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Wavelength Router as a Transport Platform for IP

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1. Introduction

Wavelength routing [1, 2] has recently seen a remarkable upsurge in interest as a potential transport technology for IP traffic since the traffic demand of the Internet and other data services is growing exponentially . This is happening in parallel to the shift away from circuit switched transport network architectures towards the Internet Protocol (IP) based architectures. Sonet / Synchronous Digital Hierarchy (SDH) was the dominant transport technology since late 1980's. Today, the the role of optical networking is becoming dominating due to it's good match to the Internet Protocol. Due to the growth of traffic, primarily data traffic and the Internet, the networks started becoming exhausted in mid 1990's. Wavelength Division Multiplexing (WDM) [5] offers a great solution for solving the fiber exhaustion. An important development was the Erbium Doped Fiber amplifiers (EDFA's) that matured to make it possible to transmit initially 16 and today up to 200 wavelength signals simultaneously in one fiber over 600 km without requiring electrical regeneration. This has resulted in very big increase in the efficiency of transport and the simplification of the long distance network because a very large number of regenerators could be eliminated. Another advantage of EDFA's is that they are transparent to both bit rate and format and thus the systems can be upgraded to higher bitrates just by changing the transmitter/receivers (transponders) at both ends.

These systems are, however, point to point systems that need to be terminated at an electrical node that will typically be an IP-router in future networks. WDM technology can carry over 100 signals at 2.5 or 10 Gb/s.When these signals are terminated at an electrical node a very high switching capacity is needed. In many cases most of the traffic is transit traffic so it would be unnecessary to convert this to an electrical form. Optical technology can provide an elegant solution to this problem by providing a possibility of optical bypass for the transit traffic by dropping the fractional traffic that is needed at a particular point. This can be done by using optical add/drop multiplexers (OADM) that are currently available in the market. However, OADM's have severe scalability limitations when networks become larger. For larger networks with multiple OADM rings, very large optical cross-connects or electrical cross-connects are needed for ring interconnection. The technology for bit rate transparent optical cross-connects with sufficient capacity is not mature yet and the electrical cross-connects that are available impose limitations to bitrate transparency and to the scalability of the network.

An elegant solution that provides sufficient bandwidth utilizes an optically transparent Wavelength Router. This is a device that consists of an all-optical switching core and interfaces. The idea of the wavelength router is similar to the IP router but the switching is done in the optical domain. Protocols from the IP and ATM world can be used to control the device. Networks could be built in a flexible way by adding new nodes while the control protocols dynamically configure the system. From the technology point of view, it is important to note that the switching core does not need to be very large since routing enables connectivity in the network despite the use of a blocking switch. This makes it possible to build architectures where the switch can be upgraded according to the traffic requirements. This is essential from the viewpoint of network migrations strategies towards IP and of cost.

The purpose of this paper is to discuss the use of wavelength router in a metropolitan network, though the discussion would apply as well to a GPRS access network. The operation of the wavelength-routed network is first discussed. Optical protection schemes are then introduced. The important part of the paper is traffic analysis of a full optical mesh network.

2. Wavelength router in the network

2.1 Network architecture

An optically transparent wavelength routed metropolitan area network is depicted in Fig. 1. The client nodes are connected to their peer nodes by a signal at a wavelength between the Wavelength Routers (WR). The conversion of the client signal to a wavelength would be normally done at the WR-node but it could also be done at the client node. This would avoid the use of one transmitter / receiver pair but, since client nodes of many types are used, would impose strict control requirements to the wavelength to avoid shift to a wrong wavelength and resulting crosstalk.

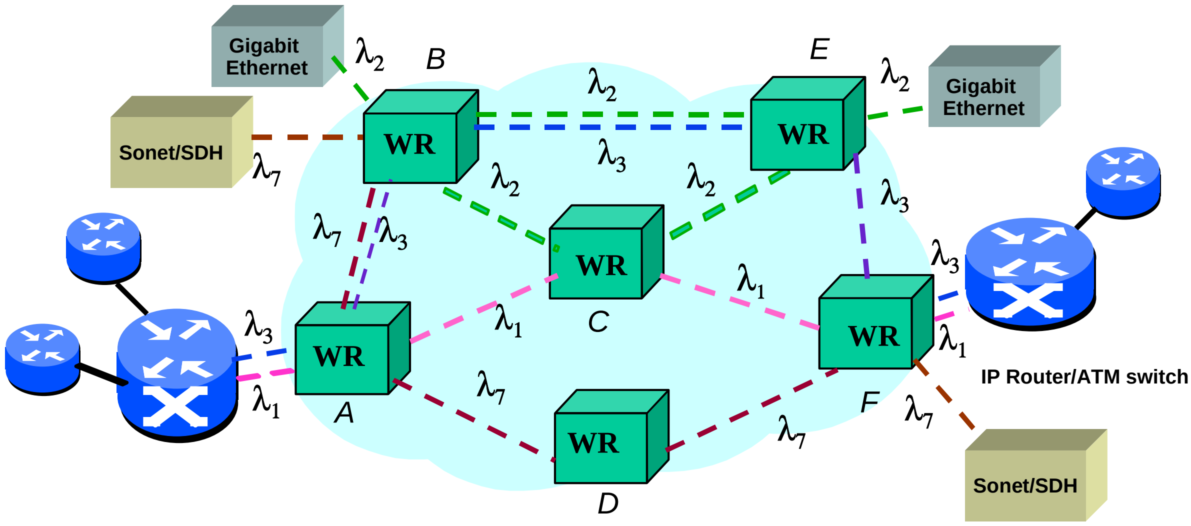

Fig. 1. Wavelength routing network consisting of Wavelength routers (WR) and a set of client nodes peers. The client nodes are connected with wavelength paths between the wavelength routers. The client nodes are typically connected to the WR-nodes with short distance non-wavelength interfaces. The interface card at the WR-node converts the signal to a wavelength to be transmitted over the network to the peer client node. In the figure, the wavelengths start from the client nodes for purpose of clearly indicating the paths between the client nodes.

As shown in the figure many different types of client nodes can be connected each with their own bitrate since, within the wavelength routed network, only pure optical signals are handled. In case of conversion to a wavelength is done at the WR-node, a separate interface for each of the different data formats and bitrates is needed. However, within the network the signals are optically routed and if e.g. the bitrate of the signal is changed, only the interface cards at the network edges need to be changed. Today most of the metropolitan transmission equipment is based on Sonet/SDH or ATM. These nodes can be connected using some wavelengths, e.g. λ_7 connecting the Sonet/SDH nodes in Fig. 1. As there will be more IP traffic at the new IP-routers it will be possible to use additional wavelengths, e.g. two interfaces of the IP-routers are connected by wavelengths λ_1 and λ_3 in Fig. 1. Increasing transfer rates from, e.g., 2.5 Gb/s to 10 Gb/s is done by just changing the interface cards at the connection points. This means that expansion and upgrade are flexible allowing a smooth migration from present legacy architectures to future IP- based network architectures without changing all the nodes in the network.

In summary, the major advantages of of the wavelength routed network are:

- Very high capacity and flexibility of capacity increase without the high first cost experienced with as provided by the optically switched Wavelength Division Multiplexing (WDM) technology.
- Smooth, future proof, migration path from present transport networks to future data centric networks due to flexibility to various data formats and bit rates.
- Savings of capacity in the IP layer due to optical bypassing and fast optical layer protection that can be made at low cost and saves interface capacity in IP domain.

Although very long distances have been achieved even without electrical regeneration, the diameter of wavelength routed network is easy to build up to about 100 km. This allows the use of low cost WDM lasers, standard optical amplifiers and other components. Thus, wavelength router would be practical for metropolitan area networks. The major advantage that can be achieved then is optical transparency, which provides a very flexible way of migrating the metropolitan area network using legacy PDH or Sonet/SDH equipment towards IP networks.

Node structure for a wavelength router is depicted in Fig. 2. Typically there are a few input and output fibers (directions of the fiber routes) to a switching node in the network. When high capacities are required each of the fibers carries several wavelengths. The wavelength router switches the wavelengths to output fibers as determined by the control protocol. WDM MUX and DEMUX components are needed to extract the wavelengths from incoming fibers and to combine signals to the outgoing fibers. In this architecture there is a potential for contention because there might be two signals carried at the same wavelength that would need to be directed to the same output fiber. The problem could be avoided by coverting one signal to another wavelength. However, bitrate transparent wavelength conversion over wide wavelength range is not mature yet and would be very expensive. In the wavelength router, the contention problem can, however, be solved by routing the signal via another path and thus wavelength conversion is not necessary. There is, naturally loss of capacity with this method but since today there are a large number of wavelengths available this is not foreseen to be a big problem in metropolitan area networks.

The node architecture without the interfaces and protection mechanisms is shown in Fig.3. The node consists of standard WDM MUX and DEMUX components to extract and combine the wavelength signals to optical fibers. The switching is the accomplished with some of the optical switching technologies, like thermo-optical switches or MEMS components. The big difference in the wavelength router is that, depending on the architecture, the size of the switch/switches does not have to be very big. Also, while the traffic volume is still small, only part of the switching capacity need to be installed. Then, when traffic volume grows, switch capacity can be upgraded to meet the need; i.e. the networks can be scaled as the needs grow. This stands in contrast to the optical cross-connect where a very large and expensive optical switch needs to be installed on day one. A drawback in this kind of architecture is that blocking occurs at the switch level and that the full capacity of all the wavelengths cannot be used. However, since the number of total available wavelengths is very high, up to 100..200, and there is no cost associated to a wavelength not being in use in a particular fiber. In a metropolitan area network this would not be a major issue .

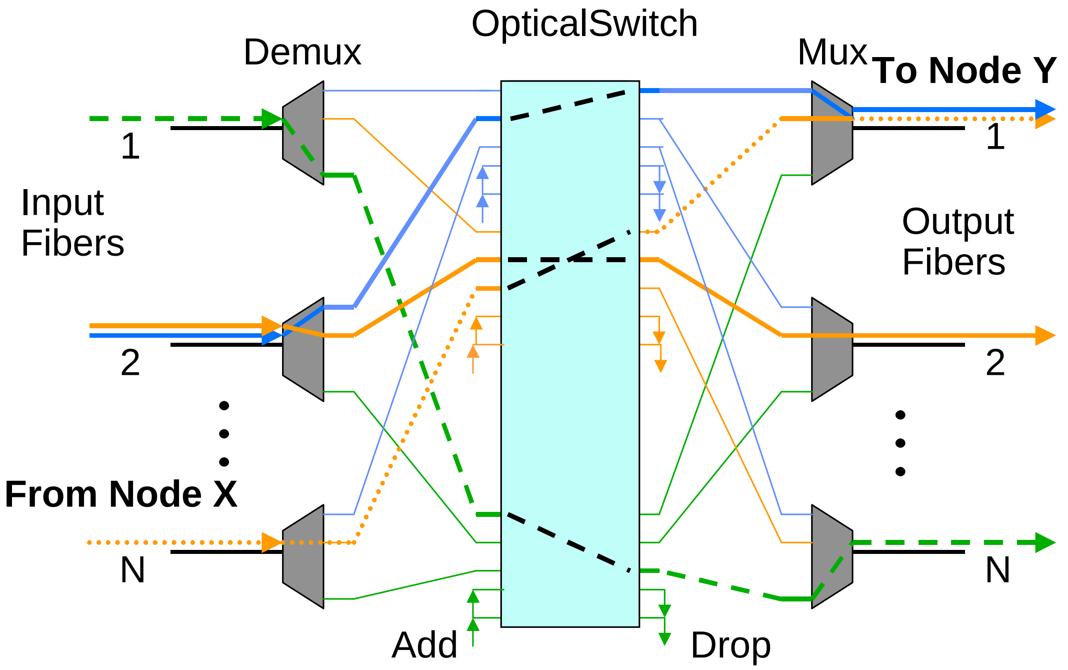

Fig. 2. Optical Wavelength Router node description. E.g. The dashed wavelength from input fiber 1 is routed to the output fiber N. Typical number of fibers ('links") could be 4..16 including the local add/drop ports. Additional to the figure Interface boards with transmitter/receiver, optical amplifiers and a control system need to be installed.

2.2 Wavelength Router network control

The basic task for the control is as follows (see [4] for discussion on the control architectures):

- Path set-up (Route Resolution)
- Route Restoration
- Failure detection/location

For practical implementations, it might make sense to have a decentralized network topology database for fault tolerance and a centralized provisioning interface that could be remotely accessible. The control of the network can be implemented using dynamic protocols already deployed in ATM networks, such as PNNI, and in IP networks, such as OSPF and LDP. It is likely that the lightpaths once provisioned would remain pinned for a considerable time because in many cases there is a need to set up an interface card when provisioning a new service. Therefore, it is also possible that semi-static algorithms could also be used for lightpath resolution.

The light-path routing protocols and other control and signaling protocols could be run in a separate system that was separated from the optical switches themselves. In this case, a single network route provisioning system could control the lightpath connection state of one or more optical switches remotely. This remote control would be effected by use of a switch control protocol such as the General Switch Management Protocol (GSMPv3)[6]. Work is currently underway on GSMPv3 to enable remote manipulation of an optical switch's wavelength resources [7].

When a new path is needed, the control protocols discover the primary path and in most cases a secondary (protection) path through the network. Naturally, to make the control flexible and reduce cost, a wavelength programmable laser is essential in the transmitter. This will also dramatically reduce the need for spare interface boards.

2.3 Optical layer protection

Fig. 3. shows the protection in the for the Wavelength Router. The common 1+1 and 1:1 schemes are depicted. The 1:1 protection scheme could also be expanded to a 1:N scheme where one light-path works as a protection path for several working paths. The important distinction between these schemes is the need of IP (or other client) layer resources. 1+1 protection provides a very simple and efficient protection method without requiring extra resources in the IP layer. The optical signal from the laser is split into two signals that traverse two independent paths to the destination node. At the destination node, a better signal is selected by an optical switch. E.g., if fiber in the working path is cut the switch automatically selects the protection path. The operation is straightforward and very fast (typically 1 ms range) since it does not depend on any signaling between the nodes. The implementation is also very cost effective.

However, the 1+1 protection uses a wavelength resource on a fiber, and therefore the 1:N control schemes familiar from the Sonet / SDH have been proposed and are in use. However, these schemes require the use of another interface board on the router, and require a complex signaling scheme that slows down the protection timing to tens of milliseconds range. Slower then 50 ms protection time is acceptable for Sonet / SDH but this would increase latency in the IP layer. In the abundance of possible wavelengths, the loss of some capacity is not so critical especially in optical mesh networks that can be realized by the wavelength router. The biggest concern is the additional capacity needed at the IP layer. Thus to the authors view, 1+1 protection is far superior especially in wavelength routed optical mesh networks.

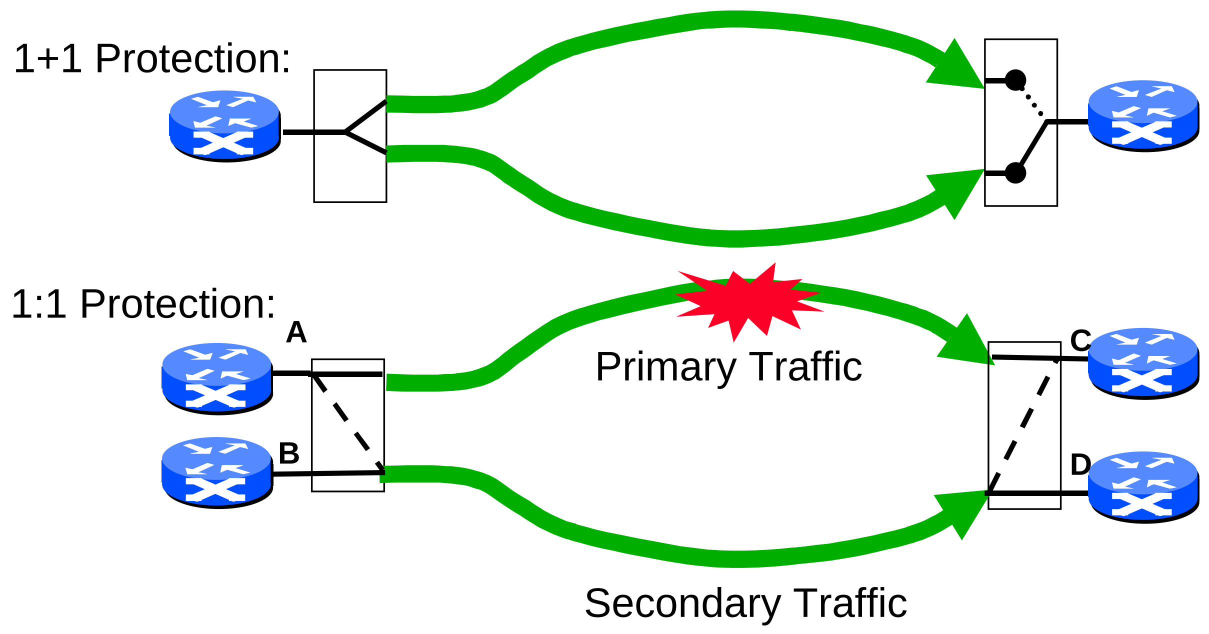

Fig. 3. Protection principles in the optical layer. In a wavelength router, the protection is put between two end nodes of the light-path. Thus, both the primary and protection signal can traverse several Wavelength router nodes.

3. Traffic analysis

For the analysis, the network architecture in Fig. 1. is used, assuming IP routers as clients. Wavelength routing also allows simultaneous connection of any other client layers such as Sonet / SDH, ATM, Gigabit Ethernet etc. in addition of the IP Core Routers shown in Fig. 1. For the IP networking case, an IP Core Routers needs to be attached to the Wavelength Routers. IP Access Routers are then connected to the core router. The reason for this is that the granularity at the optical layer is very coarse (typically 2.5 or 10 Gb/s) and to achieve full connectivity to all the access routers a core router is needed for aggregation. Otherwise, the number of wavelengths connecting the Wavelengths routers would need to match the number of all combinations down to access routers. With increasing number of nodes, the number of wavelengths becomes impractical even in networks consisting of 20-50 Wavelength Routers.

A regular topology of a full mesh network was used to analyze the efficiency of the network. Assumption was made that there would be an IP router for traffic grooming connected to each of the Wavelength Router network nodes. We studied primarily the number of wavelengths needed to interconnect the nodes (*W*), the number of hops between IP Routers (*h*) that would be made in the optical domain before the traffic needs to be terminated in the IP routers. For a network topology in which each node is connected on average to 3 other nodes, the relationship between *h* and the number of nodes (*N*) is approximately as follows:

$$h = \sqrt{0.4N} \tag{1}$$

Based on this approximation the average amount of wavelengths needed on link between two optical nodes is

$$W = \tfrac{1}{3}(N-1)\sqrt{0.4N} \approx 0.2N^{1.5} \tag{2}$$

The results are shown in Table 1. Here relative IP router traffic = IP router traffic in a network with wavelength routing divided by the IP router traffic without wavelength routing = 2/(1+h). A typical wavelength routed network would comprise of 20 nodes connected with a direct link to three other nodes. Each link carries a minimum of 18 wavelengths or 36 in case of 1+1 protection (in practice more due to non-ideal use of wavelengths and unavailability of wavelength conversion). IP traffic would bypass two IP routers and thus savings in the IP layer capacity would be 50 %.

Table 1. Wavelength routing network dimensioning

Number of Optical nodes (N)	Average number of hops between IP-Routers (h)	Average number of wavelengths per link (W)	Relative IP Router traffic, %
5	1.4	1.9	83
10	2.0	6.0	67
20	2.8	17.9	52
50	4.5	73.0	37
100	6.3	208.7	27

The operator needs to plan, or dimension the network based on some information about the traffic demand (for more elaborate review of IP network planning see [3]). Although this dimensioning task is extremely complex and no exact solution is available, we may make simple approximations about the needed capacity (C) as function of average traffic demand (A):

$$C = A \cdot \left(1 + (A_0/A)^{\beta}\right) \tag{3}$$

where A_0 defines the bit rate with which the allowed load level is 0.5 and β defines the effect of statistical multiplexing. Although 0.5 may theoretically be an apparent selection for β, it gives somewhat unrealistic results. Thus, all results presented in this document are based on the following choices: A_0 = 2 Gbps and β = 0.25. Further, the state of art in optical technology strongly favors a granularity of 2.5 Gbps. Therefore, in the following calculation, the final capacity for any traffic aggregate is rounded to the next larger multiple of 2.5 Gbps.

When formula (3) is used, the main task is to estimate the average traffic demand. If we make the assumption that the network is dimensioned based on the average busy hour traffic, then the evident parameter to be determined is the average traffic generated by a customer over that period. Although 5 kbps may seem to be small value for average traffic per customer, it means 2.25 Mbytes for every customer during one hour. Then if we assume that 15% of customers are active during the busy hour, the average traffic sent by an active customer is 15 Mbytes. This value actually appears quite large if the typical access rate is at most 64 kbps.

However, Internet traffic is growing exponentially, and what is now a reasonable estimation, could be a serious underestimation after a couple of years. Therefore, the following calculations are made also with an average traffic of 50 kbps and 500 kbps. These scenarios are possible if a majority of customers has a high-speed access with peak rate of 1 Mbps or higher. For illustration, 500 kbps corresponds to 1 million people with a continuos average access rate of 0.5 Mbps; or equivalently to 100 million users, the present amount of users in the Internet, at 5 kbps, all in *one* network.
Figure 4 illustrates the relationship between the number of optical nodes and the router interface capacity including interfaces to access routers (it is supposed that there are 1 million users and 100 access routers in total). With a full mesh, there is a point in which the capacity requirement of one router is minimized. With moderate traffic demand that minimum can be reached perhaps with 5 nodes, with high demand the minimum is around 10 nodes, and with extremely high demand it might be even 20 nodes. However, we must notice that this optimization concerns individual nodes, while the total capacity of all router interfaces in the network appears to increase practically always with the number of nodes when the total traffic demand is kept constant.

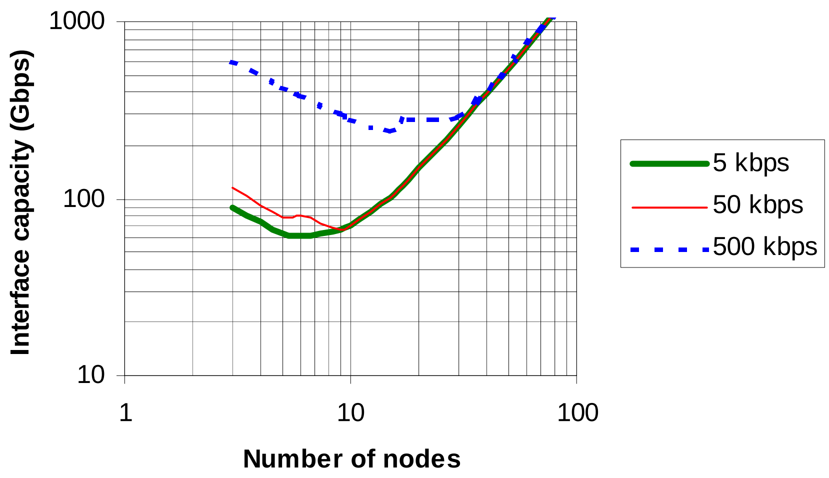

Fig 4. Total interface capacity of one router as a function of the number of core nodes. 5, 50 and 500 kbps = average traffic generated by one user, 1 000 000 users.

4. Summary and conclusions

Wavelength routing provides a very efficient mesh connectivity of the underlying electrical nodes and provides the transport functionality needed by IP layer routers without the need for intermediate ATM or Sonet / SDH layers. Our analysis indicates that the practical number of nodes in the optical domain is 10-30 to support full mesh connectivity with a practical number of wavelengths (<100 also in the protected case).

The main advantage of wavelength routing mesh network is very high capacity. This allows relatively low network utilization and thus congestion in the IP layer can be avoided in a straightforward way. Capacity savings in the IP domain are more than 50 % with 20 optical nodes due to optical bypassing. Furthermore, even in networks comprising of 20 nodes, 3 IP hops are in the optical domain which, when combined with fast optical layer protection (millisecond range), significantly improves the latency in the IP domain. The very high capacity and fast protection of the wavelength routed optical mesh network provide an ideal way of providing high quality of service (QoS) in the IP layer.

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