A LOOK INTO THE FUTURE OF IN-BUILDING NETWORKS: ROADMAPPING THE FIBER INVASION

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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 cabling. Advanced signal modulation techniques allow high-capacity services over POF. With their extra features of multi-wavelength transport and routing, fiber solutions offer a higher network throughput and flexibility, and improved sustainability.

Key words: In-building networks, techno-economics, technology evolution

1. Introduction

Now that fiber to the home is becoming a reality in ever more cities, the next step is to extend its huge bandwidth into the home, all the way to the user's communication devices. Presently there is a mixture of different wired networks in buildings, each optimized for a particular set of services (data, video, telephony, home control, …). In addition to those networks, there are wireless links to the devices such as by WLAN and femtocells, which are fed from a wired network. Optical fiber can constitute an integrated wired backbone network in the building, carrying a plethora of wirebound as well wireless services. Thus it may outperform copper cabling like Cat5e and alike. Next to silica multimode and single-mode fiber, large-core PMMA-based plastic optical fiber (POF) is a strong candidate due to its ease of installation. Following a concise comparison of the economic aspects of in-building networks regarding installation costs (CapEx) as well as operation costs (OpEx) for various network topology and cable media options (see also [1]), this paper will review the technical capabilities of these options, outline their networking capabilities, and present a roadmap according to which future wired in-building networks are expected to evolve.

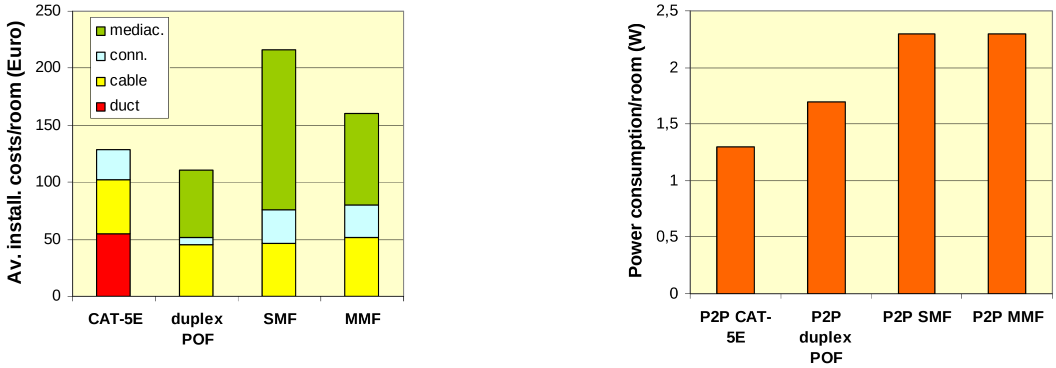
2. Economic aspects of in-building networks

From cost analyses reported earlier, it is found for the residential home, that the CapEx are the lowest for a point-to-point (P2P) topology [1] . For larger buildings, when a point-to-multipoint topology (P2MP; bus or tree) is chosen the cable costs are reduced because of the cable sharing, and this reduction can outweigh the costs of the extra network splitting elements. A bus topology is found to yield the lowest CapEx, as the sharing factor of the cable is maximum and the required duct diameters are minimum. Moreover, the large number of horizontal cables in the tree topology may prevent the fiber cables to share the duct of the electrical power wires, thus necessitating extra ducts.

The OpEx may be largely attributed to the electrical power consumption in the active network nodes and in the transceivers (the media converters) needed in the fiber-based solutions.

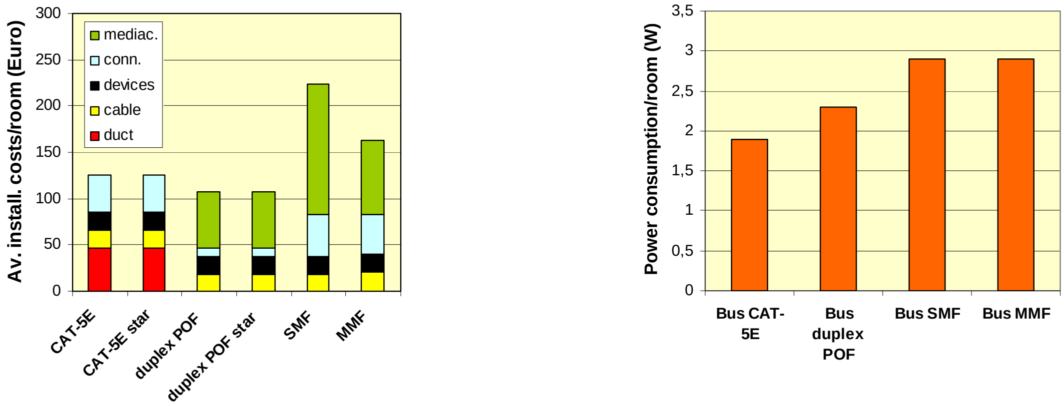
For a residential home with typical dimensions (see [1] ; 3 floors, 4 rooms per floor) and a P2P network topology, the CapEx and OpEx items are shown in Fig. 1. Similarly, the CapEx and OpEx items for a typical office building (see [1] ; 10 floors, 50 office rooms per floor) are shown in Fig. 2.

In both cases, it is observed that by sharing the ducts with the electrical power wires, regarding CapEx the duplex POF solution is cost-competitive with the Cat-5e solution, and clearly outperforms the SMF and MMF solutions. Note also the cost advantage resulting from the easy connectorizing of large-core POF. The CapEx advantage of duplex POF will become even larger when the costs of the media converters will come down (as is expected with the POF market becoming more mature). Regarding OpEx, the duplex POF solution consumes slightly more power than the Cat-5e solution, mainly because of the media converters.



a) installation costs per room b) power consumption per room

Fig. 1 CapEx and OpEx for wired in-building P2P network in a typical residential home, using duct sharing



a) installation costs per room b) power consumption per room

Fig. 2 CapEx and OpEx for wired in-building bus network in a typical office building

Overall, one may conclude that POF is a competitive alternative to Cat-5e already with today's market prices, and will become clearly the most cost beneficial solution when the POF market gets more mature.

The analysis above was made for opaque in-building networks, so with opto-electronic-optical signal conversions in the nodes. For transparent networks, however, with passive optical signal power splitting/routing functions in the nodes, there will be no electrical power consumption in the nodes and hence the OpEx will be lower for point-to-multipoint (bus, tree) topologies. As these passive node functions are not (yet) readily available for POF and MMF solutions, such transparent network topologies are only feasible with SMF.

3. Evolution roadmap for in-building networks

Supported by the techno-economical analysis above, we envisage that the evolution of wired in-building network architectures and techniques will follow the roadmap shown in Fig. 3. The timescale is only indicative: "now" means the situation regarding commercial installation as of today, "short term" as in 1 year from now, "medium term' as in 3 to 5 years from now, "long term" as in 5 to 10 years from now, and "very long term" as in more than 10 years from now. As indicated in Fig. 3, we expect the network evolution to go through a number of phases, where each phase is likely to remain present still after the next one has started, because the installation of in-building networks involves large capital investments which need to be depreciated over a long time.

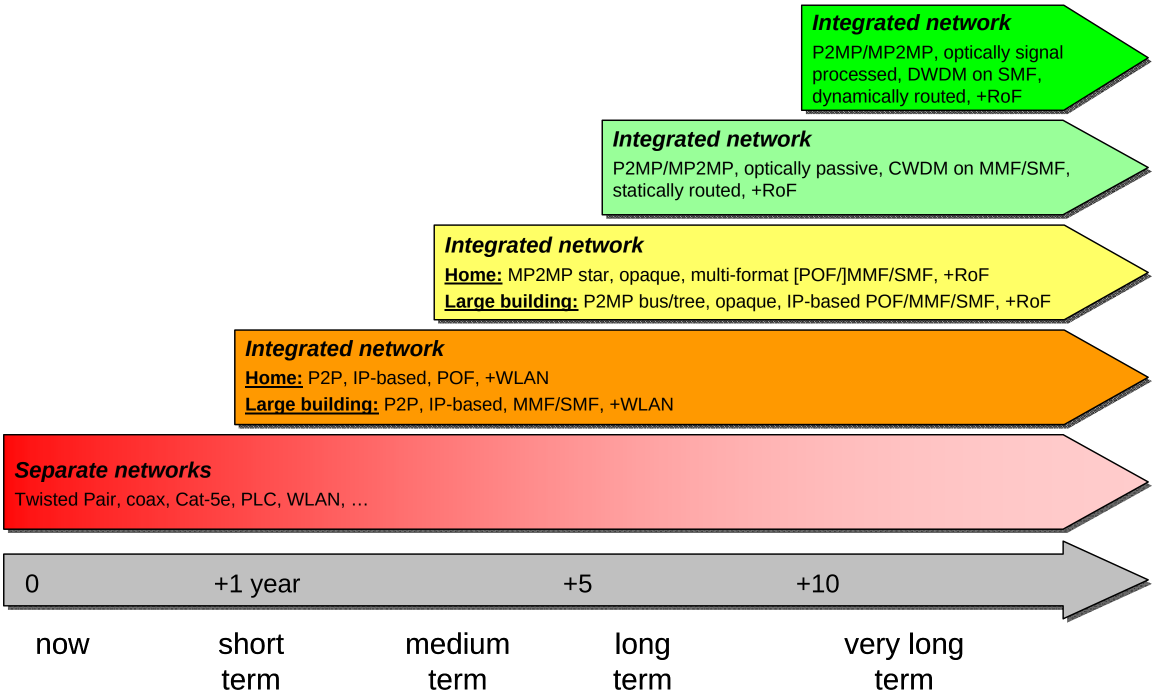
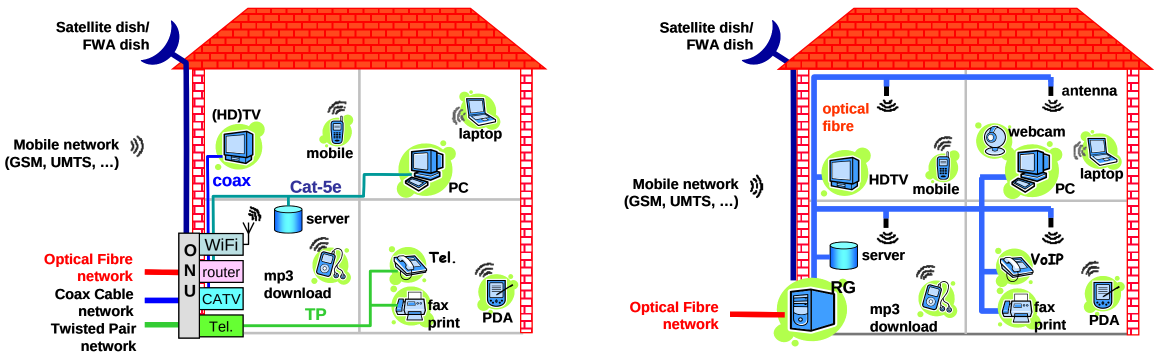


Fig. 3 Roadmap for the evolution of wired in-building networks

The evolution phases as shown in Fig. 3 are described in more detail in the subsections below.

3.1 Now

Today, as illustrated in Fig. 4.a, there is a multitude of separate networks inside a home, each optimized for a particular set of services, such as a coaxial copper cable network optimized for CATV and FM radio broadcast services, a twisted copper pair cable network for telephony services, a Cat-5e copper cable network for data communication between computer equipment (desktop PC-s, servers, printers, scanners, etc.), a power line communication (PLC) network for the same, and a wireless local area network (WLAN, based on WiFi IEEE 802.11) for the same. Drawbacks of such a mixture of networks are that it complicates maintenance, is not energy-efficient, and also requires considerable effort when services need to be updated or new services need to be introduced. With all the upcoming alternatives which avoid these drawbacks, we foresee that this situation of separate networks will fade out gradually.



a) separate networks

b) integrated network using optical fiber

Fig. 4 Service delivery networks in a building

3.2 Short term

To avoid the drawbacks mentioned above, we expect that within one to three years from now integrated network solutions will be introduced. All services (wirebound and wireless) will be based on IP, will be delivered from a single platform (the residential gateway, RG, which interfaces the in-building network with the access network), and will be carried in a single universal infrastructure. This infrastructure will preferably be based on optical fiber. In smaller buildings, P2P topologies will be preferred, using large-core PMMA duplex POF cables. The integration of services will be done by carrying them in IP format. For larger buildings, we also expect that initially P2P topologies will be preferred due to their ease of implementation and upgrading, but that MMF (or bend-insensitive SMF) will be used as the reach of POF links may be insufficient. Distribution of wireless services will be done with WLAN WiFi techniques, where the WLAN base stations are scattered around the building and are connected on an IP basis.

3.3 Medium term

Within three to five years from now, we expect that in larger buildings integrated opaque P2MP networks will be introduced with bus or tree topologies, as illustrated in Fig. 4.b. Such topologies are at one hand more complex to install and operate, but on the other hand save duct space and may be installed in the existing ducts of the electrical power cables, and their CapEx is lower than for P2P topologies (see section 2). All services will be IP-based, and the opaque network nodes will do the signal routing and restoration electronically. The links between the nodes are therefore relatively short P2P links, in which duplex POF cables can be used, or MMF or SMF cables. For smaller buildings, a star topology may be adopted deploying a single multi-format electrical switch in the star centre (located in or near the RG). Such a multi-format switch may handle not only IP-based signals but also other signal formats (such as video streams), and may e.g. use frequency band switching where the different signal formats are positioned in different frequency bands. Recently we demonstrated the frequency-multiplexed transport of high-capacity wirebound data together with wireless ultra-wideband data through a single POF link [2] . We also foresee that the demand for wireless capacity will have risen considerably, which necessitates smaller radio cells, i.e. femto- and pico-cell radio technologies. The costs of such many-cells wireless service provisioning will be lowered by simplifying the many antenna sites through the use of radio-over-fiber (RoF) techniques, in which the antenna sites are fed by analog (or digital) radio signals generated at a central location in the network [3] . Such a centralized approach alleviates the maintenance and upgrading. As the RoF signals are not IP-based, their transport, routing and regeneration needs bypassing of the opaque IP-based nodes.

3.4 Long term

Beyond five years from now, we expect that integrated optically transparent P2MP networks with static optical signal routing in the nodes will be introduced. In larger buildings, a bus (or tree) topology will be used, where in the nodes the signals will be routed optically by means of passive optical power splitters and/or passive optical wavelength routers (such as arrayed waveguide grating routers). For smaller buildings, a star topology may be used where in the star centre a passive NxN power-splitting star coupler or a wavelength router distributes the incoming optical signals to the outlets. A medium number of wavelengths may be used (e.g. each transporting a particular service), in a coarse wavelength division multiplexing scheme (CWDM). The IP-based services will be carried in one or more wavelength channels, the RoF signals will be carried in one or more other wavelength channels, and the non-IP (video) channels in separate other channels. The wavelength channels are routed statically in the network nodes, or are broadcasted wavelength-agnostically by the nodes where the terminals perform the wavelength channel selection (broadcast-and-select) statically [5] . Thus the traffic paths are fixed, and cannot be altered.

3.5 Very long term

In the distant future, say more than ten years from now, we expect that integrated optically transparent P2MP network solutions which use dynamically adaptable traffic routing will be introduced. Optical signal processing (such as all-optical wavelength conversion) will be applied in the network nodes followed by passive wavelength routing devices in order to change the wavelength paths upon external control which sets the wavelength conversion [4] . This enables to control the traffic flows in the network (the wirebound services as well as the wireless services embedded in RoF signals), and thus to provide capacity-on-demand for improved network performance and reduced energy consumption, as well as to better support the mobility of users. Many wavelength channels may be needed in a larger building, in a dense wavelength division multiplexed (DWDM) scheme, in order to create many individually controllable traffic paths. The granularity of this routing will be a compromise between the system complexity and the performance of the network; when the routing is done on a coarser scale (e.g. not routing a wavelength on a per-room basis but on the basis of a cluster of rooms) the routing node itself is less complex, but the congestion probability of the network gets higher [6] . To allow this DWDM routing techniques, the network will be based on bend-insensitive SMF in order to incorporate the active optical signal processing modules and the passive wavelength routing devices.

4. Choosing the network medium

In the previous sections, we mainly discussed the cost aspects (CapEx and OpEx) entailed by the choice of the cable medium and the network topology. Obviously, technical performance aspects need attention as well. Coarsely, one may distinguish three categories of communication media: copper media, optical fiber media, and free-space (radio waves, possibly carried partly over fiber in RoF solutions). Within each category, there are a number of options. The trend lines of the effective capacity per user terminal versus the infrastructure costs are shown in the three-dimensional graph in Fig. 5.

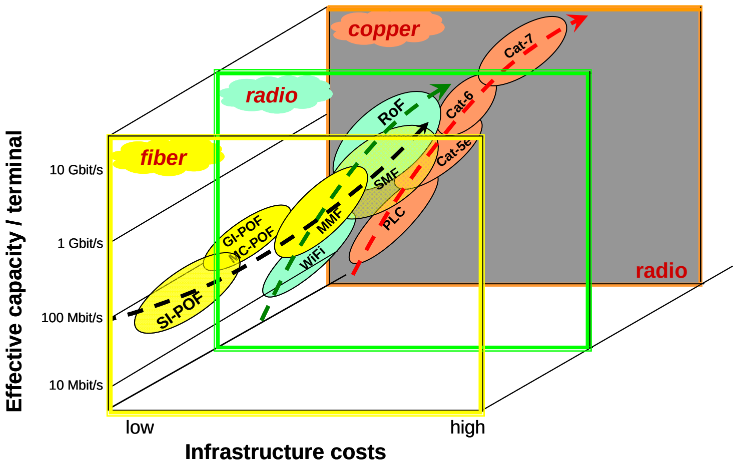


Fig. 5 Trends in effective capacity per user terminal versus infrastructure costs, for various categories of information transport media

For the copper-based solutions, (PLC, Cat-5e, Cat-6, Cat-7), the data transport capacity increases when moving from PLC to Cat-5e, Cat-6 and Cat-7, subsequently. However, also the infrastructure costs increase due to growing complexity, and do so more than linearly, as indicated in Fig. 5 by the upward curved arrowed trendline. This is due to the increasingly complex signal processing needed to combat the bandwidth limits and crosstalk in the cables, and to the increasing cable costs. PLC is the cheapest of all solutions as the cable medium (the electricity wiring) is already present; it however also has the lowest effective capacity due to the heavy EMI impact.

For the radio-based solutions, the WiFi solutions are widely available and relatively cheap, but their throughput rarely reaches their theoretical maximum (some 300Mbit/s) due to external interferences. When moving to pico-cells fed by fiber (RoF solutions), higher effective capacities per network terminal can be achieved, but at the expense of higher costs as part of the network needs installation of fiber cables. Nevertheless, the last few metres to the user device are wireless, so do not need cabling and thus make RoF solutions slightly cheaper than all-wired fiber solutions. Similarly as for the copper-based solutions, the complexity (and thus the costs) of the radio-based solutions rises more than linearly with the offered capacity, as indicated in Fig. 5 by the upward curved arrowed trendline.

For the fiber-based solutions, the infrastructure costs for various fiber types (POF, silica MMF, SMF) have been discussed in section 2. As a general trend, step-index large-core PMMA POF (SI-POF) in an opaque network architecture offers the lowest CapEx; these costs are about equal to those of a Cat-5e network, and can be lower than Cat-5e when the existing ducts of the electricity wiring are used. With the powerful DSP techniques available today [2] , the capacity of a SI-POF link can exceed that of a Cat-5e link for similar reach. Graded-index large-core POF (GI-POF) and multi-core POF (MC-POF) are more costly, but also bring a higher capacity due to their reduced dispersion. The MC-POF is less sensitive for bending than the GI-POF, thus easing installation. Silica MMF and bend-insensitive SMF have significantly lower losses and higher bandwidths than POF, but also require more delicate (and thus more costly) installation methods. However, the costs of the MMF and SMF solutions are less dependent on the capacity they have to offer, as the fiber's capacity itself is huge so no complicated equalization and/or signal modulation formats are needed. Hence, in contrast to the copper- and radio-based solutions, we expect the network infrastructure costs to grow less than linearly with the offered capacity, as indicated in Fig. 5 by the downward curved arrowed trendline.

5. Concluding remarks

By means of a techno-economic analysis based on present price levels, it can be shown that duplex POF already today is a cost-competitive medium for in-building networks as compared to mature solutions based on Cat-5e cabling. With the POF market becoming more mature, POF-based solutions are expected to outperform other solutions (incl. Cat-5e) soon, in particular when the POF cables are sharing the existing ducts with the electrical power cables.

Looking to the roadmap overall, we foresee a trend towards growing capacity and flexibility of in-building networks, in response to the booming needs for capacity driven by ever-more services and ever-higher quality demands from the user. This trend can uniquely be supported by fiber-based in-building networks, with the extra features of dynamic traffic routing brought by optical signal processing.

Therefore, taking the foreseen growth of capacity demands into account and observing the capacity-vs.-costs trends for various media choices in Fig. 5, we do expect that fiber-based solutions (incl. radio-over-fiber ones) will outperform the copper-based and all-radio-based solutions in the future, both performance- and costs-wise. Moreover, they may also outperform these solutions sustainability-wise, as copper becomes scarce, and especially at higher data rates fiber solutions tend to consume less power.

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References

[1] A.M.J. Koonen, H.P.A. van den Boom, H. Yang, C. Okonkwo, Y. Shi, S.T. Abraha, E. Ortego Martinez, E. Tangdiongga, "Converged in-building networks using POF – economics and advanced techniques", Proc. POF 2010, Yokohama, Oct. 2010

[2] E. Tangdiongga, C.M. Okonkwo, Y. Shi, D. Visani, H. Yang, H.P.A. van den Boom, A.M.J. Koonen, "High-speed short-range transmission over POF", Proc. OFC 2011, Los Angeles, Mar. 2011, paper OWS5

[3] Y. Shi, D. Visani, C. Okonkwo, H. Yang, H.P.A. van den Boom, G. Tartarini, A.M.J. Koonen, "First demonstration of HD video distribution over large-core POF employing UWB for in-home networks", Proc. OFC 2011, Los Angeles, Mar. 2011, paper OWB5

[4] C.M. Okonkwo, S.T. Abraha, Y. Shi, H. Yang, H. de Waardt, E. Tangdiongga, A.M.J. Koonen, "Simultaneous generation and routing of millimetre-wave signals exploiting optical frequency multiplication", Proc. ECOC 2010, Torino, Sep. 2010, paper Th.10.B.7

[5] F. Richard, Ph. Guignard, A. Pizzinat, L. Guillo, J. Guillory, B. Charbonnier, A.M.J. Koonen, E. Ortego Martinez, E. Tanguy, H. Li, "Optical Home Network based on an NxN Multimode Fiber Architecture and CWDM Technology", Proc. OFC 2011, Los Angeles, Mar. 2011, paper JWA80

[6] A.M.J. Koonen, N.C. Tran, E. Tangdiongga, "The merits of reconfigurability in WDM-TDM optical in-building networks", Proc. OFC 2011, Los Angeles, Mar. 2011, paper JWA63