Cost optimization of optical in-building networks

Citation for published version (APA):
Koonen, A. M. J., Boom, van den, H. P. A., Ortega Martinez, E., Pizzinat, A., Guignard, P., Lannoo, B., Okonkwo, C. M., & Tangdiongga, E. (2011). Cost optimization of optical in-building networks. *Optics Express*, *19*(26), B399-B405. https://doi.org/10.1364/OE.19.00B399

DOI:
10.1364/OE.19.00B399

Document status and date:
Published: 01/01/2011

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 23. Aug. 2022

Cost optimization of optical in-building networks

A. M. J. Koonen,[1,*] H. P. A. van den Boom,[1] E. Ortego Martinez,[2] A. Pizzinat,[3] Ph. Guignard,[3] B. Lannoo,[4] C. M. Okonkwo,[1] and E. Tangdiongga[1]

[1] *COBRA Institute, Eindhoven Univ. of Technology, Den Dolech 2, NL 5612AZ Eindhoven, The Netherlands*
[2] *Telefonica I + D, Parque Tecnológico Boecillo, 47151 Valladolid, Spain*
[3] *France Telecom R&D, Av. Pierre-Marzin 2, 22307 Lannion, France*
[4] *Ghent University - IBBT, Gaston Crommenlaan 8, 9050 Gent, Belgium*
[*] *a.m.j.koonen@tue.nl*

Abstract: Optical fiber-based in-building network solutions can outperform in the near future copper- and radio-based solutions both regarding performance and costs. POF solutions are maturing, and can already today be cheaper than Cat-5e solutions when ducts are shared with electricity power cabling. We compare the CapEx and OpEx of in-building networks for fiber and Cat-5E solutions. For residential homes, our analysis shows that total network costs during economic lifetime are lowest for a point-to-point duplex POF topology.

OCIS codes: (060.2330) Fiber optics communications; (060.4256) Networks, network optimization.

References and links

1. W. Rollins and A. Mallya, "Options for current & future POF home networks," http://www.comoss.com/press/1000_Rollins_ATT.pdf (2010).
2. F. Richard, Ph. Guignard, A. Pizzinat, L. Guillo, J. Guillory, B. Charbonnier, A. M. J. Koonen, E. Ortego Martinez, E. Tanguy, and H. W. Li, "Optical home network based on an NxN multimode fiber architecture and CWDM technology," in *Proc. of Optical Fiber Communication Conf. and National Fiber Optic Engineers Conf.*, Los Angeles, paper JWA80 (2011).
3. A. M. J. Koonen and D. Novak, (organisers), "Beyond the doorstep – can fiber also invade the home?" in *Optical Fiber Communication Conf. and National Fiber Optic Engineers Conf.*, San Diego, Workshop OMB (2010).
4. P. Polishuk, "Plastic optical fibers branch out," IEEE Commun. Mag. **44**(9), 140–148 (2006).
5. S. Randel, F. Breyer, S. C. J. Lee, and J. W. Walewski, "Advanced modulation schemes for short-range optical communications," IEEE J. Sel. Top. Quantum Electron. **16**(5), 1280–1289 (2010).
6. C. M. Okonkwo, E. Tangdiongga, H. Yang, D. Visani, S. Loquai, R. Kruglov, B. Charbonnier, M. Ouzzif, I. Greiss, O. Ziemann, R. Gaudino, and A. M. J. Koonen, "Recent Results from the EU POF-PLUS Project: Multi-Gigabit Transmission over 1 mm Core Diameter Plastic Optical Fibers," J. Lightwave Technol. **29**(2), 186–193 (2011).
7. E. Tangdiongga, C. M. Okonkwo, Y. Shi, D. Visani, H. Yang, H. P. A. van den Boom, and A. M. J. Koonen, "High-speed short-range transmission over POF," in *Proc. of Optical Fiber Communication Conf. and National Fiber Optic Engineers Conf.*, paper OWS5 (2011).
8. A. M. J. Koonen, H. P. A. van den Boom, E. Tangdiongga, H.-D. Jung, and P. Guignard, "Designing in-building optical fiber networks," in *Proc. of Optical Fiber Communication Conf. and National Fiber Optic Engineers Conf.*, San Diego, paper JThA46 (2010).
9. B. Lannoo, K. Casier, M. Gheeraert, J. Van Ooteghem, S. Verbrugge, D. Colle, M. Pickavet, and P. Demeester, "Selecting the most suitable next-generation in-building network: from copper-based to optical solutions," in *Proc. 13th Internat. Conf. on Transparent Optical Networks*, Stockholm, paper Tu.C5.5 (2011).
10. A. M. J. Koonen, H. P. A. van den Boom, H. Yang, C. Okonkwo, Y. Shi, S. T. Abraha, E. Ortego Martinez, and E. Tangdiongga, "Converged in-building networks using POF – economics and advanced techniques," in *Proc. 19th Internat. Conf. on Plastic Optical Fibers*, Yokohama (2010).
11. European FP7 project ALPHA - Architectures for fLexible Photonic Home and Access networks, http://www.ict-alpha.eu/.

1. Introduction

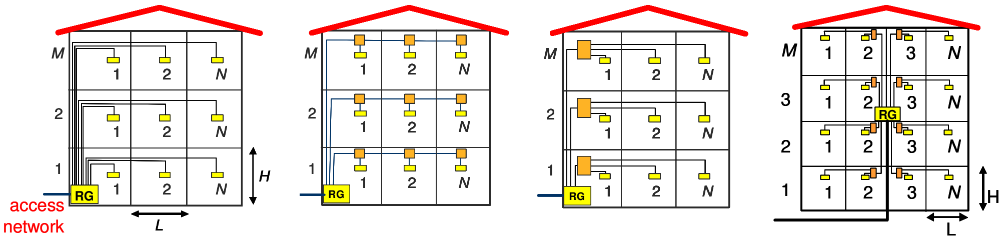
Fiber to the Home today is bringing real broadband services to the user's premises at speeds of up to 1Gbit/s. However, the challenge is to extend this highway beyond the home's doorstep, so to bring it into the home up to the user's terminals. Today's in-home networks are not suited for that [1]. They are a mix of different networks using different media, such as coaxial copper cables for TV broadcasting services, twisted pair cables for wireline telephony,

#155791 - $15.00 USD Received 30 Sep 2011; revised 4 Nov 2011; accepted 5 Nov 2011; published 21 Nov 2011

Cat-5E cables for data communication with desktop computers, printers and data servers, and WiFi for wireless laptop and tablet computers, smart phones and other wireless devices. Combining all these services into a single broadband in-home network can provide the desired highway extension, and can bring many other advantages, such as service integration, easier maintenance, easier upgrading, less power consumption, and thus lower costs. Optical fiber is excellently suited for such an in-home network [2,3]. Plastic Optical Fiber (POF) is particularly attractive, due to its ease of handling (large-core step-index or graded-index POF even lends itself for do-it-yourself installation) [4]. Advanced modulation techniques allow to surmount the bandwidth restrictions posed by the heavy multimodal dispersion of large-core POF. Such techniques may be based on single-tone multi-level pulse amplitude modulation (PAM) in combination with electronic equalization techniques, or on discrete multitone (DMT) techniques which are robust against dispersion [5,6]. With DMT techniques we achieved more than 10Gbit/s over short-reach 1mm core SI-POF links, and we also achieved transmission of ultra-wideband radio signals over short POF links [7]. Next to the transmission aspects, a important aspect is the economics, as there is heavy competition from copper-based solutions such as the popular Cat-5E networks. In previous work [8–10], it was shown that POF solutions can be already today cost-competitive with Cat-5E regarding installation costs (CapEx – Capital Expenditure). In this paper we extend this work by taking operational costs (OpEx – Operational Expenditure) into account. We analyze how total costs (so CapEx + OpEx) over the lifetime of the network evolve for POF and Cat-5E solutions, in order to facilitate economically justified choices for the design of in-building networks.

2. CapEx and OpEx analysis model

In our analysis we have assumed the basic network topologies shown in Fig. 1. In the point-to-point (P2P) topology (Fig. 1(a)), individual cables run from the residential gateway (RG; interfaces the access network with the in-building network, and performs local functions) to each room. This topology allows easy upgrading and maintenance per room, but requires a high amount of cabling with associated installation efforts and duct congestion issues, in particular in larger buildings. The bus and tree topologies (Figs. 1(a) and 1(b)) are point-to-multipoint (P2MP) topologies, in which cables are shared among rooms and the number of cables to the RG is reduced. Multiple access control techniques are required to give each room a fair part of the shared cable's capacity; nevertheless traffic congestion may occur. With POF and silica multimode fiber (MMF), the splitting nodes typically have to use optical-electrical-optical signal conversion, which is not transparent for every signal format and hence results in an opaque network. With single-mode fiber (SMF), all-optical signal splitting can be done in the nodes, allowing future fully signal-format transparent networks. In the following, opaque networks are considered. The bus solution (Fig. 1(b)) is the most cable-lean, but requires many hub nodes to connect each room. The tree solution (Fig. 1(c)) has a switch node per floor, from where individual cables run to each room; it needs more cabling than the bus solution, but less active nodes. In larger buildings, the link length restrictions of POF (and Cat-5E) cables may limit the coverage of the building. By putting the RG in a more centralized position, link lengths are reduced in a star-shaped hybrid topology, e.g. the star-tree one shown in Fig. 1(d).



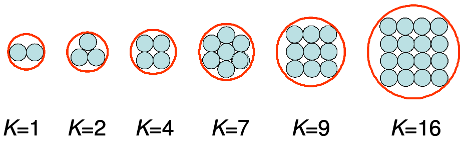
a) point-to-point b) bus c) tree d) star-tree

Fig. 1. In-building network architectures.

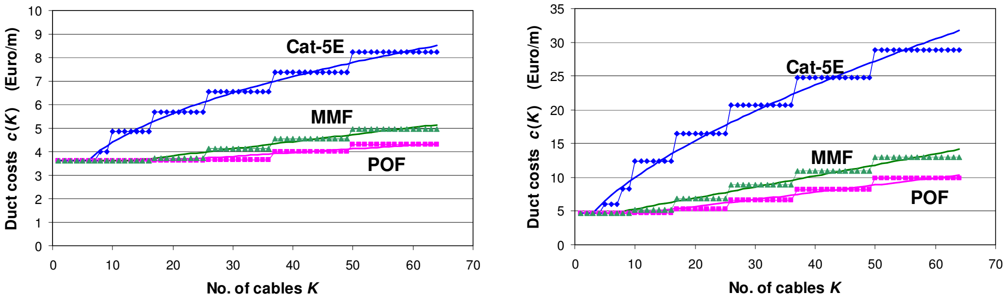
We have investigated three building scenarios: residential home (single-family house, typically with 3 floors and 4 rooms per floor), large office building (typically with 10 floors and 50 office units per floor), and multi-dwelling units (MDU) building (apartment building, with 10 floors and 16 living units per floor). For the network cost items and their power consumption, we used the typical data given in Table 1. These data are the results from extensive price studies among a range of manufacturers, done within the European project ALPHA [11]. A duct can host multiple cables in parallel. Inside a circular duct, the cables can be arranged as shown in Fig. 2(a). The duct costs $c(K)$ per unit installed length will depend on the installation method (mounted on the wall, or buried into the wall), and on the duct diameter, hence on the number and the diameter of the various types of cables hosted. Figure 2(b) shows the installed duct costs per meter when the duct is mounted on the wall, as a function of the number of cables hosted. These costs are shown for Cat-5E cable (diameter 5mm), MMF cable (diameter 2.5mm), and POF cable (diameter 2mm). The dotted curves represent the actual duct costs, and the solid curve is a continuous approximative function for these costs. Figure 2(c) shows the corresponding graphs for the installed duct costs per meter when the duct is buried in the wall (which requires more labour effort, and hence entails higher installation costs). From a market survey of the prices of circular duct pipes, empirical expressions for the approximative function $c(K)$ giving the costs of an installed duct hosting K cables have been determined for the various cable types, as listed in Table 2.

Table 1. Costs and power consumption of network items

Network item	Cat-5E	POF	SMF	MMF
Installed cable	1.8 €/m	1.7 €/m	1.74 €/m	1.95 €/m
Max. link length	100 m	70 m	1000 m	550 m
Mounted connector	13 €	3 €	15 €	14 €
Media converter	(negligible); 0.65 W	30 €; 0,85 W	70 €; 1.15 W	40 €; 1.15 W
Hub/tap	20 €; 0.2 W	20 €; 0.2 W	20€; 0.2 W	20€; 0.2 W
Switch	10 €/port; 0.3 W/port	10€/port; 0.3 W/port	10 €/port; 0.3 W/port	10 €/port; 0.3 W/port



a) Hosting *K* cables in a circular duct



b) On-the-wall mounted ducts

c) Buried ducts

Fig. 2. Costs of installed ducts (actual values and approximate curves).

Table 2. Installed duct costs per meter $c(K)$ for a circular duct hosting K cables

Cable type	On-the-wall mounted ducts		Buried ducts	
Cat-5E, Ø 5mm	3.631 €/m	for $K \leq 7$	4.631 €/m	for $K \leq 3$
	$1.938\ K^{0.356}$ €/m	for $K > 7$	$2.394\ K^{0.622}$ €/m	for $K > 3$
MMF, SMF, Ø 2.5mm	3.631 €/m	for $K \leq 16$	4.631 €/m	for $K \leq 4$
	$3.22 + 0.0301\ K$ €/m	for $K > 16$	$3.66 + 0.164\ K$ €/m	for $K > 4$
Simplex POF, Ø 2mm	3.631 €/m	for $K \leq 18$	4.631 €/m	for $K \leq 10$
	$3.22 + 0.0301\ K$ €/m	for $K > 16$	$3.56 + 0.106\ K$ €/m for $K > 10$	for $K > 10$

To calculate from all these data the CapEx and OpEx, we derived the formulas listed in Table 3 in a straightforward manner for the point-to-point, the bus and the tree topology shown in Fig. 1. In these formulas, F is the total length of fiber, D the duct costs, T the number of active node switches/hubs, MC the number of media converters (optical transceivers), C the number of fiber connectors, P_{sw} the power consumption per switch/hub port, and P_{MC} the power consumption per media converter. M, N, L and H are the building dimensions as indicated in Fig. 1, and $c(K)$ are the installed duct costs per unit length for a duct hosting K cables.

Table 3. Network design formulas

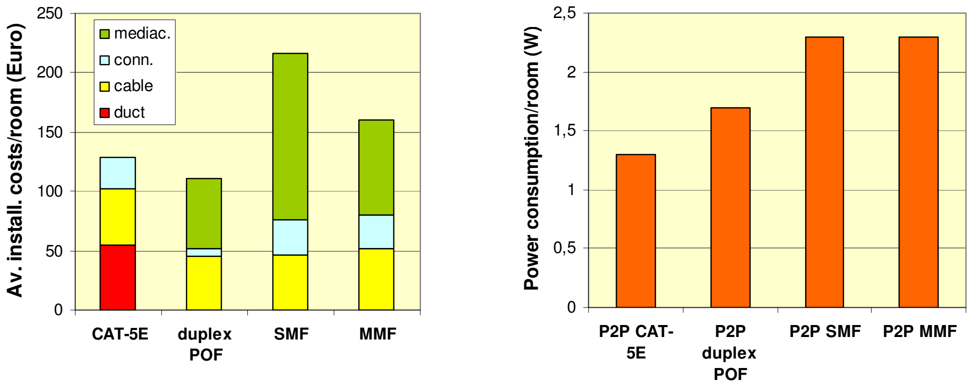
Point-to-point	
$F = \frac{1}{2} N H M (M-1) + \frac{1}{2} M L N (N-1)$	$MC = 2 \cdot M \cdot N$
$D = M \cdot H \cdot c(M \cdot N) + M \cdot (N-1) \cdot L \cdot c(N)$	$C = 2 \cdot M \cdot N$
$T = 0$	$P_{tot} = P_{MC} \cdot MC = P_{MC} \cdot 2M \cdot N$
Bus	
$F = M \cdot (N-1) \cdot L + \frac{1}{2} H \cdot M \cdot (M-1)$	$MC = 2 \cdot M + 2 \cdot M \cdot (N-1) = 2 \cdot M \cdot N$
$D = M \cdot H \cdot c(M) + M \cdot (N-1) \cdot L \cdot c(1)$	$C = 2M + 2M \cdot (N-1) + M \cdot N = 3 \cdot M \cdot N$
$T = M \cdot N$	$P_{tot} = P_{MC} \cdot 2M \cdot N + P_{sw} \cdot 3M \cdot N$
Tree	
$F = \frac{1}{2} M \cdot L \cdot N \cdot (N-1) + \frac{1}{2} H \cdot M \cdot (M-1)$	$C = 2M + 2M \cdot N = 2M \cdot (N+1)$
$D = M \cdot H \cdot c(M) + M \cdot (N-1) \cdot L \cdot c(N)$	$MC = 2M + 2M \cdot N = 2M \cdot (N+1)$
$T = M$	$P_{tot} = P_{MC} \cdot 2M \cdot (N+1) + P_{sw} \cdot M \cdot (N+1)$

3. Network costs analysis results

Using the analysis tools above, the network installation costs (CapEx) per room for a P2P topology are found to increase monotonically with the number of rooms, due to the increasing average cable lengths and duct sizes. For P2MP topologies, the CapEx per room initially decreases as the sharing factor of the common network parts increases, but for larger room numbers it increases again as the average cable and duct length start to dominate [8]. Hence for a small building (such as a residential home) a P2P architecture is attractive, also given its simplicity and easy upgradability. Figure 3(a) shows the CapEx breakdown per room for a typical residential home ($M = 3$, $N = 4$) with a P2P topology, using buried ducts (the costs are marginally lower for on-the-wall mounted ducts). For the fiber solutions, duct costs are saved by putting the fibers in the existing ducts of the electricity power wiring (duct sharing); note that this is not allowed for Cat-5E solutions for safety reasons.

For large buildings (office building, MDU building), as reported in [10], the cables and the ducts become the major cost items. Figure 4(a) shows the CapEx per room for a typical office building ($M = 10$, $N = 50$). A bus topology using duplex POF cable is preferred here: it has a large cable sharing factor, again offers installation costs savings because of duct sharing with the power cabling (which is difficult with P2P and tree topologies due to the large number of cables inside the duct), it provides coverage over the whole building as each branching node in the bus is an active switch providing regeneration (so the limited reach of a POF link is not restrictive), and it is cost-competitive with Cat-5E.

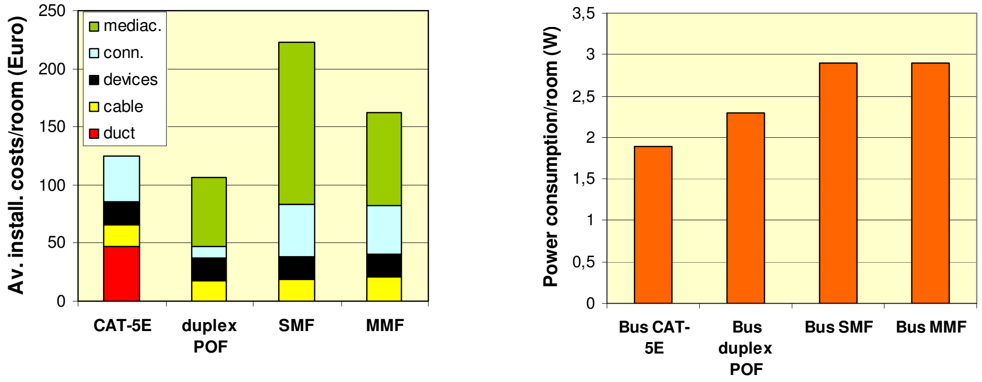
A major contributor to the OpEx is the electrical power consumption of the active network elements, which are always-on. We have analyzed the power consumption in the active network elements: in the switches/hubs in the network nodes, and in the media converters (the opto-electronic transceivers). For the residential home, we find that the P2P topology is the most power-efficient, as it avoids power-consuming network nodes. As shown in Fig. 3(b), the POF P2P solution consumes slightly more power than the Cat-5E one, but clearly less than the silica fiber (SMF, MMF) solutions. For the P2MP topologies preferred for larger buildings, a tree topology has less active elements than a bus one, and thus a somewhat lower power consumption. Taking into account the issues with duct sharing for the tree topology, however, the bus topology remains the preferred one for larger buildings. Figure 4(b) shows, similarly as Fig. 3(b), that the POF solution is the preferred fiber solution, with only slightly higher power consumption than the Cat-5E solution.



a) installation costs per room

b) power consumption per room

Fig. 3. Residential home with $M = 3$ floors and $N = 4$ rooms/floor, $H = 3.3$m, $L = 8$m; for P2P architecture, with duct sharing for the fiber solutions.



a) installation costs per room

b) power consumption per room

Fig. 4. Office building with $M = 10$ floors and $N = 50$ rooms/floor, $H = 3.8$m, $L = 10$m; for bus architecture, with duct sharing for the fiber solutions.

4. Evolution of overall network costs

In order to make a well-justified decision about which in-building network topology and cable medium to install, it is necessary to consider both CapEx and OpEx, and how these will evolve in the future. The power consumption is a major factor contributing to the OpEx. Hence, based on the above-mentioned results, we have calculated the energy costs over the economic lifetime of the network (for which we assumed 25 years). In order to assess the future evolution of the total network costs, these costs may be divided into three categories:

- *Labour costs*: related to installation works in the network (ducts, cables, network devices, connectors); these may increase following the inflation of money.
- *Material costs*: related to the network items. For non-mature products (the POF solutions), these costs may decrease remarkably in the future, as their market volume grows and production gets more efficient. For mature products (the Cat-5E solutions), the costs may slightly increase following the money inflation, or increase more significantly as the basic material (copper) gets scarce.
- *Energy costs*: related to the power consumption of the active network devices and media converters. These costs will rise with the money inflation, and even stronger due to the rising prices of primary energy sources (oil, gas, coal) and rising (CO_2-related) taxes.

The impact of money inflation may be taken out of the equation by considering the Net Present Value (NPV). For assessing the evolution of CapEx, a breakdown of the costs per installed network item into labour costs and material costs is needed; we estimated this breakdown according to Table 4.

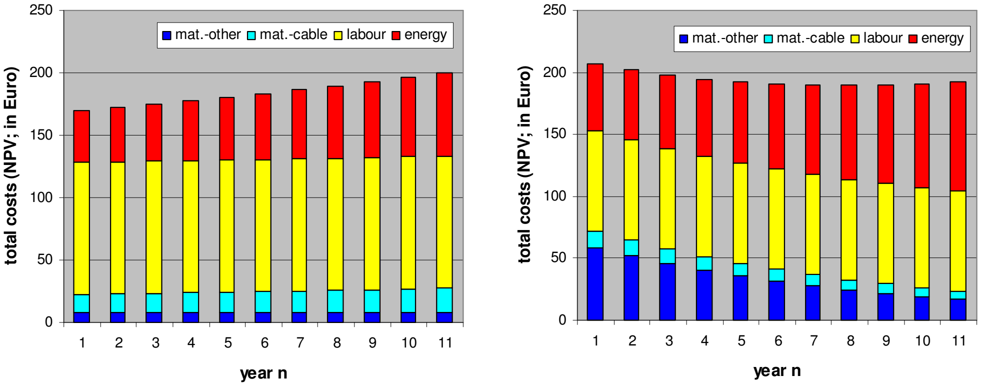
Table 4. Breakdown of CapEx per installed network item

CapEx parts	duct	cable	devices	connectors	mediaconverters
materials (%)	10	30	90	10	90
labour (%)	90	70	10	90	10

We assumed that money inflation will be 2% per year, labour costs will follow inflation, prices of POF products (cable, transceiver, connector) will go down with increasing market volume by 10% per year, prices of Cat-5E products (which are mature and of which market volume has stabilized) will follow inflation, but prices of Cat-5E cable will increase with 5% per year due to copper scarcity, and energy prices will increase with 5% per year.

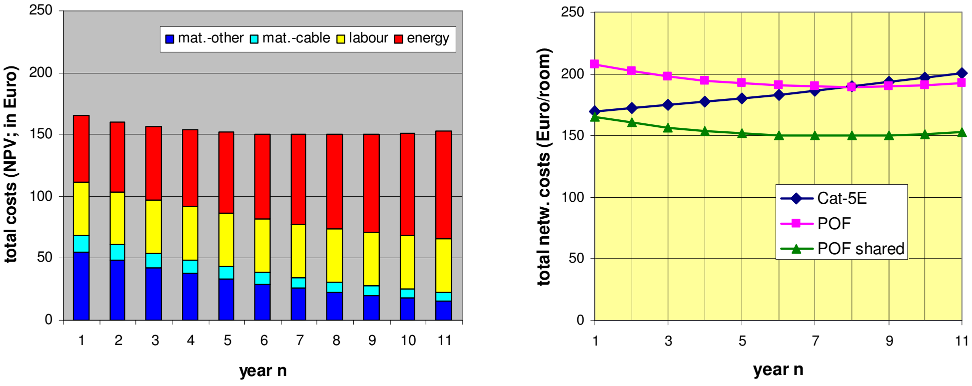
Based on these assumptions, the NPV of the total network costs per room for a residential home with P2P topology when the network is installed in year n (n = 1..11) are shown in Figs. 5(a)–5(c). For the Cat-5E solution, the total network costs over the 25 year lifetime increase due to the rising energy costs, and rising copper cable costs. Note that the impact of inflation is eliminated by using the NPV of the costs; hence the labour costs and the other material costs stay constant. For the duplex POF solution, the total network costs decrease due to decreasing cable costs, which clearly outweigh the rising energy costs. When using duct sharing, labour costs are saved, thus decreasing network costs even further. Figure 5(d) compares the evolution of total network costs: when installing a home network today (i.e. in year 1) and duct sharing can be applied, the lifetime costs of a duplex POF network are the lowest. When duct sharing is not possible, Cat-5E is today the cheapest solution, but in the future (7 years from now) it becomes economically more attractive to install duplex POF.

Received 30 Sep 2011; revised 4 Nov 2011; accepted 5 Nov 2011; published 21 Nov 2011



a) Cat-5E cabling

b) duplex POF, no duct sharing



c) duplex POF, duct sharing

d) comparison of total lifetime costs

Fig. 5. Evolution of NPV of total network costs (CapEx + OpEx) for a residential home, during its economic lifetime of 25 years, when installing the network with a P2P topology in year *n* (*n* = 1,2, …, 11).

5. Conclusions

Both CapEx and OpEx including their evolution during the network's economic lifetime have to be taken into account when deciding which topology and cable medium is economically preferable for an in-building network. For a typical in-home network, based on realistic cost trend forecasts, our analysis shows that the total lifetime network costs (CapEx + OpEx) of a P2P network which uses duplex POF and which shares the ducts with electrical power cabling, are today already lower than a network which uses Cat-5E cabling. When not using duct sharing, the duplex POF P2P solution will outperform the Cat-5E solution in a few years from now.

Acknowledgments

Partial funding of this work by the European Commission in the FP7 projects ALPHA, POF-PLUS and BONE, and by the Dutch Ministry of EL&I in the IOP GenCom project MEANS, is gratefully acknowledged.

#155791 - $15.00 USD Received 30 Sep 2011; revised 4 Nov 2011; accepted 5 Nov 2011; published 21 Nov 2011