

# Dimensioning and energy efficiency of multi-rate metro rings

Y. Pointurier, B. Ušćumlić, I. Cerutti, A. Gravey, J.-C. Antona

**Abstract**—Due to the ever-growing network capacity demand, energy-efficient and scalable networking solutions are needed in all networking segments. This paper focuses on the metro segment and compares the power consumption for four different technologies: Ethernet, Reconfigurable Optical Add-Drop Multiplexers (ROADM), Optical Transport Networks (OTN), and an optical packet switching (OPS) solution called Packet Optical Add-Drop Multiplexers (“POADM”), which was recently proposed.

A novel resource allocation strategy for POADM-based OPS multi-rate rings is proposed for the first time. The multi-rate POADM ring network resource allocation problem is shown to be NP-hard and solved using both an MILP formulation and a heuristic. The MILP formulation and the heuristic are compared, along with dimensioning results for Ethernet and ROADM/OTN ring networks. Results show that multi-rate POADM rings achieve savings up to 10% with respect to single-rate design and can be enabled by assigning a different rate to each wavelength. Furthermore, POADM rings can be up to 5 times more energy-efficient than Ethernet rings and 30% than ROADM rings, assuming similar network efficiencies.

**Index Terms**—Optical packet switching; optical circuit switching; energy efficiency; network planning.

## I. INTRODUCTION

The sky-rocketing increase of the Internet traffic [2] will soon impose a capacity scaling of the optical networks. At the same time, such traffic growth is expected to further increase the amount of power drained to process and transport the traffic data. Already today, the power consumption of networks is reaching alarming levels (e.g., 2-3% of the global carbon footprint is due to the ICT sector) and increasing at a rate of 6% per year [3]. It is therefore necessary to find solutions for an energy-efficient capacity scaling of the optical networks [4].

Technological solutions for decreasing the power consumption of networks are already available. *At the physical layer*, one of the most effective solutions is to increase the spectral efficiency of the optical channels (wavelengths) [2] as the power consumption per bit decreases with the increase of the rates for networks without opto-electro-optical (OEO) regeneration, such as the metro networks. On the other hand, to face the traffic growth, a sudden upgrade of the network with high rate wavelengths is challenging due to the required large capital investment and legacy reasons. Instead, a multi-rate solution,

i.e. the support of wavelengths at different transmission rates, appears to offer the advantages of a smooth transition, along with a large capacity increase at limited and optimal investment [5]. *At the network layer*, by exploiting packet switching paradigm, it is possible to leverage statistical multiplexing for efficiently using all of the offered capacity. This overcomes the circuit switching paradigm, in which circuits are poorly filled. In either case (circuit or packet switching), transparency can further decrease energy consumption by letting data transit through a node with no OEO conversion.

Optical packet switching (OPS) solutions, in which optical packets sustain OEO conversions only at the source and destination nodes, are expected to be competitive in terms of energy efficiency when compared with alternative technologies, such as electronic packet switching (e.g. with Ethernet switches) or optical circuit switching (e.g., with Reconfigurable Optical Add/Drop Multiplexers; ROADM, or Optical Transport Network switches; OTN). Several OPS solutions were proposed in the past, e.g., see [6] for a survey and [7], [8]. Among them, recently a ring network based on OPS technology, called “Packet Optical Add-Drop Multiplexers” (POADM) nodes, was proposed for metro networks, implemented in a testbed, and characterized at the physical layer [9]. The main strength of POADM rings is the ability to leverage statistical multiplexing of optical packets, along with the exploitation of optical transparency [6].

An assessment of the power consumption of POADM ring and a comparison with other technologies for metro rings is necessary to understand whether POADM rings are a suitable solution for reducing the power consumption in the metro segment. The power consumption has been modelled and evaluated for various OPS infrastructures [10], but, so far, not specifically for POADM rings. Furthermore, the combination of multi-rate transmission and optical packet switching has not been yet evaluated for power consumption. Whereas multi-rate has been shown to be generally energy efficient [11] with respect to single-rate in circuit-switched networks with ROADM nodes, it is not clear whether such benefits hold also in POADM rings.

This paper focuses on four different technologies for metro rings, namely optical packet switching (POADM), electronic packet switching (Ethernet), and optical circuit switching (ROADM and OTN). Such ring technologies are enabled for multi-rate support. The aim of the paper is to compare the power consumption of the different technologies, when optimally dimensioned for supporting the requested traffic demands, using single-rate or multi-rate transmission. Dimensioning aims at optimally allocating the network elements

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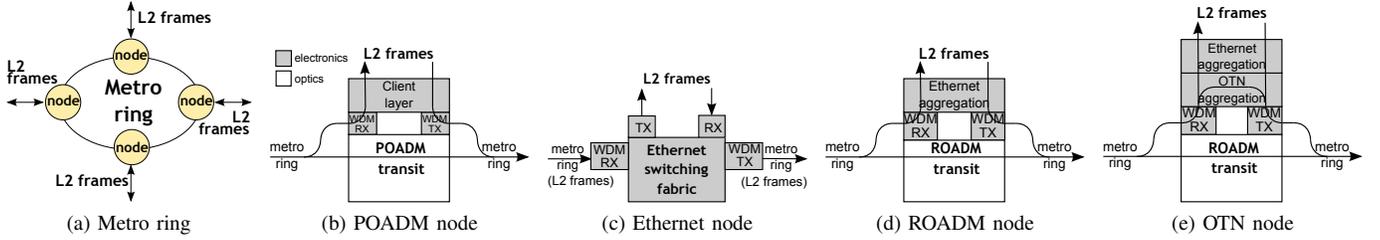


Fig. 1. Metro ring network technologies.

(i.e., transponders, client-cards, and wavelengths) with the objective of minimizing the operative costs (OPEX) and more specifically, the power consumption; CAPEX evaluations are out of the scope here. All compared technologies encompass the same set of layers (L0 to L2), which dominate network equipment deployment in metro networks.

The contribution of the paper is four-fold. *First*, the power consumption of a POADM ring is modelled for both the single and multi-rate case, by extending a model assessed to evaluate the power consumption in existing networks [12]. *Second*, the dimensioning/resource allocation problem (which is proved to be NP-hard) of a multi-rate POADM networks is formulated with a Mixed Integer Linear Programme (MILP), whose optimal solution yields the dimensioning at minimum OPEX. Two design cases are considered: fixed-wavelength rate (FRW) and variable-wavelength rate (VRW), depending on whether each wavelength is operating at a single or multiple rates, respectively. *Third*, a heuristic that approximates the MILP formulation is proposed. *Fourth*, the scaling of power consumption with load of the POADM rings is estimated through simulations and compared with ring networks based on Ethernet, ROADM and OTN nodes. Results aim at assessing the competitiveness of the POADM ring and of multi-rate dimensioning in terms of power consumption, under different scenarios of traffic (from a centralized scenario to a more distributed one) and ring size.

The paper is organized as follows. Section II presents the networking technologies that can be deployed in the metro segment, with a focus on the POADM node. Section III describes our assumptions on the power modelling of metro networks, and infers the cost in terms of power consumption for each one of the three aforementioned networking technologies. Section IV models the allocation of resources in POADM rings using a MILP. The novel heuristic to solve this problem is presented in Section V, along with algorithms to solve the same dimensioning problem for Ethernet, ROADM and OTN ring networks. The power consumption of the multi-rate metro ring networks is assessed in Section VI using extensive simulations, and conclusions are outlined in Section VII.

## II. RING ARCHITECTURES

Consider a Wavelength Division Multiplexed (WDM) ring representative of a metro network, as shown in Fig. 1a. The ring is unidirectional (a counter direction could be used for protection purposes). In the metro ring, layer-2 (L2) frames (e.g., Ethernet) are added by the source node, transit through the intermediate nodes, and then are dropped at the destination

node. The considered rings can be enabled for the support of multiple transmission rates, i.e., each wavelength is assigned a modulation format and a transmission rate that can be distinct from those of the other wavelengths.

The ring size and the optical transmission power are assumed to be small enough that the propagation impairments (except for the link loss) can be ignored for any transmission rate. However, all optical rings may be subject to power oscillations due to the coupling of the wavelengths' power caused by the amplifiers [13]. Although such oscillations may be mitigated, e.g. using amplifiers with very fast gain control, we consider here the conservative approach to use a "physical hub node" that optoelectronically regenerates all channels and breaks any oscillating phenomenon. This "physical hub" increases the power consumption of POADM and ROADM-based rings, but not of the Ethernet rings in which all nodes are opaque by design.

### A. POADM Ring

POADM (Fig. 1b) is a novel OPS technology that was introduced in [9]. POADM ring is a synchronous, multi-wavelength, time-slotted ring. In a POADM ring each link carries exactly the same number of wavelengths. The nodes (except the hub) are all optical and lack of 3R regenerators and wavelength converters. L2 data (e.g., Ethernet frames) is classified and encapsulated into short (e.g., 10  $\mu$ s), fixed-duration optical packets that are inserted in the time-slots of data channels, as depicted in Fig. 2. Time slots must be separated by a "guard-band", i.e. a physical time interval during which data cannot be transmitted, in order to allow some of the components (switching fabric, fast tunable lasers) to switch from a state to another. Those switching times and hence the guard-band duration are typically in the order of tens to hundreds of ns, much shorter than the time slot duration which is in the order of several  $\mu$ s. This introduces a loss of physical capacity of a few percent (at most 10%) which can easily be compensated with a corresponding increase ("overhead") of the physical symbol rate of the WDM transponders. This overhead may result in a comparable increase in the power consumption of the WDM transponders. However, as will be seen in Section III-A, this additional power consumption is negligible compared with the power consumption of the client layer.

A POADM node can add, drop or let packets transit to the next node on the ring. When a packet is dropped, it can be erased and a new optical packet can be added in the same time-slot, on the same wavelength. Hence, L2 data is processed

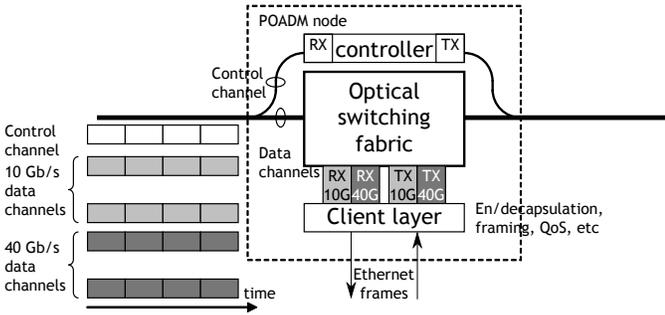


Fig. 2. POADM node: slot-size optical packets encapsulate layer-2 frames. The optical switching fabric is capable of adding, dropping or letting slots transit transparently through the node at both 10 and 40 Gb/s. The separate control channel carries the headers of all synchronous slots. In this example, each data channel is modulated at either 10 or 40 Gb/s. This can be generalized to any number of transmission rates.

in the electronic domain only twice (i.e., at the source and destination node), but still POADM can leverage statistical multiplexing thanks to OPS [14].

The hub performs OEO conversion of each wavelength. However, no wavelength conversion or traffic grooming is performed on the signal that is OEO converted, i.e., optical packets bypassing the hub are 3R regenerated and retransmitted on the same wavelength. In addition to the data channels, a single, separate control channel carries the headers of all optical packets that are synchronously carried on the data wavelengths. Contrary to optical packets that can transit through nodes transparently, the control channel needs to be electronically processed at each node. The separation between data and control channels enables the transparent forwarding of packets, i.e., packets can transit through a node with no OEO conversion.

Each POADM node is equipped with one or multiple client cards (CC) and transponders (TRX) at different rates. The CCs receive L2 frames and perform their encapsulation into slot-size optical packets, and manage Quality of Service (QoS). Similarly, the CCs also receive optical packets from the POADM ring and decapsulate the L2 data. CCs are implemented through the “Client layer” box in Fig. 1b. A TRX is a pair of (Transmitter, Receiver) (TX, RX) for sending and receiving traffic at a fixed rate over the metro ring. A POADM TRX consists of a fast tunable wavelength-transmitter (TX) and a fixed-wavelength receiver (RX). Each TX can be reconfigured on a slot basis and is able to insert optical packets in any time-slots on any wavelength. An example of TX with such capabilities is described in [15]. The RX is tuned to a given fixed wavelength: given a wavelength  $\lambda$ , all nodes can send data on  $\lambda$  but only the nodes equipped with the RX tuned to  $\lambda$  can receive the transmitted data. The various TXs and RXs operating at different wavelengths are denoted as “WDM TXs and RXs,” respectively, in Fig. 1b.

### B. Ethernet Ring

The Ethernet ring (Fig. 1c) consists of opaque nodes that can perform traffic aggregation. Opaque nodes are equipped with CCs and TRXs at different rate. L2 frames are switched in the electronic domain at every intermediate node and are received

at the destination node. Therefore, a TRX is required at each node for each wavelength to send and receive traffic over the Ethernet ring. Statistical multiplexing is achieved thanks to the OEO conversion and the possibility to retransmit the Ethernet frames on any wavelength, i.e., thanks to packet switching performed in the electronic domain, which offers wavelength conversion for free.

### C. ROADM Ring

In the ROADM ring (Fig. 1d), L2 frames are all-optically transmitted over pre-established circuits. Circuits need to be established in advance even if unused or scarcely utilized. Transiting circuits pass transparently through the optical switching fabric at each ROADM node. In a ROADM node, entering data is typically already aggregated and sent over a circuit, such that “adding” or “dropping” data merely consists in operations such as FEC, encapsulation/decapsulation. No wavelength conversion is available. The hub performs OEO conversion of each wavelength. Two different cases are considered: a hub node without wavelength conversion nor traffic grooming capabilities (i.e., optical signal bypassing the hub is 3R regenerated and retransmitted on the same wavelength) and a hub node with wavelength conversion and traffic grooming capabilities (i.e., traffic received at the hub node is aggregated at best and retransmitted on fewer, different wavelengths). In the latter case, all traffic goes through the Ethernet layer (e.g., an Ethernet switch) at the hub node.

The considered ROADM node implements Ethernet over WDM. Frame classification (e.g., the mapping between an L2 frame and an established circuit) is performed by an additional “aggregation layer”. This is represented in Fig. 1d as “Ethernet aggregation”. L2 frames are classified and processed only at the transmitting and receiving node, as in POADM ring. Due to the circuit-based nature of the ROADM ring, it is possible to assume that each ROADM TRX is tuned to a given fixed wavelength without losing generality and fairness in the comparison with the other ring technologies.

### D. OTN Ring

We also consider OTN networks with a single re-aggregation node; indeed, in current network architectures, only the node interconnecting the metro network with the core network is equipped with regrooming capability [16], [17]. A generic OTN node is depicted in Fig. 1e and implements Ethernet over OTN over WDM. An OTN node is essentially a ROADM node equipped with an (electronic) OTN layer. In the considered OTN network, only the hub node is able to perform traffic regrooming at the OTN layer, such that, at the hub node, only traffic whose source or destination is the hub node needs to go through the Ethernet layer while other traffic is regroomed within a dedicated electronic OTN switching fabric. As will be seen shortly, this electronic switch is less energy-consuming than a fully-fledged Ethernet switch such that bypassing the Ethernet layer for the regroomed traffic saves energy; however, this comes at the cost of adding a new layer (OTN) to the data path at every node, thus incurring an increase of the energy consumption for all other (not

regroomed) traffic, which may not necessarily be offset by the Ethernet layer bypassing savings. The dimensioning of multi-rate OTN networks where regrooming can take place at any node is left out for further studies.

The power consumption of the four considered technologies (i.e., POADM, Ethernet, ROADM, OTN) is discussed next.

### III. POWER MODEL

#### A. Assumptions

The power consumed by the rings is modelled as follows. We consider a ring of  $N$  nodes in which signals on a given wavelength can be modulated at a rate  $r$  selected in a set of  $|\mathcal{R}|$  possible rates, i.e.,  $r \in \mathcal{R} = \{r_1, r_2, \dots, r_{|\mathcal{R}|}\}$ .

The power consumption of the considered ring technologies is modelled under the following assumptions.

- The power consumption is due to both optical bypassing at intermediate nodes and electronic processing. More specifically, in the latter category, we discriminate between the power dissipated by the client layer/aggregation layer (e.g., frame classification), and power dissipated for sending (receiving) data to (from) the physical medium (e.g., by TRX: TX and RX).
- We assume that the power consumption of a network element is independent of the load on this network element, that is, a CC or a TRX consumes the same power whether it transmits just a few bits per second or at full transmission rate. This assumption is due to the fact that currently most of the network elements exhibit a poor energy proportionality, i.e., the amount of power consumption proportional to the load is small or negligible compared to the static power consumption. As this assumption is enforced for all the network elements and ring technologies, fairness is ensured.
- Unless otherwise stated, 3R regeneration at the physical hub node is implemented using a RX and a TX in a back-to-back configuration.
- Wavelength utilization  $\eta$  below the maximum (i.e.,  $\eta < 100\%$ ) is considered in order to account for the lack of statistical multiplexing in circuit-switched networks<sup>1</sup>.
- We consider that a fast tunable transmitter as used in a POADM-based network has the same energy requirement as a regular transmitter. Indeed the power of a laser source in a transponder represents at most 15% of the power of a 10 Gb/s WDM TRX [19], and the additional command required to “fast”-tune a laser is at lower frequency (sub-gigahertz) than the considered bitrates, and hence at lower energy-consumption.
- In the POADM model, we neglect the consumption of the opaque control channel, since it is modulated at a low (and low-consumption) rate.
- Similarly, for all ring technologies, the consumption of the Optical Supervisory Channel is neglected as it is typically operated at a very low rate.

<sup>1</sup>Network efficiency in metro networks is difficult to quantify as it is considered as confidential information by operators, however, we note that an efficiency of less than 30% was reported in [18] in the context of a backbone network. In metro networks, where flows are less well aggregated than in backbone networks, it is possible that the wavelength utilization is even lower.

- We neglect the energetic impact of the physical symbol overhead of the POADM WDM transponders mentioned in Section II-A, as this overhead is typically small (at most 10%), and the impact of this overhead on the power consumption of a WDM TRX is even smaller when compared with the power consumption of the client-layer, which can be more than 3 times larger than that of the optical layer (see Section VI-A).

For a given node, let OL indicate the optical layer, EL the OTN electronic switching layer, TL the layer performing E/O or O/E conversion, thanks to TRX, and CL the client layer. Let  $\beta_{h,l}^{r,k}$  be the power consumed by a network element installed on node  $k$  for networking technology  $h \in \{POADM, Ethernet, ROADM, OTN\}$ , at layer  $l \in \{OL, CL, EL, TL\}$  and rate  $r \in \mathcal{R}$ . The general model for the total power consumption of a ring of  $N$  nodes using technology  $h$  is:

$$P_h = P_{a,h} + \sum_{k=1}^N \sum_{r \in \mathcal{R}} \left( \beta_{h,OL}^{r,k} \Lambda_{r,k} + \beta_{h,EL}^{r,k} \Lambda'_{r,k} + \dots + \beta_{h,TL}^{r,k} TRX_{r,k} + \beta_{h,CL}^{r,k} CC_{r,k} \right) \quad (1)$$

where  $P_{a,h}$  is the power consumption of optical amplifiers for technology  $h$ ,  $\Lambda_{r,k}$  is the number of wavelengths modulated at rate  $r$  and transiting transparently through node  $k$ ,  $\Lambda'_{r,k}$  is the number of wavelengths modulated at rate  $r$  and transiting through an electronic re-aggregation switch at node  $k$ ,  $CC_{r,k}$  is the number of CCs at rate  $r$  installed at node  $k$ , and  $TRX_{r,k}$  is the number of TRXs at rate  $r$  installed at node  $k$ . The value of  $\Lambda_{r,k}$ ,  $\Lambda'_{r,k}$ ,  $CC_{r,k}$  and  $TRX_{r,k}$  can be found by properly dimensioning the given ring for the specific instances of forecast traffic.

The power model includes the consumption of optical amplifiers; indeed optical signals need to be periodically amplified in metro networks in order to compensate optical loss in nodes and optical fibers. Let  $A_h$  be the number of amplifiers for a network based on technology  $h$ . Then:  $P_{a,h} = aA_h$  where  $a$  is the power consumption of an optical amplifier. For short rings (e.g., with links of few km) link loss may not need to be compensated while for larger rings (links of few tens of km), an optical amplifier is needed to compensate for the link loss. In addition, for Ethernet rings, node loss needs not be compensated, while ROADM/OTN and POADM node loss can be considered to be comparable and can be compensated with an amplifier per node. Hence, for rings requiring link loss compensation (rings with large links) we can expect that  $A_{Eth} = N$  and  $A_{POADM} = A_{ROADM} = A_{OTN} = 2N$ , while for rings that do not require link loss compensation (rings with short links) we expect  $A_{Eth} = 0$  and  $A_{POADM} = A_{ROADM} = A_{OTN} = N$ . This model can easily be expanded to even longer rings requiring more than one amplifier per link, or for networks requiring a varying number of amplifiers per link.

To simplify the comparison of the power consumption in the different ring technologies, we further assume that the amount of power drained by a CC is the same for all technologies and is a function of the rate of the equipment. The same

assumption is also enforced for the transponders (TRX) and the optical switching fabric (for ROADM and POADM). Indeed, traffic coming from the client layer needs to sustain similar processing in each technology: frame classification, QoS handling, and switching between input port and output port (Ethernet) or between an input port and an appropriate WDM TRX (POADM and ROADM). Hence, CCs for all technologies are assumed to consume the same amount of energy for a given rate. WDM TRXs are assumed to be the same for all technologies. There is no optical switching in Ethernet ( $\Lambda_{r,k}=0$  for all  $r, k$ ) hence the value of  $\beta_{Eth,OL}$  can be set arbitrarily. Similarly, electronic re-aggregation of traffic  $\Lambda'_{r,k}$  applies to OTN only, such that  $\beta_{Eth,EL}$ ,  $\beta_{ROADM,EL}$  and  $\beta_{POADM,EL}$  are arbitrary. The energy consumption of the optical layer in POADM nodes and ROADM/OTN nodes is assumed to be coming from the electronics driving the optical switching matrix and the associated control. We assume here that the electronic to perform this function is similar for both technologies.

This last set of assumptions can be expressed, for each node  $k$ , as:

$$\beta_o = \beta_{POADM,OL}^{r_1,k} = \beta_{Eth,OL}^{r_1,k} = \beta_{ROADM,OL}^{r_1,k} = \beta_{OTN,OL}^{r_1,k} \quad (2)$$

$$\beta_t = \beta_{POADM,TL}^{r_1,k} = \beta_{Eth,TL}^{r_1,k} = \beta_{ROADM,TL}^{r_1,k} = \beta_{OTN,TL}^{r_1,k} \quad (3)$$

$$\beta_e = \beta_{POADM,EL}^{r_1,k} = \beta_{Eth,EL}^{r_1,k} = \beta_{ROADM,EL}^{r_1,k} = \beta_{OTN,EL}^{r_1,k} \quad (4)$$

$$\beta_c = \beta_{POADM,CL}^{r_1,k} = \beta_{Eth,CL}^{r_1,k} = \beta_{ROADM,CL}^{r_1,k} = \beta_{OTN,CL}^{r_1,k} \quad (5)$$

where  $\beta_o$  is the power consumed to switch all-optically one wavelength modulated at the lowest available (reference) rate  $r = r_1$ ,  $\beta_t$  is the power consumed by a generic WDM TRX at the same rate,  $\beta_e$  is the power consumed to switch electronically one wavelength modulated at the same rate, and  $\beta_c$  is the power consumed by a generic CC (i.e., of any technology) at the same rate.

At higher rates ( $r \in \mathcal{R}, r \neq r_1$ ), the power consumed by optically switching a wavelength, by a generic TRX, by processing a wavelength in the OTN layer, or by processing a wavelength in the client layer, is normalized to  $\beta_o$ ,  $\beta_t$ ,  $\beta_e$  and  $\beta_c$ , respectively, so that for each node  $k$ :

$$\beta_{POADM,OL}^{r,k} = \beta_{Eth,OL}^{r,k} = \beta_{ROADM,OL}^{r,k} = \beta_{OTN,OL}^{r,k} = \beta_o \cdot \eta_o^r \quad (6)$$

$$\beta_{POADM,TL}^{r,k} = \beta_{Eth,TL}^{r,k} = \beta_{ROADM,TL}^{r,k} = \beta_{OTN,TL}^{r,k} = \beta_t \cdot \eta_t^r \quad (7)$$

$$\beta_{POADM,EL}^{r,k} = \beta_{Eth,EL}^{r,k} = \beta_{ROADM,EL}^{r,k} = \beta_{OTN,EL}^{r,k} = \beta_e \cdot \eta_e^r \quad (8)$$

$$\beta_{POADM,CL}^{r,k} = \beta_{Eth,CL}^{r,k} = \beta_{ROADM,CL}^{r,k} = \beta_{OTN,CL}^{r,k} = \beta_c \cdot \eta_c^r \quad (9)$$

where each of  $\eta_o^r$ ,  $\eta_t^r$ ,  $\eta_e^r$ ,  $\eta_c^r$  indicates the ratio between the power consumption at rate  $r$  and at rate  $r_1$  of the OL, TL, EL,

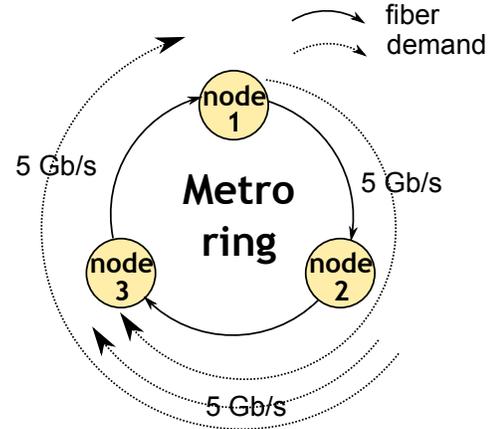


Fig. 3. Sample 3-node network with 3 demands.

TABLE I  
DIMENSIONING OF A SAMPLE 3-NODE NETWORK

	POADM	Ethernet	ROADM	OTN
$\Lambda_{r,1}$	0	0	0	0
$\Lambda_{r,2}$	1	0	1	2
$\Lambda_{r,3}$	1	0	1	2
$\Lambda'_{r,1}$	0	0	0	1
$\Lambda'_{r,2}$	0	0	0	0
$\Lambda'_{r,3}$	0	0	0	0
$CC_{r,1}$	1	1	1	2
$CC_{r,2}$	1	2	2	2
$CC_{r,3}$	1	2	2	2
$TRX_{r,1}$	2	1	3	4
$TRX_{r,2}$	1	2	2	2
$TRX_{r,3}$	1	2	2	2
$A_h$	6	3	6	6
$P_h$	$6a+2\beta_o+$ $3\beta_c+4\beta_t$	$3a+$ $5\beta_c+5\beta_t$	$6a+2\beta_o+$ $5\beta_c+7\beta_t$	$6a+4\beta_o+\beta_e+$ $6\beta_c+8\beta_t$

CL layers. As a result, Eq. (1) can be rewritten as:

$$P_h = P_{a,h} + \sum_{k=1}^N \sum_{r \in \mathcal{R}} (\beta_o \eta_o^r \cdot \Lambda_{r,k} + \beta_e \eta_e^r \cdot \Lambda'_{r,k} + \dots + \beta_t \eta_t^r \cdot TRX_{r,k} + \beta_c \eta_c^r \cdot CC_{r,k}) \quad (10)$$

in which  $\eta_o^{r_1} = \eta_t^{r_1} = \eta_e^{r_1} = \eta_c^{r_1} = 1$ , by convention.

### B. Example

The following example clarifies how the power consumption of a ring network varies with technologies used to implement the network. Consider a single-rate ( $\mathcal{R} = \{r\}$ ) unidirectional ring of  $N = 3$  nodes. Wavelengths are modulated at  $r=10$  Gb/s, node 1 is a physical hub for the ROADM, OTN, and POADM cases, and the demands are: 5 Gb/s from node 1 to node 3, 5 Gb/s from node 2 to node 1, and 5 Gb/s from node 2 to node 3, as depicted in Fig 3.

A POADM network requires the following equipment. Node 1 needs one CC to receive and send 5 Gb/s:  $CC_{r,1} = 1$ . Node 2 requires one CC to send 10 Gb/s (5 Gb/s to node 3 and 5 Gb/s to node 1):  $CC_{r,2} = 1$ . At node 2, one wavelength containing 5 Gb/s of traffic transits transparently from node 1 to node 3 ( $\Lambda_{r,2} = 1$ ). Node 3 requires one CC to receive 10 Gb/s (5 Gb/s from node 1 and 5 Gb/s from node 2):  $CC_{r,3} = 1$  while one wavelength containing 5 Gb/s of traffic

transits transparently from node 2 to node 1 ( $\Lambda_{r,3} = 1$ ). The physical hub regenerates all wavelengths hence  $\Lambda_{r,1} = 0$ . WDM TRXs are allocated to match the number of CCs on all nodes but the hub: indeed, this network requires 2 wavelengths to carry the demand (the link between node 2 and node 3 carries 15 Gb/s) hence the hub also needs two WDM TRX despite being equipped with a single CC. Hence,  $TRX_{r,1} = 2$ ,  $TRX_{r,2} = 1$ ,  $TRX_{r,3} = 1$ . In addition, 2 amplifiers per node, i.e. 6 amplifiers, are needed.

An Ethernet ring requires the following equipment. No wavelength transits through a node transparently hence  $\Lambda_{r,1} = \Lambda_{r,2} = \Lambda_{r,3} = 0$ . Node 1 receives 5 Gb/s and sends 5 Gb/s hence  $CC_{r,1} = TRX_{r,1} = 1$ . Node 2 sends 15 Gb/s of traffic (and receives 5 Gb/s) hence it needs two CCs and TRXs:  $CC_{r,2} = TRX_{r,2} = 2$ . Similarly, node 3 receives 15 Gb/s of traffic (and sends 5 Gb/s) hence it needs two CCs and TRXs:  $CC_{r,3} = TRX_{r,3} = 2$ . In addition, 1 amplifier per node, i.e. 3 amplifiers, are needed.

A ROADM ring establishes 3 circuits: a circuit carrying 5 Gb/s from node 1 node node 3, a circuit carrying 5 Gb/s from node 2 to node 3 and a circuit carrying 5 Gb/s from node 2 to node 3. To do so, 3 wavelengths are required (3 circuits go through the link between nodes 2 and 3). Hence, node 1 requires one CC (to receive and send 5 Gb/s) and 3 WDM TRX (the number of wavelengths in the ring):  $CC_{r,1} = 1$ ,  $TRX_{r,1} = 3$ ,  $\Lambda_{r,1} = 0$ . Node 2 needs two CCs and TRXs for 2 circuits, and 1 wavelength (carrying the circuit from node 1 to node 3) transits transparently through node 2:  $CC_{r,2} = TRX_{r,2} = 2$ ,  $\Lambda_{r,2} = 1$ . Similarly, node 3 needs two CCs and TRXs for the reception of 2 circuits, and 1 wavelength (carrying the circuit from node 2 to node 1) transits transparently through node 3:  $CC_{r,3} = TRX_{r,3} = 2$ ,  $\Lambda_{r,3} = 1$ . In addition, 2 amplifiers per node, i.e. 6 amplifiers, are needed.

The OTN ring with re-aggregation at node 1 only establishes 2 circuits for the demands from node 1 to 3 and from 2 to 1 (these two demands require 2 wavelengths), and another 2 circuits to support the demand from node 2 to node 3: a circuit from node 2 to node 1 where the demand can be regroomed, and a circuit from node 1 to node 3 (this demand require 2 wavelengths – 1 per circuit). Hence node 1 requires 4 TRX ( $TRX_{r,1} = 4$ ) but only 2 CCs ( $CC_{r,1} = 2$ ) to handle the 4 circuits; also node 1 re-grooms traffic on 1 wavelength in its OTN switching fabric:  $\Lambda'_{r,1} = 1$ . Nodes 2 and 3 require 2 TRX and 2 CC each as 2 circuits depart or arrive at each of these nodes:  $TRX_{r,2} = TRX_{r,3} = CC_{r,2} = CC_{r,3} = 2$ . The network requires 4 wavelengths to support the demands, 2 of which are received by nodes 2 and 3, and the other 2 wavelengths transit transparently through nodes 2 and 3:  $\Lambda_{r,2} = \Lambda_{r,3} = 2$ . In addition, 2 amplifiers per node, i.e. 6 amplifiers, are needed. Note that, for this configuration, the plain ROADM network is actually more efficient than the OTN network.

This resource allocation and the corresponding consumed powers are summarized in Table I. When  $\beta_o < \beta_c$  and  $\beta_o < \beta_t$ , POADM is more energy-efficient than both Ethernet and ROADM as it uses at the same time fewer CCs and fewer WDM TRXs. The optimization problem of designing POADM

ring is formalized next.

#### IV. RING DIMENSIONING PROBLEM AND MILP FORMULATION

##### A. Ring dimensioning problem

The ring dimensioning problem aims at allocating the optimal number of TRXs, CCs, and wavelengths for the forecast traffic. The objective of the dimensioning problem is to minimize the overall ring cost — here, its energy consumption. The cost is given by the power consumption of the TRXs and the CCs at each node, including the TRXs at the hub node installed for OEO conversion in the POADM. The cost of each TRXs and CCs is dependent on the corresponding working rate.

Solving the ring dimensioning problem requires to find the optimal routing of the traffic streams, aggregate them if and where possible to fill the wavelength capacity and assign the appropriate transmission rate to each wavelength<sup>2</sup>. Once a feasible solution is obtained by jointly solving the routing, grooming, coloring, and rate assignment sub-problems, it is possible to determine the type and number of network elements required, i.e., number and types of TRXs, CCs, and wavelengths, depending on the considered technology. A CC is always associated to a WDM TRX at the same rate. For Ethernet and ROADM rings, the number of TRXs can be derived as discussed in [5] and in [5], [11], respectively. The allocation of TRXs in a POADM ring is formalized here.

The optimal design can be classified in two different cases:

- *fixed-rate per each wavelength (FRW)*: each wavelength is assigned a single rate, i.e., the TRXs operating on a given wavelength must work at the selected rate. Therefore, on any given wavelength, all the packets must be transmitted at the selected rate.
- *variable-rate per each wavelength (VRW)*: each wavelength can support multiple rates and transmission rate can be changed slot by slot. Thus, on any given wavelength, each node can transmit at any rate, provided that the packet's transmission duration fits the time-slot duration and that the node is equipped with a TRX working at the selected rates.

##### B. MILP formulation for POADM Ring Dimensioning

At each node, except the hub, the number of TRXs at a given rate is the maximum between the number of RXs and TXs required at the node for such rate. The number of RXs is given by the number of wavelengths at such rate that carry traffic for the node. The number of TXs is given by the nearest upper integer of the ratio between the amount of traffic departing from the node using such rate divided by the rate. At the hub node, a TRX is required for each wavelength used in the ring, for either OEO converting the bypassing optical packets or for transmitting/receiving them. The number of CCs at a given

<sup>2</sup>When inserting packets on different wavelengths and destinations in an optimally dimensioned POADM ring, each node shall employ some scheduling policies in order to maximize the throughput of the traffic and to preserve the stability of the system. The problem of scheduling in POADM networks is rather complex and has been studied in other papers (e.g. [20], [21]).

rate must match the number of TRXs used for transmitting or receiving optical packets, at the same rate. The optimal allocation of TRXs and CCs, and thus the optimal routing of the traffic streams, can be modelled with the following mixed integer linear programming formulation (MILP).

### 1) FRW Design:

#### Parameters:

$G = (V, E)$ : graph with vertices  $V$  and unidirectional edges  $E$ , that models the unidirectional ring network of interest. The hub node is indicated as node ‘‘H’’;

$\mathcal{T}$ : matrix indicating the demands of L2 frame streams,  $T_{s,d}$ , from node  $s$  to node  $d$ , expressed in b/s;

$\pi_{s,d}$ : set of the links used by the path from  $s$  to  $d$ ;

$\mathcal{R}$ : set of transmission rates that the ring can support, i.e.,  $\mathcal{R} = \{r_1, \dots, r_{|\mathcal{R}|}\}$ , expressed in b/s;

$W$ : maximum number of wavelength channels;

$B_r$ : capacity (in b/s) of wavelength channels at rate  $r$ ;

$\beta_t \cdot \eta_t^r$ : cost (energy consumption) of a WDM TRX at rate  $r$  (see Section III);

$\beta_c \cdot \eta_c^r$ : cost (energy consumption) of a CC at rate  $r$  (Section III).

#### Variables:

$p_{s,d}^{w,r} \in \mathcal{P}$ : indicates the amount of traffic of the demand  $T_{s,d}$  carried on wavelength  $w$  at rate  $r$ . The set of all variables  $p_{s,d}^{w,r}$  is indicated as  $\mathcal{P}$ ;

$y^{w,r}$ : binary variable indicating whether wavelength  $w$  is used at rate  $r$  in the network, i.e., whether a transponder at wavelength  $w$  and rate  $r$  is needed at the hub node;

$u_k^{w,r}$ : binary variable indicating whether a TRX at node  $k \neq H$  is used on wavelength  $w$ , at rate  $r$ . For each TRX, a CC is also required at the same node  $k \neq H$ , and at the same rate  $r$ . For  $k = H$ , the variable indicates the number of TRXs used for transmitting/receiving traffic and equivalently the number of CCs. The overall number of TRXs (including those used for OEO conversion) at  $k = H$  is given by  $y^{w,r}$ . Notice that  $u_k^{w,r} = 1$  means that the receiver of the TRX operates on wavelength  $w$  at rate  $r$ , while the transmitter of the same TRX may operate on any wavelength at rate  $r$ ;

$u_H^{w,r}$ : binary variable indicating whether at hub node a CC is required on wavelength  $w$ , at rate  $r$ .

#### Formulation:

Objective function:

$$\min \sum_{w=1}^W \sum_{r \in \mathcal{R}} (\beta_t \cdot \eta_t^r \cdot y^{w,r} + \beta_c \cdot \eta_c^r \cdot u_H^{w,r}) + \quad (11)$$

$$\sum_{k \in V, k \neq H} \sum_{w=1}^W \sum_{r \in \mathcal{R}} ((\beta_t \cdot \eta_t^r + \beta_c \cdot \eta_c^r) u_k^{w,r} + \quad (12)$$

$$\beta_o \cdot \eta_o^r \cdot (y^{w,r} - u_k^{w,r})) \quad (13)$$

Subject to:

$$\sum_{r \in \mathcal{R}} \sum_{w=1}^W p_{s,d}^{w,r} = T_{s,d} \quad \forall s, d \in V \quad (14)$$

$$\sum_{(s,d):(i,j) \in \pi_{s,d}} p_{s,d}^{w,r} \leq B_r y^{w,r} \quad \forall (i,j) \in E, \forall w, \forall r \quad (15)$$

$$\sum_{r \in \mathcal{R}} y^{w,r} \leq 1 \quad \forall w \quad (16)$$

$$\sum_{s \in V} p_{s,d}^{w,r} \leq B_r u_d^{w,r} \quad \forall d \in V, \forall w, \forall r \quad (17)$$

$$\sum_{w=1}^W \sum_{d \in V} p_{s,d}^{w,r} \leq \sum_{w=1}^W B_r u_s^{w,r} \quad \forall s \in V, \forall r \quad (18)$$

The objective function aims at minimizing the cost for TRXs and CCs at the hub node (Eq. (11)), the cost of TRXs and CCs (Eq. (12)) and of the optical layer (Eq. (13)) at the other nodes.

Constraint (14) defines how demands are split across the wavelengths and assigned different rates. Constraint (15) states that traffic allocation to wavelength  $w$  should not exceed rate  $r$ , if the wavelength is used at such rate. This constraint also counts the number of required wavelengths, which is equivalent to the number of TRXs at the hub node. Each wavelength can be assigned at most one rate in constraint (16).

Constraint (17) ensures that at any given node (except the hub) a TRX-CC pair is installed on wavelength  $w$  and at rate  $r$ , if some traffic is received (by the considered node) on such wavelength at such rate. Constraint (18) ensures that at any given node (except the hub) there is a TRX-CC pair for wavelength  $w$  and rate  $r$  for transmitting (receiving) and processing the data to (from) such node. For the hub node, the constraints (17) and (18) are used to determine the number of required CC.

2) VRW Design: We now give a MILP formulation for the VRW network design. This formulation solves the more general case where the optical layer cost cannot be neglected.

In addition to the parameters and variables defined above, the following variables are necessary.

#### Variables:

$x_{s,d}^{w,r}$ : binary variable indicating whether the demand  $T_{s,d}$  is assigned to wavelength  $w$  and rate  $r$ .

The MILP formulation of VRW design is as for FRW design, except for Eq. (16), which is replaced by the following constraints:

$$\sum_{r \in \mathcal{R}} \sum_{(s,d):(i,j) \in \pi_{s,d}} \frac{p_{s,d}^{w,r}}{B_r} \leq 1 \quad \forall (i,j) \in E, \forall w \quad (19)$$

$$p_{s,d}^{w,r} \leq B_r x_{s,d}^{w,r} \quad \forall s, d \in V, \forall w, \forall r \quad (20)$$

$$\sum_{r \in \mathcal{R}} x_{s,d}^{w,r} \leq 1 \quad \forall s, d \in V, \forall w \quad (21)$$

Constraint (19) ensures that the wavelength capacity is not exceeded. Constraint (20) assigns a binary variable to each traffic stream. Each traffic stream is forced to be assigned a single rate, for any given wavelength in constraints (20) and (21).

In general, the optimal solution cost of VRW is less or equal than the optimal FRW cost. When the cost of the optical layer is neglected, it can be proved that the optimal VRW cost is always equal to the optimal FRW cost.

**Claim.** *The optimal solution costs of VRW and FRW are the same when  $\beta_o = 0$ .*

*Proof:* Since the FRW design space is a subset of the VRW design space (i.e., any feasible design of FRW is also a feasible solution of VRW), the optimal (minimum) cost of VRW should be less or equal to the optimal FRW cost.

Now consider an optimal VRW solution  $S$ . A feasible solution for FRW,  $S'$ , can be obtained from solution  $S$  in polynomial time by taking each wavelength and separating the traffic streams at different rates on different wavelengths. Such solution  $S'$  will have the same number and type of TRX and CC but higher number of wavelengths. Since only the cost of TRX and CC is accounted for, the cost of  $S'$  is identical to the cost of  $S$ . But since we know that the cost of  $S'$  should be always greater or equal to that of  $S$ , then  $S'$  must be also the optimal solution. Therefore, the optimal cost of VRW and FRW should be identical and the optimal solution for FRW is also an optimal solution for VRW. ■

The optimization problems defined above for FRW and VRW designs are NP-hard even in the single-rate case. Indeed, in [6] the problem of minimizing the weighted sum of the wavelength cost and the RX cost in a single-rate ring without a hub was shown to be NP-hard. The problem considered in this paper (in its single-rate version) is a special case of the problem tackled in [6] where wavelengths are the TRX at the hub and RX are the TRX at the other nodes, and hence it is NP-hard as well. For this reason a heuristic algorithm is proposed in Section V.

Note that the formulated problem is substantially different from similar problems based on multi-commodity flows and studied for instance in the field of traffic grooming in multi-hop rings (e.g., [5]). Indeed, the peculiarities of POADM networks (i.e., the presence of fast tunable transmitters, colored receivers and a hub node), and the multi-rate transmission combined with optical packet switching (previously studied only by few works, e.g. in [5] and [22]) drive the novelty of the problem and the need for novel heuristic approaches. Another relevant distinction of this problem with respect to previous works is the objective function, which is focused on energy consumption in the nodes and links.

## V. HEURISTICS FOR FRW DIMENSIONING

The problem of allocating transponders (TRX) and client-cards (CC) is addressed for FRW design using the considered ring technologies. The objective of the dimensioning is to minimize the overall power consumption, defined in Eq. (10).

### A. POADM Ring

A greedy algorithm is proposed for allocating transponders (TRX) and client-cards (CC) in a POADM ring network.

An algorithm, called “Minimize Receiver Cost First” (MRCF) was proposed in [6] to allocate colored TRX to

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### Algorithm 1 Multi-rate POADM ring dimensioning.

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**Inputs:** traffic demand  $\mathcal{T}$ , rates  $\mathcal{R}$  ordered by descending energy efficiency, optical layer cost  $(\beta_o, \eta_o)$ , WDM TRX cost  $(\beta_t, \eta_t)$ , CC cost  $(\beta_c, \eta_c)$ .  
**Outputs:** traffic allocation  $\mathcal{P} = \cup_r \mathcal{P}_r$ , numbers of wavelengths  $W$ .

---

```

1:  $(\mathcal{P}_{|\mathcal{R}|}, W_{|\mathcal{R}|}) = \text{POADM\_SR}(\mathcal{T}, r_{|\mathcal{R}|})$ ;
2: for  $i = |\mathcal{R}|$  to 2 (decrement  $i$ ) do
3:   if  $r_{i-1} < r_i$  then
4:      $\mathcal{P}_{i-1} = 0; W_{i-1} = 0$ ;
5:      $(\mathcal{P}_i, \mathcal{P}_{i-1}, W_i, W_{i-1}) = \text{UNGROOM\_RX}(\mathcal{R}, i, i-1, \mathcal{P}, W, \beta_o, \eta_o,$ 
6:        $\beta_t, \eta_t, \beta_c, \eta_c)$ ;
7:      $(\mathcal{P}_i, \mathcal{P}_{i-1}, W_i, W_{i-1}) = \text{UNGROOM\_W}(\mathcal{R}, i, i-1, \mathcal{P}, W, \beta_o, \eta_o,$ 
8:        $\beta_t, \eta_t, \beta_c, \eta_c)$ ;
9:   end if
10: end for

```

---

nodes and to count the number of required wavelengths for single-rate POADM networks only. In that algorithm the linear combination of the cost of the receivers and wavelengths was minimized, given a demand matrix  $\mathcal{T}$ . In this algorithm, the cost function is modified to enforce that each node has the same number of TX and RX, so that the modified algorithm – referred here as POADM\_SR – minimizes the number of deployed TRX. The inputs of POADM\_SR are: the traffic demands ( $\mathcal{T}$ ) and the rate used to allocate the demands (here,  $r_i$  for some rate index  $i$ ). The output of POADM\_SR is the allocation of the variables  $p_{s,d}^{w,r} \in \mathcal{P}$  at rate  $r$  and the number of wavelengths  $W_i$  needed to carry the demand.

We propose Algorithm 1 to dimension a multi-rate FRW POADM ring. Rates  $\mathcal{R}$  are ordered so that  $r_1$  is the least power efficient rate (i.e., with lowest power-per-bit defined for instance as  $\eta_c^{r_i}/B_{r_i}$  for rate  $r_i$ ) and  $r_{|\mathcal{R}|}$  is the most power-efficient rate. Wavelengths at  $r_{|\mathcal{R}|}$  are first allocated using POADM\_SR. Then, two greedy replacements of equipment at rate  $r_i$  with equipment at rate  $r_{i-1}$  for  $r_i$  decreasing (in terms of energy efficiency) from  $r_{|\mathcal{R}|}$  to  $r_2$  are carried out. The replacement of individual RXs is performed using Algorithm 2 named UNGROOM\_RX, whereas the replacement of entire wavelengths is performed using Algorithm 3 named UNGROOM\_W.

Algorithm 2 greedily replaces TRXs at some rate with TRXs at a lower rate until the network cost decreases. When no replacement can further reduce the network cost, the algorithm stops and the solution with lowest cost is returned. The function  $\text{COST}(p, W, \beta_o, \eta_o, \beta_t, \eta_t, \beta_c, \eta_c)$  implements Eq. (10) (amplification issues can be omitted at dimensioning time since amplification power is a constant that depends only on link lengths and number of nodes, and not on the traffic allocation). Given rates  $r_{i'} < r_i$ , the algorithm sequentially visits each node  $k$  and tries to remove its receivers operating at rate  $r_i$  by moving (or “ungrooming”) the corresponding traffic onto other wavelengths that are modulated at rate  $r_{i'} < r_i$ . If possible, existing equipment at rate  $r_{i'}$  is reused. Otherwise, additional equipment at rate  $r_{i'}$  is deployed in the network to support the demand. This yields resource allocation  $\mathcal{P}_{\_tmp}\{k, w\}$  and  $W_{\_tmp}\{k, w\}$ , where  $w$  is the wavelength previously used by the ungroomed traffic. The rationale is to allocate less expensive equipment at a lower rate  $r_{i'}$  to support the traffic of already-deployed but not fully utilized equipment at rate  $r_i > r_{i'}$ . If the cost of the additional required equipment

**Algorithm 2** The UNGROOM\_RX algorithm re-allocates traffic at rate  $r_i$  by greedily replacing receivers at rate  $r_i$  with receivers at rate  $r_{i'} < r_i$ .

**Inputs:** rates  $\mathcal{R}$ , rate indices  $i$  and  $i'$  ( $r_i > r_{i'}$ ), initial traffic allocation  $\mathcal{P}$  and used wavelengths  $W$ , optical layer cost  $(\beta_o, \eta_o)$ , TRX cost  $(\beta_t, \eta_t)$ , CC cost  $(\beta_c, \eta_c)$ .

**Outputs:** New traffic allocation  $\mathcal{P}'$ , new used wavelengths  $W'$ .

```

1: repeat
2:    $c = \text{COST}(\mathcal{P}, W, \beta_o, \eta_o, \beta_c, \eta_c, \beta_t, \eta_t)$ ;
3:   Initialize variables:  $\mathcal{P}_{tmp}\{k, w\} = 0$ ,  $W_{tmp}\{k, w\} = 0$  for all
   wavelengths  $w$ , for all nodes  $k$ ;
4:   for  $k = 1$  to  $N$  do
5:     for each wavelength  $w$  used at rate  $i$  do
6:       Migrate traffic received on wavelength  $w$  at rate  $i$  to RXs at rate
        $i'$ ;
7:       Install new RXs at rate  $i'$  on other wavelengths if the currently
       deployed RXs on node  $k$  are not sufficient;
8:       Denote by  $\mathcal{P}_{tmp}\{k, w\}$ ,  $W_{tmp}\{k, w\}$  the traffic allocation
       and wavelength utilization of this new configuration;
9:        $\text{cost}_{tmp}(k, w) = \dots$ 
          $\text{COST}(\mathcal{P}_{tmp}\{k, w\}, W_{tmp}\{k, w\}, \beta_o, \eta_o, \beta_c, \eta_c, \beta_t, \eta_t)$ ;
10:      end for
11:    end for
12:     $c' = \min_{k, w} \text{cost}_{tmp}(k, w)$ ;
13:    if  $c' < c$  then
14:       $(k', w') = \arg \min_{k, w} \text{cost}_{tmp}(k, w)$ ;
       $\mathcal{P}' = \mathcal{P}_{tmp}\{k', w'\}$ ;  $W' = W_{tmp}$ ;
15:    end if
16:  until  $c' > c$ 
17: Return  $\mathcal{P}'$ ,  $W'$ ;
```

at rate  $r_i$  is below the cost of the saved equipment at rate  $r_{i'}$  then the re-allocation leads to a cost saving.

Similarly, Algorithm 3 greedily moves traffic from a wavelength across the POADM ring to other partially filled wavelengths. This permits the switch-off of a full wavelength, i.e., not only of a single receiver as in Algorithm 2.

Additionally, in order to further minimize the network cost, it is possible to jointly ungroom traffic from several ( $K$ ) wavelengths onto wavelengths operating at a different rate in Algorithm 3. In our simulations, the joint ungrooming of up to  $K = 4$  wavelengths is attempted. Increasing  $K$  leads to higher computation time and decreased cost.

For simplicity we give the complexity of Algorithm 1 without the aforementioned optimizations. Let  $R = |\mathcal{R}|$ . Let  $L = \sum_{i,j} \lceil \frac{r_{i,j}}{r_1} \rceil$ ;  $L$  is the maximum number of TRX at rate  $r_1$  that can be deployed in the network and is related to the load (demand) of the network. The maximum number of wavelengths  $W$  in the network is upper-bounded by  $W \leq LR$ .

Algorithm 1 relies on 3 algorithms: POADM\_SR, UNGROOM\_RX and UNGROOM\_W. The complexity of POADM\_SR is  $O(L^2 N^2)$  [6]. The complexity of UNGROOM\_W is dominated by that of UNGROOM\_RX. The complexity of UNGROOM\_RX is dominated by the update of each  $\mathcal{P}\{k, w\}$  variable (lines 6, 7), whose dimension is at most  $WN^2$ . This is done within 3 nested loops which are run at most  $L$  times<sup>3</sup> (line 5),  $N$  times (line 4), and at most

<sup>3</sup>With the aforementioned optimization where several ( $K$ ) wavelengths are jointly ungroomed onto wavelengths operating at a different rate, this becomes  $L^K$  since any  $K$ -tuple of receivers at a given rate can be considered for ungrooming.

**Algorithm 3** The UNGROOM\_W algorithm re-allocates traffic at rate  $r_i$  by greedily replacing wavelengths at rate  $r_i$  with wavelengths at rate  $r_{i'} < r_i$ .

**Inputs:** rates  $r$ , rate indices  $i$  and  $i'$  ( $r_i > r_{i'}$ ), initial traffic allocation  $\mathcal{P}$  and used wavelengths  $W$ , optical layer cost  $(\beta_o, \eta_o)$ , TRX cost  $(\beta_t, \eta_t)$ , CC cost  $(\beta_c, \eta_c)$ .

**Outputs:** New traffic allocation  $\mathcal{P}'$ , new used wavelengths  $W'$ .

```

1: repeat
2:    $c = \text{COST}(\mathcal{P}, W, \beta_o, \eta_o, \beta_c, \eta_c, \beta_t, \eta_t)$ ;
3:   Initialize variables:  $\mathcal{P}_{tmp}\{w\} = 0$ ,  $W_{tmp}\{w\} = 0$  for all
   wavelengths  $w$ ;
4:   for each wavelength  $w$  used at rate  $i$  do
5:     Move traffic received on wavelength  $w$  at rate  $i$  on each node to
     new RXs at rate  $i'$ ;
6:     Denote by  $\mathcal{P}_{tmp}\{w\}$ ,  $W_{tmp}\{w\}$  the TRX and CC allocation
     of this new configuration;
7:      $\text{cost}_{tmp}(w) = \dots$ 
        $\text{COST}(\mathcal{P}_{tmp}\{w\}, W_{tmp}\{w\}, \beta_o, \eta_o, \beta_c, \eta_c, \beta_t, \eta_t)$ ;
8:   end for
9:    $c' = \min_w \text{cost}_{tmp}(w)$ ;
10:  if  $c' < c$  then
11:     $w' = \arg \min_w \text{cost}_{tmp}(w)$ ;
     $\mathcal{P}' = \mathcal{P}_{tmp}\{w'\}$ ;  $W' = W_{tmp}\{w'\}$ ;
12:  end if
13: until  $c' > c$ 
14: Return  $\mathcal{P}'$ ,  $W'$ ;
```

$L$  times (line 1): indeed the network cost can decrease at most  $L$  times, since receivers can be removed and replaced, in the worst case, until at most  $L$  receivers at the lowest rate are deployed. The complexity of UNGROOM\_RX is therefore  $O(LNLWN^2) = O(RL^3N^3)$ . UNGROOM\_RX is repeated  $R$  times in Alg. 1, leading to a computational complexity of  $O(L^2N^2) + R \cdot O(RL^3N^3) = O(R^2L^3N^3)$ . The proposed algorithm is polynomial in all variables<sup>4</sup>.

## B. Ethernet Ring

The dimensioning of single rate Ethernet rings can be optimally solved in polynomial time and consists in deploying TRX on a per-link basis to support the demand to be routed on each link. In a multi-rate Ethernet ring, the dimensioning problem becomes an unbounded minimum knapsack problem, which is NP-complete in the general case. We propose here a greedy heuristic to dimension a ring where two rates  $r_1$  and  $r_2$  are available. The algorithm can easily be generalized to an arbitrary number of rates.

Denote by  $T^*(i, j)$  the total traffic that must be carried over link  $(i, j)$  (node  $j$  is the node located after node  $i$  on the ring). Suppose that  $r_2$  is more energy-efficient than  $r_1$  (see Section V-A). In the first step, wavelengths with highest energy efficiency are allocated: each  $T^*(i, j) \geq r_2$  is allocated  $\lfloor T^*(i, j)/r_2 \rfloor$  TXs and  $\lfloor T^*(i, j)/r_2 \rfloor$  RXs operating at rate  $r_2$  at nodes  $i$  and  $j$ , respectively. The second step allocates TRX for remaining traffic  $T''(i, j) = T^*(i, j) - \lfloor T^*(i, j)/r_2 \rfloor$ . We compare the cost (energy consumption) of deploying TRX at either rate  $r_1$  or rate  $r_2$  for  $T''(i, j)$  and allocate TRXs (TXs at node  $i$  and RXs at node  $j$ ) at the rate that minimizes energy consumption.

<sup>4</sup>With both aforementioned optimizations the complexity becomes  $O(R^2L^{k+2}N^3)$ , where  $K$  is an algorithm tuning parameter.

### C. Circuit switched Rings

An algorithm is presented for a ROADM ring in which two rates are available. The TRX are allocated as in the Ethernet ring but on a per- $(s, d)$  pair basis (circuits), rather than on a per-link basis. Notice that the number of wavelengths and circuits in the ROADM ring depends on the physical hub capabilities. If this hub node performs only OEO conversion of the bypassing circuits (i.e., no wavelength conversion nor traffic grooming capabilities), the minimum number of circuits to be established in a ring with  $N$  nodes is  $N(N-1)/2$  when the traffic matrix is complete.

If the physical hub node  $H$  is enabled with also traffic grooming capability, then the proposed dimensioning can be performed on a transformed traffic matrix  $\mathcal{T}'$  that consider that all traffic is routed through the physical hub. The original demand matrix ( $\mathcal{T}$ ) is transformed into  $\mathcal{T}'$  by setting  $T'_{s,d} = 0$  for all  $s, d \neq H$ ,  $T'_{H,d} = \sum_i T_{i,d}$  for each node  $d$ ,  $T'_{s,H} = T_{s,H}$  for each node  $s$ . The minimum number of circuits can be reduced to  $2(N-1)$  when the traffic matrix is complete (i.e., when  $T_{s,d} > 0 \forall s, d$ ), as the circuits have to go through the physical hub even if it is not on the route between source and destination. This may lead to a waste of resources when the traffic demand is large. Hence, in the following, we report the best ROADM result out of the dimensioning for demand  $\mathcal{T}$  and for transformed demand  $\mathcal{T}'$ .

In the case of an OTN ring, TRXs are allocated as above after transforming the original demand matrix into a centralized demand matrix. Then the electronic switching matrix for the traffic bypassing the hub node is derived:  $\Lambda'_{r,1}$  is determined for each rate  $r$ ;  $\Lambda'_{r,k} = 0$  for all non-hub nodes  $k > 1$ .

## VI. NUMERICAL RESULTS

This section validates the heuristic through comparisons with the MILP formulation and assesses the energy efficiency of larger size rings for various ring network technologies.

### A. Validation of the heuristic

The MILP formulation described in Section IV is solved using IBM CPLEX solver [23]. Due to the time and difficulty of obtaining optimal solutions, optimal solutions with optimality gap of 5% or lower are limited to ring size of  $N = 5$  nodes in this section. Dimensioning is performed on 50 randomly generated traffic matrices and the found results are then averaged. Three rates  $\mathcal{R} = \{10, 40, 100\}$  Gb/s are considered. The power consumption of a non-coherent (On-Off Keying) 10 Gb/s TRX is considered as a reference. Following [19], the proportionality between the power consumption at different rates is set to  $\eta_2 = 5$  and  $\eta_3 = 7$ , corresponding to the consumption of coherent (PDM-QPSK modulated) TRXs

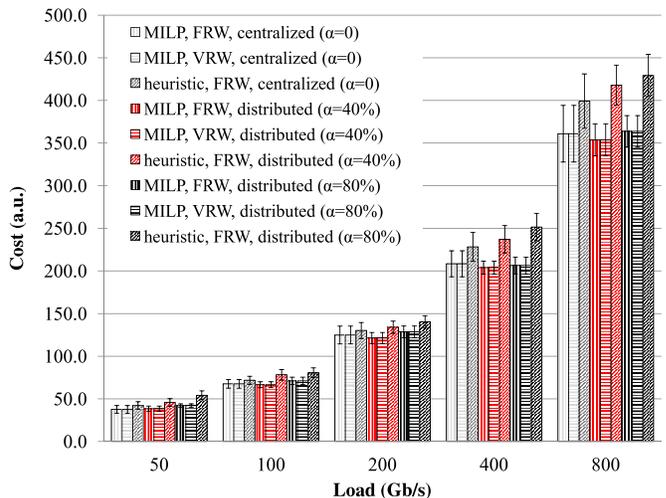


Fig. 4. Comparison of the MILP heuristic cost with the heuristic for small-scale POADM networks ( $N=5$  nodes).

which are currently used in today's networks<sup>5</sup>. Notice that the power consumption of a 40 Gb/s TRXs is more than four times higher than that of a 10 Gb/s TRX, as coherent technology used at 40 Gb/s is less power efficient. Hence we expect that 40 Gb/s wavelengths are not used in the optimized dimensioning results. Following [12], we assume that the power consumption of the CC are 3.5 times higher than that of the TRX (i.e.,  $\beta_c = 3.5 \beta_t$ ) and that  $\beta_e = 0.88 \beta_t$ . In this validation section only, we neglect the power consumption of the optical layer, i.e. we assume that  $\beta_o = 0$  to focus on the TRXs and CCs, which are the most power consuming elements in the network.

The traffic demand matrices  $\mathcal{T}$  are randomly generated. Several traffic distributions are simulated, varying between a centralized scenario (all traffic to/from the hub node, i.e., "hub-and-spoke") to a fully distributed (i.e., "any-to-any") scenario. Specifically, we denote by  $\alpha$  the "traffic distribution parameter":  $\alpha$  is the ratio of traffic between any two non-hub nodes (i.e. none of the considered two nodes is the hub) to the total traffic demand. When  $\alpha = 0$  the traffic is fully centralized, whereas for  $\alpha = 100\%$  there is no traffic arriving/departing the hub node. The ring load is defined as the overall traffic sent over the ring network ( $\text{load} = \sum_{s,d} T_{s,d}$ ).

In Fig. 4 the optimal results from the MILP formulation<sup>6</sup> are compared with the results of the heuristic for a load varying between 50 and 800 Gb/s and for 3 traffic distributions (centralized:  $\alpha = 0\%$ , mildly distributed:  $\alpha = 40\%$ , heavily

<sup>5</sup>As network capacities increase, operators are moving to coherent formats, including 40 Gb/s coherent TRXs. Coherent detection requires very powerful and energy-hungry digital signal processing (DSP); however the power consumption of the DSP chip is relatively independent of the signal rate for rates below 100 Gb/s; this is why a 100 Gb/s coherent RX (and TRX) is more energy-efficient than a 40 Gb/s RX (and TRX), hence the factor of  $\eta_3/\eta_2 = 7/5$  for the consumption of a 100 Gb/s TRX to a 40 Gb/s TRX. Also the DSP chip is significantly more energy-hungry than the electronics of a standard non-coherent 10 Gb/s receiver, hence the factor of  $\eta_2 = 5$  between the power consumption of a 40 Gb/s and that of a 10 Gb/s TRX.

<sup>6</sup>Simulations were run only for the FRW scenario, since, as explained in Section IV-B2, the optimal cost for the VRW design is provably the same as that of FRW.

distributed:  $\alpha = 80\%$ ). Each reported result corresponds to the average cost across 50 independent random draws of the demand matrix  $\mathcal{T}$ .

The heuristic algorithm for FRW design approaches well the optimal solution especially when the traffic is more centralized. For instance when  $\alpha = 0$ , the gap between the MILP formulation and the heuristic is only a few percent (at most 8%, for load=400 Gb/s). The MILP solutions show that the network cost vary slightly with traffic distribution, however the heuristic struggles to optimally groom the demands and the cost gap between the MILP formulation bound and the heuristic can reach up to 33%. Such relatively high gap is mainly due to the computational complexity of the problem which makes it difficult to design polynomial time heuristic with tight optimality gap. This gap does not grow with the load (in fact the largest gap is for the lowest load; for high load the gap is only 20-25%), hinting that the heuristic actually scales well with the load when traffic is distributed.

Given that it may take several days to dimension a single problem instantiation with the MILP solver and seconds to minutes with the heuristic, we now focus on multi-rate network dimensioning with the heuristic.

### B. Dimensioning of optical ring networks

The dimensioning algorithms described in Section V are applied to ring networks with  $N = \{5, 10\}$  nodes. In this section, we include the cost of the optical layer; following [12] we assume that the power consumption of the client layer is 10 times higher than that of the optical layer (i.e.,  $\beta_c = 10 \beta_o$ ). The value for  $\beta_o$  can be set arbitrarily, e.g.  $\beta_o = 1$ . In addition, the power consumption of a power amplifier is assumed to be equivalent to that of two 10 Gb/s WDM transponders, i.e.  $a = 2\beta_t$  [24], and links are assumed to be a few dozens of km long such that optical amplification is required as discussed in Section III-A to compensate for link and node loss.

Results are reported for two values of the traffic distribution:  $\alpha = 0$  and  $\alpha = 80\%$ , as simulations results for  $\alpha = 40\%$  are not substantially different from those for  $\alpha = 80\%$ . In this section, each data point is the average from dimensionings for 100 randomly generated traffic matrices. The 95% confidence intervals were verified to be tight; in the figures, the error bars correspond to a single standard deviation around the reported mean.

We first assess the advantage of using a multi-rate dimensioning in POADM rings. In Fig. 5, the power consumption of single-rate POADM rings of 5 nodes at 10, 40 and 100 Gb/s is depicted, along with the multi-rate 10/40/100 Gb/s case. Note that the maximum considered load, 1600 Gb/s, corresponds to an average demand of 80 Gb/s per node pair, less than a full 100 Gb/s wavelength. POADM is designed for sub-lambda granularity switching. For higher load, full lambda switching technologies such as ROADM are more appropriate. Other papers focusing on multi-rate network dimensioning (for circuit networks, e.g., [25]) report that in some conditions, single rate 100 Gb/s networks are more power efficient than multi-rate networks. This is due to the higher considered load and the physical layer effects that are considered. This work

consider lower loads, which are more appropriate for a metro ring scenario. Such load condition is also the suitable operating condition for POADM ring. Moreover physical layer effects can be neglected since the considered propagation distances are short, a few hundreds of kilometers at most.

Single rate at 10 Gb/s is power efficient for low loads while single rate at 100 Gb/s is power efficient for the higher loads. The crossing point between the two curves depends on the traffic distribution: a more distributed traffic postpones the need for 100 Gb/s channels in the single rate case. Single rate at 40 Gb/s is unable to be power efficient with respect to 10 and 100 Gb/s. Deploying a multi-rate network does not significantly reduce the power consumed by the POADM ring when traffic is centralized. However, for distributed traffic, multi-rate POADM rings are 5-10% more power-efficient than the best single rate configuration.

Fig. 6 reports the results for a 10-node ring network. The crossing point between single rate at 10 Gb/s and at 100 Gb/s occurs for a much higher load than for the 5-node ring (centralized traffic, Fig. 6a) or it does not exist (distributed traffic, Fig. 6b) on the reported load range. The results indicate also that for larger ring size there is little incentive to use a multi-rate configuration, as the power consumption is as low as the most power-efficient dimensioning at single-rate.

Power consumption of POADM, Ethernet, ROADM and OTN rings with  $N = 5$  and 10 nodes are compared in Figs. 7 and 8, respectively, for centralized and for distributed traffic. Each point corresponds to the most power efficient configuration, single rate or multi-rate, and, in the ROADM case, with or without electronic re-aggregation at the hub node. The Ethernet networks, due to their opacity, consume considerably more energy than the POADM networks. The consumption ratio can reach 5:1 with 10 nodes and 4:1 with 5 nodes. The gap between Ethernet and POADM grows with the load: POADM is more scalable than Ethernet in terms of power consumption. This better scalability is due to POADM capability of optically bypassing the traffic, which is more power efficient especially at high loads.

When considering that circuits in a ROADM (or OTN) network can be fully utilized ( $\eta = 100\%$ ), the difference in power consumption between ROADM and POADM ring is smaller, but still significant. POADM is able to save up to 30% of power with respect to ROADM for 5 nodes and distributed traffic. The power saving is reduced when the ring size increases (power saving of 20% for 10 nodes and distributed traffic) and when the traffic is more centralized (power saving of up to 10% or for centralized traffic). However, it is important to observe that ROADM/OTN networks are typically lightly loaded (i.e., over-dimensioned); for instance, in [18], a utilization of less than 30% is reported for a core network, as mentioned in Section III-A. On the other hand, POADM networks can actually leverage statistical multiplexing of the incoming traffic very efficiently using an appropriate MAC (Medium Access Control), as shown for instance in [21]. Hence, it is fair to consider a network efficiency of  $\eta = 50\%$

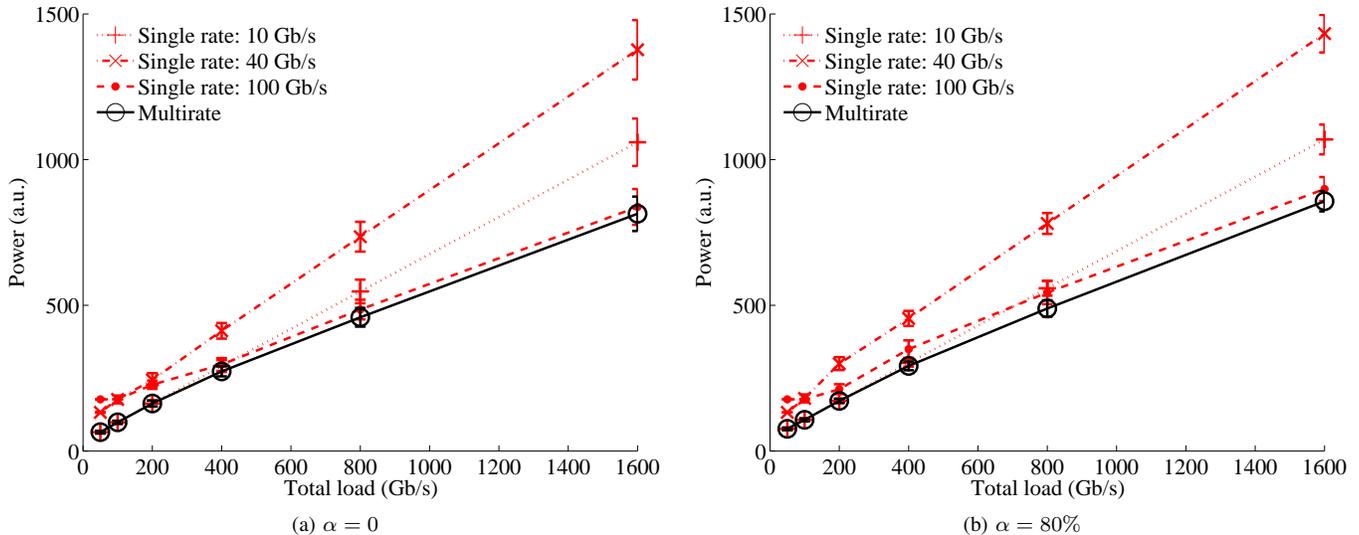


Fig. 5. Normalized power consumption of 5-node POADM networks in single-rate and multi-rate configurations.

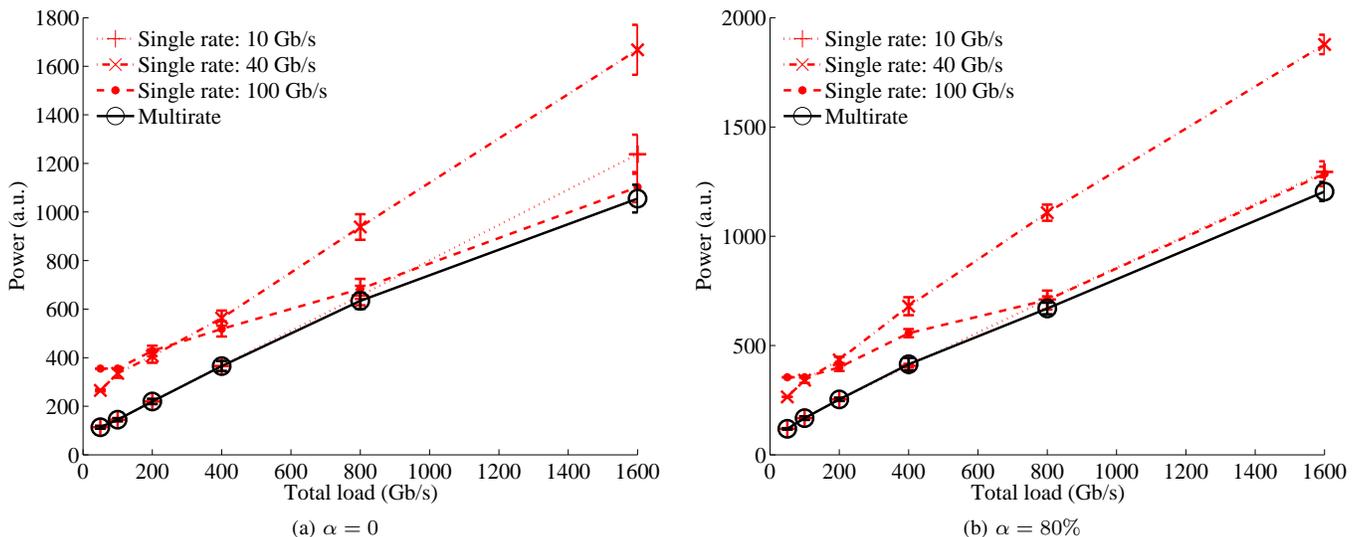


Fig. 6. Normalized power consumption of 10-node POADM networks in single-rate and multi-rate configurations.

for ROADM-based metro networks<sup>7</sup>. Under this assumption, a POADM-based metro network consumes 2 to 3 times less energy than a ROADM or OTN-based network.

## VII. CONCLUSIONS

This paper focused on the problem of dimensioning multi-rate POADM rings based on the recently proposed POADM nodes, which enable optical packet switching (OPS). The dimensioning aims at minimizing the power consumption. A MILP formulation was presented to solve the NP-hard dimensioning problem, which consists in allocating equipment (transponders, client cards) to minimize the cost (power consumption) of the network. A heuristic was presented and simulation results show that it approximates well the optimal

<sup>7</sup>For the sake of clarity, OTN simulation results for  $\eta = 100\%$  only are represented; energy in OTN networks for  $\eta = 50\%$  would follow the same trend, i.e. almost double, as with ROADM networks.

results obtained with the MILP. Two other ring technologies, namely Ethernet and ROADM/OTN, were also considered for comparison.

In POADM rings, multi-rate dimensioning is slightly (but not significantly) more power-efficient than single rate dimensioning, especially when the traffic is distributed across the nodes (any-to-any) rather than centralized (hub-and-spoke). A design with fixed-rate per each wavelength (FRW) is as efficient as a design with variable-rate per each wavelength (VRW), while being easier to implement. In addition, POADM rings are significantly (up to 5 times) more power-efficient than Ethernet rings, as POADM rings can leverage transparency. Also, POADM rings are appreciably more power-efficient than ROADM/OTN rings. Moreover, POADM rings are highly reconfigurable and can reallocate bandwidth at the packet/slot granularity (i.e., microsecond to millisecond). Further studies are required to further assess the dynamics of metro networks,

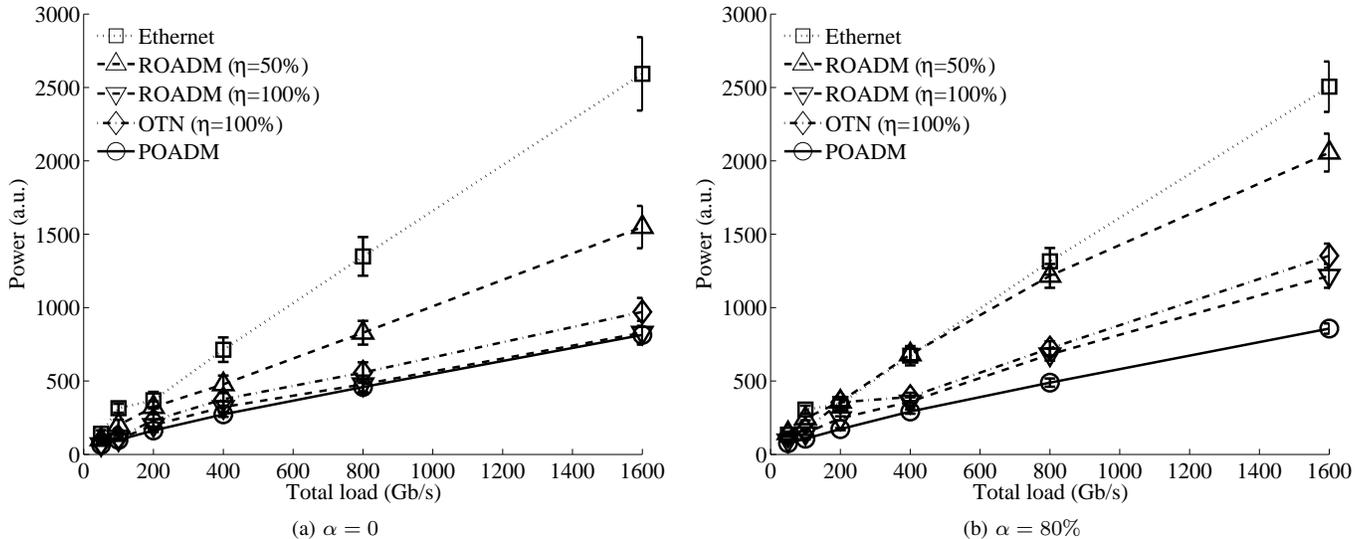


Fig. 7. Normalized power consumption of 5-node metro rings multi-rate configuration.

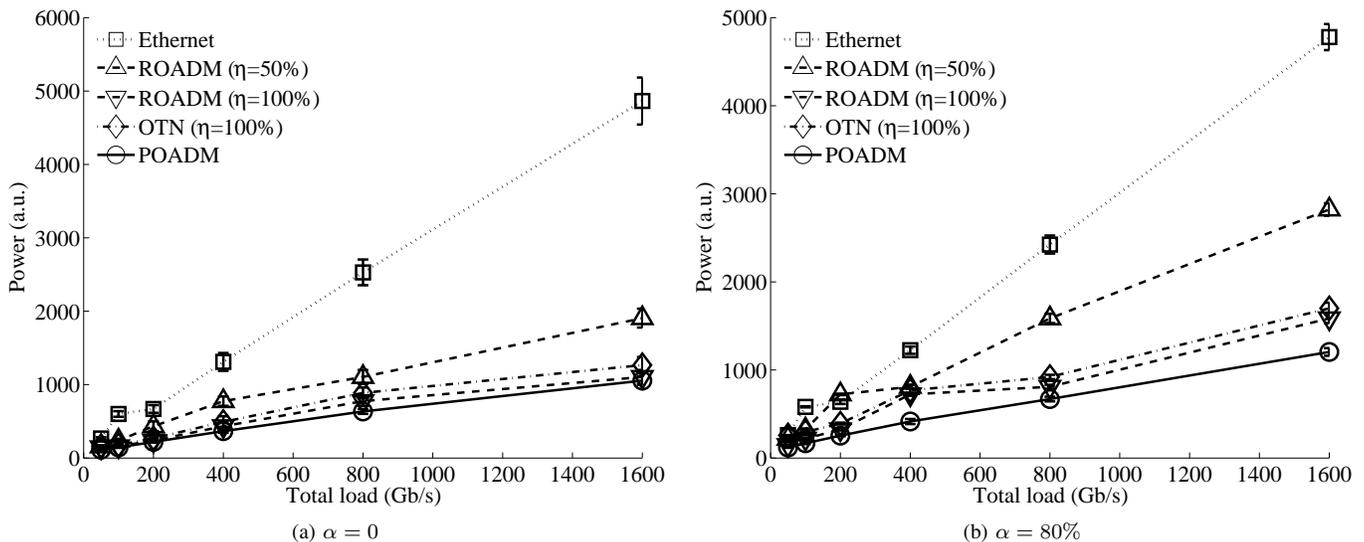


Fig. 8. Normalized power consumption of 10-node metro rings multi-rate configuration.

and its impact on network dimensioning.

#### ACKNOWLEDGMENTS

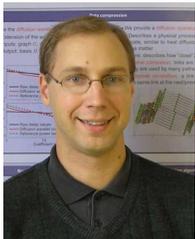
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