Traffic Grooming and Spectrum Assignment for Coherent Transceivers in Metro-Flexible Networks

Cristina Rottondi, Massimo Tornatore, Achille Pattavina, and Giancarlo Gavioli

Abstract—Novel distance-adaptive optical transmission technologies have been proposed to boost transceiver datarates and to enable more flexibility in the allocation of traffic flows. The application of this new class of transceivers is being widely investigated in core networks, while their suitability in the metro area is still an open issue. On one hand, the short metro distances enable the utilization of higher spectrally efficient modulation formats, on the other hand, the lower bitrate suggests to employ lower baud rate with respect to core networks. In this letter, we perform traffic grooming and spectrum assignment using transceivers with fixed baud rate of 28 and 14 Gbd and distance-adaptive modulation formats in optical metro networks. Comparisons with the wavelength-division multiplexing systems running over a fixed grid show that 1) significant savings in terms of spectrum occupation can be achieved, and that 2) such savings can be effectively achieved also using lower baud rate transceivers (e.g., 14 Gbd).

Index Terms—Metro network, optical coherent transmission, ring network, traffic grooming.

I. INTRODUCTION

The METRO network conveys the traffic generated by the access segment of the telecom network to the backbone portion. Its extension normally ranges from tens to hundreds of kilometers and it is traditionally based on well-known technologies such as SONET/SDH, Metro Ethernet and Resilient Packet Ring (RPR).

In the last decades, the sharp increase of metro traffic demand has been accommodated thanks to the introduction of wavelength-division multiplexing (WDM) technology. Currently, WDM technology standards [1] define a division of the fiber spectrum in channels with fixed 50 GHz or 100 GHz bandwidth. Inside these channels, signals are transmitted using transceivers at fixed rate (typically 10, 40 or 100 Gbps).

The recent development of innovative transmission technologies based on optical coherent detection and digital signal processing is paving the road towards software defined transceivers [2] which adapt their modulation format according to the reach to be covered and/or to the amount of traffic to be transmitted [3]. The introduction of finer-grained frequency slots (e.g., 6.25 or 12.5 GHz, as suggested in [4]) is expected to increase spectrum utilization, by reducing/eliminating unnecessary guard bands and by flexibly adapting the spectrum allocation to the traffic demand (flexible grid).

In our previous paper [5], we have analyzed the benefits achieved by the introduction of such elastic transceivers in metro networks in terms of spectral occupation and discussed the impact of having distance-adaptive modulation techniques and reconfigurable baud rate. Here, we expand our analysis to consider the following novel assumptions:

1) we consider coherent transceivers with fixed (specifically 28 and 14 Gbd) baud rates;
2) we consider a flexible spectrum grid with granularity of 12.5 and 6.25 GHz, according to [4];
3) we consider the possibility of fitting such transceivers in channels with bandwidth of 18.75 GHz, 25, 31.25, 37.5, or 50 GHz, in order to identify the most effective trade-off between spectral efficiency and reach;
4) we consider/model the formation of superchannels [7].

Under these new assumptions, we perform traffic grooming and spectrum assignment for a set of given traffic demands and we investigate if, in a metro network operating with narrow flexible grid, lower baud rate transceivers can provide a more effective spectrum utilization.

The remainder of the letter is as follows: Section 2 describes the metro network architecture and the design problem we address. Numerical results are discussed in Section 3, while Section 4 concludes the letter.

II. NETWORK ARCHITECTURE AND MODEL

1) Network Topology, Spectrum Grid, Transceiver Model: In our work, the metro network physical topology is modeled as a bidirectional ring network with N nodes and 2N fiber links divided in a grid of frequency slots having M GHz slot width. Each node is equipped with coherent transceivers which can support multiple modulation formats, but using a fixed baud rate B. Given a transceiver with baud rate B, the corresponding channel bandwidth or spectrum occupancy F (i.e., the exact quantity of spectrum to be reserved to serve the signal emitted by the transceiver) is evaluated on a flexible grid as an integer multiple k of the slot width M, such that $F = k \cdot M \geq B$.

Note that increasing the ratio $B/F$ between the baud rate and the channel bandwidth of a transceiver leads, on one hand, to higher spectrum efficiency but, on the other hand, to additional crosstalk due to adjacent channel coherent interference and thus reduces the maximum transmission reach, especially for odd multiples of 6.25 GHz requires optical carriers to be placed on a grid of 3.125 GHz granularity.
TABLE I
REACH VALUES FOR VARIOUS MODULATION FORMATS (km)
AND FOR 28- AND 14-GBD TRANSCEIVERS

<table>
<thead>
<tr>
<th>B (GHz)</th>
<th>F (GHz)</th>
<th>B/F</th>
<th>8-QAM</th>
<th>16-QAM</th>
<th>32-QAM</th>
<th>64-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>31.25</td>
<td>≈0.9</td>
<td>1010</td>
<td>495</td>
<td>198</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>37.5</td>
<td>≈0.75</td>
<td>1140</td>
<td>540</td>
<td>205</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.56</td>
<td>1400</td>
<td>630</td>
<td>220</td>
<td>150</td>
</tr>
<tr>
<td>14</td>
<td>18.75</td>
<td>≈0.75</td>
<td>2100</td>
<td>1100</td>
<td>400</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.56</td>
<td>2400</td>
<td>1200</td>
<td>440</td>
<td>310</td>
</tr>
</tbody>
</table>

Fig. 1. Spectrum assignment with flexible grid.

modulation formats with higher spectral efficiency. The trade-off between spectrum occupancy and transmission reach for an optical signal is investigated in the following subsection. We note that, for the sake of clarity, the basic frequency slot sets also the granularity of the filters, i.e. the minimum step of tunability of the filters.

2) Reach: The calculation of the signal reach according to the modulation format depends on different factors, as fiber type, Amplified Spontaneous Emission noise (ASE) and fiber non-linearities, chromatic dispersion and crosstalk impairments. Here, the maximum reaches for the different modulation formats (8/16/32/64-QAM) are calculated extending the analysis in [6] and are reported in Table I. Note that, for equivalent B/F ratio (e.g., 14/25 = 28/50) the reach of a 14 GBD transceiver is longer.

3) Grooming: Traffic grooming means digital-multiplexing a set of low-speed connection requests onto high-capacity optical channels. The flexible grid promises to improve the efficiency of traffic grooming, by allowing us to serve the groomed traffic with a suitable optical channel bandwidth.

4) Superchannels: When the capacity C = ηB (where η is the spectral efficiency of the modulation format in use) of a single wavelength is not large enough to support the whole groomed traffic between two nodes, the traffic can still be mapped over a single channel formed by multiple spectrally-adjacent optical signals or “carriers” with channel bandwidth defined by F, and generated by different transceivers. This set of channels is referred to as “superchannel” and is handled by the optical nodes as a single channel (see Fig. 1). Note also that in the case of a superchannel, the spectral occupancy of a superchannel is given by nF, where n is the number of carriers of the superchannel. To enable channel selection at the receiver, the superchannels (and in general any adjacent optical paths) have to be separated by a guard band G, expressed as a multiple of the grid granularity.

To carry on our analysis, we have to solve the Routing, Modulation Level and Spectrum Assignment (RMLSA) problem with flexible grid in optical rings. Such optimization problem can be formally defined as follows: given the physical topology of the ring, the traffic-demand matrix, the maximum reach for each modulation format, the grid granularity and the channel bandwidth of the transceivers, we have to find the mapping of the electronic traffic requests into flexible optical paths (grooming) and the spectrum and modulation format assignment of such flexible paths that minimizes, e.g., the overall spectrum utilized or the number of transceiver deployed. To model and solve this optimization problem, we have adapted the Mixed Integer Linear Programming formulation proposed in [5] by modifying the transceiver model according to the description in Section 2.1 and by introducing optical superchannels².

III. RESULTS AND DISCUSSION

In this Section, we compare a metro network architecture with flexible grid with the WDM metro network. In both cases, transceivers work either at 28 or at 14 GBD and support distance-adaptive modulation formats (i.e., we choose the highest modulation format compatible with the reach of each optical path). Note that 28 GBD is a commonly used baud rate enabling the 100 Gbps transmission rate. Thus, we chose 14 GBD as an alternative baud rate because it is the closest baud rate to the narrowest channel bandwidth considered here (F = 18.75 GHz), which allows a bit rate of 100 Gbps and multiple with higher spectral efficiency (e.g., 16-QAM 100Gbps). Since 14 GBD transceivers can support longer reaches and finer spectral width, we evaluate their benefits with respect to the 28 GBD elastic and WDM grid. We assume a topology with N = 8 nodes. For the WDM ring, we consider 1 THz spectrum divided into 20 wavelengths (50 GHz channel bandwidth) serving 28 GBD transceivers. For the flexible metro ring, the same spectrum of 1 THz is divided in a grid composed by M = 6.25 GHz or M = 12.5 GHz frequency slots. Guard bands are set to G = 6.25, 12.5 or 25 GHz. The modulation formats supported by the digital coherent transceivers are polarization-multiplexed n-QAM with n = 8, 16, 32, 64. The ring radius can be either 100 km or 200 km. The traffic requests, which are assumed to be static, are described as an all-to-all or one-to-all uniform traffic matrix, the former meaning that each node communicates with all the other network nodes, the latter meaning that one of the nodes is elected as gateway and all the traffic is either originated or terminated by that node. Objectives to be minimized are the spectrum occupation and the number of transceivers, which are treated separately in the next two subsections.

A. Minimization of the Overall Spectrum Occupation

We start considering an all-to-all traffic matrix: Fig. 2 compares the overall spectrum occupation (computed as the sum of the occupied grid slots on each link, including guard bands) using distance-adaptive coherent transceivers in the case of flexible grid with respect to the WDM systems, for ²Specifically, with respect to [5], Constraint (6) has been eliminated, while the objective function and Constraints (5), (11), and (12) have been modified to eliminate intermediate guard bands and allow the formation of superchannels.
Fig. 2. Overall spectrum occupation of flexible versus fixed grid, considering an all-to-all traffic matrix and $R = 200$ km. (a) Transceivers at 28 GBd. (b) Transceivers at 14 GBd.

Fig. 3. Spectrum savings (in percentage) of flexible versus fixed grid, considering an all-to-all traffic matrix and $R = 200$ km. (a) Transceivers at 28 GBd. (b) Transceivers at 14 GBd.

$R = 200$ km. The reduction of the spectrum occupation enabled by the flexible grid is relevant for both 28 and 14 GBd and, as expected, for larger $F$ more spectrum is needed.

In Fig. 3, we report the percentage reduction of the overall utilized spectrum with respect to the WDM 50 GHz-grid, for different values of the frequency slot (6.25 or 12.5 GHz) and guard bands $G$ (set to 6.25, 12.5 or 25 GHz). In case of transceivers at 28 GBd (Fig. 3(a)), the percentage of spectrum savings ranges from 28% to 35% for $F = 31.25$ GHz and $G = 6.25$ GHz, and slightly lower savings are achieved in case of $F = 31.25$ GHz and $G = 12.5$ GHz. In the scenario with $F = 37.5$ GHz and $G = 12.5$ GHz, although longer reaches are now possible due to the wider channel spacing, we have less appreciable gains (10 to 20%); if we increase $G$ up to 25 GHz, savings are smaller (or even negative), since $F + G \geq 50$ GHz. In all cases, the spectrum savings increase for higher traffic, since traffic grooming becomes more effective and the spectrum loss due to guard bands decreases thanks to the formation of larger superchannels. Results for 14 GBd show a different trend: thanks to the finer granularity of the transceivers, significant spectrum savings are achieved even for small traffic loads. In Fig. 3(b), spectrum savings of 14 GBd vs WDM exhibits more pronounced fluctuations because, while 14 GBd transceivers smoothly adapt to the traffic increase, WDM undergoes sudden changes of the optimal RMLSA configuration. Note that, even though i) the spectral occupation of 2 transceivers at 14 GBd is the same of a WDM transceiver at 28 GBd and ii) the flexible 14 GBd case has also to account for additional guard bands, nonetheless, with $R = 200$ km, 14 GBd at 25 GHz occupies less spectrum. This happens because on short metro distances, for the same bit rate, lower baud rate transceivers enable higher modulation formats.

Table II summarizes the average spectrum savings for the same scenarios of Fig. 3, but now with a shorter radius ($R = 100$ km). The savings are generically smaller, because, due to the shorter network radius, also the WDM adaptive transceivers are now able to utilize very advanced modulation formats. For example, while the scenarios with 14 GBd transceivers at $F = 18.75$ GHz are still more spectrum efficient, now 14 GBd transceivers with $F = 25$ GHz return worse performance compared to the legacy WDM.

Finally, in Fig. 4 we report the number of installed transceivers when the overall spectrum occupation is minimized. Note that results obtained for the WDM fixed grid and the flexible grid with 28 GBd transceivers are overlapped. The number of 14 GBd transceivers is almost twice as the transceivers at 28 GBd for high traffic, while it tends to be only slightly higher for low traffic. The number of transceivers grows excessively for increasing traffic, since the minimization of spectrum occupation leads the optimization towards very short (typically 1-hop) optical lines, which can support higher spectral efficiency, at the cost of increasing OEO conversion. It is worth comparing this figure with Fig. 5 (i.e., the number of transceivers when transceivers are minimized).

The results described above are confirmed by those obtained with one-to-all matrix, not reported for the sake of conciseness.
B. Minimization of the Number of Installed Transceivers

As mentioned before, when the optimization goal is the minimization of spectrum occupation, 1-hop superchannels are privileged, since short distances allow the utilization of higher modulation formats (32-QAM for 28 Gbd transceivers and 64-QAM for 14 Gbd transceivers), leading to the installation of a high number of transceivers. An alternative goal is the minimization of the number of installed transceivers. In this case, the length of the optical paths is expected to be longer to avoid unnecessary OEO conversions at intermediate nodes.

The number of installed transceivers is depicted in Fig. 5(a), for 28 Gbd and 14 Gbd. For low traffic loads, the number of transceivers at 14 Gbd exceeds the corresponding amount of transceivers at 28 Gbd only of a few units. However, even when the traffic grows, the number of 28 Gbd transceivers is never doubled by the corresponding amount of 14 Gbd transceivers, showing that lower baud rates and narrower channel bandwidths allow a consistent reduction in the unused capacity of the installed transceivers. The amount of transceivers is not dependent either on the channel bandwidth $F$ or on the width of the guard bands $G$, and the effect of the ring radius is not significant. In this scenario, the chosen modulation formats range from 8 to 32-QAM for 28 Gbd transceivers and from 16 to 64-QAM for 14 Gbd transceivers. Note that the percentage of additional transceivers requested when spectrum is minimized (about 40%) is comparable with the additional spectrum of additional transceivers requested when spectrum is minimized (about 45%).

Finally, Fig. 6 depicts the ratio of the carried traffic load (sum of the loads of all the links) and the spectrum occupation (sum of the spectrum on all the links including guard bands), $\Psi$, comparing the ITU fixed grid and the flexible grid with transceivers at 14 and 28 Gbd. This ratio provides the average spectral efficiency achieved in the different scenarios. Horizontal lines indicate the maximum theoretical values of spectral efficiency, $\eta \cdot B/F$ (assuming $\eta = 6$, which corresponds to a 64-QAM modulation format). Since $\Psi$ is highly dependent on the configuration of the optimal RMLSA, which varies with the traffic, the solution with absolute highest spectral efficiency is not univocal, but it is worth noting that 14 Gbd transceivers provide in most cases value of efficiency which are much closer to the theoretical limit, especially when minimizing the spectrum occupation. This leads us to conclude that 14 Gbd transceivers, in our scenario, represent a better trade-off in terms of spectral efficiency and bandwidth utilization when a flexible narrow grid with minimum channel bandwidth of $F = 18.75$ GHz is employed.

IV. Conclusion

In this letter, we compare, for a metro network, the performance of transceivers at 14 and 28 Gbd with distance adaptive modulation formats in fixed and flexible grids. Results show that in the considered scenarios the introduction of frequency slots at 6.25 GHz leads to significant spectrum savings, also operating with 12.5 GHz channel guard bands. Moreover, transceivers operating at baud rates closer to the narrower channel bandwidths more flexibly adapt to the configurations needed to achieve optimal RMLSA.

References