Service Fairness in Flexible Optical Networks

Franco Callegati\textsuperscript{1}, Luiz Henrique Bonani\textsuperscript{2}, Walter Cerroni\textsuperscript{1}
\textsuperscript{1}DEI - University of Bologna, Cesena, Italy – \textsuperscript{2}CECS - Universidade Federal do ABC, Santo André, Brasil
\{franco.callegati,walter.cerroni\}@unibo.it - luiz.bonani@ufabc.edu.br

Abstract: This paper investigates quality of service fairness in grid-less, multi-rate optical networks. By means of analytical modeling and simulation, results show that unfairness arises in absence of suitable control and that trunk reservation policies may solve the issue.

© 2012 Optical Society of America
OCIS codes: 060.4230, 060.4250.

1. Introduction

Elastic and flexible optical networks represent today a topic of great interest to the optical communication research community [1]. Unfortunately, the improved flexibility they provide does not come for free and problems of quality of service (QoS) management must be considered. Significant work has been reported already on test-bed demonstrations regarding the feasibility of the gridless multi-rate approach [2], [3], but less effort has been devoted to the analysis of the related logical performance.

In particular, fairness in resource usage and call blocking probability is a well-known issue when multi-rate networks are considered. In this paper we address this issue by using known analytical results, showing that the degree of unfairness may be quite high, especially when spectrum defragmentation techniques are not used. Then we show an example of solution, exploiting tools which were developed in the past for multi-service integrated digital networks [4].

2. Evaluation of call blocking in multi-rate optical networks

The scenario considered in this manuscript assumes a number $N$ of different communication services operating at different data rates and sharing a given optical link. Calls requesting channel set-up are accepted in the system according to a \emph{complete sharing policy}, i.e., a call is accepted if and only if there is enough free capacity to serve it. For the time being, let us also assume that an \emph{ideal spectrum defragmentation policy} is used in the system, meaning that existing calls are packed in such a way that all the available spectrum is grouped in a single “slice” and can be flexibly allocated to new calls. This is an ideal condition which provides optimal performance results. We will address the more realistic case of \emph{spectrum fragmentation} later in the manuscript.

Let us assume that the total fiber/path spectrum capacity is $C$. Customers of type $i \in \{1 : N\}$ send call set-up requests following a Poisson arrival process with average rate $\lambda_i$, average holding time $1/\mu_i$ and fixed bandwidth demand $c_i$.\footnote{For the sake of simplicity, in the notation we assume this is the capacity which the system must reserve for the call, including any guard bands and/or overhead, if needed.}

They also adopt a modulation format which allows to carry $b_i$ bits per seconds on the demanded bandwidth. This results in a spectral efficiency given by $\nu_i = \frac{b_i}{c_i}$ bit/s/Hz.

Under these assumptions the system can be described as a multi-dimensional Markov chain with state vector $k = (k_1, k_2, \ldots, k_N)$, where $k_i$ is the number of currently active channels of type $i$. Let us also assume that $c = (c_1, c_2, \ldots, c_N)$ is the vector of the bandwidth demands and $b = (b_1, b_2, \ldots, b_N)$ the vector of the related bit rates. Moreover, let $e_i = (0, 0, \ldots, 0, 1, 0, \ldots, 0)$ be the $i$-th unit vector of the standard basis for an $N$-dimensional Euclidean space.

If $\mathcal{S}_0 = (\mathbb{N}_0)^N$ is the $N$-dimensional space of non-negative integers, the system state $k$ can take values in a subset $\mathcal{S} \subset \mathcal{S}_0$ such that

$$\mathcal{S} = \{k \in \mathcal{S}_0 : k \cdot c^T = \prod_{i=1}^{N} k_i c_i \leq C\}$$

In general $\mathcal{S}$ is called a \emph{truncated state space} and the steady state probabilities of the system can be calculated with

\begin{equation}
\end{equation}
the product formula [4]

\[
P_k = \begin{cases} 
G(\mathcal{S})^{-1} \prod_{i}^{N} \frac{A_{0i}^{k_i}}{k_i!} & \text{if } k \in \mathcal{S} \\
0 & \text{if } k \notin \mathcal{S}
\end{cases}
\]

(2)

\[A_{0i} = \frac{\lambda_i}{\mu_i}\]

is the traffic offered by type-\(i\) customers. If we define \(G(\mathcal{S})\) with an expression similar to the one used in (2), but this time summing over the blocking states for type-\(i\) customers only, i.e., over the subset \(\mathcal{S}^+\) of blocking states:

\[\mathcal{S}^+ = \{k \in \mathcal{S} : k + e_i \notin \mathcal{S}\}\]

then it is possible to demonstrate that the blocking probability for traffic type \(i\) is given by [4]

\[\pi_{pi} = \frac{G(\mathcal{S}^+)}{G(\mathcal{S})}\]

(4)

### 3. Unfairness in multi-rate optical networks

In this work we assume that the optical link may carry channels related to the set of transport services summarized in Table 1. These values include also the bandwidth slices considered in [2] and [3].

Table 1. Summary of the characteristics of the different services

<table>
<thead>
<tr>
<th>Type</th>
<th>(c_i) (GHz)</th>
<th>(b_i) (Gb/s)</th>
<th>(v_i) (bit/s/Hz)</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650</td>
<td>555</td>
<td>0.85</td>
<td>NRZ</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>100</td>
<td>2</td>
<td>DP-QSK</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>40</td>
<td>0.4</td>
<td>OOK NRZ</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>40</td>
<td>0.27</td>
<td>OOK RZ</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>10</td>
<td>0.4</td>
<td>NRZ</td>
</tr>
</tbody>
</table>

In the following we consider the so-called normalized offered traffic, defined as \(a_i = \frac{A_{0i}}{\bar{\rho}}\), which measures the overall percentage of the total available bandwidth that is requested on average by type-\(i\) service. To allow a good direct comparison of the results presented, we assume an equal share of the overall bandwidth demand among the different services, which means that \(a_i\) has the same value for all of them. Therefore, when a link with utilization \(\bar{\rho} = 80\%\) is considered, this implies that with \(N\) different service types the normalized offered traffic for each of them is \(a_i = \frac{\bar{\rho}}{N}\) \(\forall i\) and the type-\(i\) offered traffic is \(A_{0i} = \frac{\bar{\rho}}{N} c_i\).

![Fig. 1. Call blocking probability (a) and utilization (b) for the different service types assuming ideal spectrum defragmentation; impact of spectrum fragmentation for service types 1 and 5 (c).](image)

Figures 1(a) and 1(b) show the results of the application of the model. These results have been validated with an optical network simulator built ad hoc, which provided curves perfectly matching the analysis. This was expected, since the analytical model is exact. The graphs clearly show a significant unfairness in call blocking and link utilization.
In particular, the less bandwidth-demanding services have a significant advantage, resulting in a quite small blocking probability even at high loads. This is intuitively understandable, since in some cases the bandwidth available on the link is not enough to accept calls from more demanding services, whereas it is sufficient to accommodate calls from less demanding ones.

Results shown previously assume an ideal spectrum defragmentation, which is not likely to be fully implementable in practice. If no spectrum reallocation is possible, fragmentation will also arise as a consequence of calls ending and leaving "voids" of unused capacity in the overall link spectrum. This should further increase the unfairness. Figure 1(c) reports the blocking probability for the highest and lowest bandwidth-demanding services comparing the case of spectrum fragmentation with the case of a first-fit bandwidth reallocation algorithm. These results were obtained by simulation only, since an analytical model is not available for the former case. As expected, fragmentation causes the unfairness to worsen, with an increase in call blocking for the highest bandwidth-demanding service and a decrease for the lowest one, due to the increased availability of smaller spectrum slices.

4. A possible countermeasure

A possible countermeasure to the problem outlined above is to use bandwidth reservation strategies to improve the fairness. One of the most effective is the so-called trunk reservation. The simplest implementation of trunk reservation sets a threshold on the currently used bandwidth to accept a new call. Here we follow [4] and set the threshold \( \sigma \) according to the maximum bandwidth demand, i.e., \( \sigma = C - \max_{i \in \{1, N\}} \{c_i\} \). This means that a new call of type \( i \) is accepted only if there is enough bandwidth and the total already used bandwidth is strictly less than the threshold, i.e.

\[
 k \cdot c^T + e_i \cdot c^T \leq C \quad \text{and} \quad k \cdot c^T < \sigma
\]

Simulation results obtained with this approach are shown in Fig. 2, assuming ideal spectrum defragmentation. The call blocking rate and the link utilization are equalized, providing some improvement to the more bandwidth-demanding services at some cost for the less demanding ones. Here we show only the curves for the highest and lowest bandwidth services for the sake of readability, but the simulation was run with all the 5 service types.

![Fig. 2. Call blocking probability and utilization with (D+TR) and without (D) trunk reservation.](image)

5. Conclusion

We have shown that a high degree of unfairness in call blocking and link utilization may arise in multi-rate gridless optical networks and proposed to cope with it by means of trunk reservation techniques. The trunk reservation technique presented here is a first step solution. More refined techniques, to minimize bandwidth fragmentation while controlling the QoS fairness are currently under investigation and will be subject of future works.

References