Cost vs. Reliability Performance Study of Fiber Access Network Architectures

Jiajia Chen and Lena Wosinska, Royal Institute of Technology (KTH)
Carmen Mas Machuca, Munich University of Technology
Monika Jaeger, T-Systems Enterprise Services GmbH

The work has been supported by the European Commission through both COST291 Action and the Network of Excellence "Building the Future Optical Network in Europe" (BONE).

ABSTRACT

Fiber to the home is the future-proof technology for broadband access networks. Several fiber access network architectures have been developed (e.g., point-to-point, active optical network, and passive optical network). PON is considered the most promising solution due to the relatively low deployment cost and high resource efficiency. Meanwhile, because of the growing demand for reliable service delivery, fault management is becoming more significant in all parts of communications networks. However, there is a trade-off between the cost of protection and the level of service reliability. Since economical aspects are most critical in the access part of networks, improving reliability performance by duplication of network resources (and capital expenditures) could be too expensive. Therefore, recent work has focused on PON protection schemes with reduced CAPEX. The future trend will probably migrate toward minimizing operational expenditures during the access network lifetime. The main contributions of this article include providing a general method for CAPEX and OPEX analysis that can be applied to any type of fiber access network with consideration of changed component cost in time and variable take rates, and comparing the total cost (i.e., sum of CAPEX and OPEX) for the selected representative architectures with and without protection for business and residential users in relation to reliability performance. The aim is to give a guideline for the design of the most cost-effective protection schemes, while maintaining acceptable service reliability.

INTRODUCTION

Fiber to the home (FTTH) is currently experiencing double-digit growth (or higher) [1–3] in the United States, Europe, and several Asian countries, because residential customers require high-bit-rate connections for broadband services. This demand for bandwidth has exceeded recent predictions, driven mostly by a number of factors, including the huge success of Internet video streaming services such as YouTube, the unanticipated success of high-definition television (HDTV), and the growing popularity of online social media sites where people meet, collaborate, and, more important, exchange photographs, video, and audio content with each other. The number of users demanding high bandwidth continues to increase at a rapid pace. Consequently, many service providers are planning networks capable of offering 50 Mb/s, 100 Mb/s, or higher bandwidth per customer. In contrast to many existing broadband technologies, such as digital subscriber line (DSL) and wireless access, fiber access can easily fulfill such bandwidth requirements, on a per customer basis, while still being capable of offering higher capability in the future. Several fiber access network architectures have been developed, such as point-to-point (P2P), active optical network (AON) [3] and passive optical network (PON) [4]. Furthermore, there are three main types of PONs utilizing different resource sharing technologies: time-division multiplexing (TDM) PON, wavelength-division multiplexing (WDM) PON, and hybrid WDM/TDM PON.

On the other hand, fault management in communication networks becomes more and more significant due to the demand for reliable service delivery and business continuity. It is shown that fiber access networks without any protection are characterized by very poor reliability [5, 6]. Therefore, some type of protection should be provided to satisfy growing importance of reliable access to the network services. Obviously, adding redundant components and systems will improve network reliability . However, in the access part of communication networks the costs are shared by a very limited number of users; therefore, both system deployment cost (related to capital expenditures [CAPEX]) and network management cost (related to operational expenditures [OPEX]) should be minimized. Keeping this in mind, besides our CAPEX study, we also provide an OPEX analysis for fault management and apply it to several fiber access architectures.

The remainder of this article is organized as follows. In the next section the considered fiber access network architectures are presented. We then study different cases to analyze and compare CAPEX and OPEX related to the considered architectures. We provide a comparison of the total cost corresponding to both deployment and operation of the systems in relation to reliability performance. Finally, we give some conclusions.

Fiber Access Network Architectures

In our study we consider P2P, AON, and PON architectures, which are representative schemes for fiber-based access networks. The P2P architecture is a straightforward way to deploy fiber access. In P2P a dedicated fiber is used to connect the central office (CO) to each end user (Fig. 1a). Although this is a simple architecture, in most cases it is not cost-efficient due to the fact that it requires significant outside plant fiber deployment as well as a dedicated transceiver at the CO for each end user.

AON is another common architecture for fiber access. In AON an electrical switch is deployed as a remote node (RN) close to the end users and only one single fiber is needed for the connection between the CO and the active switch (Fig. 1b). Due to the fact that active equipment is used at the RN, this architecture can provide longer reach than P2P. In addition, the total amount of deployed fiber is also reduced since only one single feeder fiber is used. However, transceivers are needed for the active Ethernet switch at the RN, and the total required number of transceivers in an AON is larger than in P2P for the same number of end users. Furthermore, the AON architecture requires electrical power at the RN. Expensive housing for the active Ethernet switch at the RN increases the CAPEX, while supply and maintenance of electrical power is considered one of the key operational costs.

Therefore, it is beneficial to replace the active switch at the RN with an inexpensive passive optical component in order to save the cost in the local loop. A PON is a point-to-multipoint optical network with no active devices in the outside plant (Fig. 1c). In a PON the elements used in the optical distribution network are passive optical components, such as optical fiber, splices, splitters/combiners, and arrayed waveguide gratings (AWGs). Due to only a single shared feeder fiber connecting the CO to the end users, a PON can have higher flexibility for resource allocation than a P2P scheme. Meanwhile, PON protection architectures are also widely studied [7–10] in order to increase the reliability of the access network. The evolution of PON protection architectures has experienced two phases. The first phase took place in the late 1990s and was based on adding more redundant components and systems. It was reflected in the development of the standard PON protection architectures that were defined by the International Telecommunication Union — Telecommunication Standardization Sector [ITU-T] [7] around a decade ago. These standard PON protection schemes are referred to as types 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, that is, the FF and optical interfaces at the optical line terminal (OLT). In type B the primary optical interface at the OLT is normally working while the second one is used as a cold standby. Type C represents 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 the FF and distribution fibers (DFs), and thus enables network providers to offer differentiated reliability levels for users. Obviously, the ITU-T standards types C and D with full protection offer high reliability, but unfortunately they require duplication of all network resources (and investment cost) to realize the protection. However, improving network reliability performance only by duplication of all components and systems is expensive, and thus not always suitable for cost-sensitive access networks. In the second phase of the PON protection scheme evolution the effort was put on the development of cost-efficient architectures. In [8–10] two neighboring optical network units (ONUs) protect each other using interconnecting fibers (IFs) for the TDM PON, WDM PON, and hybrid WDM/TDM PON. In this way the large amount of investment cost for burying redundant DFs to each ONU can be saved, and consequently, the CAPEX can be significantly reduced.

Besides CAPEX, during the access network lifetime (usually 20 years or more), saving in OPEX is a serious issue to be considered by network providers. Therefore, following the trend of minimizing the cost per subscriber, the future phase of PON protection schemes evolution will

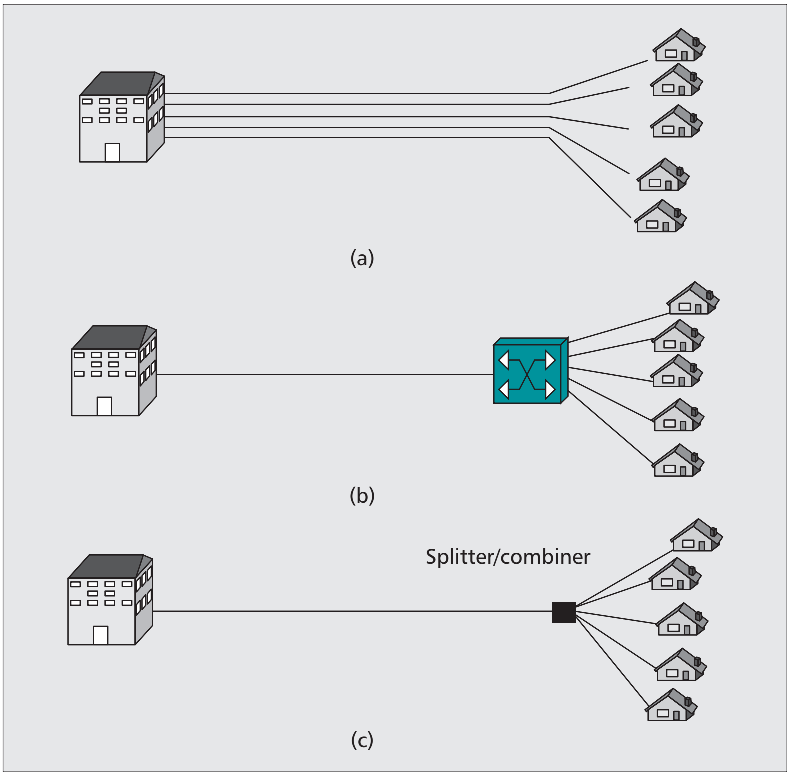

Figure 1. *Basic fiber access network architectures: a) point-to-point (P2P); b) active optical network (AON); c) passive optical network (PON).*

In our study the lifetime of an access network is considered to be 20 years. Furthermore, we assume that access networks based on P2P, AON, TDM PON, and WDM PON host 32 ONUs while a hybrid PON consists of 16 TDM PONs each of which supports 16 ONUs.

probably migrate toward the reduction of OPEX while maintaining the network reliability at an acceptable level. In this article we present two case studies,one where the component cost is changed in time and the second one with a variable take rate. Furthermore, we compare CAPEX and OPEX for several representative architectures: basic P2P, AON, standard PON defined by ITU-T [7] (i.e., basic architecture, protection scheme types A, C, and D), and some cost-efficient protection schemes for TDM PON, WDM PON, and hybrid WDM/TDM PON based on neighboring interconnection, presented in [8–10], respectively. These cost-efficient architectures were chosen here because they have similar types of protection and therefore are appropriate for a comparative study. In addition, we noticed a big advantage of these schemes: it should be relatively easy and inexpensive to upgrade the basic PON (i.e., without protection) to obtain the protection functionality proposed in [8–10]. It can be done by providing protection for feeder fiber as well as interconnecting fibers between neighboring users. This simple and inexpensive upgrade possibility may become valuable for network providers. The results for ITU-T standard type B are not presented here since we noticed that both CAPEX and OPEX results for type B are very similar to those for type A.

In both CAPEX and OPEX studies we consider the following scenarios with respect to the population density for all the analyzed architectures:

- A *dispersive scenario* corresponding to an access network deployed in sparsely populated areas. In this scenario we assume that FF, DF, and IF are 15, 5, and 2 km long, respectively.
- A *collective scenario* corresponding to an access network deployed in densely populated areas where FF, DF, and IF are assumed to be 19.5, 0.5, and 0.2 km long, respectively.

In our study the lifetime of an access network is considered to be 20 years. Furthermore, we assume that access networks based on P2P, AON, TDM PON, and WDM PON host 32 ONUs, while a hybrid PON consists of 16 TDM PONs, each of which supports 16 ONUs.

CAPEX Study

In this section we compare the investment cost (CAPEX) associated with deployment of the considered architectures. It can complement the OPEX study presented in the following section to give a total picture of the costs related to both installation and operation of the selected systems.

CAPEX issues in access networks have been extensively studied [5, 6, 10–12], due to the importance of economical aspects in this part of the communication network. We follow the methodology presented in [10] for the CAPEX calculation. In addition, the cost for equipment installation is taken into account. It can be calculated by the product of the installation time (shown in Table 1) and the hourly rate for the operator's employee (US$190/h [13]). For the equipment located at the RN and at the users, the related travel time should also be included in the entire installation process. The travel speed is assumed to be 20 km/h for driving in urban areas. Furthermore, the cost of housing the OLT is not included in this study, since usually one CO accommodates several OLTs and the related cost is shared. Hence, the housing and chassis costs in Table 1 for line terminal (LT) at the OLT only include the chassis part.

Input data for failure rate, mean time to repair (MTTR), cost, and reparation parameters used in our calculations are also shown in Table 1. The prices of fiber and components as well as the corresponding charges for housing and chassis of components are based on realistic cost figures in [5, 11, 12, 14–16], while the cost of burying fiber is based on the European labor market [10]. It should be noticed that in Table 1 reparation time is the time needed to repair/replace a failed component and is different from MTTR, which is the average value of total time to repair (TTTR) including the time to wait for the available resources and travel time along with reparation time. MTTR in Table 1 is based on figures from Bellcore [17], while reparation time and number of persons are based on estimations of T-Systems.

In order to get a complete picture of the CAPEX dependence on different scenarios, we considered fiber and components cost change over time as well as different take rates in an access network area. The take rate is defined as percentage of homes or buildings covered by the access network infrastructure that subscribe for the service [5].

Case Study I: Changed Cost in Time

In our study, the total CAPEX includes component related cost and cost for burying fibers. The component related cost consists of component and fiber cost, installation, housing, and chassis. The prices of fiber and components are expected to decrease over time according to Moore's law. In contrast, the cost related to the civil work (e.g., burying fibers, housing, and chassis) is relatively stable in time. Furthermore, the installation cost increases since the salary for the operator's employee is expected to increase in time. We assume 7 percent cost reduction per year for fiber and each component, and 3 percent increase per year for the hourly rate of the operator's employee. Figures 2a and 2b show component related cost and CAPEX per ONU calculated for all the considered architectures. Please notice that we consider cost per ONU and not a price that will be charged to users, which may depend on pricing policy and other factors. It can be seen that the component related cost is influenced strongly by cost reduction in time. In P2P and all the PON architectures, the decrease of the component related cost is similar to the assumed change of component cost in time. However, in AON it is quite different, because the expensive housing for the Ethernet switch at the RN, whose cost does not fluctuate in time, takes nearly 50 percent of the total component related cost. However, the total CAPEX per ONU for all the considered architectures does not change significantly with time,

<table>
<tr><th rowspan="2">Component</th><th rowspan="2">Failure rate (FIT**)</th><th rowspan="2">MTTR*** (hour)</th><th colspan="2">Cost ($)</th><th rowspan="2">Installation (min)</th><th colspan="2">Reparation</th></tr>
<tr><th>Housing & chassis</th><th>Component</th><th>Time (h)</th><th>No. of persons</th></tr>
<tr><td>LT*@OLT (P2P)</td><td rowspan="5">256</td><td rowspan="5">2</td><td>4500</td><td>150 per port</td><td rowspan="5">30 + 10 per port</td><td rowspan="5">1</td><td rowspan="5">1</td></tr>
<tr><td>LT@OLT (AON)</td><td>4500</td><td>3000</td></tr>
<tr><td>LT@OLT (TDM PON)</td><td>4500</td><td>7600</td></tr>
<tr><td>LT@OLT (WDM PON)</td><td>20,000</td><td>24320</td></tr>
<tr><td>LT@OLT (hybrid PON)</td><td>20,000</td><td>24320</td></tr>
<tr><td>Ethernet switch @RN (AON)</td><td>5000</td><td>24</td><td>37350</td><td>200 + 100 per port</td><td>30 + 10 per port</td><td>7</td><td>1</td></tr>
<tr><td>1:N (2:N) splitter@RN</td><td>120</td><td>6</td><td>700</td><td>50 per port</td><td>10 + 10 per port</td><td>1</td><td>1</td></tr>
<tr><td>1:N AWG@RN</td><td>200</td><td>6</td><td>800</td><td>75 per port</td><td>30 + 10 per port</td><td>1</td><td>1</td></tr>
<tr><td>1:2 splitter</td><td>50</td><td>6</td><td>—</td><td>30</td><td>—</td><td>1</td><td>1</td></tr>
<tr><td>Wavelength filter</td><td>50</td><td>6</td><td>—</td><td>80</td><td>—</td><td>1</td><td>1</td></tr>
<tr><td>Optical switch</td><td>200</td><td>6</td><td>—</td><td>50</td><td>—</td><td>2</td><td>1</td></tr>
<tr><td>Electrical switch</td><td>160</td><td>6</td><td>—</td><td>100</td><td>—</td><td>2</td><td>1</td></tr>
<tr><td>LT@ONU (P2P)</td><td rowspan="5">256</td><td rowspan="5">6</td><td>—</td><td>150</td><td rowspan="5">60</td><td rowspan="5">1</td><td rowspan="5">1</td></tr>
<tr><td>LT@ONU (AON)</td><td>—</td><td>150</td></tr>
<tr><td>LT@ONU (TDM PON)</td><td>—</td><td>350</td></tr>
<tr><td>LT@ONU (WDM PON)</td><td>—</td><td>525</td></tr>
<tr><td>LT@ONU (hybrid PON)</td><td>—</td><td>350</td></tr>
<tr><td>Fiber (/km)</td><td>570</td><td>24</td><td>—</td><td>160</td><td>$7000 for burying fibers</td><td>7</td><td>3</td></tr>
</table>

*LT: Line terminal

**FIT (failure in time) corresponds to mean number of failures during a time period of 10^9 hours

***MTTR: Mean time to repair

Table 1. *Input data.*

in particular in the sparsely populated (dispersive) scenario, since the cost of burying fiber is the dominating component of the cost for deployment of fiber-based access networks. In addition, it is obvious that among the three basic architectures (i.e., P2P, AON, and PON), the cost related to optical components and total CAPEX is lowest for PON. Furthermore, it can be observed that hybrid PON with neighboring protection is characterized by lower cost per ONU than basic PON without any protection. This is due to the larger sharing factor in a hybrid PON. However, the absolute value of CAPEX per ONU is still high and obviously not feasible to be covered by users at installation time. Usually, the price offered for users is much lower than investment cost (CAPEX) per user. In order to attract more end users, network providers apply pricing policies allowing for gradual payback of the investment from revenue during the whole lifetime. Typically, the lifetime of an access network is assumed to be 20 years. However, the fiber infrastructure can have a much longer lifetime, since it can be reused for future solutions. Therefore, it may be reasonable to charge a new user only for the component related cost, and the remaining part as well as operational cost can be included in the subscription of services and paid, for example, on a monthly basis. It can be observed in Fig. 2a that the component related cost for basic PON, type A, and both TDM PON and hybrid PON with neighboring protection is relatively low (much lower than $2500), which may be acceptable as an initial installation price for a new user. Furthermore, one can expect that after three years this cost per new user will be reduced by around 20 percent. Moreover, the component related cost for

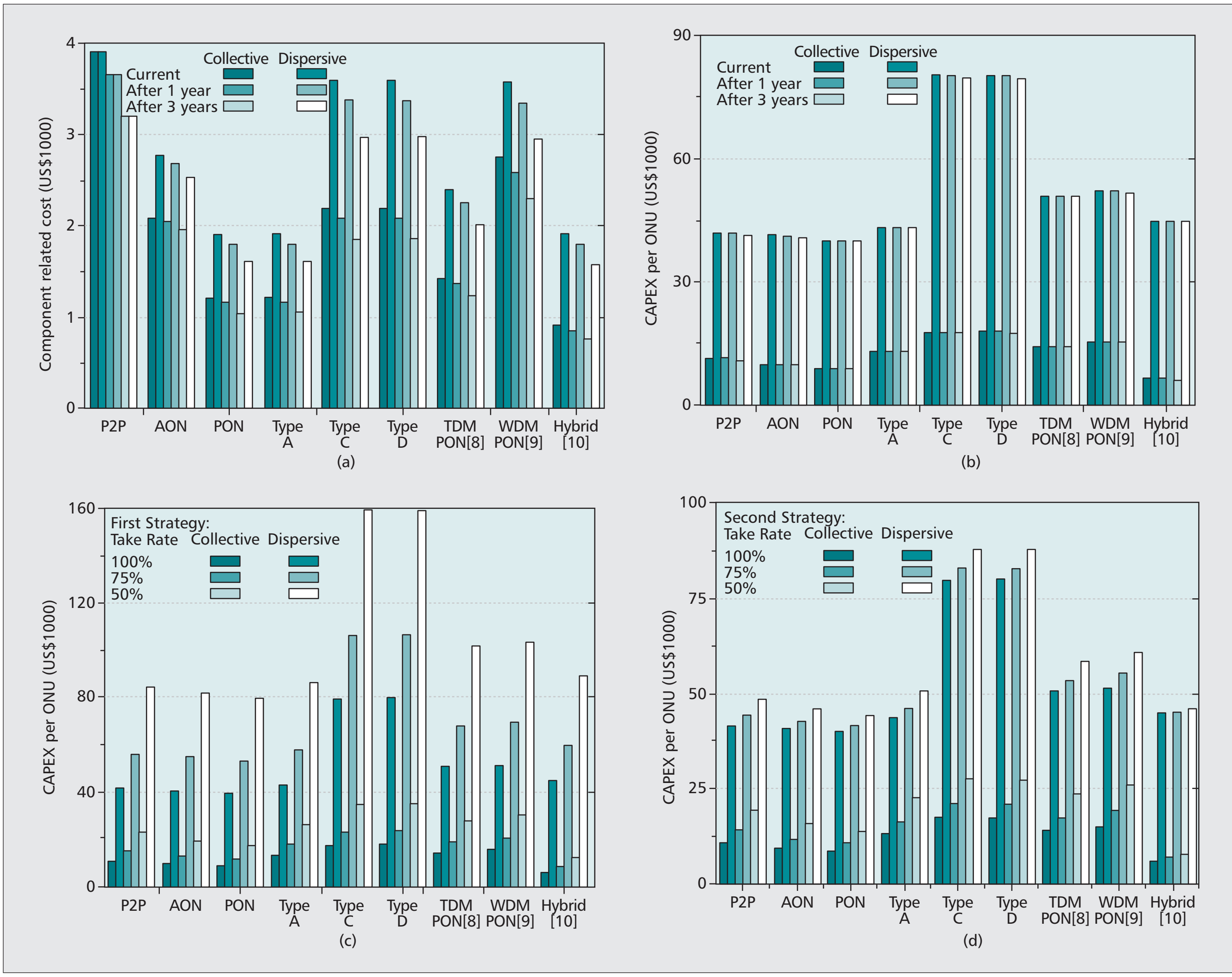

Figure 2. *Results for CAPEX. Case study I (changed cost in time) assuming 100 percent take rate: a) component related cost; b) total CAPEX. Case study II (variable take rate): c) CAPEX for the first deployment strategy where distribution fibers (DFs) are buried to all the homes or buildings from the beginning but the installation is made upon subscription; d) CAPEX for the second deployment strategy where DFs are buried only to the homes or buildings that subscribe for the service.*

WDM PON is relatively high, but on the other hand, it can offer much higher capacity per user and scale better than other architectures.

CASE STUDY II: VARIABLE TAKE RATE

In [5] it is noticed that the CAPEX per user is dependent on the take rate, which is the percentage of homes or buildings covered by the access network infrastructure that subscribe to the service. Infrastructure costs (e.g., enclosure construction and fiber deployment) may be incurred for all homes, even though they can only be recovered from the revenue of those that subscribe. In this case with respect to take rate, we consider two different strategies to bury distribution fibers. In the first one, fibers are buried to all the homes or buildings from the beginning, but installation is done upon subscription. In the second strategy distribution fibers are buried only to the homes or buildings that subscribe to the service. Obviously, when take rate is 100 percent there is no difference between these two strategies. However, as shown in Figs. 2c and 2d, when the take rate is lower than 100 percent, the cost per ONU varies more in the first strategy than in the second since burying distribution fibers is expensive, particularly in sparsely populated areas. Therefore, from a cost point of view, the second strategy for burying distribution fibers is recommended. However, in some cases the first strategy should be applied to reduce the installation time for new users after network deployment. Furthermore, if the network provider can expect that the take rate will increase soon, it might also be desirable that all distribution fibers are buried from the beginning.

OPEX STUDY

OPEX have been shown to be a very important factor of the total cost of ownership (TCO) of a telecommunication operator [18], in some cases up to 85 percent of the TCO. There is no standard classification of what costs should be considered as OPEX or CAPEX, but a widely accepted definition is that CAPEX includes infrastructure costs (i.e., network components, installation of equipment, etc.), whereas OPEX copes with costs related to the operation of the network (backup equipment, reparation of failures, establishment and maintenance of services, etc.).

One of the most costly OPEX processes is failure reparation [19], and hence, when proposing new architectures, the cost evaluation of the failure reparation process cost should be included.

The failure reparation process is triggered by the network management system (NMS) and the network operation team. This team monitors the network through the NMS, and receives alarms and traps from network components, complaint reports from clients, and so on. After fault diagnosis [20], they produce a report with a description of the failure in as much detail as possible, which may include the component that has failed, the location of the component, the importance of the failure, and other information. Based on this report, the failure reparation process starts and consists of different subprocesses:

- Check availability of:
  - Personnel with the required knowledge and equipment
  - Spare components in case the failure requires replacement of a/some/all part(s) of the failed component
  - Required means of transportation such as a car, van, or truck depending on the volume of the required reparation equipment

In this work it has been assumed that the means of transportation are available to be used when required. Hence, this study considers the availability of required personnel and spare components, and a delay cost penalty is considered when no personnel is available (the delay is the time elapsed between when the personnel is required and when the personnel is available). The number of required persons depends on the type of failure as presented in Table 1.

- Travel: Once the required personnel are available, they have to travel to the failure location. The travel time will have a cost proportional to the travel distance. In this study we assume that the reparation personnel are located at the OLT side and the travel speed has an average of 20 km/h.
- Reparation and testing: Once the reparation team reaches the failure location, time is required to fix the failure and test the signal quality to make sure it is acceptable. This reparation time depends on the type of failure, and the values considered in this study are presented in Table 1.
- Updating databases when the failure has been repaired.

In our study we consider the TTTR the failure, which can be expressed as the sum of the time to have available personnel and equipment to repair the failure (T_{ava}), the travel time (T_{trav}), and the reparation time (T_{rep}).

Two operational costs are related to failures in the network and have been analyzed in this study:

- Failure reparation cost, which includes the personnel cost for the period of time $2T_{\text{trav}} + T_{\text{rep}}$, the required spare components, and so on. We assume that an employee works 8 h/day, and the personnel hourly rate is US$190/h [13] which is the cost of a company employee, and includes salary, insurance, material, and so on.
- Penalty costs, which are proportional to the number of disconnected ONU for each failure of an unprotected component during the period of time TTTR. In this study the penalty is associated with the type of user (10 percent of the ONUs are considered to be business users, whereas 90 percent are residential users). The penalty for business users is $1200/h, whereas no penalty is given to residential users.

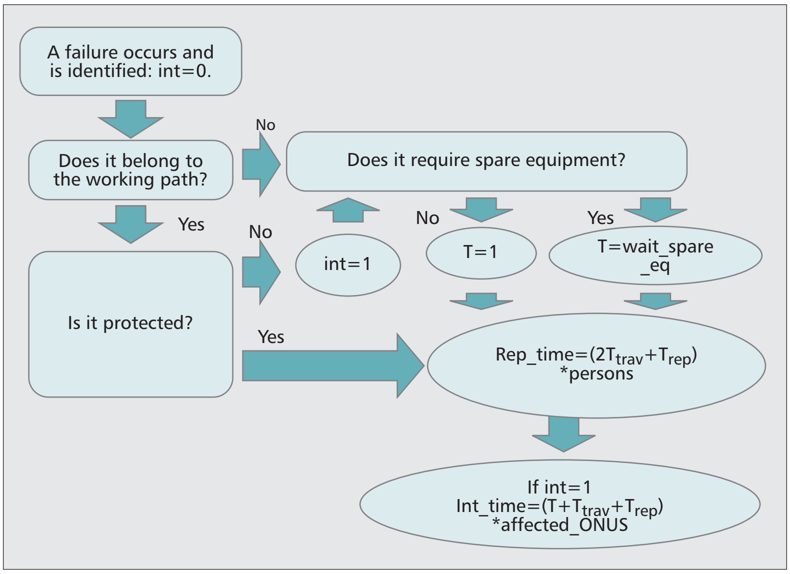

Figure 3. *Flowchart for computation of failure reparation and penalty cost.*

The calculation of these costs is based on the times computed in the failure reparation process depicted in Fig. 3. Depending on whether the failure belongs to the working path, whether it is a protected component, and whether it requires spare equipment, the corresponding reparation and penalty times are calculated. Based on these times, the costs can be derived straightforwardly.

Case Study I: Changed Cost in Time

This section studies the impact of the change of equipment cost and salaries over time. The equipment cost decreases 7 percent per year, and the salary increases 3 percent per year. The equipment cost variation will have an impact on the time at which the spare component is bought. The later it is bought, the cheaper it is, but longer TTTR and higher penalty costs can be expected. The operational costs are shown as penalty, reparation, and total costs in Figs. 4a and 4b for two different approaches:

- Approach 1: Spare components are bought at year 0 of the access network.
- Approach 2: Spare components are bought when the component fails. The waiting time to receive the spare component is assumed to be 24 h.

It can be observed that for unprotected architectures, penalty costs are higher than reparation costs, which include the spare component costs. On the contrary, protected architectures have reparation costs higher than the penalty costs

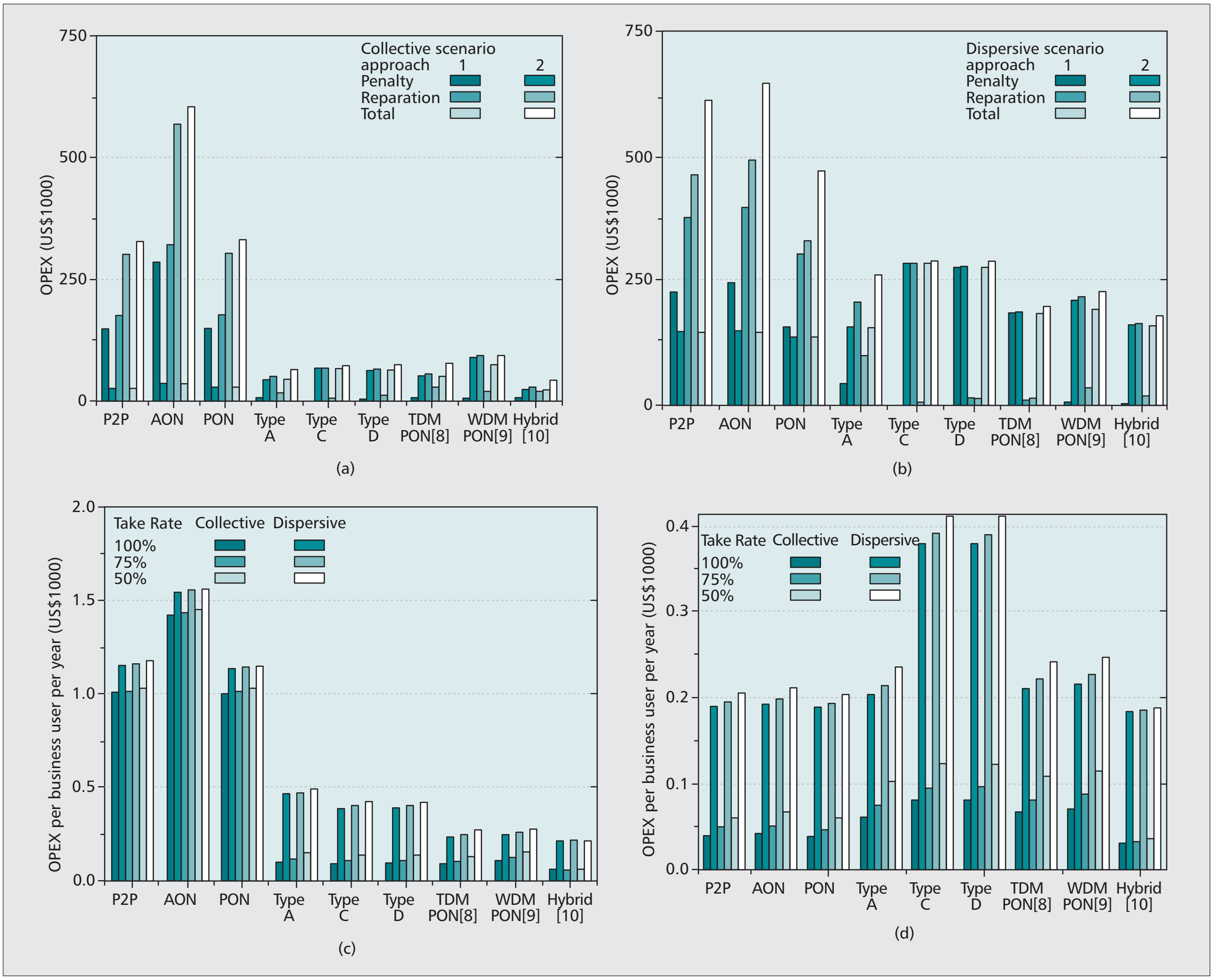

Figure 4. *Results for OPEX. Case study I (changed cost in time) assuming 100% take rate: penalty and reparation cost (including spare component cost) comparison for different architectures in; a) collective; and b) dispersive scenario when either components are bought at year 0 (Approach 1) or when the component fails (Approach 2). Case study II (variable take rate): c) OPEX per business user per year; and d) OPEX per residential user per year.*

due to the larger amount of equipment (and failures). Due to the longer fibers, the dispersive scenario implies higher OPEX cost per ONU than the collective one. Approach 2 offers lower availability and incurs higher costs than approach 1, which will encourage operators to buy spare components in advance.

CASE STUDY II: VARIABLE TAKE RATE

The take rate also has an impact on operational costs. Higher take rate implies more installed equipment and therefore higher number of failures. Three different take rates have been studies: 50, 75, and 100 percent; their impact on the operational costs for business and residential users are plotted in Figs. 4c and 4d, respectively.

It can be observed that the operational cost per business user is higher than that per residential user due to the penalty incurred when the former loses connection. In general, the higher the take rate , the higher the number of users and the lower the operational costs per user (since there are more users with whom to share the costs).

TOTAL COST VS. RELIABILITY PERFORMANCE

This section is to merge the CAPEX and OPEX figures of the considered fiber access network architectures, and show them in relation to the reliability performance in terms of connection unavailability. The CAPEX and OPEX results presented earlier correspond to a reference scenario of manufacturers (mostly related to the cost of components and burying fibers) and operators (mostly related to OPEX parameters such as hourly rate of the employee, penalty cost, etc.). Hence, CAPEX and OPEX values may vary when another scenario is applied.

Similar to the previous section, we distinguish between total cost per business user and per residential user by taking into account the penalty cost in OPEX for the former and not for the latter. Furthermore, the fiber infrastructure can have much longer lifetime than the network components, since it can be reused

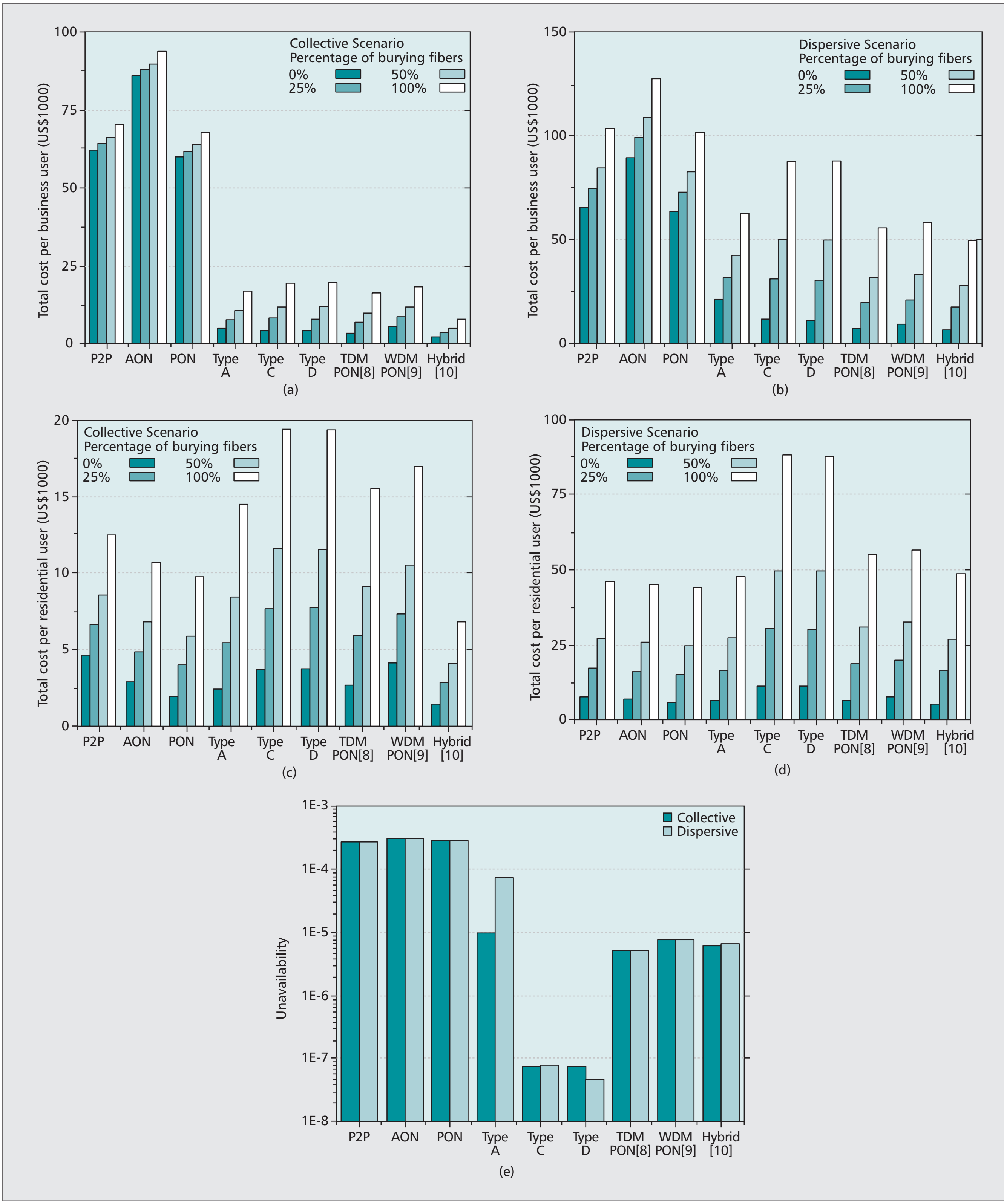

Figure 5. *Total cost per business users in; a) collective and b) dispersive scenario and total cost per residential user in c) collective and b) dispersive scenario with consideration of different percentages of burying fibers and e) result for connection unavailability.*

for future network solutions. Therefore, for all the considered architectures the total cost per user includes only a part of the cost for fiber infrastructure along with the component related cost and OPEX. Figures 5a–5d show the total cost (with consideration of different percentages of cost to bury fibers) per business and residential user in the collective and dispersive scenarios, respectively, while in Fig. 5e connection unavailability is depicted. It can be seen that PON always has the lowest total cost among all the basic architectures. For residen-

Our results show that for business users the total cost in the protection schemes based on the neighboring connection, in particular TDM and hybrid PON, is lower than the unprotected scheme and Type A.

tial users, the total cost for the PON schemes with protection is higher than the basic one. However, compared to types C and D, the cost of schemes with neighboring protection is relatively low, in particular when the percentage of cost to bury fibers is lower, while a connection availability of 99.999 percent (5 nines) can be achieved in these cost-efficient protection schemes. On the other hand, one can see that in the case of business users the OPEX, in particular the penalty cost, seems to be an important issue for the budget plan of a network operator because it is a significant part of the total cost. It can be observed that the penalty cost is relatively low for the schemes where a connection availability of 99.999 percent (5 nines) can be achieved, such as the cost-efficient schemes with neighboring protection, types C and D. In contrast, in the case of unprotected architectures and type A the connection unavailability is high, and hence the penalty cost is high. Therefore, due to the low penalty, the total cost per business user in the cost-efficient schemes with neighboring protection, in particular TDM and hybrid PON, is lower than the unprotected scheme and type A. The difference is more obvious when a lower percentage of cost to bury fibers is taken into account. Moreover, in types C and D the total cost for business users is higher than in cost-efficient protection schemes due to duplication of expensive resources and high reparation cost. Hence, these cost-efficient protection schemes may be recommended in access networks with large numbers of business users.

In addition, in the case when business customers move to an area where an unprotected or type A PON is deployed, a network operator may need to upgrade the network to satisfy the high demand for reliability of the new business customers as well as maintain the total cost at a minimum. In this situation it would not be cost efficient to choose type C or D protection. Instead, the protection functionality proposed in [8–10] can be obtained by adding interconnecting fibers between neighboring users; therefore, the upgrade along with its corresponding maintenance can be made at relatively low cost while offering an acceptable level of connection availability.

Furthermore, it should be noted that the WDM PON provides higher bandwidth per user than other schemes, and therefore its cost per unit of bandwidth may be lower.

Conclusion

In this article we present a comprehensive cost analysis for fiber access networks including both CAPEX and OPEX. A general method for CAPEX and OPEX analysis with consideration of changed component cost in time and variable take rate is proposed followed by the calculations made for some representative architectures. The reliability models of the considered protection architectures were derived for OPEX calculations, while for the connection availability calculations we follow the models in [10]. The main contributions of this work are:

- The general method for CAPEX and OPEX analysis that can be applied to any type of fiber access solutions and any operator by using appropriate parameters
- The comparison of the total cost for the selected architectures in relation to the reliability performance

Our results show that for business users the total cost in the protection schemes based on neighboring connection, in particular TDM and hybrid PON, is lower than the unprotected scheme and type A. Meanwhile, a connection availability of 99.999 percent (5 nines) can also be achieved in the schemes with neighboring protection. Furthermore, a suggestion is made for how to upgrade the basic architecture in order to obtain an acceptable level of connection availability for business customers.

References

[1] FTTH Council Europe, "Europe Breaks One Million Barrier," 2008; http://www.ftthcouncil.eu

[2] FTTH Council and TIA Press Release, "Fiber to the Home Revs Up Expansion, More than Two Million Homes Now Connected to Next-Generation Broadband," 2007; http://www.ftthcouncil.org/?t=277

[3] P. W. Shumate, "Fiber-to-the-Home: 1977–2007," *IEEE/OSA J. Lightwave Tech.*, vol. 26, no. 9, May 2008, pp. 1093–1103.

[4] F. Effenberger *et al.*, "An Introduction to PON Technologies," *IEEE Commun. Mag.*, vol. 45, no. 3, Mar. 2007, pp. S17–S25.

[5] A. V. Tran, C. Chae, and R. S. Tucker, "Ethernet PON or WDM PON: A Comparison of Cost and Reliability," *TENCON 2005,* IEEE Region 10, 2005.

[6] L. Wosinska, and J. Chen, "Reliability Performance Analysis vs. Deployment Cost of Fiber Access Networks," *7th Int'l. Conf. Optical Internet*, 2008.

[7] ITU-T Rec. G983.1, "Broadband Optical Access Systems Based on Passive Optical Network (PON)," 1998.

[8] J. Chen, B. Chen, and S. He, "Self-Protection Scheme Against Failures of Distributed Fiber Links in an Ethernet Passive Optical Network," *OSA J. Optical Net.*, vol. 5, no. 9, Apr. 2006, pp. 662–66.

[9] T. Chan *et al.*, "A Self-Protected Architecture for Wavelength Division Multiplexed Passive Optical Networks," *IEEE Photonics Tech. Lett.*, vol. 15, no. 11, Nov. 2003, pp. 1660–62.

[10] J. Chen and L. Wosinska, "Analysis of Protection Schemes in PON Compatible with Smooth Migration from TDM-PON to Hybrid WDM/TDM PON," *OSA J. Optical Net.*, vol. 6, no. 5, May 2007, pp. 514–26.

[11] M. K. Weldon and F. Zane, "The Economics of Fiber to the Home Revisited," *Bell Labs Tech. J.*, vol. 8, no. 1, July 2003, pp. 181–206.

[12] Y. Kim *et al.*, "Cost Effective Protection Architecture to Provide Diverse Protection Demands in Ethernet Passive Optical Network," *Proc. ICCT*, Beijing, 2003, pp. 721–24.

[13] S. Verbrugge *et al.*, "Impact of Resilience Strategies on Capital and Operational Expenditures," *Proc. Tagung Photonical Net. 2005*, Leipzig, Germany, May 2005, pp. 109–16.

[14] Excel Tech Optics; http://www.exceltechoptics.com/ProductDetails.asp?ProductCode=100007&Show=ExtInfo

[15] Y. Leung, "Lightpath Concentrators for All-Optical Networks," *IEEE/OSA J. Lightwave Tech.*, vol. 24, no. 9, Sept. 2006, pp. 3259–67.

[16] Australian Fiber Works; http://www.afwtechnology.com.au/wdm/filter_wavelength_division_multi.htm

[17] Bellcore GR-418-CORE, "Generic Reliability Assurance Requirements for Fiber Optics Transport System," no. 1, Dec. 1997.

[18] C. Evans, "Cost Justifying the Carriers Migration Strategy to Ethernet," *DWDM & Metro Optical Net., Metro Ethernet Forum*, Cannes, France, 2004.

[19] C. Mas Machuca, O. Moe, and M. Jäger "Modeling of OpEx in Network and Service Life-Cycles," *ECOC*, Berlin, Sept. 2007.

[20] C. Mas Machuca, O. Moe, and M. Jäger, "Impact of the Protection Schemes and Network Component Availability on the Operation Expenditures," *OSA J. Optical Net.*, vol. 7, no. 2, Feb. 2008, pp. 142–50.

BIOGRAPHIES

JIAJIA CHEN (jiajiac@kth.se) received a B.S. degree in information engineering from Zhejiang University, Hangzhou, China, in 2004, and a Ph.D. degree from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2009. Currently, she is working as a post-doctoral researcher with the Next Generation Optical Networks (NeGONet) group, KTH. Her research interests include fiber access networks and switched optical networks.

CARMEN MAS MACHUCA [M] (cmas@tum.de) received a telecommunications engineering degree from the Universitat Politècnica de Catalunya (UPC), Spain, in 1995 and a Ph.D. degree from the Swiss Federal Institute of Technology (EPFL), Switzerland, in 2000. After working at Intracom S.A. as a project coordinator and at AIT-RESIT as an assistant professor, she joined the Institute for Communication Networks at Munich University of Technology (TUM) as a researcher and lecturer. Her interests are techno-economic studies, optical networks, and fault management, among others.

LENA WOSINSKA [M] (wosinska@kth.se) received her Ph.D. degree in photonics and Docent degree in optical networking from KTH. She joined KTH in 1986, where she is currently an associate professor in the School of Information and Communication Technology (ICT), heading a research group in optical networking (NeGONet), and coordinating a number of national and international scientific projects. Her research interests include optical network management, reliability and survivability of optical networks, photonics in switching, and fiber access networks. She has been involved in a number of professional activities including guest editorship of the following special issues that appeared in *OSA Journal of Optical Networking:* High Availability in Optical Networks; Photonics in Switching; Reliability Issues in Optical Networks; and Optical Networks for the Future Internet. Since 2007 she has been an Associate Editor of *OSA Journal of Optical Networking*, and since April 2009 she serves on the Editorial Board of *IEEE/OSA Journal of Optical Communications and Networking*. Since 2005 she is General Chair of the Workshop on Reliability Issues in Next Generation Optical Networks (RONEXT), which is a part of the IEEE International Conference on Transparent Optical Networks (ICTON). She serves on the Technical Program Committees of many international conferences.

MONIKA JAEGER [M] (monika.jaeger@t-systems.com) graduated in electrical engineering from TUM. She is a senior consultant and senior project leader in the Department of Network Architecture at T-Systems Enterprise Services GmbH. Her current research interests are in the areas of design and techno-economic studies of optical transport networks. She held previous positions as a research scientist with the Fraunhofer Institute for Open Communication Systems and DeTeWe.