Business prospects of wide-scale deployment of free space optical technology as a last-mile solution: a techno-economic evaluation

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A technoeconomic evaluation of the business prospects of a wide-scale deployment of free space optical (FSO) technology as a last-mile solution is carried out. The evaluation is based on a technoeconomic tool that taking into account network topology, area characteristics, service demand, and price evolution forecasts, estimates key economic figures-of-merit. It is shown that FSO technology could provide a viable alternative in situations where the duct availability is limited, and fiber-to-the-home/office or fiber-to-the-cabinet scenarios have negative or less favorable business prospects. Hybrid fiber/FSO scenarios are also investigated taking into account different FSO coverage conditions.

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1. Introduction

Recent years have seen a widespread adoption of optical technologies [1] in the core and metropolitan area networks. Wavelength division multiplexing [2] transmission systems can currently support terabit per second transmission rates. Since optical technologies are starting to migrate toward the access network, the cost factor becomes a vital issue [3]. Optical fiber installation in populated areas requires digging up trenches for fiber ducts, which results in costly civil works affecting the viability of the business project. In areas where a large amount of fiber ducts have already been installed (such as in many western european countries), fiber-to-the-cabinet (FTTC) scenarios could provide a viable access solution in contrast to the fiber-to-the-home/office (FTTH/O) scenarios, where the investment prospects are still severely limited due to the enormous fiber roll-out [4]. However, as discussed in this paper, the duct availability crucially affects the prospects of both FTTC and FTTH/O scenarios. In the cases of limited duct availability, other broadband technologies may rate more favorably compared to the two aforementioned fiber-based deployment strategies.

Free space optical (FSO) systems [5] can be used as an alternative in order to provide high bandwidth wireless connections in the access network and to alleviate the large costs associated with fiber cable installations. In addition, FSO technology has the following advantages:

1. *Large Transmission Rate*: Older FSO links used to operate at 100 Mbits/s, but gigabit persecond links with gigabit Ethernet interfaces have also become commercially available.

2. *Vast Available Spectrum*: The FSO available spectrum extends from 0.7 to 10 μm. Most systems operate either near 0.7–0.8 μm or near 1.55 μm. Systems operating at 10 μm are considered for increased performance in adverse weather conditions [6].

3. *Limited Beam Interference*: The optical beams have small beamwidths, preventing signal interference.

4. *No license fees*: Given the vast bandwidth and the limited interference, the FSO bandwidth does not need to be regulated, rendering this technology license free.

5. *Ease of Installation*: FSO systems can be easily installed on rooftops, signs, street lamps, and even behind office windows due to their light weight and small dimensions.

6. *Safe Operation*: Provided that eye-safety conditions are met, radiation at FSO wavelengths is safe, since mankind has been exposed to this kind of radiation for thousands of years due to the Sun.

FSO systems are ideal in areas with mild or hot climates where the probability of heavy fog occurrence is rather limited. In foggy regions, a backup millimeter wave (MMW) link can also be used to achieve increased link availability exceeding 99.9% [7,8], but this increases the cost.

In this paper, a systematic and detailed investigation of the investment potential of a wide-scale FSO deployment near the customer's premises is carried out using a technoeconomic (TE) tool [9]. The tool's operation is based 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. A geometric area model is used to calculate the number of network elements and estimate the cable infrastructure and wireless equipment costs. The area characteristics considered in this paper correspond to large countries such as those located in western Europe and are described in greater detail in [10]. Given that market penetration forecast of the telecom services has to be provided and the tariffs associated with them have to be provided as well, the TE tool can then calculate revenues, investments, cash flows, and other financial results for each year of the study period. Using this methodology, the FSO scenarios are compared to both FTTH/O and FTTC from an incumbent operator point of view, and it is shown that in cases where duct availability is limited, FSO-based scenarios could provide an economically favorable alternative to both fiber-based access scenarios. Using a cost and sensitivity analysis, various other business aspects are also highlighted.

The rest of the paper is organized as follows: in Section 2, the application of the TE tool in the case of the FTTH/O and FTTC scenarios is outlined, and results concerning the relation between the business prospects of these scenarios and the duct availability are presented. In Section 3, the FSO-based scenarios considered are described and the tool is applied to evaluate their business prospects compared to the FTTH/O and FTTC scenarios. Hybrid fiber/FSO scenarios are also investigated to account for situations where a substantial fraction of the required connections do not possess line-of-sight and hence cannot be serviced by FSO. Some concluding remarks are given in Section 4.

2. Technoeconomic Evaluation of FTTC and FTTH/O

The TONIC methodology adopted for the evaluation of FSO technology is based on the TE tool developed within the IST-TONIC [9] and the CELTIC/ technoeconomics of integrated communications systems and services ECOSYS [11] European projects. The tool has been used for the evaluation of both wireless [12,13] and wired scenarios [4] in several case studies. A study period is first identified, one that is best adapted to the case at hand. For fixed network deployment, for example, an 8–10 year period is reasonable, considering the time it takes to reach market maturity. The architecture scenarios and the services to be provided must be identified, and many network architectures can be accounted for, such as tree, mesh, and ring architectures. The TE tool includes a set of geometric models that automatically calculate lengths for cables and ducting. These geometric models are actually optional parts of the methodology, and the TE tool can be used without them, e.g., for radio access technology evaluation, where no geometric models are necessary. The result of the architecture and service definition is the so-called shopping list. Using service demand forecasting, this list is calculated for each year of the study period, and indicates the volume of all network cost elements (equipment, cables, cabinets, ducting, installation, etc.), as well as the distribution of these network components over different flexibility points and link levels. The cost of the network components is calculated using an integrated cost database. The architecture scenarios are used together with the cost database to calculate investments for each year.

The geometric area model that was used to calculate the number of network elements required is illustrated in Fig. 1 and corresponds to the tree network architec-

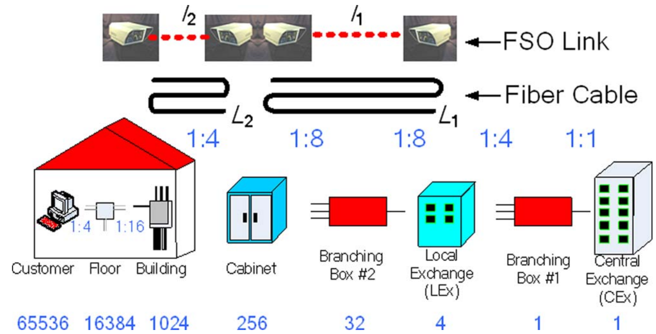


Fig. 1. Dense urban area geometric model.

ture. The area is described in terms of subscriber density, loop lengths, geographical, and market characteristics [4,10]. Three types of areas are identified: dense urban, urban, and suburban. The network model for each area is based on the metropolitan access network, starting from the central exchange, and reaching all the way to the customers. The characteristics of the three area types are summarized in Table 1, where l_1 and l_2 are the maximum cabinet-building and local exchange (LEx) cabinet distances respectively, d_s is the subscriber density, N_b is the number of buildings, and n_{sb} is the number of subscribers per building.

The services to be considered depend on the customer profiles, which are classified in residential and business customers [including small and medium enterprises (SME) and small office/home office]. Key network requirements for business customers are scalability, security, flexibility, and differentiated quality of service. The range of services required by business customers is wider than for residential customers; file transfer within an Intranet, which implies bursty traffic and highly variable bit rates, high bit rate access to the Internet, and videoconferencing with strong real time constraints. In most cases, these services require higher bit rates than typical residential services. Table 2 shows the total market potential that has been assumed, and the percentage of business customers in all types of areas. The market share of the incumbent operator is shown in Table 3. It can be noticed that there is no competition in the suburban area, but the dense urban area business market is the most competitive market. The service classes are defined in Table 4, where $D_{\max}$ and $U_{\max}$ are the maximum downstream and upstream data rates. Lower bit rate services can be provided with existing ADSL technology, and will gradually migrate to higher bit rates during the study period. Higher bit rate service classes above 23 Mbit/s will not be considered since the penetration of these services is expected to be limited. For each service class, the mean bit rate is considered in order to dimension the network. One can assume that the mean bit rate is equal to 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 5% each year. More information on the tables can also be found in [4] and [10].

Table 1. Area Characteristics

Area type	l_1 (km)	l_2 (km)	N_b	n_{sb}	d_s (km^{-2})
Dense urban	1.2	0.08	1024	64	5641
Urban	2.0	0.13	2048	32	2048
Suburban	3.2	0.20	16384	4	410

Table 2. Definition of the Market Potential

Market Potential	Dense Urban	Urban	Suburban
Customers	16,384	16,384	8192
Households (%)	90%	93%	94%
Businesses (%)	10%	7%	6%

Table 3. Market Share of an Incumbent Operator

Type of Market Share	Dense Urban	Urban	Suburban
Residential	90%	95%	100%
Business	60%	80%	95%

Table 4. Service Classes and Traffic Assumptions

Area	D_{max} (Mbits/s)	U_{max} (Mbits/s)	C_t	Example Interface
Silver residential	6.14	0.64	0.05	10 Base T
Gold residential	23.17	4.09	0.05	10/100 Base T
Basic business	6.40	6.40	0.05	10/100 Base $T3\times 10$
Silver business	8.57	8.57	0.2	10/100 Base $T4\times 10$
Gold business	23.16	23.16	0.2	10/100 Base T E3 $\times$ ATM25.6

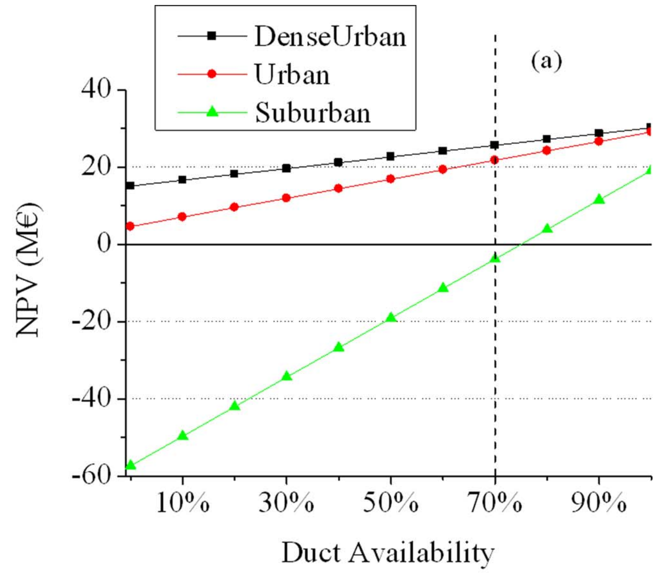
The future market penetration of the services and the tariffs associated with them, are calculated through market forecasts, and are inserted into the tool [14,15]. The tool also calculates the future price of the various network elements. The price $P(t)$ of each network element is assumed to follow the extended learning curve [16]:

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

Equation (1) reveals the fact that the cost reduction is specified using the growth period ΔT (i.e., the time taken for the total production volume to reach from 10% to 90% of its maximum value), the learning coefficient K (i.e., the price reduction experienced when the production volume is doubled), and the relative initial production volume $n_r(0)$. In cases where historical data are available, these constants can be determined using ordinary least squares regression [17]. The TE tool then calculates revenues, investments, cash flows, and other typical financial measures for each year of the study period.

The broadband access forecasts that are carried out are also used to calculate revenues, investments, cash flows, and other financial results for each year, and are calculated based on the broadband tariff structure of [14,15]. The operation administration (O&A) and maintenance costs for each network element are estimated from the cost of each of its constitutive parts based on an architectural model [4]. 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 the list price information of several vendors. The cost of repair parts is calculated by the model according to the investments in network elements, while the cost of repair work is calculated based on mean time between failure (MTBF) and the mean time to repair (MTTR). Combining service revenues, investments, operating costs, and general economic inputs (e.g., discount rate and tax rate), the TE tool can calculate outputs such as cash flows, net present values (NPVs), and other of economic figure of merits.

Figure 2 provides an example output from the TE tool regarding the NPVs for both FTTC and FTTH/O for the three types of areas, and for various values of the duct availability d_a assuming an 8 year study period (from 2006 to 2013). As expected, d_a severely affects the business prospects of the investment, and for $d_a=0$, only FTTC in dense urban and urban areas have positive NPVs. In suburban areas the NPVs remain negative even for d_a as high as 70% (which is a typical value of duct availability in dense urban areas of western European countries [4]). The NPVs of FTTH/O in urban and suburban areas is also negative regardless of d_a while, in dense urban areas, FTTH/O can be considered only if $d_a>20\%$. These considerations illustrate the problem encountered by many operators in countries where past investments in network infrastructures are limited (and hence d_a is quite low). In such cases, other alternative access technologies such as FSO may need to be examined in order to provide high bandwidth connections to residential and business users.



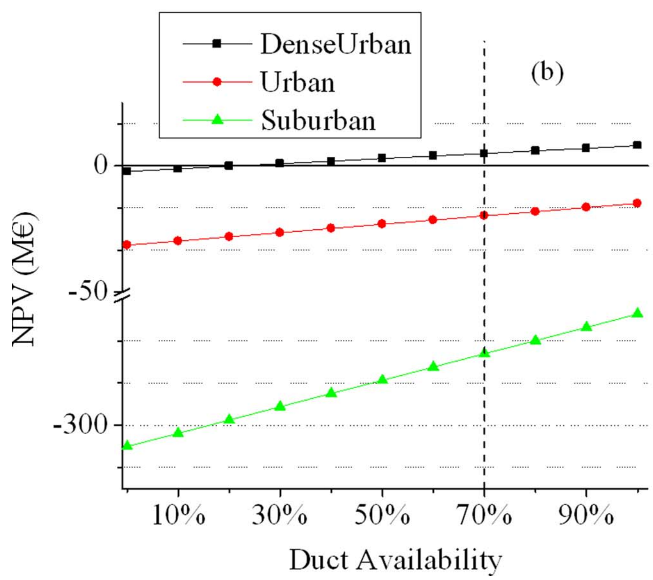


Fig. 2. Dependence of NPVs on the duct availability d_a for (a) FTTC and (b) FTTH/O scenarios.

3. Business Prospects of FSO in Dense Urban and Urban Areas

3.A. Free Space Optical Scenario Description

To investigate the business aspects of FSO technology for widespread deployment in the access network, three alternative scenarios are considered. In the FSO LEx-cabinet scenario, a number of relatively long range (LR) gigabit FSO links (GigFSOLRs) with automatic gain control (AGC) for increased reliability are deployed to connect the LEx and the cabinet. Similar to the FTTC scenario, the users are connected through very high speed digital subscriber line (VDSL) modems using the existing copper infrastructure. In the FSO1 LEx-building scenario, GigFSOLRs are used to provide wireless gigabit connections between the buildings and the cabinet. Alternatively, in the FSO2 LEx-building scenario, the cabinet/customer connections have been established using less expensive, shorter range (SR) gigabit FSO links (GigFSOSRs) without AGC.

In the FSO-based scenarios, it is assumed that there are line-of-sight conditions of the LExs and the cabinets, and between the cabinets and the buildings. This assumption is made since the primary goal of this paper is to investigate the business prospects of FSO technology as a last-mile solution. In this respect, one can compare an all-fiber scenario (such as FTTH) and an all-FSO scenario (such as the FSO LEx-building) and draw conclusions for the business prospects of a hybrid FSO/FTTH scenario as well, where fiber is used in situations where no line-of-sight exists. Specifically, if the business prospects of the all-FSO scenario prove to be better than those of the all-fiber scenario, then one can expect that, in situations where fiber is used for the non-line-of-sight portion of the optical connections, using FSO systems for the rest of the links will improve the investment prospects of the project. Hybrid fiber/FSO scenarios are also investigated in Section 3 in order to examine the business prospects of partial FSO installation in cases where a fraction of the required connections do not have line-of-sight.

It must also be noted that in situations where, for example, the cabinet is placed on the street or even below the ground, the FSO transceivers can be placed in a nearby lamp or power-line post, road signs, or can be mounted on nearby building walls, and multimode fiber cables can be used to connect the transceiver to the cabinet. Alternatively, one may use two smaller range FSO links to connect two sites without a line of sight via an intermediate third point that has a line-of-sight with the two original points. This will of course increase the average price of the FSO links, and this is partly why a sensitivity analysis is carried out later in this section with respect to an increase in the retail initial price of the links. A different approach would be to use only two FSO transceivers at the end points and a mirror at the intermediate point. Although this could be a cheaper alternative, the introduction of the mirror could complicate the alignment procedure and could introduce extra optical losses.

As was explained Section 1, fog is the primary limiting factor in determining the range of FSO links. In most cases the maximum link range is calculated taking into account fog attenuation, and a power margin is taken into account in the link budget in order to be able to tolerate mildly foggy conditions. Multiple receiver techniques, advanced modulation formats, and forward error correction may also enhance the receiver sensitivity. However, in areas with heavier fog conditions backup MMW links may have to be installed, particularly in cases where the link range is above 1 K m. For example, in the FSO LEx-building scenarios, some LEx-cabinet connections exceeding 1 K m can be backed up by a MMW link at the expense of increasing the average link retail price. This point further highlights the need for a sensitivity analysis with respect to the retail initial price of the links. In the future, 10 μm FSO systems may prove to be more tolerant to fog, but there are still no commercially available FSO components operating at this wavelength. Whether or not such systems will indeed provide increased performance at an affordable price in the future is still not very clear [18].

The link range and retail price of the FSO links are summarized in Table 5, and were identified based on information available from FSO link vendors. The transmission wavelength is set at 780 nm and the maximum bit rate is 1 Gbits/s. For each link a 1500 € initial installation cost was assumed, while the values of MTBF and MTTR were taken as 10 years and 8 h, respectively. As with any other network component, the model assumes that FSO links experience a price reduction based on the extended learning curve given by Eq. (1). For the FSO components, the values for the extended curve parameters must be postulated since not enough historical data are available in order to perform regression. Taking into account the guidelines in [16], the values $K=0.8$, $\Delta T=5$ years, and $n_r(0)=10^{-3}$ were selected for both FSO links. Most of the FSO links are installed in the beginning of the project so that price evolution is not very crucial for FSO components.

3.B. Technoeconomic Evaluation of FSO Scenarios

Table 6 compares the NPVs for an 8 year study period for the two fiber-based and the three FSO-based scenarios assuming a dense urban area and $d_a=0$ (corresponding to

Table 5. FSO Link Characteristics

Designation	Maximum Range (m)	Interface	Operation Wavelength (nm)	AGC Option	Retail Price 2006 (€) [P(0)]
GigFSOLR	1500	GbE	780 nm	Yes	20,000
GigFSOSR	200	GbE	780 nm	No	9000

limited past investments), or $d_a=70\%$ (corresponding to increased past investments). For the FSO scenarios the initial retail prices quoted in Table 5 were used for the NPV calculations. Even at such high prices for FSO, the FSO LEx-cabinet scenario is better than FTTC and both FSO LEx-building scenarios, resulting in greater NPVs than FTTH/O in the case of no duct availability ($d_a=0$). Also note that the FSO1 LEx-building scenario results in a marginally positive NPV value. Based on the above remarks, it can be deduced that FSO technology can lead to more favorable business opportunities compared to its fiber counterpart, especially if no trenches for fiber ducts have been dug up. However, the fiber-based scenarios are better than their FSO alternatives if $d_a \geq 70\%$.

Since a large part of the FSO equipment will be installed at the beginning of the study period, the NPVs are highly sensitive to the initial price of the FSO products. This is clearly demonstrated in Fig. 3(a), where the sensitivity of the NPVs with respect to the initial product price is plotted. The prices of both links are varied from 60% to 140% of the retail price quoted in Table 5. It should be emphasized that these price variations correspond to variations in the initial price $P(0)$ at $t=0$ and should not be confused with the price variation $P=P(t)$ over time as given by Eq. (1). A reduction in the initial price $P(0)$ may be a result of mass equipment purchasing, that can allow the FSO vendor to offer a substantial discount. On the other hand, an increase in $P(0)$ may be due to the fact that some of the wireless links must be hybrid FSO/MMW in order to provide increased reliability or using two smaller ranges instead of a single FSO system if some of the desired connection points do not possess line-of-sight as explained in Subsection 3.A.

It is interesting to note that the FSO LEx-cabinet is better than FTTC even for a 35% increase in the initial FSO link price. Furthermore, if FSO vendors offer a discount of 40% for their optical links, then an NPV of 25 M€ can be obtained, compared to 15 M€ of FTTC. Due to the large number of FSO links deployed (especially in the first year), such large price discounts can be expected from FSO vendors.

Referring again to Fig. 3(a), the FSO2 LEx-building scenario leads to positive NPVs for a 10% price increase and is better than the FTTH/O scenario even for a 40% increase. The FSO1 LEx-building scenario becomes worse than the FTTH/O scenario only if the initial link price rises by 30%. For a price discount of 20%, the NPV of the FSO1 LEx-building becomes marginally positive. As the discount increases, the difference in NPV for both FSO LEx-building scenarios gradually diminishes, since the cost of the FSO equipment becomes a smaller fraction of the overall investments. For example, given a larger 40% discount, the NPV of the FSO1 LEx-building and the FSO2 LEx-building are approximately 4 M€ and 6 M€ respectively. These considerations clearly emphasize the importance of adopting FSO links as a business alternative.

As far as the business aspects of FSO technology in urban areas is concerned, sensitivity calculations of the NPVs for two different FSO-based scenarios with respect to the initial price of the FSO links have been carried out and are depicted in Fig. 3(b). In these scenarios, fiber is being deployed up to the curb site (similar to FTTC), and the buildings are connected to the curb using either the LR GigFSOLR or the SR GigFSOSR links. Unlike the dense urban area case, in urban areas the mean distance between the cabinet and the LEx exceeds the range of both FSO link types and hence no FSO connections can be established between the cabinets and the LEx. In addition the NPV of the FTTH/O scenario with $d_a=0$ is plotted. In all three cases, the

Table 6. Scenario NPV Comparison

Scenario Type	NPV (M€)
FTTC ($d_a=0$)	+15.08
FTTC ($d_a=70\%$)	+25.0
FSO LEx-cabinet	+19.95
FTTH/O ($d_a=0\%$)	−8.86
FTTH/O ($d_a=70\%$)	+4.97
FSO1 LEx-building	−3.67
FSO2 LEx-building	+1.14

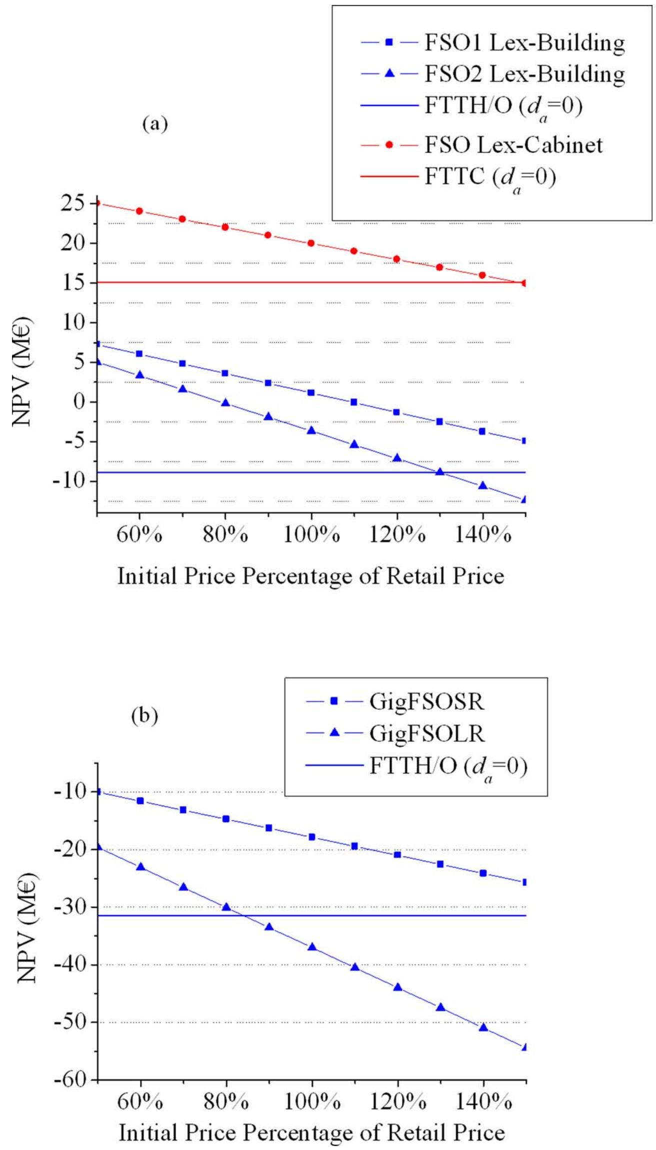


Fig. 3. Sensitivity of the NPV for (a) three dense urban FSO scenarios with respect to the simultaneous initial price variation of the GigFSOLR and GigFSOSR links, (b) two urban area FSO scenarios of either links used to connect the buildings to the cabinets.

NPV is negative but the second FSO scenario is better than FTTH/O even if the initial price is increased by 40%. The first FSO scenario is better than FTTH/O if the price discount is 10% or larger, which is likely to occur as a part of vendor–operator business agreement. Figure 3(b) reveals that, although wide scale FSO deployment in areas, other than dense urban result in unfavorable business cases, it is still preferable to FTTH/O.

To better highlight the difference between the FSO and the fiber-based scenarios, the annual revenues and lifecycle cost of the network in the case of the FSO LEx-cabinet and the FTTC scenario (with $d_a=0\%$) are plotted in Fig. 4. The initial prices for the GigFSOLR links are those given in Table 5. In the FTTC scenario the investments are broken down to fiber installation costs (dark gray color bar), and other network component related investments (light gray color bar). In the FSO scenario, a similar breakdown is shown and the dark gray color bars correspond to investments in FSO links, while the rest of the investments are depicted with a light gray color bar. The running costs correspond to component maintenance, personnel salaries, and O&A costs. The annual cash flows are calculated by subtracting the sum of the investments and running costs from the revenues. The cumulative cash flows (cash balance) in a given year are calculated as the sum of the cash flows in that year, and in all preceding years.

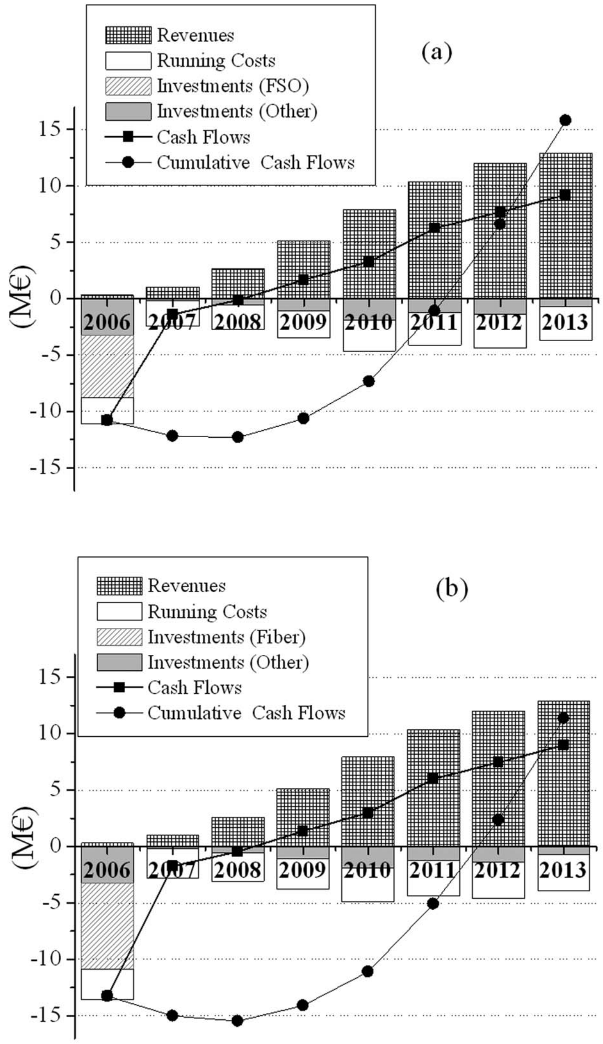


Fig. 4. Annual revenues and cost analysis for (a) the FSO LEx-cabinet and (b) the FTTC scenario with $d_a = 0\%$.

It is interesting to note that in the FTTC scenarios, most of the fiber is deployed in the first year (2006) in order to cope with the coverage demand. As expected, the largest part of the investments in FSO technology is also made in the first year of the network operation. Comparing Figs. 4(a) and 4(b), it is deduced that the better business prospects of the FSO LEx-cabinet are due to the reduced (by a factor of 35%) optical link investment costs at the beginning of the project. Note that since most of the FSO products will be installed in 2006, FSO vendors can indeed offer a substantial discount, thereby further improving the investment prospects. On the other hand, since fiber installation involves costly civil works, no significant cost reductions can be expected for FTTC, with the exception of significant subsidization measures from the public authorities' side. Further improvements in FSO related scenarios can be expected if operators strategically decide to invest in FSO technology research and manufacturing while starting to install FSO equipment in their networks. Since most FSO companies worldwide are SMEs with an active research and development department, such strategies may be realized through corporate takeovers and acquisitions.

It is also interesting to consider the business prospects of FSO deployment in cases where there is a number of customers that do not have line-of-sight connection with the cabinet, or there is no line-of-sight between the LEx and the cabinet. It was explained, that, in this case, one may install fiber to achieve connectivity according to the hybrid FSO/FTTH or FSO/FTTC scenarios presented in Subsection 3.A. Figure 5 illustrates the NPV values of these hybrid scenarios as a function of the FSO coverage

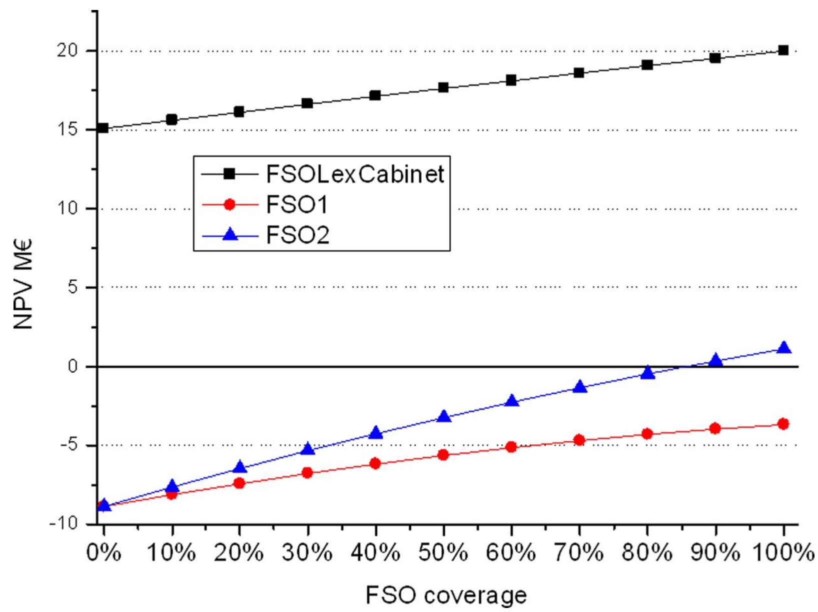


Fig. 5. NPV results for different percentages of FSO coverage.

ratio (i.e., the fraction of connections that can be accommodated using FSO). As expected, even the partial use of FSO technology significantly improves the business prospects of these scenarios. The FSO1 LEx-building scenario attains a positive NPV even if ~15% of the connections cannot be served by FSO. The FSO2 LEx-building scenario has a negative NPV regardless of the coverage. These results indicate that the hybrid FSO/FTTH or FSO/FTTC scenarios may have substantially better business prospects than their all-fiber counterparts and further supports the wider scale deployment of FSO technology in the access network, even in cases where a fraction of the desired connections do not possess line-of-sight.

4. Conclusions

In this paper, a technoeconomic evaluation of the business prospects of wide-scale deployment scenarios of FSO technology in the access network was carried out. Using key economic figure of merits, it was shown that in areas with limited fiber duct availability, FSO can provide an interesting, economically viable broadband alternative to FTTH and FTTC, since FSO installation does not require any costly civil works, which are mainly time invariable costs. As FSO equipment is mainly installed in the beginning of the deployment project, larger production volumes and therefore better performance and price reductions, due to vendor–operator agreements, can be expected, which will result in the further improvement of their business prospects.

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