

Optical Packet Switching Technology

Shivani Massey¹, Kamal Kuma Sharma²
 M.Tech Scholar, ECE, LPU, Punjab, India¹
 Professor, Deptt. of ECE, LPU, Punjab, India²

ABSTRACT:

The

telecommunication networks are experiencing a dramatic increase in demand for capacity, much of it related to the exponential take up of the Internet and associated services. To support this demand economically, transport networks are evolving to provide a reconfigurable optical layer which, with optical cross-connects, will realise a high bandwidth flexible core. As well as providing large capacity this new layer will be required to support new services, therefore, will provide a circuit switched optical layer characterised by high capacity and fast circuit provisioning. This paper considers possible network application scenarios for optical packet switching. In particular it focuses

on the concept of an optical packet router as an edge network device, functioning as an interface between the electronic and optical domains. In this application it can provide a scalable and efficient IP traffic aggregator that may provide greater flexibility and efficiency than an electronic Terabit router with reduced cost. The discussion considers the main technical issues relating to the concept and its implementation.

Key Terms: *Optical communications, optical packet switching, optical links.*

1. BRIEF INTRODUCTION

The rapidly increasing bandwidth demand, driven by the Internet, has led to a paradigm shift in the telecommunications industry from voice-optimised to IP-centric networks. In this scenario, the role of SDH/SONET will diminish and the optical transport network will directly provide a global transport infrastructure for legacy and new IP services. The utilisation of optical networking employing dense wavelength division multiplexing (DWDM) in conjunction with optical cross-

connects (OXC), presents many new opportunities for supporting faster and more flexible provision of legacy and IP services. A major driver for realizing this evolution is the potential ability of such networks to provide fast automatic set-up and tear-

down of paths across the optical network, with the capability of supporting diverse client signals

on the paths. The main focus, therefore, of today's optical network planning lies in implementing a dynamically acceptable,

reconfigurable optical transport layer based on fast OXC coupled with a suitable control and management architecture. Thus in the near future an optical transport network (OTN) will be realised capable of supporting large numbers of high capacity optical channels, with bit rates in the order of 10-40 Gb/s. This model of the network is illustrated in Figure

1. The diagram presents a possible OTN structure, which comprises the interconnection of a number of OXC in a mesh topology. As each interconnecting fibre may support many wavelengths (eg >100) and there may be many fibres (eg 32), the OXC require the capability to support the cross-connection of many thousands of wavelength channels. This optical transport network, therefore, will provide wavelength paths to clients such as IP routers, SONET/SDH network elements, ATM switches etc, and Figure 1 illustrates the network might interconnect two IP routers.

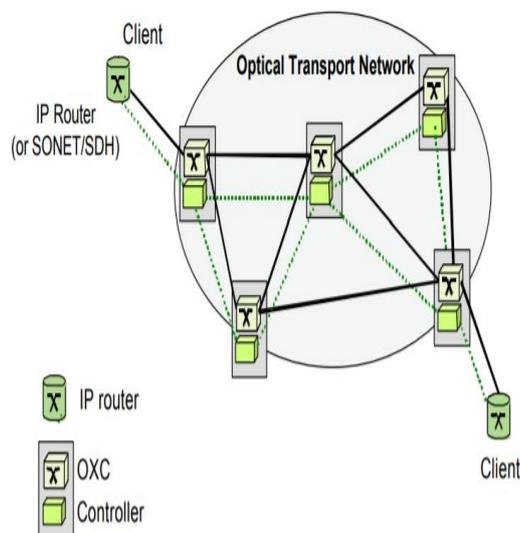


Figure 1: Optical transport network (OTN)

A signalling channel between nodes ensures that each OXC has knowledge of the network resource status, paths available etc. Current research focuses on the use of distributed management schemes such as multi-protocol label switching (MPLS) to provide the control plane necessary to ensure fast path set-up. In this type of application the label is the wavelength of the incoming signal and hence the term multi-protocol lambda switching is more commonly used. This dynamically reconfigurable optical transport network, therefore, will enable the fast allocation of high capacity paths to link clients. Also the pace of development is such that the technology (of transmission and switching) will support huge numbers of optical channels (wavelengths). It might seem therefore that in this future network bandwidth is not an issue and optical circuit switching (the technique we have been discussing) will meet all future requirements. However this is not the case for a number of reasons. The optical transport network, for example, offers granularity only at the wavelength level to the clients. Thus if the traffic source is bursty the channel capacity may be underused and this will have an impact

on the dimensioning of the network and the size of the OXCs. This argument is particularly strong as the network moves to become data rather than voice-centric. Economics will always demand that the network resources are used efficiently. A major advantage of electronic packet switching is its bandwidth efficiency and ability to support diverse services, hence research is now focusing

on bringing the packet switching concept into the optical domain, that is optical packet switching (OPS). In this article the use of OPS in the future network is discussed. First a general look at its application areas is considered, however it is believed that the first application will be as an edge router interfacing the electronic IP domain and the OTN. In the succeeding sections the technical and implementation issues relating to this concept are discussed.

2. OPTICAL PACKET SWITCHING

Research into optical packet switching has been conducted over a number of years. Pure optical packet switching in which packet header recognition and control are achieved in an all-optical manner is still many years away. For medium term network scenarios, optical packet switching using electronic control and header processing is more realistic; indeed it is not clear what major advantages the all-optical approach has to offer over this opto-electronic approach. This article focuses

on the approach in which the optical packet comprises an optical label (often realised using sub-carrier modulation techniques) attached to a payload, which may be of fixed or variable duration (other approaches such as burst or flow switching are not considered here). The client signal, such as IP packets, forms the payload, and the optical packet entity is routed through the network. Within an optical packet switch (OPS) the packet header or label is read and compared with a look-up table. The payload is then routed to the appropriate output port with a new label attached (label swapping). An important feature is that the payload is transparently routed through the switch, i.e. stays within the

optical domain, but the label processing and switch control are electronic. Some of these issues are to be discussed in more detail.

3. APPLICATIONS

The attractive feature of OPS is that it can appear as a natural evolution of the OTN. In particular the OXCs developed for the OTN can support an optical packet switch network layer. Figure 2 illustrates a network comprising OXC and OPS elements. As shown in the diagram resources can be used in a number of ways. For example some optical channels (wavelength paths) may interconnect high capacity points which will fully utilise channel capacity, such as SDH rings. Other channels might be used to support optical packet transmission for efficient use of bandwidth, either to optimise resource utilisation within the network or, for example, to support an end-to-

end point and click provisioning service where granularity may be an issue. Figure 2 therefore illustrates two key OPS application scenarios. One is the application as a core switch. Packets travelling through the network undergo switching at core nodes where ongoing route selection and label swapping take place. In this mode OPS maximises utilisation of the network resources, minimising the total network capacity required, reducing the size of the OXCs. The second application, the main source of discussion in this article, is that of an edge router interfacing the electronic IP domain to the OTN. This is illustrated in Figure 2 which shows the packet switch positioned as an edge router interfacing to both the OTN and IP domains. In this application the OPS provides a number of key functions required of the future OTN, as highlighted below.

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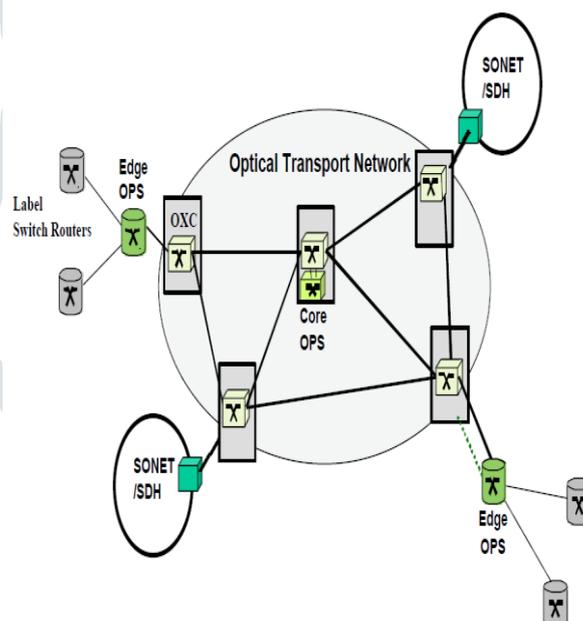


Figure 2: Applications of OPS as core and edge routers

3.a Control Planes

As discussed above, the first generation of OXCs will not perform packet level processing. The entire traffic

on any optical channel at an input port in an OXC is switched to an output port, thus the optical channel supports continuous data. IP traffic, however, cannot be constructed as continuous data-streams and therefore there is a pressing requirement to develop the framework for a data/IP aware optical transport. At present Data/IP services are provided through networks that may include three or four different electronic multiplexing and switching layers (e.g. IP,

frame relay, ATM, SONET). The multiplicity of layers produces inefficiencies, add to the latencies of connections and inhibits the provisioning of quality of service assurances. Worse, the layers are largely unaware of each other, causing duplication of transport protocols and management tasks. The first step towards optical data networking is the implementation of a network control plane, based on distributed label switched management principles such as the Multi-

protocol Label Switching (MPLS) control model, and associated with the OXC. The functions of this control plane will be initially to establish and maintain optical paths within the network and in the long term to determine, distribute, and maintain state information associated with the optical transport network (OTN). This control plane will also be responsible for updating the information in the local switch controller (Figure 1).

1). As a result, the OXCs within the OTN will switch optical channels, in similar way as Label Switching Routers (LSRs) switch packets in an electronic IP network. LSRs perform packet level operations using information carried

on the labels attached to the data packets, while with OXCs the switching information is inferred from the wavelength (MPIS) or the optical channel overhead. In networking systems involving a number of data clients and OXCs, MPLS can provide a uniform control plane strategy in order to reduce the complexity of managing dissimilar networking systems. In these future network scenarios the question of where the boundary between the service and transport layer lies is still unanswered, but there is clearly a need to maintain topology and control isolation as well as to create an efficient interface between the optical transport and the service layers. There are many reasons to separate network topologies and control, whether it is physical or logical for the OTN and the service layer. Some of the reasons are due to a number of important differences between electronic data routers and optical wavelength routers that necessitate special features to be implemented in the control plane. The first difference would be the bandwidth granularity, which is much coarser for an OXC than that for an IP router (wavelengths rather than packets). Because of the high bandwidth nature of an optical connection, one would expect them to persist for a much longer duration and involve relatively infrequent connection requests when compared to per packet routing operations. A further specific requirement for the control plane will be to maintain OTN infrastructure information in order to facilitate path selection for optical channels. Information will include fibre characteristics, amplifier positions and signal evaluation data. This information can be collected through optical supervisory channels and optical channel overhead processing and can be actively used for setting up optical paths and fault localisation. The most important reason, perhaps, for isolating the two layers is that they are likely to be under different administrative controls (or ownership) and policies. Under such circumstances the service provider who owns the OTN will wish to maintain full control of the network. Such an operator would not wish to give a client insight into the structure of the OTN layer as this is his business value. Although the service provider does not wish to give the client knowledge of the OTN, there are client services that depend on having a view of the internal structure of the OTN. Three examples are suggested.

The first involves connections diversely routed for provisioning and restoration purposes. The second involves a connection required at a future time, while the third involves being able to know which nodes can be reached via the OTN. Thus, network management features are required that allow limited internal OTN information to be accessed or manipulated by the client service layer in a manner that does not compromise the security of the operators network. Currently there are no router solutions that can satisfy all the above points and fit in a realistic future network solution able to carry efficiently a mixture of circuit switched and packet switched traffic into the OTN.

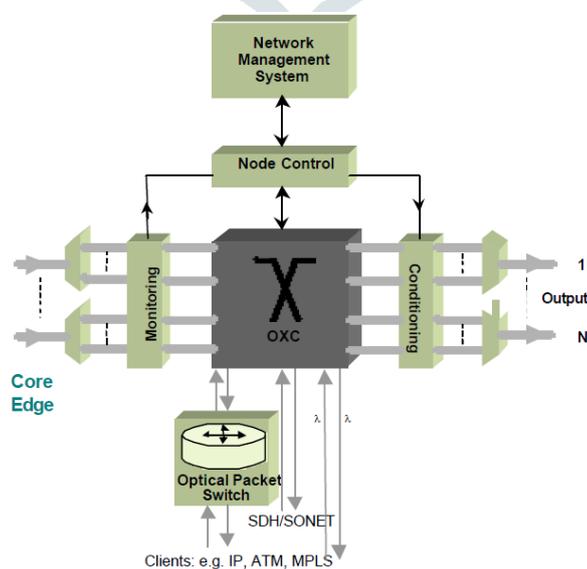


Figure 3: Interfacing of OPS with OXC

The OPS is positioned in the add-drop ports of the OXC and accesses wavelength channels dedicated to packet switching. The external electronic routers and the OPS will handle the same granularity (per packet basis), which will lead to an integrated control plane between the IP and the OPS domains. At the same time, the OPS will maintain information

on the configuration, the physical infrastructure, the topology and scale of the OXC transport. Therefore, the proposed OPS will be able to isolate the OTN from the service layer while interfacing fully with both layers:

a) with the Data/IP domain through integrated management control, and

b) with the OTN by maintaining information

on the configuration, the physical infrastructure, the topology and scale of the OXC transport. An additional benefit of the OPS will be due to the increased granularity over pure DWDM networks, which permits more efficient use to be made of the core network. One of the main disadvantages of an OTN is that there is currently no mechanism to provide direct access to the OTN with bandwidth granularity that is finer than a whole wavelength. Providing this finer granularity is central to creating a network that is efficient, from the perspective of the operator, and cost effective, for the operator's customer. A schematic diagram of the OPS functionality as an edge aggregator/router is presented in Figure

4. Here the OPS will provide an aggregation mechanism in the external OTN nodes that can accept packet type transport (i.e. IP and ATM) from a number of sources and map onto optical packets. These optical packets will be of variable length, which will be an integral multiple of a chosen time unit. The aggregating nodes will then map the optical packets onto appropriate wavelengths for transport over the OTN to deaggregating nodes that can either be egress points from the network or intermediary nodes that further map the optical packets onto new wavelength paths. During this process, the OPS will run a protocol capable of discovering the OXC network topology, and thus will be able to combine aggregation with QoS provisioning within the OTN.

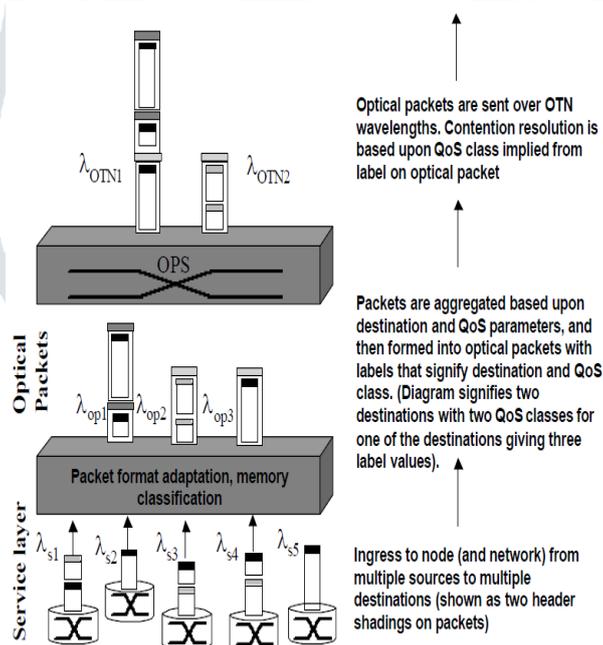


Figure 4: OPS functionality as edge aggregator/router

The optical router proposed here will provide a more scalable and efficient IP traffic aggregator compared with similar electronic Terabit router solutions. Furthermore, it will take full advantage of the capacity, scalability and functionality provided by the optical layer, a function that cannot be provided by an electronic router solution.

4. REALISATION ISSUES

The optical packet router will switch and buffer entities which may comprise multiple or single datagrams, or indeed only a part of one. To find the overall optimum packet transport solution for the optical edge aggregator, a number of issues need consideration, as described below.

4. A. The Optical Packet

In order to reduce the number of entities that the switch must process per unit time, single or multiple packets with the same destination and quality of service (QoS) class may be grouped together forming an optical packet at the edge of the network. The optical packet will be of variable length, which will be integral multiple of a unit length. While this reduces the complexity of the packet switches, it increases the complexity of the interface at the edge of the network, in fact the complexity of forming the optical packet is comparable to implementing some of the functions of an IP router. Great care must be taken when designing a packet scheduling algorithm for this type of switch, to ensure that the algorithm can be implemented in real-

time by electronic control hardware. The optical packet switched network now looks very much more like a burst switched network, the major difference being that control information is still in-band. The implementation of the optical packet can be advantageous for the edge router application, where the optical router will perform and replace some or all of the Terabit router functionality. With this approach, the header must also be read, and the label must be translated electronically, in the usual way. In an MPLS-

based approach such as that considered here, the header translation hardware will search in a table for the label held in the packet header. The entry in the table for that particular label will contain the new label (which must then overwrite the existing label in the header), and the output to which the packet must be forwarded. Label stacking is very difficult to implement in such an optical packet switch since such an operation effectively involves changing the length of the header.

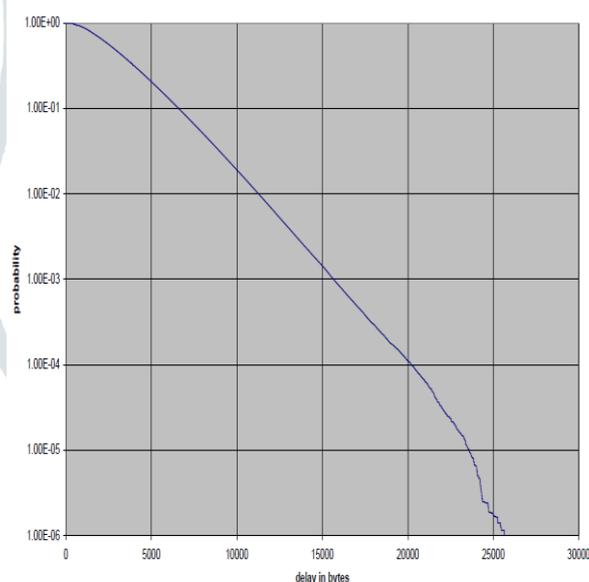


Fig.

5 Probability that a randomly chosen byte will experience a delay greater than the given value in an output-buffered switch, for self-similar traffic, with a mean traffic level of 80%.

4.B. Scheduling and control

Since optical memory is implemented with delay-lines and not RAM, the electronic scheduler for the architecture must direct the packets over the correct delay-

lines to make the architecture perform the same function as one constructed from RAM buffers. The packet scheduling algorithms for the transport solutions discussed above can be implemented using high-speed electronics, and must consider issues such as fairness, implementation of QoS classes, queue stability and queue starvation. The trade-off between electronic and optical buffering must be determined, based upon cost considerations. Initial results demonstrate that using an OPS to interface with electronic routers can produce cost savings in the net

work. Due to the bulkiness and expense of large amounts of delay-line fibre, two techniques may be used to reduce the total length of fibre required - this impacts upon the control algorithm:

1. Multiple packets

on different wavelengths may pass along a specific delay path simultaneously. For example, the total length of fibre delay-line required could be reduced by a factor of 16 by using one delay-line with 16 wavelengths instead of 16 delay lines of equal length; in both cases the same number of wavelength converters are required, ie 16.

2. The total length of fibre delay-

line memory can also be reduced by sharing fibres between different delay paths -

a simple instance of this technique is shown in Figure

6. This principle can be extended

so that a large array of fibre delays can be replaced by multiple delay-

line stages, with a dramatic reduction in the amount of fibre that is required. Packet scheduling algorithms should be amenable to parallel implementation in order to enable implementation

on programmable gate arrays to run in real time. Also, the implementation must scale to large switches such as would be encountered in practice in future.

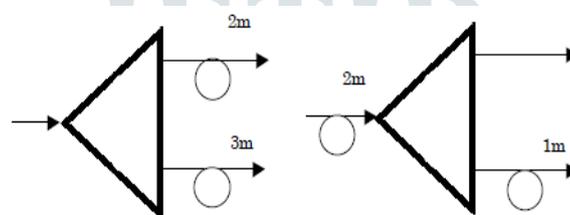


Fig.6 An example of sharing delay-lines.

5. SWITCH IMPLEMENTATION

A generic structure of the proposed packet switch consists of an input processing interface, a switching and buffering block and an output processing module, as illustrated in Figure

6a. The input interface performs delineation (i.e. identification of the packet start and end), packet format adaptation into the optical packet, classification into forward equivalent classes defined for the OTN, and electronic buffering.

The switching and buffering blocks are responsible for the routing of the optical packets to the appropriate output ports and contention resolution respectively, while the output interface is responsible for header reinsertion and per packet conditioning such as wavelength conversion to the appropriate OTN wavelengths, regeneration and power equalisation.

The proposed architecture is based

on a feedback buffering scheme to enable maximum utilisation and sharing of the available buffers. The recirculating buffers used in this architecture offer the ability to support QoS classes via packet pre-emption. Header detection and processing are performed in the electronic domain. Fast optical switching per packet can be performed using a switch matrix based

on semiconductor optical amplifier (SOA) gates or electro-optic technology. However, both technologies are scalable only up to a limited switch dimension and require some form of synchronisation at the input of the switch matrix. An alternative solution that enables fast transparent switching of individual packets enabling asynchronous operation of the switch matrix is based on tunable wavelength converters followed by a wavelength routing device such as an arrayed-waveguide grating (AWG).

In this case, routing of the packets to the required output ports of the switch is performed by controlling the wavelength of the incoming packets through the input wavelength conversion stage and subsequent transmission through the AWG. Optical wavelength conversion is performed through SOA based converters using either cross-gain modulation or cross-phase modulation techniques. Using either of the two schemes, a continuous wave (CW) source is needed

and in the case of tunable wavelength conversion this source is required to be either a fast tunable laser or a switchable laser array. The tuning speed of the converter is then determined by the tuning speed of the CW signal, which can be as fast as a few ns, thus the switching speed will also be in the ns regime.

The overall switch matrix scales with the dimension of the AWG router, which currently can be as high as 128x128. This approach was evaluated in project WASPNET. The concatenation performance of this configuration was evaluated through recirculating loop experiments [9] and Figure

6b shows measured Q factor for both back-to-

back and system (ie AWG and wavelength converter) configurations. The results demonstrate penalty-free operation for up to 25 cascaded nodes.

The buffering functionality is provided through a combination of electronic and optical buffering. The wavelength agility offered using wavelength conversion

on a per packet basis enables statistical multiplexing at the fibre bandwidth capacity level. Tunable wavelength converters may significantly reduce the buffering requirements by appropriately wavelength translating optical packets

so that they can be stored within the same fibre delay line. This not only simplifies the buffering schemes, but also has the advantage of suppressed transfer delay and packet delay variation due to the reduction of the depth of the optical buffers.

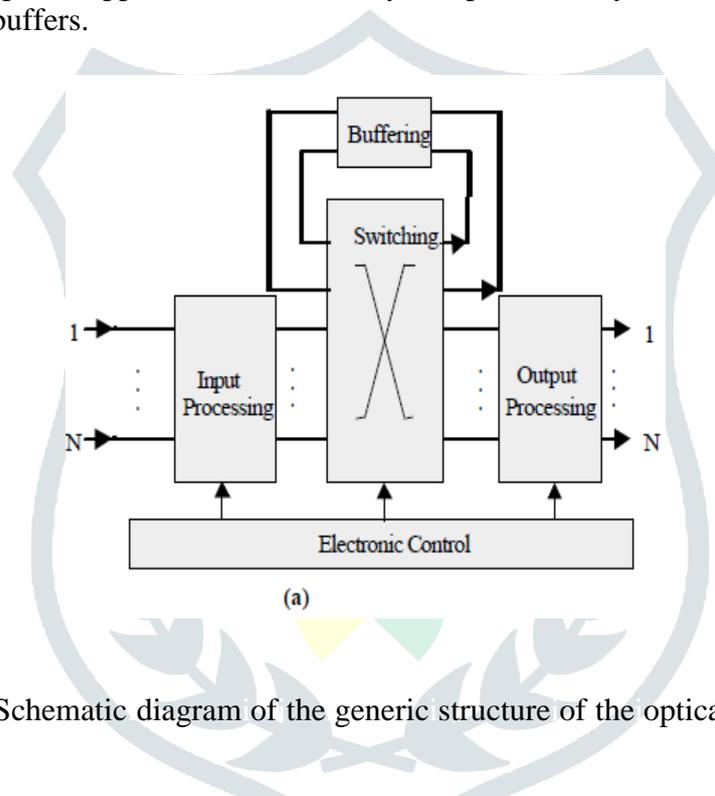
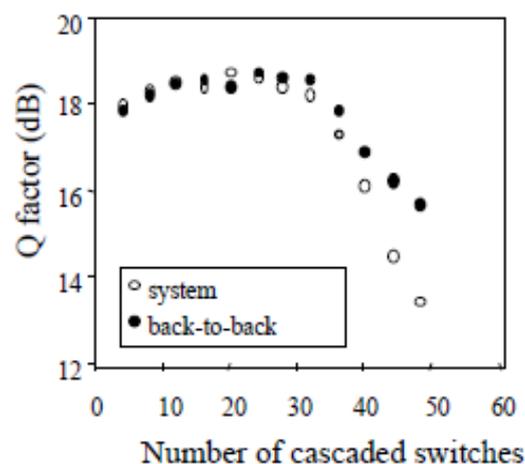


Figure 6(a): Schematic diagram of the generic structure of the optical packet switch,



(b)

Figure 6 (b) Concatenation performance of the wavelength converter and AWG arrangement, back-to-back measurement shown for comparison.

6. SUMMARY AND CONCLUSIONS

This paper presents a novel and efficient solution for a fully data/IP (i.e. IP and ATM) aware optical transport network (OTN). The current proposal is to use an optical packet switching technology (OPS) in order to:

1. Reduce the number of network layers, to simplify network management software and remove associated transport overheads.
2. Offer efficient traffic aggregation and finer service granularity (compared to current wavelength switching technology), thereby improving OTN utilisation.
3. Facilitate dynamic QoS (quality of service)-based provisioning through the OTN.
4. Provide domain isolation between the service and OTN networks.

The proposed OPS router will be a predominately edge network element, and will function as a topological and logical interface between the service and transport layer. The OPS will have the capability to aggregate the traffic from a large number of IP routers and ATM switches at the edge of the network and groom them based on QoS to a number of dedicated wavelengths in the OTN. This edge-OPS device has the potential to replace Terabit routers as a more scalable, efficient and future proof solution in the market place because it has the ability to provide a more scalable and efficient IP traffic aggregator compared with similar electronic router solutions. Furthermore, it will take full advantage of the capacity and functionality provided by the optical layer, a function that cannot be provided by an electronic router solution. Although this article has focused on the application of OPS as an edge router, it is envisaged that core OPS nodes would also be used to ensure appropriate data transport consistent with minimising the size of the OPS nodes. The core packet switch would perform label swapping whilst transparently transferring the data payload.

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