Is It Worth Adapting Sub-Wavelength Switching Control Plane to Traffic Variations?

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Abstract— This paper proposes a novel Metropolitan Area Network (MAN) architecture called Multi-hEad sub-wavElength swiTching (MEET). Compared with the current architectures, MEET proposes to aggregate traffic using passive optical nodes instead of using electrical nodes (switches and routers). Several options regarding a potential control plane are compared in terms of resource allocation efficiency. Two options are relative to the burst assembly process whereas another option is relative to the dynamicity of the resource allocation process. Performance evaluation is carried out using a simulation platform fed by real traffic traces captured on a French operator's metropolitan network. The QoS delivered to three different classes of service has been assessed in terms of latency and jitter. Obtained results show that a control plane that does not adapt to short-term variations of the real traffic may provide QoS levels compatible with an operational MAN.

***Index Terms*— Metropolitan area networks, Optical switches, Next generation networking**

I. Introduction

THE ever increasing channel bit rates in transmission systems challenge the operator that has to build a network with an efficient filling of these big pipes. Switching sub-wavelength entities inside the channels appears mandatory to benefit from the whole available bandwidth. Among the possible solutions, *Sub-Lambda Photonically Switched Network (SLPSN)* [1] is a good option as it performs sub-wavelength switching without resorting to electronic and its O|E|O (Optical/Electrical/Optical) conversion interfaces. The benefits of such transparent grooming solutions are fully obtained in lossless solutions but they require a robust control plane which avoids contentions at intermediate nodes.

In this paper we propose a new architecture for a metro-backhaul network, called *Multi-hEad sub-wavElength swiTching (MEET).* Compared with currently rolled out architectures, MEET makes aggregation without several electrical multiplexing stages and replaces them with an all-optical aggregation using a lossless SLPSN solution based on the *Time-domain Wavelength Interleaved Networking* (*TWIN*) [2] concept. According to TWIN, the source nodes are interconnected to each destination node by a multipoint-to-point tree operated on a dedicated *Wavelength Division Multiplexing (WDM)* channel. This concept is used in MEET architecture not only to interconnect the backhaul edge nodes with each other, but also to optically link these edge nodes to remote core aggregation nodes, outside the backhaul area. The transport of data between nodes is ensured by optical bursts built up by assembling electronic packets.

In order to ensure communication between network nodes, a TWIN control plane [3-6] avoids potential burst collisions at intermediate nodes of the trees by allocating disjoint time periods, on all WDM channels, to specific source-destination pairs. As the TWIN intermediate nodes are optically passive, the *control entity (CE)*, which manages the control plane, decides for each source the authorized burst transmission periods such that no bursts collision occurs in the network. To alleviate complexity, the control entity does not perform dynamic per burst allocation, but provides a global schedule, valid for a given period of time, called *control cycle*. The minimal control cycle's duration is the largest Round-Trip Time (RTT) between a node and the CE. For a Metropolitan Area Network (MAN), the minimal control cycle equals few milliseconds.

The schedule consists in a fixed duration pattern that is repeated during the control cycle. Each slot in the pattern is allocated to a given flow, i.e. traffic between a (source, destination) pair. A slot can thus be considered as the smallest optical/time resource that can be allocated by the control plane.

In this context two main approaches can be mentioned: (i) *pseudo-static* resource allocation [6], for "long" control cycles (at least a few seconds); and, (ii) *dynamic*, or *fast-adaptive* resource allocation for a "short" control cycle. In the pseudo-static case, the schedule is optimized for a given traffic matrix. In the dynamic case, the schedule is recomputed according to the traffic variations observed during the previous cycles, which is why it is "fast-adaptive".

The present paper compares the respective performance of an optimal schedule obtained for an approximate traffic matrix demand, and a heuristically obtained schedule computed on a more exact assessment of the traffic demands. A heuristic schedule is computed faster than an optimal one, and it is designed to fit with the high dynamicity of real traffic profiles. Nevertheless, as it is heuristically computed, it may thus not optimize the bandwidth utilization.

In this paper we study the MEET proposed architecture for both pseudo-static and dynamic control planes. For this purpose, we propose different burst assembly mechanisms and compare by simulation the obtained results with MAN-level *Quality of Service (QoS)* objectives in terms of latency and jitter [7]. The simulation scenario uses a real topology and traffic models derived from residential IP traffic traces

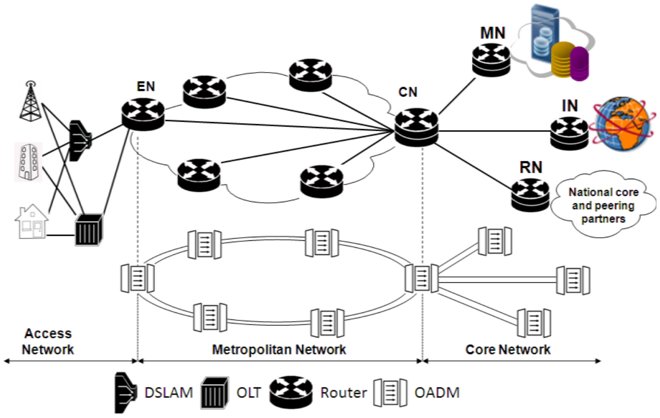

Fig.1: Architecture overview of the current backhaul network

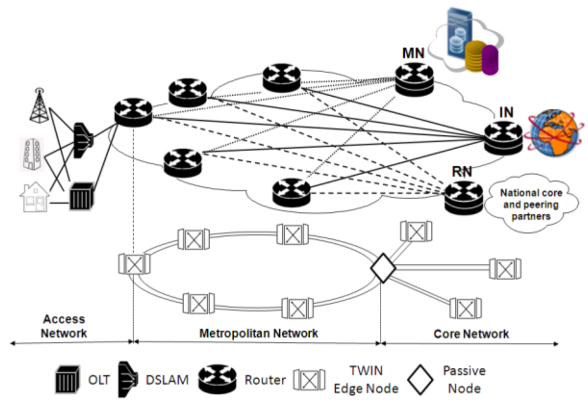

Fig.2: Architecture overview of the MEET

obtained on a French MAN.

Section II presents the MEET architecture, while Section III describes how it is operated. The simulation framework and the traffic traces are analyzed in Section IV. Sections V and VI respectively address performance evaluation in ToS-insensitive and ToS-sensitive burst assembly cases (ToS: Type of Service). Section VII concludes the paper.

II. MEET Network Architecture

Telecommunication networks are used to connect large groups of users spread over a geographical area. In order to ensure an efficient connectivity, the current operator networks are designed in a hierarchical way depending on the covered area and the traffic aggregation process. A node in a given level aggregates the traffic coming from the immediate lower level, yielding to higher stages of traffic aggregation. As shown in Fig.1, we usually define three levels of hierarchy: access, backhaul and core.

The access level covers a local area, combining multiple customers' lines by often using a broadcast star.

At the backhaul level, several access networks are connected to a *MAN*. A ring topology is commonly used to link the nodes in this network. Such backhaul nodes can be classified into two types: *Edge Nodes (ENs)* and the *Concentration Node (CN)*. ENs aggregate the fixed and/or mobile traffic coming from the access network nodes (i.e. DSLAMs, OLTs …). ENs are mostly located in medium sized cities. All the aggregated traffic in the ENs is transmitted to a CN, which is responsible for ensuring connection between the MAN and the core network. CN is the first aggregation node in the core network.

The core level interconnects several backhaul networks by means of a *Wide Area Network (WAN)* whose nodes are generally interconnected in a mesh topology. The CN aggregating all the traffic in each metro network may be connected to three types of core nodes:

- *Regional Nodes (RNs)*: they aggregate traffic coming from a set of CNs and destined to higher aggregation levels in the national core network or to other international Tier 1 networks owned by peering partners.

- *Internet Nodes (INs)*: they represent the gateway to the international Tier 1 network owned by the operator.

- *Multiservice Nodes (MNs)*: they permit operator clients to access to the managed service platforms of the operator as Video on Demand (VoD), TV and VoIP services.

It is important to highlight that the traffic rate between two metropolitan backhaul nodes is currently significantly lower than the wavelength capacity. Therefore, the adoption of SLPSN solution could provide both statistical multiplexing and O|E|O interfaces sharing which enable an efficient use of optical resources.

The above-described architecture requires a huge buffering capacity and computing resources in the CN to deal with all the traffic flows. In order to alleviate the traffic load in the concentration node and provide efficient bandwidth utilization, we propose an alternative architecture, based on the TWIN concept, to which we refer as *MEET architecture.*

According to MEET, the metropolitan network is extended to reach the RN, IN and the MN. Indeed, those three nodes can be considered as TWIN remote edge nodes. Note that the number of remote nodes in MEET is not restricted to three and other core nodes could be included in the architecture. Those nodes present electronic buffers, they assemble/disassemble bursts and they communicate with the other ENs according to the TWIN control plane. In this architecture, the CN is simply a passive intermediate node (it could be split into several passive nodes). It operates at full optical capacity without electronic buffering and processing. It represents an optical gateway between the local ENs and the three remote nodes (RN, IN, MN). The MEET architecture is shown in Fig.2. In the current architecture, the communication between local ENs is possible only via the CN, while in this new architecture, they could communicate directly with each other (these connections are not shown in Fig.2 for clearness).

Compared with the current metropolitan architecture, MEET permits an optical aggregation in the CN thanks to the utilization of the sub-lambda technology enabling the sharing of large wavelength capacity without O|E|O processing. Besides, this architecture is expected to achieve low latency performance compared with the existing one, since it removes an aggregation stage (in the CN), allowing a direct connection between the ENs and the core network nodes. Finally, this architecture provides a more distributed traffic matrix. Indeed, it radically changes the logical metro network architecture from a *hub-and-spoke* to a meshed architecture, which avoids some networking problems like bottlenecks, protection and availability issues at the CN. The physical topology may remain primarily ring-like, but its logical interconnectivity will be more meshed.

The FP7 COMBO project considers such an architecture to provide a single optically transparent MAN for future converged fixed-mobile networks.

III. TWIN OPERATION OF MEET

The MEET architecture should ideally be optically transparent and support sub-lambda granularity. A TWIN-like operation mode has thus been selected.

A. *Controlling TWIN resource allocation*

According to TWIN concept, one or several wavelengths are attributed to each destination node to receive data. Hence, the network can be viewed as overlaid optical multipoint-to-point trees. Each tree is associated to a unique destination, which represents the root of the tree, and multiple source nodes, which represents the leaves of the tree. The control plane has the task of managing burst emissions such that no burst collision occurs in the network. The control plane can be centralized or distributed. Referring to the work done in [5], we opt here for a centralized control plane.

A schedule, repeating a given allocation pattern, is considered for each control cycle. The duration of a pattern is called a *data cycle*.

Optical bursts are built by source nodes and sent over the slots made available for transmission. Adjacent bursts are interspaced by a guard time in order to take into account optical transmission constraints. Thanks to the computed schedule, source nodes have deterministic periods of time to send traffic to given destinations, while intermediate and destination nodes are collision-free.

Performance degradation, in terms of increased latency and jitter, may occur if the schedule, computed on a predicted traffic matrix, cannot accommodate the real traffic offered to MEET.

B. *Resource allocation Mechanism*

Two main resource allocation policies are proposed in [6]:

1) *Pseudo-static Resource Allocation*

The allocation mechanism is formulated as a linear optimization problem, maximizing bandwidth allocation. Since this calculation is a complex process, it is necessary to consider a sufficiently large control cycle duration (from several seconds to several minutes).

2) *Dynamic Resource Allocation*

The allocation mechanism is done dynamically based on a heuristic approach. In each control cycle, the control plane collects the bandwidth requirements for each source-destination pair. Then, it creates the slot allocation patterns according to a *first-fit* algorithm and distributes them to the sources. This approach is less complex than the first one. Thus, it can be periodically performed according to a short control cycle duration (several milliseconds).

C. *Burst Assembly Mechanism*

The burst assembler builds bursts by collecting several packets sent to the same destination, possibly depending on their Type of Service (ToS) value. As we do not consider here packet fragmentation, a packet is delayed for a later burst if it does not fit within the current one. This leads to under-utilizing allocated slots. We refer to this as *"packet granularity blocking"*.

Burst assemblers can be differentiated according to their management of available resource and their sensitivity to *ToS*.

1) *Single Slot vs. Multi-Slot Assemblers*

In the original TWIN concept, a burst is carried in a single slot, yielding per slot overhead due to the guard times. We refer to this as *Single Slot-sized burst assembly (SS)*.

Since in TWIN concept the source is fully aware of the future transmission opportunities, we propose here an alternative burst assembly mechanism which consists in building bursts covering several contiguous slots, all assigned to the same destination. In this case, the source manages these contiguous slots as a unique interval of time. This allows building large bursts occupying the transmission time of several slots, which potentially saves some guard times, and alleviates packet granularity blocking. We refer to this new scheme as *Multi-Slot-sized burst assembly (MS)*.

2) *ToS-Sensitive vs. ToS-Insensitive Approaches*

The simplest way to build burst is to assemble packets in a FIFO manner for each destination. This is *"ToS-insensitive"*.

The assembler could also be *"ToS-sensitive"*, by taking into account ToS priority when building a burst. Packets are buffered in the source node according to their destination and ToS value. Burst assembly is performed according to a Priority Queuing policy (highest priority Class of Service (CoS) packets are assembled first).

In both approaches, burst can be composed of packets from different CoSs.

TABLE I
CLASSES OF SERVICE MODEL IN MAN

CoS	Latency	Jitter	Application
1	3 ms	1 ms	Control, Games, Chat, VoIP
2	5 ms	3 ms	News, E-mail, Streaming, HTTP
3	10 ms	-	P2P, Download

In an operational network, ToS can be controlled by the network operator in order e.g. to be compliant to multi-class Service Level Agreements (SLA).

Packets are classified into traffic classes having different QoS performance objectives in terms of loss, latency, jitter, etc. Here, we consider a three-class model based on the one described in [7]:

- Class 1: real time and interactive traffic, very sensitive to data loss, delay and jitter.

- Class 2: streaming and bulk data traffic, less sensitive to delay and jitter, but still very affected by data loss.
- Class 3: best effort traffic.

The applications and the performance objectives in terms of latency and jitter of these *Class of Service (CoS)* are detailed in Table I [7].

IV. Performance Framework

In order to assess the efficiency of the proposed mechanisms, we conduct simulation studies using real metro network traffic traces as input.

A. Simulation Scenario

We evaluate the performance of the different control planes in terms of QoS objectives using a simulator based on OMNET++, implementing a TWIN scheme. Each node presents a single 10 Gbps transceiver and has infinite capacity queues. Time slot and guard time are respectively equal to 5 µs and 0.5 µs. The pattern considers 100 slots, which yields a data cycle of 500 µs. For the dynamic case, we take a control cycle equal to 10 ms.

The simulated network corresponds to a French MAN consisting of ten traffic nodes. The distances between the nodes are in the order of a few hundreds of kilometers. The propagation delay between the furthest node pairs is 1.5 ms, while being lower than 1ms for most of the pairs. The pseudo-static resource allocation is obtained using CPLEX solver.

The simulator is fed by real packet traces corresponding to 8 millions packets. The traces have been gathered at peak hour (21:00). The IP snapshot was performed by a probe, placed at core network border, and equipped with dedicated capture cards able to catch all the packets during the probe process.

We thus obtain, for each packet, its source address, destination address, ToS, size and real arrival time. We can derive from this data a set of traffic flows between ENs and the three remote nodes. In the current hub-and-spoke architecture, all the traffic goes through the CN. The CN is the single head node of the network with the most important traffic load in the upstream and the downstream directions. In MEET architecture, the traffic is mostly distributed between the local ENs and the three remote ENs. But, a small part of the traffic is directly exchanged between the local ENs.

TABLE II
NORMALIZED TRAFFIC MATRIX

	RN	IN	MN	EN1	EN2	EN3	EN4	EN5	EN6	EN7
RN	0	0	0	2.2	0.7	1.9	2.5	1.1	1.2	0.4
IN	0	0	0	0.2	0.2	0.5	0.4	0.2	0.4	<0.1
MN	0	0	0	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
EN1	0.5	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
EN2	0.2	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1	<0.1
EN3	0.4	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1	<0.1
EN4	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1	<0.1
EN5	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0	<0.1	<0.1
EN6	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0	<0.1
EN7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0

RN: access to the national core and peering partners
IN: access to international network
MN: access to operator managed services

We then build artificial packet arrival schedules by multiplying the inter-arrival times by different load factors. This yields realistic traffic profiles with intensities up to 10 Gbit/s for the most loaded node. The maximal traffic matrix is illustrated in Table II. On the basis of this matrix, we deduce less loaded traffic matrices by multiplying it by a load factor ranging from 0.1 to 0.9 (a traffic matrix having a load factor of 1 corresponds to the normalized matrix).

B. Traffic Dynamicity

In order to understand the dynamicity of traffic, we compare in Fig.3, a real traffic (a snapshot of the flow between the RN and a single EN) and a theoretical Poisson-based traffic as a function of time. Both traffics are normalized to the same load. We observe that the real traffic fluctuates more than Poisson traffic with instantaneous throughput changing from 1.7 Gbps to 3.6 Gbps in only 50 ms.

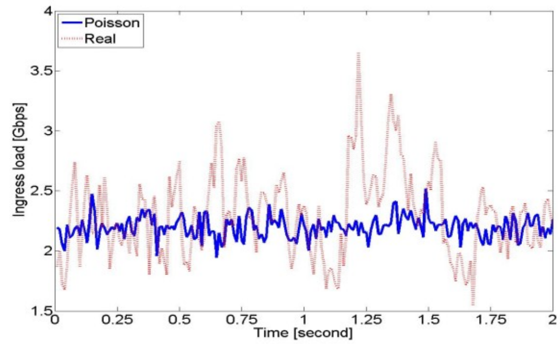

Fig. 3: Real and Poisson traffic variations of the traffic flow from the RN to the NE1

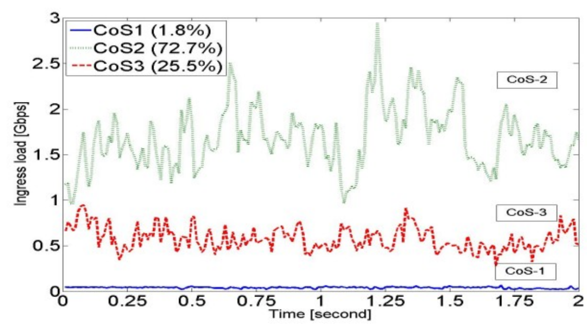

Fig. 4: Traffic variations according to the CoS of the traffic flow from the RN to the NE1

We use the same flow and we employ a traffic classification according to the above-mentioned model. Fig.4 shows that the traffic load and the variation are different from a class of service to another. In this particular case, the CoS-2 traffic is the most loaded (72%) and it experiences more dynamicity than the others, while, the CoS-1 traffic is the least loaded.

V. Performance Evaluation In a ToS-Insensitive Framework

In this Section we compare the performance of the dynamic and the pseudo-static resource allocation algorithms using the two assembly technique SS and MS with ToS-insensitive approach. We assess whether QoS objectives in terms of

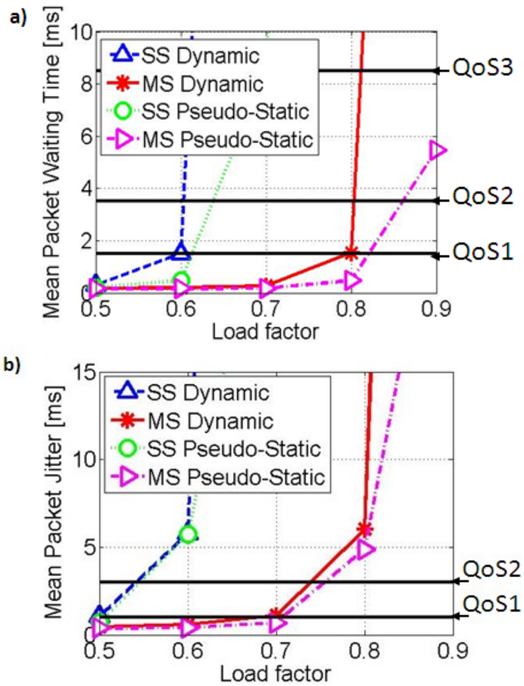

Fig. 5: Waiting time (a) and jitter (b)

latency and jitter meet the values of table I. Here, the latency is the sum of the propagation time between the source-destination couple and the time spent by a packet in the source node queue, to which we refer as the *waiting time*. As TWIN enables a passive optical switching in the intermediate nodes, the main factor of latency is the waiting time, while the propagation time is fixed between each source/destination couple. The jitter is calculated by taking the difference between the 1st percentile and the 99th percentile of the delay distribution.

The presented results are for the average waiting time and the jitter of the packets belonging to one of the most loaded flows but it was verified that results concerning the other flows exhibit the same trend.

Fig.5 shows the waiting time and jitter for all packets. We verified that all ToS classes receive the same performance, which is to be expected as packets are served similarly. We first notice that MS results are significantly better than the SS ones which are unable to meet the QoS requirements for a load factor larger than 0.6 for both the dynamic and the pseudo-static approaches.

This is first due to the fact that, unlike the SS technique, the MS assembly provides more transmission time since it exploits guard time to send data in the case of two consecutive slots attributed to the same destination. But, this is not the unique reason since the guard time accounts for only 10% of the bandwidth. This is also due to the MS technique, which alleviates the aforementioned *packet granularity blocking.* Indeed, as a burst in the MS approach is spread over several slots, it is less likely to have packet granularity blocking in the MS approach than in the SS approach, where this blocking is possible in each slot. This is verified in Fig.6, which represents the mean burst lengths for both SS and MS approaches. The SS mean burst size is close to 3.7 µs for all

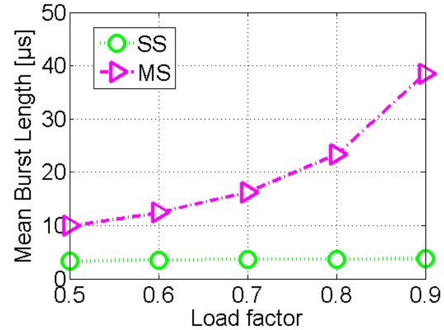

Fig. 6: Burst length in the pseudo-static allocation approach

load factors. This is because large packets (1500 bytes) represent a significant fraction of the overall traffic, whereas the time to transmit at 10 Gbit/s such a packet is large (1.2 µs) compared with the slot duration (4.5 µs). This could be alleviated by a larger slot size (e.g. 10 µs).

Fig.5 also shows that the MS pseudo-static approach meets latency objectives as long as the load factor is lower than 0.8 but is unable to meet CoS-1 and CoS-2 jitter requirement at this load. It outperforms other control planes including the MS dynamic approach. This can be explained by several factors. First, the pseudo-static approach allows an efficient allocation of resources since this process is based on an exact optimization procedure, which yields a larger number of allocated slots per data cycle than obtained with the first fit heuristic. Sources can thus deal more efficiently with traffic variations. Moreover, traffic dynamicity as illustrated in Fig.3 presents only rather short-term oscillations. Therefore, packets buffered during a peak of traffic will be shortly released, when the traffic decreases, even with a pseudo-static schedule. Lastly, an instantaneous reaction by the dynamic schedule to simultaneous traffic peaks from some flows can lead to starving other flows.

VI. PERFORMANCE EVALUATION IN A TOS-SENSITIVE FRAMEWORK

We have shown that the ToS-insensitive burst assembly process does not yield a good jitter performance at high loads. In this section we will improve delivered QoS by considering a ToS-sensitive burst assembler based on a MS technique, for the pseudo-static control plane since it has been shown to out-perform the others. Therefore, we add a ToS-sensitive burst assembler module in each edge node, operating according to a strict priority to the highest ToS packets compared with the others.

Results in Fig.7 show that ToS differentiation guarantees the QoS requirements for CoS 1 and 2 for a load factor close to 0.9.

CoS-1 packets experience a waiting time lower than 200 µs and a jitter lower than 500 µs. This is not only due to the highest priority of the CoS-1 traffic, but also to its very low load. For instance, Fig.4 shows that CoS-1 traffic for a given source/destination nodes occupies only 1.8% of the total traffic. Therefore, the attributed slots to a given source/destination couple are sufficient to empty CoS-1 queues during a data cycle. This explains well the fact that the

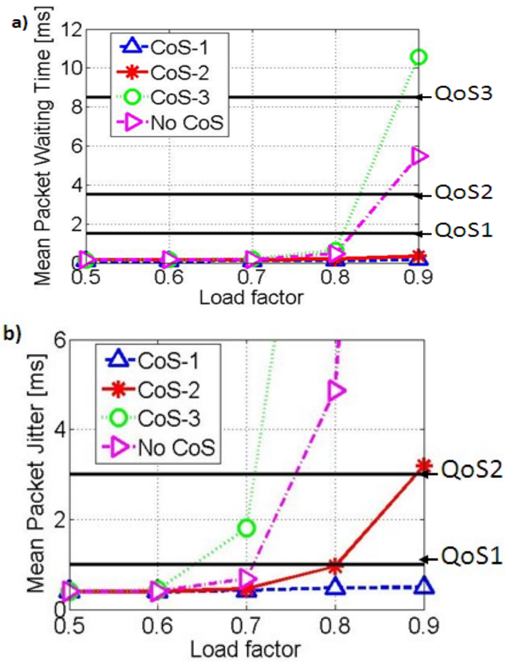

Fig. 7: Waiting time (a) and jitter (b) for the pseudo-static-MS control plane

waiting time and the jitter remain lower than 500 µs (the data cycle duration).

Despite the high load and the dynamicity of CoS-2 traffic, its waiting time is still less than 1 ms and the jitter is almost equal to 3ms for a load factor equal to 0.9. This good performance can be explained by the fact that, the CoS-1 traffic is lightly loaded and the CoS-2 has the second highest priority. In fact, in the case of a sudden traffic peak belonging to CoS-2, the assembler attributes few resources to the CoS-1 packets (since they are lightly loaded) and stops assemble CoS-3 packets (since they have the lowest priority) and then CoS-2 packets monopolizes almost all the available resources. As peaks do not last long and pseudo-static plane provides a large bandwidth, the CoS-2 packets will be rapidly and efficiently assembled.

However, Fig.7 also shows that CoS-3 traffic is significantly penalized, as it receives a QoS worse than the one obtained in a ToS-insensitive framework. This could be alleviated by considering more sophisticated ToS-sensitive frameworks using Weighted Class Based mechanisms instead of Priority Queueing mechanisms.

VII. Conclusion

In this paper, we have proposed a new architecture called Multi-hEad sub-wavElength swiTching (MEET), that could replace the current electronic backhaul architectures. This architecture is based on a lossless sub-wavelength technology enabling optical aggregation. Thus, it extends the current metro-backhaul architecture by reaching core nodes passively. This allows removing several electrical aggregation stages currently existing between the metro-backhaul and the core networks. Then, it reduces latency and potentially saves energy.

Using simulation and real traffic traces, we have evaluated different mechanisms to implement the control plane for this technology. From the resource allocation point of view, we have compared the performance delivered by a dynamic, fast-adaptive control plane with the one delivered by a pseudo-static control plane. Both packet latency and jitter have been monitored. We have considered different burst assembly techniques (Single Slot-sized burst/Multi Slot-sized burst, Priority based Tos-sensitive/ToS-insensitive).

The results indicate that although there is a significant variation of the real traffic, a pseudo-static control plane with the Multi-Slot approach meets standard QoS objectives of metro-backhaul networks even at highly loaded traffic scenarios.

We have also shown that Single-Slot burst assembly suffers from packet granularity blocking; this could be alleviated by considering longer slots and/or by allowing packet fragmentation, which is a complex process. For this reason, we have proposed Multi-Slot burst assembly to improve resource utilization by alleviating packet granularity blocking and by saving some guard times.

A priority based ToS-sensitive burst assembly process has been shown to deliver excellent performance to time sensitive traffic, by significantly decreasing the delay of non-time sensitive traffic. However, we have to note that the ToS marking of our trace was provided by the application and not overwritten by the network operator, which currently operates a best-effort backhaul. This implies that the ToS field values in the real traffic are not totally reliable. Moreover, it is to be expected that more sophisticated, weighted class based burst assembly mechanisms would lead to better results; this is to be studied in the future. As future work, we also intend to consider longer traces in order to assess the optimal duration of control cycles.

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