Optical Time-Switching Systems [and Discussion]

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Optical time-switching systems

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Within recent years there has been a significant amount of interest in applying the new and developing photonics technology for telecommunications switching. As the transmission plant has converted its facilities to fibre there is an economic interest in completing the optical path through the switching system to the terminal facilities without requiring optical-to-electrical conversions. This paper reviews some of the proposed switching systems that use time-multiplexed switching and discusses how, and if, they could fit into current telecommunications networks.

1. Multiple-channel access

In telecommunications there are often physical space channels that connect point x to point y with an available bandwidth B_c. At each of these points there are potential users requiring a bandwidth B_u between these two locations. When $B_c = B_u$ there needs to be one space channel assigned to each user. When $B_c \gg B_u$, it is desirable to share the available bandwidth between several users by allowing *multiple access* to the same space channel. Methods of providing this multiple access can be categorized according to their operational description in either the time or spectral (frequency or wavelength) domain as illustrated in figure 1. To take advantage of the time domain, the pulse widths of the information passing through the channel are shortened to use the available bandwidth. This compression of the data in time allows the compressed information of other users to be combined onto the same space channel. These techniques are referred to as time-division multiple access (TDMA). Several possible implementations of TDMA

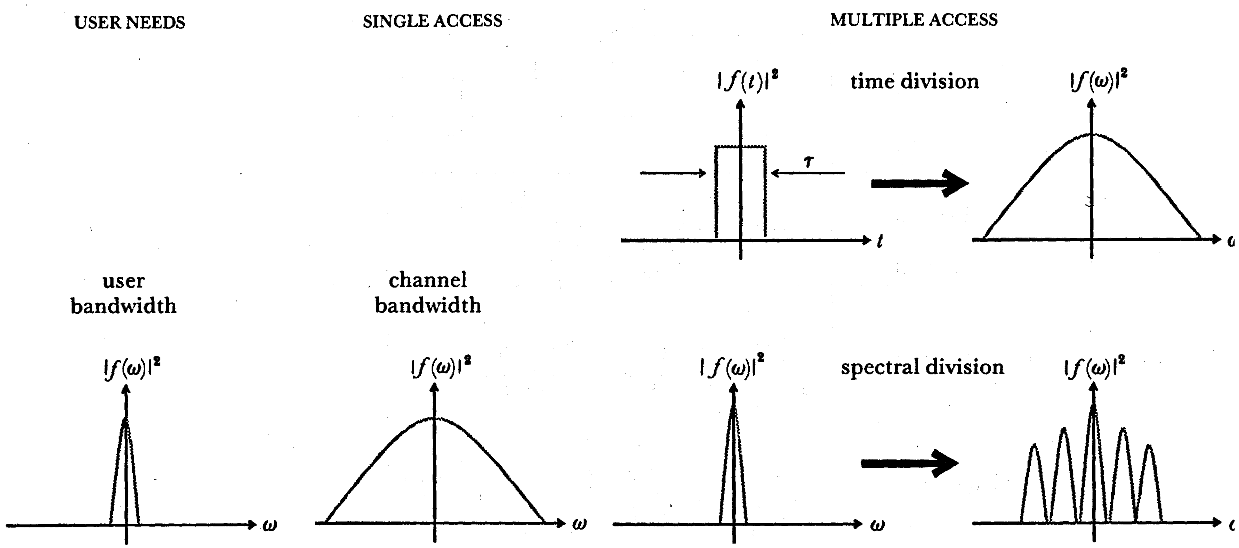

Figure 1. Bandwidth utilization of a single space channel. Time division: bit-multiplexed; block-multiplexed; code-multiplexed; packets. Spectral division: wavelength-multiplexed; frequency-multiplexed.

include bit or block-multiplexed data, code-division and packet switching. As an example, many of the commercially available switching systems have the capability of directly terminating T1 lines that operate at a bit rate of 1.544 Mb s^{-1}. Because digitized voice requires only 64 Kb s^{-1}, 24-voice users are time-multiplexed together to form the 1.544 Mb s^{-1} rate.

The second method of multiple access is to operate in the spectral domain, thus it will be referred to spectral-division multiple access. Implementations include wavelength-division multiple access (WDMA) and frequency-division multiple access (FDMA).

This section will begin by discussing TDMA techniques followed by a brief discussion of spectral-division multiple access.

1.1. *Time-division multiple access*

In this section I outline some of the multiple access techniques that can be used to multiplex information onto a single space channel. First, I discuss TDMA systems implemented by using either bit or block-multiplexed data. Then I discuss an implementation of TDMA based on code-division multiplexing. They are often referred to as code-division multiple access (CDMA) systems.

1.1.1. *Bit versus block multiplexing*

Bit-multiplexing is a method of multiple access in which the time duration of the bits entering the system is equally divided among all the users. This is illustrated in figure 2, where it is assumed that all the users' data streams are bit synchronized. This is normally the multiplexing method of choice for most transmission systems as it only requires the storage of one bit of information for each user at any time. Unfortunately, most of the bit-multiplexed transmission systems are further complicated by adding pulse-stuffing and other special control bits to the data stream. In the switching environment, this multiplexing scheme requires the capability to reconfigure the switching fabric in a time shorter than a single bit duration. For the case of NRZ formats, the reconfiguration will need to be significantly shorter than a single bit duration, whereas RZ formats allow one half of the bit time for reconfiguration.

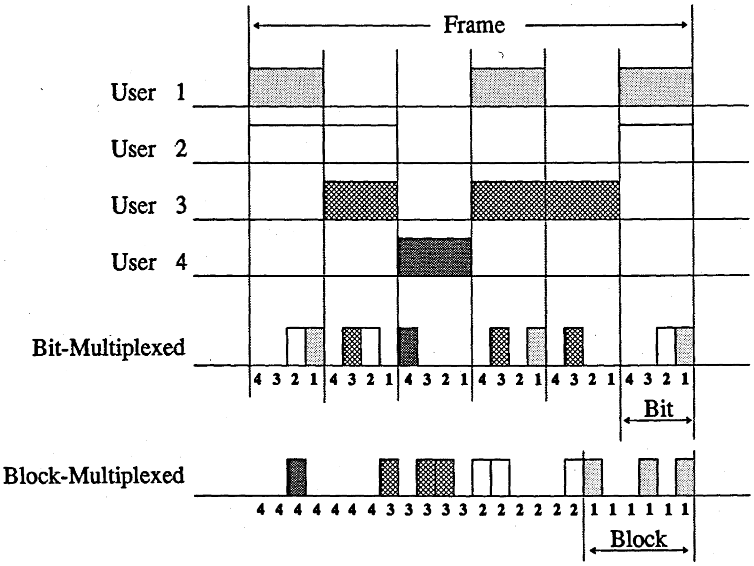

FIGURE 2. Time-division multiple access for both bit and block multiplexing.

Block-multiplexing, on the other hand, stores a frames worth of information from each of the users and then orders the bits entering the channel such that each user's data is contiguous. This also is shown in figure 2. When used in a switching environment, this multiple access method requires the switching fabric to reconfigure only at block boundaries. By allowing a small amount of dead time between the blocked-multiplexed information, the requirements on the reconfiguration time of the fabric can be relaxed. This can be attractive for switching systems, such as lithium niobate systems, that have slow reconfiguration times (Oshima *et al.* 1985).

1.1.2. *Code-division multiple access*

Another method of fully utilizing the available bandwidth, especially in optical fibre, is through the use of either orthogonal or pseudo-orthogonal codes to represent both the bits and the users (Prucnal *et al.* 1986*a*, *b*; Foschini & Vannucci 1988). In figure 3*a* different code sequences, one associated with each user, are used represent the bits. Each bit is then represented by the unique code of the user. When no bit is present, there will be no information present on the user's input channel. In figure 3*b* a conceptual implementation of multiplexing using CDMA is illustrated. Assuming bit-synchronized inputs, the CDMA scheme begins by the generation of a short pulse for every bit entering the system. In the figure this operation is labelled as the pulse generator. This pulse is then split among *k* fibre delay lines. The code sequence representing a given input channel is then composed of a unique collection of pulses (chips) of different delays. The code sequences from each of the encoders are then combined

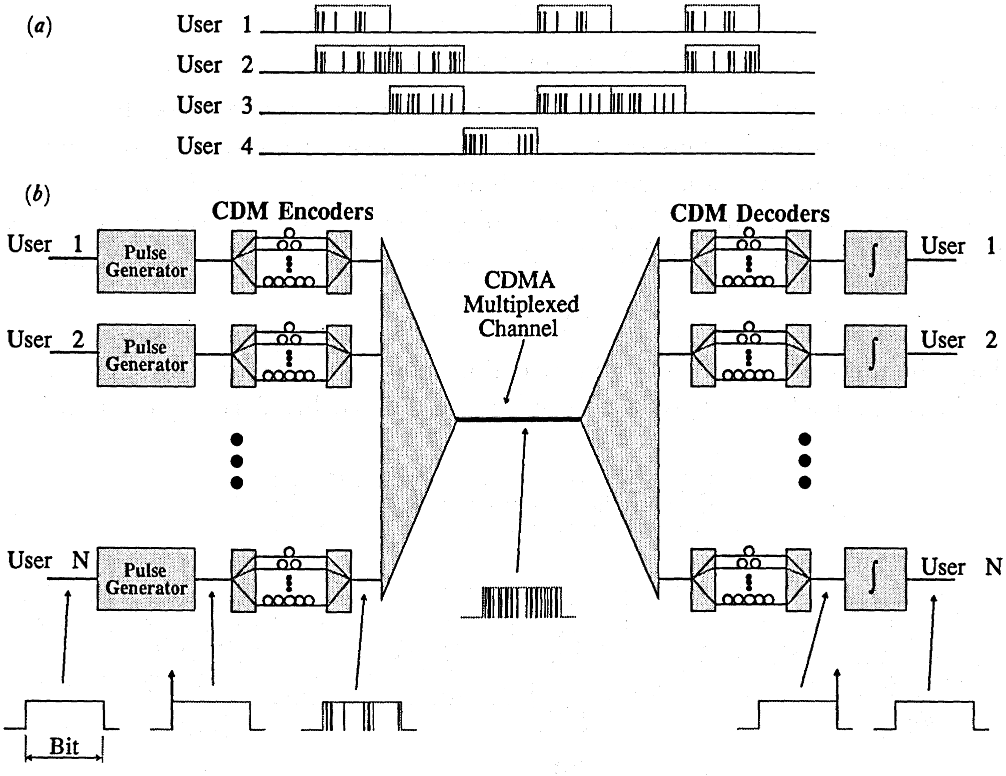

FIGURE 3. Example of code-division multiple access multiplexing where (*a*) illustrates the representation of users' bits and (*b*) is a simple CDMA multiplexing implementation.

and injected onto a single space channel. This CDMA channel is then the superposition of all the different code sequences generated by the encoders. The CDMA decoders, like the encoders, begin by splitting the optical energy among a group of fibre delay lines. The decoder for user j has to undo the code sequence generated by its corresponding encoder. The fibre delay lines in the decoder are set at the appropriate lengths to combine all the individual pulses of a code sequence into a single pulse at the end of a normal bit duration. Since the bit-codes are either orthogonal or pseudo-orthogonal, a simple thresholding decision determines whether a bit is present or not. Finally, the output of the decoder, assuming a bit is present, has to be integrated or stretched to the appropriate bit duration to communicate with the outside world.

1.2. *Spectral-division multiple access*

The other category of bandwidth utilization is to operate in the frequency domain rather than the time domain. This can be accomplished through either WDMA or FDMA. WDMA occurs when each of the users transmits and receives on a specific wavelength. For the case of switching, each user is assigned a fixed transmitting (receiving) wavelength but has the capability to receive (transmit) the wavelengths of all the other users. Thus, for the case of a fixed transmitting wavelength per user, the information to be transported from one user to the other is modulated on to its assigned wavelength λ_1. The receiving user can then lock its tunable receiver onto the wavelength λ_1 and can receive the information (Glance *et al.* 1988).

Frequency-division multiplexing, on the other hand, electronically multiplexes several different frequencies together, and then uses this composite signal to modulate an optical carrier. This is also referred to as subcarrier multiplexing (Darcie 1987).

2. TDMA SWITCHING

In this section I outline several photonic TDMA switching systems that have been either proposed or demonstrated. This section includes discussions on systems that perform bit-switching, block-switching and CDMA switching. There will then be a brief review of multidimensional systems in which other switching dimensions, space and/or wavelength, are combined with the dimension of time. Finally, packet switching will be discussed.

2.1. *Bit-switching*

Perhaps the simplest example of TDMA switching is bit-switching as shown in figure 4 (Yasui & Kikuchi 1987; Tucker *et al.* 1988). In this figure, bit-synchronized information is sampled

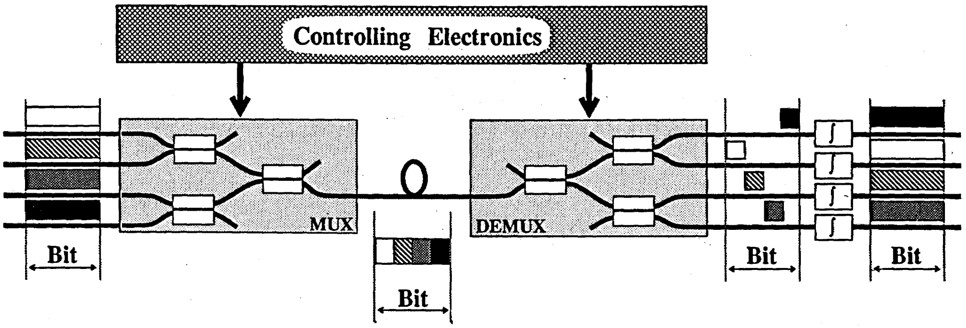

FIGURE 4. A time-division bit switch.

by the multiplexor. In this case there are four inputs forcing the bit duration of the sampled data to be one fourth of the original bit duration. Under the direction of the controlling electronics, the demultiplexor then directs each of the sampled bits to the appropriate destination. These sampled outputs must then go through a device that can stretch the sampled information to an entire bit duration. An example of this could be a bistable laser diode (Suzuki *et al.* 1986).

2.2. *Block-switching*

The first example of TDMA block-switching is the sharing of a linear bus. An example of this is the case where all users have both read and write access to the same bus. Depending on the control scheme, a user can write information onto the bus. The receiving user, once knowing when to read the bus, can receive the information. The control for bus structures can be either centralized using preassigned time-slots or distributed using a packet environment where the users continually monitor the bus, looking for information directed to them.

Another example of TDMA switching is the time-slot interchanger (TSI) illustrated in figure 5. In figure 5*a* the four input signals are time-multiplexed onto a single space channel. User A is put on the bus first, with user D being last. The TSI provides the function of interchanging these time-slots of information in time. For this example, A's time-slot has been moved into the third time-slot. Because the TDMA demultiplexor will direct the first time-slot to user A, a connection has been made between A and C. Also, notice the connections between B and D, C and B, and finally between D and A. Figure 5*b* illustrates a proposed photonic implementation of the TSI (Thompson & Giordano 1987). The input time-slots of the TSI are

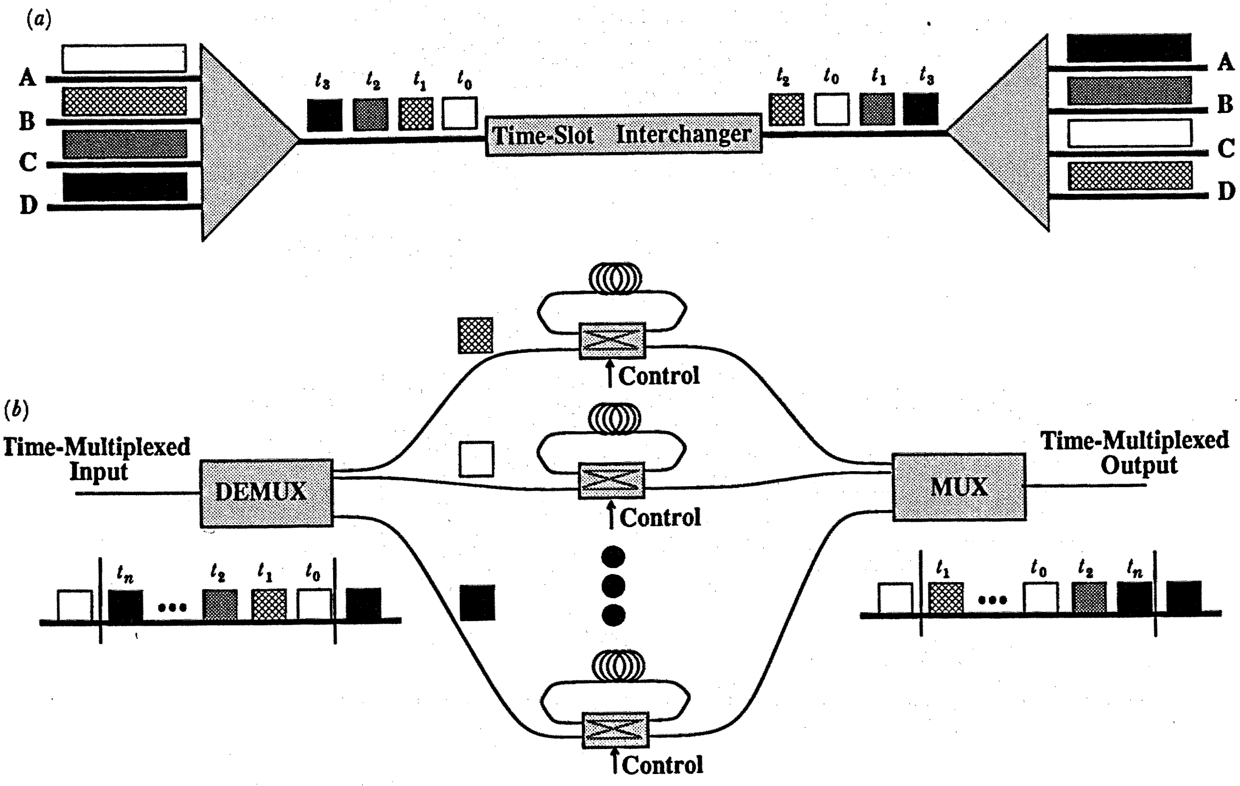

FIGURE 5. TDMA switching using block-multiplexed signal formats are illustrated using a (*a*) conceptual time-slot interchanger, and (*b*) an example of a photonic implementation of a time-slot interchanger.

directed to fibre delay lines where they can recirculate until needed at the output. The fibre delay lines must create a time delay equal to the duration of a time-slot. As an example, the input time-slot t_0 will need to pass through the fibre delay line $n+2$ times, whereas input time-slot t_n will pass through the fibre loop only once.

Regardless of the type of multiplexing used, whether bit or block, there will still be the need to synchronize the incoming data to bit and, in most cases, frame boundaries (Payne & Hinton 1987). This is illustrated in figure 6. In figure 6*a* block-multiplexed inputs are received through the input regenerators by the photonic switch. Because each of the inputs pass through a different amount of fibre, and fibre has a phase delay associated with temperature of 42 ps km^{-1} K^{-1} (Cohen & Fleming 1979), each of the input blocks could arrive at a different point in time. Regardless of how fast the photonic switch can reconfigure itself there will still be bit-phase discontinuities in the switched output channels. As an example, if there is no bit-phase alignment of the channels entering the space switch, after switch reconfiguration there will not be a constant phase relationship between adjacent bits on a given output channel. Thus, the bits on a given output channels will not have the same phase as the bits that preceded them in time. These phase discontinuities could force the regenerators downstream to begin their resynchronization process. This could prevent any information from passing through the network for hundreds of nanoseconds. This is unacceptable! To prevent this problem, elastic stores are normally used to line up both the bit and frame boundaries as illustrated in figure 6*b*.

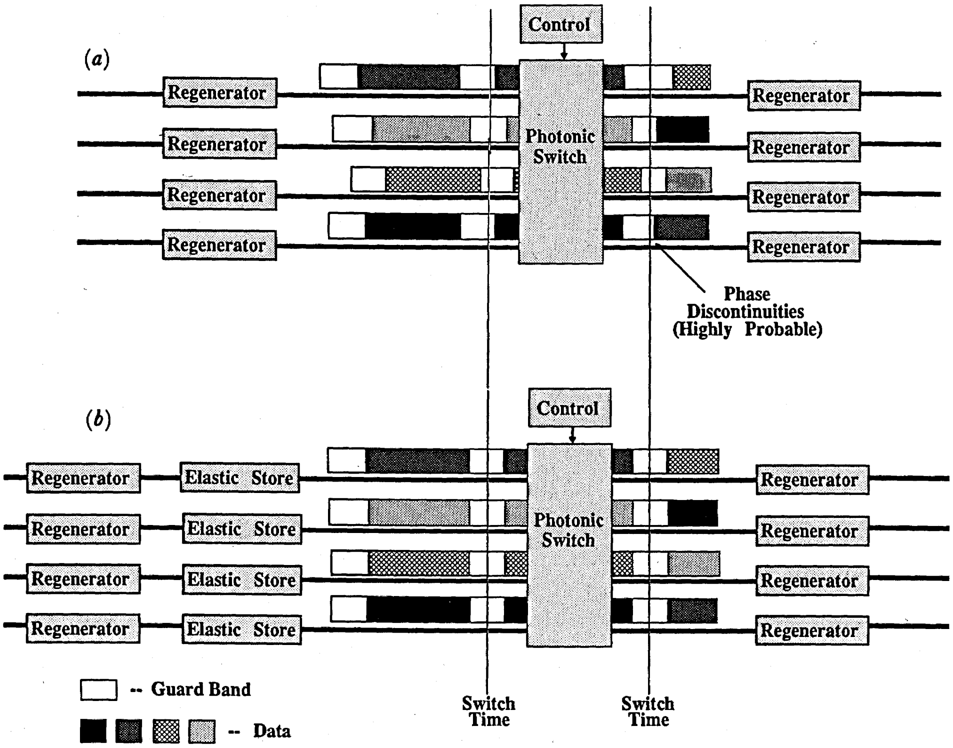

FIGURE 6. (*a*) Unsynchronized photonic switching system, (*b*) synchronization through the use of an elastic store.

A photonic elastic store can be implemented by connecting variable lengths of optical fibre with directional couplers as shown in figure 7 (MacDonald 1987). For this system, when the directional coupler is put in the bar state the incoming light will not pass through the next fibre

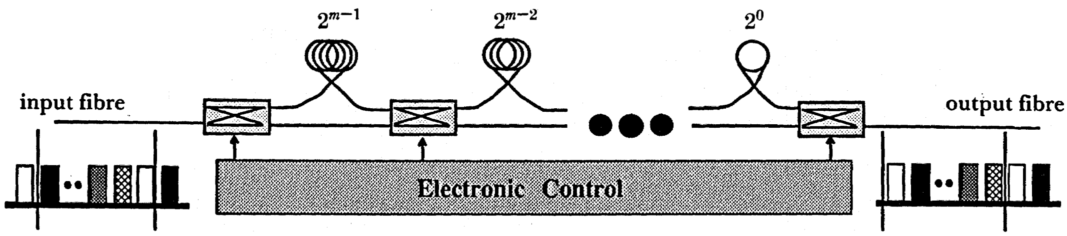

Figure 7. An example of a photonic elastic store (Oshima *et al.* 1985).

loop. On the other hand, if the coupler is put in the cross state the entering light will be forced to travel through the upcoming fibre loop. Each of these loops can be weighted to be integer multiples of minimum allowed bit error, for the bit alignment section, or integer multiples of the bit duration for the frame alignment component of the elastic store. The delay required to line up both the bit and frame boundaries can be calculated by electronically monitoring the input data stream.

2.3. *Ring networks*

Another example of TDMA switching are ring networks, as in the example shown in figure 8. For a synchronous ring structure, each user is assigned a unique piece of time (a time-slot) that is used to read the information on the ring. Other users can send information to a user by entering information into the destination user's time-slot. Access to the time-slots is arbitrated by the centralized control. This figure shows all the users reading the information in their time-slots. User 1 is receiving information from user *j*, user 2 is receiving information from user 1, and user *j* is receiving from user 1. There are also many other schemes for using ring structures for switching applications both with centralized control, as has been previously discussed, and distributed asynchronous control schemes based on packet structures (Khurshid & Rouse 1989).

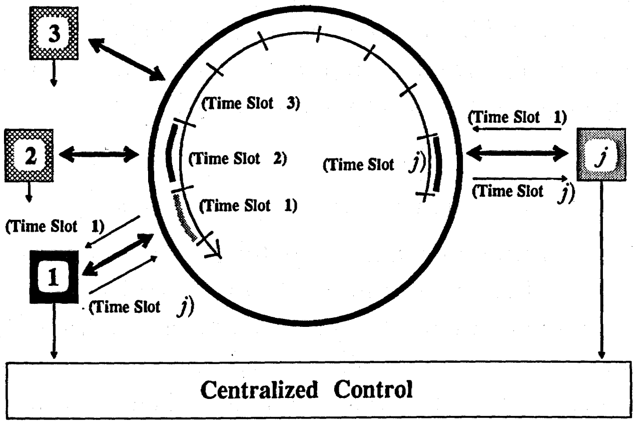

Figure 8. Ring network.

2.4. *CDMA switching*

An example of a switching system based on CDMA is shown in figure 9. The difference between the CDMA multiplexor shown in figure 3 and the CDMA switch of this figure are the tunable decoders. For a switching system, each encoder is fixed for a particular code sequence whereas the decoders must be tunable to all of the input code sequences. This implies that each decoder must contain the inverse of all delay loops present in the encoders. Another

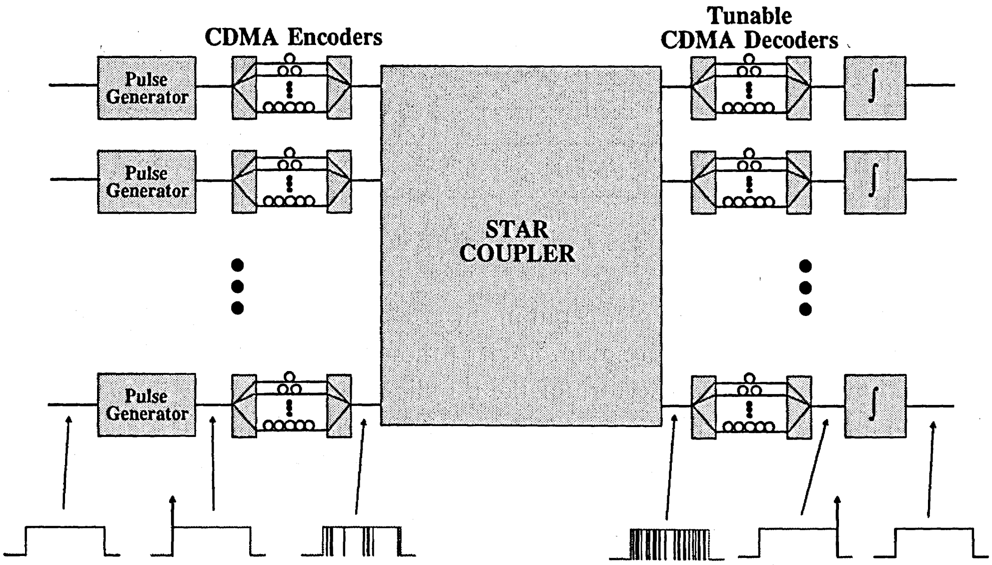

FIGURE 9. CDMA switch.

implementation could have variable encoders and fixed decoders. The star coupler used in this figure could also be used in the CDMA multiplexors described previously because their function is to distribute the signals from each input channel to all the output channels (Saleh & Kogelnik 1988). This allows each output decoder to access any of the input channels, and to provide a strictly non-blocking switch.

The strength of this CDMA switching system is that the high-speed portion of the system control is both distributed and photonic. This distributed control is the result of the code sequence being an effective address read by the designated decoder. The role of the controlling electronics is to determine which fibre delay lines are to be included for a given decoder. The weakness of these CDMA switching systems is that $k \ll N$, which limits them to smaller systems, with low traffic environments, such as local area networks.

3. MULTIDIMENSIONAL SWITCHING

In the early days of telecommunications switching, the switching fabrics used in the switching systems were space division. With the advent of digitized voice it became apparent that electronic hardware in the fabric itself could be reduced by adding the dimension of time to the space-division fabric. As an example, if a 1024×1024 space-division switch were able to switch 128 time-slots per frame (1 frame = 125 μs), then a switching fabric with a dimensionality of *ca.* 128000×128000 could be made (4ESS$^{\text{TM}}$).

There are many ways of combining these two switching dimensions; they include time–space (TS), space–time (ST), time–space–time (TST), space–time–space (STS), etc. Figure 10 is an example of a TST switching fabric. This figure has outlined the path of a time-slot from input to output. Note that for a TST switching fabric the input first sees a time-slot interchanger (TSI) which is the initial 'T' of TST. The signal then passes through a space switch (the 'S' part), and then finally the information passes through another TSI, which is the final 'T'.

Another method of extending TDMA is by blending time and wavelength together. As with time and space systems, time–wavelength division systems can be decomposed into

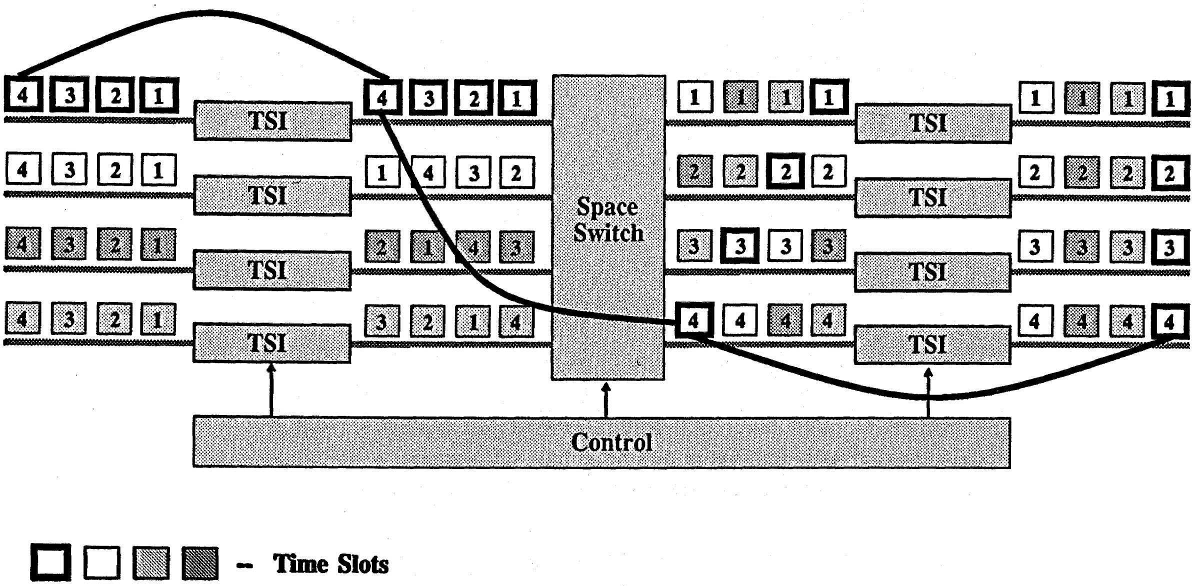

Figure 10. An example of a time–space–time switch.

wavelength–time (WT), time–wavelength (TW), time–wavelength–time (TWT), etc. Finally, switching systems can be made by using time, space and wavelength.

An example of a 512 × 512 TST switch is shown in figure 11. In this figure the input lines are partitioned into sections of 32 lines which are time-multiplexed onto a single space channel. Thus, each channel consists of 32 time-slots. If the bit-rate of the input signals is 150 Mb s^{-1}, then the time-multiplexed information stream will require a bit-rate greater than 4.8 Gb s^{-1} ($\approx$ 200 ps bit^{-1}). This TDMA signal then enters the TSI where the 32 time-slots can be interchanged. From there the information enters the space-division switch (the advantage of multidimensional switching, the size of the space switch can be small). The output of the space switch is directed to the output TSI, the output of which is then demultiplexed to the output space channels. The difficulty with TST configurations is the timing requirements imposed upon the centralized control. As an example, to avoid any phase discontinuities on the output channels from the space switch, there needs to be bit alignment of the TDMA information stream entering the 16 × 16 switch. Assuming a 5 Gb s^{-1} bit-rate implies that each bit has a pulse duration of 200 ps. Thus, to prevent these phase discontinuities on the output channels, all the input bits should be bit-aligned to within 10 ps of each other. This timing burden will be placed on the initial TDMA multiplexor or else an elastic store will have to be placed on the input to the space switch. (This assumes that the controlling electronics can recognize variations of order 10 ps.) To illustrate the critical packaging problem, if the length of fibre from two TSIs differs by 1 cm (assuming an index of refraction of 1.5 in the fibre), there will be a 50 ps difference in the bit arrival times at the space switch. In addition to the bit and frame alignment required by the space switch, each TSI will require the alignment of bit and frame boundaries to prevent phase discontinuities on its output channel.

The strength of the multidimensional switching structures, such as the TST switch previously shown, is the minimal amount of hardware required to build them. An example of a pure space-division switch, a rearrangeably non-blocking interconnection network based on perfect shuffles is shown in figure 12. The basic building block is a 2 × 2 switch, which could be a $LiNbO_3$ switch or an OEIC structure with fibres both entering and leaving the substrate. This

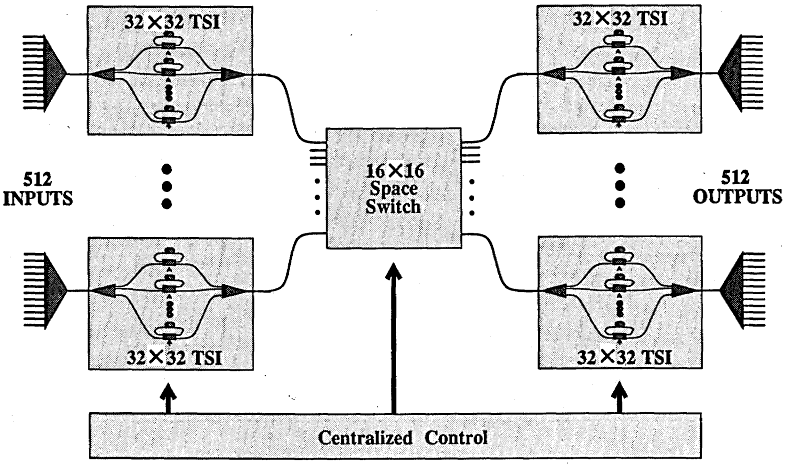

FIGURE 11. 512 × 512 time–space–time switch.

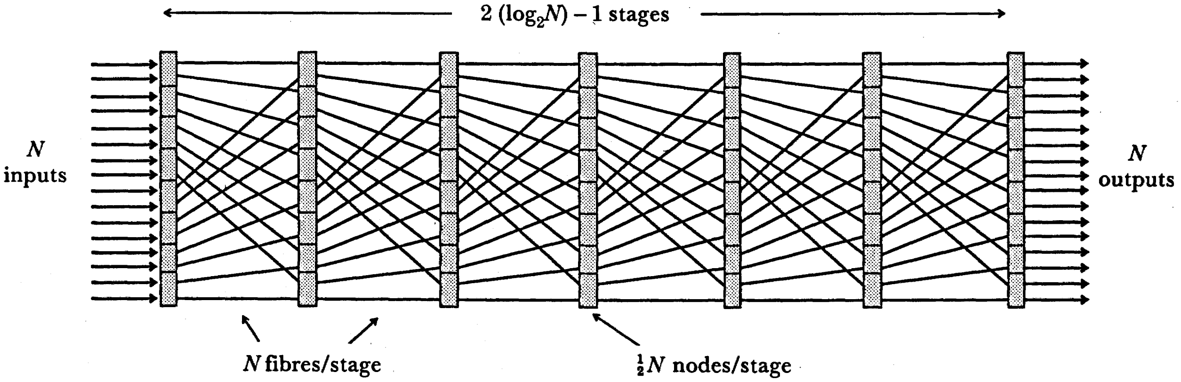

FIGURE 12. 512 × 512 rearrangeably non-blocking space-division interconnection network.

space switch requires *ca.* 13000 fibres and *ca.* 6600 2 × 2 switches. The cost of connectors for these fibres, at approximately \$100 per connector, is by itself enough to prevent it from ever becoming economically feasible. The TST switch of figure 11 requires *ca.* 2000 fibres, 32 multiplexors (demultiplexors), one 16 × 16 space-division switch, and *ca.* 1000 directional couplers for the TSIs. Even less hardware is required for a ring or linear bus network (512 × 512), which would require 512 fibres and 512 switching nodes. The disadvantage of the ring structure is the *ca.* 80 Gb s^{-1} bit-rate on the single TDMA channel. Thus the advantage of minimized hardware comes at the cost of increased timing complexity.

4. PACKET SWITCHING

Packets are another method of allocating the available bandwidth of a channel. For this approach, the bit-rate of the information passing through the channel is set at its maximum possible value. The information from the users is collected and stored in small amounts, which can be either fixed or variable lengths. When the channel is available, the data is injected into the channel with a special header directing the path to be followed by the data. The header normally provides the address information necessary for the transmitted data to get to its destination. One of the advantages of packet type systems is that their control structure is distributed rather than centralized.

5. CONCLUSIONS

This paper has presented several different implementations of photonic switching systems that use time-division to more effectively exploit the available bandwidth of the optical domain. It presented TDMA structures that implemented bit, block, CDMA and packet switching fabrics. There was also a discussion of the critical need of synchronization for most of these systems. Finally, it was pointed out that the advantage of hardware minimization comes at a cost of timing complexity.

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Discussion

J. E. MIDWINTER, F.ENG., F.R.S. (*UCL, London, U.K.*). I believe the poor extrapolation for CDMA networks between code complexity and number of terminals arises because of incoherent detection. Does Mr Hinton agree?

H. S. HINTON. Through the use of coherent detection techniques, pseudo-noise sequences can provide as many as N codes for a bandwidth expansion of N. This is because the correlation required at the receiver is based on phase information that allows both ± 1 levels. Incoherent detection, on the other hand, is confined to intensity information only (e.g. 0, 1 levels) limiting these systems to $\sqrt{N}$ sequences for a bandwidth expansion of N. Therefore, fewer orthogonal sequences can be generated for a given bandwidth expansion. However, at the present time a simple demonstration of a CDMA switching fabric is simpler to implement using the incoherent techniques.

W. J. STEWART (*Plessey Research & Technology (Caswell) Ltd, Towcester, U.K.*). The space-switch size problem is not unique to optics; an electronic switch performing a similar function is large, and this is in part why electronic exchanges do not work this way.

H. S. HINTON. Time-multiplexed switches have typically been used to create large-dimensional switching systems. As the bit-rates increase time-multiplexed switching systems will become more difficult to implement. The connectivity of free-space has the hope and potential of implementing larger space-division fabrics than are possible using electrical or guided-wave interconnects.

D. J. SKELLERN (*Hewlett-Packard Labs, Bristol, U.K.*). The target switch size Mr Hinton has set for this study is a challenging one and serves well to identify the problems for all the approaches he reports. I wonder, however, if a distributed scheme with smaller fabrics might not be a more useful proposition, even in the long term. Has he considered such distributed systems? If so, would he comment on their suitability?

H. S. HINTON. I have not studied the constraints limiting a distributed switching system. I do have several concerns: (1) the software development cost, (2) the cost of interconnects between the distributed switching elements, and (3) the control strategy required for the desired performance.

B. PICKTHORNE (*University of Aston, Birmingham, U.K.*). What are the more significant drawbacks associated with CDMA switching?

H. S. HINTON. The most significant limitation is the relatively small number of terminals that can be supported. Another practical concern is the cost per port of such a system.