the first move in such large-scale investments.

In Fig. 10, the NPVs for both scenarios for all the possible years of expansion with both the DCF and ROA methods are presented. It can be observed that the difference in the calculations are significant for the first years and then both methods seem to converge as the years pass, which can be expected as any option value decreases as the time reaches the expiration date. However, an important finding of the ROA is that in the case of investment subsidization, the option value to expand in a later phase can significantly improve the financials of the business cases, and this additional value should be taken into account. As far as any subsidization from national or local governments is related to geographic coverage, the associated flexibility valuated through ROA should be taken into account. In addition, risk-sharing schemes can be based on such a ROA valuation.

VII. Conclusions

In this paper, the alternatives of FTTC/VDSL and FTTH roll-outs in dense urban and urban areas from an incumbent's point of view have been investigated. The analyzed business cases reflect the current stance of incumbent telecom operators regarding their decision to upgrade their infrastructure toward FTTH architecture.

Both classical DCF and ROA have been used to evaluate the options that the incumbent has. ROA seems more suitable for capturing these effects compared with DCF analysis. The results reveal that for FTTC the expansion can be made even 1 year after the deployment in dense urban areas, whereas in the FTTH case it can be made after 2 years.

Since the costs associated with the deployment of FTTH are quite large and the technological and business risks can lead to market failures, the techno-economic analysis of these business cases can provide useful insights about the economic figures and the optimum strategies. Especially as the technology alternatives are always improved, this kind of study is critical for decision makers, and the analysis presented offers a complete framework for the evaluation of these technology and strategy options.

In conclusion, the techno-economic challenges of the current and next generations of FTTx networks should be addressed and several issues associated with the evolution of existing copper-based infrastructures should be analyzed taking into account technical, economic, regulatory, and environmental aspects. In light of 10G operations, the analysis should also be expanded from the access network back to the feeder and distribution networks that will be heavily utilized in the case of FTTC and FTTH deployments.

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