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Fiber Access Networks: Reliability Analysis and Swedish Broadband Market

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SUMMARY Fiber access network architectures such as active optical networks (AONs) and passive optical networks (PONs) have been developed to support the growing bandwidth demand. Whereas particularly Swedish operators prefer AON, this may not be the case for operators in other countries. The choice depends on a combination of technical requirements, practical constraints, business models, and cost. Due to the increasing importance of reliable access to the network services, connection availability is becoming one of the most crucial issues for access networks, which should be reflected in the network owner's architecture decision. In many cases protection against failures is realized by adding backup resources. However, there is a trade off between the cost of protection and the level of service reliability since improving reliability performance by duplication of network resources (and capital expenditures CAPEX) may be too expensive. In this paper we present the evolution of fiber access networks and compare reliability performance in relation to investment and management cost for some representative cases. We consider both standard and novel architectures for deployment in both sparsely and densely populated areas. While some recent works focused on PON protection schemes with reduced CAPEX the current and future effort should be put on minimizing the operational expenditures (OPEX) during the access network lifetime.

key words: *optical fiber LAN, protection, reliability, capital expenditures (CAPEX), operational expenditures (OPEX), fiber-to-the-home (FTTH), passive optical network (PON), active optical network (AON)*

1. Introduction

The significance of broadband and multimedia telecommunications for the community is growing very fast, driving the explosion of fiber access network deployment and, consequently, giving great business opportunities for both system and network providers. While core networks are currently providing a sufficient amount of resources the access part of the network is still a bottleneck in terms of bandwidth and quality of service. Therefore the focus of research and development has largely moved from core to access networks. Several broadband access technologies exist today, such as copper based Digital Subscriber Line (DSL), coaxial cable, wireless access and fiber access. However, in our opinion, the fiber access is the only viable alternative for the future access network. Fiber-to-the-home (FTTH) is the future-proof technology offering ultra-high bandwidth and long reach. Two main types of fiber access network architectures have been developed and deployed, namely Active Optical Network (AON) [1], and Passive Optical Network (PON) [2]–[11], both with different variants.

Due to increased dependency on electronic services all over society and the growing importance of reliable service delivery the network reliability issues are becoming very significant. Consequently, an efficient fault management is to be considered in both access and core part of the network to ensure an uninterrupted end-to-end service provisioning. However, there is a tradeoff between the cost of protection and the level of service reliability. In the access part of the network the economical aspects are most critical due to the low sharing factor of the network deployment and management cost. Hence, only low cost solutions can be acceptable for access networks. Both CAPEX and OPEX need to be minimized to meet this requirement. With this in mind we present the fiber access network evolution and show that one can save both investment and management cost by an appropriate choice of network architecture.

The paper is initiated with a section on the Swedish broadband market. From a fiber access deployment perspective this is a relatively mature market with some of the very first commercial FTTH deployments worldwide. Sweden is interesting because some of the trends and patterns observed here are likely to appear on other markets as well.

The paper is organized as follows. In Sect. 2 the Swedish broadband market is described from a technical point of view but also including business models. In Sect. 3 we review fiber access network evolution followed by PON protection architectures in Sect. 4 where we also present the reliability models derived for the considered architectures. Section 4 provides input data and our assumptions. Results are presented in Sect. 6. Finally, in Sect. 7 we give our concluding remarks.

2. The Swedish Broadband Market

The first fiber-to-the-home installations in Sweden were rolled out in the late 90's, and in 1999 almost 50% of Swedish broadband households had FTTH, which was world leading by then. In Sweden AON is the completely dominating FTTH technology with only a very few PON installations. The popularity of AON is probably due several factors. One is historical reasons — it simply became the de-facto fiber access technology the same way as PON is the de-facto technology in other parts of the world. Also, Ethernet is a well-known, well-approved technology that the municipalities themselves can easily design, roll out and main-

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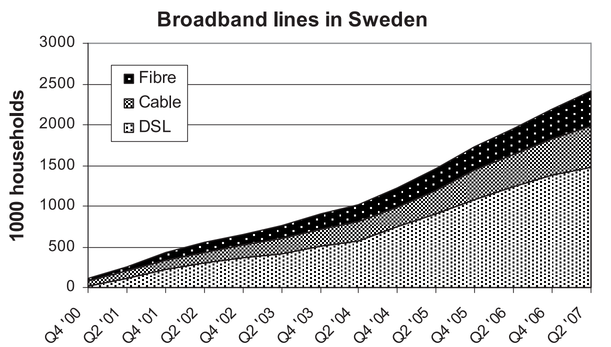

Fig. 1 The evolution of the fixed line access technology shares for Sweden's 4.4 M households. The corresponding percentages are found in the text.

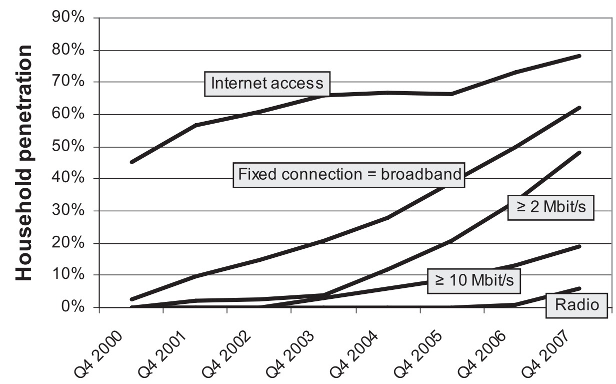

Fig. 2 Internet and broadband penetration in Sweden [12].

tain using of-the-shelves equipment — which is not the case with PON. Finally, most Swedish municipalities and housing companies require open access (see below), and such openness is easier to achieve with AON than PON.

However, the predominating access technology in Sweden today is still DSL, primarily asymmetrical DSL, ADSL, and ADSL2+ (but very high-rate DSL, VDSL, is emerging), with a share of 61% of the total broadband subscribers, see Fig. 1 [12]. This is followed by coaxial cable with 21% and LAN with 19% (almost exclusively FTTH). There is furthermore a rapidly growing share of fixed wireless access, primarily through 3G but also a few Wimax deployments. The tendency is that all access technologies are growing, however at the moment DSL is growing faster than the other fixed line technologies in numbers. In percent FTTH is the fastest growing of fixed access technologies [12].

While Sweden was "leading" in FTTH penetration up to around 2004, it is now surpassed by South Korea and Japan that have a much higher FTTH penetration. By June 2008 Sweden had 6.0 FTTH subscribers per 100 inhabitants whereas South Korea and Japan had 12.2% and 10.2%, respectively, with Denmark being fourth of the OECD countries with 3.2 FTTH subscribers per 100 inhabitants [13].

The high amount of fiber is reflected in the available bandwidth for broadband connections. Broadband is here defined as "always connected" with no bandwidth requirements. Sweden's Internet penetration per household (NB, not per inhabitants as OECD's statistics) since the year 2000 is shown in Fig. 2 [12]. Observe that Internet penetration is getting saturated: by December 2007 it was 78% and slowly growing. Total fixed broadband penetration is 62% and with only slight signs of saturation. This should be compared to Monaco, Hong Kong, South Korea and Macau which all have a household penetration of 100% or above by the end of 2008 [14]. The portion of Swedish households with a downstream connection of at least a 2 Mbit/s was 48% by the end of 2007, while the figure for 10 Mbit/s or more was 19%. For comparison, observe the rapidly growing share of mobile subscriptions which has been added in the lower right corner.

The majority of Sweden's more than 150 municipality networks and a large fraction of the housing companies are using the so-called "open access network" model where the roles of the service provider and the network owner are separated, and where the service providers should get access to the network and thereby the end customers on "fair and non-discriminatory conditions." This should be compared to the traditional vertically integrated business model where the service provider and the network operator are the same (the case for virtually all incumbent operators). In Fig. 3 the open access business model is illustrated. There are different flavors and business models of open networks, and a typical Swedish implementation is shown in Fig. 3. The so-called communication operator who is contracted by the infrastructure owner (which can be a municipality, an estate owner or something else) operates the network and opens it to all service providers on equal terms. The service providers pay a fee to the communication operator but can charge the end-users for the services.

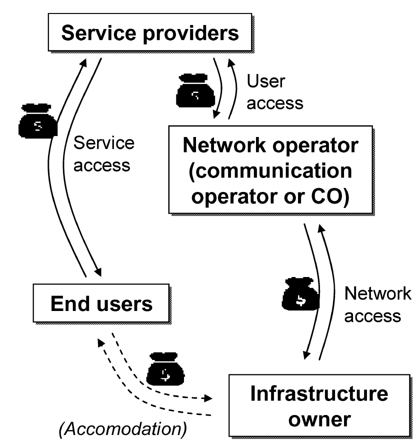

Fig. 3 A typical Swedish implementation of open access business model.

3. Fiber Access Network Evolution

We consider here passive and active optical access network architectures inclusive some representative protection schemes [1], [2], [5]–[10].

Fig. 4 Active optical network homerun architecture.

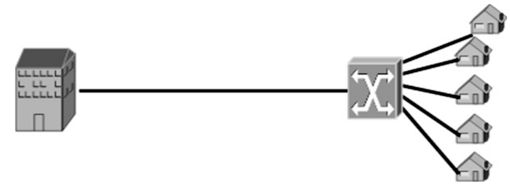

Fig. 5 Active optical network star architecture.

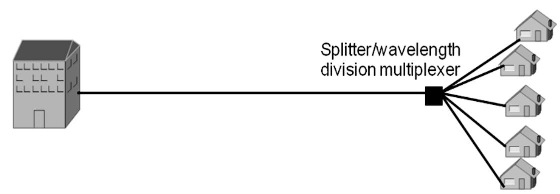

Fig. 6 Passive optical network.

3.1 Active Optical Network

Active optical network is also known as point-to-point Ethernet, P2P, active Ethernet or something similar. There is no well defined nomenclature, but here we consider two different variants; namely star network and homerun. Note these are also known under other names. The two different variants are very similar in the sense that in both cases the optical network units (ONU's - or gateways) are connected to a switch. The main difference is that in the homerun case the switch is situated at the central office (CO) whereas for the star case the switch is placed somewhere between the CO and the ONU — often but not always the switch is placed close to the ONUs. In this case the central office functionality can be distributed among the switches.

Homerun architecture
In a homerun (sometimes referred to as point-to-point P2P [1]) fiber network users are connected directly to the central office (CO) by a separate fiber as depicted in Fig. 4. It is a simple architecture but not very cost effective since a dedicated transceiver and a dedicated fiber for each end user is required in the CO). Also, compared to the star architecture and a PON it requires more space at the CO due to the large number of transceivers which also leads to higher power and cooling requirements. Note that also wavelength division multiplexing PONs (WDM PONs) lead to such concerns apart from the fact that the amount of fibers is smaller.

Star architecture
In AON *star architecture* [1] an active electrical (Ethernet) switch is located at the remote node (RN) between users and CO (see Fig. 5). Due to active equipment at the RN, in this architecture the distance between end users and CO can be extended compared to *homerun* (P2P). However, the total number of transceivers in *star architecture* is larger than in P2P since the optical signal needs to be terminated at RN. In this architecture fiber between the CO and RN is shared by all end users resulting in the better utilization of resources compared to P2P.

3.2 Passive Optical Network (PON)

In PON the active electrical switch in AON is replaced by a passive optical component, either passive splitter or a wavelength division multiplexer (see Fig. 6). Depending on the way the resources are shared one can distinguish between time-division multiplexing (TDM) PON and wavelength-division multiplexing (WDM) PON. Furthermore hybrid WDM/TDM PON is an intermediate stage in PON deployment between the currently deployed TDM PON and the future WDM PON. A hybrid PON solution can also be seen as a way to support a large number of subscribers.

Initial deployments of fiber access networks around the millennium shift were based on AON homerun and star architectures, but currently various PON deployments are dominating with gigabit-capable PON (GPON) having the largest momentum worldwide today.

In North America GPON is the most deployed FTTH technology, in Asia (particularly Korea and Japan) Ethernet PON (EPON) is the dominating technology whereas AON has it strongest foothold in Europe. However, even GPON is widely deployed in Europe, and there are large AON deployments in Korea and more limited deployments in for instance the US and in the Middle East. Furthermore, large operators tend to prefer PON whereas smaller operators especially in Europe have a preference for AON.

Current generation PON is based on time-division multiplexing (TDM PON), such as EPON and GPON. In TDM PONs a single wavelength channel is shared by multiple users and hence, a low per subscriber cost can be offered. Along with the higher bandwidth demand, increasing number of subscribers, and advances in the wavelength division multiplexing (WDM) device technology, the WDM PON has been considered as a next-generation broadband access network. However, in order to ensure the economical viability of the access network solutions, the effort should be put on the evolution from the existing TDM PONs. Therefore, the hybrid WDM/TDM PON is envisaged for the near-future deployment.

On the other hand, the importance of reliable service delivery results in development of different PON protection architectures. The evolution of protection schemes for PONs can be divided into three phases. In the first one, the standard protection architectures were defined by ITU-T [2] in 1998. They are referred to as type A, B, C and D. In

Type A only the feeder fiber (FF) is redundant. Type B protection duplicates the shared part of the PON, i.e., FF and optical interfaces at the optical line terminal (OLT) located at the CO. In Type B the primary optical interface at OLT is normally working while the second one is used as a cold standby. Type C is a typical 1+1 dedicated path protection with full duplication of the PON resources. In Type C both the primary and secondary interfaces are normally working (hot standby), which allows for very fast recovery time. Type D protection specifies the independent duplication of FF and distribution fibers (DFs) and thus, it enables network provider to offer either full or partial protection referred to as Type D_1 or D_2. Obviously, the ITU-T standard schemes Type C and Type D_2 with full protection are characterized by a relatively high reliability performance but unfortunately they require duplication of all network resources (and investment cost). Therefore, in the second phase of the PON protection scheme evolution the effort was put on development of cost-efficient architectures in order to decrease the deployment cost. Schemes proposed in [5]–[8] are based on neighboring protection where two neighboring ONUs protect each other using the interconnection fibers (IFs). In this way, the investment cost for burying redundant DFs to each ONU can be avoided and, consequently, the CAPEX can be reduced. Furthermore, ring protection is proposed in [9] and [10].

We believe that following the trend of minimizing the cost per subscriber the third (future) phase of the PON protection schemes evolution will migrate towards the reduction of OPEX. Meanwhile, OPEX is related to both protection architecture and maintenance strategy. In this paper we compare CAPEX and OPEX along with the reliability performance of some representative fiber access network architectures. The focus is on the various PON protection schemes but AON is included as well for the comparison.

4. PON Protection Architectures and Reliability Models

In our study we consider the standard PON architectures defined by ITU-T [2] (i.e., basic architecture, protection schemes Type A, B, C, and D) and some representative protection schemes for TDM PON, WDM PON and Hybrid WDM/TDM PON [5]–[10].

Figures 7–9 show reliability models illustrated by reli-

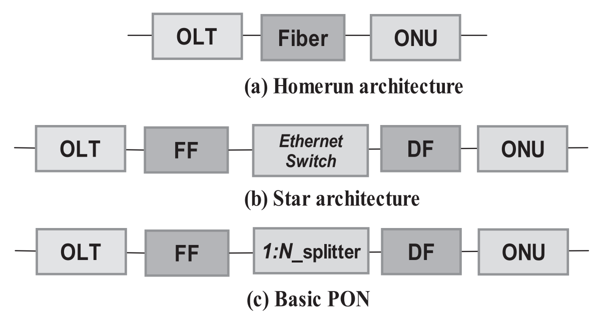

Fig. 7 Reliability block diagrams for basic schemes (without protection).

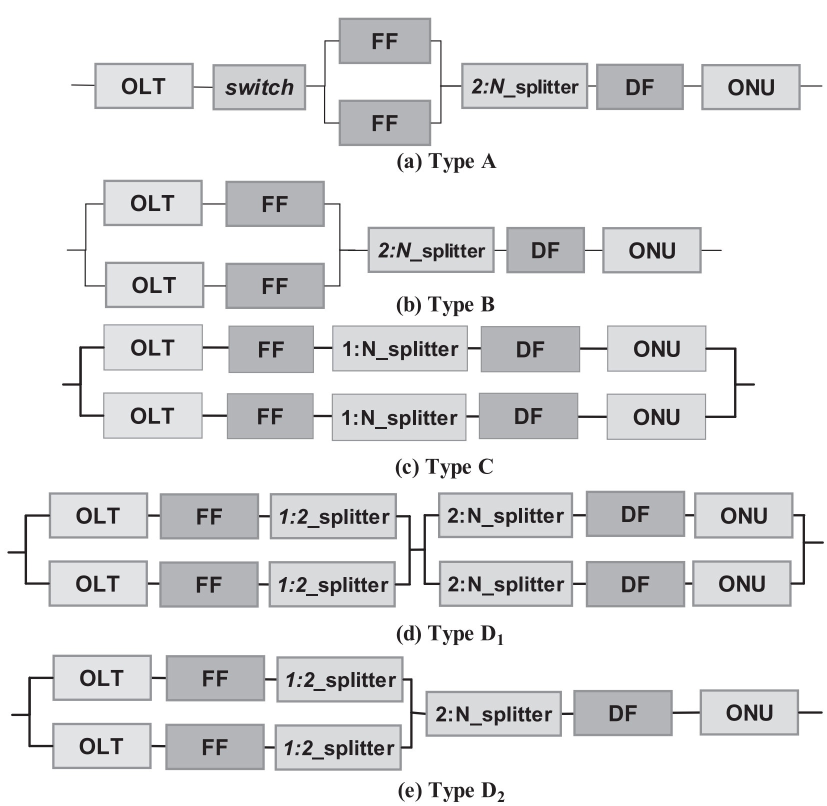

Fig. 8 Reliability block diagrams for standard protection schemes.

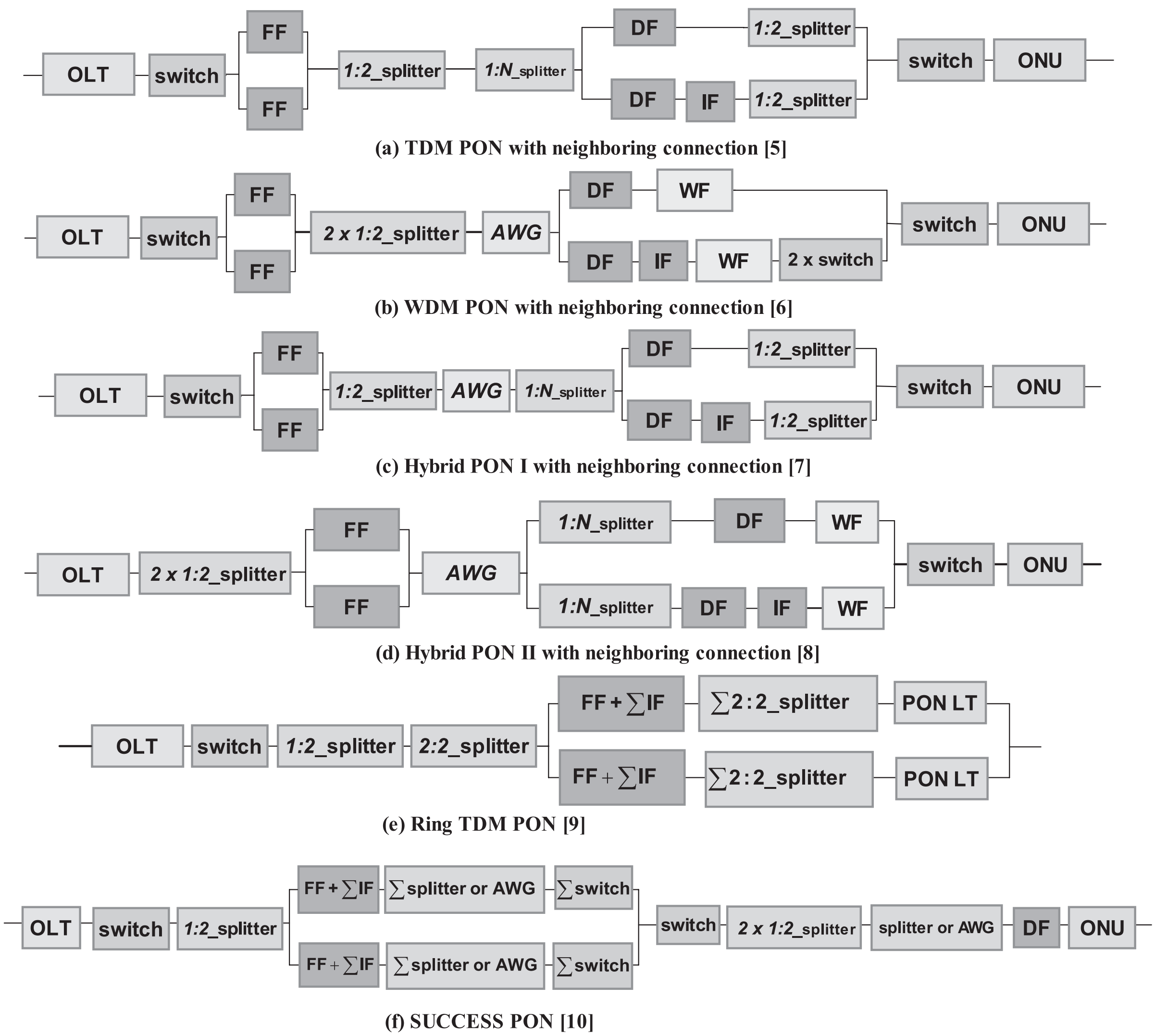

Fig. 9 Reliability block diagrams for cost efficient protection schemes.

ability block diagrams (RBDs) derived for the considered fiber access network architectures. Reliability block diagram is a graphical representation of the system reliability architecture and is a method of representing the effects of all possible configurations of functioning and failed components on the functioning of the system. Our reliability models are obtained based on the system architectures and functionality, and according to the definition of failure that we adopted in this study. We assume that a failure occurs as soon as the connection between the OLT and ONU is interrupted due to the failure of system components.

Each block in the diagram represents either a component or fiber link that has two functional states: operating or failed. A characteristic parameter for each block in the diagram is the asymptotic unavailability which corresponds to the probability that the corresponding component (or fiber link) is failed. The diagram is considered to have a start and a finish. The system is functioning if there is at least one path in the diagram that runs from start to end and does not pass through a failed component. For description of the symbols and component unavailability parameter we refer to Table 1 where N denotes the number of ONUs in each TDM PON.

The series and parallel configurations are used to describe the reliability models [15], [16]. The series configuration (series system) consists of two or more components (units) connected in series from the reliability point of view. It means that a series system fails if one or more components (units) fail. The parallel configuration (parallel system) consists of two or more components (units) connected in parallel from the reliability point of view. It means that a parallel system fails if, and only if, all of the components (units) fail.

From the reliability models the protection mechanism of the each architecture is quite clear. The basic architecture corresponds to the series system where the service will be interrupted if any of the components fails. Both Type C and Type D_2 can provide the full protection of the optical layer

Table 1 Component unavailability and cost [3], [4], [7].

Components/devices	Unavailability	cost (US $)
OLT (WDM PON) 3.2Gbps	5.12E-07	40000
OLT (TDM PON) 1Gbps	5.12E-07	12100
OLT(AON star) 1Gbps	5.12E-07	7500
OLT(AON homerun) 4Gbps	5.12E-07	10200
ONU (WDM PON)	1.54E-06	525
ONU (TDM PON)	1.54E-06	350
ONU (AON)	1.54E-06	150
1:2 (2:2) splitter	3.00E-07	50
1:N (2:N) splitter	7.20E-07	800
(optical) switch	1.20E-06	100
wavelength filter (WF)	3.00E-07	80
AWG	1.20E-06	1200
Ethernet switch (AON star)	3.00E-05	1800
Housing for RN (AON star)	---	30000
Housing for RN (PON)	---	600
Fiber (/km)	1.37E-05	160
Burying fibers (/km)	---	7000

equipment in the PON system.

5. Input Data and Assumptions

For our calculations we used component/device unavailability, mean time to repair (MTTR) and cost figures presented in Table 1 [3], [4], [7]. Observe that MTTR may vary considerably for different operators.

We assumed that the distance between OLT at the CO and ONUs at the user premises (the sum of FF and DF) to be 20 km in all the considered architectures except the ring protection. In order to make it comparable, in the ring PON the fiber length between the OLT and the first ONU is assumed to be the same as the feeder fiber in PONs based on tree topology while the distance between any two adjacent ONUs is assumed to be the same as the length of interconnection fiber in the architectures with neighboring protection since it corresponds to the distance between the adjacent ONUs. Furthermore, in the PON based on the ring topology the number of ONUs on the ring is limited due to the power loss related to the splitters that each ONU is attached to. For splitting ratio 1:1 the power at the last (say Nth) ONU is $3N$ dB lower than at the source. Thus, from the power budget point of view, 4 ONUs in a ring based TDM PON correspond to 16 ONUs in the TDM PON based on tree topology (with one splitting point). In order to make a fair comparison, in our calculations we considered 8 ONUs in each TDM PON.

Moreover, we consider two deployment scenarios, i.e. deployment in sparse and dense populated areas referred to as dispersive and collective case respectively. The following assumptions are adopted.

- Dispersive case (sparse populated area). In this scenario FF, DF and IF are 15, 5 and 2 km long respectively.
- Collective case (dense populated area). In this scenario FF, DF and IF are 19.5, 0.5 and 0.2 km long respectively.

In order to make our results comparable we assumed that each considered access network supports in total 256 users. Thus, an access network based on PON (or AON star architecture) consists of 16 PONs (or AON star architectures) with 16 ONUs each while a P2P network hosts 256 ONUs. Accordingly, a hybrid PON includes 16 TDM PONs each of which supports 16 ONUs. Furthermore, we assumed that one half of the users in Type D is fully protected (Type D_1) while the second half is partially protected (Type D_2).

Moreover, for our OPEX calculations we assumed the lifetime of an access network of 20 years, salary of the repair team 100$/h/person, connection interruption penalty of 400$/h. It should be noted that depending on the business model the MTTR and service interruption penalties may vary considerably among operators. However, in general MTTR and service interruption penalties are reversely proportional. This in turn may lead to a large uncertainty for the OPEX figures.

It should also be noted that the cost figures will be very different for different installations. For instance, burying on the country side is generally much cheaper per km than in a city, and burying in sand is cheaper than in a rocky terrain. Housing for the AON switch in the field will be expensive if new housing is needed for each switch, but placing the switch in a basement room in an already existing building or collocating it with other types of distributed field equipment such as electricity or remote heating equipment will make housing cheaper. Moreover, here the cost of a broadband connection is compared without regards to the bandwidth of the connection. If for example the cost per downstream plus upstream Mbit/s should be compared the AON architectures would be favored.

6. Comparison

We compare unavailability vs. deployment and operational cost, referred to as capital expenditures (CAPEX) and operational expenditures (OPEX), for the considered access network architectures.

OPEX includes both the cost related to repair of different kind of failures in the network and service interruption penalty during the network lifetime (assumed to be 20 years). For the repair cost calculations we adopted our reliability models in Figs. 7, 8 and 9 by deriving the number of failures during the network lifetime and multiplying by the assumed salary per hour. The service interruption penalty was calculated based on the service interruption time obtained from connection availability analysis.

Due to the uncertain cost figures we present relative CAPEX and OPEX where the deployment and operational cost are calculated relative to the cost for the PON basic architecture.

Our results for the collective and dispersive deployment scenario are presented in Table 2 and Table 3 respectively.

Table 2 Collective case: FF=19.5 km, DF=0.5 km.

Schemes			Unavailability	CAPEX per user (US $)	Relative CAPEX	OPEX per user (US $)	Relative OPEX	Relative total cost	CRM
Basic	AON	Homerun (P2P)	2.76E-04	8021	146.7%	19486	99.8%	110.0%	55.2
		Star (with housing)	3.06E-04	6914	126.5%	21613	110.7%	114.1%	72.9
		Star (without housing)		5039	92.2%	21613	110.7%	106.6%	72.4
	PON		2.76E-04	5467	100.0%	19529	100.0%	100.0%	54.7
Standard [2] (TDM)	Type A		1.05E-05	6013	110.0%	965	4.9%	27.9%	4.2
	Type B		8.75E-06	6763	123.7%	844	4.3%	30.4%	4.2
	Type C		7.55E-08	10941	200.1%	333	1.7%	45.1%	4.1
	Type D1		7.17E-08	10948	200.3%	371	1.9%	45.3%	4.1
	Type D2		7.63E-06	7018	128.4%	859	4.4%	31.5%	4.2
Neighboring Connection	TDM in [5]		5.24E-06	7081	129.5%	597	3.1%	30.7%	4.1
	WDM in [6]		7.52E-06	9064	165.8%	699	3.6%	39.1%	4.3
	hybrid I in [7]		6.44E-06	6721	122.9%	619	3.2%	29.4%	4.1
	hybrid II in [8]		4.82E-06	6775	123.9%	568	2.9%	29.4%	4.0
Ring Protection	TDM in [9]		2.39E-06	6345	116.1%	434	2.2%	27.1%	3.9
	SUCCESS in [10]		1.20E-05	6910	126.4%	964	4.9%	29.2%	4.3

Table 3 Dispersive case: FF=15 km, DF=5 km.

Schemes			Unavailability	CAPEX per user (US $)	Relative CAPEX	OPEX per user (US $)	Relative OPEX	Relative total cost	CRM
Basic	AON	Homerun (P2P)	2.76E-04	39398	105.0%	20,562	99.8%	103.2%	59.4
		Star (with housing)	3.06E-04	38966	103.9%	22,689	110.1%	106.1%	78.3
		Star (without housing)		37091	98.9%	22,689	110.1%	102.9%	78.1
	PON		2.76E-04	37516	100.0%	20605	100.0%	100.0%	59.2
Standard [2] (TDM)	Type A		7.20E-05	37942	101.1%	6349	30.8%	76.2%	9.0
	Type B		7.03E-05	38692	103.1%	6228	30.2%	77.3%	8.8
	Type C		7.64E-08	75045	200.0%	2481	12.0%	133.4%	4.9
	Type D1		4.72E-08	75052	200.1%	2512	12.2%	133.5%	4.9
	Type D2		6.92E-05	38902	103.7%	8688	42.2%	81.9%	8.8
Neighboring Connection	TDM in [5]		5.22E-06	45553	121.4%	1883	9.1%	81.6%	4.9
	WDM in [6]		7.50E-06	47392	126.3%	1984	9.6%	85.0%	5.0
	hybrid I in [7]		6.42E-06	45270	120.7%	1905	9.2%	81.2%	5.0
	hybrid II in [8]		4.80E-06	45326	120.8%	1,853	9.0%	81.2%	4.9
Ring Protection	TDM in [9]		2.41E-06	20418	54.4%	857	4.2%	36.6%	4.4
	SUCCESS in [10]		7.36E-05	39734	105.9%	6375	30.9%	79.3%	9.1

It can be noticed that AON and unprotected PON are characterized by very poor reliability performance. However the cost of AON is higher than in the case of basic PON (unprotected). In contrast, PON Type C, D1 [2] and schemes in [5]–[9] can offer very high connection availability (higher than 99.999%, i.e., 5 nines) in the both dispersive and collective cases.

In order to define cost efficiency of a certain reliability improvement we introduce the cost-reliability measure (CRM) [11] parameter.

$$\text{CRM} = \{\log(\text{cost per user})\}/\text{QA} \quad (1)$$

where QA [11] represents the reliability measure and is related to connection availability. The smaller CRM the better since it corresponds to higher efficiency of total cost for the achieved reliability improvement.

In Tables 2 and 3 it can be seen that neighboring and ring protection show the best performance since they are characterized by low CRM. It should be noticed that in the case of Type C and D the low CRM parameter is obtained due to the very low connection unavailability figures (in order of magnitude of 10^{-8}) achieved for these schemes. However, unavailability of 10^{-6} is sufficient and therefore neighboring and ring protection can be considered as the better choice from the reliability and cost point of view. In addition, we noticed that it should be relatively easy and inexpensive to upgrade the basic architecture (i.e. without protection) to obtain the protection functionality proposed in [5]–[8]. It can be done by providing protection for feeder fiber as well as interconnection fibers between neighboring users. This simple and inexpensive upgrading possibility may become valuable for network providers when high reliability access for e.g. new business customers is required.

Comparing the deployment and operational cost it is obvious that both are dependent on the deployment scenario and on the choice of the protection scheme. As expected, the CAPEX is much higher in the dispersive case than in the collective case. While providing protection is associated with the higher CAPEX it dramatically reduces the cost related to the service interruption penalty, which can be seen in the lower OPEX values. The influence of the OPEX reduction on the total cost is more significant in the collective case than in the dispersive case. The higher service interruption penalty the larger impact of the OPEX reduction obtained by protection is expected on the total cost.

Furthermore, our results indicate that in order to achieve high connection availability and low service interruption penalty in the dispersive case, all fiber links should be protected while for the collective case it can be sufficient to protect only the shared parts of PON.

7. Conclusion

We presented an evolution of fiber based access networks and compared their cost and reliability performance. Our comprehensive cost and reliability analysis shows that the combined OPEX and CAPEX costs tend to be higher for AON than for PON, For the AON homerun architecture CAPEX is high due to long reach transceivers and low resource sharing factor. For the AON star architecture on the other hand the OPEX is high due to the high failure rate of the access switch. However, the cost differences between PON and AON are less pronounced in the dispersive case where the remote note is placed further away from the end users. It is because the cost related to burying fiber is dominating. The main cost associated with both PON and AON is burying of fiber, and apart from that the largest cost associated with the AON star architecture is the housing of the switch between the CO and the end user.

Different PON protection schemes were compared and it turned out that protected PONs are superior to unprotected PONs from a reliability performance and cost point of view. The incremental CAPEX for extra equipment should be compared with the OPEX savings over time due to the higher reliability (reduced service interruption). This is especially pronounced for the collective case where the remote node is placed close to the end users. Due to the increasing dependency of reliable broadband connections all over society operators need to consider different protection schemes for the fiber access network, and our analysis showed that protected PONs are indeed more cost efficient over time than unprotected PONs. In the collective case around 80% of the total cost may be saved by providing protection and reducing the service interruption penalty expected during 20 years of operation. This gain is lower for the dispersive case where CAPEX is dominating due to the high cost of burying long distribution fibers.

As with all such cost comparisons it should be observed that the cost figures may vary a lot depending on the specific deployment and the applied business model. Moreover, if the cost per bandwidth were included the AON homerun architecture — which is an otherwise costly alternative — could be favored.

Furthermore, a suggestion is made for how to upgrade the basic architecture in order to obtain an acceptable level of connection availability for e.g. business customers.

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