

Deploying Agile Photonic Networks over Reconfigurable Optical Networks

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Abstract

The advantages and issues in deploying a fast photonic network on top of a reconfigurable WDM network are discussed. The agile photonic network is deployed as another user of the reconfigurable optical WDM network (RON), with the reconfigurable optical switches setting up the optical circuits that define the virtual topology for the agile network. The services provided by the agile network are then carried over the wavelengths that are assigned to it by the global control plane of the RON. Such deployment would allow the agile network to provide the fast optical time division multiplexing (OTDM) scheduling techniques warranted for fast-changing, low-capacity traffic flows typical of metropolitan and access networks; while sustained, high-capacity flows would remain in whole lightpaths provided at the RON level to other users. Connectivity options are described for edge and core nodes, as well as the functionality requirements of the global control plane that would manage such a deployment.

1. Introduction

1.1. The reconfigurable optical network

In traditional optical networks, Wavelength Division Multiplexed (WDM) transmission has been used only as a point-to-point transmission technology in order to make the most of the increased capacity it offers. With electronic routers being used at each node of the network, the number of conversions to the electrical domain is enormous and the routing/queueing delays at the nodes are significant.

Currently, WDM networks are being deployed as Reconfigurable Optical Networks (RON, Figure 1) that, instead of electronic routers at the nodes, use wavelength-routing devices such as wavelength cross-connects (WXC), reconfigurable optical add-drop multiplexers (ROADMs), wavelength selective

switches (WSSs), arrayed waveguide gratings (AWGRs) and other similar devices to layout the lightpaths in an end-to-end fashion [1].

Time Division Multiplexing (TDM) is also being used on the optical domain to improve the utilization of each wavelength by reducing the bandwidth granularity. Ideally, the reconfigurable devices listed above would permit the implementation of TDM over WDM to optimize the efficiency of the network, but the current technologies are capable of changing their configuration only in a “slow” fashion (tens of milliseconds) and are therefore not suitable to provide the fast Optical TDM (OTDM) scheduling techniques that would further improve the statistical multiplexing.

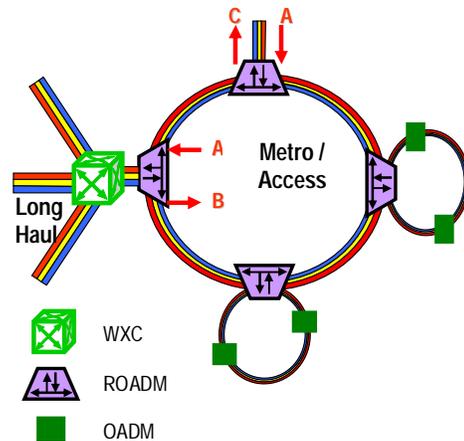


Figure 1. A reconfigurable optical network.

1.2. The agile all-photonic network

A very fast, i.e. *agile*, photonic network capable of much higher switching speeds, such as an Agile All-Photonic Network (AAPN) [2] [3], may be deployed on top of a RON as another user of the WDM network, with the “slowly” reconfigurable WXC/ROADM switches setting up the optical circuits that define the virtual topology for the agile network.

In the case of AAPN, the topology is an overlaid

star (Figure 2) formed by edge nodes interconnected by bufferless optical core nodes. The edge nodes aggregate incoming traffic in larger fixed-size data units called "slots" and transmit them over the photonic links. The core nodes consist of a wavelength stack of bufferless transparent photonic switches (a set of space switches, one switch for each wavelength) and perform fast switching in order to provide bandwidth allocation in much finer sub-wavelength granularities. To allow for larger numbers of edge nodes in the topology, selectors may be used as shown in figure 3.

To share the network bandwidth, the AAPN employs OTDM, where time is "slotted" and the slots arrive at the core switch synchronously. A centralised or distributed scheduling method is necessary to synchronize transmission, to allocate the available bandwidth, and to solve contention among the edge nodes; all this with the consideration that there are wavelength and timeslot continuity constraints.

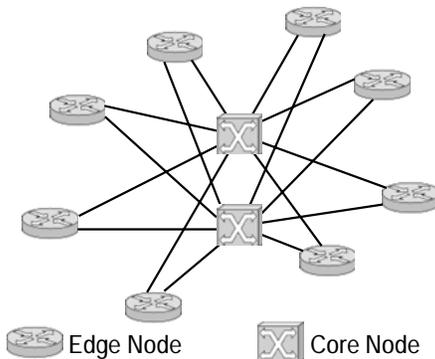


Figure 2. Overlaid star topology that characterises the AAPN [2].

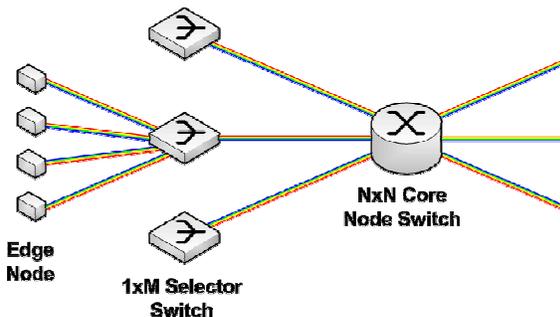


Figure 3. Use of selectors in AAPN to allow for large numbers of edge nodes (image from [3]).

1.3. The paradigm and benefits

With the all-photonic network deployed as a user of

the RON, the services provided by the agile network are then carried over the wavelength(s) that are assigned to it by the global control plane of the RON. Given that the core photonic switches in agile networks operate in nanosecond ranges (from a few ns and up to hundreds of ns); such deployment would allow the agile network or AAPN to provide various forms of OTDM scheduling [4] [5] [6] to fast-changing, low-capacity traffic flows typical of metropolitan and access networks; while sustained, high capacity flows would remain in whole lightpaths provided at the RON level to other users.

One of the most important benefits of all-photonic networks is the reduction in power consumption. Further to the elimination of electronic routers in the core network; transponders can also be eliminated with this approach. In optical networks, and most commonly in SONET/SDH, transponders are used to regenerate the signal at the electrical level and, since they can only regenerate one wavelength at a time, existing WDM networks still require separation of individual wavelengths for o-e-o conversion; which scales very poorly as the number of wavelengths on a WDM link increases. Eliminating the transponders in the core of the photonic network therefore reduces the costs (both CapEx and OpEx) significantly [1] [7]. Additionally, it makes the core network transparent to bit rates; another highly desirable feature in the long term.

It is important to note as well that the available fibre infrastructure is limited and will remain limited at least in the medium-term. Even though new fibre access networks are currently being widely deployed in response to customer demand for a triple-play service of voice, data and video; once this deployment phase subsides there will be a reluctance to make further whole-scale investments given the very high capital expense it represents.

2. Deployment over a reconfigurable mesh network

Wavelength assignment in current reconfigurable optical networks is quasi-static. Software systems for management exist, but assignment of whole wavelengths is still performed largely manually by network administrators. An automated mechanism to dynamically manage the wavelengths in the RON is therefore desirable. In such a system, the lightpaths provided by the RON to the agile network are remotely reconfigurable and the topology can be modified at any time to form different topologies or when new

core/edge nodes are added to, or removed from, the agile network.

2.1. Models for deployment

Considering the models for hybrid networks described in [8], the management of wavelengths of the RON in the deployment of virtual topologies for the AAPN would be:

- Client-server model: The AAPN is the client and its services can be node- or application- driven. The RON is transparent and the edge node only uses AAPN services.
- Parallel model: The AAPN and the RON are independent but operate in parallel. A node chooses either for the different classes of traffic.
- Integrated model: Traffic may be transported in AAPN or RON mode on any link as chosen by the global control plane (both are transparent to the edge node). Transitions between modes require dropping data into the electronic domain.

The complexity required in the global control plane will increase for the parallel model and even more for the integrated model since more layers of the network hierarchy (transport, session, application) must be integrated within it.

The model proposed for an AAPN deployment is a *dynamic* version of the client-server model, in which edge nodes and core nodes may be added or removed from the AAPN at any time, depending on the traffic demands and the services it offers.

A powerful global control plane is required to manage the use of resources in the RON by remotely reconfiguring the switching devices. Such a control plane would be a more complex version of, for example, the “user-controlled lightpaths” scheme studied in [9], where the network nodes are “slow” MEMS-based optical crossbar switches configured in response to requests at the user or application level.

3. Conforming the topology

In a star network such as AAPN, the paths between core and edge nodes must be all disjoint and there can be only one edge node per disjoint path (or one selector/concentrator, as shown in Figure 3). Since there is a wavelength constraint, the edge-node paths are formed by *link-fibre-wavelength* triplets. The core node therefore connects at most to a number of edge nodes (or concentrators) equal to the fibre degree of the RON node.

A similar topological design problem is studied in

[5] where heuristic and optimization algorithms based on traffic demands are used; the model, however, does not consider the wavelength constraint, assumes high core node degrees, and assumes as well that fibre can be deployed as needed.

Figure 4 shows the basic deployment of a star on top of two rings connected by a four-degree ROADM or WXC. In the AAPN the core node is an edge node with extended control functionality and thus the figure represents a five-ray star topology.

3.1. Separate concentrators attached to the RON node

Using a deployment as the one depicted in Figure 4, if concentrators/selectors are used, they would be simply deployed independently from the RON as shown in Figure 5; connected to the ports where the assigned wavelength(s) is dropped/added.

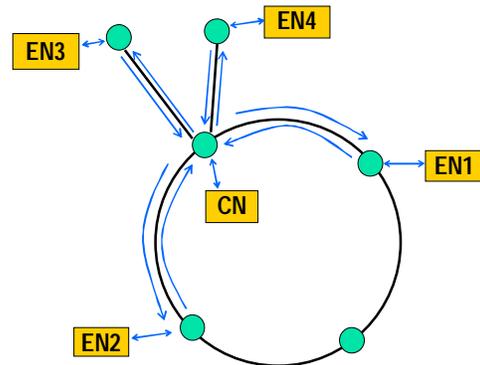


Figure 4. A five-ray star deployed on top of two ring networks (or a ring and two any other fibre links).

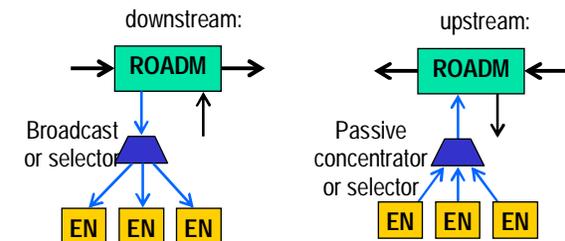


Figure 5. Deployment of concentrators and selectors separate from the RON.

3.2. Using the path/ring as concentrator

It is possible to use a path or ring within the RON as a selector/concentrator. In this case, the bandwidth along a path/ring is divided by the number of edge nodes that share it, and each edge node uses one or

several larger time slots of the wavelength along the path (larger than the OTDM timeslots defined in the photonic network), with the partitioning determined by the RON and therefore being independent from the OTDM scheduling of the agile network. Topologies with cycles requires the total delay around a cycle to be an integer number of OTDM timeslots, requiring a timeslot synchronizer at the edge node.

The larger RON timeslots not used by the photonic network can be assigned by the global control plane to another user of the RON. The partitioning of the assigned wavelength in the ring network could be managed by a scheme similar the ones presented in [10] for a single ring, or in [11] for a mesh network.

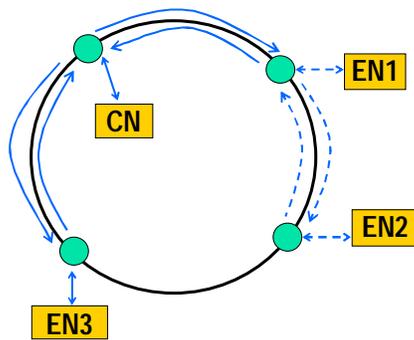


Figure 6. Using a ring or path as a concentrator of the AAPN. EN1 and EN2 share the wavelength time in halves.

4. Deployment of Agile Photonic Nodes

4.1. Core node deployment

Core nodes are better placed at the network nodes with the highest degrees in order to maximize the number of edge nodes that can be attached to the AAPN. Figure 7 shows the AAPN agile core node deployed next to a four-degree ROADM that could be, for example, joining two rings of the RON. Each direction of the ROADM (East 1&2, West 1&2) drops and adds the wavelength(s) assigned to the AAPN. The feasibility of a similar system with a two-degree, 16-wavelength ROADM and a fast optical switch attached to it, has been proved in [12].

4.2. Edge node deployment

For the deployment of the edge nodes, in the simplest case each ROADM simply drops and adds the assigned wavelength(s) to the corresponding edge node, as shown in Figure 8.

If the ring or path is used as a concentrator, the deployment would be achieved by connecting the drop port to the add port. In the upstream direction, the edge node transmits by coupling the signal on the add port, as shown in Figure 9. The “drop and continue” function of a WSS, if available [13], may be used in the downstream direction in this deployment to simplify connectivity.

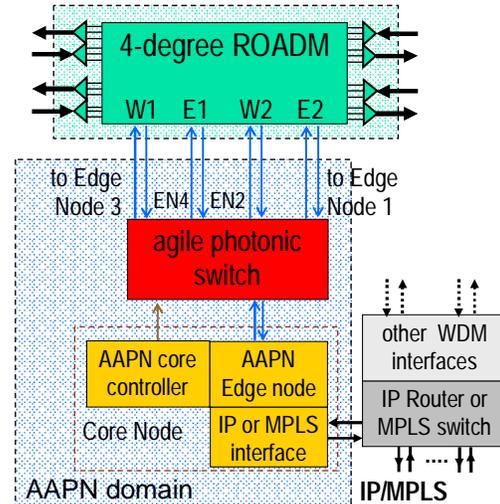


Figure 7. Agile switch and core node deployment attached to a 4-degree ROADM of the RON.

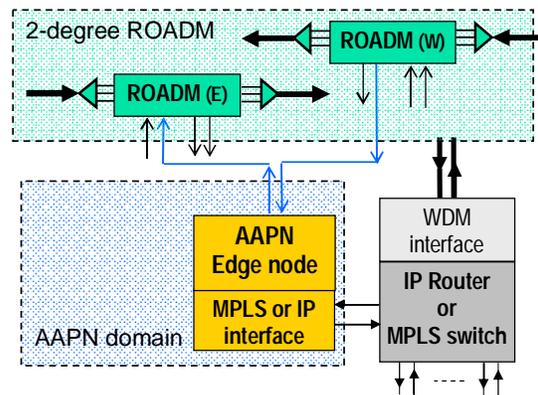


Figure 8. Agile edge node deployment attached to a 2-degree ROADM of the RON.

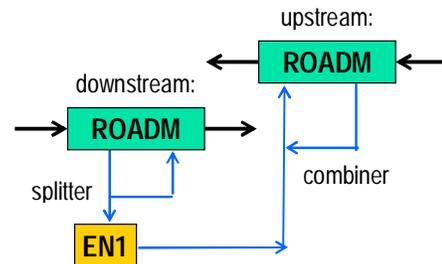


Figure 9. Agile edge node deployment attached to a 2-degree ROADM when the WDM path/ring is used as selector/concentrator.

5. Core node degree issues in the RON

Current RON deployments are likely to have low degree nodes, which limits the number of edge nodes attached to the photonic core switch.

While the AAPN assumes no wavelength conversion (WC), in this kind of deployment all-optical WCs could be used at the core to increase the node degree by allowing several wavelengths on the same fibre to belong to the agile network.

When the RON allows the interconnection of several rings/paths, multi-degree ROADMs will be needed to interconnect them. Multi-degree ROADMs have only recently entered the market (e.g., [14] [15]). A modular ROADM architecture scalable to very large degrees is also proposed in [16] for the interconnection of several rings. With this architecture, node degrees could be upped gradually, both for the RON and the AAPN, without replacing existing switches.

The core node degree problem may also be mitigated by deploying more than one AAPN star with lower core node degrees and interconnecting these independent star networks via their intersecting edge nodes. In this case, a compromise must be made with the increased complexity of the control planes of both the RON and the AAPN, but using sparsely populated stars interconnected by intersecting edge nodes would permit to cover all the nodes in a WDM mesh network.

6. Other considerations

Optical power must be constantly monitored at the reconfigurable WDM nodes to avoid transmission errors. In particular, at the moment of reconfiguration, gain transients may occur due to the adding and dropping of channels in the WDM link, which can cause transmission errors in the surviving channels. This effect may be mitigated with the use of particular fibre amplifiers such as praseodymium-doped fluoride fiber amplifiers [17].

While most ROADM devices are implemented by using switching-based architectures (e.g. MEMs), there are also tuning-based architectures. When a tuning-based ROADM changes the dropped wavelength by tuning from one wavelength to another, it is not allowed to cross a working wavelength

because it interferes with it. In this case, the global control plane that assigns the wavelengths of the RON will have an additional *tuning constraint*. Dynamic set-up of lightpaths with this constraint has been investigated in [18] for ring networks.

7. Experimental test-bed

A reconfigurable optical ring network with WSS-based ROADMs has been built in order to characterize the power budget in this kind of deployment and to measure the cross-talk performance [16]. A simple software to control the WSSs has also been implemented, which corresponds to a first version of the control plane. It is intended to deploy a prototype of the AAPN [19] on top of an expanded version of this reconfigurable optical network with a more complete control plane.

8. Discussion and conclusions

In the deployment of an AAPN that reconfigures in the order of nanoseconds, the first possibility would be the assignment of a set of whole fibre links to it but the cost of this is prohibitive. Instead, such a network may be deployed on top of a “slowly” reconfigurable WDM network, with the reconfigurable devices laying out the topology of the fast network by dynamically establishing end-to-end lightpaths between the edge nodes. In this model, users with high demands would be provided with whole lightpaths at the RON level; while fast-changing, low-capacity flows typical of metro/access networks are serviced by the AAPN. Sharing resources with emphasis in separating high-capacity from low-capacity flows improves efficiency and link utilization overall in the RON without having to implement the complexities of TDM over the whole WDM network.

The advantages of such a deployment are:

- we may change the topological dimensions of the AAPN dynamically
- it is possible to change the location of the core node to adapt to traffic demands or if it improves the performance of the global RON network
- significant savings in power consumption are achieved since a large number of o-e-o conversions are avoided
- we may have a different set of edge nodes served at different times
- survivability provision at the wavelength level can be left to the RON
- many WXC and ROADMs in the market

already have their corresponding software to manage wavelengths, on-site or remotely, which can be used to build the global control plane

- the costs of operation are greatly reduced by automating the wavelength assignment

While the AAPN architecture assumes no WC, it appears that all-optical WC will be necessary to make more efficient use of the WDM network, especially when the node-degree is small. Wavelength routing is an NP complete problem in mesh networks but studies using linear programming and/or heuristics conclude that partial equipping with WCs is as good (and consequently cheaper) as full equipping; i.e., a few WCs will suffice. The availability of WCs should not be a limitation in the long term since all-optical WC technology is maturing quickly.

While routing in a star network may not result in the shortest possible path, the variations/increases in transmission delays are insignificant in metro-access scenarios. Moreover, the principles of this deployment are not restricted to a star network and many concepts can be applied to any topology. The fast TDM scheduling and synchronization techniques are more complex to be implemented in a mesh network, but most of the advantages of deploying an all-photonics network on top of the RON are still applicable.

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