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Optical interconnection technology in switches, routers, and optical cross connects

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ABSTRACT
The performance of data- and telecommunication equipment must keep abreast of the increasing network speed. At the same time, it is necessary to deal with the internal interconnection complexity, which typically grows by N^2 or NlogN, where N is the number of ports. This requires new interconnection technologies to be used internally in the equipment. Optical interconnection technology is a promising alternative and much work has already been done. This paper reviews a number of optical and opto-electronic interconnection architectures, especially from a data and telecommunication equipment point of view. Three kinds of systems for adopting optical interconnection technology are discussed: (i) optical cross connects (OXCs), (ii) switches and routers with some kind of burst switching and (iii) switches and routers that redirect traffic on the packet or cell level. The interconnection technologies and architectures are discussed according to their suitability for adoption in the three system types.

1 Introduction

Novel optical technologies offer possibilities for new solutions for the increasing bandwidth demands of data communication and telecommunication equipment. This paper uses a primarily architectural approach to explore the possibilities of using optical interconnections in such equipment. Some selected groups of concepts are selected here in order to give a reasonably broad view in the scope of a single paper.

The interconnection architectures are evaluated according to three system types with different switching time requirements. These types are: (i) optical cross connects (OXCs), (ii) switches and routers with some kind of burst switching and (iii) switches and routers that redirect traffic on the packet or cell level.

OXCs have relatively slow timing requirements, i.e. in the order of milliseconds or even tens of milliseconds. On the other hand, it is valuable if the signals remain optical all the way through the switch, including possible queuing systems, i.e. there is optical transparency. In this way it is easier to scale up the bit rate or change protocols.

With burst switching, packets with the same destination, like the same exterior gateway, can be grouped together to reduce switching time requirements. This has for instance been discussed for use in all-optical packet switching [1,2]. The switching time requirements are in the order of sub-microseconds.

For pure switching at the packet level, the switching time requirements are in the order of nanoseconds. With longer switching times, the overhead between the packets will be too large. All-optical packet switching has been proposed but much work remains to reach purely optical routers [1]. However, some experiments have been done and several architectures that are more or less purely optical have been proposed [3-7].

The interconnection networks reviewed are intended for use in, or as substitution of, the switch core in data or telecommunication equipment. Other components needed in addition to the switch core vary between different equipment. As an example, a simple switch might be implemented without much more components, while an IP router needs components to manage the routing table. The acceptable cost of an interconnection network can also vary depending on whether it is to be used in a core router, where many users share the cost, or in equipment near the end-user.

Another driving application domain for optical system-level interconnections, in addition to data and telecommunication equipment, is parallel and distributed computing systems [8-11]. Important work in the field of optical interconnections in computing and communications started in the mid 1980s. Of the early publications, a good paper on system aspects was published by Goodman et al. in 1984 [12], while publications by Miller et al. can represent work on specific components. Other examples of early work in the field are [13-16].

The rest of the paper is organized as follows. Switch fabrics are generally reviewed in Section 2, and Section 3 describes optical link technologies. Section 4 presents fiber-optic interconnection networks. Integrated optical interconnection systems and optical and optoelectronic switch-fabrics are described in Sections 5 and 6, respectively. Sections 7 and 8 give a discussion and a summary, respectively.

2 Switch Fabrics

An example of a switch or router is shown in Figure 1, where the switch fabric transfers traffic from input ports to output ports on the basis of decisions made by some control logic. One of the simplest ways to implement or simulate an electrical switch fabric is to have a shared medium to which I/O interfaces, control processors or the like are attached and over which the traffic is time multiplexed (see Figure 2). A common way of implementing a shared-medium network is to use the bus topology, where only one node is allowed to send at a time, but a shared-medium network can also be a ring for example. The great advantage of a shared-medium network is the easy implementation of broadcast, which is useful in many situations. The disadvantage is that the bandwidth does not scale with the number of nodes (ports on a switch).

The crossbar is the most flexible switch fabric and can be compared with a fully connected topology, i.e. all possible pairs of input and output ports are connected by point-to-point connections. The drawback, however, is the increase by N^2 in cost/complexity of the switch, where N is the number of ports. Systems with a single electrical true crossbar are therefore limited to small or medium-sized systems. A $140 \times 140 \times 3.2$ Gbit/s single-chip switch is commercially available [17].

In multistage shuffle-exchange networks, the cost function is reduced to $N \log_2 N$, but here $\log_2 N$ stages must be traversed to reach the desired output port. An example of this kind of a network is the Omega network (Figure 3), which provides exactly one path from any input to any output. The different switch functions of the 2×2 switch that is used as the building block are shown in Figure 4, where the two right most configurations are used for broadcast. Switches larger than 2×2 can also be used. Each stage of the switches in an Omega network is preceded by a perfect-shuffle interconnection pattern. In contrast to a crossbar network, which is a *nonblocking* network, an Omega network is a *blocking* network. This means that there may not always exist a path through the network as a result of already existing paths that block the way. *Rearrangeable* networks are another category of multistage networks where it is always possible to find a path through the network. However, if all paths are not routed at the same time, it may be necessary to reroute already existing paths.

3 Optical Link Technologies

This section discusses two main categories of optical links, fiber-ribbon links and bit-parallel WDM links. Single-channel single-fiber solutions are not treated.

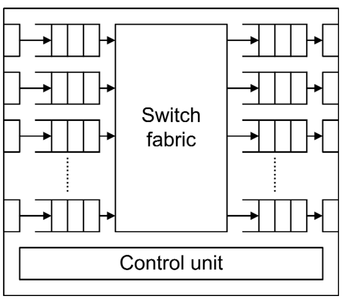

Figure 1: An example of switch architecture.

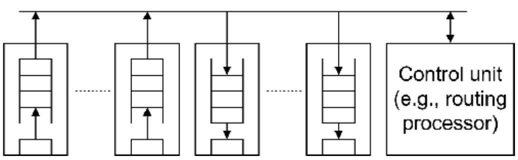

Figure 2: Bus-based switch architecture.

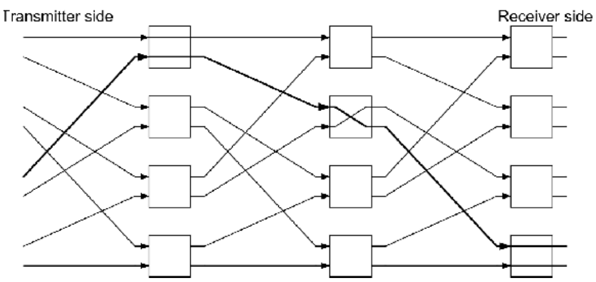

Figure 3: Eight-channel Omega network. One path through the network is highlighted.

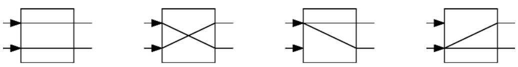

Figure 4: Possible states of a 2×2 switch.

3.1 Fiber-ribbon links

A system component that reached the market some years ago is the fiber-ribbon link. As an example of an early commercial link, the Motorola OPTOBUS has ten parallel fibers, each carrying data at a bit rate of 400 Mbit/s, which gives an aggregated bandwidth of 4 Gbit/s [18]. Bi-directional links are also possible, where some fibers in the fiber-ribbon cables are dedicated for each direction [19]. Further references to reports on fiber-ribbon links are found in [20].

In scaling up the bandwidth of a fiber-ribbon link where a dedicated fiber carries the clock signal, the main problem is channel-to-channel skew. The skew is mainly the result of differences in propagation delay between different fibers and variations of lasing delay time among different laser diodes [21]. The 400 Mbit/s OPTOBUS has a specified maximum skew of 200 ps, excluding the fiber-ribbon cable for which 6 ps/m is assumed for standard ribbons [18]. Even though the distances are rather short in the systems discussed in this paper, the scaling to higher speeds calls for a discussion of techniques to reduce the effect of the skew.

One technique is to actually reduce the skew, either by using low skew ribbons or employing skew compensation. Fiber ribbons with a skew below 1 ps/m have been developed [22], which essentially increases the possible bandwidth distance product. All the fibers in the same ribbon are sequentially cut to reduce the variation in refractive index among the fibers. In the fiber-ribbon link described in [23], a dedicated fiber carries a clock signal used to clock data on 31 fibers. The transmitter circuitry for each channel has a programmable clock skew adjustment to adjust the clock in 80-ps increments.

Another technique is to extract the clock signal from the bit flow on each fiber instead of using a separate fiber to carry the clock signal. The disadvantage is increased hardware complexity when a clock recovery circuit and a buffer circuit for each channel in the receiver are added. A hybrid solution is to skip the separate clock channel and encode clock information on the data channels while still sending in bit-parallel mode, as reported in [24]. In this case, a deskew unit relying on FIFO registers (First In First Out) ensures that parallel data words that are output from the receiver are identical to those which were sent. A possible $\pm$ 15-ns deskew was reported. A similar system is reported in [25].

The techniques mentioned above introduce either increased hardware complexity or a more sophisticated fiber-ribbon manufacturing process. If the manufacturing process allows for adding more fibers in each ribbon, this may be a cheaper alternative. For example, a fiber-ribbon link with 32 fibers, each with a bit rate of 500 Mbit/s, was described in [23], and researchers at NEC have developed a module in which 8×2 lasers are coupled to two fiber-ribbons [26]. Links with 48 channels [27] and 72 channels (36 in each direction) [28] have recently appeared on the market. Instead of fiber ribbons, fiber imaging guides (FIGs) with thousands of pixels can be used [29]. In the system described in [30], both a 14000-pixel FIG and a 3500-pixel FIG were coupled to an 8×8 VCSEL (Vertical Cavity Surface Emitting Laser) array in different set-ups. Over short communication distances, the fiber ribbon can even be replaced by some optical elements to obtain free-space communication. A 256-channel bidirectional intra-PCB (Printed Circuit Board) free-space interconnection system is described in [31].

3.2 Bit-Parallel WDM Links

A bit-parallel WDM link is another way to synchronously transmit on several channels in parallel. In this way we get bit-parallel byte-serial transmission [32]. However, compensation for bit skew caused by group delay dispersion, where different wavelength channels travel at different speeds in the fiber, may be needed in these systems [33].

A dedicated wavelength in a bit-parallel WDM link can be used for clock information. Wavelengths, or fibers in a fiber-ribbon cable, can also be dedicated to other purposes such as frame synchronization and flow control. Significantly higher bandwidth distance products can be achieved when using bit-parallel WDM over dispersion-shifted fiber instead of fiber-ribbons [34]. If, however, there is only communication over shorter distances, like a few meters, the bandwidth distance product is not necessarily a limiting factor. Transmission experiments with an array of eight pie-shaped VCSELs arranged in a circular area with a diameter of 60 μm, to match the core of a multimode fiber, have been reported [35]. Other work on the integration of components for short distance WDM links has been reported, e.g. a 4×2.5 Gbit/s transceiver with integrated splitter, combiner, filters etc. [36].

4 Fiber-Optic Interconnection Networks

Fiber-optic network architectures, especially passive ones, are discussed below. First, different basic passive fiber-optic network architectures are described. WDM star, WDM ring, and AWG networks are then respectively discussed. Fiber-ribbon ring networks are presented last.

4.1 Passive Fiber-Optic Networks

In an all-optical network, the data stream remains in the optical form all the way from the transmitter to the receiver. Three basic architectures for all-optical multi-access networks are the ring, the bus and the star (see Figure 5). These will be discussed below. Most work on passive optical networks has focused on LANs or similar structures but they can also be used as

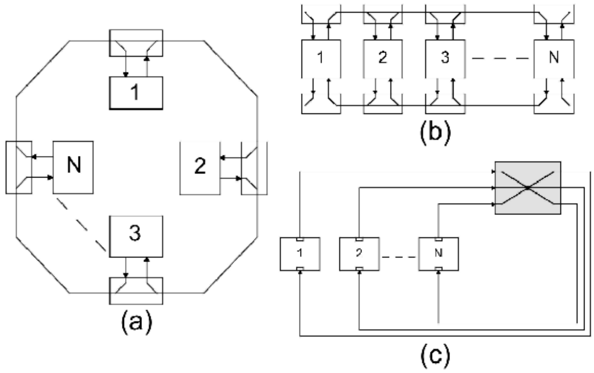

Figure 5: Passive optical network architectures: (a) ring, (b) (dual) bus, and (c) star.

substitutes for switch fabrics in data and telecommunication equipment. It should be noted that if one of these networks is used in an OXC or the like as a switch fabric, the signal is normally converted to electrical and back to optical form at the entrance and the exit of the switch fabric.

An all-optical multiple-access ring network differs from a traditional ring network in the sense that all other nodes can be reached in a single hop without any intermediate optoelectronic conversion. Only a fraction of the optical power contained in the bypassing fiber is tapped to the receiver, which gives all nodes the opportunity to read the message. In other words, multicast or broadcast is possible. Outgoing messages are inserted into the ring. A node removes its own messages from the ring after one round.

In an optical bus, the light travels only in one direction, making two buses necessary (upper and lower), one for each direction (higher or lower node index of destination nodes). This kind of bus architecture is called *dual bus*. The disadvantage of the dual bus is that two transceivers are needed in each node. This is avoided in the *folded bus*, where the two buses are connected with a wrap-around connection at one end of the buses (see Figure 6). In the folded bus, transmitters and receivers are connected to the upper and lower bus, respectively.

In a star network, the incoming light waves from all nodes are combined and uniformly distributed back to the nodes. In other words, the optical power contained in the middle of the star is equally divided between all nodes.

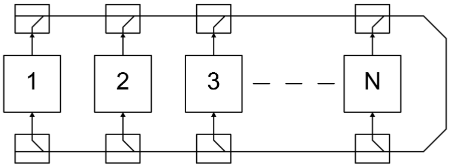

Figure 6: Folded fiber-optic bus.

All of the three basic network architectures offer different advantages. The ring has the least amount of fibers, a bus network's medium access protocol can utilize the linear ordering of the nodes, and the star has the best power budget in practice. Star networks are the most popular, however, judging from the number of published reports.

While passive optical networks that offer only one shared channel are not promising alternatives, they form the basis for more powerful networks using WDM. These networks can be promising solutions as switch fabrics in some kinds of data and telecommunication equipment.

4.2 WDM star

By using WDM, multiple wavelength channels can carry data simultaneously in the network. Figure 7 shows an example of a WDM star network configuration. Each node transmits on a wavelength unique to the node, while the receiver can listen to an arbitrary wavelength [37]. One can say that this kind of network architecture implements a distributed crossbar. The flexibility is hence high, and multicast and single-destination traffic can co-exist. WDM star networks have been proposed especially for internal use in packet switches [38-41].

Tunable components with tuning latencies in the order of a nanosecond have been reported, but they often have a limited tuning range [42]. At the expense of longer tuning latencies, however, components with a broader tuning range can be used [43]. Such components can be used to achieve a cheaper network in systems where much of the communication patterns remain constant for a longer period.

Complete removal of the ability to tune in a WDM star network gives a multi-hop network [44]. Each node in a multi-hop network transmits and receives on one or a few dedicated wavelengths. If a node does not have the capability of sending on one of the receiver wavelengths of the destination node, the traffic must pass one or several intermediate nodes. The wavelengths can, for example, be chosen to get a perfect-shuffle network [45]. A network in which several topologies, like a ring and

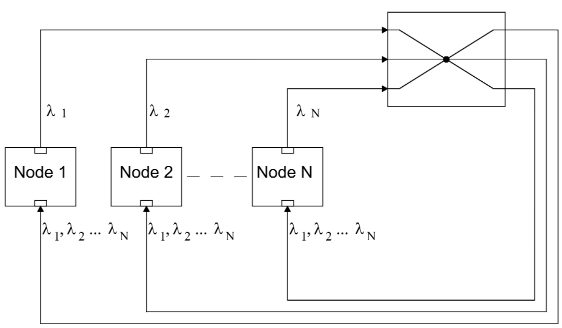

Figure 7: WDM star network.

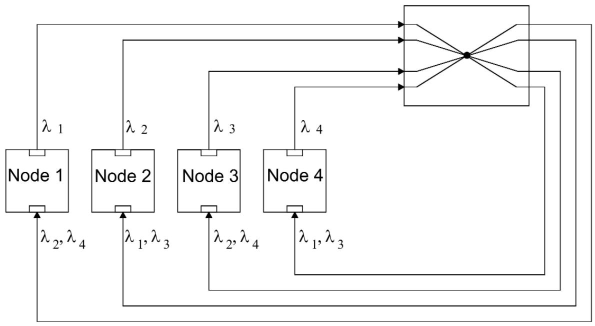

Figure 8: WDM star multi-hop network.

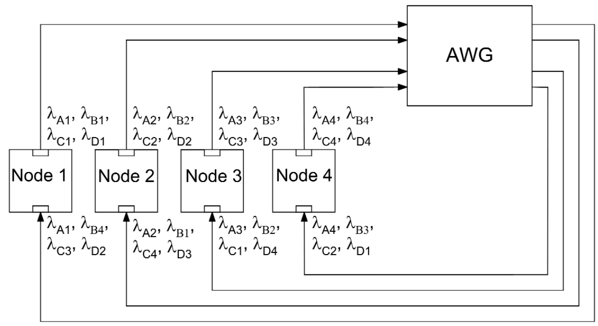

Figure 10: AWG network.

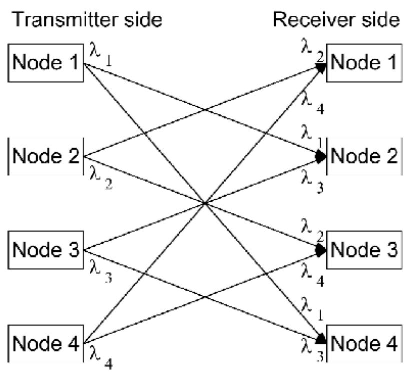

Figure 9: Multi-hop topology.

a hypercube, are embedded can also be chosen. An example of a multi-hop network is shown in Figure 8. This configuration of wavelength assignments corresponds to the topology shown in Figure 9.

4.3 WDM ring

A WDM ring network utilizes ADMs (Add Drop Multiplexers) in all nodes to insert to, listen to and remove wavelength channels from the ring. In the WDMA ring network described in [46], each node is assigned a node-unique wavelength on which to transmit. The other nodes can then tune in an arbitrary channel on which to listen. This configuration is logically the same as that of the WDM star network with fixed transmitters and tunable receivers. The distributed crossbar again gives good performance for general communication patterns.

4.4 AWG networks

AWG (Arrayed Waveguide Grating) networks are related to WDM star networks, but here the passive optical star is exchanged with an AWG [47]. The AWG routes wavelengths such that spatial reuse of wavelengths is possible, as seen in Figure 10. Only N wavelengths (λ_A, λ_B, λ_C, and λ_D,) are needed to get a fully connected $N \times N$ network with N^2 optical channels (λ_{A1}, λ_{A2}, . . . λ_{D4}). The AWGs have been proposed for use both as a stand-alone network component [48] and as a component in routers [4].

4.5 Fiber-ribbon pipeline ring network

Bit-parallel transfer can be utilized when fiber-ribbon links are used to connect the nodes in a point-to-point linked ring network. In such a network, one of the fibers in each ribbon is dedicated to carrying the clock signal thus making clock-recovery circuits unnecessary in the receivers. Other fibers can be utilized for frame synchronization and other control purposes. Figure 11 shows how a ring network is used as a switch fabric.

As seen in Figure 12, aggregated throughputs higher than 1 can be obtained in ring networks with support for spatial bandwidth reuse, sometimes called pipeline rings. This feature can be effectively used when most of the communication is to the nearest downstream neighbor. Two fiber-ribbon pipeline ring networks have recently been reported [49]. The first has support for circuit switching

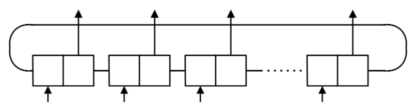

Figure 11: Ring network as switch-fabric.

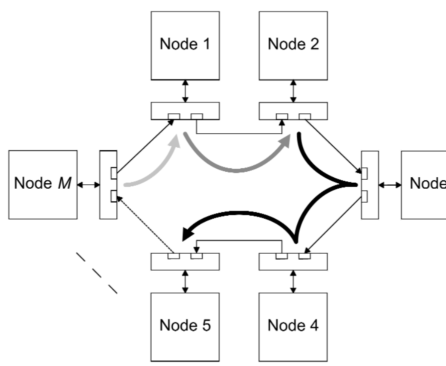

Figure 12: Example of spatial bandwidth reuse. Node M sends to Node 1 at the same time that Node 1 sends to Node 2 and Node 2 sends a multicast packet to Nodes 3, 4, and 5.

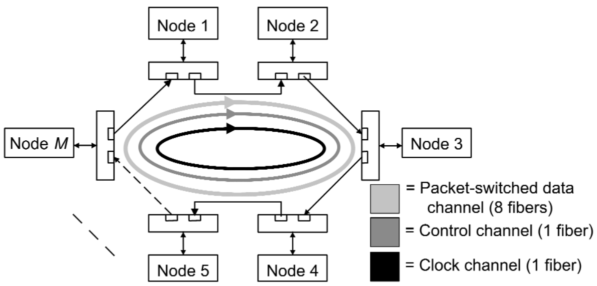

Figure 13: Control channel based network built up with fiber-ribbon point-to-point links.

on 8 + 1 fibers (data and clock) and packet switching on an additional fiber. The second network is more flexible and has support for packet switching on 8 + 1 fibers and uses a tenth fiber for control packets (see Figure 13). The control packets carry MAC information for the collision-less MAC protocol with support for slot reserving. Slot reserving can be used to get RTVCs (Real-Time Virtual Channels) for which guaranteed bandwidth and a worst-case latency are specified (compare with circuit switching). The fiber-ribbon ring network can offer rather high throughputs due to the aggregated bandwidth of a fiber-ribbon cable, especially when there is a great deal of nearest downstream neighbor communication. However, the spatial reuse will probably be limited if used in data or telecommunication equipment owing to more evenly distributed destinations as compared to the parallel computing systems for which the network was first proposed.

Another fiber-ribbon ring network is the PONI network (formerly USC POLO), which is proposed for use in clusters of workstations and similar systems [50,51]. Integrated circuits have been developed for the network, and tests have been done [52,53].

5 Integrated Optical Interconnection Systems

This section describes three types of more or less purely integrated optical interconnection systems. This type of interconnection system can be used to interconnect electronic switch chips or I/O interfaces. Integrated fiber and waveguide solutions, planar free space optics, and free space optical backplanes are discussed.

5.1 Integrated fiber and waveguide solutions

Fibers or other kinds of waveguides (hereafter commonly denoted as channels) can be integrated to form a more or less compact system of channels. Fibers can be laminated to form a foil of channels for use as intra-PCB or back-plane interconnection systems [54-56]. Fiber-ribbon connectors are applied to fiber end-points of the foil. An example is shown in Figure 14, where four nodes are connected in a ring topology. The medium is simply changed into an even more compact variant of the fiber-ribbon ring network. In addition, there is a clock that distributes clock signals to the four nodes via equal length fibers to keep the clock signals in phase. In other words, a fiber-optic clock distribution network and a data network are integrated into one system. If one foil is placed on each PCB in a rack, they can be passively connected to each other via fiber-ribbon cables or a backplane foil. Using polymer waveguides instead of fibers offers advantages such as the possibility of integrating splitters and combiners into the foil and the potential for more cost effective mass production [54].

Another way is to follow the proposed use of an array of passive optical stars to connect processor boards in a multiprocessor system via fiber-ribbon links, for which experiments with 6 × 700 Mbit/s fiber-ribbon links were done (see Figure 15) [57]. Of course, the processors boards can be exchanged with transceiver cards and/or switch cards. As indicated above, such a configuration can be integrated by the use of polymer waveguides. The power budget can, however, be a limiting factor to the number of nodes and/or the distance. Advantages are simple hardware owing to bit-parallel transmission, like other fiber-ribbon solutions, and the broadcast nature, but the star array can become a bottleneck as in all bus-like systems. In a similar system, the star array is exchanged with a chip with optoelectronics that has one incoming ribbon from each node and one output ribbon [58]. The output ribbon is coupled to an array of 1 × N couplers so

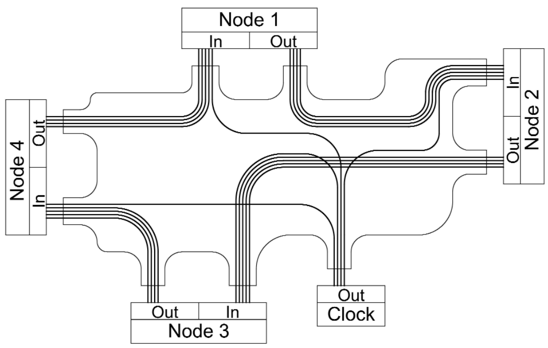

Figure 14: A foil of fibers connects four nodes and distributes clock signals to them.

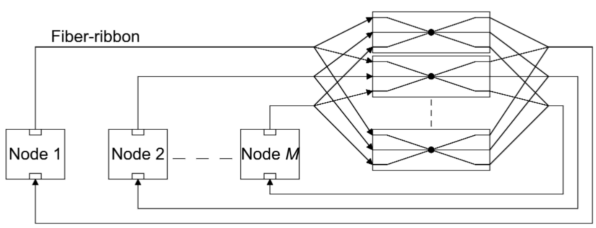

Figure 15: An array of passive optical stars connects a number of nodes via fiber-ribbon cables.

that each node has a ribbon connected to its receiver. The chip couples the incoming traffic together in a way that simulates a bus. At contention, the chip can temporarily store packets.

Other similar systems include the integration of fibers into a PCB for the purpose of clock distribution [59]. Distribution to up to 128 nodes was demonstrated. The fibers are laminated on one side of the PCB, while integrated circuits are placed on the reverse side. The end section of each fiber is bent 90 degrees to lead the light through a so called via hole to the reverse side of the PCB.

5.2 Planar free space optics

Placing electronic chips, including optoelectronic devices, and optical elements on a substrate where light beams can travel gives a planar free space system (Figure 16) [60-61]. Electronic chips are placed in a 2-dimensional plane, while light beams travel in a 3-dimensional space. In this way, optical systems can be integrated monolithically, which gives compact, stable and potentially inexpensive systems [61]. A flexible network can be obtained by using spatial light modulators to dynamically direct the optical beams. Using only fixed interconnection patterns and electronic switching can give shorter switch times, however. A planar free space optical crossbar switch has been reported [62].

5.3 Free space optical backplanes

Several different optical backplanes have been proposed, three of which are discussed below. As shown in Figure 17a, using planar free space optics is one means of transporting optical signals between PCBs. Holographic gratings can be used to insert/extract the optical signals to/from the waveguide, which may be a glass substrate [63]. Several beams or bus lines can be used so each arrow in the figure represents several parallel beams [64].

In the system shown in Figure 17b, 2-dimensional arrays of optical beams (typically 10 000) link neighboring PCBs together in a point-to-point fashion [65]. Smart pixel arrays then act as intelligent routers that can, e.g., bypass data or perform data extraction operations where some data pass to the local PCB and some data are retransmitted to the next PCB [66]. Each smart pixel array can typically contain 1 000 smart pixels arranged in a 2-dimensional array, where each pixel has a receiver, a transmitter, and a simple processing unit. One way to configure the system is

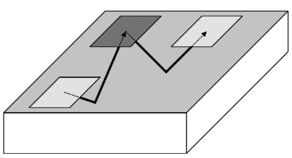

Figure 16: Example of a planar free space system. The beam direction is steered by the optical element on its way between two chips.

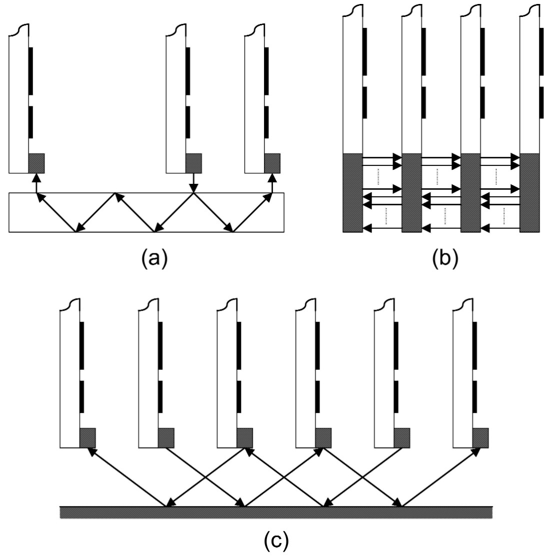

Figure 17: Optical backplane configurations: (a) with planar free space optics, (b) with smart pixel arrays, and (c) with a mirror.

to connect the smart pixel arrays in a ring, where the ring can be reconfigured to embed other topologies [67].

The configuration shown in Figure 17c is similar to the optical backplane based on planar free space interconnects, but the waveguide is replaced here by a mirror [68]. An optical beam leaving a transmitter is simply bounced once on the mirror before it arrives at the receiver. A regeneration of the optical signal might be needed on the way from the source to the final destination.

Of the three types of optical backplanes discussed, the one with smart pixel arrays seems to be the most powerful. On the other hand, a simple passive optical backplane may have other advantages. Other optical backplanes proposed include a bus where optical signals can pass through transparent photo detectors or be modulated by spatial light modulators [69].

6 Optical and Optoelectronic Switch-Fabrics

This section introduces optical and optoelectronic switch-fabrics. The combination of optical interconnections and electronic crossbars is treated first and a discussion is then presented of WDM/SDM switches.

6.1 Optical interconnections and electronic crossbars

The switch itself can be modified to increase performance or packing density. A single-chip switch core where fiber-ribbons are coupled directly to optoelectronic devices on the chip is possible [70]. Attaching 32 incoming and 32 outgoing fiber-ribbons with 800 Mbit/s per fiber translates to an aggregated bandwidth of 204 Gbit/s through the switch when there are eight data fibers per link.

A 16 × 16 crossbar switch chip with integrated optoelectronic I/O was implemented for switching packets transferred using bit-parallel WDM [71]. Each node has two single-mode fibers coupled to the switch, one for input and one for output. Another switch system supporting an arbitrary topology uses 8 × 8 crossbars, where a 12-channel fiber-ribbon link is connected to each port [72]. The aggregated throughput of a single switch is 64 Gbit/s. Multistage networks with free-space interconnections between electronic crossbars have also been reported [10,73,74]. Chips or multi-chip-modules with surface-attached optical I/O are stacked to obtain a 3-dimensional multistage system.

6.2 WDM/SDM switches

The architecture with optical interconnections and electronic crossbars is flexible and powerful. In addition to simply in the I/O interface or as optical interconnections between electronic crossbars, optics and optoelectronics can also be used internally in a switch fabric, however. A broad spectrum of solutions has been proposed, and some examples are given below.

SDM (Space Division Multiplexing) switches [13,75-77] and WDM switches (with, e.g. wavelength converters and wavelength selective components) [78–79] can be used both as stand-alone switches and as building components in larger switch fabrics [80]. As an example, a Banyan multistage network built of 2 × 2 $LiNbO_3$ switch elements has been described [81-82], while a crossbar equivalent system is described in [83]. Another multistage network uses both WDM and SDM switches but in different stages [84]. A multistage network can also be implemented using chips with processors placed on a 2-dimensional plane [85]. The processors then communicate with each other by a mirror that bounces the beam back to the plane but to another processor. Switching is made on the chips while each pass between two switch stages corresponds to a bounce on the mirror.

A multistage switch incorporating both electrical and optical switching, but in different stages, has also been reported [86]. Some work has focused on the communication between stages. An example is perfect shuffle with lenses and prisms [14]. Switch times for SDM switches in the order of 1 ns have been reported [77], while some SDM switches have switch times in the order of 1 ms [87]. A switch can be placed on a dedicated board in a cabinet and be connected to processor boards or line cards via fibers or an optical backplane [88].

A system that implements a distributed crossbar, or a fully connected system, connecting N nodes with only passive optics between the transmitters and receivers has been demonstrated [30]. All optical channels turned on from a transmitter's 2-dimensional $\sqrt{N} \times \sqrt{N}$ VCSEL array are inserted into a fiber image guide. The fiber image guides from all transmitters end at a central free space system with lenses. The lenses are arranged such that the light from each VCSEL pixel in a VCSEL array is focused on a single spot, together with the corresponding pixels in all other arrays. This gives N spots at which each is focused into a single fiber leading to a receiver. Hence, selecting a pixel in a VCSEL array to be turned on corresponds to addressing a destination node. More solutions with free-space connectivity, the fastest with nanoseconds switching, are found in [9].

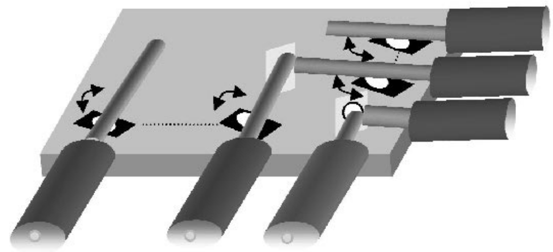

Figure 18: 2-dimensional optical MEMS switch.

Wavelength converters are important components in many WDM switches. A way of building fast wavelength converters is to have conversion first to the electrical domain and then back to the optical domain but on another wavelength. However, this is not a valid solution if an all-optical switch is desired.

A great deal of attention has recently been paid to using MEMS (microelectromechanical systems) technology to build all-optical SDM switches [89]. As reported in [90-91], an array of electrically controlled mirrors can be used to build an 8 × 8 non-blocking OXC (see Figure 18). The optical beams move in 2-dimensional space where each mirror is controlled so that it is either in the down position (no beam bounce) or the up position (beam bounce). The disadvantage of the 2-dimensional MEMS switch is that N^2 mirrors are needed in an $N \times N$ OXC. A more scalable solution is to let the beams travel in 3-dimensional space and to use mirrors for which the angle can be controlled in two axis. In an $N \times N$ OXC, two arrays of size $\sqrt{N} \times \sqrt{N}$ are used. Each beam will first bounce on an input-specific mirror in the first array and then on an output-specific mirror in the second array. Lucent Technologies has already announced 256 × 256 OXCs based on the 3-dimensional MEMS technology for release on the market [92]. Due to the relatively low loss that can be achieved in MEMS switches, multistage MEMS switches are also possible [93]. In this way, rather large optically transparent switches can be built. In addition to pure SDM switches, the MEMS technology can be used in equipment for wavelength routing networks, consisting of wavelength splitters, a MEMS SDM switch and wavelength combiners. More information on all-optical switching is found in [94].

7 Discussion

When designing interconnection fabrics for use in communication equipment one must consider the characteristics of the specific equipment. For example, the interconnection network must have satisfactory blocking property. A blocking network for use in a true or burst-switching packet-switch might be good enough if its capacity well exceeds what is required on average. Splitting packets into fixed-sized cells might also ease the use of a blocking network if the network configuration and transfer of cells are synchronized to occur at regular intervals. If the interruption of a long-duration bit-stream is prohibited, however, even a rearrangeable network might be unacceptable.

Another design issue with impact on the latency and the bandwidth is whether or to what extent an interconnection network includes delaying elements and elements with bandwidth bottlenecks. Examples of elements delaying the data are components that convert the signal between an electrical and optical form, long paths with propagation delays, processing delays and queuing delays. Examples of possible bandwidth bottlenecks are low-quality optoelectronic components, electronic paths like in optoelectronic wavelength converters, protocol processing, queue bandwidth and optical signal degradation. It should, however, be noted that the bandwidth or throughput is not directly limited by delays as experienced in a computer, where a memory read delay can place the computer in an idle state. Instead, the low delay through optoelectronic components can often be neglected when studying the total delay of crossing cities or countries. The delay through network equipment typically becomes considerable first when accounting queuing delays at network congestion.

The interconnection architectures reviewed are summarized in Table 1 with remarks on their suitability in different aspects in data and telecommunication equipment. Switch time is marked as slow (ms), medium (sub-microsecond) or fast (ns) in the table depending on the suitability of adoption in OXCs, packet switches with burst switching or true packet switches, respectively.

Optical transparency is valuable for obtaining protocol-independent OXCs. The MEMS technology is promising for such systems, at least as long as the requirements on switch times are moderate. Multistage networks using MEMS technology can be especially good alternatives because of their scalability. All-optical packet switches, however, will probably not become a mature technology in the near future. One must also think of the flexibility

	Switch Time	Optical Transparency	Scalability	Blocking	Notes
WDM star distributed crossbar	fast	internally	poor to medium	non-blocking	At slow switching, the component's tuning time requirements are relaxed.
WDM ring	fast	internally	poor	non-blocking	At slow switching, the component's tuning time requirements are relaxed.
Fiber-ribbon pipeline ring	fast	no	poor	blocking	Can be compared with a high performance bus but with spatial bandwidth reuse.
Free space optical backplanes	varies a lot	internally for some systems	varies a lot	varies a lot	Scalable if there are many I/O channels on one card. Switching and line cards can be mixed.
Nonblocking MEMS system	slow	yes	medium (or better)	non	
Multistage MEMS system	slow	yes	good	topology dependent	Scalable and optically transparent for systems with relaxed switching time requirements.
WDM/SDM switches	slow (or better)	yes (for some systems)	varies a lot	topology dependent	For optical transparency, only all-optical wavelength conversion is allowed.
Optical interconnections and electronic crossbar	fast	no	poor to medium	non-blocking	Many optoelectronic I/O channels can be integrated on a switching chip/module.
Planar free space optics	fast if no SLMs	no	good	topology dependent	Chips are placed only in two dimensions. Promising in terms of assembly.

Table 1: Summarizing evaluation of reviewed interconnection architectures.

and power of electronic switches and of electronic processors to control the switches.

Scalability is desirable to be able to build equipment with many in/output ports. We state the scalability as poor if only tens of ports are realistic, medium for hundred to a few hundred ports and good for a thousand ports or more. Different multistage networks and free space optical backplanes with a high density of optical channels seem to be good candidates from a scalability point of view. When building smaller systems instead the WDM star distributed crossbar with its passive optical star can be a good and simple alternative.

If an interconnection network implements a true crossbar (like the WDM star distributed crossbar) it is non-blocking, while whether a network is blocking or non-blocking is topology dependent for many of the architectures reviewed. It should however be noted that the fiber-ribbon pipeline ring network is blocking. On the other hand, the increasingly good price/performance ratio for fiber-ribbon links indicates a great success potential for interconnection systems using fiber-ribbon links.

It might be possible to build larger switch-fabrics with high transmission capacities using optics inside a switch. The suitability of the different free space systems depends a great deal on the more detailed configurations of the systems. For example, planar free space systems can be arranged in arbitrary topologies.

Integrated fiber and waveguide solutions make possible the building of compact systems, especially for networks that use fiber-ribbons. The same reasoning about compactness can be argued for free space systems. Optical backplanes may earn their success from their similarities with current rack-based systems, while future planar free-space systems might give the possibility to integrate optics and electronics in a compact and easy to assemble way.

For a more application-oriented comparison, Table 2 summarizes about the suitability of the different interconnection architectures for OXCs, packet switches with burst switching and true packet switches. The switch times of the different interconnection networks have the largest influence on this suitability. In addition to the pure interconnection demands, one must consider how

	OXCs	Packet switches with burst switching	True packet-switches
WDM star distributed crossbar	Not suitable when optical transparency is needed	Good for moderate number of ports	Good for moderate number of ports if tuning time is low
WDM ring	Not suitable when optical transparency is needed	Good for small number of ports	Good for small number of ports if tuning time is low
Fiber-ribbon pipeline ring	Not suitable when optical transparency is needed	Good for small systems if capacity is enough to deal with blocking	Good for small systems if capacity is enough to deal with blocking
Free space optical backplanes	A passive optical backplane can connect other optical components placed on inserted boards	Passive backplanes can connect boards while smart-pixel based backplanes even can participate in the routing decisions	Passive backplanes can connect boards while smart-pixel based backplanes even can participate in the routing decisions
Nonblocking MEMS system	2D MEMS is good for small systems, while 3D MEMS can support rather many ports	Not suitable because of long switch times	Not suitable because of long switch times
Multistage MEMS system	High number of ports is possible, when power budget is acceptable	Not suitable because of long switch times	Not suitable because of long switch times
WDM/SDM switches	A wide area of solutions exists, where wavelength routing functionality often is integrated	Typically not targeted for switching-times short enough for burst switching	Typically not targeted for switching-times short enough for packet switching
Optical interconnections and electronic crossbar	Not suitable when optical transparency is needed	Flexible solution for both small systems (single crossbar) and large systems (multistage or similar)	Flexible solution for both small systems (single crossbar) and large systems (multistage or similar)
Planar free space optics	Integration of reconfigurable all-optical devices must be investigated	Can interconnect electronic crossbars in desired pattern	Can interconnect electronic crossbars in desired pattern

Table 2: Application suitability remarks.

buffering and routing intelligence are included in the communication equipment. Such components or functions can both be integrated into the interconnection fabric and at the entrances and exits of the fabric. A more detailed study of this is out of the scope of this paper, however.

8 Summary

In this paper, we have surveyed a number of interconnection architectures and technologies for use in interconnection fabrics in communication equipment. Some of the technologies can be used in OXCs, burst-switching packet-switches and true packet-switches, while a MEMS-based interconnection fabric is limited to use in an OXC because of its long switch-time. On the other hand, the MEMS technology offers a good choice when requiring optical transparency. In packet switches instead, including electronic crossbars or other electronics can offer required intelligence and flexibility for protocol processing.

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