Economics of Time and Wavelength Domain Multiplexed Passive Optical Networks

Theodoros Rokkas, Dimitris Katsianis, Thomas Kamalakis, and Dimitris Varoutas

***Abstract*—Passive optical networks (PONs) are being widely considered as a means to implement fiber-to-the-home (FTTH) and deliver broadband access to business and home users. However, technical and consequently regulatory and economic complexities arise in light of their deployment. In this paper, an evaluation of the business prospects of time division multiplexed (TDM) and wavelength division multiplexed (WDM) PON architectures for FTTH deployments under different rollout conditions is performed, based on the ECOSYS techno-economic methodology and tool. The importance of various cost components (fiber installation, optoelectronic components, etc.) is discussed. Using sensitivity analysis, the effect of various parameters such as duct availability, cost of civil works, etc. on the prospects of the investment are investigated. These results reveal several important techno-economic aspects that should be considered by telecom operators, regulators, and policy makers towards a successful FTTH deployment strategy.**

***Index Terms*—Business economics; Optical networks; Communication systems economics.**

I. Introduction

In recent years, the world has witnessed an unprecedented increase in network capacity in both core and metropolitan area networks. Wavelength division multiplexing (WDM) made it possible to transmit several wavelength channels over the same fiber providing terabit-per-second aggregate transmission rates [1]. However, due to the high installation costs, fiber deployment in the access network is still rather limited, preventing the end user from taking full advantage of this bandwidth abundance. Next-generation access networks are therefore expected to bridge the gap between the capacity at the core/metropolitan networks and the capacity delivered at the user premises. Digital subscriber line (DSL) technologies may provide a short-term solution to this problem. DSL has the advantage of using the existing copper cable infrastructure, but at high data rates, the customer's terminal needs to be located near the digital subscriber line access multiplexer (DSLAM) (the distance should typically not exceed 300 m). Very high-speed DSL (VDSL) [2] can theoretically be used to provide symmetric access of 100 Mb per second, but the actual performance quickly deteriorates as the communication distance increases. To support higher access rates, alternative technologies must be considered. In the long run, installing fibers up to the customer premises, usually referred to as the fiber-to-the-home (FTTH) alternative, is perhaps the only possible candidate to support the increasing bandwidth demands and low-latency requirements of future applications.

Several telecom operators are currently considering various access network evolution scenarios towards fiber-to-the-building (FTTB)/FTTH. Such a network upgrade must be carefully planned, especially taking into account the large associated costs. FTTH is a rapidly growing market in Japan [3]. In May 2010 there were over 17 million subscribers for FTTB/FTTH, 62% of which were FTTH subscribers. Interestingly enough, in Japan, the number of FTTH customers has surpassed that of DSL. In South Korea, the FTTB/FTTH penetration has surpassed 50% [4,5]. Recent policy changes are also expected to favor the penetration of such solutions in the United States [6]. According to data provided by the FTTH council, in April 2010, the number of fiber-connected homes was estimated to be 5.8 million in the USA, corresponding to a penetration of about 6%, while that of the homes that are "passed" (i.e., that can be easily connected to the network because of their proximity to the infrastructure) is about 18.2 million [7]. In Europe, in May 2010, it was estimated that FTTH/FTTB penetration was above 10% in Lithuania, Norway, and Slovenia [4].

FTTH can be implemented on a point-to-point (Pt-Pt) basis where a dedicated fiber pair is used to connect each customer's optical network terminal (ONT) to the optical line termination (OLT) at the central office. This requires the installation of a large amount of fiber cable and can lead to significant OLT line card density resulting in large costs for footprint, power, thermal, and interconnect management [6,8]. A more efficient approach is to use a shared fiber connecting the OLT to a group of customers through a remote node (RN), as shown in Fig. 1. The user ONTs are connected to the RN with dedicated fiber cables of much shorter length. Active routing equipment could be placed at the RN, but this results in increased powering and maintenance cost. To alleviate these costs, passive equipment can be used at the RN, in which case the network architecture is referred to as a passive optical network (PON). Ethernet-based PONs (EPONs) are a special case of time domain multiplexed passive optical networks (TDM/PONs) where a

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The authors are with the Department of Informatics and Telecommunications, University of Athens, Panepistimiopolis, Ilisia, Athens, Greece (e-mail: arkas@di.uoa.gr).

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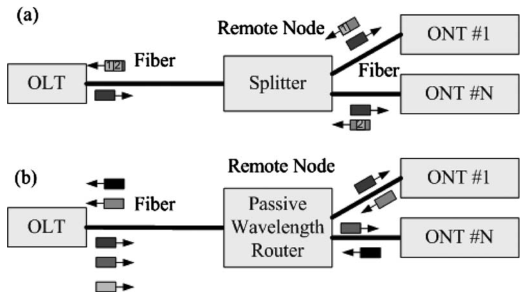

Fig. 1. PON architecture: (a) TDM/PON and (b) WDM/PON.

single wavelength is used to accommodate the downstream traffic from the OLT to an entire customer group [3]. A different wavelength is used to route the upstream data from the customers back to the OLT. In order to provide higher data rates, one solution is to use WDM and assign a different wavelength for the traffic carried from the OLT to and from each user, which is referred to as the WDM/PON architecture. Future upgrades of the TDM/PON to a WDM/PON infrastructure are expected to provide subscribers with gigabit-per-second data rates. Korean Telecom (KT) is currently undertaking a series of field trials in order to evaluate the potential of WDM/PON technology in the access network [5].

Before such wide-scale investments are carried out, however, it is important to investigate their business prospects with realistic techno-economic tools. The cost of civil works, optical components, network operation, administration, and maintenance complicate decisions regarding upgrades in the access network. During the past several years there have been an increasing number of research papers trying to identify the infrastructure installation first cost (IFC) for various optical networks. In [9], the reasons for the slow FTTH adoption in the Unites States are analyzed. In [10,11] the installation costs of various access architectures are examined, while [12,13] focus on the techno-economic analysis of municipality-owned networks and their associated costs. An analysis of the migration path from FTTC to FTTH can be found in [14], and an algorithm for minimizing the cost for a PON is presented in [15]. A complete techno-economic analysis and comparison of TDM/PON and WDM/PON architectures is still missing despite the fact that the decision making on this issue is timely and critical in light of FTTH developments worldwide.

In this paper, we discuss how the techno-economic framework developed in the European project ECOSYS [16] can be applied to study and compare the business prospects of TDM/PON and WDM/PON architectures and provide support to the decision-making process regarding access network installations. The rest of the paper is organized as follows. Section II describes the alternative PON architectures considered in this paper, while in Section III the techno-economic methodology and tool that is used in the analysis are presented along with the geographical area characteristics and the assumptions made for the evolution of the prices for optoelectronic components. Section IV investigates the business prospects of the TDM/PON and WDM/PON architectures, highlighting the importance of factors such as the duct availability and length, the optical component price, the tariff policies, and the installation year. Finally, Section V summarizes the conclusions for the prospects of the examined scenarios.

II. PON Architecture Description

A. TDM/PON

The TDM/PON and the WDM/PON architectures are illustrated in Figs. 1(a) and 1(b), respectively. In the TDM/PON scenario, downstream data are broadcast to the users connected to the OLT through a simple optical splitter located at the RN. Downstream data are broadcast from the OLTs over a single specified wavelength that can be shared on a time domain basis, assigning different time slots for each user. In the uplink, another wavelength channel is used to carry upstream data transmitted by the ONTs. The same wavelengths are used in all ONTs of the PON. This architecture has the advantage of being simple to implement, but the splitter introduces splitting losses that scale linearly with $1/N$, N being the number of users [6] limiting the reach and the number of users that can be connected to a single RN. Splitters usually provide splitting ratios that are powers of 2, so in practice the losses may be $1/M$, where $M=2^m$ is the smaller power of 2 for which $M \geqslant N$ (m is an integer). Bandwidth sharing and network reach are two important factors limiting the TDM/PON's scalability. In addition, the data sent by the multiple ONTs have to go through the OLT involving electronic processing, which inevitably introduces latency and degrades the throughput of the network. In many applications such as virtual private networks (VPNs), grid computing and online gaming, latency can become a major issue affecting the quality of service provided by the network [17].

The IEEE 802.3ah EPON (Ethernet passive optical network) and ITU-T G.984 GPON (Gigabit passive optical network) architectures are two of the available standardized solutions for optical access networks [18–22]. An EPON network permits data rates of 1 Gb/s, while GPON permits 2.5 Gb/s by encapsulating Ethernet frames. In this paper, we have selected GPON as the TDM/PON technology of choice in our techno-economic evaluations. 10GPON is an advanced GPON architecture that will permit a transmission speed of 10 Gb/s for downstream [19]. ITU-T Q2/15 has started standardizing XG-PON (where X stands for the Roman number 10, i.e., XG-PON means 10G-PON) as the future successor to GPON.

In GPON, signals destined for different users are multiplexed in the time domain and are broadcast to all ONTs [18]. ONTs recognize and receive their own data while they block the rest. In the upstream direction, ONTs take turns transmitting within their assigned timeslot. GPON uses the 1.49 μm wavelength for downstream data transmission and 1.31 μm for upstream. At the former wavelength, a GPON system takes advantage of the fiber's low optical loss coefficient near 1.5 μm. Distributed feedback (DFB) lasers can be used as the source in the OLT and the ONT. A GPON system can typically accommodate 32 users at a maximum distance of 20 km (OLT to ONT). The power splitter usually consists of a tree of successive Y-junctions [6].

B. WDM/PON

The WDM/PON is one approach to deliver higher bandwidth, over potentially significantly longer fiber spans. Instead of sharing the bandwidth by assigning users to slots, the WDM/PON separates users and/or traffic classes by using unique virtual connections across reserved wavelengths of an optical signal. One approach is to assign a pair of wavelengths per OLT/ONT connection, one for downstream and one for upstream data. In order to distribute the wavelengths to the users, a static wavelength router such as an arrayed waveguide grating (AWG) is used [6]. The device's cyclic spectral properties enable a single AWG to route the downstream and upstream wavelengths simultaneously. Alternatively the same wavelength can be used to retransmit the data back from the ONT to the OLT in an attempt to double the number of ONTs that can be connected with a given number of wavelengths. WDM/PON link budgets are not burdened from $1{:}N$ power splitting, increasing the overall network reach.

Recent advances in integrated optical technology have enabled the commercialization of athermal AWGs, in which the central wavelength does not shift due to temperature variations. Despite the increased cost of the WDM/PON scenario the users enjoy an increase in bandwidth, since a dedicated wavelength channel is assigned to each of them. Depending on the transceiver used, the data rates can extend into the gigabit-per-second regime [23]. In the upstream direction, it is possible to use low-cost multimode Fabry–Perot laser diodes, which can be directly modulated. Specially designed bidirectional optical filters (often referred to as BiDi) can be used to distinguish the upstream and downstream traffic on the customer premises. WDM/PON multiwavelength downstream technologies are, however, still immature, and there is currently a wide range of competing choices [18]. Each ONT is assigned one wavelength for downstream data. Accurate wavelength control of this source is required, but high downstream data rates in the gigabit-per-second regime can be supported using direct modulation. At the user side, no tuning is required since the AWG and the optical filter ensure that the downstream wavelengths are properly routed to their destined receivers. There is, however, the issue of upstream wavelength selection: Each user must transmit at a specific wavelength in order for the AWG to route the upstream signals back to the OLT. This necessitates the use of wavelength-specific (colored) transmitter modules at the user side hindering network design flexibility and scalability. Ideally, the ONT should be made colorless: Upon installation, its transmission wavelength should be adjusted automatically depending on the existing network topology. Colorless ONTs are useful to reduce inventory complexities, provisioning, record keeping, installation, and fault management. Colorless ONTs can be based on either reflective semiconductor optical amplifiers (RSOAs) [24] or injection-locked field-programmable logic devices (FPLDs) [25]. Figures 2(a) and 2(b) show the colorless-ONT-based WDM/PON architectures considered in the techno-economic evaluations of this paper corresponding to a RSOA and an injection-locked FPLD-based ONT, respectively. A detailed description of these architectures can be found in [24,25]. The architectures illustrated in Fig. 2 were used in order to evaluate the cost of optoelectronic components associated with the WDM/PON installation, as discussed in Subsection III.B.

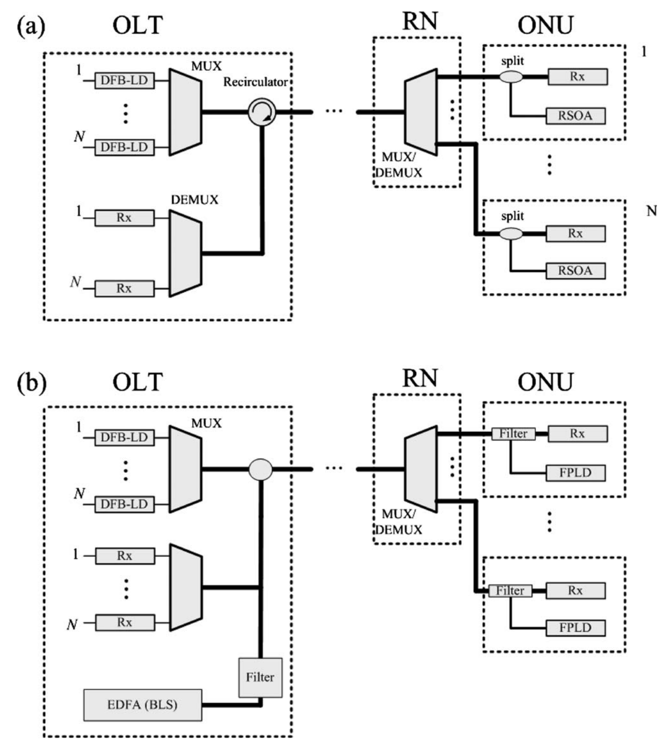

Fig. 2. Colorless ONT-based WDM/PON architectures considered in this paper: (a) reflective SOA and (b) injection-locked FPLD. EDFA, erbium-doped fiber amplifier; BLS, broadband light source.

It should be noted that although WDM/PONs provide a solution to the reach and bandwidth sharing problems of TDM/PONs, the issue of latency remains since the data from every ONT still need to be electronically processed at the OLT.

III. Techno-Economic Methodology

A. Methodology

The tool used in this study is the ECOSYS techno-economic tool that has been used in the evaluations of various wireless and wireline access technologies [26–29]. The application of the model relies on its database, where the cost figures of the various network components are kept and are constantly updated from data gathered from the biggest European telecommunication companies.

Figure 3 depicts the various components of the ECOSYS techno-economic tool.

The study period is best adapted to the case at hand. For fixed network deployments, for example, an 8-year period is reasonable, considering the time it usually takes to reach market maturity. The services to be provided must be specified. This includes the definition of the market penetration of these services over the study period. Also the tariffs for services have to be defined, i.e., the part of the tariff that is attributed to the network under study. From the combination of yearly market penetration and yearly tariff informa-

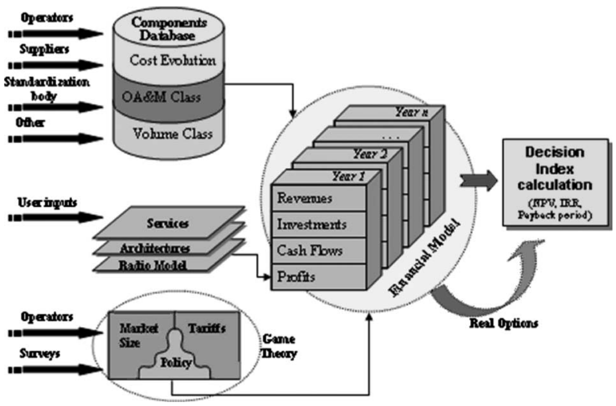

Fig. 3. The ECOSYS techno-economic methodology [16].

tion, the ECOSYS tool calculates the revenues for each year for the selected service set. Next, the architecture scenarios to provide the selected service set must be defined. This needs network planning expertise and is mostly outside of the framework of the ECOSYS methodology. Many network architectures can be accounted for, such as tree, mesh, or ring architectures. The ECOSYS tool includes a set of geometric models that assist in the network planning by automatically calculating lengths for cables and ducting. These geometric models are optional parts of the methodology and the ECOSYS tool can be used without them, e.g., for radio access technology evaluation, where no geometric models are necessary. The result of the architecture scenario definition is the so-called shopping list. This list is made for each year of the study period and it shows the volumes of all network cost elements (equipment, cables, cabinets, ducting, installation, etc.) and the distribution of these network components over different flexibility points and link levels. The costs of the network components are calculated using an integrated cost database. Architecture scenarios are used together with the cost database to calculate investments for each year.

Price forecasting is an essential part of the techno-economic methodology used in this study. The price evolution over time $P(t)$ uses the extended learning curve [27]:

$$P(t)=P(0)[n_r(0)^{-1}\{1+e^{\ln[n_r(0)^{-1}-1]-2\ln 9/\Delta T t}\}^{-1}]^{\log_2 K}. \qquad (1)$$

In Eq. (1), $n_r(t)=n(t)/\max\{n(t)\}$ and $n(t)$ are the normalized and actual accumulated production volume of the product at time t, respectively, and ΔT is the growth period of the product defined as the time taken for the total production volume to reach from 10% to 90% of its maximum value. K is the learning curve coefficient.

A generalization of the logistic model can be used for demand forecasting. The 4-parameter logistic model used in the ECOSYS tool was introduced in [27] and is described by

$$Y(t)=S(1+e^{a+bt})^{-c}, \qquad (2)$$

where $Y(t)$ represents the demand (penetration) of the service in a specific population; S represents the saturation level of penetration; and a, b, and c are parameters related to the characteristics of the curve. Such models are based on the diffusion theory, a methodological approach used for estimating the adoption of technological innovations or other products or services.

B. Area and Component Characteristics

The area is described in terms of subscriber density, loop lengths, and geographical and market characteristics. The area model chosen corresponds to a dense urban area and is shown in Fig. 4. The area's surface is 12 km^2, and there are 5,641 customers per km^2. It is assumed that there is one central office, where the required OLTs are installed, serving 65,536 customers in total. The area under consideration corresponds to a dense urban area and each building has 16 floors of 4 apartments each (see [28] and references therein). The customers are divided to groups of 32, and each group is served by a power splitter (in the case of TDM/PON) or an AWG (in the case of WDM/PON) installed at the RN (cabinet), which is connected via a dedicated fiber to the OLT. There is also a dedicated fiber pair connecting each user to the RN. The area between the OLT and the cabinet are defined as main network and the rest as access network.

The cost of the primary optoelectronic equipment used for the evaluation of the cost per subscriber for both PON solutions is presented in Table I. The table reflects the cost of discrete components and along with Figs. 2(a) and 2(b) has been used in order to estimate the optoelectronic component cost for connecting 32 users to the network. For the injection-locked FPLDs, the cost was about 28,000€ per 32 subscribers, which compared very well with existing 100 Mb/s commercial solutions. For the RSOA-based WDM/PON the optoelectronic component cost for connecting 32 users was about 40% higher, due to the increased cost of commercially available RSOAs. Because of the smaller cost of injection-locked FPLDs, it has been assumed that all ONTs are based on this technology. The prospects of RSOA-based ONTs are discussed in the sensitivity analysis carried out in the next sections. One should note that the optoelectronics cost could be different if the transmitters and the receivers are combined in transceiver circuits. This matter is addressed in a later section using sensitivity analysis.

Tariff policy is another critical issue that can have a strong influence on the business prospects of a telecom investment project. In the present study the tariff structure of [30,31] has been adopted and adapted to the broadband services of Table II. The tariff policy remains the same in both projects and the tariff drops 2% each year in the 8 year study period. Based on this tariff structure, the residential users that choose the Silver Residential Service Class

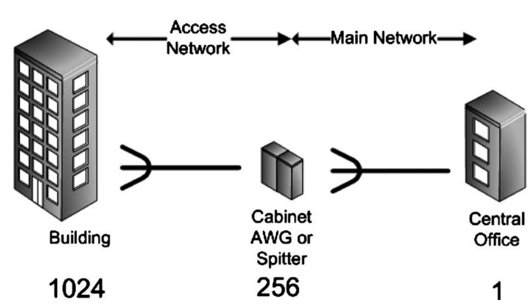

Fig. 4. Network area model.

TABLE I
OPTOELECTRONIC COMPONENT COST

PON Component	Reference Price [Year 2010] (in €)
AWG	500
Splitter	500
FP-LD	50
DFB-LD	200
RSOA	600
EDFA (BLS)	4000

(100 Mb/s access) are charged 34€ per month in 2010, and this rate gradually diminishes to 29€ in 2017. Such rates are comparable to FTTH access rates [32].

C. Service and Customer Definitions

The services to be considered depend on the customer profiles that are classified in residential and business customers, including small and medium enterprises (SME) and small office/home office (SOHO). Key network requirements for business customers are scalability, security, flexibility, and differentiated quality of service (QoS). The range of services required by business customers is wider than for residential customers: file transfer within an intranet, which means bursty traffic and highly variable bit rates; high bit rate access to the Internet; and videoconferencing with strong real-time constraints. Out of the 65,536 users in each study area, 90% of them are considered residential while the remaining 10% are business users. The service classes offered are defined in Table II. For each service class, the mean bit rate (MBR) is considered in order to dimension the network. To calculate these values, one assumes that the MBR equals the maximum bit rate multiplied by a traffic concentration factor (C_t). The first year, this factor is set to 5% for all residential service classes, and 20% for all business service classes. Then the increase of bandwidth requirement is taken into account by assuming that the mean bit rate is growing by 10% each year. In addition there is a migration of the users to enriched service baskets following market and service competition as depicted in Fig. 5

D. Operation Administration and Maintenance Costs

The operation, administration, and maintenance (OA&M) costs are divided into three separate components. The first component represents the cost of repair parts, is driven by the investments in network elements, and is included auto-

TABLE II
SERVICE CLASSES AND TRAFFIC ASSUMPTIONS

Area	D_{max}/U_{max} (Mb/s)	C_t	Monthly Rates 2010(€)
Silver Residential	100	5%	34
Gold Residential	1000	5%	57
Silver Business	100	20%	99
Gold Business	1000	20%	240

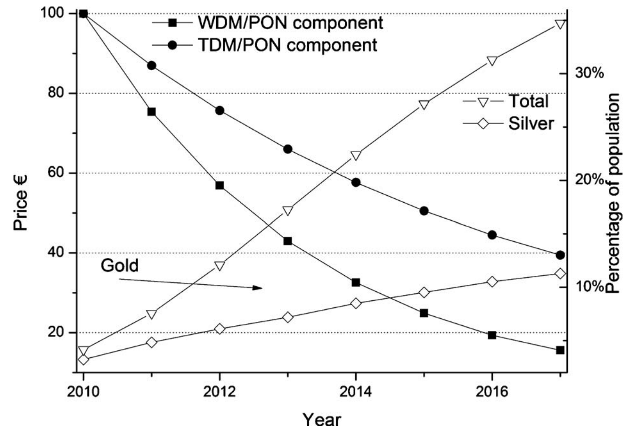

Fig. 5. Price curves for optoelectronics components and demand forecast.

matically in the models. The second cost component C_i represents the cost of repair work calculated at each year i of the study period and for each component

$$C_i = (V_{i-1} + V_i)(P_i R_{class} + C_b)/2, \tag{3}$$

where

$$C_b = P_{labour} \cdot \frac{\mathrm{MTTR}}{\mathrm{MTBR}}. \tag{4}$$

P_{labour} is the cost of the work hour (€/hour), MTBR and MTTR stand for mean time between repairs (in years) and mean time to repair (in hours), V_i is the equipment volume in year i, P_i is the price of the cost item in year i, and R_{class} is the maintenance cost percentage (defined by choosing maintenance material class for every cost component).

MTBR and MTTR figures for each cost component are kept in the tool database. In order to calculate the total cost of repair work throughout the study period one must sum the C_i over all network components and years under study. The third cost component corresponds to operation and administration (O&A) costs that have to be included manually when building the models. Typically this would be driven by services, say by number of customers, or by number of critical network elements. By combining service revenues, investments, operating costs, and general economic inputs (e.g., discount rate, tax rate), the tool can calculate outputs such as cash flows and other economic figures of merit.

E. Penetration and Evolution of the Price of Components

Figure 5 presents the penetration forecast over the study period for the residential users. The penetration is calculated based on Eq. (2) using the same parameters as in [28]. Also shown is the price evolution of an optical component described by Eq. (1) over the study period. It is assumed that the two components initially have the same reference value $P(0)$ in 2010 equal to 100€. The price evolution does not correspond to a specific component of the network, such as a DFB or an RSOA, but it rather indicates how the equipment cost is reduced on average due to the increased demand and production volume. The parameters of the price evolution should be different for the two technologies. For TDM/PON $n_r(0)=0.01$ and $\Delta T=10$ have been selected while for the component used in WDM/PON $n_r(0)=0.001$ and $\Delta T=5$. This is assumed since these components are less mature than the TDM/PON components (see [33] for further details on how to choose the learning curve parameters). Because the WDM/PON components are an emerging market the price declines faster. Consequently, a buyer paying 100€ for WDM/PON equipment in 2010 would pay significantly less at the end of the study period. The reduction is, however, slower for TDM/PON prices since these are more mature products. The impact of the optical component price in the business prospects of the investment is investigated later in Section V using sensitivity analysis.

IV. Results

A. Greenfield Case and Preliminary Sensitivity Analysis

Using the model described in the previous sections, the two PON scenarios were evaluated in the case of a greenfield telecom operator, where the PON main and access network must be built from scratch (i.e., no fiber ducts are available from any previous deployments), in the dense urban area case. The net present value (NPV) was calculated for a study period of 8 years starting at 2010 and is shown in Table III. According to these results, the TDM/PON scenario appears better compared with the WDM/PON scenario.

In order to gain further understanding of these results and consider the uncertainties involved, a sensitivity analysis is performed for both PON architectures. Sensitivity analysis consists of the study of the impact of changes in a single parameter while all other parameters are kept constant. The parameters chosen for the sensitivity analysis were customer tariffs, service penetration, optoelectronic component prices, calculated duct length, the household density, and the duct availability. All the parameters (except the duct availability that will be studied separately in a later section) were varied within an interval of ±50% of their initially assumed values.

Figures 6 and 7 illustrate the sensitivity results for TDM/PON and WDM/PON scenarios, respectively. In both scenarios, the most crucial parameter affecting the NPV is the customer's tariff price. In the case of TDM/PON, a 50% increase in the monthly rates of Table II (e.g., bringing it to 51€/month in the case of a silver residential subscriber) results in a positive NPV, while in the case of WDM/PON, it can improve its NPV by as much as 10 M€. On the other hand, if the value is reduced by 50% (e.g., 17€/month in the case of a silver residential subscriber), the investment projects attain an NPV about two times less than the base case. It should be pointed out that, although the dependency on tariff pricing is strong, no major variations in these prices are expected due to the competition from other operators.

TABLE III
Greenfield Operator Results

Scenario	NPV (M€) (base case)
TDM/PON	−8.5
WDM/PON	−14.5

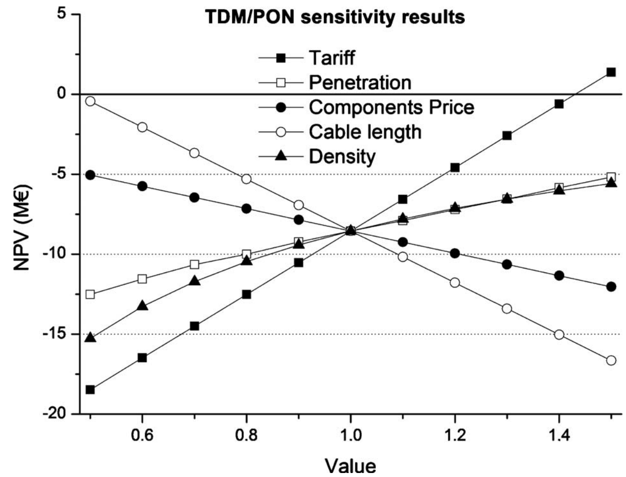

Fig. 6. Sensitivity for TDM/PON.

The next crucial parameter under consideration is the duct length that the operator has to dig in order to deploy the network and connect the customers. For the TDM/PON, if the duct length drops by half, then the project has an NPV of −0.5 M€, whereas if it increases by 50%, then the NPV becomes twice as low (−16.6 M€). The total duct length used in these calculations was estimated using an accurate geometric model and so no major variation in the initial value is expected. For further details on the geometric model the reader can read [28] and references therein.

Of course, one could interpret changes in these values as the result of varying the cost for civil works since in the estimations of the fiber infrastructure cost, the total duct length is multiplied by the average cost of installing the fiber ducts per unit length. The initial average cost was assumed 80€/m corresponding to a dense urban Western European area and includes digging, trenching, installation of duct and fiber cables, and finally road restoration. Reducing the duct length by half is the same as reducing the average

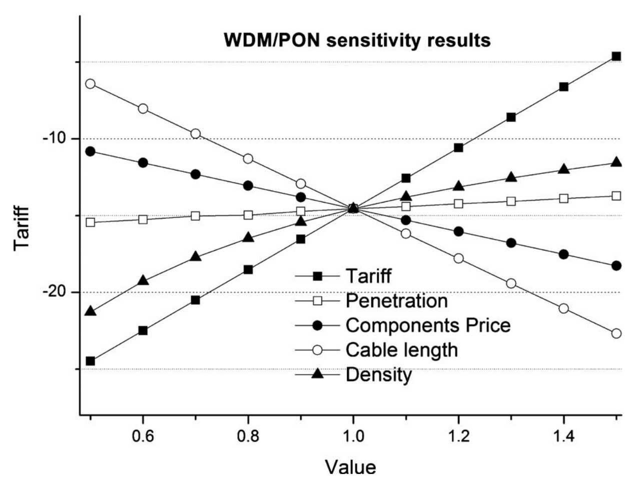

Fig. 7. Sensitivity for WDM/PON.

cost at 40€/m. In large-scale projects where major discounts are expected, the reduced value can lead to a viable economic project in the case of FTTH deployment.

The next important parameter is the cost of optoelectronic components. This includes the necessary optoelectronic equipment for PON technologies: AWGs, lasers, filters, etc. A 50% reduction in price improves the NPV by 40% and 30% for TDM/PON and WDM/PON, respectively. The impact of this parameter will be further analyzed in Subsection IV.C. Regarding household density, a 50% increase improves the NPV by 75%, whereas a decrease by the same amount reduces the NPV by 45%, for the TDM/PON case. In the WDM/PON the corresponding percentages are 49% and −25%, respectively. The least important factor among the ones studied here seems that of service penetration. A 50% increase improves the financial results of TDM/PON by 35% and by 15% for WDM/PON.

B. Impact of Duct Availability

As already mentioned, in all the FTTx projects, the cost of digging up trenches and installing ducts and cables is crucial for the economics of the project, and in our case, it was calculated using the geometric model developed in [28]. In the previous subsection, the impact of the total duct length to the economic prospects of the project for a greenfield operator was examined. In this subsection, it will be clarified even further how the duct availability affects the business prospects of the project. Incumbent operators in Europe have access networks with duct availability (denoted with d) that can vary significantly. Figure 8 illustrates the project's NPV for the TDM/PON and WDM/PON architectures, assuming two different scenarios with different duct availabilities. In the case where d is 0%, no ducts are available and the operator must dig the entire service area in order to install them (greenfield operator). In the second scenario where $d = 100\%$, there are ducts available but only in the main network (e.g., only from the OLT to the RN as shown in Fig. 4). This is a case of an operator that already has upgraded the entire main network in dense urban areas in order to offer VDSL to the customers. The results in Fig. 8 are based on the assumption that there are no ducts in the access part of the network, e.g., between the RNs and the customer buildings. The figure also illustrates the impact of choosing a different first installation (rollout) year for both architectures. The NPV values remain mostly negative for the two alternative PON technologies and duct availability scenarios, regardless of the year of first installation. This is with the exception of TDM/PON with $d = 100\%$ when the installation takes place after 2011. Furthermore the scenario of WDM/PON with $d = 100\%$ is slightly better than the TDM/PON scenario with $d = 0\%$. As expected, the TDM/PON has better economic prospects, relying on more mature GPON technologies with lower optoelectronic component prices than the WDM solution. Figure 8 suggests that the best strategy for the operator is to wait until the component price is reduced (say by 2012–2013) before proceeding to such an investment.

In Western European countries, a typical value for the main network duct availability is 80% for most incumbent operators. Duct availability between the cabinets and the customer premises can, however, vary significantly from country to country. In Fig. 9, the NPV for both architectures is calculated assuming an 80% main network duct availability and three different access network duct scenarios: a) 0%, b) 50%, and c) 100% access duct availability. The case with 0% access duct availability corresponds to the situation of most incumbent operators in Europe, where a significant part of the last mile access network is still based on copper. In all scenarios considered in Fig. 9, TDM/PON performs better than WDM/PON. This is quite logical since the market is more mature (higher demand and revenue figures) and all necessary components are lower priced. The NPV in the case of TDM/PON is positive if FTTH launches after 2013, even under no duct availability in the access part of the network. For WDM/PON, the NPV is always negative if there is no duct availability independently of the year of installation.

In the case where the access duct availability is either 50% or 100%, NPV becomes positive for TDM/PON deployment launched in 2010. For the WDM/PON architecture, positive NPV is obtained only after 2012 if there is 100% duct availability. Figures 8 and 9 clearly illustrate that both

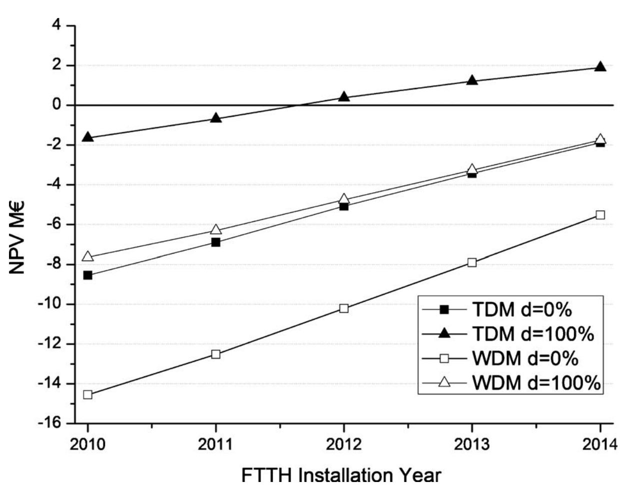

Fig. 8. NPV of the TDM/PON and WDM/PON solution depending on duct availability in the main network.

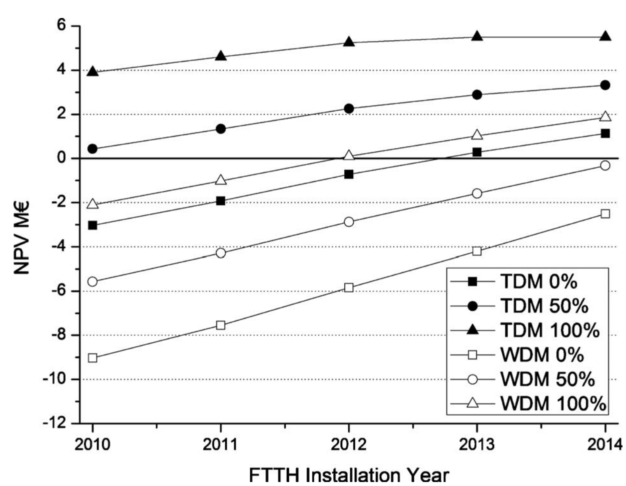

Fig. 9. NPV of the TDM/PON and WDM/PON solution depending on duct availability in the access network (80% present at main network).

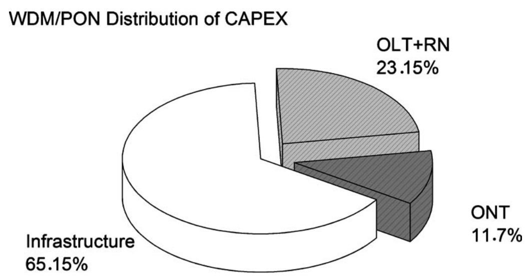

Fig. 10. Distribution of investments for the WDM/PON solution.

main and access network duct availability significantly influence the value of the NPV, thereby altering the business prospects of either of the PON solutions.

In addition, from the comments made in the previous subsection (the sensitivity analysis) it can be deduced that reducing the infrastructure cost is actually the same as having increased duct availability. For example, the reduction of the installation cost by half essentially corresponds to having double duct availability. In this sense, these figures also illustrate the importance of reducing the installation cost of the fiber infrastructure. Note that the previous discussion applies under the assumption that no competitor is entering the market before FTTH is launched (if this is not true, then the market share can be reduced significantly).

C. Importance of Cost Components

In order to identify the most critical cost components, Figs. 10 and 11 illustrate the distribution of the capital investments for WDM/PON and TDM/PON architectures, respectively, in the case where no duct is available (greenfield operator). The largest part of the total costs for both architectures is the infrastructure expenses (digging and installing optical cables). The cost of optoelectronic components includes network equipment installed at the OLT premises (transceivers, switches, etc.) and the RN (AWGs, splitters, etc.) and is more expensive for the WDM/PON than the TDM/PON. The ONT includes all equipment installed at the user premises (ONT, indoor fibers, transceivers, etc.). In the case of WDM/PON, the ONT is more expensive because of the more advanced optical components that must be installed and is almost 12% of the total investments compared to 5% in the TDM/PON case. This difference can be explained due to the higher prices of optoelectronic components used at the ONTs. As discussed in Subsection 3.B, the WDM/PON optoelectronic component base cost value is calculated assuming injection-locked FPLDs at the customer premises.

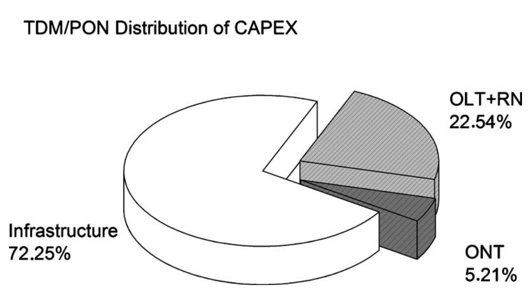

Fig. 11. Distribution of investments for the TDM/PON solution.

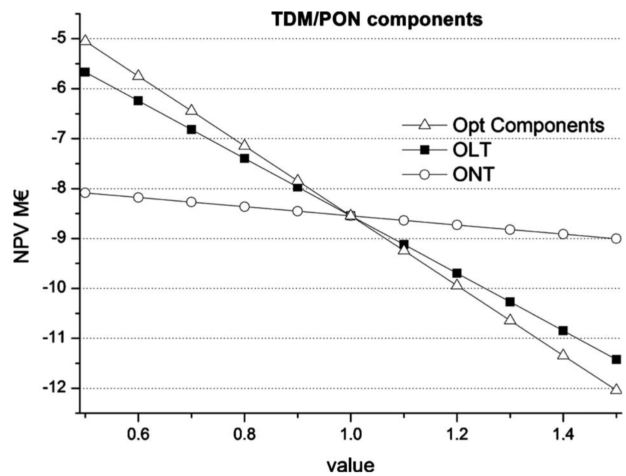

Fig. 12. Sensitivity analysis of the NPV of the TDM/PON with respect to the initial price of the optoelectronic components.

In order to further investigate the effect of the cost of the optoelectronic components, a sensitivity analysis is carried out with respect their initial price $P(0)$. Figures 12 and 13 illustrate the overall impact of changing $P(0)$ in the case where the network installation takes place in 2010 and also illustrates the impact of the OLT and ONT in the NPV for both cases. Changes in the OLT and ONT cost can be due to the fact that the transmitters and receivers can be integrated in transceiver circuits. For WDM/PON solutions, a 50% reduction in the total component prices gives a 25% improvement in NPV values, whereas in the TDM/PON solution this amount is 40%. Figure 12 illustrates that in TDM/PON, the price of the OLT has a more important impact in the NPV compared to the ONT. If the price varies by a factor of 50%, the NPV changes are 34% and 5% for OLT and ONT, respectively. In the case of WDM the same variation in price gives a 16% and 9% change in the NPV for the OLT and ONT, respectively. Again the difference can be explained in terms of technological maturity. As already discussed in Fig. 5, the cost of WDM/PON components is expected to decline faster than those for TDM/PON, while in the future there will be demand for higher volumes and more technologically mature products.

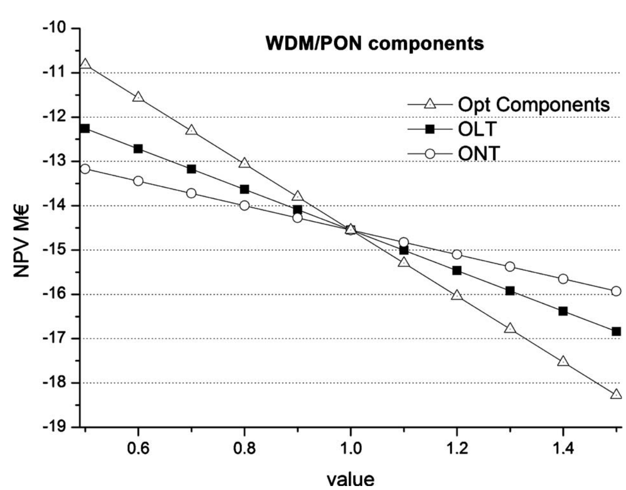

Fig. 13. Sensitivity analysis of the NPV of the WDM/PON with respect to the initial price of the optoelectronic components.

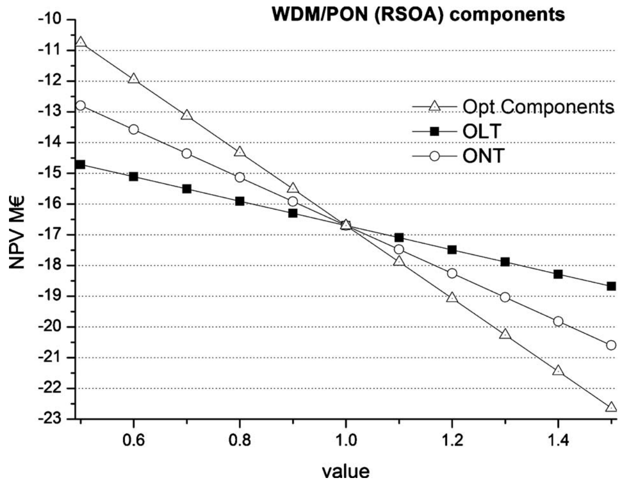

Fig. 14. Sensitivity analysis of the NPV of the WDM/PON RSOA with respect to the initial price of the optoelectronic components.

Finally a comparison between injection-locked FPLD and RSOA-based ONTs for WDM/PON deployment was performed. For the greenfield case, the latter solution is at present more expensive; with the same initial parameters the NPV is −16.7M€ presenting a decrease of 15% compared to the injection-locked FPLD solution. This difference is due to the deployment of the more expensive RSOAs at the ONT although the price of the OLT is reduced (because of the absence of the BLS). A sensitivity analysis shown in Fig. 14 confirms that the ONT cost is now more significant compared to the OLT cost for the economic prospects of the project. A 50% reduction in the price of optical components improves the NPV by 36%, while the same reduction in the ONT and OLT price improves the NPV by 23% and 12%, respectively.

V. Conclusions

In this paper, the economic prospect of PON-based, FTTH deployment scenarios was discussed assuming both TDM and WDM architectures. The study revealed that both projects demonstrate a negative NPV, with the TDM/PON solution to be economically more preferable. However, WDM/PONs can provide the individual subscriber with a higher net data rate. Using sensitivity analysis, the various factors affecting the investment prospects were considered, such as tariff policy, duct length and availability, and the cost of optoelectronic components. In the case of WDM/PON, two colorless ONT technologies were assumed, one based on injection-locked FPLDs and the other based on RSOAs. At present, injection-locked FPLDs resulted in better NPV because of the high cost of commercially available RSOAs. The paper also considered various access network scenarios, including a greenfield scenario where the access network must be built from scratch. Results were presented for the case in which fiber ducts are available because of previous access network deployments.

The techno-economic analysis carried out in this paper revealed that infrastructure installation remains the higher cost component. If these costs can be reduced, say by using existing duct availability, or reducing the cost of civil works, then the prospects of both FTTH deployment scenarios are improved significantly. The European Commission and a number of national regulatory authorities consider WDM/PON as a potential technology in order to offer unbundled access to PON-based networks. The analysis also suggests that the optimal strategy would be first to commence the installation of TDM and implement the costly infrastructure civil works and later upgrade to the WDM solution when the price of WDM components will probably fall. This upgrade will use the infrastructure already deployed and will upgrade the optoelectronic equipment (ONTs, OLTs, etc.). The low NPV of both projects unveiled that the business potential of both WDM/PON and TDM/PON scenarios is limited, especially for the operators with no duct availability or existing infrastructure.

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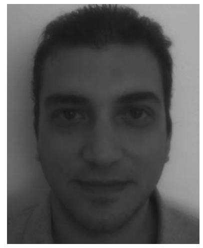

Theodoros Rokkas received his B.Sc. degree in physics in 2000 and the M.Sc. degree in electronics and radiocommunications in 2002, both from the University of Athens, Greece. Currently he is a research associate and working toward the Ph.D. degree in techno-economic evaluation of telecom networks in the Department of Informatics and Telecommunications at the same university. His research interests include techno-economic evaluation of network architectures and services, mobile communication systems, broadband and wireless systems, and networks.

Dimitris Katsianis received the informatics degree; the M.Sc. in signal processing and computational systems from the University of Athens, Department of Informatics and Telecommunications; and the Ph.D. from the same university in techno-economics of telecommunications networks. He is a research fellow with the Optical Communications Group, participating in several European R&D projects and working as an expert scientific advisor in the field of techno-economic and network design studies. His research interests include broadband communications and methodology of network design with techno-economic aspects. He has more than 50 publications in journals and conferences, and he serves as a reviewer for journals and conferences.

Thomas Kamalakis obtained his B.Sc. in informatics, M.Sc. in telecommunications with distinction, and Ph.D. in integrated optics from the University of Athens in 1997, 1999, and 2004, respectively. Since 2005 he has been a Research Associate in the Optical Communications Laboratory of the University of Athens. In 2008, he was appointed a Lecturer in the Department of Informatics and Telematics at the Harokopio University of Athens. Dr. Kamalakis is the author or co-author of more than 50 publications in scientific journals and conferences in the fields of optical communications and techno-economics.

Dimitris Varoutas (M'03) holds a physics degree and M.Sc. and Ph.D. diplomas in communications and techno-economics from the University of Athens. He is a Lecturer on telecommunications techno-economics in the Department of Informatics and Telecommunications at the University of Athens. He has been participating in numerous European R&D projects since the early 1990s. He actively participates in several techno-economic activities for telecommunications, networks, and services such as the ICT-OMEGA and the CELTIC/CINEMA projects, as well as conferences on telecommunications techno-economics. He also participates in or manages related national activities for techno-economic evaluation of broadband strategies, telecommunications demand forecasting, price modeling, etc. He has published more than 60 publications in refereed journals and conferences in the area of telecommunications, optoelectronics, and techno-economics, including leading IEEE journals and conferences. His research interests span design of optical and wireless communications systems to techno-economic evaluation of network architectures and services. Dr. Varoutas is a member of IEEE and serves as reviewer of several journals and conferences.