Long-Term CAPEX Evolution for Slotted Optical Packet Switching in a Metropolitan Network

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***Abstract*—In this paper, we assess a new technology, WDM Slotted Add/Drop Multiplexer (WSADM) which has been proposed as a new transport network technology based on sub-wavelength switching. This solution is envisaged to be deployed in the metropolitan area in order to improve bandwidth utilisation and minimise the overall cost of the network. In order to assess the relative cost of WSADM, we compare it, on the one hand, with OTN over WDM as a dominant transport solution in the current metropolitan network, and, on the other hand, with POADM (Packet Optical Add/Drop Multiplexer) and TWIN (Time-domain Wavelength Interleaved Network) as two other promising sub-wavelength switching solutions. The cost assessment is carried out over a ten-year period of time, taking into account the predicted traffic evolution. We consider a hub-and-spoke virtual network mapped on a physical topology inspired from a European operator network. The comparative study shows that, considering the adopted cost model, WSADM presents a lower cost than other technologies, and a limited growth during the studied period.**

***Index Terms*—Optical packet switching, metropolitan network, cost assessment.**

I. INTRODUCTION

The optical communications market is undergoing a seismic shift. This is driven in part by the continuous growth of the traffic and also by the transition of the operators' networks toward a fast-paced cloud, software-driven, and data centre-optimised design model. This disruptive network model is leading to a tremendous increase in deployed capacity and a fast ramp-up of 100 Gbps transport technologies such as Optical Transport Network (OTN). The challenge of the emerging network model is that it should be built on an underlying technology enabling the transition towards a scalable and high-volume transport network, but that it should also be a low-cost solution enabling an efficient utilisation of the optical resources.

In this context, Optical Packet Switching (OPS) solutions have been proposed as candidates for the next generation transport networks, as they facilitate network resource optimisation thanks to their excellent switching granularity. Many OPS solutions have been presented in the literature [1] but few have proved their efficiency [2]. POADM (Packet Optical Add/Drop Multiplexer) and TWIN (Time-domain Wavelength Interleaved Network) are two such promising OPS solutions that have been shown able to meet the next-generation network requirements in terms of performance [3]. Nevertheless, these technologies rely on custom optical components that are not currently commercially available, in particular on fast-tunable burst-mode emitters.

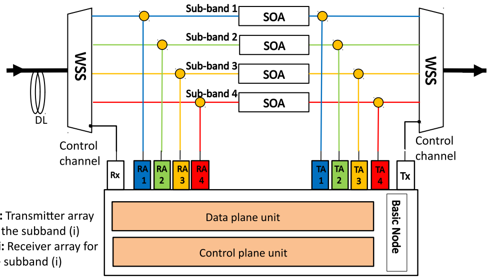

Fig. 1: WSADM node structure

In the perspective of relying on more widely available components, the WDM Slotted Add/Drop Multiplexer (WSADM) technology has recently been proposed in [4] as a new transport network technology. WSADM builds on POADM as it is a slotted optical packet switching technology operating on ring-shaped virtual networks and relying on a similar control plane. However, WSADM differs from POADM in its data plane, which relies on optical components that are more mature than those requested by the POADM data plane.

A new technology (such as TWIN, POADM and WSADM) can be introduced in the network only if it is expected to satisfy network requirements with lower cost than existing technologies, typically OTN/WDM which dominates the metro transport networks. Therefore, the present study aims at assessing the cost of OPS technologies compared to OTN/WDM.

We focus here on cumulative Capital Expenditures (CAPEX), assuming that a network is deployed today, and that its capacity is increased when necessary to take account of a yearly traffic growth of 30%. The objective of the present study is not to find the cheapest technology because our cost model indeed cannot perfectly predict the cost of non-commercialised components. Moreover, the price of equipment depends on complex business relationships and on equipment manufacturers' marketing strategies. However, under a set of realistic tariff assumptions which are applied to all technologies, the study attempts to discriminate between OPS-based and legacy transport technologies.

Section II presents WSADM and the other competing technologies, and highlights their important features. Section III describes the network scenarios and the cost model. Section IV discusses the obtained results and Section V concludes the paper.

II. BENCHMARKED TECHNOLOGIES

A. WSADM description

WSADM is a sub-wavelength switching solution based on synchronous time-slotted access to the medium. The optical packet is segmented in ten pieces that are transmitted in parallel on ten wavelengths during a time slot of 1 μs. The transmitter is an integrated device including an array of ten fixed lasers, an AWG and a Semiconductor Optical Amplifier (SOA) to boost the WDM signal. Before sending the optical packet, the source node checks whether the slot is available or not thanks to a control channel that carries control slots (one per slot). When a node emits an optical packet, the control slots marks the data slot as ”busy”. Once transmitted, the optical packet transits transparently (without Optical to Electrical conversion) through the intermediate nodes. Indeed, along its path to the destination node, the optical packet passes, at each intermediate node, through an optical coupler that splits it into two replicas. If the current node is the final destination, the first replica is received by an integrated WDM Rx, including one pre-amplifier, one AWG and an array of ten photo-diodes, while the second replica is blocked and erased by an optical gate; the control slot is then modified to indicate that the data slot is available. The optical gate is a SOA and is related to one specific sub-band of wavelengths as shown in Fig. 1. Otherwise (the current node is only a transit node), the first replica is discarded and the second replica of the optical packet crosses the optical gate and continues its way towards the final destination.

We distinguish two types of nodes in WSADM: those on the ring (described as “optical bridge nodes”) and the node that “closes” the ring by an electrical node (described as “optical switch node”). In normal conditions, no traffic crosses this switch node. The electrical node is only used in case of single cable failure in order to preserve global connectivity.

Such an architecture is well suited to a concentration/distribution (i.e. hub-and-spoke) traffic matrix where the optical switch node interfaces with another network (another ring, or the backbone network).

We assume here that WSADM uses an opportunistic emission scheme in which a node having a packet to transmit uses the first available time slot.

B. *Legacy technology : OTN/WDM*

The Optical Transport Network (OTN) [5] technology is based on circuit switching and relies on a connection oriented paradigm. OTN over WDM has already been rolled out in large operators’ backbone networks and gets progressively closer to the access network. As depicted in Fig. 2, an OTN switch is connected to the fiber via a Reconfigurable Optical Add and Drop Muliplexer (ROADM) that ensures the insertion, the extraction or the transparent switching of data. OTN network nodes provide functions related to transport, multiplexing, switching, management, supervision and survivability of optical channels.

In OTN, the path between source and destination nodes is pre-established. Switching at intermediate nodes is performed either optically by ROADM or electrically by the OTN electrical switch. Consequently, it is possible to limit the network cost by reducing the number of transponders (which represent the major cost of an optical network). However, savings are not systematic and depend on many factors such as the distribution of the traffic matrix and its evolution, the degree of meshing of the network topology and the flow granularity (ratio between the client and the line bit rates).

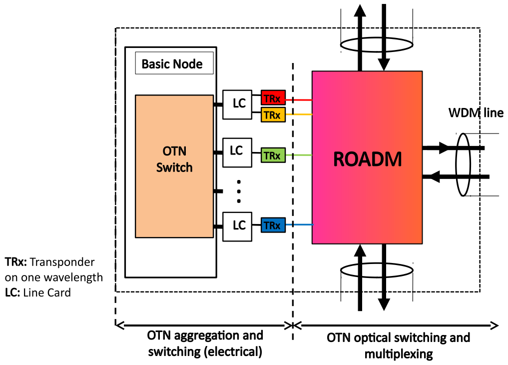

Fig. 2: OTN node structure

C. *Competing Optical Packet Switching technologies*

1) POADM: After pre-amplification, the optical packets arriving at a POADM node are wavelength de-multiplexed. Then, each optical packet passes through an optical coupler that splits it into two replicas. The first one is dropped towards a wavelength receiver (Rx) that discards optical packets in transit and only processes the optical packets that should be received. The second replica crosses an optical gate which can be either in ON state to let transit traffic pass, or in OFF state to block optical packets that should not go beyond the node. The optical gate could consist in a SOA. New optical packets can be inserted on any available wavelength in an opportunistic manner (as in WSADM) using a fast tunable transmitter (Tx). Transit and new optical packets are optically multiplexed and amplified. The control packet carried over the control channel is updated to report the occupancy status of each WDM slot to the next node. The POADM node structure is illustrated in Fig. 3 [6]. Several medium access control (MAC) protocols have been proposed in the literature for POADM [7]. In the present study, we adopt an opportunistic MAC [8] which allows each node to send a single optical packet whenever a slot is available.

2) TWIN: In TWIN [9], a separate wavelength is allocated to each destination nodes. When a source has an optical packet to send to a given node, it tunes the laser to the wavelength associated to that node for the duration of the packet. Between the source and the destination node, the optical packet is

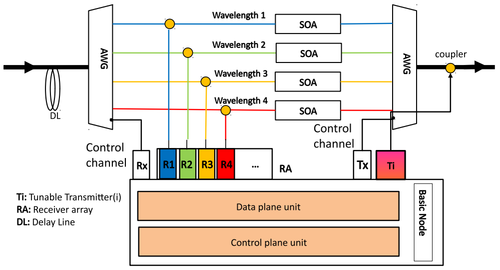

Fig. 3: POADM node structure

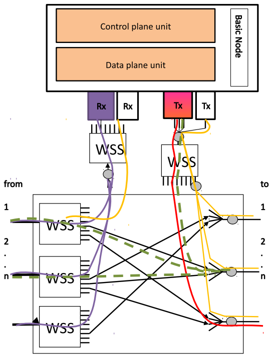

Fig. 4: TWIN node structure

transparently, wavelength-routed by the "intermediate" nodes using an optical switch based on WSS (Wavelength Selective Switches). The paths between the source nodes and a given destination node form a multipoint-to-point tree. WSS are used to reconfigure the trees at network setup, when a failure occurs, or when a new branch is created. Fig. 4 illustrates the TWIN node structure with a fixed wavelength Rx and a tunable Tx.

The fact that all sources share the same medium to reach a specific destination leads to possible collisions at each merging point of the tree. To resolve this problem, TWIN relies on a scheduler to coordinate sources transmission [10]. The purpose of the scheduling is to periodically assign specific slot(s) to source-destination pairs in such a way that no collision occurs at the intermediate nodes. A schedule consists of a predefined number of slots. For each source node, the scheduler specifies the periodic pattern that shall be used to transmit optical packets to any destination node.

III. NETWORK SCENARIO AND COST MODEL

The assessment of the cost of WSADM, OTN, TWIN and POADM technologies is done in a "hub-and-spoke" (HAS) scenario, where the traffic is concentrated at a specific node, referred to in the following as hub, that sends/receives traffic to/from all the other edge nodes. All connections between edge nodes have to pass through the hub. We distinguish two HAS scenarios, the "symmetric HAS" and the "asymmetric HAS". In the first scenario, we assume that the same amount of traffic is exchanged between the hub and each edge node of the network. In the second scenario, the amount of traffic exchanged between the hub and the edge nodes depends on an (arbitrary) weight attributed to each node. Weights vary between 0.01 and 0.25.

This scenario is inspired from the current metropolitan network where the concentration node (hub) is responsible for ensuring connection between the metropolitan area nodes and the core network. For this scenario, we assume that the upstream traffic load (from the edge nodes to the hub) and the downstream traffic (from the hub to the edge nodes) are respectively equal to 20% and 80% of the total traffic exchanged between the hub and the edge nodes (spokes).

The considered network topology illustrated in Fig. 5 is derived from a European core network composed of 17 nodes and 26 links. We generate a synthetic yearly traffic matrix for a metropolitan area network with ten million users inspired from [11]. The set of traffic demands presents a yearly growth of 30% which corresponds to a tenfold increase of the traffic over ten years.

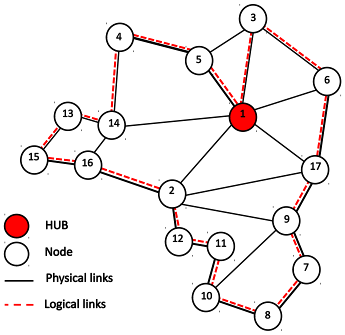

Fig. 5: Network topology

The logical topology considered for both POADM and WSADM consists in one ring that crosses all the nodes as depicted in Fig. 5. We consider a bi-directional WSADM/POADM network, and each node selects the direction in which to send optical packets based on the shortest path in terms of distance. We assess the cost of WSDAM using two transponder array bitrates: 10x10 Gbps (referred to in the following as 10G-WSADM) and 10x100 Gbps (referred to in the following as 100G-WSADM). For POADM, we consider an array of ten receivers at the reception side.

To build the TWIN trees, we firstly construct a spanning tree [12] that covers all the network. Then, for each node of the network, we deduce from the spanning tree one tree per node, where the node in question represents the root and the other nodes represent the leaves of the tree.

For OTN, the shortest path algorithm is used to build paths between the hub and each edge node. In the following, we consider two types of OTN: "transparent OTN", where wavelengths are dropped only at the final destination node, and "opaque OTN", where wavelengths are dropped at each intermediate node along the path. In this case, the dropped traffic is aggregated with the traffic of other nodes arriving over other interfaces and with the traffic emitted by the local node. It is then re-emitted towards its destination.

The dimensioning of the network relies on heuristics:

- for OTN and TWIN, the sent/received traffic by one Tx/Rx, should not exceed 80% of the total capacity of each element [13];
- for POADM and WSADM, the wavelength utilisation should not exceed 80% [6].

The respective cost models of OTN and OPS technologies used in the paper are shown in table I and table II. The cost values are normalised to the cost of one 10 Gbits/s transponder and are inspired from previous studies [14] and [15]. In the model cost, the basic node includes the chassis, the physical and mechanical assembly, the switch, power supplies cooling and control and management plane hardware and software.

In the cost analysis, in order to consider the fibre cost, we have included the cost of a 50 GHz channel /km/year.

TABLE I: Cost of OTN/ROADM

Components	Cost
OTN Switch (8 slots)	5
OTN Switch (16 slots)	7.3
OTN Switch (32 slots)	12
OTN Switch (64 slots)	30
OTN Switch (128 slots)	75
Line Card 1x100G	12
Fixed wavelength TRx-100G	8
N-degree colorless OXC ($2 \leq N \leq 9$)	N*16.8
N-degree colorless OXC ($9 < N \leq 20$)	N*20.8
Wavelength leasing cost (per km/year)	0.004

TABLE II: Cost of OPS technologies

Components	Cost		
	TWIN	POADM	WSADM
Basic node	4	4	4
Array of 10 x fixed TRx-10G			5
Array of 10 x fixed TRx-100G			35
Tunable Tx-100G	24	24	
Fixed wavelength Rx-100G	6		
Array of 10 x fixed wavelength Rx-100G		18	
SOA		0.4	0.4
WSS	4		4
AWG/MuX		0.9	
Fixed TRx-10G for control plane	1	1	1
Wavelength leasing cost (per km/year)	0.004	0.004	0.004

This cost is derived from a dark fibre leasing cost divided by the number of possible channels, that we consider here equal to 80. This parameter - which reflects that a deployed fibre + amplifiers infrastructure offers a finite spectral resource - was already taken into account in past works on POADM dimensioning [16] and recently became more commonly used in the context of flexgrid network cost analysis [17]. The cost that we assumed in [16] was based on typical dark fibre cost in the past decade [18]. We have updated these costs by taking into account recent data [19] indicating a signification reduction of the dark fibre leasing cost (mainly due to the increase of the fibre content of the recently installed cables).

IV. Results and discussion

A. Symmetric hub-and-spoke scenario

Using our heuristic dimensioning methods, we have computed the evolution of the total cost over the ten-year period for the studied technologies. As traffic increases, more resources (equipments, wavelengths) have to be provisioned and deployed. Fig. 6 illustrates this evolution for the six considered technologies and shows that 100G-WSADM presents the lowest cost. It is 45% and 10% cheaper than transparent OTN in the first and tenth year respectively; it is also 55% and 50% cheaper than opaque OTN in the same years. The WSADM cost is close to that of POADM during the first 8 years, then, it becomes lower by around 10% in the tenth year, whereas, compared with TWIN, the cost of WSADM is consistently lower over the years.

In order to analyse more finely the obtained results, we decompose the cost into three parts:

- the cost of transponders (i.e., Tx/Rx cost),
- the cost of electrical and optical switch (i.e., switching cost),
- the cost of leasing the wavelengths (i.e., wavelength cost).

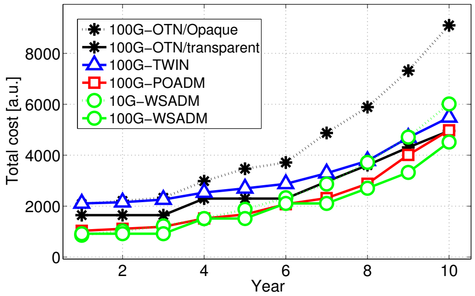

Fig. 6: Total cost of the symmetric HAS scenario

This is shown in Fig. 7. We note that for all technologies, the cost of Tx/Rx is quite significant whereas the cost of wavelengths has a minor impact. The importance of the switching cost depends on the technology: it is more important for OTN and TWIN than for POADM and WSADM, for which the transponders' cost is the lion's share of the total cost (more than 90% in the case of WSDAM-100G).

As the cost of Tx/Rx has an important impact on the total cost, we plot in Fig. 8 the number of transponders (TRx) required by each technology over the years. To compute the number of TRx in the case of TWIN and POADM, we take the maximum between the number of Rx and the number of Tx. We note that the number of TRx for WSDAM-10G and POADM is the highest and steeply increases with the traffic over the years. Indeed, the ring network is shared between all the nodes for WSDAM and POADM. Therefore, with a yearly traffic increase of 30%, the maximum capacity of one band/one wavelength of WSDAM-10G/POADM is quickly reached, and additional resources have to be provisioned. For WSDAM-100G, the high capacity of the band (i.e., 1 Tbps) allows avoiding a steep growth of the number of TRx, although the ring is also shared between all the nodes.

On the other hand, for TWIN, as a wavelength is shared only between the flows intended to a given destination node, the number of Tx/Rx increases slowly over the years. For OTN, the wavelength is dedicated for only one source/destination couple in the case of transparent OTN, or it is shared between

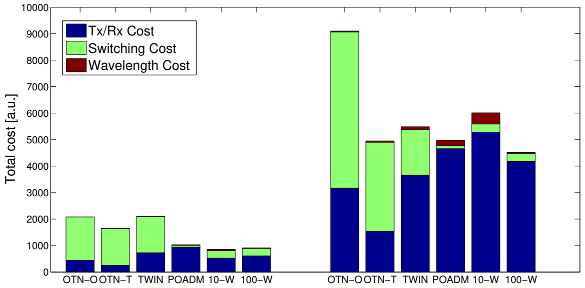

Fig. 7: Stacked cost of the symmetric HAS scenario (year=1 and year=10)

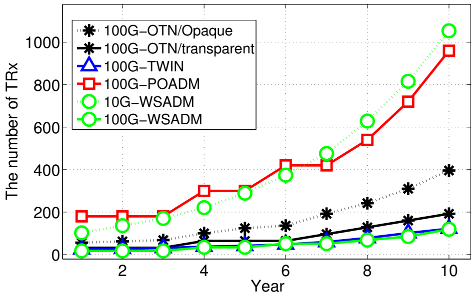

Fig. 8: Total number of TRx for the symmetric HAS scenario

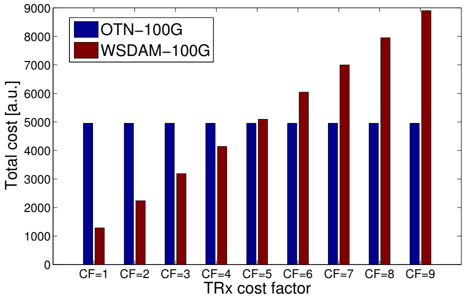

Fig. 9: The impact of the TRx cost factor on the total cost of WSDAM in the symmetric HAS scenario

only flows crossing the same link in the case of opaque OTN. Thus, the number of resources (e.g. TRx) yearly added to the network is lower than that of POADM and 10G-WSDAM.

Actually, the real cost of the TRx of WSDAM cannot be accurately estimated because they are not commercialised. Therefore, we define the factor cost as the ratio between the cost of a single array of ten 100G TRx of WSDAM and the cost of single 100G TRx of OTN. In Fig. 9, we compare the total cost of WSDAM and transparent OTN in the tenth year by varying the cost factor from 1 to 9. WSDAM achieves a positive saving compared to OTN if the cost factor is inferior to 5.

B. Asymmetric hub-and-spoke scenario

We perform the same comparison in the asymmetric case. In Fig. 10, the cost of 100G-WSADM is the lowest and is stable during the first four years; then, it increases by the same pace every two/three-year period. In the tenth year, the cost of 100G-WSADM represents only 45% of the cost of the transparent OTN and 65% of the cost of the opaque OTN. The cost of 10G-WSADM is close to the cost of 100G-WSADM but it increases at a faster pace during the ninth and the tenth years. For OTN, TWIN and POADM, the cost is increased every year in order to absorb the traffic growth.

Fig. 11 shows the distribution of the total cost in the asymmetric case. Similarly to the symmetric HAS scenario, the cost of Tx/Rx is dominant, especially for POADM and WSADM. The impact of the wavelength cost is less significant, but in the case of POADM and 10G-WSDAM, it still reaches 7% of the total cost. This is due to, firstly, the large number of wavelengths required by these two technologies and, secondly, to the ring-based logical topology of the network that makes the distances between the hub and the edge nodes longer than in the mesh-based logical topology.

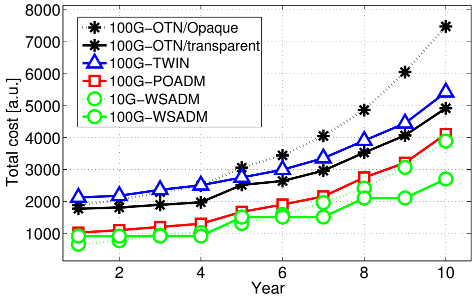

Fig. 10: Total cost of the asymmetric HAS scenario

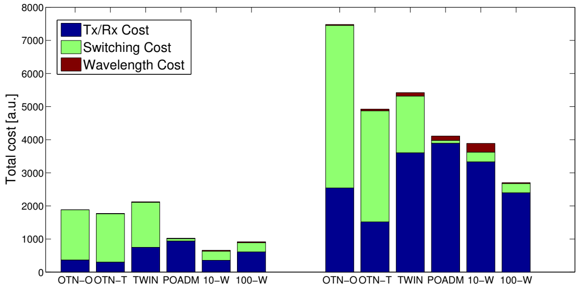

Fig. 11: Stacked cost of the asymmetric HAS scenario (year=1 and year=10)

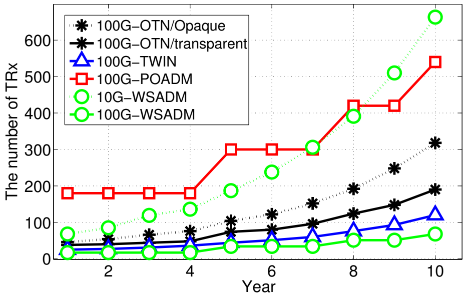

Fig. 12: Total number of TRx for the asymmetric HAS scenario

The evolution of the number of TRx over the years is plotted in Fig. 12. Compared to transparent OTN, WSDAM saves 55% of the number of TRx in the first year and 64% in the tenth year. The number of TRx in TWIN is close to WSDAM but the total cost of TWIN is almost twice as high as that of WSDAM. This is firstly due to the high cost of the tunable Tx for TWIN; another cause is the importance of the cost of switching for TWIN (roughly 30% of the total cost for TWIN according to Fig. 11).

Fig. 13 shows that the total cost of WSDAM is lower than that of OTN as long as the cost of a the array of 10 fixed 100G TRx of WSDAM is cheaper than 9 times the cost of a single 100G TRx of OTN.

V. CONCLUSION

In this paper we have considered WSADM, a new optical packet switching technology relying on a slotted ring and

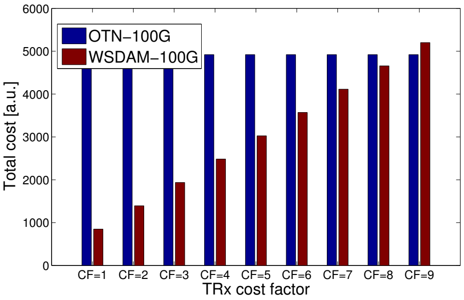

Fig. 13: The impact of the TRx cost factor on the total cost of WSDAM in the asymmetric HAS scenario

parallel sending of the optical packet over ten wavelengths. The main difference between WSADM and the other OPS technologies is that it relies on less complicated optical components (especially the avoidance of fast tunable lasers).

The introduction of WSADM as a new networking technology will be possible only if it proves its ability to satisfy key challenges in terms of cost and performance. In this study, we focus on assessing the cost of WSADM in comparison with Optical Network Transport (OTN) technology that is increasingly deployed in the metropolitan network. We also compare the cost of WSADM cost with those of the other two sub-wavelength switching technologies, TWIN and POADM, that have shown an excellent ability to achieve high spectral utilisation and excellent performance.

Cost assessment is carried out over a period of ten years using traffic predictions based on [11]. The yearly traffic growth is assumed to be 30% which corresponds to a tenfold increase of the traffic during ten years. Candidate architectures are firstly dimensioned using simple heuristics (roughly applying a 20% over-dimensioning factor). Then, their cost is assessed using a cost model inspired from previous studies. In this model, the cost value for each component is normalised to the cost of one 10 Gbits/s transponder.

This study shows that the major cost comes from transponders for all the compared technologies. Moreover, in terms of cost and amount of used resources, WSADM is cheaper and needs less transponders than the other technologies. Although the results of this paper depend on the proposed model cost, that could imperfectly reflect the real cost in the market, the significant difference between the cost of WSDAM and the other technologies indicates that it is definitely a solution to assess for the next generation metro/core network.

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