A WAVELENGTH ROUTING APPROACH TO OPTICAL COMMUNICATIONS NETWORKS

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ABSTRACT

A class of wavelength routing optical networks is described based upon the interconnection of wavelength multiplexed channels. Unlike previously described optical network structures, these networks allow the re-use of wavelengths in different transmission sections and this leads to fewer wavelengths being needed. A choice of structures using a common set of components leads to the opportunity to design a network according to the geographical distribution of the switching nodes. The structures provide for a set of point to point interconnections and, with modest numbers of wavelengths, full interconnection between the opto-electronic nodes is possible at the optical level. In bypassing intermediate electronic stages the networks appear to offer good reliability characteristics. Providing the components in an initial network are designed to utilise bandwidth efficiently, the networks could be upgraded to incorporate more channels, optical switching and other forms of optical processing at the optical nodes.

1. INTRODUCTION

The interconnection of switching nodes in today's communication networks is achieved using a combination of electrical and optical stages. The optical sections are used simply to transport signals from one point to another and all other network functions such as switching and multiplexing are performed in the electrical domain. The trend towards new and improved optical components however leads to the possibility of shifting the currently accepted position of the opto-electronic interface and in the future the balance between optical and electrical technologies is likely to change. Electrical switching for example can be well matched to low speed transmission rates but optical switching may find attractive applications at higher levels in the transmission hierarchy. One of the purposes of switching in a network is to raise the traffic carrying efficiency of the transmission links and, over the years, the complexity of switching systems has increased to maintain an economic balance between transmission and switching. However the use of WDM in fiber transmission can raise the traffic capacity of a link far beyond that achievable with TDM alone [1] and if vast increase in transmission capacity is possible, this may allow some relaxation in the complexity of switching. For this to be possible a high degree of interconnectivity is needed between the switching nodes in the network and this paper considers such a situation.

Full interconnection could be provided by means of a fibre mesh network in which a separate fibre path interconnects each node with every other node, but in large networks this would lead to impractically large numbers of point to point transmission systems. In practice, where nodes lie along a linear route, the traffic between them is electrically (TDM) multiplexed to reduce the number of systems and thereby raise the route efficiency. However, although this reduces the number of systems necessary, additional electrical multiplexing/demultiplexing equipment is needed and line transmission rates are increased. Higher transmission rates in turn lead to shorter transmission spans before repeaters become necessary.

In this paper new network topologies are described in which the multiplexing function is performed optically using passive WDM elements. Unlike previously reported structures based on optical power coupler arrays [2], [3], [4], [5] the networks use wavelength selective elements which allow the re-use of wavelengths in different parts leading to fewer wavelengths being required. Wavelength selective elements can also offer lower loss than power coupler arrays and this can be used to raise the number of channels in systems which are power budget limited [6]. The networks make efficient use of fibre and the data rates of individual optical channels are not increased by the multiplexing process. As a result the networks can carry high volumes of data with infrequent repeaters. The structures all offer good potential for upgrading to provide either
additional facilities or increased capacity.

2. STAR STRUCTURE

If a set of switching nodes are to be interconnected by means of WDM systems, the star interconnection pattern shown in Fig. 1 allows a set of identical WDM transmission systems to provide an optical channel between each pair of nodes via a low loss optical path. A total of N(N-1) optical channels are needed for full interconnection. In a "broadband" optical star network based on power coupler arrays the number of wavelengths needed would also be N(N-1). However in this case the network allows the wavelengths to be re-used in different parts so that the minimum number of different wavelengths needed to allow full interconnection of the N nodes is (N-1).

A network of this type can be operated in a variety of ways. For example, in the passive form shown in Fig. 1, the network simply provides a set of high intensity channels linking each pair of nodes and any switching takes place electronically at the nodes. The network can support synchronous or non-synchronous traffic and can operate as a ring with appropriate electronics at the nodes. It can also provide alternative routing to protect for example against the failure of a transmitter or receiver or against traffic overload (Fig. 2). Protection against cable faults is only possible by providing additional fibre or cable routes. Thus a node protected in this way could employ two WDM links for the transmit path and two for the receive. In this case additional wavelengths are needed so that each protection route can be treated as if supplying an additional node.

Because the channels appear in parallel form at the star point access can be made, if needed, to each optical channel (Fig. 3). For example optical amplifiers could be provided at this point to extend the range of the network. As the peak power of optical amplifiers is limited, separate amplifiers for each channel within this parallel array could lead to higher channel launch powers than by using a single amplifier in the multiplexed path leading to or from each terminal node.

A network variant is shown in Fig. 4 where an additional wavelength is inserted into each transmitted wavelength multiplex which feeds into an optical space switch at the star point to give an overlaid circuit switching capability. Such an arrangement could give a network management facility, allowing for example selected channels to be shut down temporarily whilst their traffic is carried via the switch on the reserve wavelength. A protection system could also be developed around this principle. A further variant is shown in Fig. 5 where a switch array and a coupler array are combined to give a switchable broadcasting capability using the additional wavelength.

In principle it should be possible to increase the capacity of the wavelength routing star network by filling each optical channel with a "fine grain" WDM structure [6], as shown in Fig. 6. For this to be possible, the original "coarse grain" channel passband characteristic needs to be sufficiently wide to allow a fine grain multiplex to pass through with minimal amplitude-frequency distortion. In addition, for the fine grain multiplex channels to work over the same distances as the coarse grain channels, some means of enhancing the power budget would be needed. Low loss fine grain multiplexers, higher transmitter powers, increased sensitivity receivers and optical amplifiers can all play a part in achieving this.

3. CHAIN STRUCTURE

Other network architectures can be used to fully interconnect a set of nodes and the chain structure (Fig. 7) is suited to connecting nodes on a linear route. Because the transmission sections overlap additional wavelengths are needed. If there are N nodes then for full interconnection between all nodes the minimum number of wavelengths needed is:

for N even, no. of wavelengths = (N/2)²
for N odd, no. of wavelengths = (N-1)(N+1)/4

In this structure as shown the transmission losses are increased because two multiplexers are introduced into the cascade at each node. However, as in the star structure, optical amplifiers could be used to overcome the path losses.

When the nodes are fully interconnected a similar set of operational features are available as explained for the star network. Synchronous or non-synchronous traffic can be supported and alternative routing can be provided. Additional functionality such as optical switching, amplification and broadcasting can be included at points in the network where the signal appears in "parallel" form between the pairs of multiplexers at each node. In this case the additional components must be distributed among the various nodes principle. A further variant is shown in Fig. 8.
Fig. 1  Wavelength routing star network fully interconnecting 4 nodes using 8 identical WDM systems. The principle can be extended to N nodes using \((N-1)\) wavelengths.

Fig. 2  Alternative routing options in a wavelength routing star network. A direct channel is available between A and B and also two alternatives via C and D. In a larger network more options are possible.

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Fig. 3  Wavelength routing star network with amplification in the parallel array. Wavelength allocation is as shown in Fig. 1.

Fig. 4.  Wavelength routing star network with an overlaid optical switching capability. An additional wavelength in each section links into a space switch.
Fig. 5  Wavelength routing star network providing a switchable broadcast capability. The switch selects the optical channel to be fed to the coupler array and on to the destination terminals.

Fig. 6  Wavelength routing star network showing coarse grain and fine grain multiplexing structure. The fine grain multiplex can be reserved as an upgrade option.
Only one direction of transmission is shown.

Fig. 7 Wavelength routing chain network fully interconnecting 5 nodes using 6 different wavelengths. The principle can be extended to N nodes using $(N/2)^2$ (N even) or $(N-1)(N+1)/4$ (N odd) wavelengths.

Fig. 8 Wavelength routing tree network. For full interconnection $N_A N_B$ wavelengths are needed in a given link.
4. TREE STRUCTURE

Tree networks are usually thought of as providing connection from each node back to a common point. In this situation a minimum of \((N-1)\) wavelengths are needed for \(N\) nodes. However if full interconnection of nodes is needed then interconnection via the common point would lead to an inefficient use of wavelengths as every single channel not intended for the common point would have to pass twice through the final link to the common point. A more efficient use of wavelengths can be achieved by using a structure in which channels can be routed in any direction through the branching points. Fig. 8 shows such a network. In any section the number of wavelengths needed is \(N_1 N_2\), where \(N_1\) and \(N_2\) are the number of terminal nodes served by the two ends. Each section is assumed to consist of two unidirectional links, one for each direction of transmission (though this detail is not shown in Fig. 8). Compared to a star network the network losses are higher because a greater number of multiplexers are needed in the path.

5. RING STRUCTURE

A ring structure can be formed by joining the ends of the chain structure together to complete a loop (Fig. 9). Even though unidirectional transmission around the loop is assumed the network can still provide for two-way transmission between nodes by using complementary sections of the ring for the two directions of transmission. Under these circumstances the number of wavelengths needed to fully interconnect \(N\) nodes is \(N(N-1)/2\) which is almost twice the number of wavelengths required by the chain network. However to cater for two-way transmission the chain network must be duplicated or must operate bi-directionally.

6. SPECTRAL CONSIDERATIONS

Networks of this type could be expected to operate within a broad spectral fibre window and typically this could be 1500nm to 1600nm. Ten nodes on such a network could be a useful number of terminal nodes served by the two ends. Each section is assumed to consist of two unidirectional links, one for each direction of transmission (though this detail is not shown in Fig. 8). Compared to a star network the network losses are higher because a greater number of multiplexers are needed in the path.

7. NETWORKING CONSIDERATIONS

The various optical structures can all offer similar facilities to an interfacing electronic system. For example, dedicated channels between any two nodes can be provided, additional channels can be switched in when required and all could operate with synchronous or non-synchronous transmission or switching systems. As an alternative to an electronic interface (eg to a switching system), the network inputs and outputs could be optically linked through to an adjacent optical network, for example one operating at the next level in the hierarchy. In this case it may be possible to provide an optical broadband switch at the interface.

Because of the operational similarity of the networks, it may be advantageous to deploy different optical network structures to fit the geography of a particular situation. The optical network is there to provide a set of point to point paths (which may be time/traffic variable) between switching nodes and the means by which it achieves this can be determined independent of the switching process. Although it has only been described for the star network, any fully interconnected structures shown can provide alternative routing between two nodes via any third node, by making suitable switching arrangements within the three nodes.

CONCLUSIONS

A wavelength routing approach to the design of high capacity optical networks has been described. The method depends on the use of efficient wavelength multiplexers, single mode lasers operating at a number of specified wavelengths and receivers with high sensitivities. The networks permit wavelengths to be re-used in different parts so that fewer
Fig. 9 Wavelength routing ring network fully interconnecting 4 nodes using 6 different wavelengths. The principle can be extended to N nodes by using N(N-1)/2 wavelengths.
different wavelengths are needed to fully interconnect a given number of nodes with dedicated optical channels than is the case for optically broadband networks based upon power coupler arrays. A choice of topological structures is possible using a common set of components, giving the opportunity to design a network according to the prevailing geography. In addition each structure is sufficiently versatile to offer a variety of more advanced network functions. At present the design of components suitable for these systems is still at the research stage but improvements in component technology are anticipated which should allow demonstration in the next few years.

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