Benefits of Integrated Packet/Circuit/Wavelength Switches in Next-Generation Optical Core Networks

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Abstract: We investigate the use of integrated packet/circuit/wavelength switches in next-generation optical core networks and compare different node architectures for a 46 node, 25,840 route-km US network.

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1. Introduction

Next-generation optical core networks provide the infrastructure for a reliable delivery of high-capacity packet and circuit services. To keep pace with steady traffic growth, estimated here to be of 30-70% annually, Multi-Tb/s networks are required in which packet flows, time-division multiplex (TDM) circuits and dense wavelength division multiplex (DWDM) wavelengths can be seamlessly transported and switched. Recent progress in transport technologies allows such networks to be built and operated in a scalable, flexible and automated way.

Advances in digital signal processing, coherent reception and multi-level phase modulation have made 100 Gb/s dual-polarization quadrature phase shift keying (DP-QPSK) the de-facto modulation format standard for high-capacity long-haul networks [1]. In conjunction with hybrid Raman/EDFA amplification, it enables 9.6 Tb/s (96 x 100 Gb/s) DWDM transmission over 2500 km without optical dispersion compensation.

Multi-degree reconfigurable optical add/drop multiplexers (MD-ROADMs) form the foundation of an agile DWDM layer. They eliminate unnecessary electronic signal regeneration points and facilitate an automated establishment of end-to-end wavelength circuits. Equipped with contentionless [2] add/drop capabilities, MD-ROADMs make any wavelength of any direction accessible on any add/drop port (triple-“a”), thereby simplifying network planning and node configuration and avoiding wavelength blocking.

The optical transport network (OTN) standard [3] provides digital wrapper and multiplexing technologies for an efficient mapping of circuit and packet clients onto 100 Gb/s wavelengths. OTN offers TDM switching at Optical Channel Data Unit (ODU0/1/2/3/4/flex) granularity and facilitates interoperability in multi-domain scenarios. It is best suited for delivering constant bit rate (CBR) point-to-point services of ≥ 1 Gb/s.

The packet layer complements the OTN layer with statistical multiplexing/packet aggregation, multi-cast and an efficient transport of ≤ 1 Gb/s traffic. It uses MPLS technology for an end-to-end delivery of IP and Ethernet services. Packet traffic is mapped into ODU containers before being transported as fractional or full DWDM wavelength.

In this paper, we investigate the use of integrated packet/circuit/wavelength switches in next-generation optical core networks. Whilst the advantage of a transparent optical wavelength layer has already been proven in several studies (e.g. [4]), the appropriate level of integration between the packet/circuit/wavelength layers is the subject of an ongoing debate. We define three different node architectures and analyze their suitability in a US network study.

2. Network node options

When investigating integrated packet/circuit/wavelength switches, three principal node architectures can be distinguished:

In the parallel architecture (Fig. 1a), separate MPLS and ODU switches exist for the packet and circuit traffic. Both traffic types are independently mapped into ODU/OTU4 and transported over the optical layer. A sharing of the same wavelength for packet and circuit traffic is not possible thereby creating network inefficiencies.

In the layered architecture (Fig. 1b), the packet traffic is not directly mapped onto a wavelength but always passes through the ODU switch first. The connection between the MPLS and the ODU switch can be realized in various ways. Here, we assume that grey OTU4 intra-office interfaces are used. Packet flows are mapped into ODUflex units using the generic mapping procedure (GFP) and occupy an integer number of 1.25 Gb/s tributary slots of the higher order ODU4 bearer signal. Multiple ODUflex signals can be multiplexed into one ODU4 until its 80 tributary slots are exhausted.

In the integrated architecture (Fig. 1c), a hybrid switch matrix is used for processing both the packet and the circuit traffic. The hybrid switch allows full flexibility in grooming, mapping and multiplexing circuit and packet traffic.
services on individual wavelengths. Compared to Fig. 1b), the integrated architecture saves the optical interfaces between the MPLS and the ODU switch and requires a smaller overall switch capacity. Compared to Fig. 1a), packet and circuit traffic can share the same ODU4 container leading to better wavelength exploitation.

All nodes use the same contention-less MD-ROADM-based optical layer with a nodal degree ≤ 8 and up to 96 DWDM channels per line interface. Each DWDM channel carries an OTU4-framed 100 Gb/s-DP-QPSK signal which is generated/terminated in a colored interface in the electrical switch equipment. It is optically connected to the ROADM add/drop ports and then transparently switched to the best suited line interface. Client traffic is handed off to the core network nodes via multiple 10 GbE (packets) and OTU2 (circuits) interfaces. TDM and leased line traffic having a granularity lower than 10 Gb/s is multiplexed into ODU2 containers.

Table 1 contains normalized interface cost estimates for all three node options. Included in the table are only OTN interfaces without packet processing capabilities. Costs of packet interfaces embracing IP/MPLS switching capabilities and hybrid interfaces offering both IP/MPLS switching and ODU multiplexing functions are modeled by $C_{\text{hybrid,packet}} = 1.15 \times C_{\text{OTN}}$. Common equipment is not listed explicitly but distributed over the associated interfaces. As the number of ROADM line ports and optical amplifiers is the same for all three node models, they are not considered further.

3. Network Study

To compare the three node architectures of the previous section, we analyze the US reference network with 46 nodes and 62 links [5][6] depicted in Fig. 2a (left). The average and maximum nodal degree of the network are 2.7 and 5, respectively, the network size is 25,840 route kilometers. Regular fiber spans are assumed with in-line optical amplification every 80 km. The maximum transparent optical path length for a 100 Gb/s signal between any two electrical regeneration points is 2500 km. Depending on the traffic characteristics, either ports of the circuit/packet switch or dedicated 100 Gb/s regenerators can be used for regeneration.

The traffic matrix consists of a mix of packet and circuit services between the 1350 node pairs. The circuit traffic is derived from a population model [7] using population data from 46 major cities [8]: The traffic originating in a node is determined by the ratio of the inhabitants of that city to the inhabitants of all cities. The fraction of this traffic routed to another city is derived from the ratio of the population of the destination city to the cumulative population of the remaining cities (excluding the originating city). The originating packet traffic is modeled analogously to the circuit traffic. Because of the dominance and the hierarchical nature of residential IP over the total packet traffic, however, the traffic distribution in our model is determined by the number of internet exchanges (IXP) [9] at a destination node rather than its population.

Following these considerations, the traffic matrix for the network study is determined by defining the total network capacity and the relative split between packet and circuit services. Based on service provider traffic

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**Fig. 1. Network node options: a) parallel, b) layered, c) hybrid packet & circuit switch. All DWDM channels are using 100 Gb/s line rate.**

**Table 1: Interface costs**

<table>
<thead>
<tr>
<th>Interface Type</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey OTU2 interface 10G</td>
<td>1</td>
</tr>
<tr>
<td>Grey OTU4 interface 100G</td>
<td>20</td>
</tr>
<tr>
<td>Colored OTU4 interface 100G</td>
<td>30</td>
</tr>
<tr>
<td>ROADM add/drop port</td>
<td>1.2</td>
</tr>
</tbody>
</table>
predictions, a typical aggregate capacity for a US core network in 2010 is 8 Tb/s. Using 2012 as reference year for the network study, a 50%-50% split of packet and circuit services in 2010 along with a 70%-30% compound annual growth rate (CAGR) yields 11.56 and 6.76 Tb/s of packet and circuit traffic in 2012, respectively.

The network design is based on a greedy multilayer routing and grooming heuristic using four layers: the demand graph, the fiber graph, an OTN graph (representing the virtual topology for the ODU and MPLS services) and an auxiliary graph which represents the candidate (optically feasible) lightpaths. This auxiliary graph model facilitates the optical performance evaluation as well as the efficient routing and grooming using optical bypass. Demands are sequentially routed on the OTN layer. If not enough capacity is available in the OTN layer, an additional lightpath is installed by routing the traffic on the auxiliary candidate lightpath graph, and subsequently performing routing and wavelength assignment on the fiber layer. When a wavelength channel can be found, the lightpath is installed and the virtual link is created in the OTN layer.

4. Results

The results of the network study are summarized in Fig. 2 below. The used routing and grooming algorithm achieves a high average lightpath load in any scenario. The layered and hybrid model reach a better loading efficiency than the parallel model as packet and TDM traffic can be groomed on the same lightpath. In the layered architecture, however, the possibility to re-groom packet traffic on layer 1 does not compensate the disadvantage of the additional optical interfaces required between the MPLS and the ODU switch in realistic ranges of $C_{\text{hybrid, packet}}/C_{\text{OTN}} \leq 1.3$.

![Fig. 2. Network cost in dependence of $C_{\text{hybrid, packet}}/C_{\text{OTN}}$ (left) and detailed study outcome (right).](image)

5. Conclusion

We described different node architectures for packet/circuit/wavelength switches suitable for next-generation optical core networks. A node architecture which integrates packet (MPLS) and circuit (ODU) switching by means of a single, protocol-agnostic switch matrix is most flexible in the assignment of circuit and packet traffic, provides the minimum number of optical interfaces, and allows the best exploitation of the available fiber capacity. For a 46-node US core network with 18.32 Tb/s of mixed packet and circuit traffic, we demonstrate that a layered approach where both packet and circuit traffic needs to pass a dedicated ODU switching layer only provides benefits if the cost ratio between packet and pure TDM is very high. If the incremental cost of packet processing is negligible, the hybrid model achieves 23% of cost savings over the layered model.

6. References