

## Recent research advancements in in-building optical networks

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# Recent Research Advancements in In-Building Optical Networks

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## ABSTRACT

For in-building communication, a powerful backbone network can be created by means of optical fibre, which in a single infrastructure can offer a wealth of both fixed and wireless service connections to the users. Next to the technological challenges, important aspects to be taken into account are the economics of network installation and operation, and sustainability. An overview is given of recent research results regarding the optimization of network architectures, and regarding advanced signal processing for economical and sustainable delivery of high-capacity wired and wireless services over various types of multimode (plastic) optical fibre.

**Keywords:** in-building network, techno-economics, plastic optical fibre, radio-over-fibre, wavelength routing.

## 1. INTRODUCTION

To meet the rapid growth of bandwidth demand from the users, driven by the exploding gamma of internet services, video services, fast peer-to-peer file exchange, etc. etc., the roll-out of fibre-to-the-home networks is not sufficient [1]; the information highway needs to be extended beyond the doorstep of the user's home, into the home itself, up to his communication devices. The communication traffic inside the home may ask for even higher bandwidths, such as for fast transfer of large files to and from data servers. Presently, there is a mixture of separate networks in the residential home, each optimised for delivery of a specific set of services: twisted pair for telephony services, coaxial cable for TV and FM radio broadcast services, Cat-5E cables and WiFi for computer data services, and possibly other networks for other home appliances such as controlling the central heating, burglar alarms, door bell, etc. A single network in which the delivery of all services is integrated offers many advantages: easier installation, easier maintenance, easier upgrading and introduction of new services, facilitating communication between devices with different network interfaces, etc. The signal processing, storage, translation and intelligent routing functions can be handled in a centralised module, the residential gateway (RG), which also provides the interfacing with the access network, and takes care of other tasks such as assuring security and privacy. Optical fibre is the ideal transport medium for such an integrated in-home backbone network. Silica multimode fibre (MMF) and single-mode fibre (SMF) have excellent characteristics, but are fragile and need careful handling during installation. Plastic optical fibre (POF) is easier to install due to its ductility, and especially large-core POF reduces installation costs as it is very easy to couple ('do-it-yourself').

In this paper, we will report about recent studies on the cost analysis of in-building networks, comparing different network topologies and cable media choices and addressing both network installation costs (CapEx, capital expenditures) and network operation costs (OpEx, operational expenditures). We will also discuss advanced signal routing functions to improve the utilisation of the network's resources and to reduce the energy consumption.

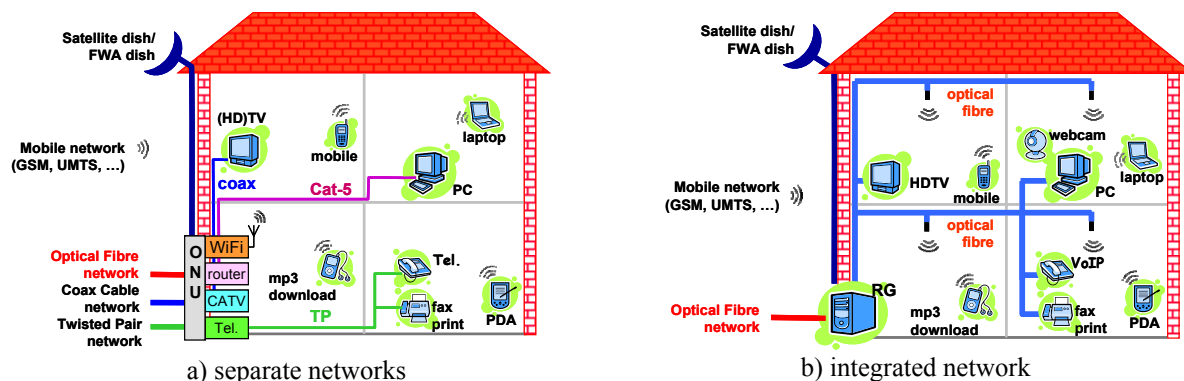


Figure 1. Service provisioning networks in the home.

## 2. OPTIMIZING IN-BUILDING NETWORK ARCHITECTURES

Depending on the layout of a building, a wide variety of network topologies may be considered. For our costs analysis, we have considered the basic topologies shown in Figure 2: a point-to-point (P2P) topology, point-to-multipoint (P2MP) bus and tree topologies, and hybrid topologies such as star-tree (which enable coverage of

a larger building given the restrictions on the individual link length due to the cable medium properties). Table 1 lists the typical cost and power consumption data of the network items, which we have used to estimate the CapEx and OpEx of these topologies. We have assumed an opaque network architecture carrying gigabit Ethernet traffic, so a network with active opto-electronic-optical signal conversions in the nodes (e.g. for IP packet routing). The details of our analysis method have been reported in [2]. We have analysed three typical building scenarios: a residential home (single family house, with 3 floors and 4 rooms per floor), office building (10 floors, 50 office rooms per floor), and a multi-dwelling units (MDU) building (apartment building, with 10 floors and 16 living units (LUs) per floor). As reported in [3], we found that for smaller buildings (such as a residential home) a P2P topology has the lowest network installation costs. When large-core (1mm diameter) duplex POF cabling is used, the CapEx per room is only slightly higher than when Cat-5E cabling is used. When the duplex POF cables are put in the ducts which are already hosting the electrical power cables, duct costs are saved and the duplex POF P2P network solution is already cheaper than the Cat-5E one, notwithstanding the fact that the market volume of POF is still ramping up. For larger buildings (such as an MDU or office building), we found that the CapEx is lowest when a bus topology is adopted.

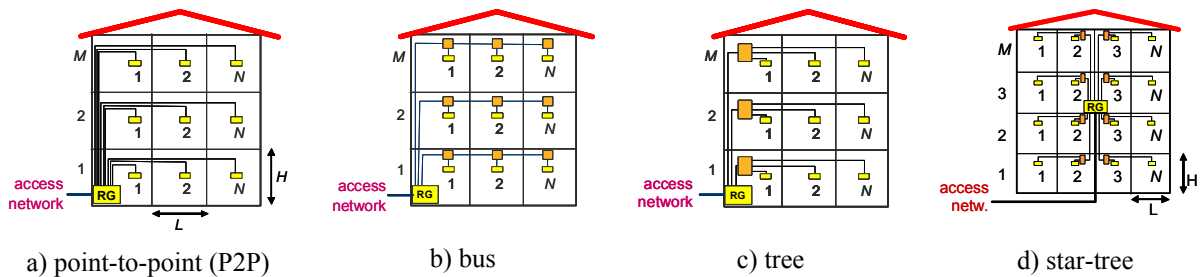


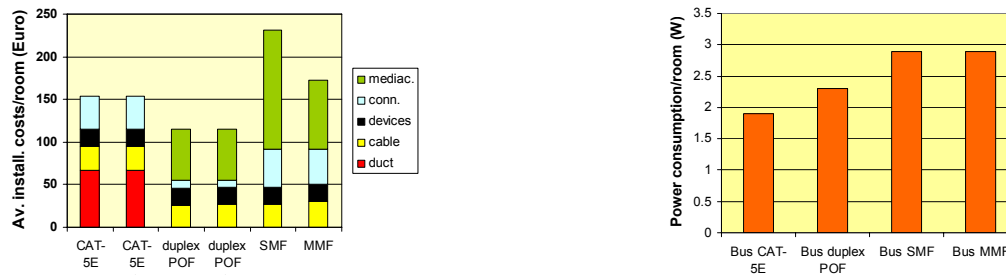
Figure 2. In-building network topologies

Table 1. Costs of network items and their power consumption.

	Cat-5E	POF	SMF	MMF
Installed cable costs	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 costs	13 €	3 €	15 €	14 €
Media converter costs; power cons.	negligible; 0.65 W	30 €; 0.85 W	70 €; 1.15 W	40 €; 1.15 W
Hub/tap costs; power consumption	20 €; 0.2 W	20 €; 0.2 W	20€; 0.2 W	20€; 0.2 W
Switch costs, power consumption	10 €/port; 0.3 W/port	10€/port; 0.3 W/port	10 €/port; 0.3 W/port	10 €/port; 0.3 W/port

Figure 3a shows the network installation costs per LU when typical dimensions are assumed for the MDU building (10 floors, 16 LUs per floor, LU height 4 m, link length 14m between outlets in neighbouring LUs). The installation costs of the duplex POF solution are clearly the lowest, where the cost advantage with respect to the Cat-5E solution is mainly due to duct sharing with the electricity wiring. The media converters (optoelectronic transceivers in the active bus network nodes) still contribute strongly to the installation costs; when the POF transceiver market gets larger and the products more mature the media converter costs are expected to come down remarkably.

Figure 3b shows the power consumption per LU in the MDU building, which is a major contributor to the OpEx per LU. As the Cat-5E bus network does not need media converters in the bus nodes, the power consumption of the Cat-5E solution is the lowest; the power consumption of the duplex POF solution is only slightly higher.



a) installation costs per LU (with duct sharing for the fibre-based solutions)

b) Power consumption per LU

Figure 3. Installation costs and power consumption per living unit of a bus network in a multi-dwelling units building (10 floors, 16 living units per floor).

When deciding which cable medium to take, one must consider the total costs of a network solution, so the CapEx plus the OpEx during the network's lifetime. These are dependent on future price evolutions of the CapEx and OpEx items. As a first estimate, the total costs of the duplex POF bus network solution for an MDU building appear to be lower than those of the Cat-5E solution.

### 3. DYNAMIC RECONFIGURATION OF THE IN-BUILDING NETWORK

The efficiency of service provisioning in a large in-building network can be considerably improved when the available capacity is not assigned statically to all the rooms in the building, but when it is dynamically routed to those places where there is an actual traffic demand. In particular for wireless services, the local traffic demand may fluctuate considerably when users roam throughout the building (e.g. students moving from one classroom to another one).

The dynamic routing of traffic streams may be implemented by using wavelength multiplexing of these streams and wavelength routing in the network nodes. Using our optical frequency multiplying technique [4], we can efficiently generate mm-wave radio signals remotely while only a moderate sweep frequency signal is needed at a centralized location in the building (i.e. the residential gateway). As shown in Figure 4, at the RG the radio data signal (generated by the vector signal generator, at 120Mbit/s in a 64-QAM format on an IF carrier frequency of 3.6GHz) is intensity-modulated with negligible chirp on a specific CW wavelength channel, and subsequently phase-modulated by a sinusoidal sweep signal of 6GHz [5]. After transversing an optical amplifier (EDFA) and an SMF link, a microring resonator (MRR) filter tuned to the wavelength channel acts as an add-drop multiplexer and drops the wavelength channel to a local photodiode. When operating on the filter slope of the MRR, the phase modulation impressed on the wavelength channel is converted to intensity modulation. As this is a heavily non-linear process, many harmonics of the 6 GHz sweep frequency are generated. Selecting the 6<sup>th</sup> harmonic by means of an electrical bandpass filter after photodetection yields the desired 39.6 GHz mm-wave radio signal. Thus we demonstrated the remote generation and wavelength-selective routing of an 39.6 GHz 120 Mbit/s 64-QAM radio signal, with an error vector magnitude of less than 5%.

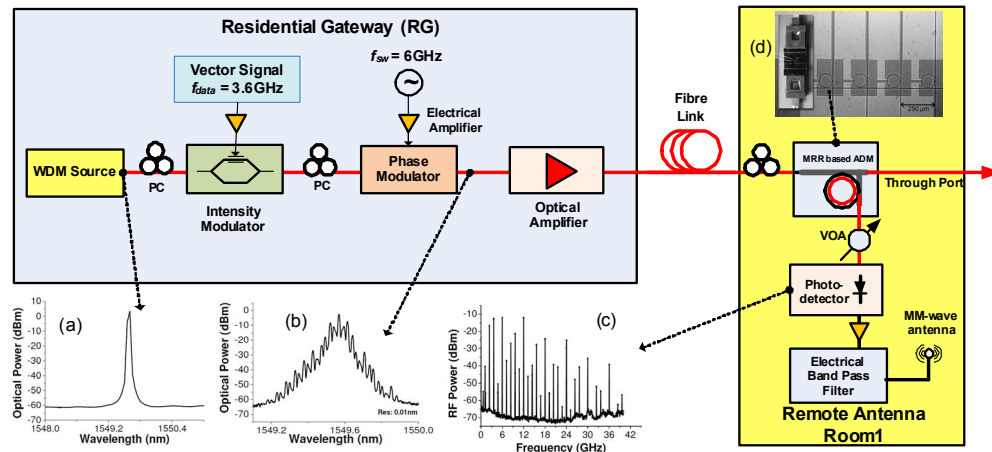


Figure 4. Micro-ring assisted generation and routing of an mm-wave radio signal.

We have analysed how the actual network performance can be improved with wavelength routing techniques [6]. The network performance has been measured by means of the network congestion probability, i.e. the probability that anywhere in the network a call is blocked due to a lack of capacity in a wavelength channel. We have analytically modelled the traffic statistics per LU as an on-off process, where the LU needs a capacity  $R$  when active. We assumed  $W$  wavelength channels, each with a data transport capacity  $B$  (so the total network capacity is  $W \cdot B$ ). We also assume that the LU-s behave independently, and that the probability of  $k$  of the  $N$  LU-s being active (with probability  $p$  that an individual LU is active) can be modelled with a binomial distribution. By using Chernoff's upper bound, we can derive that

$$\Pr[k > D] \leq \left(\frac{p}{D}\right)^D N^N \left(\frac{1-p}{N-D}\right)^{N-D}.$$

Network congestion in a wavelength channel will occur when  $D > B/R$  LU-s want to get access to a wavelength channel. When wavelength routing is applied, a call from an LU may be allocated flexibly to any wavelength channel. Therefore, when a wavelength channel is exhausted, the call may be allocated to a wavelength channel where still capacity is available, and thus the call can still be accepted. Obviously this reallocation process is the most successful when it can be done per individual LU. However, this requires wavelength-routing per LU, which will lead to considerable network complexity and thus higher network costs. The wavelength routing may also be done per cluster of LU-s, as illustrated in Figure 5a. A cluster can be moved to another wavelength

channel when needed to avoid congestion, implying that a number of LU-s are together reallocated. The larger the cluster is, the lower the complexity and thus the costs of the network; but larger clusters have also less chance to get successfully reallocated, so the network congestion probability will get worse. Without wavelength routing, the probability of network congestion is

$$\Pr_{no\_reconfig}(\rho) = 1 - (1 - \Pr_{block}(\rho))^W = 1 - (1 - \Pr[k > (B/R)])^W,$$

where the average relative network load  $\rho = p \cdot N \cdot R / (W \cdot B)$

When wavelength routing can be done per individual LU, and assuming that a reallocated call can fit fully in the other wavelength channel without fragmentation, the probability of network congestion is

$$\Pr_{reconfig}(\rho) = \Pr[k > (W \cdot B / R)].$$

We have analysed this dynamic network reconfiguration process by means of numerical simulations, for an MDU building with 10 floors and 16 LU-s per floor, so  $N = 160$  LU-s. We assumed  $W = 10$  wavelength channels, each with 1GbE capacity, and also assumed that an LU when active requires a capacity  $R = 100$  MbE (so each wavelength channel can accommodate up to 10 active LU-s, and the whole network up to 100 active LU-s). The results of our analysis are shown in Figure 5b, which shows the network congestion probability versus the relative network load. Curves are given following the analytical equations mentioned above, and following the simulation results for various cluster sizes  $c$ . The two outermost curves clearly show the impact of wavelength routing: the one to the utmost left depicts the congestion probability without wavelength routing, and the one to the utmost right the congestion probability with wavelength routing per individual LU (so  $c = 1$ ). For a given acceptable congestion probability of say  $10^{-3}$ , without routing the allowable network load is only some 25 – 30%, whereas with finest-grain routing ( $c = 1$ ) the load may go up to 76%. When the cluster size  $c$  is increased, the allowable network load clearly becomes less, but this also is favourably accompanied by a lower network complexity. With  $c = 4$  the allowable network load is still up to 60%, while network complexity is significantly reduced, so for this case  $c = 4$  seems to be a suitable compromise between network performance and costs.

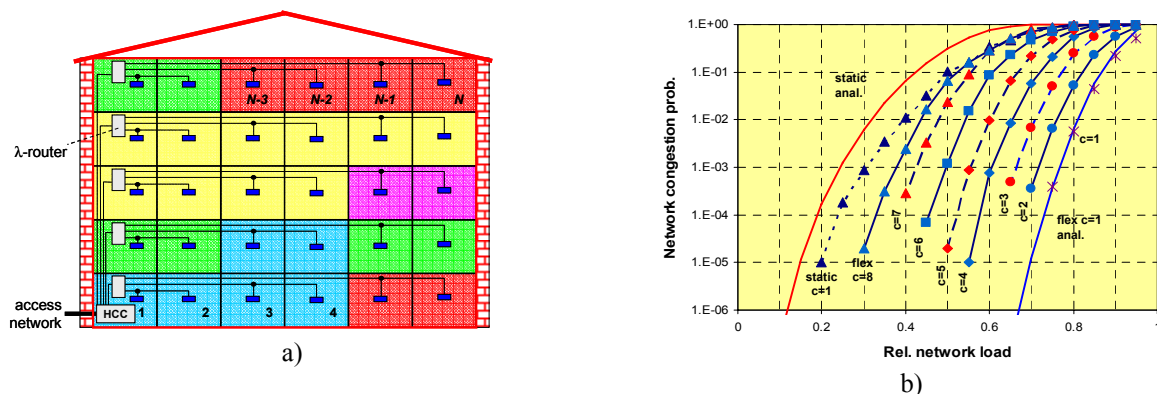


Figure 5. MDU building with wavelength routing; a) routing per cluster of LU-s, with a cluster size of  $c=2$  LU-s; b) network congestion probability without and with wavelength routing for various cluster sizes (markers indicate simulation results).

#### 4. CONCLUSIONS

Large-core duplex POF is an attractive medium for low-cost broadband in-building networks. For large buildings such as an MDU, a bus topology using duplex POF and opaque routers in the network nodes can be more cost-efficient than a Cat-5E solution, in particular when duct sharing with the electricity wiring is used. When using SMF, flexible wavelength routing may be employed in larger buildings, and the average network load can be significantly increased. For a typical MDU building, with wavelength routing per cluster of 4 living units, the average network load may roughly be tripled. This implies that less network resources are needed for a certain acceptable call rejection rate, and network installation and energy consumption costs can be reduced.

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