A wavelength routeing approach to optical communication networks

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A class of optical networks is described which employs wavelength division multiplexing elements as building blocks. These networks can provide high interconnectivity and appear to offer good reliability and growth characteristics. Together with new component technology they also have the potential to offer enhanced network management facilities.

1. Introduction

The penetration of optical fibre systems into the British Telecom network has grown rapidly over the last few years. Currently some 50% of the total transmission capacity in the trunk network is carried by fibre and this figure will increase as older coaxial cable systems are replaced. New opto-electronic technology has allowed the systems to not only carry higher informaton rates but also to span greater distances without repeaters. Consequently few repeaters are needed in the new systems and active electronic equipment can be concentrated in exchange buildings. This has been a significant factor in achieving improved network reliability.

Further improvements in network reliability seem most likely to be achieved by adopting new network structures in which the opto-electronic interface is shifted from its currently accepted position and in which some of the network functions traditionally performed in the electrical domain are performed in the optical path. For this approach to be practical high performance optical transmission systems are needed to tolerate the higher losses that will occur in the optical path, and greater use must be made of the full optical bandwidth of the fibre system. This requires a range of new components, but seems attractive as other benefits may be gained at the same time. For example, there is the opportunity to introduce new network management facilities and, by offering high capacity and long span, it may be possible to simplify the task of network planning.

In the last few years a variety of optical network structures have been proposed which are based on the transmission of wavelength multiplexed signals over networks which use broadband optical star couplers. This paper presents an alternative way of constructing optical networks using wavelength selective elements instead of star couplers [1,2]. The basic structures described are high capacity transmission networks, but their functionality can be enhanced by incorporating additional stages into the optical path.

2. High capacity networks

A typical communication network requirement is to fully interconnect a set of nodes. 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 must be provided.

In this paper it is shown that new network topologies are possible when the multiplexing function is performed optically using passive wavelength division multiplexing (WDM) elements. Unlike previously reported structures based on optical power coupler arrays [3-6] wavelength selective elements are used which allow the reuse of wavelengths leading to fewer being required. Wavelength selective elements can also offer lower loss than power

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coupler arrays and this can be used to raise the number of channels in systems which are power budget limited [1]. 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 few repeaters. The structures all offer good potential for upgrading to provide either additional facilities or increased capacity.

3. Star structure

If a set of switching nodes is 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 bothway 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 reused in different parts so that the minimum number of different wavelengths needed to allow full interconnection of the N nodes is $(N-1)$.

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 without risk of crosstalk. 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

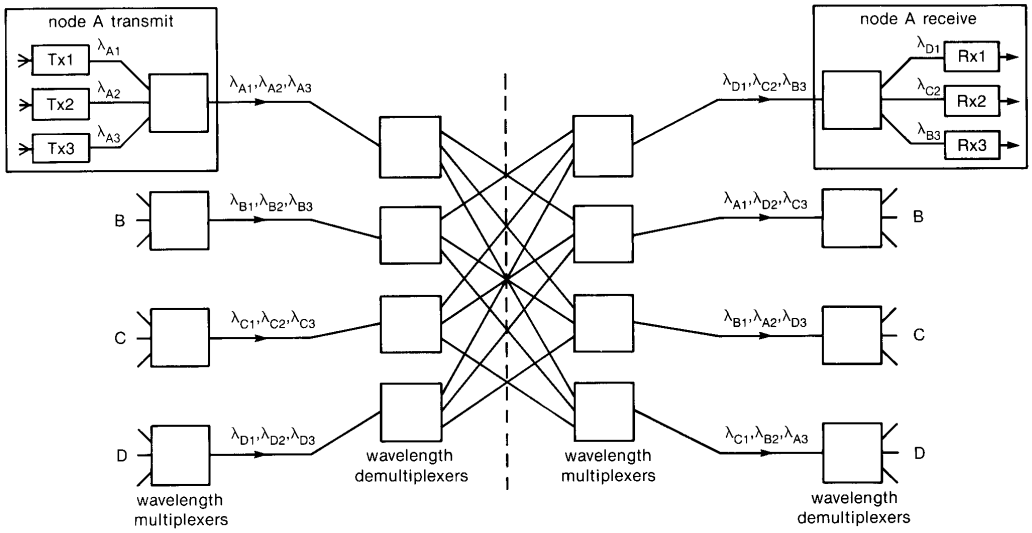


Fig 1 Wavelength routeing star network fully interconnecting 4 nodes using 8 identical WDM systems. The principle can be extended to N nodes using $(N-1)$ wavelengths.

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 capacity 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 routeing to protect, for 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.

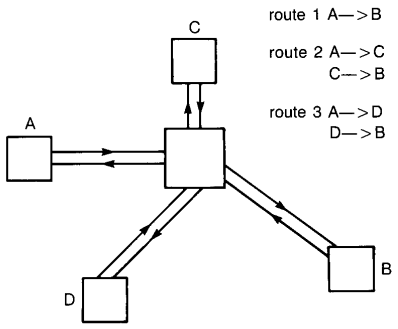


Fig 2 Alternative routeing options in a wavelength routeing star network. A direct channel is available between A and B and also two alternatives via C and D. In a larger network more options are possible.

Low loss fine grain multiplexers, higher transmitter powers, increased sensitivity receivers and optical amplifiers can all play a part in achieving this.

4. Chain structure

Other network architectures can be used to fully interconnect a set of nodes and the chain structure (Fig 7) is suited to interconnecting 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.

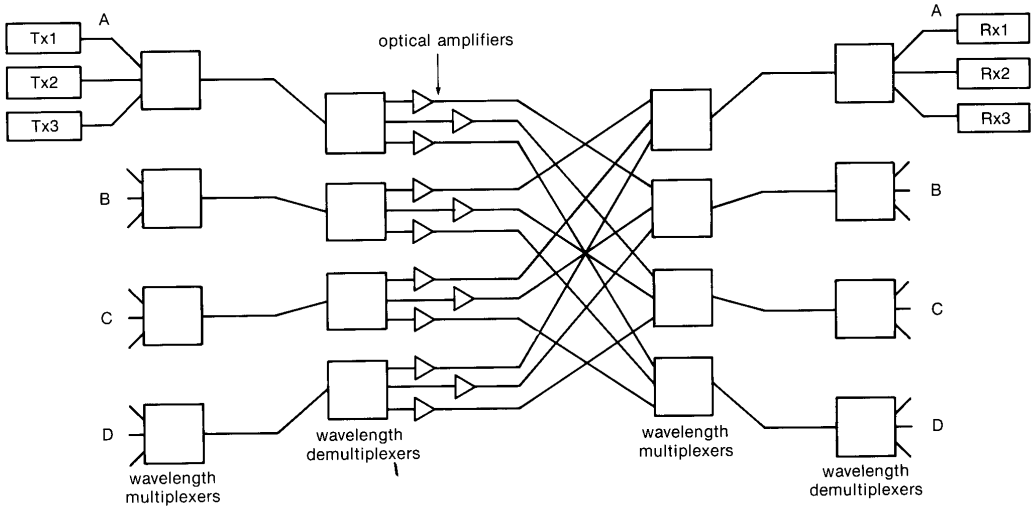


Fig 3 Wavelength routeing star network with amplification in the parallel array. Wavelength allocation is as shown in Fig 1.

In principle, it should be possible to increase the capacity of the wavelength routeing star network by filling each optical channel with a 'fine grain' WDM structure [1], 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.

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 routeing can be provided. Additional functionality such as optical switching, amplification and broadcasting can be included

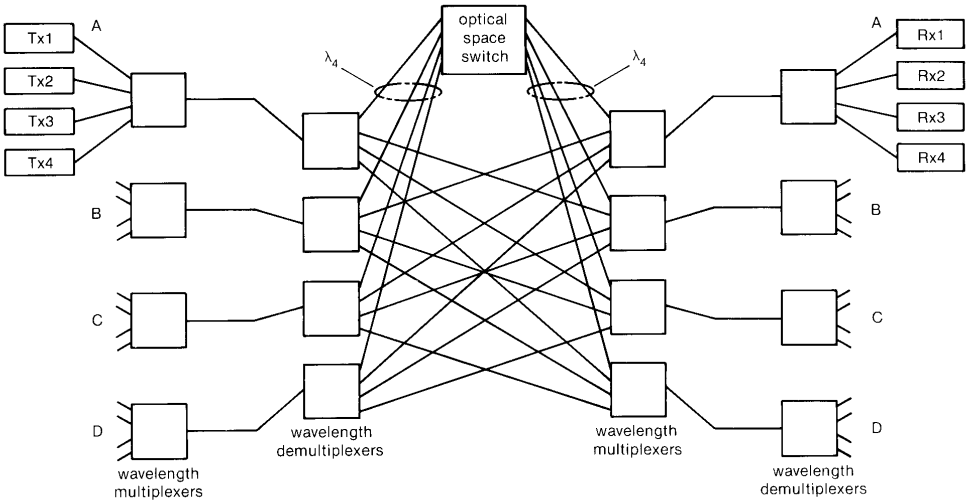


Fig 4 Wavelength routeing star network with an overlaid optical switching capability. An additional wavelength in each section links into a space switch.

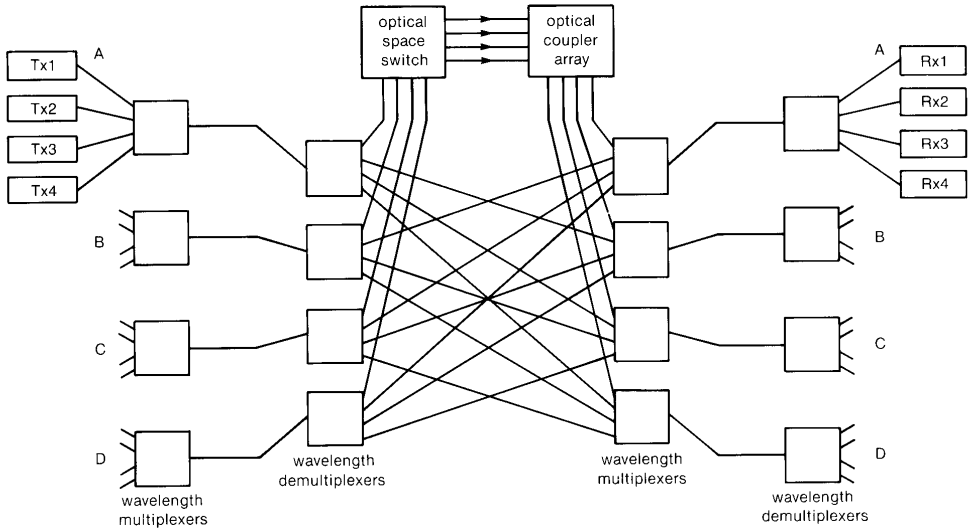


Fig 5 Wavelength routeing star network providing a switchable broadcast capability. The switch selects the optical channel to be fed to the coupler array and on to the destination termals.

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 rather than be concentrated at a single point as in the star topology.

5. 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 wavelength can be achieved by using a structure in which channels can be routed in any direction through the branching points. Figure 8 shows such a network. In any section the num-

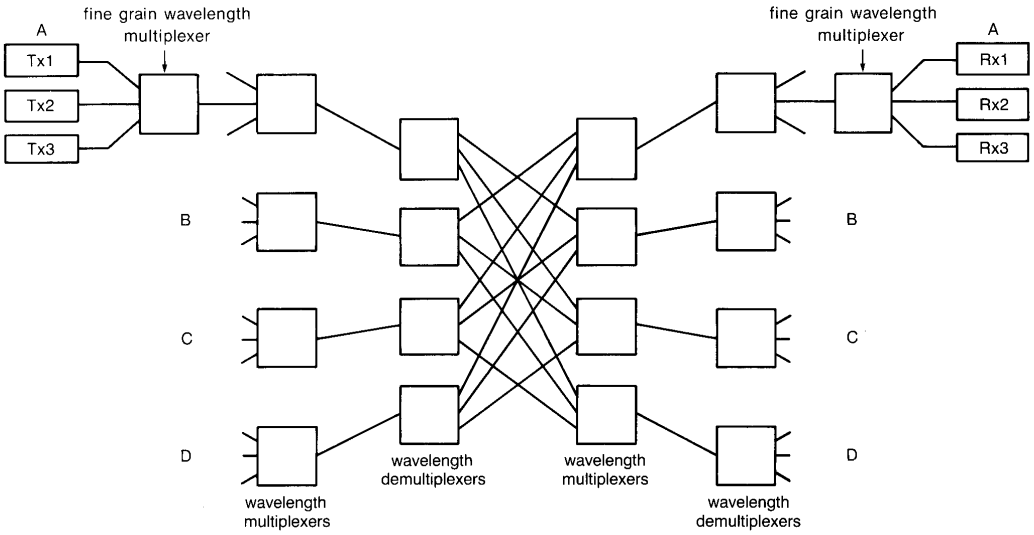


Fig 6 Wavelength routeing star network showing coarse grain and fine grain multiplexing structure. The fine grain multiplex can be reserved as an upgrade option.

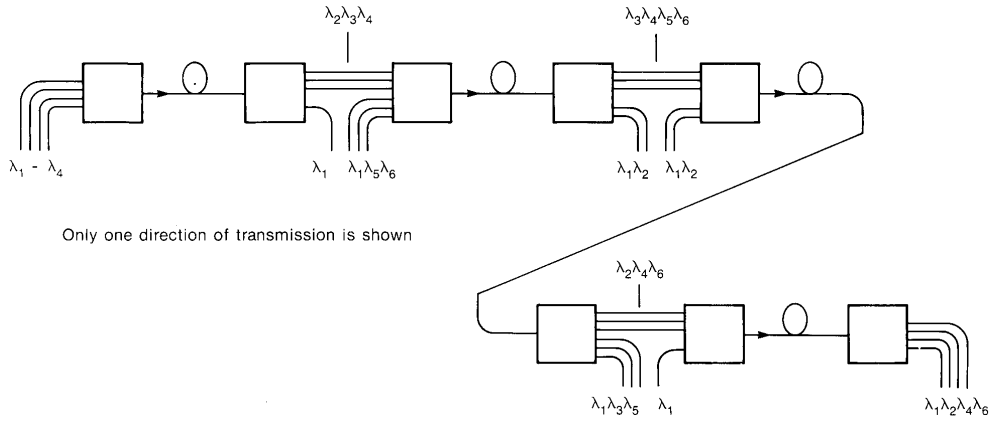


Fig 7 Wavelength routeing chain network fully interconnecting 5 nodes using 6 different wavelengths. The principle can be extended to N nodes using $(N/2)^2$ (N even) or $(N-1)(N+1)/4$ (N odd) wavelengths.

ber of wavelengths needed is $N_A.N_B$, where N_A and N_B are the number of terminal nodes served by the two ends of the section. 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.

6. 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 bothway transmission between nodes by using complementary sections of the ring for the two directions

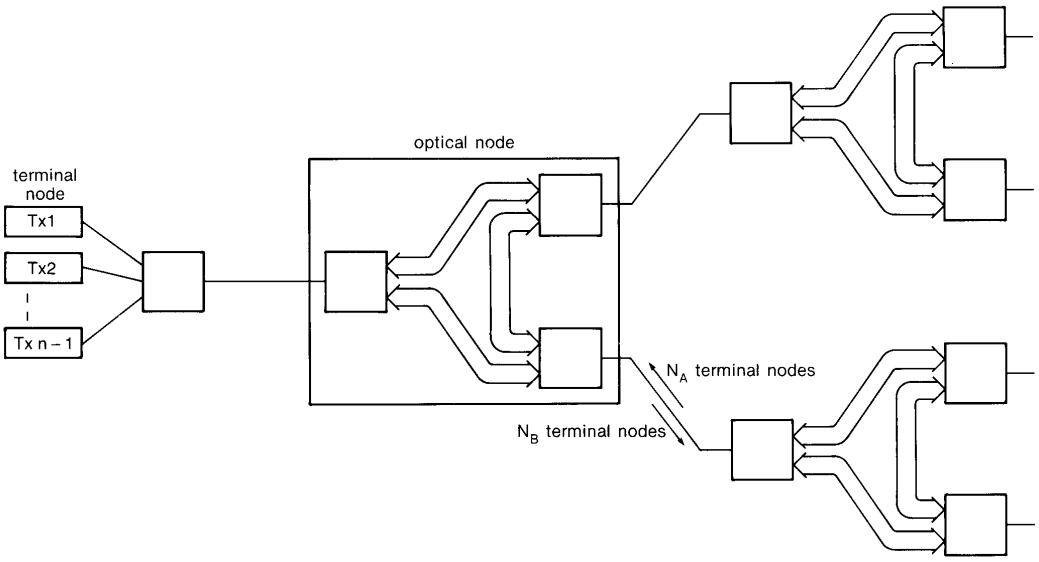


Fig 8 Wavelength routeing tree network. For full interconnection $N_A.N_B$ wavelengths are needed in a given link.

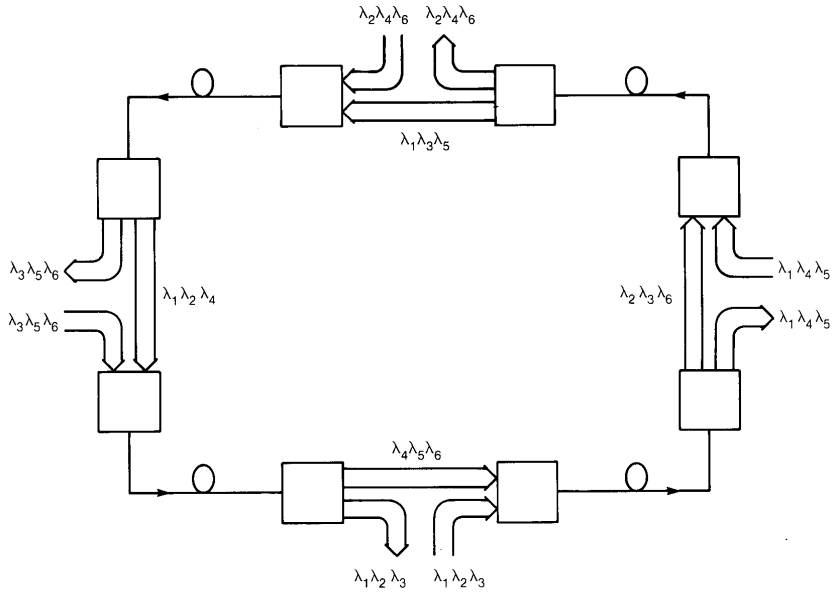


Fig 9 Wavelength routeing ring network fully interconnecting 4 nodes using 6 different wavelengths. The principle can be extended to N nodes by using $N(N-1)/2$ wavelengths.

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.

7. Spectral considerations

Networks of this type could be expected to operate within a broad spectral fibre window and typically this could be 1500 nm to 1600 nm. Ten nodes on such a network could be a useful target to aim for and in the case of the star network this could be realised with nine wavelengths. Allowing a further three wavelengths for network management purposes, leads to a channel spacing of 8 nm. Spectral utilisation of 37% has been demonstrated in a grating component [7] and this level of performance would allow a channel bandwidth of circa 3 nm. Although much higher spectral utilisation is feasible (at the expense of a small loss increase), this should be sufficient to allow the use of carefully toleranced DFB lasers with simple temperature control in a simple and early network realisation. In a more refined realisation, fine grain multiplexing could be added operating with channel spacings as low as a few GHz [1]. In this case more precise laser frequency control would be needed.

Two approaches to fine grain demultiplexing appear to be feasible. One is to use a heterodyne receiver with a local oscillator laser which can be tuned to the necessary wavelength [8]. The other is to use a fine tunable optical filter (such as a tunable Fabry-Perot or transversely coupled fibre Fabry-Perot [9] or a Mach-Zehnder [10]) in front of a direct detection receiver. By using an optical pre-amplifier with a direct detection receiver [11] the sensitivity difference of the two approaches could be small.

8. 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 (e.g. 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 adantageous to deploy different optical network structures to fit the geography of a particualar situation. The optical network simply provides 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 independently of the switching process. Although it has only been described for the star network, all the fully interconnected structures shown can provide alternative routeing between two nodes via any third node, by making suitable switching arrangements within the three nodes.

8. Conclusions

A wavelength routeing approach to the design of reliable, 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 high performance transmitter/receiver systems. The networks permit wavelengths to be reused in different parts so that fewer different wavelenths 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.

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