Impact of OXC Failures on Network Reliability

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ABSTRACT
The paper studies the impact of OXC equipment failure on online end-to-end optical circuit provisioning in WDM networks. A selection of representative OXC architectures combined with different switching technologies is assessed with respect to their influence on network level reliability.

At the node level, the equipment reliability is calculated using proven component level reliability models that are tailored to represent the selected OXC architectures. At the network level, end-to-end optical circuits are provisioned using various levels of reliability, thus providing network Differentiated Reliability. The shared path protection (SPP) switching scheme is considered for best resource-efficient service provisioning. Simulation results are used to compare the selected OXC architectures in terms of both network blocking probability of incoming circuit requests and OXC cost.

Keywords: OXC reliability, online RWA problem

1. INTRODUCTION
Quality of Service awareness gained vital importance in service provisioning with the roll-out of applications imposing quality requirements on data transfer. Fulfilling these requirements necessitates also that the underlying networking technology be capable of offering end-to-end transport service at different reliability levels.

In order to meet end-to-end quality requirements the influence of all used network components on the service quality should be evaluated. Moreover, all this data should be included in the optimization process to determine network resource allocation for demands.

Apart from some pioneers (such as Hayashi et al.) previous work on optical network reliability addresses this issue exclusively with the assumption that failure probability of the equipment deployed at network nodes is negligible when compared to link failure probabilities. However, the existence of several possible Optical Cross-Connect (OXC) architectures combined with different switching technologies offers a wide range of reliability (and cost) options. This observation suggests that OXC choice may have distinct significance in different networking scenarios. Nevertheless, the knowledge accumulated throughout solving network level problems and that derived from designing switching equipment have not been unified so far, even though both fields share the same target: providing cost-effective solutions of adequate reliability.

Another shortcoming of existing research results is that until recently the emphasis was put on single failure scenarios, that is, the probability of network states in which more than one component is down was considered to be too small to be taken into consideration. As the number of components prone to failures increases in the network the validity of the single failure approach needs to be carefully examined and justified, even if in general it seems acceptable.

This paper aims at the investigation of OXC equipment failure on the end-to-end optical circuit provisioning in WDM networks. To achieve this a dynamic call admission scenario is considered, in which the topology and

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the capacity of the network including the switching equipment deployed at network nodes is considered to be given and known. Simulations can then be run where incoming calls arrive with specified reliability requirements, and a centralized decision mechanism is used for call admission. Decisions are made based on solving a Routing and Wavelength Assignment (RWA) problem adapting the Differentiated Reliability (DIR) approach.2

The novelty of the approach of our paper is that it combines node level and network level reliability calculations. At the node level, equipment reliability will be calculated using proven component level reliability models that are tailored to represent the deployed OXC architecture and technology. The result of node level reliability calculations is then plugged into the network level decision mechanism, thus the effect of node reliability on end-to-end service provisioning can be investigated.

By changing the architecture and the applied switching technology of OXC equipment deployed at nodes the advantages and drawbacks of different choices can be highlighted based on call blocking probability recorded during the simulations and cost of the tested OXC implementations. Thus conclusions can be drawn regarding favorable OXC choice in different networking scenarios.

2. NETWORK RELIABILITY

When modelling reliability one has to declare all the assumptions, as reliability analysis offers a wide set of tools and methods for evaluating system reliability, and different assumptions require significantly different approaches.

First of all, encapsulating a possibly detailed node level analysis into a single component we assumed that the network consists of atomic nodes and links that connect these nodes. All components can have two states: they are either operating or failed. We also assumed that the reliability characteristics of the components in the network are independent of each other and given in advance.

2.1. Reliability requirements

Reliability requirements may be specified basically from either the aspect of the operator or the aspect of the customer. We can also distinguish between probability-based requirements and failure state-based requirements, that is, either the asymptotic probability can be specified that a certain call request will not be disrupted by any failure combinations or a certain set of failure combinations can be specified (such as all single failures or all single or double failures) which the call request has to survive. Customers are more interested in the probabilistic specification, while operators might have multiple targets.

For the reliability requirements we applied the probability-based approach, thus the failure combinations to inspect can be derived from the specified probability. Even though there is increasing concern among operators to provide solutions that are robust in the presence of multiple simultaneous failures, restricting the set of failure situations to be inspected to single failures could be a feasible approach.

A strong argument supporting this decision is that the set of failure states of any network of practical size cannot be handled, because it is an exponential function of the number of components. Several reliability analysis techniques exist to decrease the set of states of interest to a tractable size, however, their application in an on-line call admission context is questionable due to the complexity they introduce.

Another strong argument supporting the single failure approach is that in case of single failure states there is no need to take into account dependence of failure probabilities of different components, which would greatly increase the difficulty of the necessary calculations.

These practical observations help decrease the complexity of the problem thus getting closer to a feasible solution. However, the applicability of these observations has to be carefully examined. Let graph \( G(V,E) \) represent the network, where \( V \) is the set of nodes and \( E \) is the set of edges, representing links. If \( P_f(e) \) is the asymptotic unavailability of link \( e \in E \), and \( P_f(v) \) is that of node \( v \in V \) in the network, then the probability that multiple components are failed is

\[
P_{mf} = 1 - \prod_{i \in C} (1 - P_f(i)) - \sum_{i \in C} P_f(i) \prod_{j \in C, j \neq i} (1 - P_f(j)), \tag{1}
\]

where \( C = E \cup V \) is the set of components prone to failures in the network.
If the set of inspected failure combinations is restricted to that of single failures, then the guaranteed survivability of a demand might be at the highest $1 - P_{m,f}^{E,V}$, provided that it was given the necessary resources to survive every possible single failure. Note that it is a worst case estimation, since a significant portion of possible multiple failures will not affect the set of resources allocated to the demand.

As a consequence, calculating $P_{m,f}^{E,V}$ gives important information about when the single-failure approach is applicable; in other words, when it is reasonable and necessary to deal with multiple failures.

If we restrict ourselves to single failure scenarios, however, the notion of conditional failure probability (CFP) might be used, which greatly simplifies failure calculations. The CFP of a component is the probability that the component is failed on the condition that a single failure has occurred in the network. The CFP of component $i$ in the network might be formally expressed as

$$P_{C}^{(i)}(j) = \frac{P_{f}(i) \prod_{j \in C, j \neq i} (1 - P_{f}(j))}{\sum_{k \in C} P_{f}(k) \prod_{j \in C, j \neq k} (1 - P_{f}(k))} = \frac{P_{f}(i)}{1 - P_{f}(i)}, i \in C,$$

where $C = E \cup V$ is the set of components prone to failures in the network.

Demand reliability requirements can also be easily converted to conditional failure probability. Let $D = \{(v_1, v_2) | v_1, v_2 \in V\}$ be the set of demands. Let $R_{f}(d)$ be the maximum allowed probability that demand $d \in D$ will not survive a failure in the network. If $R_{f}(d) \geq P_{C}^{C}$ then the maximum allowed conditional failure probability of demand $d$ is expressed as

$$R_{C}^{C}(d) = \frac{R_{f}(d) - P_{m,f}^{C}}{\sum_{i \in C} P_{f}(i) \prod_{j \in C, j \neq i} (1 - P_{f}(j))}.$$

### 2.2. Differentiated Reliability for single link failures

Provided that we have a network together with an appropriate description of its reliability characteristics, the next problem is then to decide how to allocate resources for incoming call requests between source and destination nodes so that the service meets certain reliability requirements and resources are used in an economical way. This involves finding unoccupied or reusable wavelengths along routes between the source and destination nodes of the given call request, and rejecting the call request (often termed as demand) if the reliability requirements cannot be met. If the call request is accepted, it is assigned one or more wavelengths on each link along one or more paths between its source and destination nodes. A wavelength on a link can be considered as a transport channel, and the concatenation of these channels is called a lightpath.

The problem of determining the necessary lightpaths is called the Routing and Wavelength Assignment (RWA) problem, and has already been in the focus of attention of researchers for a long time. Various constraints can be introduced such as the availability of wavelength converters, or the type of the resilience mechanism applied, which lead to different instances of the problem that require different solutions.

We restrict our investigation to networks where wavelength converters are not available, that is, a lightpath must be assigned the same wavelength on all the links it traverses.

When solving the RWA problem outlined above, depending on the reliability requirements one may find that assigning resources along a single path to a call request is not enough to meet the specified reliability threshold. Then arrangements must be made to ensure that if a failure occurs along this path there will be additional resources available so that the demand will be served with at least the specified reliability.

The possible arrangements to provide resilience are various and they range from pure protection (to assign backup resources to demands before letting them into the network) to pure restoration (to begin to seek for resources for demands only after a failure disrupts them). The selected resource allocation method is an efficient improvement over the Shared Path Protection (SPP) approach, which has long been used in optical networks. In what follows we address the problem of single link failures first.

The basic idea of SPP is that the demand is assigned two disjunct lightpaths: a working lightpath and a protection lightpath. If any of the links used by the working lightpath are failed, the communication is switched
to the protection lightpath. However, the resources allocated for protection lightpaths might be shared among multiple demands, provided that their working lightpaths do not use common resources, so the shared protection resources may only be needed for the protection of one demand at any time. Note that this way the demands will survive any single link failure, even though they do not need that much reliability.

The idea of Differentiated Reliability (DIR) might be applied with any kind of protection mechanism, however, we will stick to the improvement of SPP in our discussion here. The basic notion of DIR is to provide only the desired level of protection for demands, which will eventually lead to more efficient resource usage. The extent of resource sharing might be increased if demands do not require protection against every single link failure along their working lightpath. In this case the failure of some of the links of the working lightpath might not trigger switching to the protection lightpath, whose resources might be used by another demand whose working lightpath also traverses the failed link but it requires protection against this link failure.

Let us introduce the notation $H_w(d) \subset E$ and $H_p(d) \subset E$ for the set of links used by the working lightpath and the protection lightpath of demand $d \in D$, respectively. Thus $H_w(d) \cap H_p(d)$ must hold true for any demand $d$. Let $U(d) \subseteq H_w(d)$ be the set of unprotected links along the working lightpath of demand $d$. Then $P_{cf}^E(d)$, the conditional failure probability of demand $d \in D$ in case of single edge failures can be calculated using the conditional failure probabilities as

$$P_{cf}^E(d) = \sum_{e \in U(d)} P_{cf}^E(e) \leq R_{cf}^E(d),$$

(4)

where $P_{cf}^E(e)$ and $R_{cf}^E(d)$ are obtained by substituting $C = E$ in formulas (2) and (3), respectively. The inequality of (4) must hold true to meet the reliability requirements of demand $d$. Sharing of resources between the protection lightpaths of demands $d_1$ and $d_2$ is possible as long as

$$(H_w(d_1) \cap H_w(d_2)) \subseteq (U(d_1) \cup U(d_2))$$

remains true. Note that in case of SPP $U(d) \equiv \emptyset$ for any demand $d$. Also note that $R_{cf}^E(d)$ might be as low as zero, that is, the demands might request to be protected against every single link failure.

2.3. Introduction of node failures

The possibility of node failures, however, changes the idealistic situation described in the previous section. The introduction of node failures requires more than the mere extension of the set of components to be taken into account. If nodes are imperfect then demand $d = (v_1, v_2)$ cannot survive the failures of its source and destination nodes, $v_1$ and $v_2$, which means that $R_{cf}^{E \cup V}(d)$ cannot be zero, as opposed to $R_{cf}^E(d)$. Therefore, no protection is necessary against the failures of the end nodes. As a consequence, resource sharing might be improved, because end nodes should not be taken into account when common resource usage is determined.

To extend the formulas to node failures we introduce the following additional notation. Let $H'_w(d)$ and $H'_p(d)$ be the set of intermediary nodes* along the working lightpath and the protection lightpath of demand $d$, respectively. Let $U'(d)$ be the set of unprotected intermediary nodes of the working lightpath of demand $d$.

Using these extensions $P_{cf}^{E \cup V}(d)$, the conditional failure probability of demand $d = (v_1, v_2) \in D$ in case of any single failures can be calculated using the conditional failure probabilities as

$$P_{cf}^C(d) = \sum_{e \in U(d)} P_{cf}^C(e) + \sum_{v \in U'(d)} P_{cf}^C(v) + P_{cf}^C(v_1) + P_{cf}^C(v_2) \leq R_{cf}^C(d),$$

(6)

where $C = E \cup V$.

Additionally, resource sharing between the protection lightpaths of demands $d_1$ and $d_2$ must meet not only condition (5), but also

$$(H'_w(d_1) \cap H'_w(d_2)) \subseteq (U'(d_1) \cup U'(d_2)).$$

(7)

*The set of intermediary nodes excludes the end nodes of the path.
3. NODE RELIABILITY

3.1. Switching component technologies

Optical switches can be classified into two categories: solid state (or integrated optic) and free-space. There are also a number of materials that switches can be made of (e.g., lithium niobate, indium phosphide, silicon, etc). Switch performance is then dependent on the component technology. For a certain application one have to consider the required switching speed, crosstalk, insertion loss and so on as well as reliability and price.

Integrated optical switch matrices are typically characterized by small number of input/output ports. Therefore, building large switching systems based on the integrated optic switches appears uncertain. However, for smaller switches, up to 8x8, they could be a viable alternative. Semiconductor optical amplifier based switches offer loss compensation and high extinction ratio but they have the problems of the amplifier noise accumulation and ring lasing in a WDM network.

The most promising free-space switches are known as Micro-Opto-Electro-Mechanical Systems (MOEMS) Optical MEMS. These switches are characterized by a lower switching speed (typically a few seconds) than integrated optical switches. However, MOEMS matrices with switching time of 100 ms have been reported. For a MOEMS matrix, the port-to-port interconnect is internal to the switch (free space), which offers the good performance, reliability, size, and cost.

MOEMS switches are based upon well-understood silicon planar technology. Two types of MOEMS switches were considered: sliding or pop-up vertical mirrors and planar tilt mirrors, both on a silicon optical bench. Fundamental to the successful operation of the tilt mirror matrix type, as well as a feature of these tilt mirrors is a servo controlled tilt adjustment that minimizes the insertion loss (maximizes power transfer), thus, compensating for spatial drift due to thermal expansion, creep, or other such phenomenon. The reliability of these components is greatly enhanced by the inclusion of servo control.

In this paper, the choice of an optical switch component was made based upon the basic requirements of -45 dB crosstalk, -50 dB return loss and minimum insertion loss. Moreover, in contrast to a packet switch, for crosses connect the switching time is not a very critical parameter. Therefore, the MOEMS technology, which offers a good reliability performance and relatively low price is widely considered for the OXC application. In this paper two switching component technologies are considered, i.e., the planar tilt mirror type MOEMS and semiconductor optical amplifier based (indium phosphide) technology.

The planar tilt mirror type MOEMS switch was selected here because of their superior properties, high reliability and relatively low price. Indium phosphide technology on the other hand offers high switching speed, low insertion loss and high extinction ratio but it suffers from extremely high price and poor reliability performance.

3.2. Node architectures

We consider a representative internally non-blocking node architecture (see node architecture A shown in Figure 1) with N input and output fibers and four wavelength channels carried on each fiber to fit our network model. N corresponds to the node degree, which varies from 2 to 7 in the network example studied in Section 4. We have selected this node architecture due to its low complexity, which allows for high reliability and relatively low price.

In order to improve node reliability and provide additional functionality to the node an inherent redundancy was proposed. The modified node architecture (node architecture B) is illustrated in Figure 2. An optical tap is used to split the signals prior to wavelength demultiplexing. One part of the signal enters an optical space switch that serves as the primary switch core. The tapped portion is connected to a tunable receiver at the protection switch and switched to appropriate tunable transmitter by the electronic cross-point switch (when necessary). The switched wavelength channels are recombined by WDM’s to the output fibers. In the case of the failure of one N x N switch matrix, the appropriate wavelength channels are guided through the protection circuit and added to the output links by the optical couplers.
Figure 1. Node architecture A (without redundancy).

Figure 2. Node architecture B (with 1:4 redundancy).
3.3. Node level reliability model

Wosinska et al.\textsuperscript{7} propose a component-based approach for node reliability calculations. They assumed that all equipment is composed of independent components that have two states: they are either operating or failed, and the whole equipment is also assumed to have only these two states. This node reliability model is in compliance with the requirements of the model proposed in Section 2.

Applying the basic principles of reliability performance evaluation reliability block diagrams can be constructed based on the node architecture and functionality. These diagrams reflect the importance of the different elementary components such as splitters, transmitters, receivers etc. for the entire node reliability.

Reliability measures are then assigned to the individual components of these block diagrams, which can either be based on measurements or statistics. Based on these component level data eventually system level, or in our case node level reliability measures may be derived from the interconnections represented by the block diagram by decomposing the system to some well-known configurations (such as the series, parallel or k-out-of-n configuration) and then applying the properties of these configurations. The derived node level reliability measures include the asymptotic availability and unavailability; the former is defined as the probability that the system (or component) is operating at any time, while the latter is the complementary probability.

Equipment reliability is strongly influenced by complexity. Besides the applied technologies and the redundancy of the architecture complexity of OXC’s depends on the switching capacity. Throughout our reliability calculations and the traffic simulations later to be discussed, we assumed that each link had a capacity of four wavelengths, which thus determined the necessary switching capacity: each OXC had to support four wavelengths on all of its interfaces.

Table\textsuperscript{1} presents our node level reliability results expressed by asymptotic node unavailability, i.e., the probability that node is failed, and mean downtime per year. Our calculations are based on the component reliability figures already presented\textsuperscript{7,6} . When calculating the reliability characteristics, the mean repair time was assumed to be 6 h.

<table>
<thead>
<tr>
<th>Node arch./technology/NxN</th>
<th>Unavailability [s x 10^{-6}]</th>
<th>Mean downtime/year [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/ indium phosphide / 2x2</td>
<td>194.0</td>
<td>1.680</td>
</tr>
<tr>
<td>A/ indium phosphide / 4x4</td>
<td>581.0</td>
<td>5.018</td>
</tr>
<tr>
<td>A/ indium phosphide / 7x7</td>
<td>1886.0</td>
<td>16.298</td>
</tr>
<tr>
<td>A/ indium phosphide / 8x8</td>
<td>1930.0</td>
<td>16.672</td>
</tr>
<tr>
<td>A/ MOEMS / 2x2</td>
<td>26.4</td>
<td>0.228</td>
</tr>
<tr>
<td>A/ MOEMS / 4x4</td>
<td>28.8</td>
<td>0.249</td>
</tr>
<tr>
<td>A/ MOEMS / 7x7</td>
<td>32.4</td>
<td>0.280</td>
</tr>
<tr>
<td>A/ MOEMS / 8x8</td>
<td>33.6</td>
<td>0.290</td>
</tr>
<tr>
<td>B/ indium phosphide / 2x2</td>
<td>2.4</td>
<td>0.021</td>
</tr>
<tr>
<td>B/ indium phosphide / 4x4</td>
<td>5.0</td>
<td>0.043</td>
</tr>
<tr>
<td>B/ indium phosphide / 7x7</td>
<td>10.6</td>
<td>0.091</td>
</tr>
<tr>
<td>B/ indium phosphide / 8x8</td>
<td>11.9</td>
<td>0.103</td>
</tr>
<tr>
<td>B/ MOEMS / 2x2</td>
<td>2.4</td>
<td>0.021</td>
</tr>
<tr>
<td>B/ MOEMS / 4x4</td>
<td>4.8</td>
<td>0.041</td>
</tr>
<tr>
<td>B/ MOEMS / 7x7</td>
<td>8.4</td>
<td>0.073</td>
</tr>
<tr>
<td>B/ MOEMS / 8x8</td>
<td>9.6</td>
<td>0.083</td>
</tr>
</tbody>
</table>
Figure 3. Probability that a link is failed as a function of the link span length. Note that a loglog scale is used.

4. STUDY OF A DYNAMIC TRAFFIC SCENARIO

In what follows we demonstrate the influence of OXC failures on end-to-end reliability by applying the proposed model in a dynamic call admission control scenario in WDM networks without wavelength converters.

4.1. Networking scenarios

Several different networking scenarios could be envisioned where WDM networks are a feasible option, or are operating already in place. These networks might be grouped based on various criteria. In this paper the size of the covered area was selected for categorization as it has a direct effect on the length of cable spans, which, as discussed later on, has important consequences on link reliability characteristics.

The paper addresses three basic scenarios distinguished by network size. The first one is that of networks of continental size, which serve many countries in a certain region. As an example a European WDM network was chosen. This network has 19 nodes, and its node degrees vary from 2 to 7. The network has 39 links with an average link length of 621.1 km. The second category of interest is that of national networks, which are represented by the European network data with the distances divided by 5. Finally, the last category includes metropolitan area networks, represented by the European network data with the distances divided by 50.

4.2. Reliability characteristics of components

The asymptotic unavailability of each component has to be determined in order for the proposed model to be applied. The output of the method described in Section 3.3, which considers the full structure of the equipment deployed at the node, gives the unavailability for the whole node. In case of links, however, the asymptotic unavailability is expressed as the Down Time Ratio (DTR) using the formula

$$DTR = \frac{hxy}{1 + hxy},$$

where $x$, $y$, and $h$ are the failure rate of a cable span of unit length, the mean repair time and the length of the cable span, respectively. Note that the failure rate is considered to be directly proportional with the length of the cable span, while the mean repair time is independent of it. Based on statistical data $4 * 10^{-6}$ is a reasonable estimation for the DTR of a cable of 1 km.

Figure 3 demonstrates that when link spans get in the tens to hundreds of kilometers range the failure probability of links and that of node equipment will be close to each other. Under this range network failures
will be predominantly due to node failures, while beyond this range links will most probably determine the reliability of the network.

4.3. Validation of the single-failure approach

Having obtained the reliability characteristics of the components it is possible to verify the guarantees that could be obtained by applying the single-failure approach detailed above. To illustrate this Table 2 shows some representative values of $P_{m_j}^{EUV}$ for each of the networks to be examined.

<table>
<thead>
<tr>
<th>Network size</th>
<th>Most reliable node equipment</th>
<th>Least reliable node equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>European</td>
<td>0.0173809</td>
<td>0.0206922</td>
</tr>
<tr>
<td>National</td>
<td>0.0007777775</td>
<td>0.00168889</td>
</tr>
<tr>
<td>MAN</td>
<td>0.00000836593</td>
<td>0.000258563</td>
</tr>
</tbody>
</table>

Based on Table 2 we can conclude that in case of networks of continental size the probability that more than one network component is failed is significant, no matter how reliable the applied node equipment is. This justifies the multiple failure approach in case of networks of this size. However, for MANs node equipment has a strong impact on the probability of multiple failure scenarios, and applying reliable node equipment leads to a situation where the single failure approach is effective, and will probably give satisfactory results. As to national networks, the applicability of the single failure approach has to be evaluated on a case-by-case basis.\(^1\)

4.4. Simulation

In order to assess the effect of OXC failures on end-to-end reliability by simulation the described centralized decision mechanism has been implemented. The basis of the implementation was a simulator which was designed for investigating the efficiency of the SPP-Dir method in a dynamic scenario considering single link failures only.\(^2\)

The simulation takes the network configuration, the $\lambda$ call generation rate and the $R_f$ reliability requirement of calls as the input and it generates random calls in the network. The interarrival time of calls is of exponential distribution with a parameter $\lambda$, while source and destination nodes are selected uniformly. The reliability requirement is considered to be the same for all calls to ease comparison. The established connections release resources after a time of exponential distribution with a parameter $\mu = 1$. A single-slot central buffer is used to ensure fairness, and calls wait in this buffer until enough resources are freed in the network to serve them. If the single slot is already occupied call requests are rejected.

Economical resource allocation for calls is done by running an optimization process based on Simulated Annealing (SA). The discussion of near-optimal path selection subject to the discussed constraints is out of the scope of this paper, however, for the sake of completeness we include the definition of the cost function for the optimization of the resource allocation for demand $d$, which is

$$\text{cost}(d) = \frac{|H_w(d)| + |H'_w(d)|}{2} + \frac{|H_p(d)| - |U(d)| + |H'_p(d)| - |U'(d)|}{2} + P_{c_f}^{EUV}(d) - R_{c_f}^{EUV}(d).$$

(9)

For other details regarding the optimization the reader is referred to Tacca et al.\(^2\)

The number of rejected and total call requests are recorded, and the ratio of the two gives the call blocking probability, which has been used to point out the difference between the performance of different network configurations.

\(^1\)Note that the detailed approach is always applicable, however, in the outlined scenarios the expected results will be significantly different.
Figure 4. Blocking probabilities for different reliability requirements in a network of national scale as a function of offered network load. (a) $R_f \equiv 0.05$ (b) $R_f \equiv 0.01$ (c) $R_f \equiv 0.005$ (d) $R_f \equiv 0.001$

To properly address the statistical evaluation of the blocking probability observations the statistical module of the ATM Networks Call Level Simulator (ANCLES) has been used. The results presented are the confidence intervals for a confidence level 0.95 with an accuracy of 10%.

5. DISCUSSION OF RESULTS

As predicted, equipment choice has indeed different influence on the expectable blocking probability depending on the reliability requirements. Figures 4(a)-4(d) demonstrate this over the national scale. In case of the least stringent reliability requirement (see Figure 4(a)) the necessary node architecture and switching technology might be selected based on other considerations (such as cost or switching speed). However, increasing the reliability requirement, that is, decreasing $R_f$, means a drawback for the less reliable InP-based switching technology applied without redundancy, demonstrated by the gaps between the curves on Figure 4(b) and 4(c). The results for the most stringent reliability requirement, depicted on Figure 4(d), on the other hand, show a similar situation to that of the low reliability case, except that due to protection, which was not necessary in the low reliability case, the capacity of the network becomes more restrictive, thus blocking probability will increase at the same load.

Compared to the already discussed set of results Figures 5(a)-5(d) demonstrate how the feasible ranges of blocking probability versus reliability change over different network scales. On the continental scale (Figure 5(a)) the reliability of node equipment has a minor impact on the achievable reliability guarantee, because link unavailabilities become extremely high, as it was already pointed out in Table 2. As opposed to this, moving to the metropolitan scale means links of greater availability, which in turn leads to improvements in the achievable overall reliability. Nevertheless, similar conclusions can be drawn from the simulation results obtained with a metropolitan network (Figures 5(b)-5(d)) to the ones already mentioned when discussing the national network.
Figure 5. Blocking probabilities for different reliability requirements in networks of continental and metropolitan scale as a function of offered network load. (a) European network, \( R_f \equiv 0.05 \) (b) MAN, \( R_f \equiv 0.001 \) (c) MAN, \( R_f \equiv 0.0005 \) (d) MAN, \( R_f \equiv 0.0001 \)

Note that on Figures 4(d) and 5(d) the results for the InP-based technology with the non-redundant architecture are missing, as \( P_{K_0}^{R_f} \) was higher than \( R_f \), consequently the reliability requirements could not be guaranteed with the single failure approach.

Another interesting conclusion could be drawn from the results by taking note of the fact that all of the curves stay in a certain area on the plots. The upper limits of this area could be seen e.g. on Figure 5(d), while the lower limits are clearly visible e.g. on Figure 5(a). The extension of this area is probably a function of the network topology, while its boundaries are determined by the capacity of the network, as the best blocking is available when the resource utilization is the lowest, that is, when no protection is necessary, and, conversely, the worst blocking could be expected when resource sharing is highly limited because of the need for total protection. This observation motivates new research directions aiming at the characterization of network capacity from the reliability perspective.

6. CONCLUSION

The paper investigated the effect of OXC equipment choice on end-to-end reliability of connections in WDM networks without wavelength conversion. A reliability model was introduced that unifies the results of research carried out on optical component and equipment reliability and on Routing and Wavelength Assignment optimization.

The use of node architectures with and without redundancy using two representative switching technologies was simulated in optical networks of continental, national and metropolitan scale. The results based on realistic reliability characteristics of the examined components provide guidelines when node equipment choice is important from the reliability point of view. The limits of the applicability of reliable connection provisioning based only on single failure scenarios were also demonstrated.
The findings may serve as a motivation for research on reliable connection provisioning considering multiple failure scenarios, and also on network capacity characterization as a function of reliability requirements.

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