Relative costs of WDM rings and PONs for metro optical packet networks

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Abstract: A relative CapEx costing study shows that WDM PONs can provide a lower-cost alternative to WDM rings using active add-drop nodes in metropolitan optical packet networks, for a chosen benchmark traffic scenario. Optical hardware dimensioning is based on mean traffic requirements and packet-level medium access control protocol simulations, using various scheduling algorithms, subject to physical layer constraints. The main cost benefits of PONs are that they require fewer amplifiers than rings, fewer wavelength multiplexers and approximately the same amount of fibre when operated bi-directionally.

Keywords: WDM, ring, PON, optical packet network, scheduling

Introduction

This relative costing study is based upon the benchmarking traffic scenarios studied in the EU IST project DAVID [1], for interconnecting 16 nodes locally within a metro area network of 100 km circumference and remotely to the WAN via a central buffer-less, optical hub switch. A cost comparison is made between the optical CapEx requirements of DAVIDv2 WDM rings, which use active OPADM nodes [2], and a PON-based star topology for constructing the metro network (including the hub switch). Due to the power budget limitations of DAVIDv2 rings [3], this study compares the following two structures for supporting the DAVID project's 80 Gbit/s mean traffic benchmarking scenario:

- 1 PON of 16 nodes + 1 PON for the gateway to the WAN
- 2 rings of 8 nodes + 1 ring for the gateway to the WAN

Section 2 describes physical design issues relating to WDM rings (with active OPADM nodes) and PON-based star networks, i.e. network topologies and physical layer performance, in order to establish conditions under which a star network might be lower cost than a ring network. Hub switch designs suitable for rings and PONs are also described. The mean traffic matrix from the 80 Gbit/s benchmarking scenario is presented In Section 3. It is applied to the resulting design choices, for both PONs and rings, and the optical component requirements required to support it are manually counted in Section 4. Section 5 describes the packet scheduling algorithms used in the medium access control protocol simulations. Packet scheduling simulations are then run to compare component and network requirements under more realistic statistical traffic fluctuations, using a maximum packet delay criterion of 1,000 time slots. Section 6 then applies relative costs to the resulting component quantities, and compares the overall relative costs of PON and ring solutions for the same 80 Gbit/s mean traffic scenario. Only CapEx costs of optical components are considered.

2. Physical design issues

To minimise the complexity of this study, and to enable comparisons between rings and PON-based stars to be made analytically, the physical topology of the metro network is taken to be a circle of radius R km, with all nodes plus the metro network hub switch equally spaced around it. Such a perfect structure is certainly not normal, but it is no more unique nor less meaningful for comparing rings and PONs than any other arbitrary, real-life node distribution.

2.1 DAVIDv2 rings

DAVIDv2 rings are slotted WDM optical packet rings employing active OPADMs in each node to enable spatial re-use [2]. A ring has 2 fibres (working + protection), each supporting 32 WDM channels. These are partitioned into 8 wavelength bands each of 4 channels. OPADMs can be equipped with up to 8 babyboards, each tunable over one of the wavelength bands using 4 switchable fixed-wavelength DFB lasers, one wavelength selector acting as a tunable Rx and a second wavelength selector to block dropped channels from continuing around the ring. Wavelength selectors employ λdemux, 4 SOA gates and λmux. In addition, every OPADM contains an EDFA. Even so, spectral narrowing and noise accumulation limit each DAVIDv2 ring to supporting only up to 9 OPADM nodes [3]. Since two rings are needed to support 16 nodes, the total working + protection fibre is:

$$\text{ring fibre} = 8\pi R \quad \text{km} \qquad [1]$$

For a circumference $2\pi R$ of 100 km, this is 400 fibre.km, independent of the number of nodes.

2.2 PON-based star networks

PONs provide coupling and splitting more efficiently than rings, so power budgets are less stringent and PONs can support more nodes with fewer amplifiers. Although amplified PONs can potentially support tens of thousands of nodes [4], the benchmarking scenario only requires the power budgets and noise performance to support 16 nodes. For protection, the entire PON is duplicated.

The hub switch lies on the perimeter of the circular metro network, from which a single fibre carrying all the PON traffic goes to the centre of the circle where the first stage of 1x8 splitters/couplers is placed, together with the upstream (gated) and downstream EDFAs. The second 1x2 splitter/coupler stage is located R/2 km from the centre towards the nodes on the perimeter. A single fibre is assumed for both upstream and downstream traffic by operating the PON bi-directionally; 16 channels upstream, 16 downstream. This halves the PON fibre quantity for N nodes, which is then doubled again for protection to:

$$\text{star fibre} = \left[N\left(\frac{1}{2} + \sqrt{1 + 4(1 - \cos\theta)}\right) + 2 \right].R \quad \text{km} \quad [2]$$

where $\theta = \pi/(N+1)$ rad [3]

For N=16 nodes and $2\pi R$=100 km this is 422 fibre.km, which is only 22 fibre.km more than rings require.

When nodes are connected by PONs, they obviously do not need a second wavelength selector to block received channels, unlike OPADMs in ring nodes.

2.3 Hub designs

The hub is an optical switch that interconnects rings or PONs. For rings and PONs controlled by a frame-based packet scheduling algorithm and rings using a more heuristic algorithm, a metro hub would use a DAVID broadcast and select switch capable of interconnecting wavelength bands or individual channels on a slot-by-slot basis [2]. For PONs using a non-frame-based, heuristic scheduling algorithm the metro hub switch would use a SONATA-like design [4], employing an nxn wavelength router with banks of wavelength converters within a set of dummy ports which are only slowly reconfigured as the traffic matrix changes.

The DAVID broadcast and select switch contains amplifiers, splitters for broadcasting, 8-way SOA gate arrays for input fibre selection and channel selection, as well as 3R regenerators/wavelength converters for all channels on the input side of the switch as well as the output side, to overcome signal degradation and convert the 32 channels within the fibres to and from the 16 channels used internally. 5 stages of λmux/λdemux are required. But when used to interconnect bi-directional PONs, the DAVID hub is assumed not to require the input bank of 3R regenerators/wavelength converters, because the PONs only have 16 incoming and outgoing channels. Consequently just 3 stages of λmux/λdemux are required.

3. 80 Gbit/s traffic scenario

The scenario assumes 80 Gbit/s total traffic capacity to and from the 16 nodes of a metro network [1]. All 16 nodes can be supported in a single PON, but must be partitioned into two 8-node DAVIDv2 rings. The hub traffic goes via its own ring or PON to and from the WAN gateway. Table 1 summarises the mean traffic matrix in Gbit/s between 4 node types (server, big, medium and small), giving both the individual node-node capacity and the number of node pairs having that capacity between them. No node transmits to itself. The individual node capacities (Tx and Rx) and the total capacities are also shown for each node type.

from / to	hub	server node 1 off	big nodes 2 off	med. nodes 4 off	small nodes 9 off	total	Rx per node
hub	0	10.36 x1	2.0736 x2	1.024 x4	0.512 x9	23.2112	
server node	1.6 x1	0	0.0512 x2	0.0256 x4	0.0128 x9	1.92	1.92
big nodes	5.4912 x2	0.96 x2	0.0512 x2	0.0256 x8	0.0128 x18	13.44	6.72
med. nodes	3.1392 x4	0.48 x4	0.0384 x8	0.0192 x12	0.0096 x36	15.36	3.84
small nodes	1.5664 x9	0.2 x9	0.0256 x18	0.0128 x36	0.0064 x72	17.28	1.92
total	39.2368	16.0	5.12	5.0944	5.76	71.2112	
Tx per node		16.0	2.56	1.2736	0.64		

Table 1. Traffic matrix between nodes and hub in Gbit/s.

4. Network dimensioning for mean traffic

The quantities of the most costly components are summarised in Table 2 for PONs using frame-based scheduling and for DAVIDv2 rings with and without spatial re-use, including the PON and ring to the WAN gateway.

component	relative cost	PONs, frame-based	DAVIDv2 rings without spatial re-use	DAVIDv2 rings with spatial re-use
λmux ports	0.96	1144	1456	1376
EDFAs (+16dBm)	-	14	48	48
EDFAs (+25dBm)	4x +16dBm	2	0	0
fibre.km	1.0	423	400	400
SOA gate arrays	5.3	70	85	79
10 Gbit/s fixed-λ Txs	1.5	160	160	144
10 Gbit/s Rxs	3.7	44	44	40
λconverters/3R regenerators	7.5	8	18	17

Table 2. Major component quantities for mean traffic.

Traffic-dependent component quantities are calculated from the traffic matrix. For PONs, from Table 1, the total downstream traffic to the WAN PON via the hub is 23.2112 Gbit/s. Because all Txs/Rxs are assumed to be 10 Gbit/s, this therefore requires 3 wavelength channels from the hub. The total downstream traffic from hub to node PON is 71.2112 – 23.2112 = 48.0 Gbit/s, requiring 5 channels. So 8 channels are needed downstream from the hub in total, hence requiring 8 wavelength converters. The numbers of fixed-λ Txs and Rxs needed by each node are similarly derived from the Tx and Rx capacities per node in Table 1. The numbers of Txs and Rxs needed in the WAN PON are derived from the total capacities to and from the hub.

For DAVIDv2 rings more wavelength converters are required partly because the traffic is fragmented between two 8-node rings but mainly because 3R regeneration/wavelength conversion are needed at the hub input as well as the output. Spatial re-use provides modest component savings.

The major component savings between PONs and DAVIDv2 rings are in wavelength multiplexers and EDFAs.

5. Packet scheduling simulations

5.1 Scheduling algorithms

In both PONs and rings, frame-based scheduling algorithms are employed using separate matching and time-slot assignment. Time-slot assignment is equivalent to the routing of circuits in a Clos network while the Maximal Weight Matching algorithm is known to be the optimal solution for matching [5]. In real implementation, the complexity of rigorous matching and time-slot assignment is impracticable, therefore we adopt heuristic algorithms.

The packet simulations over rings use a time-domain, multi-slot heuristic algorithm based on a Critical Weight Matching algorithm [2]. Two algorithms are used for PONs: a greedy "first-fit" algorithm [6] and a frame-based "no-overbooking" algorithm [5].

5.2 Simulation results

The packet scheduling simulations begin with the component resources that would be installed to support the mean traffic capacities. But packet delays caused by selfsimilar traffic sources and matching algorithm inefficiencies, which particularly affect the server node, require more resources (channels, Txs and Rxs) to be added, in discrete increments, until a maximum queueing delay below 1,000 time slots is obtained. Figure 1 shows the maximum delay vs. offered load curves (i.e. delay vs. traffic capacity) for the 4 resulting PON and ring networks, each now requiring different installed capacities. The loads corresponding to the 80 Gbit/s scenario are ringed. These are the only points for which each network supports precisely 80 Gbit/s mean traffic with minimum resources to guarantee less than 1,000 slot maximum delay. PONs with frame-based scheduling (and a hub with slot-by-slot switching between channels) require the smallest of the 4 network capacities and hence achieve the highest load for the allowable 1,000 slot queueing delay. 11 downstream channels and hence λconverters are needed in total, instead of 8, which increases the network capacity to 110 Gbit/s, allowing the traffic load for the 80 Gbit/s scenario to become 71.2112/110=0.647. DAVIDv2 rings and PONs using a greedy scheduling algorithm all require greater network capacity, and hence provide lower loads, than PONs using frame-based scheduling.

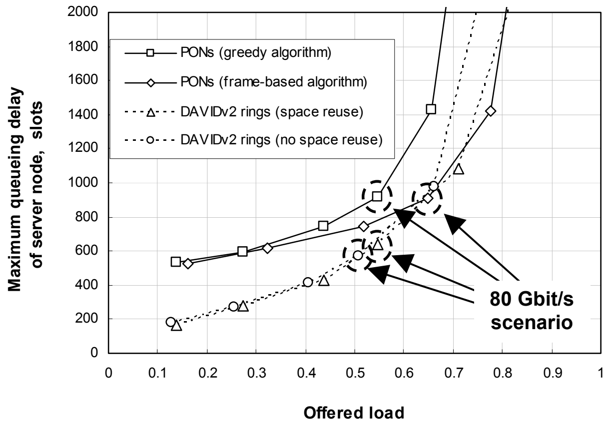

Figure 1 : Maximum queueing delay vs offered load

6. Cost comparison between rings and PONs

Because fibre quantities are the most consistent between PONs and rings in Table 2, the cost comparison assigns a component cost relative to that of one fibre.km. Assumed relative costs are also given in Table 2. The cost comparison is in terms of the percentage PON/ring network cost ratio, using frame-based scheduling for PONs. This is plotted as a function of the relative cost of a +16 dBm EDFA in Figure 2, for rings with and without spatial re-use.

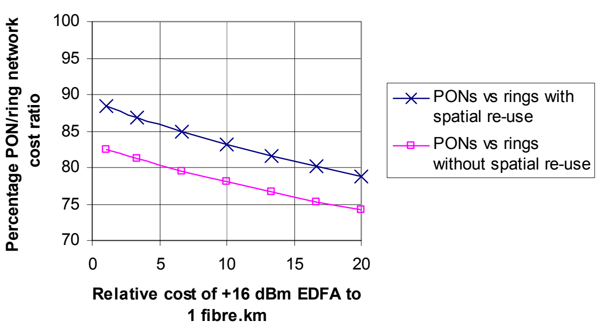

Figure 2 : Percentage PON/ring network cost ratio

Evidently PONs can offer significant cost reductions over DAVIDv2 rings for this 80 Gbit/s traffic scenario, for increasing amplifier costs.

7. Conclusion

A relative CapEx costing study of the optical component requirements for constructing a metropolitan optical packet network, to support the DAVID project's 80 Gbit/s benchmarking traffic scenario, has shown that PONs can provide significant cost reductions over DAVIDv2 rings with active OPADM nodes, particularly with increasing amplifier costs. This is mainly because PONs require fewer amplifiers and λmuxes than rings (including those within the hub switch). An important requirement is that PONs should be operated bi-directionally, to halve their fibre quantities.

The hardware quantities have been assessed initially to support the mean traffic capacities, but then appropriately increased by simulating the various packet scheduling algorithms relevant to the PON and ring architectures, in order to ensure maximum packet delays below 1,000 time slots. WDM PONs using frame-based scheduling support higher offered loads than both slotted WDM rings using a multi-slot algorithm based on Critical Weight Matching and PONs using a greedy scheduling algorithm.

8. Acknowledgement

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9. References

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10. Glossary

CapEx:	Capital Expenditure
EDFA:	Erbium Doped Fibre Amplifier
λmux:	Wavelength Multiplexer
OPADM:	Optical Packet Add-Drop Multiplexer
PON:	Passive Optical Network
SOA:	Semiconductor Optical Amplifier
Tx/Rx:	Transmitter/Receiver
WAN:	Wide Area Network
WDM:	Wavelength-Division-Multiplexing