Designing In-Building Optical Fiber Networks

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Abstract: Optical fiber in-building networks carrying wired and wireless services can outperform CAT-5E networks regarding versatility and installation costs. POF-based point-to-point architectures are optimum for small buildings, and (optically routed) SMF-based bus architectures for larger buildings.
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1. Introduction

Fiber To The Home (FTTH) is becoming a reality in many places all over the world, and offers broadband capacity up to the home's doorstep. However, this is not the end-game yet; the fiber's vast capacity should be extended further into the home itself, thus providing truly broadband services up to the end user. Inside today's homes, there typically is a mixture of networks, each designed for a specific purpose: twisted copper pair networks for telephony and fax, coaxial cabling for TV, video and radio services, CAT-5E cabling for PC-s, servers, printers, etc., wireless LAN for laptop computers, PDA-s, etc., plus some other wired solutions for domotica applications (fire and burglar alarms, central heating control, etc.). From a maintenance and upgrading perspective, many advantages can be gained when combining the delivery of all these services into a single network. Thanks to its transparency and ultra-wideband characteristics, optical fiber is considered to be the optimum medium for implementing a single integrated in-building backbone network.

In the following, a number of basic architectures for such a network are discussed, using silica single-mode fiber (SMF) or plastic optical fiber (POF). Next to SMF, large-core POF has shown its ability to transport Gbit/s data streams for wired services [1] as well as microwave radio-over-fiber (RoF) signals for broadband wireless services [2] . A cost analysis of the architectures using SMF or POF is made, and comparisons are made with the main competing wired solution, i.e. CAT-5E cabling for all-IP networking.

2. Basic in-building network architectures

Fig. 1 shows a number of basic architectures which may be considered for the fiber backbone of the in-building network: point-to-point (P2P), bus, tree, and star. In the P2P architecture, a fiber runs from the residential gateway (RG) to every room. The RG connects the in-building network to the access network, and carries out all the necessary signal translation functions; moreover, it can provide local data storage functions, security functions, and other in-building intelligence. The bus and tree architectures are point-to-multipoint (P2MP) ones, and thus parts of the fiber network are each shared by a number of rooms. The multipoint-to-multipoint (MP2MP) star architecture is about as fiber-rich as the P2P one, but by means of a star coupler device allows to set up connections between rooms without involving the RG. In order to save some fiber cabling, the star coupler may be located at a more central position in the home, so not necessarily next to the RG.

The network splitting devices in the P2MP and MP2MP architectures may provide opaque splitting, i.e. perform O/E/O signal conversions; examples are IP-based hubs and routers. Alternatively, they can provide all-optical splitting, such as signal-transparent power splitting or wavelength routing. These optical splitting functions are readily available in SMF-based devices. They are harder to realize with multimode (silica or plastic) fiber, as one should avoid any mode-selective process, which leads to modal noise and hence may cause serious performance degradation (e.g., bit error rate floors). Bulk-optics solutions with discrete lenses and (wavelength-selective) beam splitters allow to build non-mode-selective splitters, but are complex and not readily available (yet).

When opting for the opaque splitting, the fiber links are O/E terminated at both ends, and can be implemented with SMF, multimode silica fiber or POF. When upgrading of services or introducing of new services is required, this may necessitate modifications of the internal O/E/O functions of all the opaque network splitting devices. This reduces significantly the versatility of the network; e.g., when the opaque splitters are IP-based, it requires many cumbersome modifications to introduce non-IP-based services.

On the other hand, when opting for all-optical splitting, the paths set up via the splitting nodes are fully transparent for any signal format. Using all-optical splitting thus provides a truly future-proof solution, able to carry both IP- and non-IP-based services, for wired as well as wireless terminals. Thus e.g. analog radio-over-fiber (RoF)

signals may be carried next to high-speed digital data signals over the same fiber network. Also, when using wavelength routing devices, flexible routing of signals may be realized in the network by means of wavelength-tunable transmitters and tunable wavelength converters. E.g., wavelength-routing of 40GHz RoF signals deploying the robust Optical Frequency Multiplying technique has recently been demonstrated for in-home networks [2][3]. As the all-optical functions cannot readily be realized in compact multimode fiber-based devices, these future-proof versatile network solutions are restricted to the deployment of SMF.
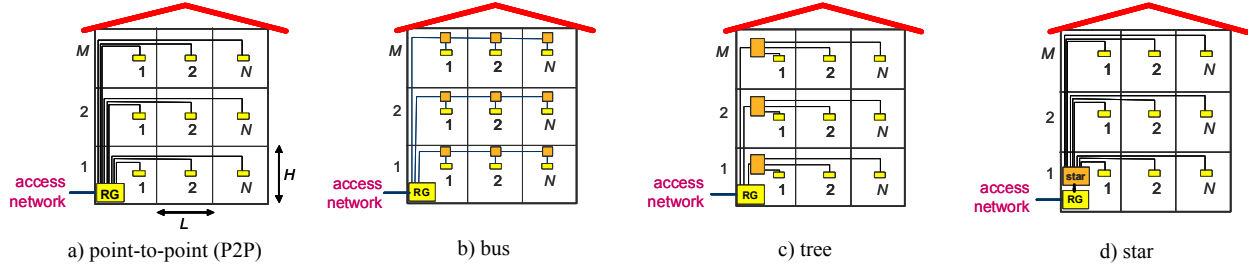

a) point-to-point (P2P)   b) bus   c) tree   d) star

Fig. 1   Basic in-building network architectures

3. Cost analysis of the network architectures

An analysis has been made of the network installation costs for the P2P, bus and tree architectures of Fig. 1. The building is assumed to have M floors, and N rooms per floor, where each room has a height H and length L. As the cabling of the star architecture is largely similar as that of the P2P one, its installation costs are also expected to be largely the same. Four cost items have been taken into account: the costs of the fiber cable, of the ducts, of the network splitting devices, and of the connectors. A duct will host multiple fiber cables in parallel, and it is assumed that the duct costs including installation grow proportional with the square root of the number of cables inside (as its diameter does).

For the *P2P architecture*, the length of fiber F needed as a function of the building dimensions M and N is

$$F = \sum_{i=1}^{M}\sum_{n=1}^{N}\{(i-1)H+(n-1)L\} = \sum_{i=1}^{M}\sum_{n=1}^{N}(i-1)H + \sum_{i=1}^{M}\sum_{n=1}^{N}(n-1)L = NH\frac{M}{2}(M-1) + ML\frac{N}{2}(N-1)$$

where the first term represents the costs of the riser fiber cables, and the second one the costs of the horizontal cabling. The installed duct costs D are (with c being the duct costs per unit of length for a single-fiber duct)

$$D = M \cdot H \cdot c\sqrt{MN} + M \cdot (N-1) \cdot L \cdot c\sqrt{N}$$

where the first term accounts for the riser ducts, and the second one for the horizontal ducts. The number of fiber connectors C (one connector at each side of an individual fiber link) is

$$C = 2 \cdot M \cdot N$$

As there are no (active or passive) network splitters, the costs of the in-line devices is obviously zero.

For the *tree architecture*, the fiber length F, the installed duct costs D, the number of in-line devices T, and number of fiber connectors C are

$$F = M\sum_{n=1}^{N}(n-1)L + \sum_{i=1}^{M}(i-1)H = M \cdot L \cdot \frac{N}{2}(N-1) + H \cdot \frac{M}{2}(M-1)$$

$$D = M \cdot H \cdot c\sqrt{M} + M \cdot (N-1) \cdot L \cdot c\sqrt{N}$$

$$T = M$$

$$C = 2M + 2M \cdot N$$

For the *bus architecture*, these items are

$$F = M \cdot (N-1) \cdot L + \sum_{i=1}^{M}(i-1)H = M \cdot (N-1) \cdot L + H \cdot \frac{M}{2} \cdot (M-1)$$

$$D = M \cdot H \cdot c\sqrt{M} + M \cdot (N-1) \cdot L \cdot c$$

$$T = M \cdot N$$

$$C = 2M + 2M \cdot (N-1) + M \cdot N$$

Based on these expressions, the costs for installing each of the architectures using opaque network splitting devices has been calculated. Also three media types have been compared. For the POF type, 1mm core diameter step-index PMMA POF with NA=0.5 has been assumed. The losses of such fiber are considerably higher than those of silica SMF; it should be operated in the visible light wavelength range, and has ca. 145dB/km loss for red (650nm), 85dB/km for green (520nm), and 120dB/km for blue (460nm) light. This limits the achievable link length typically to some 100 meters, which is quite adequate for P2P links in residential buildings, but for larger buildings

restricts its usage to opaque bus or tree P2MP architectures. Moreover, the large core size and high NA make it very easy to splice the fiber; cutting with a simple razor blade and butt-joining make it a cheap do-it-yourself (DIY) technique. On the other hand, the severely reduced bandwidth of this large core POF requires advanced spectrum-efficient and dispersion-robust signal modulation techniques; recently with real-time DMT coding very promising 1.25 Gbit/s transmission over 100 meters has been achieved [4] . For the SMF type, bend-insensitive fiber has been assumed, which allows low-loss installation in tight bending situations. The diameter of the SMF cable can be comparable to that of POF, and due to their EMC-immunity both POF and SMF cables can advantageously share the same ducts as the electrical power lines. However, connectorizing an SMF cable (typically by fusion-splicing a pre-assembled connectorised SMF-pigtail, and mounting the splice in a protective enclosure), is considerably more labor-intensive than that of a POF cable.

As the main competitor for fiber, CAT-5E cable has also been taken into the analysis. Such cable is considerably thicker than POF and SMF cable, and thus needs larger ducts. Due to EMC issues it cannot share ducts with power lines. Moreover, connectorizing a CAT-5E cable again requires considerably more effort than that of POF (although typically less than that of an SMF).

Using the formulas given earlier, the cost analysis results for a building with M=10 floors are reported in Fig. 3 versus the number of rooms N per floor. For the various network items, typical costs as found from market studies have been assumed, and are listed in Table 1. E.g., Fig. 2 shows the cost items for a bus with M=10 and N=10.

Table 1 Cost items for the media types

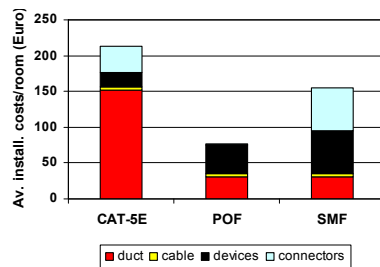|	CAT-5E	POF	SMF
no. of floors M		10	
room heigth H (m)		5	
room size L (m)		6	
duct (Euro/m)	20	4	4
cable (Euro/m)	0,6	0,6	0,6
max. link length (m)		100	1000
mounted connector (Euro)	12	0,2	20
OEO hub (Euro)	20	40	60
OEO switch (Euro/port)	10	20	30

Fig. 2 Cost items for bus architecture, M=10 floors, N=10 rooms/floor
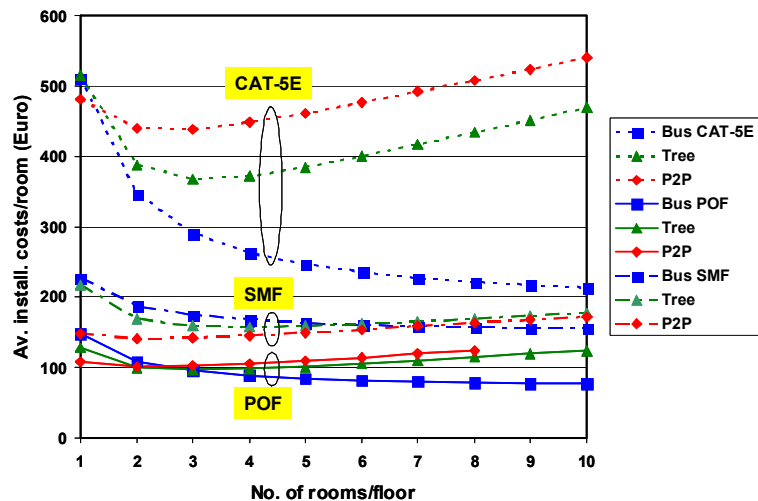

Fig. 3 Green-field average installation costs per room, for bus, tree and P2P architectures, and for POF, SMF, or CAT-5E cabling

From Fig. 3, it can be observed that POF from an installation costs point-of-view is an attractive medium for opaque in-building networks. In comparison with SMF, it offers easier (DIY) installation. Compared with CAT-5E, due to its much smaller diameter it offers the opportunity to deploy smaller ducts; it may even share the ducts of the power line cables. For larger buildings with multiple services, all-optical SMF-based bus architectures are preferred.

4. Conclusions

Integrated delivery of broadband wired and wireless services can advantageously be realized in a single fiber-based backbone network, which is more versatile and cheaper to install than a CAT-5E network. For small (residential) buildings, a multimode POF-based P2P architecture is preferred; it is easy to upgrade and is well suited for low-cost do-it-yourself installation. For larger (professional) buildings, an all-optical bus architecture based on bend-insensitive SMF is optimum; it is future-proof, can transport any service, and enables all-optical (wavelength) routing techniques which improve the efficiency of the network's resources by facilitating capacity-on-demand.

5. References

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