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Dominique Chiaroni

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# Modelling packet insertion on a WSADM ring

A. Gravey<sup>\*‡</sup>, D. Amar<sup>\*§</sup>, P. Gravey<sup>\*§</sup>, and M. Morvan<sup>\*§</sup>

<sup>\*</sup>IMT Atlantique, Brest, France

email: `firstname.lastname@imt-atlantique.fr`

<sup>‡</sup>UMR CNRS 6074 IRISA, France, <sup>§</sup>UMR CNRS 6285 Lab-STICC, France

B. Uscumlic and D. Chiaroni

Nokia Bell Labs, Paris Saclay, France

`firstname.lastname@nokia-bell-labs.com`

**Abstract**—The WDM slotted Add/Drop Multiplexer (WSADM) technology relies on time slotted WDM rings, where a slot can carry a single WDM packet. All stations can insert and receive these WDM packets. This differs from previous architectures in which packets were carried over a single wavelength, while multiple packets could be carried in a single slot, thus taking advantage differently of the WDM dimension. The WSADM architecture is expected to reduce costs by exploiting low cost technologies. We propose mathematical models for evaluating the performance offered by WSADM optical packet rings, under two different packet insertion policies. In the slot reservation mode, a station can only use the slots that are periodically reserved for its exclusive usage. In the opportunistic insertion mode, a station can use any slot that is neither reserved, nor already occupied. These modes are bench-marked with a channel reservation mode in which each wavelength is dedicated to a single station.

**Keywords**—Wavelength Division Multiplexing, Optical Packet Switching, Metropolitan Area Network, Network Performance

## I. INTRODUCTION

The distribution/aggregation network segment, also called Metropolitan Area Network (MAN), is expected to be particularly impacted by the current traffic growth. Different traffic sources, varying from small Digital Subscriber Line Access Multiplexers (DSLAMs) to large data centers, generate highly variable types of traffic, which favors using packet-based transport technologies in MANs. Ethernet rings with specific protection protocols are often considered. The main issues with “opaque” networks are, on the one hand their high energy consumption, and on the other hand the Ethernet packet granularity that is convenient for Metro Access areas, but too fine for Metro Core ones. Optical Packet/Burst Switching (OPS/OBS) technologies have been for many years considered as potential options for combining sub-wavelength granularity and optical transparency but the lack of viable optical buffering technologies has precluded implementing them. However, time-slotted OPS rings such as TWIN or POADM have been shown to provide both an efficient use of transmission resources and carrier-grade performance without optical packet buffering. Nevertheless, these technologies rely on custom optical components (in particular on fast-tunable burst-mode emitters) that are not currently commercially available.

In order to rely on more widely available components, the WDM slotted Add/Drop Multiplexer (WSADM) technology has been recently proposed [1]. The key optical devices required in a WSADM are integrated multi-wavelength laser sources that are fully in line with the trend of optoelectronic industry, and Semiconductor Optical Amplifiers (SOA) gates that are naturally suited to operate on WDM packets because of their wide optical bandwidth. Preliminary CAPEX

comparisons have suggested that WSADM technology could compete favorably with existing electronic packet technologies and other OPS/OBS options [1], [2].

To the best of our knowledge, the network performance of WSADM technology has yet to be assessed. The present paper proposes a set of models for assessing WDM packet insertion performance in a WSADM ring. Packet insertion has a structuring impact on the global performance, as all inserted packets travel transparently till their destination, resulting in loss-less transfer and deterministic latency once packets are inserted. The introduction of WSADM raises several questions. For example, the comparison between a purely opportunistic insertion mode and a fully (or partially) deterministic one: how do these modes impact on network performance, in particular on latency and what is the impact of the number of wavelengths on their respective merits? More generally, the stringent requirements on latency, notably in the framework of future 5G deployments, make worth performing a detailed analysis of the packet insertion process in a candidate technology for future metro/aggregation networks.

Section II describes the network architecture considered in this work. Section III presents the various mathematical models developed for WSADM networks. A partial validation by simulation of the models is presented in the next section. The main performance assessments are summarized in section V and conclusions are drawn in section VI.

## II. NETWORK ARCHITECTURE

We consider WDM packets as described in [1]. Multiple Service Data Units (SDU) are aggregated within a single Packet Data Unit (PDU); a typical SDU is e.g. an Ethernet Frame. To be transported over the optical ring, the PDU is split over  $K$  wavelengths.

The network is controlled by both a fast (i.e. real time) control realized in line, and a slower, although dynamical, control realized thanks to a SDN controller. The fast control is implemented through a control channel carried over a separate wavelength, and synchronized with the data channel: during a time slot, both a control packet and a data packet (which carries, or not, a PDU) are transmitted. The SDN controller provides a “provisioning oriented” type of control: it is in charge of station provisioning, of specifying the control information associated to PDUs before insertion and of specifying the operation (reception, pass-through, erasure) associated with PDUs carried over the ring. A similar “provisioning oriented” control has been described in a different context in [3]. As the present paper focuses on transfer plane performance, it shall not provide a detailed specification of the SDN control.

We assume that each station presents a single  $D$  Mbit/s interface (typically, in a metro network,  $D = 10$  Gbit/s), which is equal to the rate of a single wavelength. Let  $Z$  be the size, in bytes, of a PDU.  $Z$  should be large enough to contain many Ethernet frames, in order to avoid segmentation/reassembly and to limit the proportion of resources wasted due to the fixed overhead necessary for each packet (guard-band, preamble and framing). On the other hand,  $Z$  should not be too large. Indeed, in order to limit the latency due to the network, the time taken to fill a PDU by SDUs shall most likely be limited by a timer, unless it is filled before the timer runs out. Were  $Z$  too large, either latency would be negatively impacted by an overly long timer value, or PDUs would be systematically sent partially filled, timers having run out before the PDU was full, thus wasting resources. For the sake of generality, define  $T = Z/D$  to be the time it takes to fill a PDU at rate  $D$ .  $T$  is split into  $K$  slots, where  $K$  is the number of channels over which a packet is split to be transmitted;  $T/K$  is thus slot duration.

Stations are organized into a single uni-directional ring, in which each station can both insert and extract PDUs from the optical packet ring. Once a PDU is inserted, it cannot be lost till it is received by the final destination station, as it is passed transparently through the transit stations; therefore, PDUs are not lost within the network; a PDU could however be lost within a station, due to insertion buffer overflow. End-to-end PDU latency is the sum of the sojourn time in the insertion buffer and of the (fixed) propagation delay between source and destination stations (typically in the order of 0.1-1 ms). The performance offered to PDUs is thus mostly characterized by the performance of the PDU insertion process. The performance offered to SDUs also depends on how SDUs are aggregated in PDUs, and on whether timer-based policies are implemented, or not, in order to control latency. This is not considered in the present paper which focuses on the performance offered to PDUs in terms of latency and jitter.

### III. MODELLING PACKET INSERTION

Insertion performance is first driven by the PDU arrival process. As we consider a metro network, where each station aggregates the traffic of thousands of customers, it is justified to assume that PDUs arrive according to a Poisson process with parameter  $\Lambda$ . Let  $\gamma_j(x)$  be the probability that  $j$  PDUs arrive during an interval of duration  $x$ :

$$\gamma_j(x) = e^{-\Lambda x} \frac{(\Lambda x)^j}{j!} \quad (1)$$

The number of arrivals during an interval of duration  $x$  is thus Poisson with parameter  $\Lambda x$ . Insertion performance also depends on slot availability, characterized by the insertion mode applied to PDUs. We shall benchmark two slot insertion modes, ‘‘slot reservation’’ and ‘‘opportunistic insertion’’, with a classical channel reservation mode, in which each wavelength is dedicated to a station.

#### A. Slot Reservation Mode

In the slot reservation mode, the PDU can be inserted only on a slot that is marked as being available for its class. It is assumed that there is a reserved slot every  $R$  slot. Let a ‘‘reservation period’’ start at the beginning of a reserved slot, and end just before the next reserved slot. If at least one PDU is in the system at the beginning of the reservation period,

there is an exit at the end of the reserved slot. Otherwise, no PDU is served during the period. We assume that system capacity is finite of size  $B$ . In the following, we shall derive the distribution for  $N_r$ , number of PDUs in system at the beginning of a reservation period,  $M_r$ , number of PDUs seen by an arriving PDU,  $P_{loss}^r$ , the probability that an arriving PDU finds  $B$  PDUs in the system and  $W_r$ , sojourn time of a PDU which enters the system.

We first derive the transitions probabilities for  $N_r$ . As system capacity is  $B$ ,  $N_r$  varies between 0 and  $B$ , and the transitions are as follows:

$$\begin{aligned} P^r(0, i) &= \gamma_i \left( \frac{RT}{K} \right) & (B-1) \geq i \geq 0 \\ P^r(0, B) &= \sum_{j=B}^{\infty} \gamma_j \left( \frac{RT}{K} \right) \\ P^r(n, i) &= \gamma_{i+1-n} \left( \frac{RT}{K} \right) & B \geq n > 0, \quad (B-1) \geq i \geq 0 \\ P^r(n, B) &= \sum_{j=B-n+1}^{\infty} \gamma_j \left( \frac{RT}{K} \right) & B \geq n > 0 \end{aligned}$$

Let  $\pi^r = \{\pi_i^r, 0 \leq i \leq (B-1)\}$  be the probability distribution for  $N_r$ ;  $\pi^r$  is numerically derived by solving  $\pi^r P^r = \pi^r$ .

In order to derive the distribution for  $M_r$ , let us consider the probability that, knowing that a PDU arrives during  $[0, RT/K[$ , it arrives in the interval  $[x, x+dx[$ , and that exactly  $j$  other PDUs arrived before it, in the same reservation period. As the arrival process is Poisson, within a reservation period of length  $RT/K$ , the probability that the PDU arrives during an interval of length  $dx$  is  $Kdx/RT$ . The date of arrival  $x$  and the number of arrivals between the beginning of the period and  $x$  are related as follows:

$$\begin{aligned} P(\text{tagged arrival in } [x, x+dx[, j \text{ arrivals during } [0, x[) \\ = \frac{Kdx}{RT} \gamma_j(x) \end{aligned}$$

The previous joint probability is independent from the state of the system at the beginning of the period.  $M_r$  depends both on  $N_r$  (number of PDUs in the system at the beginning of a period), and on whether the tagged PDU arrives before the end of the reserved slot, or not. Indeed, if the the tagged PDU arrives after the end of the reserved slot, and if  $N_r > 0$ , one PDU has been served before the arrival of the tagged PDU; on the other hand, if it arrives during  $[0, T/K[$  it sees all the PDUs present in the system at time 0. Let  $\nu_k^r$  be the probability for  $\{M_r = k\}$ . For  $k$  smaller than  $B$ ,

$$\begin{aligned} \nu_k^r &= \frac{K}{RT} \left[ \pi_0^r \int_0^{RT/K} \gamma_k(y) dy \right. \\ &+ \sum_{n=1}^k \pi_n^r \int_0^{T/K} \gamma_{k-n}(y) dy \\ &+ \left. \sum_{n=1}^{k+1} \pi_n^r \int_{T/K}^{RT/K} \gamma_{k-n+1}(y) dy \right] \end{aligned}$$

which yields, after integrating (1):

$$\begin{aligned} \nu_k^r = & \frac{K}{\Lambda RT} \left[ \pi_0^r \sum_{k+1}^{\infty} \gamma_j \left( \frac{RT}{K} \right) + \sum_{n=1}^{k+1} \pi_n^r \gamma_{k-n+1} \left( \frac{T}{K} \right) \right. \\ & \left. - \pi_{k+1}^r + \sum_{n=1}^{k+1} \pi_n^r \sum_{j=k-n+2}^{\infty} \gamma_j \left( \frac{RT}{K} \right) \right] \end{aligned} \quad (2)$$

The loss probability  $P_{loss}^r$  is  $\nu_B^r$ , and can be derived similarly:

$$\begin{aligned} P_{loss}^r = & \frac{K}{\Lambda RT} \left[ \pi_0^r \sum_{i=B+1}^{\infty} (i-B) \gamma_i(RT/K) \right. \\ & + \sum_{n=1}^B \pi_n^r \sum_{j=B-n+1}^{\infty} \gamma_j(T/K) \\ & \left. + \sum_{n=1}^B \pi_n^r \sum_{i=B-n+2}^{\infty} (i+n-B-1) \gamma_i(RT/K) \right] \end{aligned} \quad (3)$$

The number of PDUs seen by an arriving PDU which is not lost is distributed as  $\nu_k^r / (1 - \nu_B^r)$  ( $k < B$ ). The mean sojourn time of such a PDU is then derived using Little's formula:

$$E(W_r) = \frac{1}{\Lambda(1 - \nu_B^r)} \sum_{k=0}^{B-1} k \nu_k^r \quad (4)$$

In order to derive the distribution for  $W_r$ , let  $U_r$  be the time between the arrival of the tagged PDU and the end of the reservation period. Let also  $A_R(U_r)$  be the number of PDUs arriving before the tagged PDU in the same reservation period. The distribution for  $W_r$  depends on both  $N_r$  and  $U_r$ . If  $N_r$  is null, the tagged PDU is delayed only by the PDUs arriving before it, in the same reservation period. If  $N_r$  is positive, it is also delayed by the  $(N_r - 1)$  PDUs arrived in previous reservation periods (one PDU is served during the reservation period).  $W_r$  is thus equal to the sum of the time till the end of the reservation period during which it arrived ( $U_r$ ),  $k$  reservation periods, where  $k$  is the number of PDUs which are in system when the PDU arrives, and which are not served during the reservation period during which the tagged PDU arrived, and its own service time  $T/K$ . By conditioning on  $N_r$  and on the number of other PDUs that arrived before a tagged PDU, in the same period (which are independent), we can directly obtain the distribution for  $W_r$ , valid for  $k$  smaller than  $(B - 1)$  and  $x$  in  $\left[0, \frac{RT}{K}\right]$ .

$$\begin{aligned} P\left(W_r \in \left[ \frac{(kR+1)T}{K} + x, \frac{(kR+1)T}{K} + x + dx \right] \right) = & \\ & \frac{K dx}{RT(1 - \nu_B^r)} \left( \pi_0^r \gamma_k(RT/K - x) \right. \\ & \left. + \sum_{n=1}^{k+1} \pi_n^r \gamma_{k-n+1}(RT/K - x) \right) \end{aligned} \quad (5)$$

For  $k = (B - 1)$  we need to ensure that the tagged PDU is not lost, which could occur for  $x$  larger than  $(R - 1)T/K$ . The

next result is thus only valid for  $x$  in  $\left[0, \frac{(R-1)T}{K}\right]$ :

$$\begin{aligned} P\left(W_r \in \left[ \frac{((B-1)R+1)T}{K} + x, \frac{((B-1)R+1)T}{K} + x + dx \right] \right) = & \\ = & \frac{K dx}{RT(1 - \nu_B^r)} \left( \pi_0^r \gamma_{B-1}(RT/K - x) \right. \\ & \left. + \sum_{n=1}^B \pi_n^r \gamma_{B-n}(RT/K - x) \right) \end{aligned} \quad (6)$$

Lastly, the sojourn time in a system of capacity  $B$  is upper bounded by  $BRT/K$  which implies that:

$$P^r(W_r \in [x, x + dx]) = 0 \quad x \notin \left[ \frac{T}{K}, \frac{BRT}{K} \right] \quad (7)$$

### B. Opportunistic Insertion Mode

Under the opportunistic insertion mode, once the station decides that a PDU should be inserted, it inserts the PDU on the first available slot. A slot is unavailable either because it already carries a PDU, or because it is reserved to be used by another PDU class. In order to obtain a tractable model for opportunistic insertion, we assume that slot availability is modelled by a Bernoulli process with parameter  $q_K$ . A PDU which arrives and finds an empty system only starts its service at the beginning of the next slot; if a slot is available, the service finishes at the end of the slot with probability  $q_K$ ; otherwise, the service lasts at least another slot. More precisely, the service time is equal to  $l$ ,  $l > 0$  with probability  $q_K(1 - q_K)^{l-1}$  (geometric distribution with parameter  $q_K$ ). In the following, we shall derive the distribution for  $N_o$ , number of PDUs in system just at the end of a slot,  $M_o$ , number of PDUs seen by an arriving PDU,  $P_{loss}^o$ , the probability that an arriving PDU finds  $B$  PDUs in the system and  $W_o$ , sojourn time of a PDU which enters the system.

As system capacity is  $B$ ,  $N_o$  cannot be larger than  $B$ . Transition probabilities are as follows:

$$\begin{aligned} P^o(0, i) &= \gamma_i(T/K) & i \leq B-1 \\ P^o(0, B) &= \sum_{j=B}^{\infty} \gamma_j(T/K) \\ P^o(n, i) &= (1 - q_K) \gamma_{i-n}(T/K) \\ &+ q_K \gamma_{i-n+1}(T/K) & 1 \leq n \leq B, i \leq B-1 \\ P^o(n, B) &= (1 - q_K) \sum_{j=B-n}^{\infty} \gamma_j(T/K) \\ &+ q_K \sum_{j=B-n+1}^{\infty} \gamma_j(T/K) & 1 \leq n \leq B \\ P^o(n, i) &= 0 & \{i > B\} \cup \{n > B\} \end{aligned}$$

Let  $\pi^o = \{\pi_i^o, 0 \leq i \leq (B-1)\}$  be the probability distribution for  $N_o$ ;  $\pi^o$  is numerically derived by solving  $\pi^o P^o = \pi^o$ .

$M_o$  differs from  $N_o$ , as PDUs can arrive before  $x$ , arrival time of a tagged PDU, in the same slot. However, thanks to the fact that a Poisson process is memory-less, the arrival process of PDUs after the beginning of the slot is independent from  $N_o$ . We can thus derive  $\nu_k^o$ , the probability for  $\{M_o = k\}$ , by

summing on  $n$  and integrating on  $x$ . For  $k$  smaller than  $B$ :

$$\begin{aligned} \nu_k^o &= \frac{K}{T} \sum_{n=0}^k \pi_n^o \int_0^{T/K} \gamma_{k-n}(x) dx \\ &= \frac{K}{\Lambda T} \sum_{n=0}^k \pi_n^o \left( \sum_{i=k-n+1}^{\infty} \gamma_i(T/K) \right) \end{aligned} \quad (8)$$

The loss probability  $P_{loss}^o$  is  $\nu_B^o$  and can be derived similarly:

$$\begin{aligned} \nu_B^o &= \frac{K}{T} \sum_{n=0}^B \pi_n^o \int_0^{T/K} \sum_{j=B-n}^{\infty} \gamma_j(x) dx \\ &= \frac{K}{\Lambda T} \sum_{n=0}^B \pi_n^o \sum_{i=B-n+1}^{\infty} \gamma_i(T/K) (i - B + n) \end{aligned} \quad (9)$$

The number of PDUs seen by an arriving PDU which is not lost is distributed as  $\nu_k^o / (1 - \nu_B^o)$  for  $k < B$ . Little's formula yields the mean sojourn time of such a PDU:

$$E(W_o) = \frac{1}{\Lambda(1 - \nu_B^o)} \sum_{k=0}^{B-1} k \nu_k^o \quad (10)$$

In order to derive the distribution for  $W_o$ , let  $U_o$  denote the time elapsed between the arrival of the tagged PDU and the beginning of the next slot.  $W_o$  is equal to the sum of  $U_o$ , of the tagged PDU's service time, and of the time it takes to serve the PDUs which are in system when the PDU arrives, and whose service does not stop at the end of the tagged slot. In particular, this implies that  $W_o$  is larger than  $T/K$ .

$$P(W_o \in [x, x + dx]) = 0 \quad x < T/K$$

Note that if  $N_o = 0$ , no PDU can be served during the slot, even if PDUs arrive before the tagged PDU in the same slot. Otherwise, a PDU is currently being served and its service can finish at the end of the slot with probability  $q_K$ . Let  $S_k$  be the service for the  $k^{\text{th}}$  PDU to be served,  $S$  be the service for the tagged PDU and  $\bar{S}_1$  be the remaining service time for the PDU currently being served at the beginning of the slot, if any. The sojourn time  $W_o$  of an arriving PDU which is not lost is thus derived as follows:

$$\begin{aligned} P(W_o \in [iT/K + x, iT/K + x + dx]) &= \frac{1}{(1 - \nu_B^o)} \\ &\left( \sum_{j=0}^{\min(B-1, i-1)} P(N_o = 0, \right. \\ &\quad j \text{ arrivals during } [0, T/K - x], \\ &\quad U_o \in [x, x + dx], S_1 + S_2 + \dots + S_j + S = iT/K) \\ &+ \sum_{j=1}^{\min(B-1, i)} \sum_{n=1}^j P(N_o = n, \\ &\quad (j-n) \text{ arrivals during } [0, T/K - x], \\ &\quad U_o \in [x, x + dx], \bar{S}_1 + S_2 + \dots + S_j + S = iT/K) \end{aligned}$$

$\bar{S}_1$ ,  $S_k$  and  $S$  are independent.  $S_k$  and  $S$  are identically distributed, but  $\bar{S}_1$  follows a different distribution. Due to the memory-less property of the geometric distribution,  $\bar{S}_1$  is equal to  $l$ ,  $l \geq 0$ , with probability  $q_K(1 - q_K)^l$ . Thanks to the memory-less property of the Poisson Process and of the

geometric distribution, we know that what happens before the beginning of the slot (which determines  $N_o$ ), what happens during the slot (which determines  $U_o$  and potential arrivals during  $[0, T/K - U]$ ), and what happens after the slot (which determines the value for the sum of geometrically distributed services) are independent. We finally obtain:

$$P(W_o \in [iT/K + x, iT/K + x + dx]) = \frac{1}{(1 - \nu_B^o)} \quad (11)$$

$$\begin{aligned} &\left( \sum_{j=0}^{\min(B-1, i-1)} \pi_0^o \gamma_j(T/K - x) \binom{i-1}{j} q_K^{j+1} (1 - q_K)^{i-1-j} \right. \\ &+ \sum_{j=1}^{\min(B-1, i)} \sum_{n=1}^j \pi_n^o \gamma_{j-n}(T/K - x) \binom{i}{j} q_K^{j+1} (1 - q_K)^{i-j} \end{aligned}$$

### C. Channel Reservation Mode

A typical benchmark corresponds to dedicating each data channel to a single station. The behaviour of this system is modelled by an  $M/D/1$  queue, with load  $\rho = \Lambda T = \lambda$ . Both the  $M/D/1$  and the  $M/D/1/B$  queues are well known models. In particular, the distribution for the number of PDUs seen in the system by an arriving customer  $M_c$  (which is also the stationary number of customers  $N_c$  in the  $M/D/1$  queue thanks to the PASTA property) is given below (see section 5 in [4]).

$$\begin{aligned} \pi_0^c &= 1 - \lambda & \pi_1^c &= \pi_0^c (e^\lambda - 1) \\ \pi_n^c &= \pi_0^c \left( e^{n\lambda} + \sum_{j=1}^{n-1} (-1)^{n-j} e^{j\lambda} \left[ \frac{(j\lambda)^{n-j}}{(n-j)!} + \frac{(j\lambda)^{n-j-1}}{(n-j-1)!} \right] \right) \\ &\text{if } n \geq 2 \end{aligned} \quad (12)$$

Moreover (see section 8.2.3 in [4]), the distribution for the sojourn time  $W_c$  in the station can also be explicitly derived:

$$\begin{aligned} P(W_c \leq t) &= (1 - \lambda) \sum_{i=1}^k e^{-\Lambda(iT-t)} \Lambda^{i-1} \frac{(iT-t)^{i-1}}{(i-1)!} \\ &\quad t \in [kT, (k+1)T], \quad k \geq 1 \\ &= 0 \quad t < T \end{aligned} \quad (13)$$

The mean sojourn time is given by

$$E(W_c) = T \left( 1 + \frac{\lambda}{2(1 - \lambda)} \right) \quad (14)$$

## IV. VALIDITY OF QUEUEING MODELS

There is no need to check the validity of the slot reservation, as long as an exact reservation period can be maintained in a real life scenario. Note that this may not always be possible as all reservations have to be organized into a single schedule, which may not always ensure a perfect periodicity for all reservations. Further studies are requested to assess the impact of the schedule design. The validity of the opportunistic insertion model is however more questionable as slot availability depends on the activity of the other stations whereas it is modelled in Section III-B by a Bernoulli process with parameter  $q_K$ . A ns3 simulation software has been developed in order to assess the global performance of a WSADM network. A WSADM ring is simulated, with a varying number of stations (link length between two stations = 4 km). Each station generates PDUs according to a Bernoulli process. PDUs

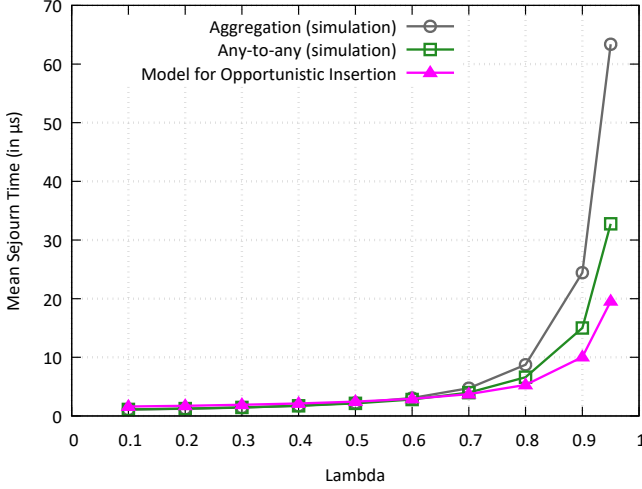


Fig. 1: Mean Sojourn Time: model versus simulations are stored in a finite buffer of size  $B = 99$ .  $T$  and  $K$  are respectively equal to  $10\mu\text{s}$  and to 10. Each simulation runs during 1 second. Fig. 1 compares the mean sojourn times obtained by the model of Section III-B with the sojourn times measured by simulation in two scenarios. In the “any-to-any” scenario, the sojourn time is measured in one station of a WSADM ring of 20 stations, exchanging traffic in an any-to-any scenario. In the “aggregation” scenario, the sojourn time is measured in a station, which sees the traffic aggregated from 10 other stations. In the model and the simulations, a station offers the same traffic  $\lambda = \Lambda T$ , and experiences the same mean slot availability. Fig.1 shows that the model is quite close to simulation results, although it is slightly pessimistic at low load, and rather optimistic at high load. It is also closer to the “any-to-any” case than to the “aggregation” case.

#### V. ASSESSING PACKET INSERTION PERFORMANCE

This section provides a performance analysis of a WSADM ring based on the previous models. We focus on traditional MAN scenarios, in which WSADM rings link stations that aggregate the traffic of a large number of customers (at least several tens of thousands of customers for a MAN access ring, up to several hundreds of thousands of customers for a MAN core ring). Although MANs are usually statically dimensioned, data center interconnection may necessitate a more dynamic operation of these networks in the future. This is why the flexible control plane considered for WSADM could be beneficial, compared with a static channel reservation case.

##### A. Impact of the number of WDM channels

Consider a station generating PDUs according to a Poisson process with parameter  $\Lambda$ . Two cases are shown below: in the first case ( $\Lambda T = 0.8$ ), a full wavelength channel allocation makes sense, whereas in the second case ( $\Lambda T = 0.4$ ), it would represent a significant over-allocation. Both WSADM insertion modes offer the same amount of resources to the station, i.e.  $R = 1/q_K$ . We assume that  $B$  ensures that the loss probability is negligible. The mean sojourn times in the three models (given respectively in equations (4), (10), (14)) represent the mean time taken to insert a PDU on the MAN for the three considered modes. Actually, if the buffer is infinite, a closed-form formula for the mean sojourn time in slot reservation mode is given by

$$E(W_r) = \frac{T}{K} \left( 1 + \frac{KR}{2(K - R\lambda)} \right) \quad (15)$$

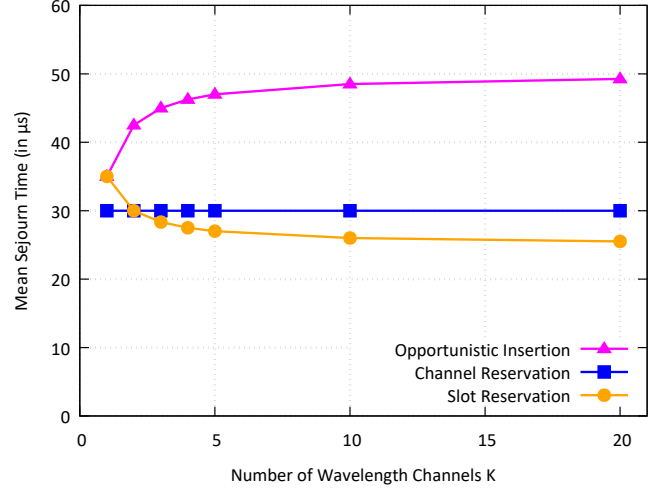


Fig. 2: Mean Sojourn Time versus  $K$ ; high station load

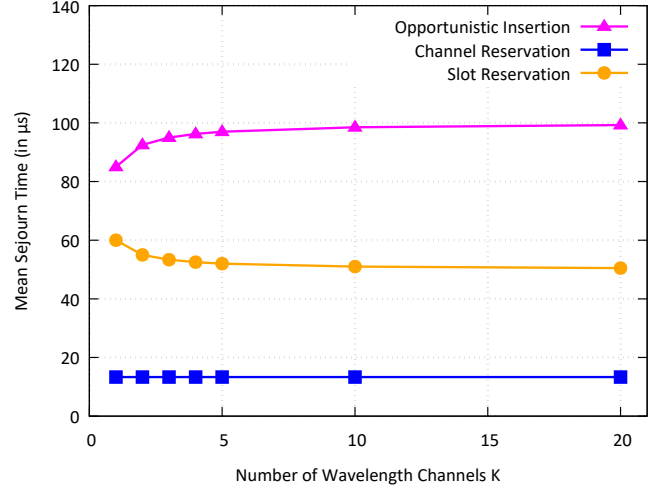


Fig. 3: Mean Sojourn Time versus  $K$ ; low station load

Indeed, the slot reservation model waiting time is quite close to an  $M/D/1$  queue with a service time equal to the reservation period  $RT/K$ ; however, as the service in the WSADM model is provided only at the beginning of the reservation period, statistically, it is necessary to add half a reservation period, and lastly to add the service time  $T/K$ .

Fig. 2 and Fig. 3 represent the mean sojourn times versus  $K$ , for increasing WSADM capacity but fixed offered traffic and provided resources (i.e.  $\Lambda$  and  $Kq_K = K/R$  fixed). The channel reservation mode is obviously independent from  $K$ , as a single channel is dedicated to the station, whatever is  $K$ ; the sojourn time is constant, equal to  $T(1 + \frac{\lambda}{2(1-\lambda)})$ . Moreover, the mean sojourn time decreases with  $K$  in the slot reservation mode while it increases with  $K$  in the opportunistic mode. In Fig2, the sojourn time for slot reservation mode is smaller than the one for channel reservation mode except for  $K = 1$  (in this particular case, both opportunistic and slot reservation cases can use each slot, but as service is slotted, the mean sojourn time exceeds the  $M/D/1$  sojourn time by  $T/2$ ). In both figures, the mean sojourn time varies quickly for small values of  $K$ , but the variation is smaller for larger values of  $K$ . The limit value for the sojourn time in the opportunistic case corresponds to the  $M/M/1$  sojourn time, as a geometrically distributed service converges to an exponential service, and as

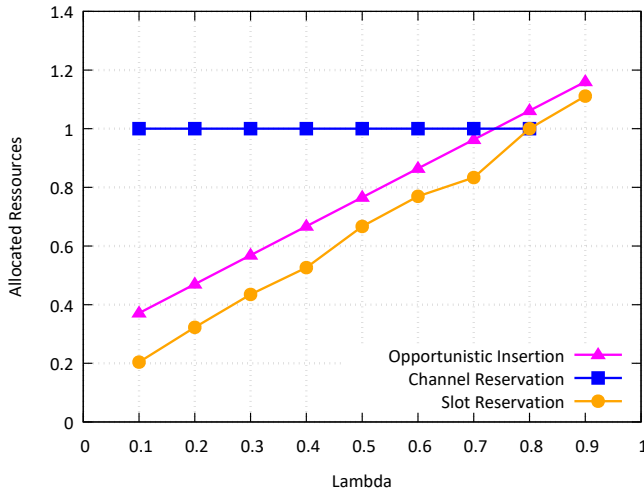


Fig. 4: Resources ensuring  $P(W > 250\mu s)$  smaller than  $10^{-3}$  versus  $\lambda$  for  $K = 10$

slotting service times has little impact for a small slot size; in the present case, this limit value is  $\frac{T}{K/R-\lambda}$ . Using equation (15), we see that the limit value for  $E(W_s)$  is  $\frac{T}{2(K/R-\lambda)}$  which is half the limit value for the opportunistic insertion case. We also see that the slot reservation mode at high load is almost equivalent to the channel reservation mode. At a low station load, channel reservation is an inefficient use of optical resources, although it provides of course a better performance than both reservation and opportunistic modes.

### B. Supporting transport level performance

We address here the dimensioning issue, i.e. identifying the amount of resources needed to support offered traffic. Performance objectives for Ethernet Frames are provided by the MEF for different performance tiers [5]. The performance delivered by a WSADM network to SDUs is not fully assessed in the present paper as the aggregation of SDUs within PDUs is not taken into account. However, it is possible to dimension the network, for the various modes, by setting some objectives for PDU transfer that are significantly smaller than the performance objectives set for Ethernet Frames for the Metro Performance Tier (PT1), i.e. spanning up to 250km. In the following table, the first line is extracted from [5], whereas the second line corresponds to the targets set for the WSADM network. Dimensioning is performed by identifying the amount of resources ensuring  $P(W > 250\mu s)$  is smaller than  $10^{-3}$  versus  $\lambda$  (the 99.9 percentile is selected as in [5]). The case  $K = 10$  is considered, as advocated by [1].

One-way Performance Objectives for the Metro Portion			
	Loss	Delay	Jitter
MEF 23.2 [5]	$10^{-4}$	10ms	3ms
WSADM PDU level	0	2.5ms (propagation) 0.25ms (insertion)	0.25ms insertion

Fig. 4 depicts dimensioning for varying  $\lambda$ . The benchmark circuit allocation case corresponds to the horizontal line, as a full channel is allocated for all  $\lambda$  values. Using (13), it is assessed that channel allocation supports the set target up to  $\lambda = 0.86$ . Opportunistic and slot reservation insertion modes are in most cases more efficient than channel reservation,

especially for medium and small  $\lambda$  values; they are also more flexible due to their sub-wavelength granularity. The slot reservation mode is more efficient than the opportunistic insertion mode, especially for small  $\lambda$  values. If the constraint is relaxed (i.e considering a larger target delay for the quantile), this difference would however decrease.

## VI. CONCLUSION

Models for assessing the transfer plane performance in a WSADM network have been derived. They focus on the PDU (or slot) level performance that is governed by the PDU insertion process, as PDUs experience neither loss nor jitter once inserted. The models assume that PDU arrive according to a Poisson process, which is a realistic assumption in a metro network. Slot reservation and opportunistic insertion have been considered, and bench-marked with channel allocation. Both modes have been shown to easily support MEF performance targets, and to present significant resource allocation gains compared to a classical channel allocation.

As we assume a constant channel bit rate, the global ring capacity is proportional to  $K$ . This implies that, as insertion latency is less impacted by  $K$ , selecting  $K$  should be mainly determined by techno-economic issues. As an example, a ring with 10-channel transponders would have the same capacity as 10 rings with single-channel transponders and would deliver a similar insertion latency (slightly shorter when using a reservation mode and slightly larger in case of opportunistic insertion). However, the cost benefits of using integrated WDM transponders and a single SOA for the 10-wavelength band, as discussed in [2], together with the benefit of managing a single ring, clearly favour WSADM.

Regarding WSADM, the reservation mode slightly outperforms the opportunistic mode in terms of insertion latency and resource usage. However, dimensioning for the opportunistic mode is quite simple: it only implies ensuring that enough resources are available for each station. On the other hand, dimensioning for the slot reservation mode is more complex as it relies on building a global schedule taking into account all flows, each with its own period. However, the two modes are not exclusive as the opportunistic mode only uses slots that are neither already occupied, nor reserved, which makes the WSADM technology quite flexible.

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