Traffic Grooming in WDM Optical Packet Rings

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***Abstract*—The present paper considers a WDM optical packet ring in which multiple wavelengths are operated in a synchronous manner. This architecture attempts to blend packet switching techniques with optical transparency in order to offer a flexible MAN architecture able to accommodate large amounts of traffic demands. This architecture also performs traffic "grooming" (aggregation between different flows) but does not necessitate Optical-Electrical-Optical conversion in transit nodes. In each time slot, a station can send a single packet, selecting the wavelength on a per-slot basis. Once inserted on the ring, the packet is transmitted transparently to its destination. We consider 2 cases regarding receivers: in the non-WDM case, a station can only receive packets on a single wavelength whereas in the second case, a station can receive packets on all the wavelengths used in the network. In both cases, wavelengths can be shared between the stations. We address both network dimensioning and network capacity issues. The use of optical packet switching is first shown to greatly simplify the network configuration compared to any circuit-switched solution. We also show that with WDM receivers, a simple strategy of load balancing on all the wavelengths used in the network allows to increase the capacity of the network, with the same number of wavelengths, or even allows to dimension the ring with a smaller number of wavelengths. This shows that, in terms of traffic grooming, the system under study behaves similarly to non-transparent optical packet ring architectures that rely on Optical-Electrical-Optical conversion in transit nodes. On the other hand, it is expected to outperform those architectures in terms of node complexity and power consumption.**

I. INTRODUCTION

The deployment of FTTx technologies and the introduction of high bandwidth services for the residential customer have a strong impact on access networks. This is obvious for the last mile, since new technologies are deployed to sustain broadband uplink and downlink bitrates. Interconnection/aggregation networks, also called Metro Area Networks (MAN), are also impacted since they have to support a sharp increase in utilization, together with a strong demand on functions (such as multicast support) that were not used by traditional telephony services. MAN networks used to be predominantly based on SONET/SDH ring architectures [18] but they are increasingly relying on optical fiber links. Furthermore, network technologies for metro area will very likely rely on WDM transmission and/or packet switching.

Several requirements should be fulfilled by future MANs:

- they should be very *flexible*, in order to easily adapt to varying traffic demands; in particular, they should be able to support both client-server applications and peer-to-peer applications which represent an increasing portion of offered traffic;
- they should efficiently support a *large volume of traffic demands*, in both uplink and downlink traffic.

These requirements seem contradictory and, thus, difficult to be achieved simultaneously. Flexibility is usually provided by packet switching technologies, whereas high capacity is provided by transparent optical switching.

This paper addresses a network architecture which attempts to blend packet switching with optical transparency. This architecture is a WDM optical packet ring, called ECOFRAME, in which multiple wavelengths are operated in a synchronous manner. In each time slot, stations have the opportunity to transmit a packet on any of the wavelengths. Packet-based transmission ensures flexibility while the optical transfer of packets to the destination stations ensures a high degree of optical transparency. We attempt to show that this network architecture can meet MAN requirements as stated above.

The characteristics of the synchronous WDM optical packet ring under study are presented in Section II. In Section III we address the dimensioning problem of the optical packet ring where either *non-WDM* or *WDM receivers* are used. Section IV identifies the reasons why the use of WDM receivers improves network capacity. Finally, the last Section concludes the document.

II. WDM OPTICAL PACKET RINGS

Throughout the years, a number of architectures for WDM optical packet rings have been proposed and studied in various projects [11].

A. State of the art on optical packet rings

The HORNET project [23] was based on fixed optical add-drop multiplexers (OADM) that implied the opto-electronic conversion of all packets transported by a given wavelength independently of their destinations. The DBORN project [12] focused on passive optical devices in the node and could be seen as a ring extension of the PON concept. In both projects, variable length packets were used.

In the FLAMINGO project [8], the use of a reduced set of different packet lengths was envisioned, in order to improve the encapsulation efficiency of IP packets. In the DAVID project [7] fixed-length packets are supported. Various OADM architectures were studied including an active one where the added and dropped packet wavelengths belonged to a given sub-set of the ring wavelengths. The RINGO project [4] also focused on fixed length packets, but the final network structure was no more a ring as it was based on two different sections of the same fiber for the insertion and dropping of packets. Different MAC and fairness control protocols for WDM packet rings were simulated in [15], for non-WDM receivers.

In all the above projects, optical packet rings are missing to fully exploit the packet switching capabilities in the WDM dimension that may provide the required flexibility and high-capacity. Exploiting these features is the main objective of the ECOFRAME project described below.

B. The ECOFRAME system characteristics

The ECOFRAME ring is studied in the framework of the eponym French research project. Participants to the projects include Alcatel-Lucent (leader of the project), France Telecom, several academic partners and SMEs.

The ECOFRAME ring is a WDM ring, with typically 40 wavelengths and 10 Gb/s per wavelength. It has a unidirectional ring topology (in normal operation when no protection mechanism has been activated) with 300 km of circumference. The stations are connected to the ring via an optical packet add/drop multiplexer.

In an ECOFRAME ring, user data (e.g., Ethernet frames) are multiplexed into data packets which are then inserted by the station in an available time slot. The packets are extracted by the destination station, demultiplexed and sent to the egress of the station. Although the end-to-end performance analysis of ECOFRAME should obviously take into account of the multiplexing and demultiplexing stages, the present work addresses only packet transport, since the multiplexing and demultiplexing phases are identical for any type of receivers.

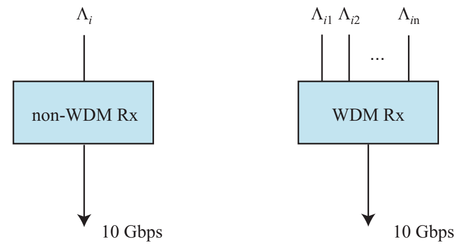
The physical layer protocol structures each wavelength into an optical channel. It divides each optical channel into time slots of equal duration on a synchronous basis. Stations can access the ring only at regularly spaced moments, i.e. the whole system operates on a discrete-time basis.

One of the optical channels is dedicated to system control and is reserved for the transport of OAM information. The others are data channels, used to transmit data packets. All optical channels are synchronized and the control channel carries information concerning the packets carried in the same time slot. In particular, each station processes each control packet, and thus identifies which data packet it should receive in the same time slot.

A time slot on a data channel can contain a single optical packet, i.e., fixed-length packet. Hence, the time slot status is either empty or occupied. Once inserted on the ring, optical packets remain in the optical domain till their destination station. Hence, stations do not process transit packets electronically.

Stations are provided with fast tunable transmitters, which enable a packet-by-packet selection of the wavelength on which a packet is to be inserted. A given transmitter can insert a single packet per time slot, even when several wavelengths present empty slots.

Stations are provided with receivers that, in each time slot, can receive one packet on any wavelengths they operate on. A receiver thus listens to a subset of all the wavelengths present in the ECOFRAME ring. If it accesses a single wavelength, the receiver is a *non-WDM receiver*; otherwise, it is a *WDM receiver* (see Fig.1). In the followings, the impact of using WDM receivers versus using (cheaper) non-WDM receivers is addressed. Although, in the case of WDM receivers, a station can receive several packets in each time slot, we assume here that the egress rate of a station corresponds to the capacity of a single wavelength. Therefore, in case of WDM receivers, stations have to provide a further demultiplexing stage in which they shape the packet traffic to the station egress rate.



(a) non-WDM receiver, receiving on a wavelength Λ_i

(b) WDM receiver, receiving on the wavelength subset $\Lambda_{i1}, \Lambda_{i2}, \dots, \Lambda_{in}$

In both cases, receiver output rate is equal to the max. wavelength rate, e.g. 10 Gbps.

Figure 1. A functional representation of non-WDM and WDM receivers

In [21] we presented the performance analysis of a single wavelength ring by using an analytical model based on Geo/Geo/1 queues and ns2-based simulations. In this work we start addressing the performance of the optical packet ring with multiple data wavelengths in order to evaluate the benefits of ECOFRAME's wavelength flexibility.

C. Expected benefits and open issues regarding WDM optical packet rings

Let us first present a simple example where the potential gains of using packet switching in optical WDM rings are identified. Consider the WDM ring in Fig. 2. There are only 3 traffic flows that are routed in the counter-clockwise direction of the ring:

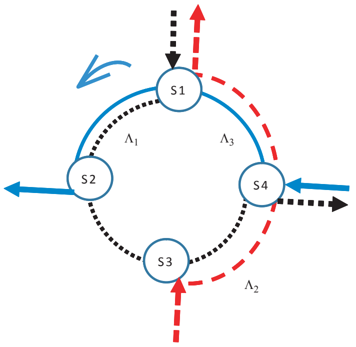


Figure 2. Supporting a given traffic matrix with optical circuits: a simple example

1) one demand from S_1 to S_4,
2) one demand from S_3 to S_1,

3) one demand from S_4 to S_2.

Assume that the rate of each flow corresponds to the rate of a single wavelength and that the network initially has non-WDM receivers.

Without wavelength converters, 3 wavelengths are required to support the traffic flows. Indeed, assume that Λ_1 carries the flow from S_1 to S_4 and Λ_2 carries the flow from S_3 to S_1; Λ_1 is unavailable between S_1 and S_2, while Λ_2 is unavailable between S_4 and S_1. It is, therefore, necessary to activate another wavelength Λ_3 to support the third traffic demand.

On the other hand, if there is a wavelength converter in S_4, 2 wavelengths are sufficient to accommodate the traffic demands. However, optical wavelength conversion technologies are not mature enough for practical deployment, i.e. wavelength conversion implies the use of Optical-Electrical-Optical (OEO) conversion on each packet.

Another solution to reduce the number of wavelengths from 3 to 2 is to consider packet switching. This benefit is well-known in WDM rings with OEO conversion in all or in some selected nodes. OEO conversion permits to perform wavelength conversion, as well as to electronically aggregate, or "groom", the traffic. A well known example of this architecture is the Resilient Packet Ring network (RPR) [13]. In RPR, if traffic flows are split into packets, 2 wavelengths are sufficient to accommodate the 3 flows[1].

However, packet switching as understood in ECOFRAME also allows the same gain, while avoiding OEO at transit nodes. Indeed, in an ECOFRAME network, where each station has WDM receivers, only 2 wavelengths are required if each source station splits equally its flow on Λ_1 and Λ_2. In other words, by exploiting WDM and packet switching, optical traffic grooming can achieve the same benefits as electronic traffic grooming without any OEO conversion nor wavelength conversion (nor slot interchange [17]) at the intermediate stations.

Actually, the so-called "optical traffic grooming" is just the design of the packet insertion process on the WDM optical packet ring. The traffic is "groomed" because different flows can share wavelengths although they may have different sources and different destinations on the ring. This is highly desirable, since avoiding electronic traffic grooming and replacing it by optical traffic grooming allow designing an energy-efficient network [20].

However, the gain to be expected in using optical traffic grooming (i.e. packet switching, coupled with optical transparency in transit nodes) does not come for free. The use of multiple wavelengths in ECOFRAME raises indeed many issues some of which are addressed in the present paper.

The first issue is network dimensioning. To achieve the above mentioned benefits, an optimal ring design is required. Wavelength assignment in unidirectional rings (assuming that each traffic stream has a rate equal to the wavelength capacity) is well studied [19]. However, in many publications, it is assumed that OEO is used to perform the aggregation of traffic in the intermediate nodes of the ring (traffic grooming) and to allow wavelength conversion, in order to achieve an efficient use of the wavelength capacity. This implies that the obtained results cannot be directly applied to ECOFRAME dimensioning (see Section III).

The second issue is related to the wavelength agility of the stations. While the use of tunable transmitters is a common hypothesis for all scenarios investigated in the ECOFRAME project, several options are considered for optical receivers: non-WDM receivers (i.e. single wavelength receivers), fully flexible WDM receivers (able to detect a packet on all the wavelengths used in the ring), partially-flexible WDM receivers (able to detect a packet on a sub-set of the wavelengths used in the ring). The physical implementation of these receivers differ in complexity, but this is beyond the scope of the present paper, which, however, analyzes the impact of selecting one given type of receiver on the efficiency of the network.

A last issue is the efficiency of statistical multiplexing. Optical traffic grooming, as it is implemented in ECOFRAME, results from the use of several "parallel" optical (shared) channels between a source and a destination. Note that in the above example, if each station has a single non-WDM receiver, 3 wavelengths are required to accommodate the offered traffic. It is only in the case of WDM receivers (here, a WDM receiver can receive traffic on 2 wavelengths) that the network can accommodate the offered traffic with 2 wavelengths. We generalize this observation in Section IV, where we analyze why WDM receivers enhance the capacity of the network.

In the present paper, analyzing both network dimensioning and statistical multiplexing, we obtain some insights on the performance that can be expected from an ECOFRAME network with several data wavelengths, and we show the gain using WDM receivers versus non-WDM receivers.

III. CAPACITY DIMENSIONING PROBLEM

In this section the dimensioning problem for WDM optical packet ring, with either WDM or non-WDM stations, is addressed. The dimensioning problem aims at finding the minimum number of wavelengths required to support a given set of traffic flows, under the assumption that there is a single receiver per station.

Notice that this dimensioning problem is different from the previously studied dimensioning problem for networks with electronic traffic grooming. The main difference is that the main cost in networks with electronic grooming is given by Add-Drop Multiplexer (ADM) electronic ports, or equivalently the receivers required at the destinations and in intermediate nodes [2], [6], [22], along with wavelength costs [5].

Optical grooming avoids the need of additional electronic ports and enforces wavelength continuity constraint at intermediate nodes [1], [10], [14].

A. Dimensioning for non-WDM stations

Non-WDM stations have a single receiver operating on a single wavelength. Thus, traffic flows cannot be split among

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[1] The statistical multiplexing due to packet switching is neglected.

different wavelengths. Traffic rate of flows arriving at each station is assumed to be smaller than the wavelength capacity.

Finding the minimum number of wavelengths to support a given traffic matrix in a WDM ring with non-WDM receivers is an NP-hard problem [19].

Due to problem complexity and space limitations, our results concerning the optimal design of ECOFRAME with non-WDM receivers shall be published elsewhere. Here, an upper bound on the minimum number of wavelengths is considered. The bound is based on the MATISSE network [16], which is a WDM optical packet ring where each station receives on a different wavelength. For a MATISSE ring with N stations, the minimum number of wavelengths required is

$$W_{nonWDM} = N. \tag{III.1}$$

B. Dimensioning for WDM receivers

WDM stations have WDM receivers. Traffic flows can be on different wavelengths. As sketched in the example in Section II-C, the dimensioning problem is simplified when WDM receivers are available. This is achieved thanks to the following lemma.

Lemma: Assume that each WDM receiver can receive packets on all the wavelengths. Assume that packets of different traffic flows can be freely transmitted onto the same wavelength (i.e. no pre-allocation of transmission opportunities to stations or flows). Let A be the maximum load (expressed as a multiple of the wavelength capacity) over all links of the ring. Then, the ring can operate with $\lceil A \rceil$ wavelengths.

Proof: To demonstrate the lemma, start from the maximally loaded link. Consider all flows, and equally split each flow on all wavelengths. The traffic can be supported. Consider the next link, considering the already assigned (split) traffic flows on the wavelengths. Such link carries at most A, since the previous one was maximally loaded. Then, the amount of traffic that is received by the station is equal or more than what the station has to insert. Therefore, the amount of capacity available on each wavelength is sufficient to insert the traffic to transmit, provided that is equally split among the wavelengths.

Consider any other links of the ring. The reasoning is the same: the amount of traffic dropped from the ring from the maximally loaded link to the considered link is at least as large as the amount of traffic that is added in the ring. Therefore, the capacity is sufficient to insert the traffic to transmit, provided that it is equally split among the wavelengths.

This lemma indicates that when it is possible to split the traffic (i.e., with WDM stations) among a set of wavelengths large enough to carry the overall load (i.e., $\lceil A \rceil$), the wavelength assignment problem need not to be solved. Moreover, the lemma finds the minimum number of wavelengths required for dimensioning and shows that – contrary to the case of non-WDM stations – load balancing among the different wavelengths can be achieved for free.

Thus, for WDM stations the dimensioning problem can be solved by resorting to the above lemma. When traffic flows can be split on different wavelength sets, then the minimum number of wavelengths required to carry the traffic is $\lceil A \rceil$. Assuming uniform and complete traffic matrix with rate a, the minimum number of wavelengths is

$$W_{WDM} = \lceil N(N-1)/2 \cdot a \rceil. \tag{III.2}$$

C. Dimensioning Comparison

The requirements in number of wavelengths for rings with non-WDM and WDM stations are compared, assuming that traffic matrix is uniform and complete with traffic rates equal to a. Fig. 3 compares the minimum number of wavelengths versus N, for $a = 0.1$. The use of WDM stations allows to greatly reduce the number of wavelengths required in the network. Fig. 4 shows the minimum number of wavelengths versus a, when $N = 6$. The reduction of the number of wavelengths achieved in ring with WDM stations is significant even at high traffic load.

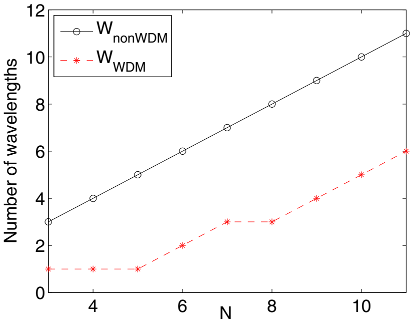

Figure 3. Number of wavelengths vs. ring size, when $a = 0.1$

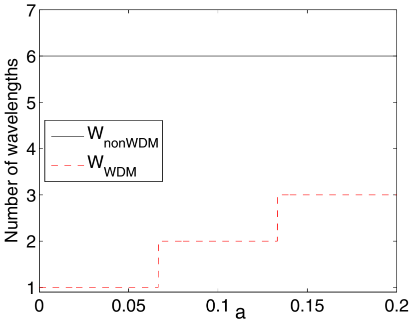

Figure 4. Number of wavelengths vs. a, when $N = 6$

Furthermore, the expressions (III.1) and (III.2) give an upper bound on the traffic rate a, for which $W_{WDM} \leq W_{nonWDM}$:

$$a \leq 2/(N-1). \tag{III.3}$$

The last inequality is always satisfied, as we suppose the traffic rate of flows arriving at each station to be smaller than the wavelength capacity, which is equivalent to $(N-1)a \leq 1$, i.e. $a \leq 1/(N-1)$. This implies that rings with WDM receivers require a smaller number of wavelengths.

IV. WHY DO WDM RECEIVERS INCREASE THE CAPACITY OF THE NETWORK?

This Section identifies two reasons explaining the positive impact of WDM receivers on network's capacity.

It is not easy to provide an effective and well-accepted definition of network capacity. From a practical point of view, a network operator is interested in knowing whether a given network can support a given traffic matrix, and if it does, how robust is the network to a traffic increase. This shows that the notion of "network capacity" is not as simple as one could think and that the techniques used for dimensioning the network have a central role in determining the capacity of a network.

A. *The impact of load balancing*

Consider the set of n-tuples $(a_1, ..., a_n)$, where for all i, $0 \leq a_i \leq 1$, and $a_1 + ... + a_n = A$. It is obvious that the minimum of $max\{a_1, a_2, ...a_n\}$ is obtained for $a_i = A/n$ for each i.

This result directly applies to a ring network with K stations and n wavelengths. Any given traffic matrix mapped on a set of n wavelengths induces different loads on the different links between stations. On a given link, let a_i denote the amount of traffic carried by wavelength Λ_i (expressed as a proportion of the optical channel capacity). A robust dimensioning is obtained when the *remaining bandwidth* on the *most heavily loaded wavelength* is maximized. Obviously, this is obtained if the total load to carry on the link is equally balanced over the set of n wavelengths.

A perfect load balancing on each link is easily obtained if each source station S_s balances the traffic for any destination station S_d over the n available wavelengths.

The above policy implies that each station S_s should be able to transmit on any wavelengths (which is an assumption that is made in the ECOFRAME framework). It also implies that each station S_d should have a WDM receiver that can listen to the complete set of wavelengths used in the ring, which is not always the case. Clearly, if stations have non-WDM receivers it is not possible. More generally, it is reasonable to expect that the industry provides receivers for sets of size k (e.g. $k = 4$ or $k = 10$ seem likely choices). Let m denote the number of wavelengths yielded by a dimensioning process assuming that each receiver can listen to all active wavelengths on the network. If $m > k$, providing a single receiver per station is not sufficient, and a more complex dimensioning process should be conducted; this is for further study.

In any case, load balancing is a technique to take into account in the dimensioning process as explained in Section III.

B. *The impact of statistical multiplexing*

This section assesses the impact of using WDM receivers on the insertion time of the packets, under the (optimistic) assumption that each station can both transmit and receive on all available wavelengths.

The following assumptions are taken. The packet arrival process at each station follows a Bernoulli process with parameter λ. The probability that a time slot on a given wavelength is idle (i.e., available) is assumed to follow a Bernoulli process with parameter μ. The occupancy on the different wavelengths is assumed to be independent. These assumptions are supported by the fact that an ECOFRAME network is a MAN where each station multiplexes a large number of independent user data flows. Therefore, the traffic tends to behave as a memoryless process, as shown in [3].

Let us then assume that each station can receive packets on any of n wavelengths. Since each station can insert a packet in a time slot on any idle wavelength, the above independence assumption yields that packet insertion in a slot is possible with probability

$$\mu(n) = 1 - (1 - \mu)^n$$

The insertion time can thus be modeled by a Geo/Geo/1 queue, with "Arrival First" policy [9]. The mean number of customers in the queue is thus $\lambda(1 - \lambda)/(\mu(n) - \lambda)$. Due to the "Arrival First" hypothesis, this is also the mean number of customers seen in the system by an arriving customer. Little's formula then yields the mean insertion time in the ring expressed in slot times:

$$E(I_n) = \frac{1 - \lambda}{\mu(n) - \lambda} = \frac{1 - \lambda}{1 - (1 - \mu)^n - \lambda}. \qquad \text{(IV.1)}$$

Note that $E(I_n)$ is always larger than 1 (since it takes at least a time slot to insert a packet), and that it decreases quickly to 1 when n increases.

In order to evaluate the expected gain in the sojourn time in the ring, Fig. 5 identifies working condition where the mean insertion time is larger than 2 time slots for increasing values of n. For a given value of n, the area on the right hand side of the curve corresponds to systems (characterized by μ and $\rho = \lambda/\mu$) where the mean insertion time is smaller than 2 time slots. This curve shows that if μ is at least 0.5, the mean insertion time is always smaller than 2 as long as $n \geq 2$. Also, if μ is at least 0.2 (that is if each wavelength is occupied 80% of the time), the mean insertion time is less than 2 if $n \geq 5$.

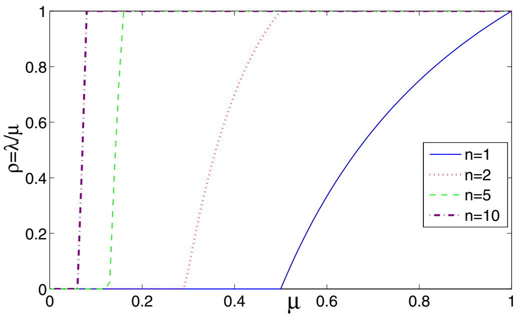

Figure 5. Determining whether the mean insertion time is smaller or larger than 2

However, with WDM receivers, there is a demultiplexing stage at the station egress since several packets can arrive at destination in a single time slot. Once again, we can model the arrival of a packet for the station on any wavelength by a Bernoulli process with parameter λ/n (since each source performs load balancing on all available wavelengths). A model for the extraction time is then a nGeo/D/1 queue, where the duration of a service time is 1 (slot time). The mean extraction time from the ring is thus:

$$E(E_n) = 1 + \frac{1-1/n}{2(1-\lambda)}. \tag{IV.2}$$

The limit for the mean extraction time is the mean sojourn time in an M/D/1 queue with parameter λ/n. It is limited to a few slot times, unless λ is very large (which is very unlikely in an operational MAN environment).

The above results show that WDM receivers drastically improve the delivery performance even for a small value of n: the increase in extraction time is negligible compared to the decrease in insertion time. This suggests that even if WDM receivers can only receive on a limited number of wavelengths (e.g. 4), there would still be a gain in using them instead of non-WDM receivers.

C. Capacity comparison at equal network cost: an example

The qualitative results stated in the above sections are now validated and quantified on a simple example.

Consider a unidirectional ring connecting 6 identical stations, S_1 to S_6; L_i denotes the link between S_i to S_{i+1}. We assume an "any-to-any" traffic, where each station sends the same amount of traffic to all the others, in a counter clockwise manner. Let a denote the amount of traffic, expressed in percentage of a wavelength capacity, sent by one station to another.

Two different interconnection scenarios are assessed and compared:

1) non-WDM receivers (see Fig. 6): 3 stations S_1, S_3, S_5, receive traffic on wavelength Λ_1 and the other stations S_2, S_4, S_6, receive traffic on wavelength Λ_2. All stations can send traffic either on Λ_1 or on Λ_2, depending on the destination of the packet. Only one packet can be sent by a station in a given time slot.
2) WDM receivers: all stations can receive traffic either on Λ_1 or on Λ_2. Only one packet can be sent by a station in a given time slot, but a station can receive 2 packets per time slot.

The total amount of traffic sent or received by a station is thus $5a$, and two wavelengths Λ_1 and Λ_2 are available in both rings.

1) Capacity of the network with non-WDM receivers: The maximum capacity is limited by a number of constraints. The first constraint is that the traffic carried by a given wavelength on a link between 2 stations is less than the wavelength capacity. Obviously, wavelength Λ_1 carries a traffic of magnitude $9a$ on each of the links arriving in stations S_1, S_3, S_5, and a traffic of magnitude $6a$ on each of the links arriving in stations S_2, S_4, S_6. Similarly, wavelength Λ_2 carries a traffic of magnitude $9a$ on each of the links arriving in stations S_2, S_4, S_6, and a traffic of magnitude $6a$ on each of the links arriving in stations S_1, S_3, S_5. This yields the first constraint:

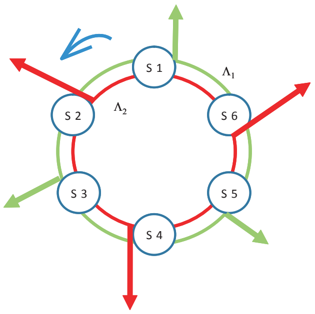

Figure 6. Optical packet ring with non-WDM receivers

$$a \leq 1/9 \approx 0.111. \tag{IV.3}$$

In a circuit switching scenario, this constraint would be sufficient, because traffic shaping would have been performed prior the insertion on the ring. However, in the current scenario, traffic shaping is performed in each station and we have to ensure that the sojourn time in the station, prior to transmission on the ring, is small enough. To assess this sojourn time in the station, an approximate queuing model is presented. This approach is similar to the model developed in [21].

Consider a station that can transmit one packet in each time slot, but has two queues to serve. Queue i is fed by traffic to be transmitted on wavelength Λ_i ($i = 1, 2$). We assume that the arrival process on queue i is Bernoulli with parameter λ_i. The traffic slot on wavelength Λ_i is assumed to be free with probability μ_i, independently of what happens on other time slots and on the opposite wavelength. Moreover, "Arrival First" policy is considered [9].

If $N_i(k)$ denotes the number of packets in queue i just before instant k, $(N_1(k), N_2(k))$ is a discrete time Markov process. Since it is a bit cumbersome, we derive an approximate model by approximating queue i by a Geo/Geo/1 queue with a Bernoulli arrival process with parameter λ_i, but with a modified probability μ'_i of a "free" slot on wavelength Λ_i. μ'_i is obtained by stating that the slot on wavelength Λ_i can be used for transmission if it is free and if the other queue does not use it. In order to estimate the probability that the opportunity for transmission is used by the other queue, we assume that, when the slot is free for the 2 wavelengths, the station selects the queue to be served as:

- the non-empty queue, if one of the queues is empty;
- proportionally to the arrival rates on the queues, if none of the queues is empty.

This single queue model is an approximation because it assumes that the service processes for the 2 queues are independent, which is obviously not true.

Considering the queue in front of Λ_1, this simplifying assumption yields

$$\mu'_1 \approx \mu_1 - \mu_1 \mu_2 P(N'_2 > 0) \frac{\lambda_2}{\lambda_1 + \lambda_2}. \tag{IV.4}$$

In a Geo/Geo/1 queue, $P(N'_2 > 0) = \lambda_2/\mu'_2$, therefore

$$\mu'_1 = \mu_1 - \mu_1\mu_2 \frac{\lambda_2^2}{(\lambda_1 + \lambda_2)\mu'_2}. \tag{IV.5}$$

As expected, we see that $\mu'_1 \leq \mu_1$. Define $\alpha_i = \mu'_i/\mu_i$. The above equation then reads

$$\alpha_1 = 1 - \frac{\lambda_2^2}{(\lambda_1 + \lambda_2)} \frac{1}{\alpha_2}. \tag{IV.6}$$

A similar equation can be derived for the second queue. By combining both equations, we see that $\alpha_2 = \alpha_1 - \lambda_1 + \lambda_2$, and that α_1 is a solution to:

$$x^2 + (\lambda_2 - \lambda_1 - 1)x + \frac{\lambda_1^2}{(\lambda_1 + \lambda_2)} = 0. \tag{IV.7}$$

Straightforward algebra can be used to prove that the above equation has 2 solutions in $[0, 1]$.

A solution corresponds to a stable Geo/Geo/1 queue iff $\lambda_1/\mu'_1 < 1$, that is $\alpha_1 > \lambda_1/\mu_1$. Similarly, $\alpha_2 > \lambda_2/\mu_2$ which is equivalent to $\alpha_1 > \lambda_2/\mu_2 + \lambda_1 - \lambda_2$. Depending on the relationships between $\lambda_1, \lambda_2, \mu_1, \mu_2$, one of these inequalities is more stringent than the other.

The above results are now applied to the scenario in Fig. 6. Consider the 2 queues in station S_1. Since S_1 transmits a to each of the other stations $\lambda_1 = 2a$ and $\lambda_2 = 3a$. As pointed out previously, the slots on Λ_1 on L_6 are busy with probability $9a$. However, station S_1 receives $5a$ on Λ_1, which means that $\mu_1 = 1 - 4a$. Similarly, the slots on Λ_2 on L_6 are busy with probability $6a$; however, station S_1 does not receive traffic on Λ_2 and therefore $\mu_1 = 1 - 6a$. Eq. (IV.7) becomes

$$P_a(x) = x^2 + (a - 1)x + 4a/5 = 0 \tag{IV.8}$$

and the stability constraint for the Geo/Geo/1 queues is

$$\alpha_1 > 2a\frac{1 + 3a}{1 - 6a}. \tag{IV.9}$$

Eq. (IV.8) has 2 solution between 0 and 1 and is negative between those solutions. The stability constraint reduces to $P_a(2a\frac{1+3a}{1-6a}) < 0$, which in turn yields

$$69a^2 + 2a - 1 < 0 \tag{IV.10}$$

and finally

$$a < \frac{\sqrt{70} + 1}{60} \approx 0.107. \tag{IV.11}$$

Note that the constraint on a in Eq. (IV.11) is more stringent than the link load constraint in Eq. (IV.3). Dimensioning the system would set an even tighter bound on the value of a, in order to limit, e.g., a quantile of the sojourn time in the stations. This limit is the price to pay for traffic grooming and non-WDM receivers.

The accuracy of the above model is assessed in Fig. 7 which shows the mean sojourn times in the queues, obtained analytically by this approximate model and by simulation. The simulation results are given with the confidence interval of 10%, at confidence level of 95%. In Fig. 7 the performance results are shown both for the stations inserting packets on the wavelength used by the station to receive traffic ("same" wavelength) and on the other wavelength used in the ring ("opposite" wavelength). This figure shows that the model is reasonably accurate, but has the tendency to over-estimate the mean sojourn time. This is due to the approximation introduced in the model with (IV.4).

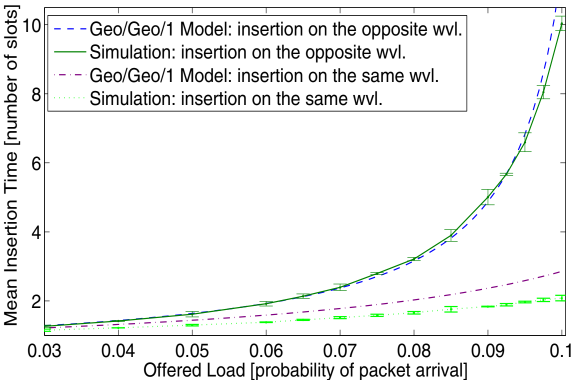

Figure 7. Mean insertion time with non-WDM receivers vs. a

2) *Capacity of the network with WDM receivers:* A load balancing assumption is made in the case of WDM receivers. We assume that on each link L_i, the total load $15a$ is equally shared between Λ_1 and Λ_2. This is achieved when each station equally splits its traffic to each one of the other stations on the 2 wavelengths. A first constraint is therefore

$$a \leq 2/15 \approx 0.133, \tag{IV.12}$$

which represents a 20% increase in capacity from the equivalent constraint (IV.3) for non-WDM receivers.

The constraint on capacity due to statistical multiplexing is assessed using the model developed in Section IV-B. The queue is stable iff $\lambda/\mu(2) < 1$, where $\lambda = 5a$ and $\mu(2) = 1 - 25a^2$. Therefore

$$a < \frac{\sqrt{5} - 1}{10} \approx 0.124. \tag{IV.13}$$

Here also, we note that the constraint on a in (IV.13) is more stringent than the link load constraint (IV.12). But the maximum value for a is still significantly larger than the one obtained in Eq. (IV.11).

The accuracy of the model with WDM receivers is assessed in Fig. 8 which shows that the model is very accurate. The confidence intervals of 10%, at 95% confidence level, achieved by simulations are indicated in the figure.

V. CONCLUSION

This paper points out the benefits provided by WDM optical packet technology to perform traffic grooming in metropolitan rings. A major benefit comes from using packets instead of circuits. A second one comes from the sharing of wavelengths between stations. The sharing avoids to explicitly dedicate

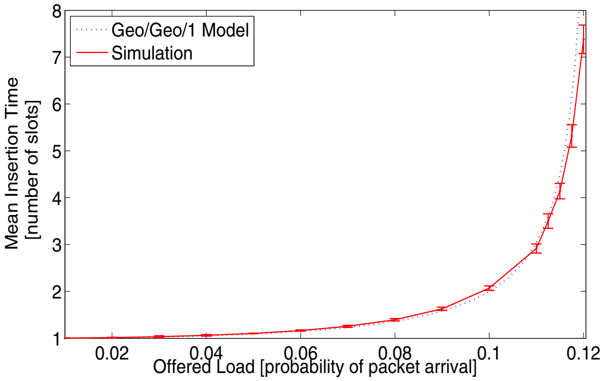

Figure 8. Mean insertion time with WDM receivers vs. a

wavelengths to stations. This benefit is more evident when stations have little traffic to transmit, as it could happen in access networks that predominantly carry downstream traffic. A third benefit comes from the use of fully tunable WDM-receivers as they enhance the flexibility of packet transmissions.

This paper quantitatively assessed those benefits by combining two main approaches, namely WDM ring dimensioning and performance evaluation by simulation and analytical modeling. The performance was evaluated using the approaches on several representative configurations including a 6-node / 2-wavelength ring. Both dimensioning and performance results emphasized the importance of load balancing.

Several issues need to be addressed in future studies, in order to provide accurate conclusions for large size rings.

The first one is the design of the scheduling mechanism used to control packet insertion in stations. Scheduling is a major issue since traffic grooming is only performed at insertion time. We can list some requirements that schedulers should satisfy:

1) the scheduler should respect the dimensioning process that has mapped traffic demands on wavelengths;
2) a scheduler should be "non-blocking", i.e. should be able to serve a packet as long as there are available wavelengths in a time slot and non empty queues;
3) the scheduler should "fairly" serve the various destinations to ensure that the delays for all destinations are similar;
4) the scheduler should be easily configured: it is not realistic to expect the network operator to implement time and traffic dependent scheduling rules in each station.

A second relevant issue is related to the dimensioning process. A more accurate and precise model, that accounts for both receiver and wavelength cost, should be used during the dimensioning.

These issues are also related to the availability, or cost, of WDM receivers. Indeed the policy of equally splitting each traffic flow on all active wavelengths is probably not realistic in large networks, and the impact of partial splitting is left for further study.

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