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Cost-effective single-hub WDM ring networks: A proposal and analysis

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Abstract

In this paper, we study a new concept of traffic grooming in wavelength-division multiplexing (WDM) ring networks that aims at eliminating both the bandwidth underutilization and the scalability concerns that are typical of all-optical wavelength routed ring networks. Our objective is to reduce the network cost while preserving the benefits of all-optical WDM ring networks. In order to assess the efficiency of our proposal, all underlying network costs are compared. These costs include that of the transceivers required at node level, as well as the number of wavelengths. Our results show that the proposed aggregation technique can significantly improve the resource utilization while reducing the network cost.

Keywords: Traffic grooming; Optical networking; All-optical and opaque ring networks; Network dimensioning; Cost evaluation

1. Introduction

During the last decade, we have witnessed a continuous growth in data traffic. This growth, driven primarily by the proliferation of the Internet, has created a rising demand for robust networks, with increasingly high-link capacity and node throughput. Due to the new incumbent challenges, operators are progressively migrating towards optical core networks thus taking advantage of the tremendous transmission capacity offered by the optical technology. Thanks to the wavelength-division multiplexing (WDM) in core networks, the need for more capacity may be satisfied. However, there is a need for an efficient solution for transporting and switching huge amounts of data at the boundaries of backbone networks, especially at metropolitan and local area networks.

In metropolitan area networks, infrastructures are generally organized over a ring topology (Fig. 1). Typically, a metro network consists of a feeder ring network and multiple access nodes. Each node serves one or more access networks. Most of the traffic from the access networks is destined to

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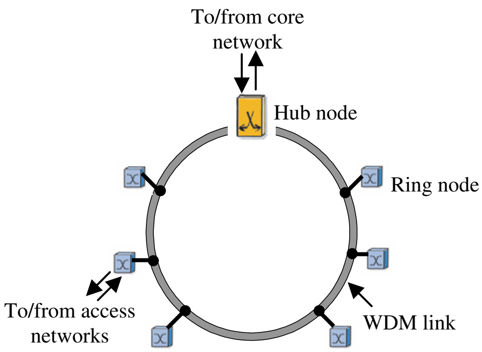

Fig. 1. Single-hub WDM ring.

nodes outside of the ring network. Such traffic, carried to the core via the hub node, is called hubbed traffic. In this paper, we consider hubbed traffic since it is an important class of traffic and is often observed in access ring networks.

One of the main issues when designing metro networks is cost-effectiveness. Minimizing cost becomes the main concern in network design, since such a network handles much smaller group of end users compared to long-haul networks. For metro networks, we can save cost in two ways: by sharing bandwidth efficiently and by reducing usage of expensive network equipment.

In optical networks, a significant portion of the network cost is due to the equipment used to convert signals from the electrical to the optical domain. In view of this, the optical layer is migrating from an opaque network, consisting of WDM links with electrical processing at the ends of the link, to an all-optical network, where traffic is switched at intermediate nodes in the optical domain. The optical layer here provides circuit switched lightpaths to the higher layer equipment such as SONET and IP boxes.

Using optical pass-through instead of electrical processing, can lead to an order of magnitude savings in the cost. Nonetheless, the rigid routing granularity entailed by such an approach can lead to bandwidth waste. In order to use the link bandwidth efficiently, we have to allow different access nodes to share a single wavelength. In addition, routing at the wavelength level puts a serious strain on the number of wavelengths required in the network. For full connectivity, an N node all-optical ring suffers from the N-squared problem, since each node requires $N-1$ lightpaths. Even for moderate values of N, the total ring capacity is quickly exhausted.

In contrast, an opaque ring has the advantage of being able to use efficiently the link bandwidth. Nonetheless, this results in a maximum transceiver cost since nodes do not have an optical bypass. In the long term, optical packet switching (OPS) appears as a promising solution. In fact, a major advantage of electronic packet switching is its bandwidth efficiency achieved through statistical multiplexing. However, OPS is not ready yet and it is hampered by major technology limitations due to the issues related to the fine switching granularity adopted at high bit rate [1].

To alleviate the aforementioned problems, we propose a new solution, which combines the advantage of the optical bypass in transparent wavelength routed networks with statistical multiplexing gain. In this technique, a lightpath, which remains entirely in the optical domain, is shared by the source node and all the intermediate nodes up to the destination. So, in essence, a single lightpath is used to establish a multipoint-to-point (MptoP) connection. We refer to this technique as the distributed aggregation scheme.

To a certain degree, the approach proposed in this paper can be seen as an extension of an earlier proposal called the Dual Bus Optical Ring Network (DBORN). The DBORN architecture is described in this paper. For more details please see Ref. [2].

In this study, we provide a typical design of ring networks that function according to the distributed aggregation scheme. This new architecture is called the MptoP all-optical ring network. Moreover, we assess the cost savings introduced by the MptoP architecture with respect to DBORN, all-optical and opaque ring networks. To achieve this, all underlying network costs are evaluated. These costs include that of the transceivers required at the node level and the number of wavelengths. Note that in practice, the transceiver cost dominates the cost of the number of wavelengths in a network.

The rest of the paper is organized as follows. In Section 2 we give a literature review and point out our position relative to previously published papers. A detailed description of this new approach is given in Section 3. The DBORN architecture and its main features are given in Section 4. The general problem statement is presented in Section 5, and in Section 6, all underlying network costs are evaluated. In Section 7, a cost comparison between our proposal and existing solutions is drawn based on a mathematical model. Finally, the conclusions are given in Section 8.

2. Related work

In optical network literature, several studies deal with traffic grooming in WDM ring networks [3,4]. The trend is towards switching packets directly in the optical domain, as this can take advantage of both packet flexibility and optical transparency. Currently, widely deployed all-optical wavelength routed networks are not based on packet switching. However, in the next-generation networks, packet-based data traffic of bursty nature will become prevalent. Hence, the lack of packet switching in the current optical networks may lead to underutilization of critical resources. Consequently, two major enabling factors are identified as crucial for the evolution process of next-generation networks architecture: packet switching and optical transparency.

Packet switching provides the necessary ingredient needed for building bandwidth efficient and flexible networks [1]. Asynchronous transmission, which is more suitable for bursty traffic in comparison with slotted WDM networks, must be jointly addressed in the future. Moreover, a finer granularity than a full wavelength must be achieved while trying to preserve the optical transparency property in order to avoid extra expensive electronic conversions.

To cope with these requirements, many interesting solutions have been proposed in the literature, see [5–12]. These solutions fall into two categories: optical packet switching (OPS) and optical circuit switching (OCS). In what follows, we review these new technologies, pointing out how they reconcile optical transparency and sub-wavelength grooming.

2.1. Optical packet switching-based solutions

A lot of research is currently focusing on how to implement packet switching in the optical domain. However, OPS is hampered by major technology bottlenecks, such as the lack of optical processing logic, optical memories, and cost-effective fast switching and synchronization technologies. Two promising solutions: have been identified that bypass some of these technological problems, namely, photonic slot routing (PSR) [5] and optical burst switching (OBS) [6].

2.1.1. Photonic slot routing

In this technology [5], time is slotted and data is transmitted in the form of photonic slots which are fixed in time and span across all the wavelengths of a fiber link. Each wavelength in the photonic slot contains a single packet and all the packets in the photonic slot are destined to the same node. By requiring the packets to have the same destination, the photonic slot may be routed as a single integrated unit without the need for demultiplexing wavelengths at intermediate nodes. The basic aim of such approach is the use of wavelength-insensitive components at each node, resulting in less complexity, faster routing and lower cost with regard to classical OPS concept.

As such, the PSR approach relieves some typical issues of OPS. But, it still requires high-speed configurable optical packet switches, where the data processing and switching is done on a slot basis. In addition, the implementation of PSR in a mesh environment is an even more challenging key issue, as it involves maintaining the synchronization of photonic slots at each node.

2.1.2. Optical burst switching

Optical burst switching (OBS) [6] avoids the very short switching time required by OPS. A burst is an aggregation of many packets with the same egress node, and the same class of service. Using large bursts of data, the processing on the network can be reduced compared to OPS. Optical burst switching can be considered therefore as a hybrid approach between coarse-grained circuit switching and fine-grained packet switching. The bursts are aggregated by edge nodes and transmitted all-optically towards their destination. Each burst is preceded in time (offset time) by a control packet which is used to reserve resources at each switch in the core network. The offset time must be large enough so that each switch has the time to configure its switch fabric prior to the arrival of the burst.

In this regard, compared to the wavelength routed switches (i.e., OCS), the OBS edge routers need complex interfaces to implement burst assembly, disassembly, and queue fairness algorithms. Thus, the access unit design may become challenging at high data rates. Furthermore, in OBS, there is no guarantee that a burst will be successfully transmitted without being dropped by intermediate nodes due to contention of bursts going to the same outgoing port. Depending upon the nature of the transmitted data, a dropped burst may have to be retransmitted, which of course decreases the network's throughput.

2.2. Optical circuit switched-based solutions

OPS, and in particular PSR, is a solution that may become feasible in the future. Meanwhile, the trend is to improve the efficiency of existing mature all-optical networks. In this regard, recently, there has been much emphasis on circuit switched all-optical networks, where the goal in this context is shifted more toward the improvement of optical resource usage by means of new traffic aggregation schemes, rather than toward the attempt to realize optical packet switching.

2.2.1. The multi-hop approach

The key idea behind multi-hop (MH) networks is to allow electronic processing at some intermediate nodes of the all-optical circuit switched network in order to increase its grooming capacity [7]. Accordingly, a packet may undergo electronic processing at some intermediate nodes before reaching its final destination. Hence, lightpaths can be seen as chains of physical channels through which packets are moved from a router to another toward their destinations. At intermediate nodes, the transit lightpaths are switched transparently through an OXC that does not process transit data. Instead, incoming lightpaths destined to the current node are terminated and converted to the electronic domain, so that packets can be extracted, processed, and possibly retransmitted on outgoing lightpaths, if the current node is not the final destination of the data.

Although the significant cost that may be introduced by such electronic processing operation at intermediate nodes, it enables a better use of the network resources and can reduce the total network cost compared to the all-optical circuit switched networks [7]. The main challenge, in this case, is to identify the optimal logical topology that minimizes the total network cost, while accommodating all the traffic requests. It has been demonstrated that the identification of the optimal logical topology is computationally intractable for large size networks [13]. In view of this, several heuristic approaches were proposed in literature [7].

2.2.2. The super-lightpath and lightpath dropping approaches

The super-lightpath concept [8] and the lightpath dropping [9] approach increase the grooming capacity of a regular all-optical circuit switched network, as they transform the concept of the lightpath from a point-to-point (PtoP) pipe to a point-to-multipoint (PtoMP) pipe. In other words, the source node of a super-lightpath or a multiply dropped-lightpath does not limit its transmission to the end nod node of that lightpath; instead, it can transmit its traffic to all the intermediate nodes along the route. This allows the super-lightpath or the multiply dropped-lightpath to carry multiple connections, resulting in better wavelength utilization.

The super-lightpath technique uses a simple Optical Time Division Multiplexing (OTDM) method, which permits splitting the bandwidth of a wavelength among several traffic flows. Accordingly, each bit in a given position of the fixed-size TDM frame, called bit slot, identifies a particular sub-channel. Using a bit interleaver, the transmitter multiplexes sub-channels into the frame, and transmits the resulting stream into one lightpath. With regard to reception, each intermediate node splits the transit signal, synchronizes its receiver to a particular bit slot, and only receives data in that particular sub-channel.

The super-lightpath and the lightpath dropping techniques present many advantages. First, they reduce the number of transmitters per node since the same transmitter will be used to send data to more than one receiver. Moreover, they improve the lightpath utilization. Specifically, in [9], the authors show that the lightpath dropping approach leads to better performance in terms of blocking probability when compared to the MH approach [7]. The main concern with these PtoMP methods is related to the limited length of the super-lightpath or dropped-lightpath. Specifically, a significant portion of the passing-through optical signal is tapped at each receiving intermediate node, and therefore, due to power limitations the number of traversed nodes is limited.

2.2.3. The TWIN (time-domain wavelength interleaved networking) approach

Unlike the super-lightpath concept, which uses a PtoMP approach to improve the traffic grooming capacity in a traditional OCS network, the TWIN technique adopts a MptoP approach [10]. Specifically, TWIN makes use of optical MptoP trees that are overlaid on the top of the physical topology. In TWIN, a particular wavelength is attributed to each egress node, and it is used to receive data. Doing so, sources that have information to transmit to a particular destination, tune their transmitters to the particular wavelength. As such, the optical signals from various sources to a particular destination may be merged at the intermediate nodes. Thus, TWIN technology requires special OXCs, which are able to merge incoming signals of the same wavelength to the same outgoing wavelength.

Despite the complex scheduling algorithms entailed by such an approach, the MptoP concept is in itself interesting. It avoids the limitations on the length of a super-lightpath introduced by the PtoMP approach, since no splitting operations are performed.

Nevertheless, the MptoP concept as described in TWIN suffers from scalability issues. The assignment of multiple wavelengths to each egress node (according to the volume of its destined traffic) makes a serious stress on the number of wavelength channels required on each fiber link. Moreover, TWIN may lead to fiber link underutilization due to the lack of wavelength reuse, since a particular wavelength, wherever the link that belongs to, can only be used to transmit to a specific egress node.

2.2.4. The optical light-trails approach

The light-trail (LT) is an OCS-based technology that minimizes active switching, maximizes wavelengths utilization, and offers protocol and bit rate transparency [11,12]. So far, we have presented a PtoP approach (i.e., MH), a PtoMP approach (i.e., super-lightpath) and a MptoP approach (i.e., TWIN), which aim at achieving these goals. The LT solution is a MPtoMP approach where intermediate nodes can both receive and transmit data on the pass-through channel.

The basic operation of this scheme is as follows. Each intermediate node *i* of the LT taps a sufficient amount of optical power from the incoming signal, using a splitter, in order to recover its corresponding packets sent by the upstream nodes. On the other side, with regard to transmission, the original transit signal is coupled with the local signal, by means of a coupler, before it continues its path to serve the remaining downstream nodes of the LT.

The main concern with this method is the design of a MAC protocol that avoids collisions between transit and locally inserted packets. A simple MAC protocol based on intra-band signaling was suggested in the original LT proposal [11]. Accordingly, each intermediate node *i*, wishing to transmit a packet, first sends a beacon signal to order downstream nodes to stop their activities on the shared medium. Then, after a guard band, it transmits its data packet. Note that, node *i* may receive a beacon signal from upstream nodes during its transmission of a beacon signal or a data packet. In this case, it preempts instantaneously its transmission and the truncated packet is lost.

Due to the above scheme, the performance of the LT method is questionable. This is because, such a MAC scheme may result in low resource utilization due to the guard band, extra signaling packets and wasted truncated packets. In this regard, many studies are now focusing in the development of more efficient MAC schemes adapted to the LT technology [14]. Also, additional protocols are required to avoid fairness issues among the sharing LT nodes [15]. Furthermore, since a significant portion of the signal is tapped at each intermediate node, the LT length may be limited. This limitation, however, can be overcome using a power compensator, such as a semiconductor optical amplifier (SOA). Finally, we note that packets received by an intermediate node are not removed from the LT, which prevents bandwidth reutilization by downstream nodes. This feature becomes interesting only when dealing with multicast applications.

As explained before, methods based on multiple node reception, such as super-lightpath and LT, suffer from power limitations due to the required multiple splittings. Moreover, the multiple nodes reception feature in LT, is effective only when dealing with multicast applications due to the lack of bandwidth reutilization of the shared lightpath. In view of this, the MptoP strategy appears as the best choice to improve the grooming capacity of a lightpath. In this context, TWIN technology is a good candidate. However, this technique suffers from inherent scalability and lack of wavelength reuse. In order to ameliorate this situation, we propose a new MptoP OCS-based solution, called the distributed aggregation scheme.

3. Distributed aggregation scheme

The key idea underlying our proposed scheme is to allow sharing of a lightpath among several access nodes. Instead of limiting the access to the lightpath capacity at the ingress point, each node along the path can fill the lightpath on the fly according to its availability. In this case, a lightpath can be shared by multiple connections with a common destination (i.e., MptoP lightpaths). Wavelength routing is performed in a similar way as in all-optical networks, i.e., signals remain in the optical domain from end to end and are optically switched by intermediate nodes. Since the lightpath remains transparent at intermediate nodes, a MAC (Medium Access Control) protocol is required to avoid collision between transient optical packets and local ones injected into the lightpath. In [16], we have already proposed a simple MAC protocol based on void/null detection. This mechanism, described below, guarantees collision-free packet insertion on the transient wavelength at the add port level of an intermediate node.

3.1. The distributed aggregation scheme: an example

To illustrate the distributed aggregation mechanism, we consider the simple three-node network example shown in Fig. 2. We assume that each fiber has one wavelength and each node is equipped with a fixed transmitter and a fixed receiver. Two connection requests are to be served: (0,2) with a bandwidth requirement equal to half of the wavelength capacity; and (1,2) with a bandwidth requirement equal to quarter of the wavelength capacity.

In the classical wavelength routed all-optical network case (Fig. 2a), only the connection (0,2) will be served. The connection (1,2) between nodes 1 and 2 will be rejected even if the wavelength between these two nodes is not being fully used by the (0,2) connection. Hence, an extra wavelength between nodes 1 and 2, and a new receiver at node 2 are required in order to satisfy the two connection requests.

In the case of the distributed aggregation scheme (Fig. 2b), the traffic demand could be satisfied by establishing one lightpath from node 0 to node 2, which will be shared by both connections. The second connection (1,2) would be carried using the spare capacity of the existing lightpath. Note that the lightpath $0 \rightarrow 1 \rightarrow 2$ is still routed optically through node 1, thus preserving the benefit of optical bypass.

The merit of distributed aggregation is that multiple connections with fractional demands can be multiplexed onto the same lightpath. As a result, the wasted bandwidth problem associated with pure wavelength routed networks is alleviated. In addition, due to the sharing of lightpaths, the number of admissible connections in the network is increased. Furthermore, the destination node handles fewer lightpaths as connections from different nodes to the same destination are aggregated onto the same lightpath. In view of this, fewer physical components, such as wavelengths and transceivers, are used, resulting in savings on equipment. Moreover, in order to provide connections between all access node pairs using MptoP lightpaths, a total number of O(N) lightpaths is required since only one lightpath per individual egress node could be sufficient. Thus, we alleviate the scalability issue encountered in classical all-optical wavelength routed networks.

3.2. The MptoP ring network architecture

This is an optical ring network, which uses the distributed aggregation scheme. As shown in Fig. 3, a typical MptoP ring network consists of N nodes labeled $0, 1, \ldots, N-1$ clockwise, interconnected by fiber links. Assuming that lightpaths are routed along the shortest path and N is odd, the network can be described as follows.

Each node i ($i = 0, \ldots, N-1$) sets up two lightpaths to carry its traffic towards the farthest nodes in the ring as shown in Fig. 3. The intermediate nodes can use the spare capacity of the pass-through lightpaths to inject their traffic intended to the destination of the lightpaths. Recall that lightpaths are still routed optically through intermediate nodes, thus preserving the benefit of optical bypass. Specifically, a lightpath remaining entirely in the optical domain is shared by a source node and all intermediate nodes up to the destination. If sufficient capacity exists, intermediate ring node traffic would be carried by the spare capacity of the pass-through

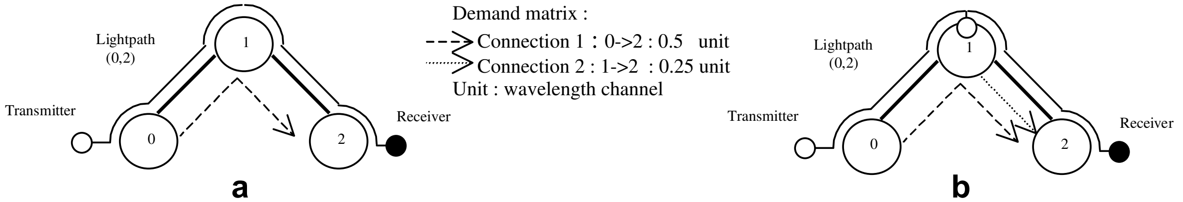

Fig. 2. A simple demonstration network. (a) All-optical wavelength routed networks. The connection request (1,2) is rejected. (b) Distributed aggregation scheme. All connection requests are satisfied.

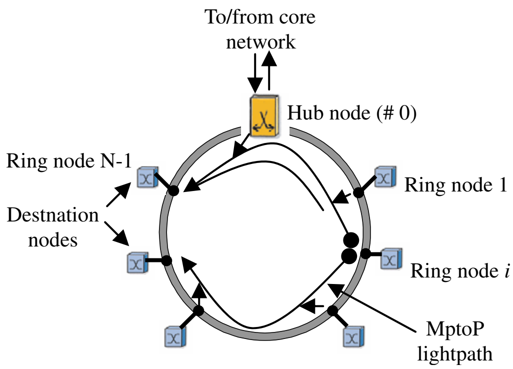

Fig. 3. MptoP WDM ring: lightpaths initiated by node *i*.

lightpaths. Otherwise, the intermediate ring node has to create new lightpaths to handle the remaining local traffic destined to the destination node of the pass-through lightpath (see Fig. 3: case of ring node 1).

Each node *i* receives two MptoP lightpaths carrying the aggregate traffic coming from each half of the ring as shown in Fig. 4. Each half has $(N-1)/2$ ring nodes. Node *i* terminates its associated lightpaths, electronically processes the packets and delivers them to users.

3.3. The MAC protocol

Let us consider *J* nodes placed along a unidirectional lightpath. Buffered packets at each node level are transmitted onto the lightpath towards the node where the lightpath is terminated. These packets travel along the lightpath without any electro-optic conversion at intermediate nodes.

The main issue with this scheme is collision-free packet insertion on a shared MptoP lightpath. Neither active optical devices nor electronic conversions are employed to handle the packet insertion. Instead, traffic control mechanisms are used at the electronic edge of the access nodes to avoid collisions with transit traffic.

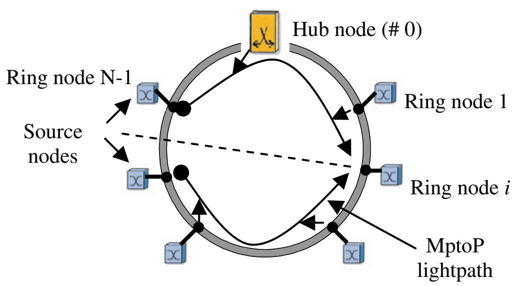

Fig. 4. MptoP WDM ring: lightpaths terminated by node *i*.

We believe that asynchronous transmission allows for a better use of resources as opposed to synchronous transmission. Asynchronous transmission is more appropriate for high-speed bursty traffic. Hence, we focus in this paper on a contention-based media access protocol rather than on a time-sharing solution.

In a fixed-slotted system with fixed-size packets, void (i.e., slot) filling can be carried out immediately upon its detection, since the void duration is a multiple of the fixed-size packet duration. The detected void is therefore guaranteed to provide a minimum duration of one packet length. However, in non-slotted systems with variable packet length and arbitrary void duration, a collision may occur if a packet is immediately transmitted upon the detection of the beginning of a void.

To meet these requirements, each node along the shared lightpath must retain the upstream traffic flow within the optical layer while monitoring the medium activity. Specifically, as shown in Fig. 5, each node first uses an optical splitter to separate the incoming signal into two identical parts: the main transit signal and its copy used for control purposes. With regard to the control part, as in [17], low bit rate photodiodes (ph) – typically 155 MHz – are used to monitor the activity of the transit lightpath. Once a free state of the medium is detected, the MAC unit measures the size of the progressing void.

To do so, a fiber delay line (FDL) is introduced on the transit path to delay the upstream flow by one maximum frame duration augmented by the MAC processing time. The length of the FDL is

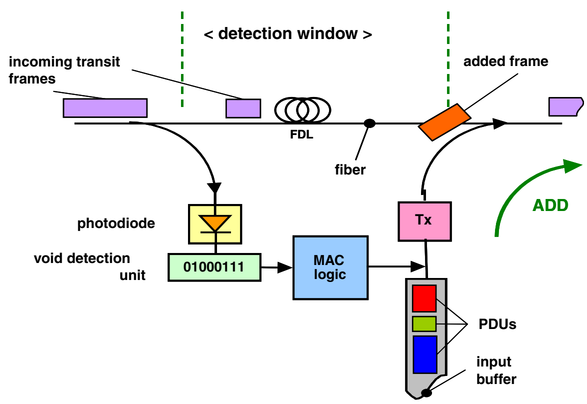

Fig. 5. Schema of the CSMA/CA based MAC.

slightly larger than the maximum transmission unit (MTU) size allowed within the network, in order to provide the MAC unit with sufficient time to listen and to measure the medium occupancy. The node will begin injecting a packet to fill the void only if the null period is large enough (i.e., at least equal to the size of the packet to be inserted). Undelivered data will remain buffered in the electronic memory of the node until a sufficient void space is detected. This way, collision-free packet insertion on the pass-through lightpath from the add port is ensured.

It is easy to see that this access scheme relies only on passive components (couplers, FDL, ph) with relatively low cost. The cost introduced by the MAC unit is negligible compared to the transceiver cost. However, with this basic packet insertion mechanism, head of the line blocking and fairness issues could arise.

3.4. Resolving fairness and head of line blocking issues

It is obvious that this scheme introduces an unfair advantage to nodes closer to the source node. The fairness of this scheme was examined in [16]. Specifically, we demonstrated that the mismatch between the idle period distribution, resulting from the upstream node utilization of the medium and the packet size distribution of the downstream nodes, often leads to bandwidth waste as well as fairness problems with regard to resource access. Once a packet of maximum size is at the head of the insertion buffer of an intermediate node, it blocks the node's emission process until an adequate void is found: this is the well-known HoL blocking problem. Monitoring the distribution of voids on the medium reveals a low probability of finding regular and sufficiently large gaps of free bandwidth. Thus, sharing the bandwidth fairly but arbitrarily among nodes is not sufficient to ensure satisfactory results. The sharing process must thus be done smartly in order to preserve a maximum of useful bandwidth for the downstream nodes. In this context, we showed in [16] that the token bucket (TB) algorithm cannot resolve this issue. In the TB algorithm, the free bandwidth (stated in bit/s) allocated to each node is theoretically sufficient to handle its traffic. However the main issue is that the free bandwidth is fragmented into unusable gaps. Hence, as a basic rule one should avoid a random division of the optical resource. To achieve this, we proposed the TCARD (Traffic Control Architecture using Remote Descriptors) mechanism [16].

In TCARD, each transmitting station is provided with anti-tokens that are used to prevent the station from transmitting a packet during a gap in the optical packet stream. These anti-tokens permit some of the gaps to go by unused, and therefore, they can be used by other downstream stations. The rate of generation of the anti-tokens at a station is set equal to the rate of the aggregate downstream transmission. Hence the key idea of TCARD is to force each node to preserve free bandwidth for its downstream neighbors in the form of gaps of size equal to the MTU (Maximum Transmission Unit) size. This also avoids the HoL blocking problem, since downstream nodes can transmit large packets due to the reserved big-enough gaps.

3.5. Efficiency of the medium sharing method

To evaluate the performance of the proposed fairness control and MAC protocols, we consider eight nodes sharing the same MP-to-P lightpath terminating at a common destination D. Each node receives traffic from the access networks to be forwarded to node D at a mean rate of 0.1 Gbit/s. Thus the traffic transmitted by all the access nodes represents 80% of the wavelength capacity, which is assumed to be 1 Gbit/s. In our simulation, we assume that the packet length is 50 bytes, or 500 bytes, or 1500 bytes. These packet lengths are representative of packet sizes in Ethernet. The total traffic volume comprises 50% of 1500 bytes, 40% of 500 bytes and 10% of 50 bytes packets. Moreover, packets arrive at each node according to a Poisson process. The capacity of the electronic buffer at each node level is set equal to 1 Mbytes. The key behavior metrics in such networks are the access delay and the packet loss rate (PLR) at each node contending for the access to the shared medium. These two metrics were evaluated using the NS-2 simulator, for an eight-node MP-to-P lightpath when TCARD is enabled, when the TB algorithm is enabled, and when both TCARD and TB algorithms are disabled. The results are reported in Figs. 6 and 7.

Fig. 6 depicts the average access delay experienced by packets arriving at each node. Results confirm the limitations of the TB algorithm and highlight the unfairness issue already discussed. We point out that the performance degradation, when TCARD is disabled, is not due to the medium saturation since the obtained channel occupancy is

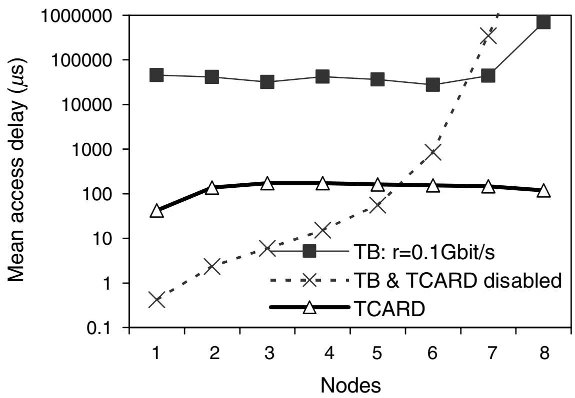

Fig. 6. Mean access delay in the eight-node MptoP lightpath with an input load representing 80% of the medium capacity.

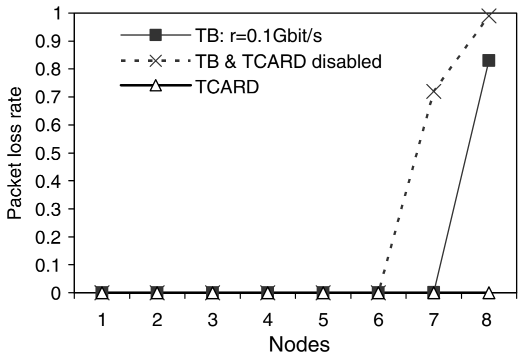

Fig. 7. Packet loss rate in the eight-node MptoP lightpath with an input load representing 80% of the medium capacity.

below 70%. Recall that the input load is 80%. This difference is simply due to the packet loss resulting from buffer overflow at downstream nodes, due to not finding adequate idle periods to transmit packets. On the other hand, TCARD enables fairness and better use of the resource by sharing efficiently the bandwidth between competing nodes. The mean access delay is around 160 µs for all the nodes. In addition, simulations show that TCARD improves the resource utilization, which increased from 70% to 80%.

Fig. 7 depicts the packet loss rate (PLR) at each access node. As expected, when TCARD is disabled, the packet loss increases as the nodes get closer to the destination node D. This is because downstream nodes do not find suitable idle periods to transmit their packets. In particular, the packet loss rate at node 8 is above 99% in the absence of any control mechanism and it exceeds 80% when TB is enabled.

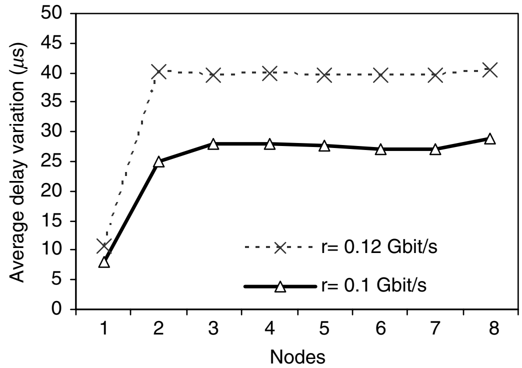

Fig. 8. Average delay variation in the eight-node MptoP lightpath for different arrival rates.

In contrast, with TCARD, no packet loss is recorded in the network due to its efficient share of bandwidth among nodes.

So far, we focused on the evaluation of the access delay and PLR at each ring node level. We now proceed to investigate the delay variation resulting from our MptoP insertion method. The delay variation for packets transmitted by node i measured at the destination node D is calculated as the average difference in access delay between successive packets transmitted by node i to node D. Such a metric is important for real time applications such voice, teleconference, etc. To assess this metric, we consider again the scenario described above that consists of eight ring nodes sharing the same MptoP lightpath. Fig. 8 depicts the delay variation experienced by packets at each node for different arrival rates. Two cases are considered, in which packets arrive at each node at rates 0.1 Gbit/s and 0.12 Gbit/s, respectively. Two main findings can be identified in Fig. 8. First, the delay variation is practically the same for all the access nodes, which highlights again the fairness of our insertion scheme. Second, the delay variation is insignificant. It is less than 40 µs even for heavy-loaded medium. This result shows clearly that real time applications can be efficiently handled through our MptoP access network.

4. The DBORN architecture

In this section, we describe the DBORN architecture [16]. This network has a node, designated as the hub, which has lightpaths directly connecting it to all the other nodes (Fig. 9). A connection request between two ring nodes has to traverse two light-

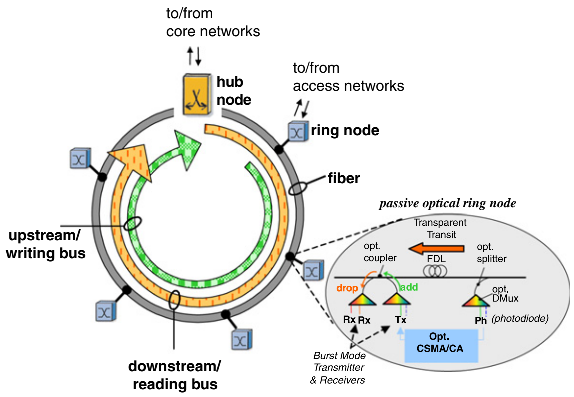

Fig. 9. Overview of DBORN and node architecture.

paths before it reaches its destination. The hub node connects the ring to the backbone network.

The network can be described as a unidirectional fiber split into downstream and upstream channels spectrally disjointed (i.e., on different wavelengths). The downstream bus, initiated at the hub node, is a shared medium for reading purposes, while the upstream bus, initiated at the ring nodes, is a multiple access-writing medium. In the downstream direction, the ring is a point-to-multipoint network, and in the upstream direction it is a multipoint-to-point network that uses the distributed aggregation scheme.

Let us consider N nodes placed along the unidirectional ring, as shown in Fig. 9. With regard to the direction from the access networks to the feeder ring, the ring node plays the role of a concentrator. Buffered packets are transmitted on the upstream bus towards the hub without any electro-optic conversion at intermediate nodes. The intermediate nodes can use pass-through lightpaths to inject their local traffic towards the hub. Specifically, a lightpath remaining entirely in the optical domain is shared by a source node and all intermediate nodes up to the hub.

The hub terminates the upstream wavelengths and electronically processes the packets. According to its destination, a packet is forwarded either into the backbone network or through the downstream bus to reach the ring nodes to which it is destined. In the downstream direction, the hub maintains lightpaths to various ring nodes. Each lightpath can be shared in reception by several ring nodes. To do so, each ring node copies the downstream signal, originating from the hub, using a splitter, from which it recovers the transmitted packets. Once split, the main signal is no longer processed by the node and it continues its path towards the other ring nodes sharing the lightpath. Each ring node terminates the copied lightpath, electronically processes the data packets and delivers them to users.

As stated before, the main issue with this scheme is the collision-free packet insertion on the shared upstream bus, which can be solved using the MAC protocol described above.

This architecture is suitable for the hubbed traffic networks, which are often found in access rings. The spectral separation allows the use of a simple passive structure for the optical part of ring nodes. In this context, this architecture inherits the advantages of passive optical networks (PON) [18]. In addition, as described above it provides a fraction of the wavelength capacity to each ring node, a single wavelength for all upstream nodes, and a single head-end receiver at the hub node. Hence, the hub transceiver needs are also reduced.

Moreover, each ring node sends/receives all its aggregate local traffic towards/form the hub node, which plays the role of an electronic concentrator. In view of this, each DBORN node (i.e., excluding the hub node) requires no transceivers except for handling its local traffic when communicating with the hub node.

In the MptoP all-optical ring, each node also needs transceivers only to handle its local traffic thanks to the optical transparency. However, each node has to transmit its traffic using $N-1$ separated lightpaths to reach all the ring nodes. In contrast, a DBORN node transmits all its traffic towards the hub, thus using a single lightpath. To achieve this, the DBORN hub node has to deal with all the traffic in the ring, thus requiring a maximum transceiver cost. In this regard, the cost gain achieved at the ring nodes may be lost because of the hub node.

5. General problem statement

A typical single-hub WDM ring network is shown in Fig. 1. It consists of N nodes labelled $0, 1, \ldots, N-1$ clockwise, interconnected by fiber links. Each link carries high-rate traffic over different wavelengths. This network has a node, designated as the hub (denoted by node 0), which connects the ring to the backbone network. In the remainder of this paper, we will consider the case where N is odd, but similar results could be easily obtained when N is even.

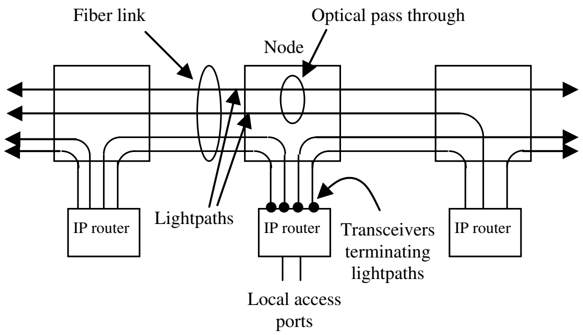

Fig. 10. A WDM ring node.

A typical node in a WDM ring is shown in Fig. 10. Note that some of the lightpaths pass-through the node in optical form. They carry traffic not intended for the node. The remaining lightpaths are terminated at the node by transceivers, and their traffic is converted into electronic form, and processed electronically. In Fig. 10, the IP router is shown representing all the electronic processing, and the transceivers are located at the interface of the IP router and lightpaths.

In this paper, we provide a cost analysis of all underlying ring networks. Specifically, we obtain formulae that quantitatively link network resources to traffic parameters. The following costs are used:

(a) *Number of wavelengths W*: This is the maximum number of lightpaths that goes through any link.
(b) *Transceiver cost Q*: This is the average number of transceivers per node in the network. It seems that the transceiver cost may reflect actual costs better than the number of wavelengths. The number of transceivers is defined as

$$Q = (Tx + Rx)/2, \tag{1}$$

where $Tx(Rx)$ denotes the average number of transmitters (receivers) respectively per node.

The traffic distribution will be represented by a traffic matrix T, where $T(i,j)$ represents the amount of traffic between nodes i and j, expressed in lightpaths. For example, if the traffic between the node pair (i,j) is 15 Gb/s and the wavelength capacity is 10 Gb/s, then $T(i,j) = 1.5$. The networks will be compared using the costs W and Q, assuming the following static hubbed traffic (see Fig. 11):

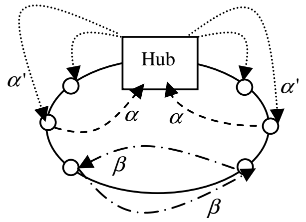

Fig. 11. Static hubbed traffic matrix.

$$T(i,j) = \begin{cases} 0, & \text{if } i = j \\ \text{otherwise} & \begin{cases} \alpha' = \tau\left(R + 1 - \frac{1}{R'}\right), & \text{if } i = 0, \\ \alpha = \tau\frac{R}{R'}, & \text{if } j = 0, \\ \beta = \frac{\tau}{(N-2)R'} & \text{otherwise.} \end{cases} \end{cases} \tag{2}$$

In this traffic pattern, the amount of traffic sent by node i $(i = 1, \ldots, N-1)$ to the hub is R times the amount of traffic sent by node i to the remaining nodes of the ring. That is,

$$\alpha = R(N-2)\beta,$$

R represents the hubbed traffic metric ($R \geqslant \frac{1}{N-2}$). In addition, the amount of traffic received by node i is R' times the amount of traffic that it sends. That is,

$$\alpha' + (N-2)\beta = R'[\alpha + (N-2)\beta].$$

The traffic matrix is thus asymmetric with ratio R' ($R' \geqslant 1$). Note that for this range of R and R', we have always $\alpha \geqslant \beta$ and $\alpha' \geqslant \beta$. The equality $\alpha = \alpha' = \beta$ is obtained, when $R = \frac{1}{N-2}$ and $R' = 1$. In this case, T is simply a static uniform traffic with the following pattern:

$$T(i,j) = \begin{cases} \frac{\tau}{N-2} & \text{if } i \neq j, \\ 0, & \text{otherwise.} \end{cases}$$

To gain insight into the traffic matrix pattern defined in (2), we consider the simple example of a hubbed asymmetric ring network with parameters $R = 2$ and $R' = 4$, respectively. In other words, each ring node i $(i = 1, \ldots, N)$ downloads four times more traffic than what it uploads. Moreover, the traffic generated by each node i for destinations outside of the ring (i.e., inter-traffic) is $R = 2$ times the amount of intra-traffic destined to nodes inside the ring. Substituting R and R' by their values in (2), we get the amount of traffic exchanged by each ring node as a function of the parameter τ. Using τ, we can vary the amount of traffic exchanged by each ring node. For instance, assume that the traffic sent by each ring node i to the hub is equal to $\alpha =$

1 Gbit/s. Hence, τ is given by $\frac{R'}{R} \times \alpha = 2$ Gbit/s. Substituting τ by its value in (2), we get the amount of traffic exchanged each pair of ring nodes.

The following optical rings will be considered in the analysis:

– *Opaque WDM ring:* This network does not have true optical nodes. Lightpaths do not pass-through nodes and traffic at each node is processed electronically.
– *All-optical ring:* Between each pair of nodes i and j, there are $\lceil T(i,j) \rceil$ lightpaths. Traffic between the nodes is carried directly by these connecting lightpaths. This is a wavelength routed all-optical ring and it has no electronic traffic grooming. It is therefore the opposite of the opaque WDM ring, which has maximal traffic grooming capabilities. Note that it is well suited for static traffic if the traffic is high enough to fill in the lightpaths.
– *DBORN optical ring:* This is an optical ring, which limits the utilization of the distributed aggregation scheme to the upstream bus.
– *MptoP all-optical ring:* This is a wavelength routed optical ring, which uses the distributed aggregation scheme.

6. Optical WDM ring cost quantification

6.1. Opaque WDM ring

A special case of an optical ring network is the opaque WDM ring network shown in Fig. 12. Here, each link in the network carries a one-hop lightpath on each of its wavelengths. Each node has a single IP router that routes traffic from all the lightpaths. The opaque ring has the advantage of being able to efficiently use the link bandwidth for time-varying traffic. Its disadvantage is that its nodes do not have optical pass-through, resulting in maximum transceiver cost.

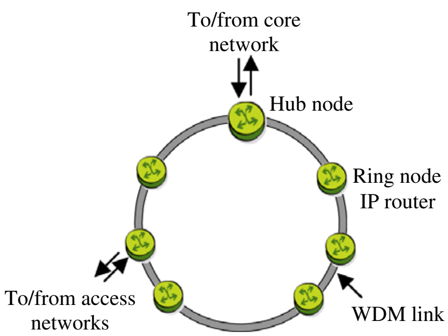

Fig. 12. An opaque single-hub WDM ring.

Assume the opaque ring network and static hubbed traffic as before. Let us consider the link Li binding the node i to the node $(i+1) \bmod N$. The number of wavelengths traversing Li can be determined using two phases as follows:

1. Start by serving β lightpath of traffic between each node pair.
We assume that all traffic is routed along the shortest path in the ring and that N is odd. Then, the average number of hops, H, needed to route traffic from its source to its destination is

$$H = \frac{N+1}{4} \quad N \text{ odd.}$$

Therefore, the amount of traffic going through each link Li is

$$L = \frac{H \times \text{Total traffic}}{\text{Number of links}} = \frac{H \times \sum_i \sum_j T(i,j)}{N} = \frac{N^2 - 1}{4} \cdot \beta.$$

2. To satisfy all the connection requests as described in the traffic pattern (2), it remains to serve $\alpha' - \beta$ worth of traffic between the hub and each ring node and $\alpha - \beta$ worth of traffic between each ring node and the hub node.

The additional amount of traffic going through each link Li in the clockwise direction is given by

$$l'i = \begin{cases} (\alpha' - \beta)\left(\frac{N-1}{2} - i\right) & \text{if } i = \left(0 \ldots \frac{N-3}{2}\right), \\ 0 & \text{if } i = \frac{N-1}{2}, \\ (\alpha - \beta)\left(i - \frac{N-1}{2}\right) & \text{if } i = \left(\frac{N+1}{2} \ldots N-1\right). \end{cases}$$

In the other direction, the additional amount of traffic going through each link Li is

$$l''i = \begin{cases} (\alpha - \beta)\left(\frac{N-1}{2} - i\right) & \text{if } i = \left(0 \ldots \frac{N-3}{2}\right), \\ 0 & \text{if } i = \frac{N-1}{2}, \\ (\alpha' - \beta)\left(i - \frac{N-1}{2}\right) & \text{if } i = \left(\frac{N+1}{2} \ldots N-1\right). \end{cases}$$

Hence, the total amount of traffic going through each link Li is equal to $(l'i + l''i + L)$. As lightpaths are unidirectional, the number of wavelengths required by each link Li is

$$Wi = \left\lceil l'i + \frac{L}{2} \right\rceil + \left\lceil l''i + \frac{L}{2} \right\rceil. \quad (3)$$

It is easy to see that both L_0 and $LN-1$ are the most loaded links, since $\alpha \geqslant \beta$ and $\alpha' \geqslant \beta$. Thus the number of wavelength is simply:

$$W = W0 = WN - 1. \tag{4}$$

Also recall that the number of transceivers per node is

$$Q[i] = Tx[i] = Rx[i] = \frac{Wi}{2} + \frac{W(i-1)\bmod N}{2}. \tag{5}$$

The average number of transceiver per node is therefore:

$$Q = \frac{\sum_{i=0}^{N-1} Wi}{N}. \tag{6}$$

6.2. All-optical ring

In this network $\lceil T(i,j) \rceil$ lightpaths have to be set up between each source and destination nodes. This type of network has been considered in [19], but assuming full duplex lightpaths and static uniform traffic. Let us consider the static hubbed matrix and unidirectional (half duplex) lightpaths as before. Assume all traffic is routed along the shortest path in the ring. The most loaded links are L_0 and $LN-1$. W is, therefore, the number of wavelengths traversing L_0, and it can be determined recursively as follows:

1. Start with three nodes on the ring including the hub node (see Fig. 13). Two lightpaths need to be set up between each pair of nodes. The link L_0 will require $(\lceil \alpha \rceil + \lceil \alpha' \rceil)$ wavelengths.
2. (Recursive step) Let k denote the number of nodes currently in the ring. While $k \leqslant N-2$, add two more nodes to the ring so that they are diametrically opposite to each other, i.e., separated by the maximum number of hops (see Fig. 14). The two new nodes divide the ring into two parts. Let us consider the part that contains the link L_0. This part comprises $(k-1)/2$ old nodes and the hub. Each old node sets up a pair of lightpaths to each new node. The two pair of lightpaths use disjoint routes. In view of this, only one pair of lightpaths traverses L_0 when connecting each old node to the new nodes. This requires $2\lceil \beta \rceil$ wavelengths. Thus, a total of $(k-1)\lceil \beta \rceil$ new wavelengths are required to pass-through L_0. The hub node does the same thing and requires $(\lceil \alpha \rceil + \lceil \alpha' \rceil)$ new wavelengths through L_0. The old nodes in the other part of the ring connect to the new nodes without requiring any wavelength through L_0. The two new nodes are also connected via the other part of the ring. Finally, we need to add a total of $\lceil \alpha \rceil + \lceil \alpha' \rceil + (k-1)\lceil \beta \rceil$ new wavelengths. So the number of wavelengths needed is

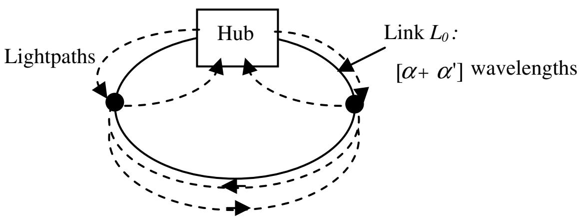

Fig. 13. Setting up two lightpaths between each pair of nodes (Step 1).

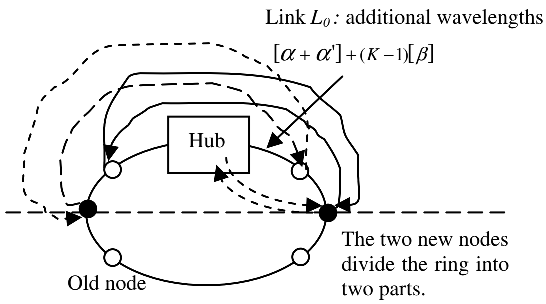

Fig. 14. Setting up lightpaths for two new nodes (Step k).

$$W = \frac{N-1}{2}(\lceil \alpha \rceil + \lceil \alpha' \rceil) + \frac{(N-3)(N-1)}{4}\lceil \beta \rceil, \tag{7}$$

where N is odd.

In addition, the number of transmitters and receivers required per node is

$$Tx[i] = \begin{cases} \lceil \alpha \rceil + (N-2)\lceil \beta \rceil & \text{if } i = (1 \ldots N-1), \\ (N-1)\lceil \alpha' \rceil & \text{if } i = 0, \end{cases}$$

$$Rx[i] = \begin{cases} \lceil \alpha' \rceil + (N-2)\lceil \beta \rceil & \text{if } i = (1 \ldots N-1), \\ (N-1)\lceil \alpha \rceil & \text{if } i = 0. \end{cases}$$

The average number of transceivers per node is thus:

$$Q = \frac{N-1}{N}((N-2)\lceil \beta \rceil + \lceil \alpha \rceil + \lceil \alpha' \rceil). \tag{8}$$

6.3. The DBORN optical ring

As stated earlier, an intermediate node i ($i = 2, \ldots, N-1$) can use the traversing lightpaths to inject its local traffic intended to the hub node. If sufficient capacity exists, the ring node i traffic would be carried by the spare capacity of the pass-through lightpaths. Otherwise, node i has to create new lightpaths to handle the entire amount of its local traffic destined to the hub node. Here, we suppose that the traffic injected by the different ring nodes is perfectly multiplexed in the upstream wavelengths.

Two algorithms can be used to realize the assignment of the network resources. The first minimizes the number of wavelengths, whereas the second minimizes the number of required transmitters at each ring node.

To illustrate both algorithms, we consider a simple six-node MptoP lightpath example as depicted in Fig. 15. We assume that each node has to transmit 0.4 lightpath of traffic to the destination node of the MptoP lightpath (i.e., node 6). To transmit its traffic, node 1 sets up a single-wavelength lightpath with node 6. This lightpath contains sufficient available bandwidth to carry the node 2 local traffic. In contrast, node 3 has to set up a new single-wavelength lightpath to transmit its traffic towards node 6. This can be done in two ways:

– Node 3 uses the available bandwidth of the pass-through lightpath and transmits the remaining part of its local traffic through the new lightpath (see Fig. 15a). In this case, the wavelength utilization is optimal. This scheme minimizes both the number of wavelengths and the number of receivers at node 6. This requires, however, two transmitters at node 3. Each transmitter emits only 0.2 lightpath of traffic. We refer to this scheme as the minimum-wavelength scheme (MW).
– Node 3 leaves free the insufficient available bandwidth of the pass-through lightpath. It transmits the entire amount of its local traffic in the new lightpath (see Fig. 15b). In this case, Node 3 uses a single transmitter. This scheme minimizes the number of transmitters at the ring nodes. We refer to this technique as the minimum-transmitter scheme (MT). We underline that a node leaves free an insufficient available bandwidth on a pass-through lightpath, only if its utilization increases the number of required transmitters. For instance, assume that node 3 has to transmit 1.2 worth of traffic instead of 0.4. In this case, node 3 uses the available bandwidth and carries the remaining local traffic via the new lightpath, since the number of required transmitters remains equal to 2.

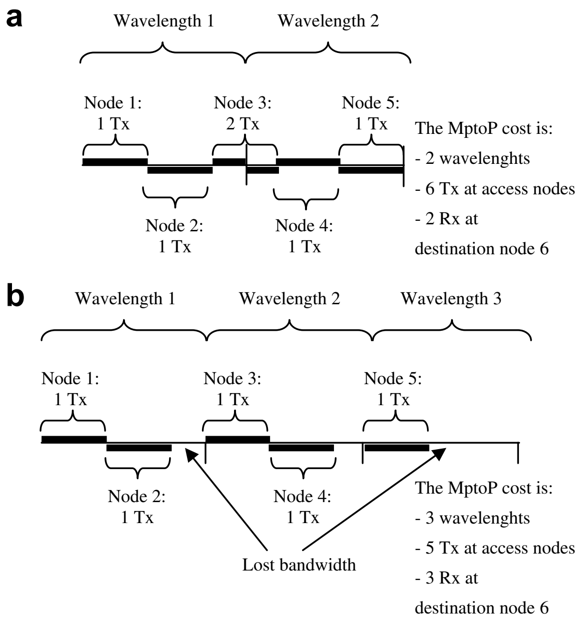

Fig. 15. A six-node MptoP lightpath: (a) The MW case. (b) The MT case.

6.3.1. Minimum-wavelength scheme (MW)

Each node i ($i = 1, \ldots, N-1$) sends all its local traffic (Λ_{sent}) towards the hub node via the upstream bus and receives all its associated traffic ($\Lambda_{\text{received}}$) from the hub node through the downstream bus. Considering the static hubbed traffic with parameter R and R', Λ_{sent} and $\Lambda_{\text{received}}$ are equal to:

$$\Lambda_{\text{sent}} = \alpha + (N-2)\beta = \frac{\tau}{R'}(1+R),$$
$$\Lambda_{\text{received}} = R' \cdot \Lambda_{\text{sent}} = \tau(1+R).$$

Then, the number of the upstream wavelengths is

$$W_{\text{up}} = \lceil (N-1)\Lambda_{\text{sent}} \rceil. \tag{9}$$

Likewise, the number of downstream wavelengths is

$$W_{\text{down}} = \lceil (N-1)\Lambda_{\text{received}} \rceil. \tag{10}$$

Thus, the total number of required wavelengths is

$$W = W_{\text{up}} + W_{\text{down}}. \tag{11}$$

Let us consider ring node i ($i = 1 \ldots N-1$). Node i has to transmit Λ_{sent} lightpaths of traffic to the hub node. The available bandwidth seen by node i on the traversing lightpaths coming from upstream nodes (i.e., nodes $1, \ldots, i-1$) is

$$Bw(i) = \lceil (i-1)\Lambda_{\text{sent}} \rceil - (i-1)\Lambda_{\text{sent}}.$$

The required number of transmitters at node i is then:

$$Tx[i] = \lceil \Lambda_{\text{sent}} - Bw(i) \rceil + \lceil Bw(i) \rceil.$$

It can be demonstrated that the total number of transmitters at all ring nodes (excluding the hub node) is provided by the expression:

$$\sum_{i=1}^{N-1} Tx[i] = N - 2 + W_{\text{up}} - \sum_{i=1}^{N-2} 1 | \lceil i\Lambda_{\text{sent}} \rceil - i\Lambda_{\text{sent}} = 0.$$

The number of required transmitters at the hub node is

$$Tx[0] = W_{\text{down}}.$$

Hence, the average number of transmitters per node is

$$Tx = \frac{1}{N} \sum_{i=0}^{N-1} Tx[i] = 1 + \frac{W - 2 - \sum_{i=1}^{N-2} 1 | \lceil i\Lambda_{\text{sent}} \rceil - i\Lambda_{\text{sent}} = 0}{N}. \tag{12}$$

Similarly, we obtain the average number of receivers per node

$$Rx = \frac{1}{N} \sum_{i=0}^{N-1} Rx(i) = 1 + \frac{W - 2 - \sum_{i=1}^{N-2} 1 | \lceil i\Lambda_{\text{received}} \rceil - i\Lambda_{\text{received}} = 0}{N}. \tag{13}$$

The average number of transceivers per node is thus:

$$Q = \frac{Tx + Rx}{2}. \tag{14}$$

6.3.2. Minimum-transmitter scheme (MT)

This scheme minimizes the number of required transmitters at ring nodes. It is easy to see that each node i ($i = 1, \ldots, N-1$) requires $\lceil \Lambda_{\text{sent}} \rceil$ transmitters. As stated before, node i uses the available bandwidth of a pass-through lightpath, as long as the resulting number of required transmitters remains equal to $\lceil \Lambda_{\text{sent}} \rceil$. In view of this, the number of upstream wavelengths can be calculated as below.

Let us first revisit the example of Fig. 15. Assume that each node transmits 1.4 lightpath of traffic to node 6 (i.e., hub node). Considering the MT scheme, each node is equipped with the minimum number of transmitters (i.e., $2Tx$). Specifically, node 1 sets up a double-wavelength lightpath with node 6 in order to transmit its local traffic. Node 2 uses the free bandwidth of the pass-through lightpath (0.6 of wavelength capacity) and sets up a new single-wavelength lightpath with node 6 (see Fig. 16). In contrast, node 3 keeps free the available of the pass-through lightpath (0.2 of wavelength capacity); otherwise it requires three transmitters instead of two. Node 3 has to set up a new double-wavelength lightpath to transmit its traffic towards node 6. As for nodes 1 and 2, node 4 shares the same band of wavelengths with node 3. In this case, each two successive nodes share the same band of $\lceil 2 \cdot \Lambda_{\text{sent}} \rceil$ wavelengths (see Fig. 16).

To generalize, given an arbitrary Λ_{sent} and N-node MptoP lightpath, each n successive nodes share a common band of $\lceil n \cdot \Lambda_{\text{sent}} \rceil$ upstream wavelengths, where

$$n = \left\lfloor \frac{1}{1 - (\lceil \Lambda_{\text{sent}} \rceil - \Lambda_{\text{sent}})} \right\rfloor. \tag{15}$$

Thus, the number of upstream wavelengths is

$$W_{\text{up}} = \left\lfloor \frac{N-1}{n} \right\rfloor \lceil n \cdot \Lambda_{\text{sent}} \rceil + \left\lceil \left(N - 1 - \left\lfloor \frac{N-1}{n} \right\rfloor n \right) \Lambda_{\text{sent}} \right\rceil. \tag{16}$$

A special case is when $\lceil \Lambda_{\text{sent}} \rceil - \Lambda_{\text{sent}} \in \left[0, \frac{1}{2}\right[$. In this case $n = 1$. In fact, the intermediate nodes never use the available bandwidth of the pass-through

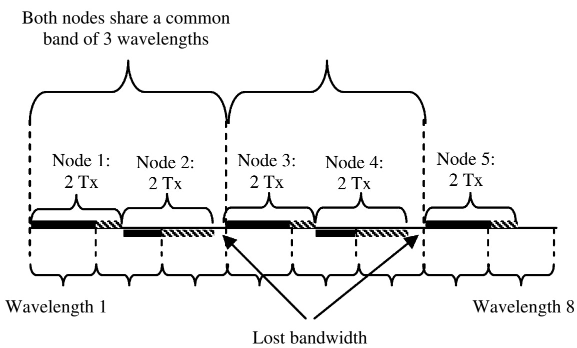

Fig. 16. A six-node MptoP lightpath: the MT case.

lightpaths. The number of upstream wavelengths is therefore:

$$W_{\text{up}} = (N-1)\lceil \Lambda_{\text{sent}} \rceil.$$

Likewise, we derive the number of downstream wavelengths:

$$W_{\text{down}} = \left\lfloor \frac{N-1}{n'} \right\rfloor \lceil n' \cdot \Lambda_{\text{received}} \rceil + \left\lceil \left(N - 1 - \left\lfloor \frac{N-1}{n'} \right\rfloor n \right) \Lambda_{\text{received}} \right\rceil, \quad (17)$$

where

$$n' = \left\lfloor \frac{1}{1 - (\lceil \Lambda_{\text{received}} \rceil - \Lambda_{\text{received}})} \right\rfloor.$$

Thus, the total number of required wavelengths is

$$W = W_{\text{up}} + W_{\text{down}}. \quad (18)$$

Recall that the number of transmitters and receivers required per node is

$$Tx[i] = \begin{cases} \lceil \Lambda_{\text{sent}} \rceil & \text{if } i = (1 \ldots N-1), \\ W_{\text{down}} & \text{if } i = 0, \end{cases}$$

$$Rx[i] = \begin{cases} \lceil \Lambda_{\text{received}} \rceil & \text{if } i = (1 \ldots N-1). \\ W_{\text{up}}, & \text{if } i = 0. \end{cases}$$

The average number of transceivers per node is therefore:

$$Q = \frac{(N-1)(\lceil \Lambda_{\text{sent}} \rceil + \lceil \Lambda_{\text{received}} \rceil) + W}{2N}. \quad (19)$$

6.4. The MptoP all-optical ring

In this network, each node $i (i = 0, \ldots, N-1)$ has to set up two lightpaths with the farthest nodes of the ring (i.e., nodes $\left(i + \frac{N-1}{2}\right) \bmod N$ and $\left(i - \frac{N-1}{2}\right) \bmod N$). To reach the remaining ring nodes, node i can use the spare capacity of pass-through lightpaths. In view of this, $2N$ MptoP lightpaths are required to serve all the traffic requests. Each lightpath traverses $(N+1)/2$ nodes (including the source and destination nodes). As before, the resource assignment can be done in two ways, according the MW or MT schemes.

6.4.1. Minimum-wavelength scheme (MW)

Let k $(k = 1, \ldots, (N+1)/2)$ denote the node position on a transit lightpath. Recall that node k $(k = 1, \ldots, (N-1)/2)$ can inject its local traffic into underutilized pass-through lightpath towards the destination node at position $(N+1)/2$. Let Λ denote the amount of traffic to be sent by node k to node $(N+1)/2$. Let Λ' denote the aggregate traffic sent by upstream nodes (i.e., $i = 1, \ldots, k-1$) towards node $(N+1)/2$. The available bandwidth seen by node k on the pass-through lightpath is

$$Bw(k) = \lceil \Lambda' \rceil - \Lambda'.$$

Then, the number of required transmitters at node k to send its local traffic (Λ) towards node $(N+1)/2$ is equal to:

$$\lceil \Lambda - Bw(k) \rceil + \lceil Bw(k) \rceil = \lceil \Lambda - (\lceil \Lambda' \rceil - \Lambda') \rceil + \lceil \lceil \Lambda' \rceil - \Lambda' \rceil. \quad (20)$$

Let $Tx[k]$ $(k = 1, \ldots, (N-1)/2)$ denote the number of transmitters required by all the ring nodes once they are situated at the kth position on the $2N$ lightpaths. The total number of transmitter in the ring is simply equal to:

$$Tx = \sum_{k=1}^{\frac{N-1}{2}} Tx[k].$$

Assume the static hubbed traffic as before, $Tx[k]$ can be determined as follows:

1. First, let us consider both lightpaths terminated by the hub node. In this case, each node along the lightpath sends α lightpath of traffic towards the hub node. Based on (20), the total number of required transmitters at both kth nodes of the considered lightpaths is
$$X1[k] = 2(\lceil \alpha - (\lceil (k-1)\alpha \rceil - (k-1)\alpha) \rceil + \lceil \lceil (k-1)\alpha \rceil - (k-1)\alpha \rceil).$$
2. Let us consider now, the remaining $(2N-2)$ lightpaths, which are not destined to the hub node. Two cases are to be distinguished:
   2.1. First, let us consider both lightpaths, where the hub node is at the kth position. Using (20), the number of required transmitters at the hub node to transmit in these lightpaths is
   $$X2[k] = 2(\lceil \alpha' - (\lceil (k-1)\beta \rceil - (k-1)\beta) \rceil + \lceil \lceil (k-1)\beta \rceil - (k-1)\beta \rceil).$$
   2.2. Let us consider now, the remaining $(2N-4)$ lightpaths. In this case, both the kth node and the destination node of each lightpath are different from the hub node. Two subcases are to be distinguished:

2.2.1. The hub node is one of the upstream nodes traversed by the lightpath before passing-through node k. That is, the hub node has the position i on the lightpath where $i = 1\ldots k-1$. This is the case of $2(k-1)$ lightpaths. Using (20), the total number of required transmitters at all the nodes situated at the kth position to transmit in the considered lightpaths is

$$X3[k] = 2(k-1)(\lceil \beta - (\lceil (k-2)\beta + \alpha' \rceil - ((k-2)\beta + \alpha')) \rceil + \lceil \lceil (k-2)\beta + \alpha' \rceil - ((k-2)\beta + \alpha') \rceil).$$

2.2.2. In this case, all the nodes at the ith position ($i = 1\ldots k$) of a lightpath are different from the hub node. This is the case of the remaining $2(N-1-k)$ lightpaths. Based on (20), the total number of required transmitters at all the nodes situated at the kth position to transmit in the considered lightpaths is

$$X4[k] = 2(N-1-k)(\lceil \beta - (\lceil (k-1)\beta \rceil - (k-1)\beta) \rceil + \lceil \lceil (k-1)\beta \rceil - (k-1)\beta \rceil).$$

Finally the total number of transmitters needed in the ring is

$$Tx = \sum_{k=1}^{\frac{N-1}{2}} X1[k] + X2[k] + X3[k] + X4[k]. \quad (21)$$

With regard to the reception part, each node $i (i = 0,\ldots,N-1)$ receives two MptoP lightpaths carrying the aggregate traffic coming from both half of the ring as shown in Fig. 4. Each half has $(N-1)/2$ ring nodes. The number of receivers at node i is simply:

$$Rx[i] = \begin{cases} \lceil \frac{N-3}{2}\beta + \alpha' \rceil + \lceil \frac{N-1}{2}\beta \rceil & \text{if } i = (1\ldots N-1), \\ 2\lceil \frac{N-1}{2}\alpha \rceil & \text{if } i = 0. \end{cases}$$

Hence, the total number of required receivers in the ring is

$$Rx = \sum_{i=0}^{N-1} Rx[i]. \quad (22)$$

The average number of transceivers per node is therefore:

$$Q = \frac{Tx + Rx}{2N}. \quad (23)$$

As stated before, both L_0 and $LN-1$ are the most loaded links, since $\alpha \geqslant \beta$ and $\alpha' \geqslant \beta$. W is, therefore, the number of wavelengths traversing L_0, and it can be determined as follows:

1. In the clockwise direction, L_0 is traversed by $(N-1)/2$ lightpaths initiated by nodes $\{\frac{N+3}{2},\ldots,N-1,0\}$ and terminated by nodes $\{1,\ldots,\frac{N-1}{2}\}$ respectively (see Fig. 17). The position of the hub node on each of these lightpaths is $k = 1,\ldots,(N-1)/2$. Each lightpath collects traffic from $k-1$ ring nodes and the hub node before passing through L_0. Thus, the number of wavelengths passing through L_0 in the clockwise direction is

$$W' = \sum_{k=1}^{\frac{N-1}{2}} \lceil \alpha' + (k-1)\beta \rceil. \quad (24)$$

2. In the opposite direction, L_0 is traversed by $(N-1)/2$ lightpaths initiated by nodes $\{1,\ldots,\frac{N-1}{2}\}$ (see Fig. 17). The number of wavelengths passing through L_0 in this direction is simply:

$$W'' = \left\lceil \frac{N-1}{2}\alpha \right\rceil + \sum_{k=1}^{\frac{N-3}{2}} \lceil k\beta \rceil. \quad (25)$$

The total number of wavelengths is therefore:

$$W = W' + W''. \quad (26)$$

6.4.2. Minimum-transmitter scheme (MT)

In this case, each node is equipped with the minimum number of transmitters to handle its local traffic. Recall that each node uses $N-1$ different lightpaths to connect to the $N-1$ nodes of the ring. The number of required transmitters per node is therefore:

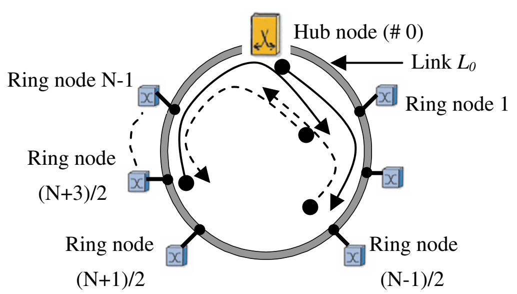

Fig. 17. MptoP WDM ring: lightpaths passing through link L_0.

$$Tx[i] = \begin{cases} \lceil \alpha \rceil + (N-2)\lceil \beta \rceil & \text{if } i = (1 \dots N-1), \\ (N-1)\lceil \alpha' \rceil & \text{if } i = 0. \end{cases}$$

Hence, the total number of required transmitters in the ring is

$$Tx = \sum_{i=0}^{N-1} Tx[i]. \tag{27}$$

With regard to the reception part, each node $i(i = 1, \dots, N-1)$ (excluding the hub) receives two MptoP lightpaths carrying the aggregate traffic coming from both half of the ring as shown in Fig. 4. Each half has $(N-1)/2$ ring nodes. The number of required receivers at node i can be determinated as follows:

1. First, let us consider the half that does not contain the hub node. In this case, each node along the MptoP lightpath sends β worth of traffic to node i. According to the MT scheme (16), each n successive nodes share a common band of $\lceil n\beta \rceil$ wavelengths, where:

   $$n = \left\lfloor \frac{1}{1 - (\lceil \beta \rceil - \beta)} \right\rfloor.$$

   Hence, the number of required receivers at node i to terminate the wavelengths coming from this half of the ring is

   $$Rx1 = \left\lfloor \frac{N-1}{2n} \right\rfloor \lceil n\beta \rceil + \left\lceil \left(\frac{N-1}{2} - \left\lfloor \frac{N-1}{2n} \right\rfloor n \right) \beta \right\rceil. \tag{28}$$

2. Let us consider now, the half that contains the hub node. In this case, the number of receivers at node i depends on its relative position with respect to the hub node. To simplify the analysis, we suppose that the hub node always creates its own $\lceil \alpha' \rceil$-wavelength lightpath to connect to node i. That is, the MptoP lightpath traveling to node i is shared by the remaining $(N-3)/2$ ring nodes. Note that this approximation will increase the real number of required receivers at node i at most by a factor one. The number of required receivers at node i to terminate the wavelengths coming from this half of the ring is therefore:

   $$Rx2 = \lceil \alpha' \rceil + \left\lfloor \frac{N-3}{2n} \right\rfloor \lceil n\beta \rceil + \left\lceil \left(\frac{N-3}{2} - \left\lfloor \frac{N-3}{2n} \right\rfloor n \right) \beta \right\rceil, \tag{29}$$

   where $n = \left\lfloor \frac{1}{1-(\lceil \beta \rceil - \beta)} \right\rfloor$.

Thus, the number of required receivers at each node $i(i = 1, \dots, N-1)$ is

$$Rx[i] = Rx1 + Rx2. \tag{30}$$

Likewise, the hub node receives two MptoP lightpaths coming from both parts of the ring. Each MptoP lightpath is shared by $(N-1)/2$ ring nodes. Each node along the lightpath transmits α worth of traffic towards the hub node. Thus, the number of required receivers at the hub node is

$$Rx[0] = 2\left(\left\lfloor \frac{N-1}{2n} \right\rfloor \lceil n\alpha \rceil + \left\lceil \left(\frac{N-1}{2} - \left\lfloor \frac{N-1}{2n} \right\rfloor n \right) \alpha \right\rceil \right), \tag{31}$$

with

$$n = \left\lfloor \frac{1}{1 - (\lceil \alpha \rceil - \alpha)} \right\rfloor.$$

Hence, the total number of required receivers in the ring is

$$Rx = \sum_{i=0}^{N-1} Rx[i]. \tag{32}$$

The average number of transceivers per node is therefore:

$$Q = \frac{Tx + Rx}{2N}. \tag{33}$$

As before, W is the number of wavelengths traversing L_0, and it can be determined as follows:

1. In the clockwise direction, L_0 is traversed by $(N-1)/2$ lightpaths initiated by nodes $\left\{\frac{N+3}{2}, \dots, N-1, 0\right\}$ and terminated by nodes $\left\{1, \dots, \frac{N-1}{2}\right\}$ respectively (see Fig. 17). The position of the hub node on each of these lightpaths is $k = 1, \dots, (N-1)/2$. Let lightpath k refer to each of these lightpaths according the hub node position. Lightpath k collects traffic from $k-1$ ring nodes and the hub node before passing through L_0. To simplify the analysis, we suppose that the hub node sets up its own $\lceil \alpha' \rceil$-wavelength

lightpath to connect directly to each ring node. Thus, the number of wavelengths passing through L_0 and required by lightpath k is

$$W'[k] = \lceil \alpha' \rceil + \left\lfloor \frac{k-1}{n} \right\rfloor \lceil n\beta \rceil + \left\lceil \left(k - 1 - \left\lfloor \frac{k-1}{n} \right\rfloor n \right) \beta \right\rceil,$$

with

$$n = \left\lfloor \frac{1}{1 - (\lceil \beta \rceil - \beta)} \right\rfloor.$$

The total number of required wavelengths in the clockwise direction through L_0 is therefore:

$$W' = \sum_{k=1}^{\frac{N-1}{2}} W'[k]. \tag{34}$$

2. In the opposite direction, L_0 is traversed by $(N-1)/2$ lightpaths initiated by nodes $\{1, \ldots, \frac{N-1}{2}\}$ (see Fig. 17). The position of the hub node on each of these lightpaths is $k = 2, \ldots, (N+1)/2$. Let lightpath k refer to each of these lightpaths according the hub node position. Lightpath k collects traffic from $k-1$ ring nodes before passing through L_0. As before, the number of wavelengths passing through L_0 and required by lightpath k is simply:

$$W''[k] = \begin{cases} \left\lfloor \frac{k-1}{n} \right\rfloor \lceil n\beta \rceil + \left\lceil \left(k - 1 - \left\lfloor \frac{k-1}{n} \right\rfloor n \right) \beta \right\rceil, & \text{if } k = 2, \ldots, \frac{N-1}{2} \\ \left\lfloor \frac{N-1}{2n'} \right\rfloor \lceil n'\alpha \rceil + \left\lceil \left(\frac{N-1}{2} - \left\lfloor \frac{N-1}{2n'} \right\rfloor n' \right) \alpha \right\rceil, & \text{if } k = \frac{N+1}{2}, \end{cases}$$

with

$$n = \left\lfloor \frac{1}{1 - (\lceil \beta \rceil - \beta)} \right\rfloor \quad \text{and} \quad n' = \left\lfloor \frac{1}{1 - (\lceil \alpha \rceil - \alpha)} \right\rfloor.$$

The total number of wavelengths passing through L_0 in this direction is therefore:

$$W'' = \sum_{k=2}^{\frac{N+1}{2}} W''[k]. \tag{35}$$

The total number of wavelengths is therefore:

$$W = W' + W''. \tag{36}$$

7. Cost comparison

In this section, we compare the different WDM ring networks. In all the figures, except when indicated, $N = 9$. We study the impact of ratio R and R', as defined in (2), on the ring cost. We focus merely on the MT scheme, since in our model the transceiver cost is dominant.

Fig. 18 shows values for Q, for the case of $R' = 1$, $R' = 2$ and $R' = 4$. The hubbed metric R remains constant and equals to $\frac{1}{N-2} = \frac{1}{7}$. In this case, $\alpha = \beta = \frac{\tau}{7R'}$. That is, each ring node $i (i = 1, \ldots, N-1)$ sends the same amount of traffic (β) to all the remaining ring nodes including the hub node. The figures present the variation of the cost Q with respect to the total amount of local traffic handled by each ring node (Λ), where

$$\Lambda = \Lambda_{\text{sent}} + \Lambda_{\text{received}} = 8\beta(R' + 1).$$

Recall that when $R' = 1$ (Fig. 18a), the traffic pattern is a static uniform matrix.

Based on these results, the MptoP and DBORN solutions appear to be the best choices since they have the lowest transceiver cost. DBORN outperforms MptoP when the asymmetric ratio R' is large. In this case, $\Lambda_{\text{received}}$ dominates Λ_{sent}. Specifically, DBORN is better as long as $\alpha = \beta \leqslant 1/2$. That is, the traffic exchanged between each pair of

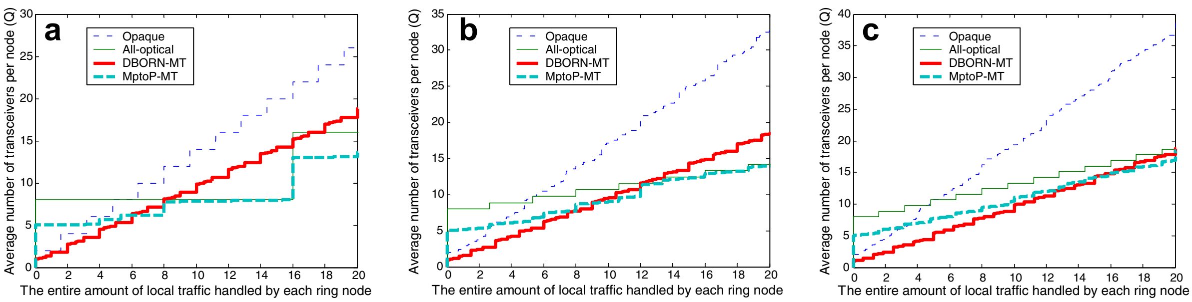

Fig. 18. The transceiver requirement per node in the WDM ring networks for different values of the asymmetric ratio R': (a) case $R' = 1$, (b) case $R' = 2$ and (c) case $R' = 4$.

nodes is relatively small. For instance, this is achieved as long as $\Lambda \leqslant 8$ when $R' = 1$. Recall that a DBORN node transmits all its traffic ($\Lambda_{\text{sent}} = 8\beta$) towards the hub node, thus using a single lightpath. Instead, a MptoP ring node has to set up $N-1$ lightpaths in order to transmit its local traffic to the remaining nodes of the ring. In view of this, the traffic grooming in DBORN nodes is higher than in the MptoP nodes. To achieve this, the DBORN hub node has to deal with all the traffic in the ring, thus requiring a maximum transceiver cost. In this regard, the cost gain achieved by DBORN at the ring nodes level is lost at the hub node when β becomes relatively large.

The all-optical ring is also a reasonable choice only if the traffic between each pair of nodes is high enough to fill in the entire lightpaths capacity. Opaque rings typically have the highest transceiver cost since the nodes do not have optical pass-through.

Fig. 19 shows values for W, for the case of $R' = 1$, $R' = 2$ and $R' = 4$. As before, R remains constant and equals to $\frac{1}{N-2} = \frac{1}{7}$. We note that, if we have few wavelengths, the opaque approach is a logical choice for WDM ring networks. Opaque rings always provide the most efficient use of wavelength. The MptoP solution also stands out as a good choice thanks to its statistical multiplexing features. It outperforms all-optical and DBORN solutions. We observe that DBORN requires the largest number of wavelengths. This result is expected, since a DBORN connection request may traverse twice the same link before reaching its final destination.

Further, we analyse the impact of the hubbed metric R. To do so, we fix the value of the asymmetric ratio $R' = 1$ and we vary R. That is, we consider a symmetric hubbed matrix with the following pattern:

$$T(i,j) = \begin{cases} 0, & \text{if } i = j, \\ \text{otherwise} & \begin{cases} \alpha = \alpha' = 7R\beta & \text{if } i = 0 \text{ or } j = 0, \\ \beta = \frac{\tau}{(N-2)} = \frac{\tau}{7} & \text{otherwise.} \end{cases} \end{cases}$$

Fig. 20 shows values for Q in function of $\Lambda_{\text{sent}} = \alpha + 7\beta$, for the case of $R = 1/7$, $R = 1$ and $R = 4$. As before, the MptoP and DBORN solutions are the best choices. DBORN outperforms MptoP when R is large. In this case, the major part of the traffic from each access node is destined out of the ring network. That is α dominates β. In contrast, for a fixed value of R, the MptoP ring outperforms DBORN when Λ_{sent} increases. Specifically, once $\beta \geqslant 1/2$, the cost gain achieved at DBORN ring nodes is lost at the hub node, and the MptoP solution becomes more interesting.

Fig. 21 shows values for W, for the case of $R = 1/7$, $R = 1$ and $R = 4$. The MptoP solution presents near optimal results. The MptoP curve is very close to the optimal opaque results. The MptoP ring always outperforms the all-optical ring thanks to the statistical multiplexing gain. Finally, as stated before, if we have few wavelengths, the DBORN approach is not a sensible choice for WDM ring networks.

Figs. 22 and 20 show values for Q and W respectively. We only consider the DBORN and MptoP ring networks. R and R' are set equal to 1/2 and 1 respectively. In the figures, we present both results of the MW and MT schemes. As expected, the MW assignment scheme enables for a better use of wavelengths at the price of a transceiver cost increase. Note that this example confirms the previous results. Fig. 23 shows that MptoP ring allows for a better use of resources as opposed to DBORN. Fig. 22 shows that MptoP and DBORN architectures provide better transceiver costs over different

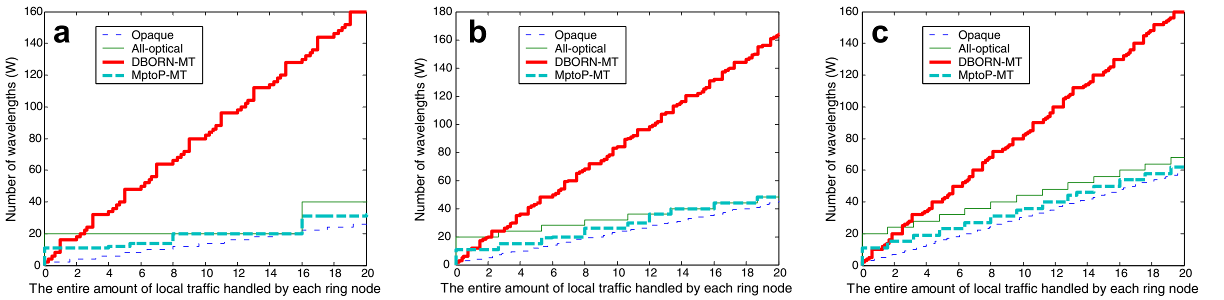

Fig. 19. The number of required wavelengths in the WDM ring networks for different values of the asymmetric ratio R': (a) case $R' = 1$, (b) case $R' = 2$ and (c) case $R' = 4$.

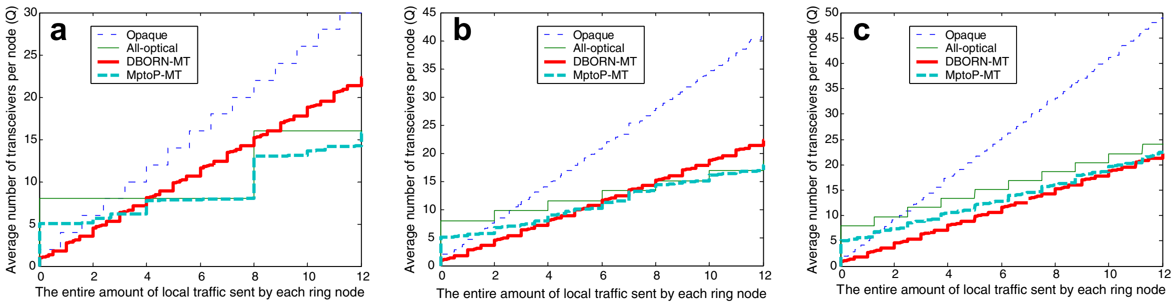

Fig. 20. The transceiver requirement per node in the WDM ring networks for different values of the hubbed ratio R: (a) case $R = 1/7$, (b) case $R = 1$ and (c) case $R = 4$.

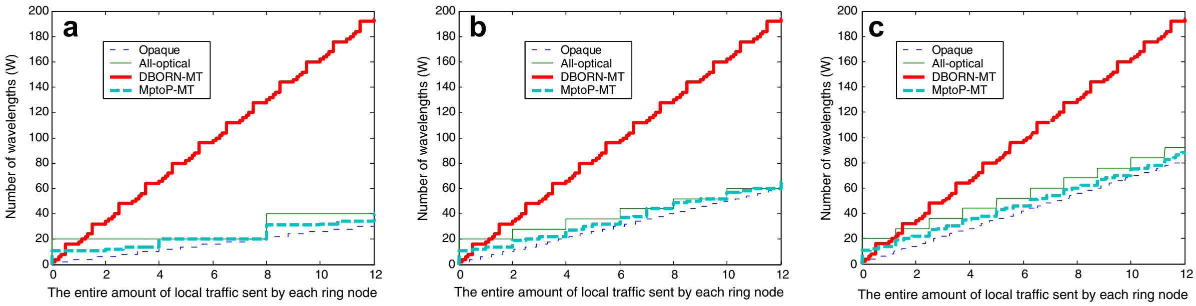

Fig. 21. The number of required wavelengths in the WDM ring networks for different values of the hubbed ratio R: (a) case $R = 1/7$, (b) case $R = 1$ and (c) case $R = 4$.

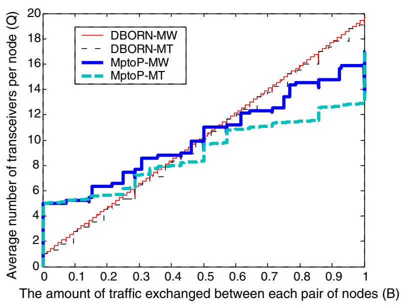

Fig. 22. The transceiver requirement per node in MptoP and DBORN architectures using both MT and MW schemes.

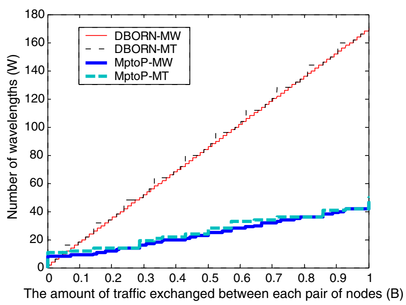

Fig. 23. The number of required wavelengths in MptoP and DBORN architectures using both MT and MW schemes.

values of β. Specifically, when $\beta \geqslant 1/2$, the MptoP ring outperforms the DBORN solution. Recall that for this range of β, the gain achieved by DBORN over MptoP at ring nodes level is lost at the hub node.

So far, for the sake of simplicity, we reported only results regarding the particular case of 9 node ring network. In what follows the costs Q and W are derived considering different ring network sizes in term of number of access nodes. This is depicted in Figs. 24 and 25, where we consider three ring networks with $N = 7$, $N = 9$ and $N = 11$ nodes, respectively. In this case, the ratios R and R' are set equal to 1/2 and *1*, respectively. Again, we observe that for the different ring sizes, the MptoP strategy leads to the smallest transceiver cost (Fig. 24) and enables an efficient use of the link bandwidth (Fig. 25).

Finally, it is important to note that achieving MptoP lightpaths requires Burst Mode transmitters (Integrated Laser Modulator (ILM) + Semiconductor Optical Amplifier (OSA)) and Burst Mode receivers. Both are based on mature technologies

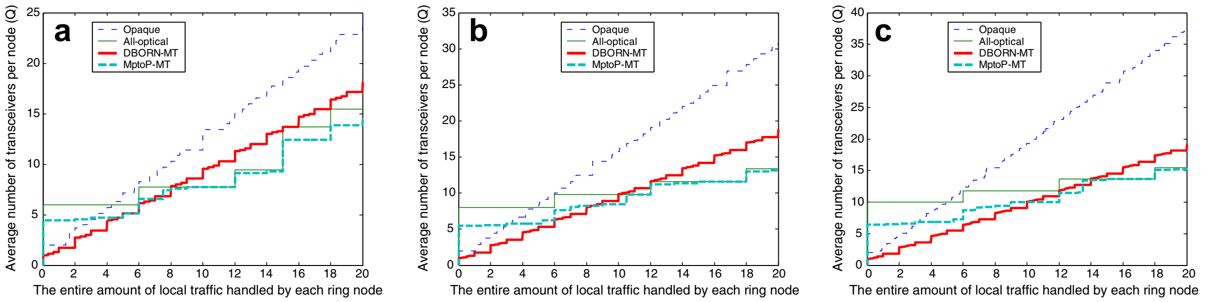

Fig. 24. The transceiver requirement per node for different WDM ring network sizes N: (a) case $N = 7$, (b) case $N = 9$ and (c) case $N = 11$.

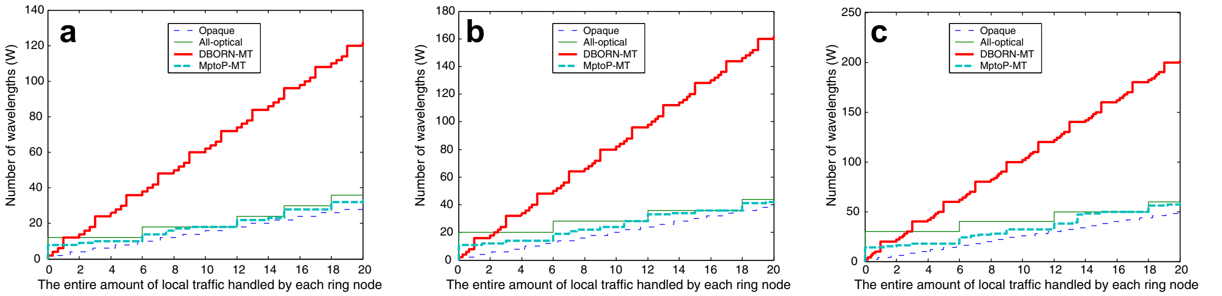

Fig. 25. The number of required wavelengths for different WDM ring network sizes N: (a) case $N = 7$, (b) case $N = 9$ and (c) case $N = 11$.

and have been experimentally validated in Passive Optical Networks (PoN). To take into account the difference in cost between such asynchronous equipment and the continuous wave transceiver used in all-optical and opaque networks, we introduced a new cost ratio $\phi > 1$. Accordingly, the cost of a Burst Mode transceiver (BMT) is ϕ times the cost of a continuous wave transceiver (CWT).

Fig. 26 shows the new transceiver requirements for the different strategies in terms of CWT. In this case, R and R' are set equal to 1/2 and 1, respectively. Moreover, the amount of traffic exchanged between each pair of nodes (i.e., β) is set respectively equal to 0.1, 0.2 and 0.3 of the wavelength capacity. The transceiver cost is plotted for various values of the ratio ϕ that range between $[1, 3/2]$. As optical technology keeps maturing, the BMT cost decreases progressively. Meanwhile, BMT and CWT will have comparable costs.

Fig. 26 shows that the MptoP ring has near always the smallest cost. The obtained gain with respect to classical all-optical an opaque rings decreases logically with ϕ. But it remains significant even for high value of ϕ. As stated before, we expect that this gain increases progressively. Based on Fig. 26, we can conclude that the MptoP insertion

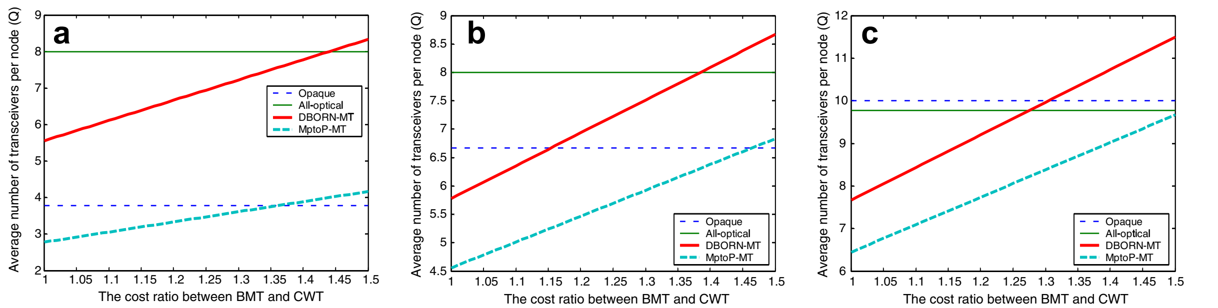

Fig. 26. The transceiver requirement per node in term of CWT for different values of the exchanged traffic between each pair of nodes β: (a) case $\beta = 0.1$, (b) case $\beta = 0.2$ and (c) case $\beta = 0.3$.

enables great cost savings despite the relatively high cost of the needed BMT.

In summary, most of the time, the MptoP ring has the smallest transceiver cost and leads to an efficient use of the wavelength resources. This architecture combines the merits of optical pass-through, leading to great savings on the transceiver cost, and statistical multiplexing gain, which allows an efficient use of the wavelengths. The DBORN architecture is also a good choice if the wavelengths are plentiful. In this case, the transceiver savings over the MptoP solution increase with the increase of R and R', and decreases with the increase of β.

8. Conclusion

In this paper, we considered single-hub WDM ring networks. We proposed a new architecture for such ring networks. This approach combines the merits of both the optical bypass of all-optical wavelength routing and the multiplexing gain of sub-wavelength routing. A cost comparison for our proposed scheme and existing solutions was given. Results show that our proposal always has the smallest transceiver cost and provides an efficient use of the wavelength resources.

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