Node Architectures for Next Generation ROADMs: A comparative study among emergent optical solutions

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***Abstract*— Reconfigurable optical add and drop multiplexers (ROADMs) are key components to increase the dynamicity and flexibility of optical networks. In its first generation, solely based on PLC and WSS-technology, ROADMs allowed service providers to automate some of its network operations, reducing the OPEX and improving the quality of service offered to the customer. However, the current solution is limited to several constrains such as direction, color and contention, and still demands truck rolls and manual reconfiguration depending on the desired operation. To address this limitation, new optical components are emerging and particularly two node architectures are being considered as most promising candidates: multicast switch with optical amplification array and dense low loss fiber optical cross-connect with MUX/DEMUX AWGs. This paper compares both solutions, and a third variation using fiber OXC in conjunction with WSS, from a CAPEX and OPEX perspective. It concludes that depending on the network scenario one solution is more suitable than the others and probably, in the next generation reality, different node architectures will be required in different portions of a same network.**

***Index Terms*—** ROADM, next generation optical network, multicast switch, cross-connect, WSS.

I. INTRODUCTION

All-optical switching network presents several advantages over electronic switching networks like SDH (synchronous digital hierarchy) and OTN (optical transport network) such as: lower power consumption, lower cost per bit, much higher bandwidth capacity and no need for optical-electrical-optical (OEO) conversion in the core nodes. Besides that, it is agnostic to the signal modulation format and rate, characterizing a future-proof solution.

With the advance of integrated optics technology, 2-degree ROADM using PLC (planar lightwave circuit) switches that started to be deployed in the telecom operator´s networks in the mid 2000s, followed by N-degree ROADM using WSS (wavelength selective switch) few years later. PLC switches allowed the deployment of ring topologies and WSS switches the interconnection of rings and, more recently, mesh topologies.

Through the use of ROADMs, lightpaths can be configured remotely in wavelength granularity.

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Before them a circuit provisioning could take several weeks to be set, once static optical data plane required truck rolls to all network sites where the circuit went through, making the offering of optical circuit services directly to the end user impossible in many cases due the OPEX (operational expenditure) cost associated to it.

The deployment of the first generation of ROADMs made the dynamic optical networks a reality in the telecom scenario, especially for WDM core nodes, and, in some cases, also for metro- and aggregation-nodes. Nevertheless, considerable disadvantages remain using this solution, specially related to the flexibility on dealing with the client signal, like the inability to accept any wavelength on any port, or sending it to any direction. These kinds of operations still demand manual interaction.

In order to push all-optical network closer to the end user ROADM architectures need to evolve to overcome these limitations related to A/D (add and drop) operations, achieving the so-called NG-ROADM (next generation ROADM) [1]. It did not happen when first generation arose due the lack of viable optical devices. However, the increasing demand for all-optical solutions pushed the development of such devices. In that sense two main approaches are being proposed by both academy and industry: (a) high loss multicast switch (MCS) with an array of optical amplifiers [2], and (b) low loss high density fiber cross-connect (OXC) with MUX/DEMUX AWG (arrayed waveguide gratings) [3]. These devices are still being introduced to the market and today the main open question related to next generation WDM network is which node architecture will be the dominant one.

This paper addresses this issue. The two node architectures using MCS with an array of optical amplifiers and fiber OXC with AWG, and a third variant using fiber OXC with WSS [4], [5], are compared in terms of cost, scalability and power consumption. It concludes that depending on the number of degrees (network ports) and the percentage of local A/D, one solution is more suitable than the others. This conclusion suggests that for the next generation network, differently than the current one, different node architectures will be required in a same network depending on the role of the node in the network.

This work is organized as follows. Section I presents the history of first generation ROADMs and the trends for next-generation, and the objective of the paper. Section II details the requirements for the NG-ROADM. Section III presents the emerging proposals for next generation node architectures. Section IV shows the comparative study among the presented node architectures and Section V ends the paper with the results discussion and conclusions.

II. REQUIREMENTS FOR NG-ROADM

As stated in Section I, WSS allowed the consolidation of optical dynamic networks in the telecom scenario, especially for complex mesh topologies. Figure 1 shows the classical architecture of first generation WSS-ROADM in a three-degree configuration. In this architecture power splitters (PS) are used to send a fraction of the signal to all WSS switches and to the drop AWG DEMUXs. At the same time the add AWG MUXs also send the clients signal to the WSS switches. Optical amplifiers at the ingress and egress of each degree are used to compensate for power loss. Wavelengths can be freely switched from one degree to another provided that its frequency is available in the destination port. This operation is commonly referred as express path switching.

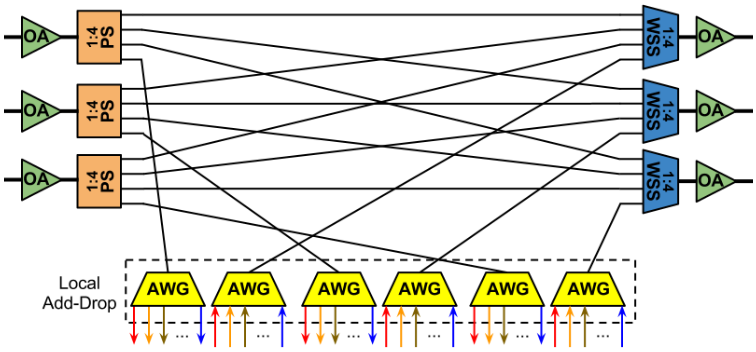

Fig. 1 - First Generation WSS-ROADM architecture.

Although it is a quite flexible architecture considering express path switching, add- and drop-operations are limited due to the A/D structure composed by AWGs [6], [7]. In this case, one specific wavelength coming from one degree can be dropped to one fixed port. Once the fiber span coming from the client site is connected to one A/D port the client signal can be inserted to or removed from the network only to a specific wavelength and degree. Any reconfiguration in that sense requires a truck roll to the node site since a manual fiber change is necessary. Because A/D ports are tied to one specific degree it is commonly called local add and drop port. In order to reduce its OPEX, network operators demand node architecture which are able to send the client signal to any direction using any wavelength.

At the time WSS-ROADMs started to be deployed it was considered that the natural evolution would be the use of a N:M WSS, where N is the number of degrees and M the number of A/D ports [8]. This architecture is shown in Figure 2. In this case a N:M WSS is able to receive any wavelength from a N port, and send it to any M port, even when two N ports are dealing with the same set of wavelength coming from different degrees. Several banks can be added to the A/D structure in order to increase the number of client ports, resulting in a scalable solution of global A/D ports. The term global is given since it is able to reach any degree.

Nevertheless, N:M WSS is not a reality and it is not clear if it will be available to the market within the next years. A poor approach was proposed to emulate N:M WSS using two 1:N WSS, Figure 3 depicts the arrangement. This solution is able to provide directionless and colorless A/D operation. However it results in wavelength contention. Considering that a same wavelength can be dropped by different degrees to different user ports this constraint is a substantial drawback. Furthermore, it is a costly solution since it requires two WSS switches and one of them needs to provide an M number of ports, where M is expected to be higher than some dozens. Although 1:20 WSS is currently being introduced to the market and higher order WSS are being proposed [9], the price per WSS port basically remains the same compared to the low order ones like 1:5 or 1:9, making such an approach in viable in terms of cost.

A variation of this approach is being adopted for some network operators. It replaces the 1:M WSS by an AWG DEMUX. Although it increases the number of client ports and reduces the overall price, it also makes the client ports colored. Due this limitation, this architecture usually mixes both local and global ports, in an attempting to deal with direction and color restrictions.

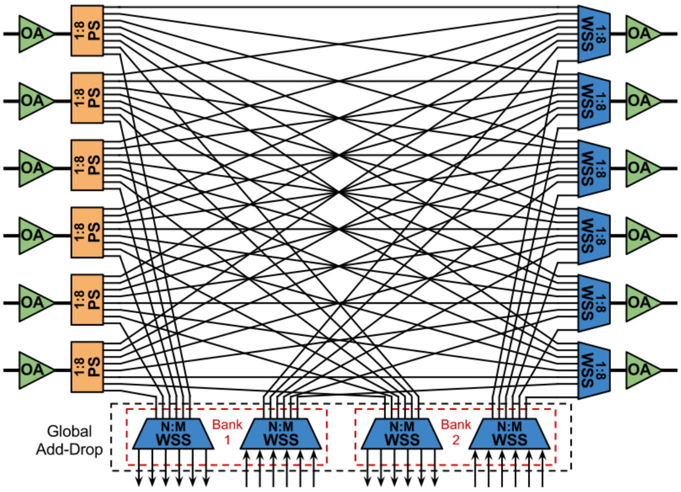

Fig. 2 - Conceptual architecture of NG-ROADM using N:M WSS.

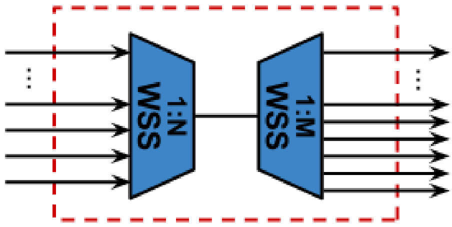

Fig. 3 - Contention N:M WSS using two convention WSS switches.

Summarizing, next generation WDM networks demands colorless, directionless and contentionless (CDC) ROADMs in order to increase the network dynamicity and reduce OPEX. As commented by [10] another feature that is being required is flexibility in terms of spectral grid for the purpose of supporting the transmission rates beyond 100 Gbps planned for the next years. This issue requires WSS switches based on LC (liquid crystal) instead of MEMS (microelectromechanical systems) technology. Nonetheless, it is not an issue for the A/D structures discussed in this work.

As presented in this Section, WSS alone (actual ROADMs topologies) cannot fully provide CDC features required by telecom operators. The next Section presents the emerging proposals based on the latest achievements in optical component design.

III. NG-ROADM ARCHITECTURES

As described in Section II, N:M WSS are the key component for NG-ROADMs supporting full CDC features. Since N:M WSS is not an available technology, other proposals are emerging in order to accomplish the same task albeit through different architectures. Two particular approaches are getting to the market, both with advantages and disadvantages. The first one proposes the use of

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optical multicast switches with an array of optical amplifiers and the second one proposes the use of low loss high density OXCs with AWG. A variant of the former using 1:N WSS switches is also considered a viable solution.

All propose using the same arrangement of PS and 1:N WSS switches for the express path switching, as shown previously in Figures 1 and 2. The differences among the proposals are restrained to the A/D structure. In the following each of these architectures is described in details.

A. MCS approach

Multicast switch, in some cases referred as TPA (transponder aggregator), is an optical module that integrates power splitters and N:1 fiber switches [2], [11]. MCS is available in the market in 8:8, 8:16 and 8:24 configurations. Due the use of PS the power loss is high and demands an optical amplifier array (OAA) at the ingress, as shown in Figure 4. OAA is one of the main challenges in this approach and some project decisions, like sharing the same pump laser among the amplifiers, is required to lower its cost.

At the egress (M side) tunable filters are required for the drop since multiple wavelengths can reach the same port. When coherent modulation is used optical tunable filters (OTF) are no longer required since coherent detection can be applied, also lowering the overall cost. To increase A/D percentage several structures can be cascaded. To do so, a 1:N WSS is required at the ingress and egress of each degree, in this case N represents the maximum number of replicated A/D structures, and the maximum number of A/D ports is given by NxM.

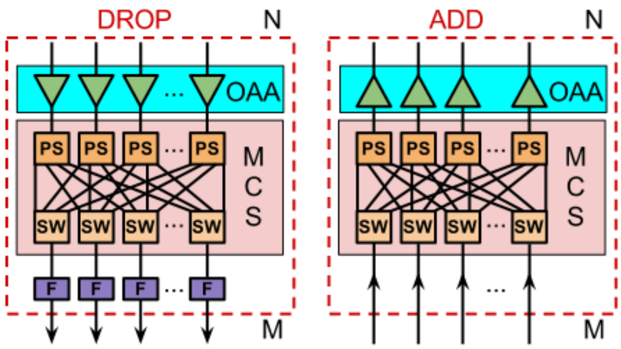

Fig. 4 - A/D structure using MCS, optical amplifiers array and tunable filters.

B. Fiber OXC approach

Recently low loss high density fiber OXC was introduced to the market. A 192:192 configuration is available and 384:384 is already considerable feasible [12].

Figure 5 presents a generic version of the A/D structure introduced by [3]. In this architecture all wavelengths from all degrees must reach one of the upper OXC ports. AWGs are used to separate all wavelengths from each degree. Power splitters are connected to the lower OXC ports enabling the client ports to reach any wavelength and vice-versa.

Differently than the MCS approach it does not scale up through the addition of similar structures connected via a 1:N WSS, instead, a different arrangement using more dense OXC or more OXCs

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linked with power splitters is used to increase the number of A/D ports. Depending on the arrangement, optical amplifier arrays may be required to compensate for power loss.

Although this A/D structure allows full CDC, the use of one PS for each port makes the architecture hard to assemble. A simpler approach is presented next; in this case moderate contention occurs but may be minimized through the use of a RWA (routing wavelength assignment) algorithm.

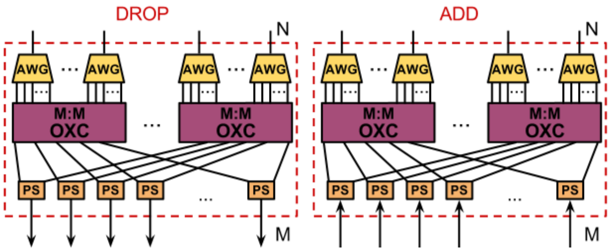

Fig. 5 - A/D structure using M:M OXC, AWGs and PS.

C. *OXC with WSS approach*

Another variant using fiber OXC is proposed by [4]. Figure 6 presents a generic version of this proposal with a minor change; instead of using colorless MUX/DEMUX (not available to the market) it uses regular AWG MUX/DEMUX.

Like reported by [5], this architecture results in wavelength contention due the use of 1:N WSS to connect the degrees to the A/D structure. However a RWA algorithm can define lightpaths using the banks efficiently, mitigating contention and achieving a lightpath blocking lower than 0.1% for most of the scenarios using a bank number of k=2. Real contentionless can be achieved having one bank per node degree, however, in such condition this architecture becomes more expensive than the one previously presented.

The number of A/D ports can be increased in two different ways; using a denser OXC or replicating the same structure. For both cases one extra port in express path WSS switches and power splitters is required per used banks.

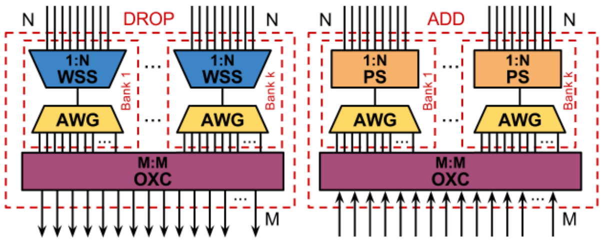

Fig. 6 - A/D structure using 1:N WSS, AWG and OXC.

IV. COMPARATIVE STUDY AND RESULTS

Section III presented the main emergent solutions for NG-ROADM that address the colored and directional limitations present in the first generation WSS-ROADM without adding contention restriction, or adding it in a controllable fashion.

In the following cost and power consumption are compared among the three architectures (Figs. 4-6) resulting in a CAPEX (capital expenditure) and OPEX analysis capable of defining which architecture suits best a given condition. Here, CAPEX indicates the amount of money spent on the purchase of capital goods of a certain company and OPEX refers to the cost associated with the maintenance of equipment, consumables expenses and other operating expenses.

Studies on the overall energy-efficiency for backbone communication networks have been presented, providing a simplified analytical model on the energy consumption as a function of the average traffic demand [13], as well as power consumption per costumer model for optical networks [14], [15] and values for individual network devices [13]. More specific work for EDFAs, generalized models [16], models of EDFAs from a thermodynamic point of view [17] and of multi-stage EDFAs [18] have been reported. In [19]-[21], the fundamental limitations on energy consumption in optical communications is well explored. In this paper, for a comparison of cost and energy consumption, the respective contributions of all major components must be considered. However, one major difficulty results from the fact that parts of these components are not even technically mature yet. Nevertheless, improvements in power consumption, heat dissipation and footprint are in constant research by manufactures. So, to simplify the problem the equipment power consumption (commercial) per unity is used as a figure of merit to estimate OPEX. Further, to evaluate CAPEX all cost figures assume forward pricing at fully ramped-up high production volumes. Table 1 gives an overview of cost and power consumption figures of the most relevant components for the architectures under analysis.

Table 1 – Cost and power consumption parameters

Components	Type	Cost [cost unit]	Power [W]
WSS	1x5	7950	20
	1x9	10000	20
	1x20	17500	20
OXC	192:192	125000	75
MCS	8x16	7500	10
EDFA	20 dBm	1495	5
PS	1x2	20	0
	1x4	23	0
	1x6	78	0
	1x8	26	0
	1x12	130	0
	1x16	55	0
	1x24	160	0
	1x32	90	0
OAA	1x2	1400	10
	1x4	2200	10
	1x6	3100	10
	1x8	3900	10
OTF	1x1	2490	0.5
AWG	96 chs	3250	0

For each of the three architectures, different configurations were vastly considered as a result of the multiple combinations of node degrees and percentage of add and drop. The number of degree considered were 2, 4, 6 and 8 with the percentage of A/D up to 100% assuming a full DWDM range of 96 channels per degree. Optical components prices and nominal power consumption values were surveyed among several suppliers.

Since broadcast and select (B&S) WSS structure is common to all architectures its cost and power consumption were not added to the results. However, when additional ports were required for A/D structures on these PS and WSS switches, the increments were considered, especially for the CAPEX study. For example, a usual 4-degree ROADM uses one WSS 1x5 with four ports to B&S and the other one to A/D. Additional ports in the B&S structure to A/D results in an analysis of power budget depending on the number of PS it is more cost effective to use a WSS.

The following power losses were assumed: MCS=17dB, WSS=6dB, AWG=4dB and OXC=1dB. For the PS the power loss varies depending on the number of ports, and it was considered case-by-case using standard values. The defined power reception threshold was -14dBm, and every time this threshold was surpassed OAA was used. OAA parameters were defined considering a shared pump laser configuration. Secondary costs like mechanics and control electronics were not considered.

Cost per port (C_{PORT}) can be obtained from the total cost of the ROADM (C_{TOTAL}) subtracted from the cost of B&S structure ($C_{B\&S}$) and the result divided by the number of ports for add-drop (N_{PORT}): $C_{PORT} = (C_{TOTAL} - C_{B\&S}) / N_{PORTS}$. Once C_{PORT} was estimated for each solution under analysis, due to different steps of increment, a normalization process was considered.

Fiber OXCs were applied in the 192:192 configuration as suggested in [3], and MCS 8:16 as advised in [11]. WSS switch ports varied from 4 to 20. For the MCS architecture OTFs were used in 25% of the A/D ports for the legacy transponders using OOK (on-off keying) modulation. The use of tunable filter in all A/D ports would make the MCS approach in viable in terms of cost. It is important to notice that all considered architectures only use optical components already available in the market.

For the three architectures Figure 7 presents the normalized cost per A/D port for a 4-degree node varying the A/D percentage up to 100%. In this scenario MCS approach starts with the lowest cost but when A/D percentage increases over 20% OXC with WSS approach becomes a better option, and above 40% OXC becomes better than MCS. In addition, over 20% A/D percentage, MCS architecture needs extra ports in B&S structure resulting in a supplementary WSS 1x9 instead of power splitters to perform A/D. In the range of 50 to 80% MCS cost becomes more advantageous compared to OXC again. This happens because in OXC architectures the A/D ports are increased with an increment of 192 while in MCS it occurs in a softer increment of 16. In this way, MCS shows to be a technology more scalable. However, over 90% OXC architecture becomes advantageous over MCS once an extra WSS 1x20 rather than PS to perform A/D.

A similar comparison considering the same components used to evaluate cost per port for each structure is presented in Figure 8, but in this case power consumption is evaluated. The behavior is also similar. Since MCS follows a softer incremental approach power consumption increases accordingly. On the other hand, the other two architectures present steady power consumption until a second OXC module is needed. Above 25% of add and drop OXC approaches become more efficient

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in terms of power consumption than MCS approach.

The cost analysis allows the judgment of which architecture represents the lower CAPEX in a given condition. Considering that the three approaches provide the same features, once deployed their operations are basically the same. In that sense OPEX differs from each other in terms of power consumption.

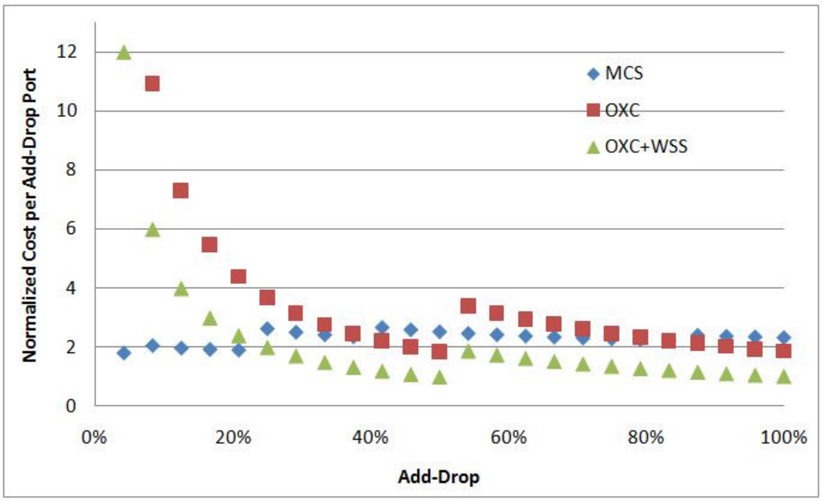

Fig. 7 - Cost per A/D port comparison in a 4-degree ROADM.

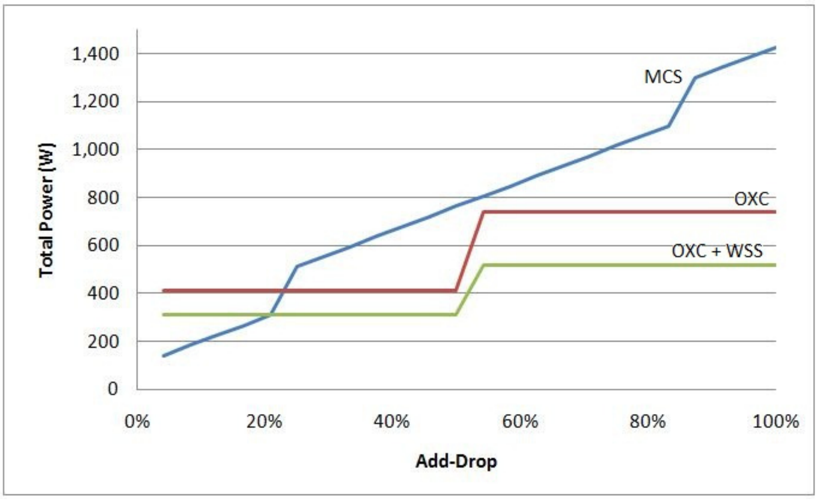

Fig. 8 - Power consumption comparison in a 4-degree ROADM.

The same process was repeated for 2, 6 and 8 degree scenarios. Taking the intersection points of Figures 7 and 8, and the correspondent ones for 2, 6 and 8 degree, it is possible to define which architecture presents better trade-off for CAPEX and OPEX in a given scenario. Figure 9 shows these results comparing MCS approach with each OXC approach. Because OXC with WSS always presents better trade-off compared to OXC, no further comparison between them is necessary.

For instance, looking to Figure 9a it is possible to define that for a 2-degree node MCS presents the best trade-off for CAPEX until it reaches 30% of add and drop. Above that OXC becomes more advantageous. From the OPEX point of view OXC is a better option above 20%, shown in Figure 9b.

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V. RESULTS DISCUSSION AND CONCLUSIONS

As discussed all over this work optical WDM networks needs to evolve in order to provide better flexibility in dealing with the client signal. Colorless, directionless and contentionless are indispensable features for high availability ROADMs. Since N:M WSS is not an available solution, other approaches are emerging.

Two full-CDC architectures and a third software contentionless variant were presented and compared in terms of CAPEX and OPEX in several scenarios. Figure 9 summarizes the results.

Considering the CAPEX, for most scenarios MCS is superior compared to OXC. However, OXC is superior for most of the scenarios from the OPEX perspective. A more consistent result is achieved when MSC approach is compared to OXC with WSS approach. In these cases a pattern becomes clear for both CAPEX and OPEX; The MCS approach is only better for lower add and drop rates, and the higher the node degree is, the lower its rate becomes.

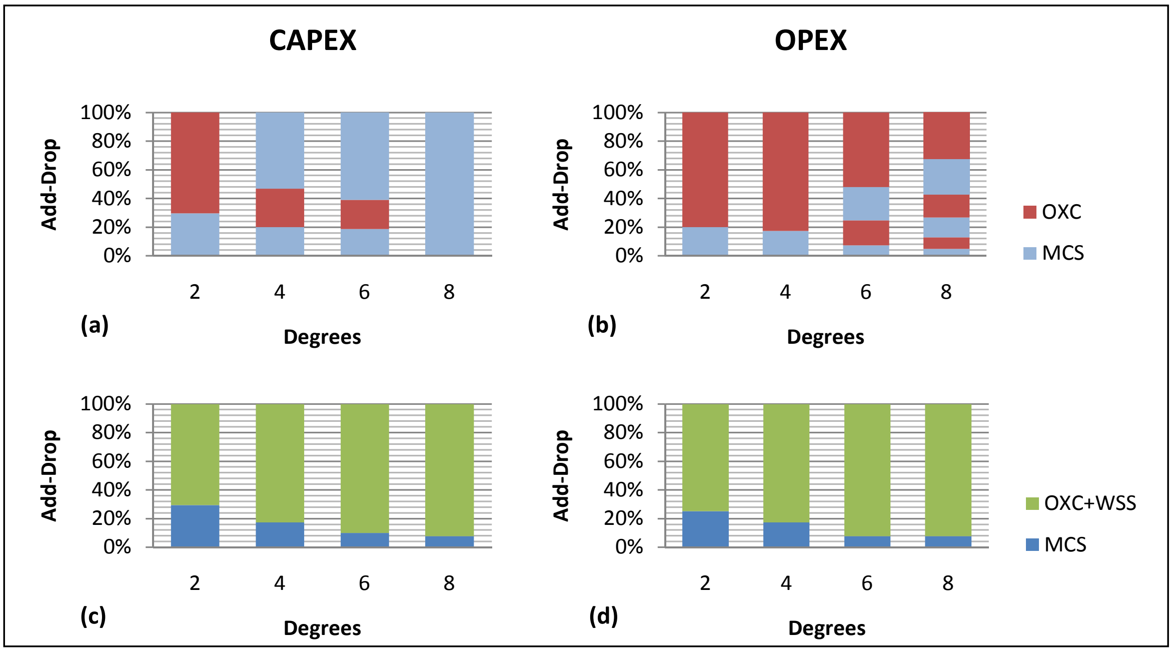

Fig. 9 - Best CAPEX and OPEX trade-off between architectures.

Consider a complete network scenario. Nodes closer to the borders naturally have few degrees, usually 2 to 4, and high add and drop rate, 30% or higher. This happens because these nodes are responsible for traffic aggregation. On the other hand, core nodes need much more degrees, usually up to 8, and low add and drop rate, commonly less than 10%. These nodes need to handle the aggregated traffic, but usually have few local clients.

Results shown in Figures 9c and 9d strongly suggest that these two architectures will be the dominant ones in the next generation WDM networks, the MCS approach being the best option for the core nodes, and OXC with WSS approach the most suitable for the edge nodes.

Considering the deployment, OXC with WSS architecture leads to the conclusion that all A/D ports planned for the site will be installed from day 1, since it does not follow an incremental approach. MCS A/D ports, on the contrary, will be added as needed.

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Nonetheless, as stated in section III, these conclusions are based in two assumptions: (a) 25% of legacy support for OOK transponders is enough (considering the legacy), since all the calculation for MCS architecture considered only this percentage of tunable filters (for coherent technologies), and (b) RWA algorithm is actually able to virtually eliminate the contention inherent to the OXC with WSS architecture.

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REFERENCES

[1] P. D. Colbourne and B. Collings, "ROADM switching technologies", in Optical Fiber Communication Conference. Optical Society of America, 2011, p. OTuD1.
[2] T. Watanabe et al., "Compact PLC-based transponder aggregator for colorless and directionless ROADM", in Optical Fiber Communication Conference. Optical Society of America, 2011, p. OtuD3.
[3] R. Jensen et al., "Highly Scalable OXC-based Contentionless ROADM Architecture with Reduced Network Implementation Cost", in Optical Fiber Communication Conference., Optical Society of America, 2012, p.NW3F.7.
[4] M. D. Feuer et al., "Intra-node contention in dynamic photonic networks", J. Lightwave Technol., vol. 29, no. 4, pp. 529–535, Feb 2011.
[5] P. Pavon-Marino and M. Bueno-Delgado, "Distributed online RWA considering add/drop contention in the nodes for directionless and colorless ROADMs", in National Fiber Optic Engineers Conference, Optical Society of America, 2012, paper NW3F.4.
[6] S. Perrin, "The need for next-generation ROADM networks", Heavy Reading, September 2010.
[7] L. Eldada, "ROADM architectures and technologies for agile optical networks", DuPont Photonics Technologies, 100 Fordham Road, Wilmington, MA, 01887, USA, 2007, p. Proc. SPIE 6476.
[8] J. Zyskind and A. Srivastava, "Optically Amplified WDM Networks", ser. Academic Press. Elsevier, 2010.
[9] Y. H. Ishii et al., "MEMS-based 1x43 wavelength-selective switch with flat passband", in European Conference on Optical Communication, 2009.
[10] S. Tibuleac and M. Filer, "Trends in next-generation ROADM networks", in 37th European Conference and Exposition on Optical Communications. Optical Society of America, 2011, p. Th.12.A.1.
[11] I. W. Winston, "Optimum Architecture for MXN Multicast Switch-Based Colorless, Directionless, Contentionless, and Flexible-Grid ROADM", in Optical Fiber Communication Conference. Optical Society of America, 2012, p. NW3F.5
[12] R. Jensen, "Optical switch architectures for emerging colorless/directionless/contentionless ROADM networks", in Optical Fiber Communication Conference. Optical Society of America, 2011, p.OThR3.
[13] W. V. Heddeghem et al, "Power consumption modeling in optical multilayer networks", Photonic Network Communications, vol. 24, pp. 86-102, Jan. 2012.
[14] J. Baliga et al, "Energy Consumption in Optical IP Networks", J. Lightw. Technol., vol.27, n. 13, pp. 2391-2403, Jul. 2009.
[15] D. C. Kilper et al, "Power Trends in Communication Networks", J. Sel. Topics Quantum Electron., vol. 17, n. 2, pp. 275-284, Apr. 2011.
[16] G. P. Agrawal,"Fiber-optic Communication Systems". Wiley, 2010.
[17] S. Aleksic, "Energy and entropy flow in erbium-doped fiber amplifiers: a thermodynamic approach", J. Lightw. Technol., vol.30, pp. 2832-2838, Sept. 2012.
[18] A.W.Naji et al, "Modeling and characterization of a new three-stage quadruple pass EDFA", pp. 458-461 in ICCCE, Jul. 2012.
[19] R. S. Tucker, "Green Optical Communications—Part I: Energy Limitations in Transport", IEEE Journ. of Selected Topics in Quantum Electronics, vol. 17, no. 2, pp. 245-260, Mar.-Apr., 2011.
[20] R. S. Tucker, "Green Optical Communications—Part II: Energy Limitations in Networks", IEEE Journ. of Selected Topics in Quantum Electronics, vol. 17, no. 2, pp. 261-274, Mar.-Apr., 2011.
[21] K. Grobe et al. "Cost and energy consumption analysis of advanced WDM-PONs", Communications Magazine, IEEE , vol.49, no.2, pp. 25-32, Feb. 2011.

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