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Economics of In-Building Optical Fiber Networks

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Abstract: Optical fiber in-building networks integrating wirebound and wireless services can outperform Cat-5E networks regarding versatility and costs, in particular when sharing ducts with electricity wiring. POF-based point-to-point topologies are optimum for small buildings, and POF-based opaque bus topologies for larger buildings.

1. In-building networks

Regarding technical performance, an optical fiber in-building network is optimally suited to extend fiber-to-the-home's large capacity and service flexibility into the home [1], [2]. To gain wide acceptance, however, also the economical aspects are of major importance. Silica single-mode fiber (SMF) offers the ultimate bandwidth performance, but its tiny core requires precision tools and skilled personnel for installation. Silica multimode fiber (MMF) is easier to handle and less vulnerable due to its larger core, but still needs delicate tools for connectorization. Large-core (1 mm diameter) plastic optical fiber (POF), due to its large core and ductility, is very easy to handle, making it even suitable for do-it-yourself installation. With respect to SMF and MMF, the POF's higher losses and lower bandwidth restrict its use to shorter lengths. Advanced signal modulation techniques allow to overcome the bandwidth restrictions and thus to realize multi-Gbit/s data links as well as microwave radio-over-fiber systems, albeit over short link lengths (up to about 100 meters), which are however well-suited for in-building networks. In the in-building domain, Cat-5E solutions with their enormous market volume have reached low cost levels. Next to the technical performance superiority, also the economics of fiber-based solutions therefore have to be assessed. The installation costs (CapEx, capital expenditure) and operational

costs (OpEx, operational expenditure) of various fiber network solutions will be investigated, and compared with those of Cat-5E solutions.

2. Network topologies

A number of basic network topologies have been considered, see Fig. 1.

Fig. 1: In-building network topologies

In the point-to-point (P2P) topology (Fig. 1a), individual cables run from the residential gateway (RG) 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 are point-to-multipoint 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 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 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. 1b) is the most cable-lean, but requires many hub nodes to connect each room. The tree solution (Fig. 1c) 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, such as the star-tree one shown in Fig. 1d.

Three typical building scenarios have been analyzed: a single-family residential home, an office building, and a multi-dwelling building (a.k.a. apartment building). The typical dimensions are listed in Tab. 1.

Table 1: Building scenarios

	No. of floors M	No. of rooms per floor N	Distance between floors H (in m)	Duct length between wall outlets L (in m)
Residential home	3	4	3.3	8
Office building	10	50	3.8	10
Multi-dwelling bldg.	10	16	4.0	14

3. Network cost analysis method

In order to analyze the costs of the various network topologies, the cost items considered are: cables (including installation in a duct), cable ducts (including installation), connectors (including mounting), media converters (optical transceivers, for opto-electronic signal conversion), and signal routing devices (electrical switches, hubs). The market prices of these items vary widely. Based on extensive market surveys, typical values for the prices and power consumption numbers are listed in Tab. 2.

Table2: 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

A duct can host multiple cables in parallel. Its costs $c(N)$ per unit installed length will depend on the installation method (mounted on the wall, or buried into the wall), and the duct diameter. The latter depends on the number of cables N and the cable diameter. From a market survey of circular duct pipes,

empirical expressions for $c(N)$ have been determined for the various cable types, as listed in Tab. 3.

Table 3: Installed duct costs per meter $c(N)$ for a circular duct hosting N cables

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

Table 4: Amount of network items needed and total power consumption for different network topologies, as a function of the building dimensions

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

The amount of network items depends on the building dimensions, i.e. the number of floors M , the number of rooms per floor N , the distance between floors H , and the duct length between wall outlets L (see Fig.); note that the duct usually will not follow the shortest path, so L typically will exceed the room width. The total cable length F , the total installed duct costs D , the total number of connectors C , the number of in-line devices (switches, hubs) T , the number of media converters MC , and the total power consumption P_{tot} can be expressed as functions of the building dimensions; see Tab. 4.

4. Network cost 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 [1]. Hence for a small building (residential home) a P2P architecture is attractive, also given its simplicity and easy upgradability. Figure 2.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); this is not allowed for Cat-5E solutions for safety reasons.

Fig. 2: Breakdown of CapEx per room with duct sharing for the fiber solutions

For larger buildings (office building, MDU building), the cables and the ducts become the major cost items. Hence a bus topology, which maximizes the sharing of cables and ducts, yields the lowest CapEx per room. Figure 2.b shows the CapEx breakdown for a typical MDU building ($M=10, N=16$).

As shown in Fig. 2, by means of sharing the ducts of the electricity wiring, the duplex POF solution is a strong competitor regarding CapEx of the established Cat-5E solution; in the near future POF can be expected to outperform Cat-5E, when POF technologies mature, POF market volumes increase, and prices of the media converters decrease.

A major contributor to the operational costs (OpEx) is the electrical power consumption of the active network elements, which are always-on. Figure 3 shows the power consumption per room for a residential home and for an MDU building. A P2P topology has the least active elements, and hence the lowest OpEx. A bus topology has more active elements; a tree topology has less active elements than a bus one, and thus somewhat lower power consumption, but that OpEx advantage may be offset by the higher CapEx.

Fig. 3: Electrical power consumption per room

5. Concluding remarks

Large-core POF, in particular when sharing the duct with electricity wiring, is attractive for creating service-integrated in-building networks, from both technical and economical perspective. The cost advantages will increase further when the POF market gets more mature. For smaller buildings (residential homes), a P2P network topology is preferred, and for larger buildings (offices, multi-dwelling buildings, etc.) an opaque bus topology. Partial funding by the European Union in the FP7 projects ALPHA, POF-PLUS and BONE is gratefully acknowledged.

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