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Influence of the ROADM architecture on the cost-per-bit in C+L+S multi-band optical networks

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ABSTRACT

A detailed cost-per-bit analysis of four C+L+S multi-band (MB) reconfigurable optical add-drop multiplexers architectures is presented and discussed. A network cost analysis, including these MB nodes is also presented. The MB common-band architecture, based mainly on C-band components, is the most cost effective architecture in almost all the network scenarios considered.

Keywords: cost-per-bit, multi-band, optical networks, reconfigurable optical add-drop multiplexers.

1. INTRODUCTION

Nowadays, optical networks are required to have more capacity and flexibility due to the growth of new services, such as autonomous driving, virtual reality, cloud and 5G services. The foreseeable traffic generated by these new services will consume all available C-band resources in a near future, and, so, multi-band (MB) and spatial division multiplexing (SDM) solutions have been being explored in recent years to increase network capacity [1].

The MB solution consists in the exploitation of the full low attenuation spectrum available in a single mode optical fiber, allowing transmission beyond the C-band, and is seen as a near to medium-term solution to solve the capacity problem [1]. Several studies have already addressed both transmission issues, and node architecture solutions for operating a MB network [2–4]. In particular, in [3], a cost analysis considering a C+L+S network scenario is studied considering both transmission and node architecture issues. The node architectures considered were the MB baseline, where switching between bands is not allowed, and the MB common-band architectures, that uses mainly C-band components. In [2], a MB all-optical wavelength converter (AO-WC) architecture was presented and , in [4], a MB architecture called compact architecture that uses only components that work in all bands has been proposed and a network performance analysis has been done. Despite there are already, at least, four types of MB ROADM architectures proposed in the literature to the authors best knowledge a comprehensive cost analysis comparison between these architectures remains to be done.

In this paper, a detailed cost-per-bit analysis of all four MB reconfigurable optical add-drop multiplexer (ROADM) architectures proposed in the literature - the MB baseline, the MB AO-WC, the MB common-band and the MB compact architectures - is presented and discussed considering the C+L+S band scenario. A comparison with a SDM node scenario is also performed.

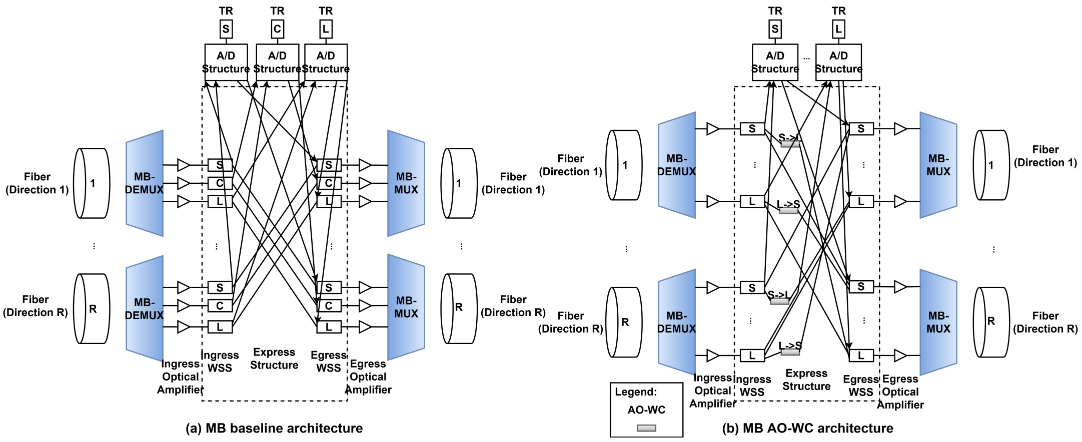
This paper is organized as follows. In section 2, the four MB architectures are presented, as well as their cost model. In section 3, the cost-per-bit of the four MB architectures is calculated and the cost-per-bit considering the British Telecom (BT-UK) and CONUS networks is studied considering the four MB node architectures. A comparison with a SDM node is also performed. In section 4, the main conclusions are drawn.

2. C+L+S MULTI-BAND ROADM ARCHITECTURES COST MODELLING

This section presents the MB architectures studied in this work, as well as the cost of each one of the components used to build these MB architectures. Fig. 1 shows the four R-degree MB architectures studied: the MB baseline architecture is shown in Fig. 1a [3], the MB AO-WC architecture is shown in Fig. 1b [2], the MB common-band architecture is shown in Fig. 1c [2, 3], and the MB compact architecture is shown in Fig. 1d [4].

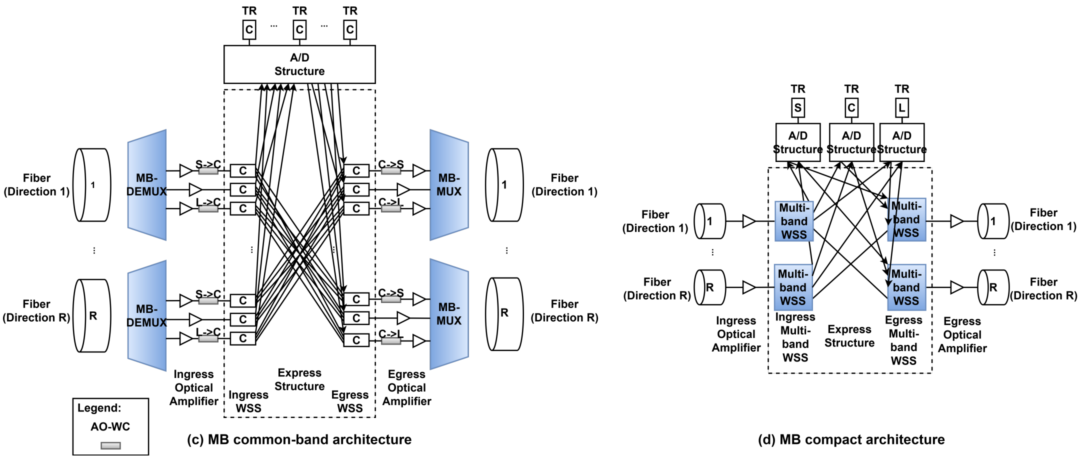
The MB baseline architecture shown in Fig. 1a, consists of a MB demultiplexer (DEMUX) and MB multiplexer (MUX), optical amplifiers (two Erbium-doped fiber amplifiers (EDFAs) for C- and L-bands and one Thulium-doped fiber amplifier (TDFA) for S-band) at the DEMUX output and at the MUX input, and a bank of parallel single-band wavelength selective switches (WSSs), which are connected to single-band WSSs at the output ROADM directions. The wavelengths can be switched to any direction within each band, however, switching between bands is not possible. As a main advantage, the equipment dedicated to other bands may not be acquired at the beginning of network operation, when the network traffic is not enough to justify the use of other bands [4].

To add the possibility of switching wavelengths between bands, the MB architectures presented in Figs. 1b, 1c and 1d were proposed in [2–4]. The AO-WC and common-band architectures use AO-WCs, which have the function of converting multiple wavelengths between bands. The AO-WC architecture uses dedicated band components in the express and add/drop (A/D) structures, whereas the common-band architecture uses only C-band components on express and A/D structures thanks to the AO-WCs, reducing the node complexity and cost. A disadvantage of using the AO-WC and common-band architectures is the use of AO-WCs, which is a technology, that is still in a research phase [3]. The compact architecture uses in the express structure, MB WSSs that work simultaneously in multiple bands and reduce the amount of equipment needed. However, the use of this architecture requires the acquisition of MB components at the beginning of the network operation, leading to a high initial investment as opposed to the previous architectures.



(a) MB baseline architecture

(b) MB AO-WC architecture



(c) MB common-band architecture

(d) MB compact architecture

Fig. 1: R-degree MB route-and-select (R&S) architectures.

To compute the cost of each MB ROADMs, the number of channels considered in the C-, L- and S-bands is, respectively, 87, 130 and 148 channels for a 50 GHz channel spacing, and a R&S ROADM architecture with colorless and directionless (CD) A/D structure with an A/D ratio of 25% is considered. The component costs, presented in Table 1 are extracted from [3], and are calculated in relation to the cost of a C-band EDFA. The L-band components are assumed 20% more expensive than C-band components, and the cost of the S-band components depends on a multiplicative factor α, which ranges from 1.2 to 1.5 [3, 5]. The AO-WC cost depends on the C-band transponder (TR) cost, with the parameter β ranging from 0.5 to 2, and the fiber lease cost is 0.33 per fiber/km/year [3, 5]. In our calculations, we considered α=1.5 and β=2, which corresponds to a less favourable cost scenario.

Table 1: Relative cost of components for C-, L- and S-bands

Components	Cost			
	C-band	**L-band**	**S-band**	**Variable name**
EDFA	1	1.2	-	$Cost_{xDFA,b}$
TDFA	-	-	α	$Cost_{xDFA,b}$
1×2 WSS	1.25	1.5	1.25α	$Cost_{WSS,b}$
1×4 WSS	2.5	3	2.5α	$Cost_{WSS,b}$
1×9 WSS	5	6	5α	$Cost_{WSS,b}$
1×20 WSS	7.5	9	7.5α	$Cost_{WSS,b}$
1×40 WSS	15	18	15α	$Cost_{WSS,b}$
1×80 WSS	30	36	30α	$Cost_{WSS,b}$
Transponder (TR)	36	43.2	36α	$Cost_{TR,b}$

Components	Cost	
	C+L+S-bands	**Variable name**
Optical Amplifier (C+L+S bands)	2.2167+α	$Cost_{MB,EDFA}$
1×N_{bands} MB MUX/DEMUX	0.04	$Cost_{MB,MUX/DEMUX}$
AO-WC	36β	$Cost_{AO-WC}$
1×9 MB WSS	7α	$Cost_{MB,WSS}$
1×20 MB WSS	10α	$Cost_{MB,WSS}$
1×40 MB WSS	20α	$Cost_{MB,WSS}$
Cost per fiber/km/year	0.33	-

The cost of the CD A/D structure of the MB ROADM is given by

$$Cost_{A/D,CD,b} = 2N_{A/D}Cost_{WSS,R\times 1,b} + 2N_{A/D}Cost_{WSS,1\times M,b} + MCost_{TR,b} \qquad (1)$$

where $N_{A/D}$ is the number of A/D cards, M is the number of TRs and the variable b identifies the band dependence, with b=C, L or S, since (1) can be used to calculate the cost of the CD A/D structure for any of the bands. The express structure total cost of the baseline, AO-WC and common-band architectures (Fig. 1) is given by,

$$Cost_{Express} = \Sigma_b^{N_{bands}}(Cost_{Express,b}) + N_{AO-WC}Cost_{AO-WC} + 2RCost_{MB,MUX/DEMUX} \qquad (2)$$

where N_{AO-WC} is the number of AO-WCs and $Cost_{express,b}$ is the express structure cost in each band given by

$$Cost_{Express,b} = R(2Cost_{WSS,a} + 2Cost_{xDFA,b}) \tag{3}$$

where a=b, for the baseline and AO-WC architectures express structure cost and a=C, for the common-band architecture express structure cost. The express structure total cost of the MB compact architecture is given by

$$Cost_{Compact,Express} = R(2Cost_{MB,WSS} + 2Cost_{MB,EDFA}) + 6RCost_{MB,MUX/DEMUX} \tag{4}$$

For comparison purposes, we also model the cost of a SDM ROADM architecture with wavelength granularity switching without lane changes [6]. The SDM ROADM A/D structure and the express structure costs are given, respectively, by $3 \times Cost_{A/D,CD,b}$ and $3 \times Cost_{Express,C}$, since we use 3 fibers working on the C-band.

3. RESULTS ANALYSIS

In this section, a cost-per-bit analysis of the four MB ROADM architectures is performed in section 3.1, alongside with a comparison with a SDM ROADM with 3 fibers per direction. In section 3.2, a MB network scenario is analysed, and two different networks (BT-UK and CONUS 60) are considered.

3.1. Cost comparison between MB node architectures

This subsection studies the cost-per-bit of the four MB architectures presented in section 2. The cost-per-bit is defined as the ratio between the total node cost and the total node A/D capacity, which depends on each TR bit rate (100 Gb/s per transponder is assumed) and on their number. The cost-per-bit is normalized to the cost of a reference scenario, a R&S C-band node with 2 directions, where the total node A/D capacity is 4.4 Tb/s.

Fig. 2a shows the normalized cost-per-bit of each R&S CD MB ROADM architecture and of the SDM ROADM considering 2, 4, 8 and 16 directions. In addition, Fig. 2b shows the required number of AO-WCs considering R=2, 4, 8 and 16, for the AO-WC and common-band architectures.

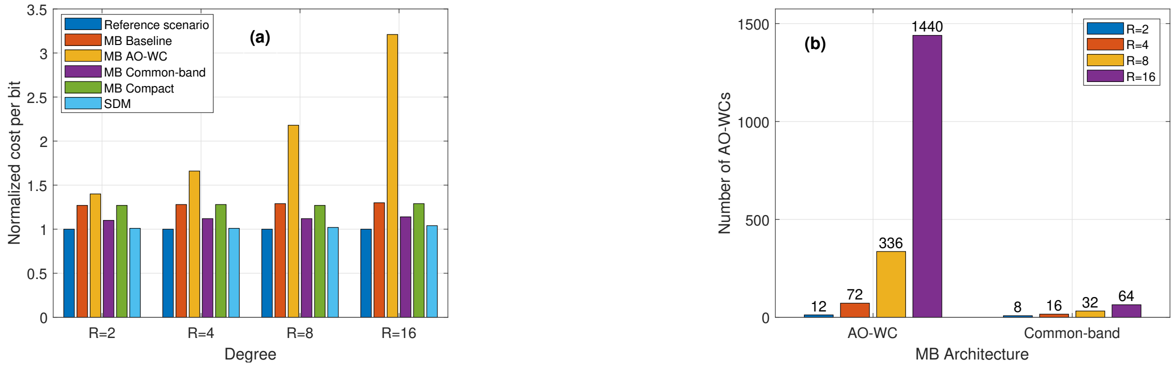


Fig. 2: Normalized cost-per-bit of the MB and SDM ROADM architectures (a) and number of AO-WCs for AO-WC and common-band architectures (b).

As can be observed in Fig. 2a, the cost-per-bit of the SDM architecture is quite similar (only approximately 2% higher) to the reference scenario cost, since both SDM architecture total cost and the node A/D capacity depend practically only on the TRs number. The cost-per-bit of the SDM architecture is lower compared to the four MB architectures due to the lower cost of the C-band TRs. The cost-per-bit of the SDM, baseline, common-band and compact architectures remains unchanged with the number of directions increase since their cost is mainly dependent on the TRs cost (the number of TRs roughly doubles with the number of directions, for R=2, 4, 8 and 16 are, respectively, 183, 365, 730 and 1460 TRs). The common-band architecture cost-per-bit is very similar to the reference scenario cost, being the compact and MB baseline architectures slightly expensive. For the common-band architecture, the number of AO-WC doubles with the number of directions, Fig. 2b, but their contribution to the total node cost is low. While, for the AO-WC architecture, the number of AO-WCs increases hugely with the number of directions, resulting in a significant contribution to the total node cost for a higher number of directions, as shown in Fig. 2a, being the AO-WC architecture the most costly architecture. The results obtained in Fig. 2a for the baseline, common-band and SDM architectures, are very similar to the results of Fig. 3 of [3], for α=1.5, β=2, without considering the fiber lease cost.

3.2. Cost comparison between two MB networks

This subsection studies the cost-per-bit of two MB networks, a smaller network - BT-UK, and a larger one - CONUS 60 [5, 7]. The BT-UK network topology has 22 nodes, an average link length of 147 km and an average node degree of 3.2. In the CONUS 60 network, the total number of nodes is 60, the average link length is 445 km and the average node degree of 2.6.

Figs. 3a and 3b show the cost-per-bit for the BT-UK and CONUS 60 networks, respectively, as a function of the fiber lease cost per km and year considering MB and SDM R&S CD ROADM architecture with an A/D ratio of 25%. The duration of the fiber lease considered is 5 years. From Figs. 3a and 3b, it is observed that the cost-per-bit of MB architectures has a smooth increase with the fiber lease cost since only one fiber per direction is used, as opposed to the sharper increase in the SDM network scenario where 3 fibers per direction are considered. Fig. 3 also shows that, the compact and baseline architectures present a similar cost-per-bit due to the use of a similar A/D structure. The common-band architecture presents the lower cost-per-bit compared to the other MB architectures for both topologies due to the use of only C-band components. For the real fiber lease cost (0.33), the common-band architecture presents the lowest cost-per-bit compared to the other MB architectures for both topologies. The cost-per-bit in Fig. 3a increases less than in Fig. 3b for all the architectures, since the CONUS 60 network has a higher number of nodes and a longer total network length, than the BT-UK network. Furthermore, in the CONUS 60 network, the SDM architecture exceeds the cost-per-bit of all MB architectures before the real fiber lease cost (0.33) is reached. In the BT-UK network, below the fiber real cost, only the cost-per-bit of the common-band architecture is exceeded by the SDM solution cost. As concluded previously, the AO-WC architecture is not a good choice in terms of cost-per-bit compared to the other MB architectures.

The results presented in Fig. 3 are similar to the ones presented in Fig. 3 of [3], for α=1.5 and β=2 and in Figure 3 of [5], for the MB baseline, common-band and SDM architectures.

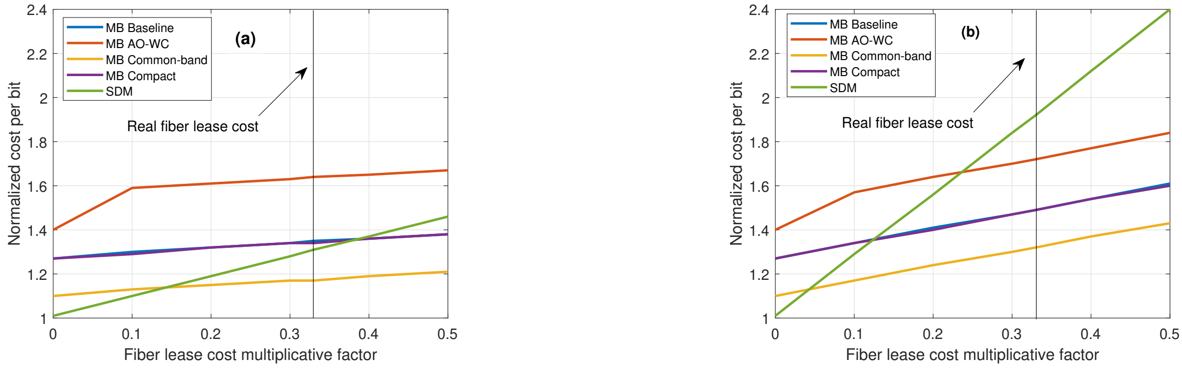


Fig. 3: Normalized cost-per-bit as a function of the fiber lease cost considering both MB and SDM ROADMs for the (a) BT-UK network, and (b) CONUS 60 network.

4. CONCLUSIONS

In this work, we have studied the required number of hardware components, cost-per-bit and suitability of four C+L+S MB node architectures and their impact in network scenarios. We have concluded that the AO-WC node architecture presents the highest cost-per-bit compared to the other MB architectures, due to the high number of AO-WCs and is regarded has an architecture to be discarded. The common-band architecture presents the lowest cost-per-bit due to the use of only C-band components, decreasing the total cost of the node. Both compact and baseline MB node architectures have similar costs. In the BT-UK and CONUS 60 networks scenarios, the most economically promising architecture is the common-band architecture, since it is less expensive than SDM for fiber lease costs above 0.15, however, it relies on a technologically immature component, the AO-WC. For an immediate network deployment, the MB baseline architecture seems advantageous over the compact architecture, although their very similar cost-per-bit, due to its use of commercially available hardware components.

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