Cost of Stable Dimensioning in Optical Packet Ring with Uniform and Symmetric Traffic

Bogdan Uščumlić, Veselin Gredić, Annie Gravey, Philippe Gravey, Michel Morvan, and Petar Matavulj

***Abstract* —Optical packet switching allows very efficient bandwidth use in the metropolitan ring networks, in comparison to optical circuit switching. However, when dimensioning an optical packet switching network, the stability of the network needs to be planned carefully, as these networks encounter the same stability issues as the electronic packet networks (e.g. Ethernet or Resilient Packet Ring). In this paper, we show which stability conditions need to be satisfied by inserting nodes, in an optical packet switching network. On an example, we illustrate the impact that the stability has on the network QoS performance and incite the introduction of the stability constraints in network design. Next, we explain a network design method and the corresponding CAPEX cost assumptions. Finally, we study the stability in a small metropolitan ring with a uniform and symmetric traffic matrix, in order to evaluate the impact of stability on the network cost and capacity. Numerical results show that the stability constraints induce the average increase in network CAPEX cost of around 9%.**

***Keywords* — linear programming, metropolitan networks, optical packet switching, stability.**

I. Introduction

DIFFERENT projects and testbeds in recent years addressed the optical packet switching (OPS) alternatives to the traditional optical circuit switching (OCS) technologies in the metropolitan area networks (e.g. see [1] for a survey). It is shown that OPS achieves high bandwidth efficiency in comparison to OCS, and in combination with optical transparency offers a cost effective alternative for a future metropolitan network.

Network planning in optical networks with OCS consists in routing the circuits and assigning the wavelengths to them, so that the overall network cost (either OPEX or CAPEX) is minimized. In the nodes of these networks, switching is performed at the circuit (wavelength) level, i.e. after mapping of client traffic into the optical containers is already done (at the upper layers), so there is no fear that client traffic will suffer from a congestion at the optical transport level. In OPS networks, the situation is different: if there is too much arriving traffic, the optical packets scheduled for insertion will experience high delays and might be lost, due to the insertion buffer limits. Since each optical packet carries several client packets, the delay or the loss of optical packets leads to client traffic QoS performance degradation. The stability issues due to packet multiplexing are analogue to the ones in electronic packet switching networks (like Ethernet or Resilient Packet Ring).

This paper explains how the stability can be included in the network design, in case of OPS rings. It also quantifies the trade-off between the cost of the stability guarantees and the network CAPEX cost.

In what follows, Section II describes the OPS ring in study, while in Section III the focus is on the stability model. This section also contains a motivating example, explaining the interest of stability. Section IV defines the stable dimensioning model for the OPS ring. Section V contains the numerical results assessing the cost and capacity impact of the stability. Finally, concluding arguments are given in the last Section.

II. POADM Ring Architecture

The studied network is characterized by the unidirectional WDM fiber ring connecting the network nodes (typically 5-12 of them), and a time slotted operation. Each node is equipped with one fully tunable transmitter, one or multiple fixed receivers and Packet Optical Add/Drop Multiplexers (POADMs) [2], as shown in Fig. 1. The entering WDM optical signal is first demultiplexed, and then the optical packets are received on all the wavelengths for which the node has the

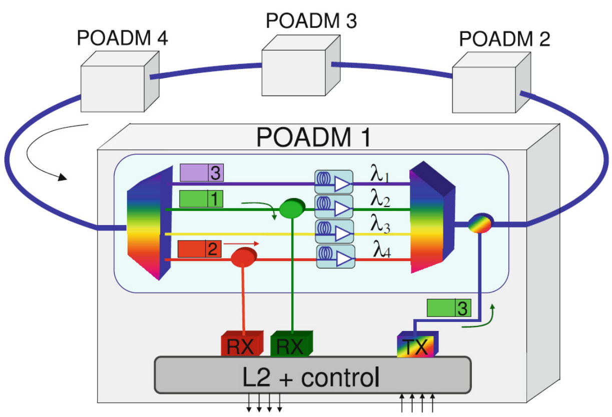

Fig. 1. POADM node architecture.

corresponding receivers. By using optical gates realized with semiconductor optical amplifiers (SOAs), the time slots on different wavelengths are either let to transparently transit or they are erased, if they carry the

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packets destined to the node itself. This stage allows a POADM node to reuse the same time slot for sending the next optical packet. A new packet is added to the wavelength comb, after the final multiplexing stage.

Thus, a POADM station can insert only a single packet during a time slot, but it is capable of extracting several packets during a time slot. The receivers that operate at the same wavelengths can be used by several destinations. The wavelength rate is supposed to be 10 Gbps.

Two types of the basic information units are used by POADM nodes: *Service Data Unit* (SDU) and *Protocol Data Unit* (PDU). A SDU is formed by a client frame in the encapsulation process. Consequently, SDUs have a variable size. Each PDU (optical packet) is created from one or more SDU in a process in which the segmentation is eventually used. The size of PDU is fixed. The problem of stability in this paper is assessed at the level of PDUs, i.e. the optical packets.

Apart from data channels, which are used for transport of the payload, there is a single, separate control channel used in the ring. The control channel transports the information concerning the optical containers of data channels, including the time slot status of data channels (a time slot can be either free or busy), the class of service of the optical containers and the information related to the reservation mechanisms.

III. Stability in POADM Ring

In accordance with the described architecture, it is assumed that from the point of view of packet insertion, the POADM node can be described with a set of FIFO queues accepting packets to be sent on different wavelengths, and serviced by one server with a capacity of one packet per time slot. Each queue corresponds to one wavelength, and waiting lines do not share a wavelength. Thus, the packet insertion model is equivalent to a discrete parallel server system with a single server. The number of waiting lines is *w*, while the probability of packet arrival in queue *i* is a_i. Obviously, $\sum_i a_i < 1$. Finally, it is also assumed that the probability that the wavelength is free in a given time slot is constant, equal to p_i, $0 \le p_i \le 1$.

A. Stability according to Tassiulas and Ephremides

Tassiulas and Ephremides have studied the equivalent single server discrete system in [3], where they presented a *throughput optimal* scheduling for multi-hop packet radio networks. In their subsequent paper [4], the same authors considered the stabilizing scheduling policy for a wireless network with time-varying connectivity. The later paper shows the stability conditions of the equivalent system in case when Longest Queue First (LQF) packet insertion policy is applied.

The results concerning stability from that work are summarized in the following theorem..

Proposition 1. *Consider* w *wavelengths* $\{\lambda_i, i = 1,2,..., w\}$. *There is a FIFO queue in front of each wavelength. Assume that* n *queues are served by a single server that can send at most a single packet per time slot. Let* p_i *be the probability that wavelength* λ_i *is available for transmission in a given slot, and let* a_i *be the arrival rate for queue* i. *If LQF is the scheduling policy then the sufficient and necessary stability conditions are:*

$$\sum_{i \in Q} a_i < 1 - \prod_{i \in Q} (1 - p_i), \forall Q \subset \{1,2,..., w\}. \quad (1)$$

The above result on stability applies to the model of POADM node and it provides a direct, simple relationship between the parameters a_i and p_i. The POADM node inserting traffic is stable iff conditions (1) are satisfied.

B. Motivating example

To understand how the stability impacts the OPS ring performance in terms of QoS, consider the example in Fig. 2. It is a 6 node ring with four traffic flows: A to D = 0.28, A to E = 0.35, C to B = 0.7 and D to C = 0.6 (values are normalized to wavelength capacity).

If stability conditions (1) are not taken into account, the possible routing and allocation of network flows on different wavelengths is as in Table 1.

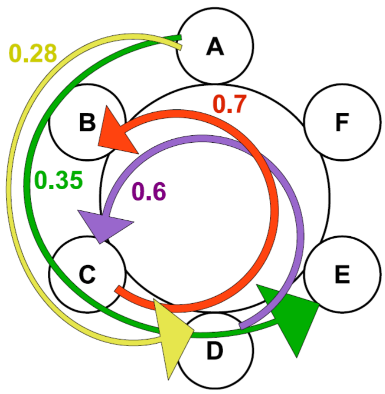

Fig. 2. Motivating example: traffic scenario.

Table 1: Design of ring from Fig. 2 without stability guarantees.

	A to D	*A to E*	*C to B*	*D to C*
λ_1	0.28		0.7	
λ_2		0.35		0.6

According to (1), the stability conditions for node A are:

$$a_1 < p_1, a_2 < p_2, \quad (2)$$

$$a_1 + a_2 < 1 - (1 - p_1)(1 - p_2). \quad (3)$$

From Table 1 it can be concluded that $a_1 = 0.28$, $a_2 = 0.35$, $p_1 = 1 - 0.7 = 0.3$, and $p_2 = 1 - 0.6 = 0.4$, as flows 0.7 and 0.6 are routed on wavelengths λ_1 and λ_2, respectively. Next, we see that conditions (2) are satisfied, but condition (3) is not satisfied. This means that the design proposed in Table 1 is not stable (because it is not stable at node A).

Such design will lead to long delays of packets waiting to be inserted at node A. To illustrate this, we have simulated the network from Table 1 with the computer network simulator ns-2. The scheduling policy that is used is LQF, according to Proposition 1. The measured parameters were the number of packets queued at node A, and destined to node D (waiting to be inserted on wavelength λ_1) and to node E (waiting to be inserted on wavelength λ_2). The results are summarized in Fig. 3, and show that the number of packets in both waiting lines at node A steadily increases. The instability of the system leads to large queuing delays and mandatory loss of client traffic, because the buffers for PDUs are limited.

To overcome this problem, a stable dimensioning of the ring from Fig. 2 is proposed in Table 2. Another wavelength (λ_3) is added to design, in order to achieve the stability. The insertion process at node A was once again tested with computer simulator for LQF scheduling, and the results are shown in Fig. 4. Now the system is obviously stable, and the queues contain only a small number of packets. The example confirms the strong interest for introducing the stability guarantees into the OPS network design.

TABLE 2: DESIGN OF RING FROM FIG. 2 WITH STABILITY GUARANTEES.

	A to D	*A to E*	*C to B*	*D to C*
λ_1	0.28			
λ_2		0.35		0.6
λ_3			0.7	

IV. IMPLEMENTING THE STABILITY CONSTRAINTS

Network design consists in resolving the routing and wavelength assignment (RWA) problem for the given input traffic matrix, so that the CAPEX cost is minimized. The result of design is the network configuration in terms of the number of wavelengths needed in the network, the allocation of wavelengths to the traffic flows and distribution of fixed single wavelength receivers at ring nodes. The routing problem in a unidirectional ring is trivial, so its solution is not part of the expected results. The CAPEX cost of the ring is composed of two main costs: wavelength leasing cost (C_w) and fixed single wavelength receiver cost (C_r). The costs are normalized and given in arbitrary units.

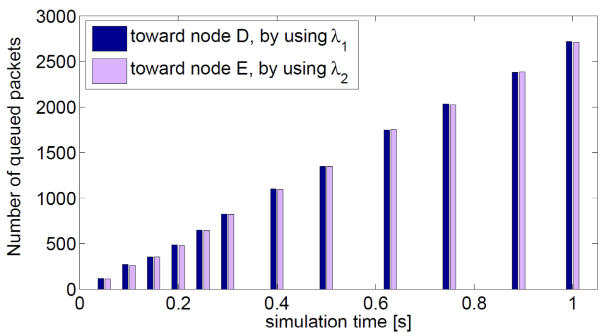

Fig. 3. Performance of node A (Fig. 2) in a ring with connections routed according to Table 1.

The problem of dimensioning is usually expressed by means of linear programming (LP). The mathematical LP formulation of the dimensioning problem with and without stability conditions (1) is out of the scope of the present paper, and is given in detail in [5]. Here, we study the impact of stability conditions on the overall network cost and achievable capacity, under the supposition of uniform and symmetric traffic pattern.

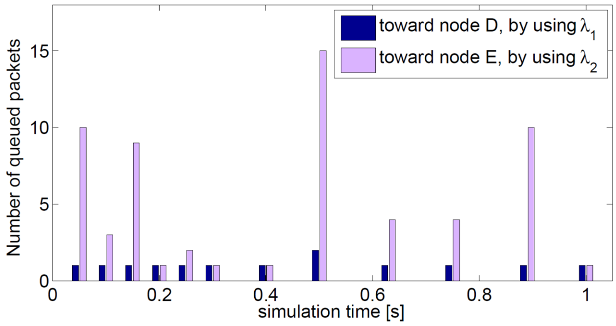

Fig. 4. Performance of node A (Fig. 2) in a ring with connections routed according to Table 2.

V. NUMERICAL RESULTS

In this section, the optimal dimensioning results are given for a 5 node ring, for a uniform and symmetric traffic matrix. Such a traffic matrix can be described as “any-to-any” traffic, because between each two network nodes there is a traffic demand of the same amplitude α (normalized to wavelength capacity). The focus is on evaluating the cost increase and the level of occupancy of wavelengths in a network dimensioned to take into account the conditions for stability.

A. Network cost increase due to stability constraints

1) Case I: $C_w = 1, C_r = 0.1$. Wavelength cost is considered to be dominant. Fig. 5 shows the overall CAPEX cost as a function of the traffic amplitude, for a design with/without stability guarantees. Stable design is obviously more expensive, up to 67%, which is achieved for α =0.1. However, not all the designs without stability conditions were actually unstable. In Fig. 6, the components of CAPEX cost (number of wavelengths and number of receivers in the design) are shown only for values of α for which the stability problems existed. From that figure we can see how the stability conditions influence the number of wavelengths and receivers in the design. At some points (α ={0.1,0.18, 0.20, 0.24}) the stability increases the CAPEX cost, because it increases the wavelength number in the design.

At point α =0.22, the cost is increased because of the receiver number increase. Finally, at points α ={0.12,0.14} the application of stability conditions did not result in the increase of network cost. This is so because the stability condition resulted in a stable rerouting of the traffic flows by keeping the same number of receivers and wavelengths in the ring.

If averaged over all unstable points (shown in Fig. 6), the average increase in CAPEX cost due to stability is equal to ≈22%. The average increase in the number of wavelengths is ≈33.3%. The stability usually increases the number of wavelengths, while the number of receivers might be increased or decreased.

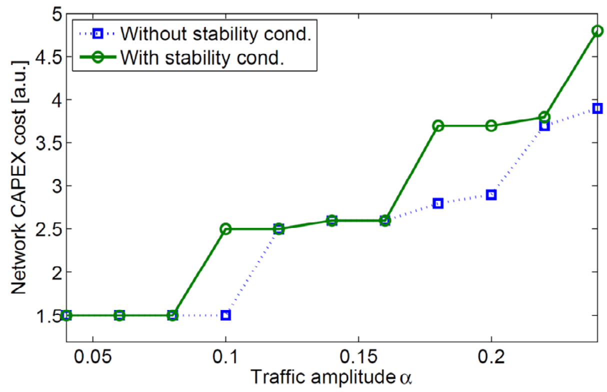

Fig. 5. Dimensioning cost for $C_w = 1, C_r = 0.1$.

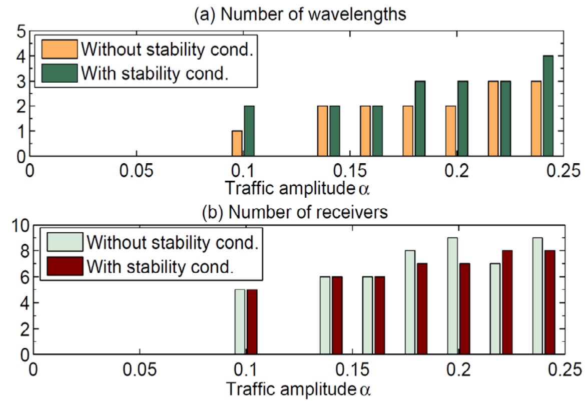

Fig. 6. CAPEX cost components for $C_w = 1, C_r = 0.1$.

2) Case II: $C_w = 1, C_r = 1$. In this case, the two CAPEX costs are the same. Fig. 7 shows that the CAPEX cost is increased only in a single point (for α =0.1). This is due to the increase in the number of wavelengths in the stable solution (Fig. 8). For α =0.18, the increase in the number of wavelengths is compensated by the decrease of the number of receivers, while in other unstable points, the stability did not affect the number of CAPEX cost components (Fig. 8). The average increase in CAPEX cost in this example is ≈3%.

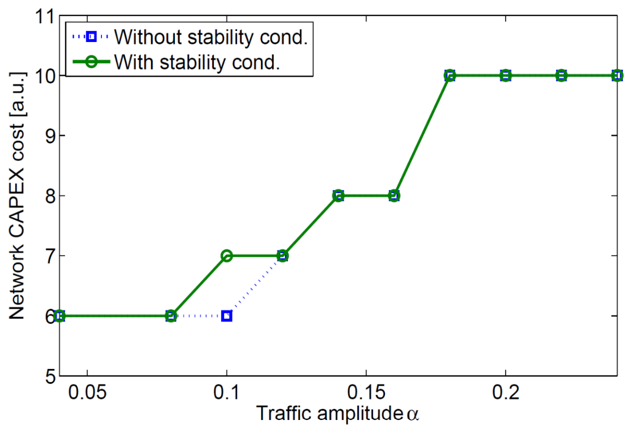

Fig. 7. Dimensioning cost for $C_w = 1, C_r = 1$.

3) Case III: $C_w = 0.1, C_r = 1$. For the sake of completeness, in Fig. 9 we show the optimal results in the case when wavelength cost is much smaller than receiver cost. As the stability conditions mainly impact the number of wavelengths in the design (by usually increasing them) in this case there is only a single unstable point (α =0.1), and the average CAPEX cost increase is ≈2%.

To summarize, the previous results show that stability has a greater impact on CAPEX cost if the cost of wavelength is important. The numerical findings yield that the overall average increase of CAPEX cost is ≈9%, for a 5 node ring with uniform and symmetric traffic.

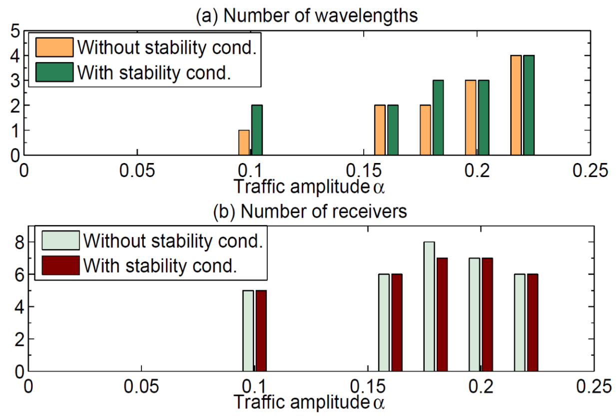

Fig. 8. CAPEX cost components for $C_w = 1, C_r = 1$.

B. The impact of stability guarantees on the network capacity

As shown previously, the stability conditions mainly affect the number of wavelengths in the network, by increasing their number to satisfy the stability criteria. This is so because the stability criteria cannot be satisfied, if the wavelengths are too loaded. Consequently, by limiting the level of the wavelength occupancy, i.e. by reducing the total network capacity, a stable network could be obtained, even without using the stability conditions (1). In order to evaluate the cost of this alternative approach, in this section, the "wavelength occupancy factor" γ is introduced. By definition, 0< γ ≤ 1, and this factor indicates the amount of wavelength capacity that can be occupied by traffic, in the optical ring, on each available wavelength. The simulations are performed for Case I, from the previous section, where $C_w = 1, C_r = 0.1$.

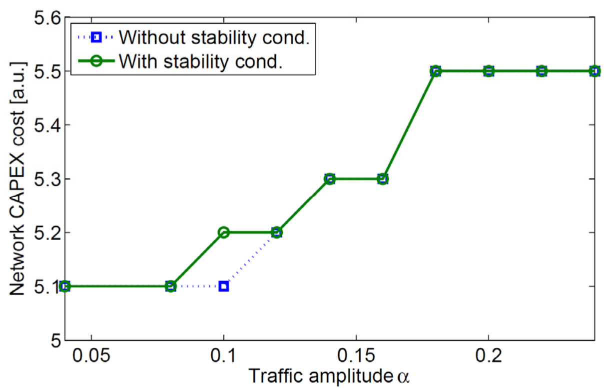

Fig. 9. Dimensioning cost for $C_w = 0.1, C_r = 1$.

Fig. 10 shows the instability occurrence, i.e. the percentage of unstable solutions in the overall number of solutions, when network is designed without stability conditions. The instability occurrence is given as a function of factor γ, and is defined for a range of input traffic amplitudes, which here corresponds to the traffic range in Case I. For the maximum value of γ (γ=1), the instability occurrence is as high as in Fig. 6. When γ decreases, less and less traffic is allowed to be routed per each wavelength, which leads to a decrease of the number of unstable solutions.

The number of unstable solutions falls to zero for γ=0.79, i.e. if the wavelengths are allowed to be loaded up to 79%, all the network dimensioning solutions will be stable, even when the stability conditions are not imposed.

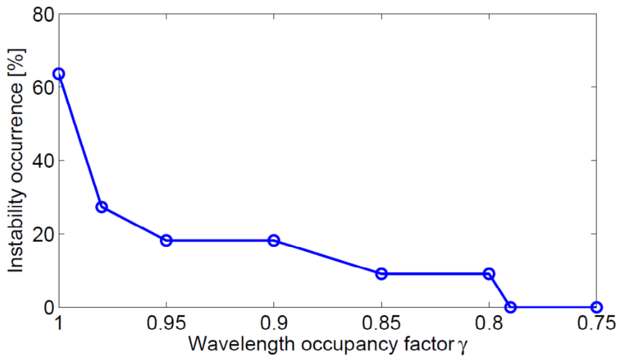

Fig. 10. Instability occurrence in scenario from Fig. 4 (Case I).

However, avoiding stability conditions (1) by limiting the wavelengths load up to 79% of their total capacity does not come for free. The stability is achieved at a price of additional network cost and of having optical rings with under-loaded wavelengths. To illustrate the dimensioning cost increase, Fig. 11 shows how the network cost evolves with the decrease of the wavelength occupancy factor γ. For γ=0.79, the dimensioning cost can be over 70% more expensive (achieved for α=0.1 in Fig. 11), in comparison to a network design without stability conditions (for γ=1). In average over all simulated points, this cost increase is greater than 35%, and is mainly due to the wavelength number increase in the network.

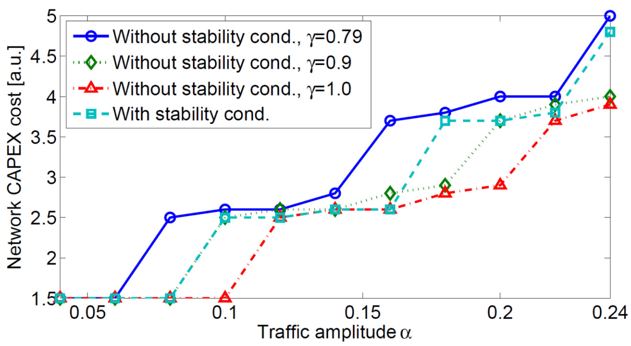

Fig. 11. Dimensioning cost in Case I, for different values of factor γ.

To assess the network capacity of network with stable design, Fig. 12 shows the average wavelength occupancy in the same scenario, for different values of factor γ. The values are calculated over all nodes and all wavelengths in the ring. Results show that stable design benefits from a highly efficient use of the network wavelengths. In average (over all simulated points), the wavelengths use ratio is ≈92%, for network designed with the stability conditions. Note that a part of wavelength band that is wasted due to mandatory guard bands between different optical packets is neglected here. Finally, from Fig. 12 it is obvious that the achievable network capacity is significantly decreased for lower values of γ, as expected.

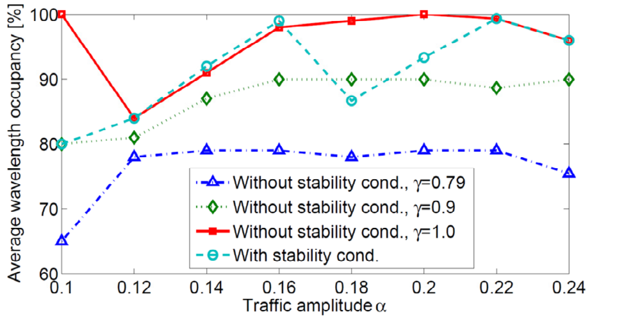

Fig. 12. Average wavelength occupancy in Case I, for different values of factor γ.

In conclusion, although by limiting the ratio of wavelength use it is possible to trade the network capacity for the network stability, a much more efficient solution is obtained by using the stability conditions (1), what is an expected result.

VI. Conclusion

In this paper, the interest of introducing the stability constraints in the design of OPS networks is shown. The trade-off between the stability guarantees and the network CAPEX cost is quantified for uniform and symmetric traffic. For such traffic, the average increase of CAPEX costs with the stability is around 9%. It is also shown that an optical packet ring designed by using the stability conditions achieves a high efficiency in total wavelength capacity use. Although by limiting the level of wavelength use it is possible to trade the network capacity for its stability, the use of the stability conditions is much more cost efficient.

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