Duality Relationships Among "Space," "Time," and "Wavelength" in All-Optical Networks

Hisashi Kobayashi, *Fellow, IEEE,* and Ivan P. Kaminow, *Life Fellow, IEEE*

Abstract— **All-optical networks (AON's) are emerging as the next generation broadband networks for both wide-area and local-area networks. New optical devices such as wavelength routers, and wavelength division switches are currently being developed to realize these AON's. In this paper, we examine "dual" properties that exist among "space," "time," and "wavelength" in multiplexed signals in AON's. This observation will clarify relationships among architectural alternatives and suggest novel space-time-wavelength switching structures. It will also lead to a performance analysis of all-optical networks, by exploiting some well studied results obtained for classical circuit switched systems. A study on call blocking probabilities will be reported in a separate paper [11].**

I. Introduction

All-optical networks (AON's) are emerging as the next generation broadband networks for both wide-area and local-area networks. The term AON includes networks based on wavelength routing over all or part of their span, providing optical transparency to modulation format. In order to fully exploit the enormous bandwidth that optical channels can provide, it is essential to make the best use of WDM (wavelength division multiplexing), TDM (time division multiplexing), and SDM (space division multiplexing).

The purpose of the present study is to investigate network architectures that can provide maximal connectivity among a large number of end users. We propose new forms of optical routers and switches, which are obtained by investigating duality relationships that exists among space, time, and wavelength. Throughout the paper we assume that a given network operates in the circuit-switching mode. In other words, in order to establish a circuit connection between a pair of end users, a scheduler must allocate a path between them by finding available wavelength(s) and time slot(s) in each link along the path. In order to support a large number of "calls" simultaneously, the network must provide sufficient connectivities. We are thus interested in designing switches that can provide a variety of connection patterns at the network level. Such switches will be extremely useful, for example, as *cross-connect* nodes in high-capacity optical networks.

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H. Kobayashi is with the Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA.

I. P. Kaminow was with AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733 USA. He is now serving as IEEE Congressional Fellow on the staff of the House Science Committee.

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It should be noted that in the circuit-switching mode no contention exists among accepted "calls." It is the responsibility of a scheduler, often called CAC (call admission control, or connection admission control) to insure that a given set of time slot, wavelength, and port should not be assigned to more than one call. When a new call connection is requested but the scheduler cannot find any circuit (which consists of available time slot, wavelength, and port over each link along a satisfactory path), the call is blocked or lost. Thus, the call blocking probability is a main measure of QoS (quality of service) in circuit-switched networks. In a related paper [11], we report the performance analysis of all-optical networks of the type discussed in the present paper.

A space division switch can be viewed as a device that establishes circuit connections simultaneously among a number of terminals (end-users) that are spatially separated. A space division switch can be implemented by means of an interconnection network, and a considerable body of knowledge exists on this subject (see, e.g., Hui [8] and references therein). Similarly, time division switching can be viewed as a means that provides simultaneous connectivity for many calls that are time multiplexed; different calls occupy different time "slots" in a frame. Time division switching can be performed by a device called TSI (time slot interchanger). A TSI is the time-domain analog of the space division switch, and the functional equivalence between time division switching and space division switching is well studied (see e.g., [8], [10], [14]).

For optical networks, several types of space division switches are being developed. One type is based on 2×2 $LiNbO_3$ switching elements interconnected as a multi-stage network. An optical TSI, on the other hand, is yet to be developed, although some limited forms of TSI have been reported in the literature [7], [9], [15]. The main difficulty with optical TSI lies in the fact that there is no optical analog of the electronic buffer with random access capability. An optical fiber used as a delay line could serve in principle as an optical memory, but its extensive usage is clearly limited to increments of fixed delay with storage capacity proportional to the delay element. Furthermore, although FIFO (first-in, first-out) "write-in" and "read-out" capabilities are available in such optical memory, random access is limited due to the serial nature of the delay line.

In optical networks, frequency division multiplexing (FDM) is often referred to as wavelength division multiplexing (WDM). A device called "wavelength grating router (WGR)" (also known as $N \times N$ multiplexer) has been developed to provide interconnections, for example, between smaller subnetworks (e.g., LAN's) in an AON, and allow wavelengths to be reused in different parts of the network (see Alexander *et al.* [1]).

In Section II, we discuss in some detail properties of the WGR. A wavelength analog of TSI is what is called a "wavelength interchanger," "wavelength division switch (WDS)," or "frequency division switch (FDS)," and can be implemented by using an array of "wavelength converters (WC's)." It is an emerging optical device, and some prototype devices have been recently reported. The objective of the present study is to investigate how the availability or unavailability of TSI and WDS will impact the capability of AON's in terms of channel connectivity.

II. Wavelength Routers: Static Router and Dynamic Router with Space Switching

An important element in a class of AON's discussed in [1] is a wavelength grating router (WGR) [5]—or an $N \times N$ multiplexer [4] or static wavelength router [1]—which is shown schematically in Fig. 1(a). The WGR can also be represented by an array of demultiplexers, followed by an array of multiplexers as shown in Fig. 1(b) [2], [6]. If WDM optical signals are routed by this device, we can represent the input signal by a pair (λ_f, σ_n), where λ_f represents the *wavelength* ($f = 0, 1 \cdots, F-1$); and σ_n represents the *space* identifier or port number of the router ($n = 0, 1, \cdots, N-1$). Although a special case, where F (i.e., the number of available wavelengths) and N (the number of input and output ports) are equal, is often discussed [1] and [2], it is not necessary to impose the constraint $N = F$. The function of the $N \times N$ WGR of Fig. 1 can be viewed as a mapping between the input pair and the output pair

$$\phi_{N\times N}\colon \quad (\lambda_f, \sigma_n) \rightarrow (\lambda_f, \sigma_{n'}) \tag{1}$$

where $f = 0, 1, \cdots, F-1$; $n, n' = 0, 1, \cdots, N-1$. The output port index n' is uniquely determined by

$$\begin{aligned} n' &= n + f \pmod N, \\ &\quad 0 \le n, n' \le N-1, \quad 0 \le f \le F-1. \end{aligned} \tag{2}$$

If we define the *degree of connectivity* C as the number of realizable distinct circuit connections between end node pairs, we find that the $N \times N$ WGR with WDM signals provides

$$C = NF, \quad \text{for} \quad N \times N \text{ WGR} \tag{3}$$

where N and F are the degrees of multiplexing in space and wavelength, respectively. The mapping rule of (2) allows us to route individual wavelengths λ_f of each input σ_n to appropriate output $\sigma_{n'}$ with no interference, i.e., no more than one input signal is routed to the same output using the same wavelength. Hence, we can establish NF circuit connections *simultaneously.* The mathematical representation of WGR in terms of (1) and (2) suggests that we consider an $N \times N'$ WGR, where N and N' are not necessarily equal. In other words, we consider the following mapping:

$$\phi_{N\times N'}\colon \quad (\lambda_f, \sigma_n) \rightarrow (\lambda_f, \sigma_{n'}) \tag{4}$$

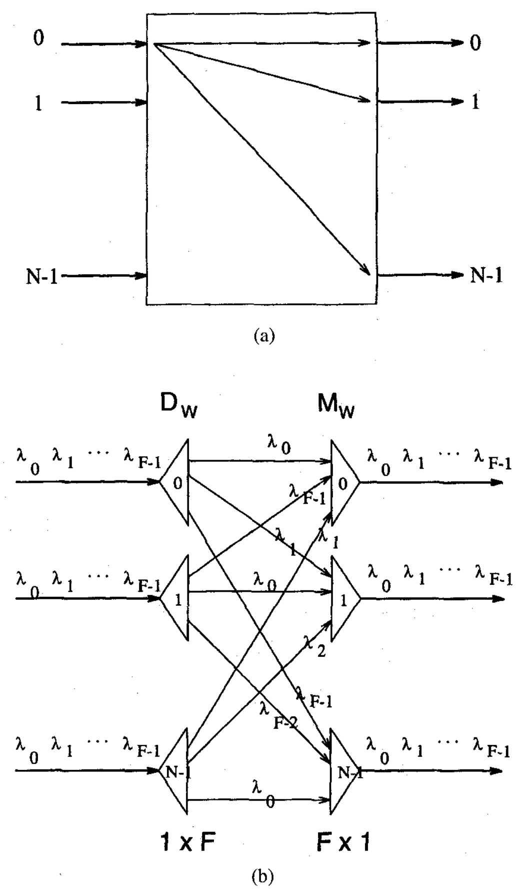


Fig. 1. (a) $N \times N$ wavelength grating router (or static wavelength router) and (b) demultiplexer–multiplexer representation of the $N \times N$ WGR.

where

$$\begin{aligned} n' &= n + f \pmod{N'}, \\ &\quad 0 \le n \le N-1, \quad 0 \le n' \le N'-1, \\ &\quad 0 \le f \le F-1. \end{aligned} \tag{5}$$

The $N \times N$ WGR implementation proposed by Dragone [4] can be generalized to construct the above defined $N \times N'$ WGR. Equation (3) for the degree of connectivity should now be modified to

$$C = \min\{N, N'\}F, \quad \text{for} \quad N \times N' \text{ WGR} \tag{6}$$

because for a given wavelength, no more than one input signal should be routed to some output to avoid an interference.

Brackett [2] shows that the $N \times N$ WGR can be represented by the N array of demultiplexers ($1 \times F$) followed by the N array of multiplexers ($F \times 1$), as is shown for the special case $N = F$ in Fig. 1(b). If we insert an array of space switches of the size $N \times N$ between the demultiplexers array and the multiplexer array, we obtain what is called a "dynamic router" [1], or a "wavelength-space division hybrid router" [6]. The structure can be generalized to the $N \times N'$ router proposed above, and we obtain the configuration of Fig. 2. Switch S_f performs space switching on signals that are carried by wavelength λ_f, ($f = 0, 1, \cdots, F-1$).

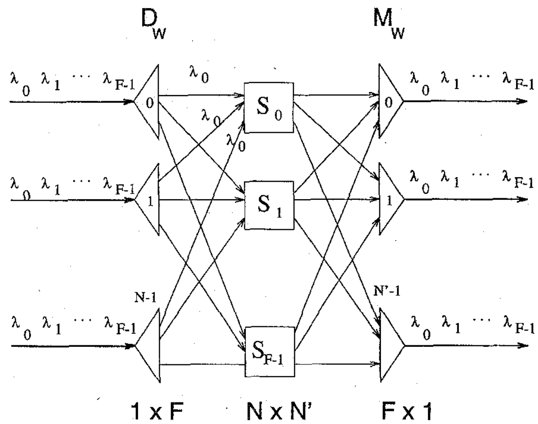


Fig. 2. $N \times N'$ wavelength router with space switching (or $N \times N'$ dynamic wavelength router) routing patterns (2) for the $N \times N$ WGR.

The degree of connectivity is now increased to

$$C = NN'F, \quad \text{for} \quad N \times N' \text{ dynamic router.} \tag{7}$$

Note that the total number of circuit connections (point-to-point) that can be supported simultaneously is still $\min\{N, N'\}F$: the insertion of the F spatial switches increases the total number of realizable connections, but many of these connections interfere at the output ports.

It will be instructive to note that the router of Fig. 2 will reduce to the static router of Fig. 1, if we fix the connection matrices of space switches, $S_0, S_1, \cdots, S_{F-1}$. If $N = N'$, then the following $N \times N$ constant matrices represent the connection patterns that correspond to wavelength routing patterns (2) for the $N \times N$ WGR:

$$\mathbf{S}_0 = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} = \mathbf{I}$$

$$\mathbf{S}_1 = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & 0 & 0 & \cdots & 0 \end{bmatrix} \doteq \mathbf{D}$$

$$\mathbf{S}_2 = \begin{bmatrix} 0 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 1 & 0 & \cdots & 0 \end{bmatrix} = \mathbf{D}^2$$

$$\mathbf{S}_f = \mathbf{D}^f, \quad f = 0, 1, 2, \cdots, F-1 \tag{8}$$

where $N \times N$ matrix $\mathbf{D} = \mathbf{S}_1$ corresponds to a cycle shift operation, and the addition and multiplication are done in the "modulo 2" operation, i.e., $1 + 1 = 0$, $1 \times 1 = 1$, etc. The (n, n') entry of the matrix $\mathbf{S}_f$ is unity (=1), if the signal carried by wavelength λ_f entering input port σ_n is routed to output $\sigma_{n'}$; the (n, n') entry is zero, otherwise. Note that

$$\mathbf{D}^N = \mathbf{I} = \mathbf{S}_0 \tag{9}$$

where $\mathbf{I}$ is the $N \times N$ identity matrix. Hence, if $F > N$, then $\mathbf{S}_N = \mathbf{S}_0, \mathbf{S}_{N+1} = \mathbf{S}_1, \cdots, \mathbf{S}_{F-1} = \mathbf{S}_{F-1_{(\text{mod } N)}}$. This observation confirms (6) for the connectivity.

III. Time-Domain Dual of Dynamic Wavelength Router and Introduction of Wavelength Converter

Before we further discuss properties of the dynamic wavelength router, let us consider its time domain counterpart. In Fig. 3(a) we reproduce the dynamic wavelength router of Fig. 2 in somewhat simplified form. D_W represents a demultiplexer for WDM signals, and M_W is a wavelength multiplexer. Fig. 3(b) represents its time-domain counterpart, where the input signals are time-division demultiplexed by a device denoted D_T, and space-switched by an array of $N \times N$ space switches, labeled $0, \cdots, T-1$, where T is the number of time slots per frame of the incoming TDM signals.[1] The switched outputs are then multiplexed by M_T. The ith space switch acts on signals in the ith time slot of the N TDM signals ($i = 0, 1, \cdots, T-1$). It may be appropriate to call this structure a "dynamic time slot router" in analogy to the dynamic wavelength router. If the T space switches are realized by one space switch that is time shared, the resulting structure is what is known as time-multiplexed space switch (TMS) in digital switching [14]. The degree of connectivity for this router/switch is

$$C = NN'T, \quad \text{for a "dynamic time slot router" or TMS.} \tag{10}$$

Let us insert an array of TSI (which we simply denote T in Fig. 4(b) and the following diagrams) between the array of D_T (demultiplexers) and that of space switches. Let each of the time switches be $T \times \tau$, where τ is the number of time slots per frame in the TSI output. When we use a TMS switch for the center-stage space switches, it must operate at the rate of τ slots per frame time. The significance of the parameter τ will become clear in the following discussion. Similarly, we insert another array of TSI ($\tau \times T$ switches) between the array of space switches and that of M_T (multiplexers). The resulting structure is equivalent to what is known as a T-S-T, a three-stage switched network. This T-S-T switch is mathematically equivalent to a Clos network. Therefore, by applying the results by Clos, Slepian, and Paull [3], [8], [12] we find the following properties.

1) The T-S-T switch of Fig. 4(b) is *nonblocking* if and only if

$$\tau \geq T + T' - 1. \tag{11}$$

2) The T-S-T switch is *rearrangeably nonblocking*, if and only if

$$\tau \geq \max\{T, T'\}. \tag{12}$$

[1] We also use the symbol "T" to denote a "time division switch" or TSI in some of the diagrams. This should not be confused with T, the degree of multiplexing in TDM.

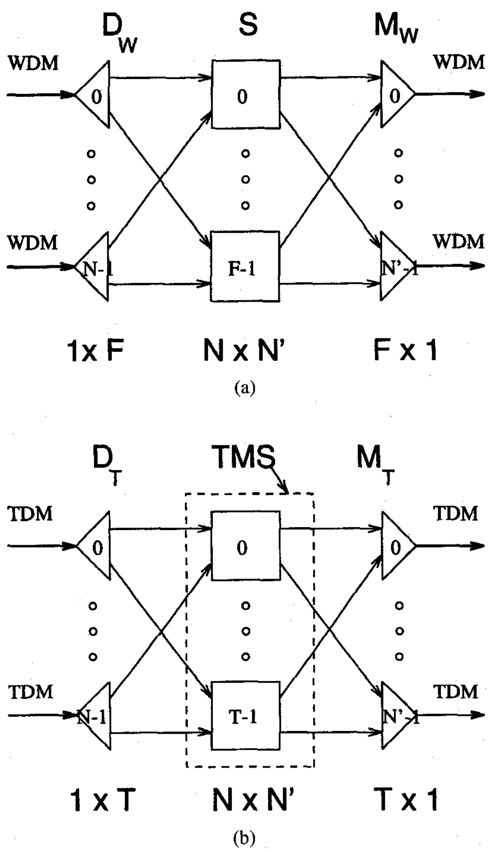


Fig. 3. (a) Dynamic wavelength router and (b) dynamic time slot router, or time multiplexed space (TMS) switch.

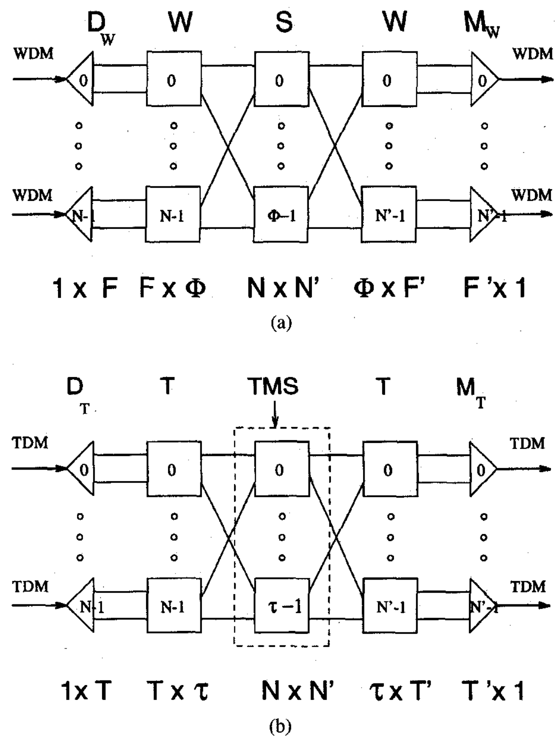


Fig. 4. (a) W-S-W switches with WDM signals and (b) T-S-T switches with TDM signals.

3) The number of existing connections (i.e., circuits) that need to be rearranged in (2) is at most $\min\{N, N'\}$.

Now if we replace the time domain in the structure of Fig. 4(b) by the wavelength domain, we will obtain the structure shown in Fig. 4(a). The $F \times \Phi$ switch, W, is the wavelength counterpart of the TSI switch T and can be implemented by using an array of wavelength converters, WC's, (also called frequency changers), followed by a router, whose outputs ought to be in the right order, i.e., $\lambda'_0, \cdots, \lambda'_{\Phi-1}$, independent of the ordering at the inputs $\lambda'_f, \cdots, \lambda'_g$, as shown in Fig. 5(b). The sequence of wavelengths in the spectrum is analogous to the sequence of time slots in a frame. The signal is determined by the bit-stream modulated in a given time slot or wavelength. The WC changes the carrier wavelength but leaves the data bits unchanged.

We should note that Φ, the number of output wavelengths can be different (preferably greater) than F, the number of input wavelengths. Furthermore, an element of the set $\{\lambda_0, \lambda_1, \cdots, \lambda_{F-1}\}$ need not be the same as any element of the set $\{\lambda'_0, \lambda'_1, \cdots, \lambda'_{\Phi-1}\}$. The latter set is locally defined within the individual W switch. Therefore, we may be able to choose the parameter Φ much greater than F or F' where F' is the number of wavelengths at the output switches W'. The $\Phi \times \Phi$ "router" in Fig. 5(b) is functionally similar to the WGR of Fig. 1, but the incoming signal to each input port is not a WDM signal, but one wavelength signal. Furthermore, only $F(\leq\Phi)$ input ports are active at any given time. One way to realize this "router" is to have a wavelength "combiner" followed by a grating-based demultiplexer ($1 \times \Phi$), as shown in Fig. 5(c). Note that a wavelength combiner is different from a wavelength multiplexer: the latter is wavelength sensitive and is typically realized by a grating, and the assigned order of wavelengths in the input ports matters, whereas the former is wavelength insensitive and simply combines multiple inputs. An optical star coupler, for instance, can serve as a combiner. In a $\Phi \times 1$ combiner, only $1/\Phi$ of the power at a given input appears at the output.

Using an argument parallel to the one that led to the blocking properties of the T-S-T switch, we can make the following statements.

1) The W-S-W switch of Fig. 4(a) is *nonblocking* if and only if

$$\Phi \geq F + F' - 1. \tag{13}$$

2) The W-S-W switch is *rearrangeably nonblocking*, if and only if

$$\Phi \geq \max\{F, F'\}. \tag{14}$$

3) The number of existing connections (i.e., circuits) that need to be rearranged in 2') is at most $\min\{N, N'\}$.

The degree of connectivity of the three stage switches in Fig. 4(a) and (b) are given by

$$C = NN'FF', \quad \text{for the W-S-W switch with WDM signals} \tag{15}$$

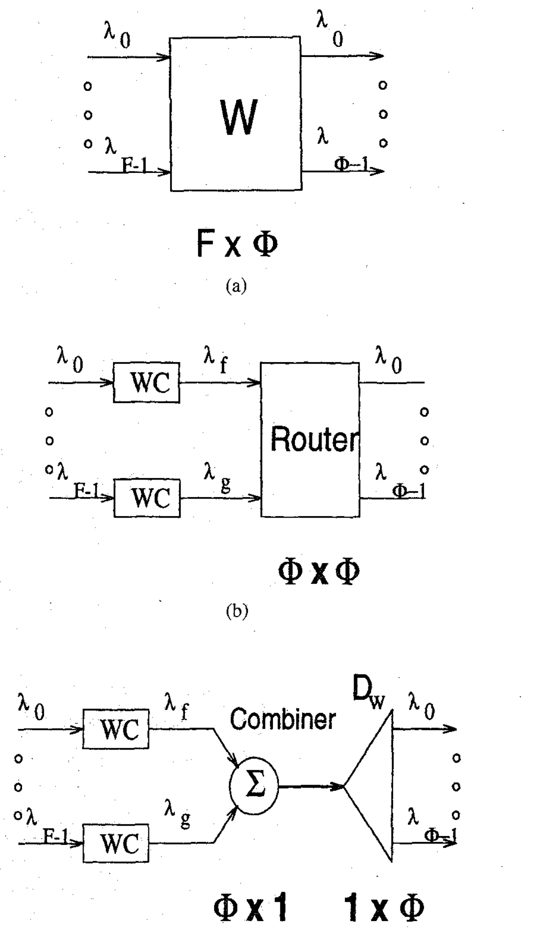


Fig. 5. (a) Wavelength interchanger, (b) wavelength converters followed by a "router", and (c) actual implementation example.

and

$$C = NN'TT', \quad \text{for the T-S-T switch with TDM signals.} \tag{16}$$

The maximum of simultaneous circuit connections (point-to-point) are $\min\{NF, N'F'\}$ and $\min\{NT, N'T'\}$, respectively.

Suppose that $T' \geq T$ in the T-S-T switching network of Fig. 4(b). If we choose τ equal to T', this three-stage switch is not nonblocking, but rearrangeably nonblocking. Then each of the output TSI's is a $T' \times T'$ switch. The output TSI switches are required only if a specific sequence order is to be provided at the output. They are not really necessary in order to realize connectivities of TDM signals.

Similarly, consider the case $F' \geq F$ in the W-S-W switch of Fig. 4(a). If we choose Φ equal to F', then the three-stage switch is not nonblocking, but rearrangeably nonblocking. Using the same argument as presented above, the output wavelength interchangers (W switches) may not be necessary, unless a specific sequence of carrier wavelengths for the output channels is required. We show these simplified routers in Fig. 6(a) and (b). The degree of connectivity remains unchanged by the deletion of the output W switches and T switches:

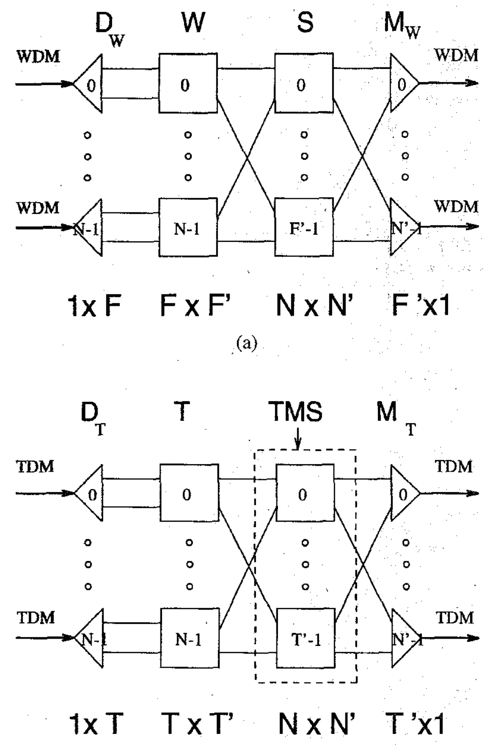


Fig. 6. (a) W-S switches (i.e., no output Ws) and (b) T-S switches (i.e., no output TSI's).

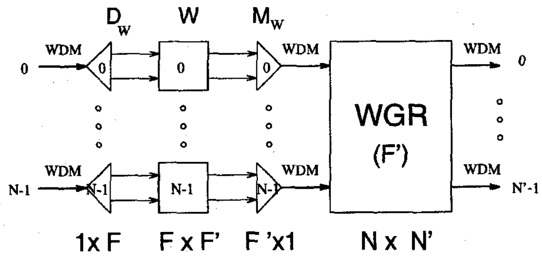
$$C = NN'FF', \quad \text{for the W-S switch with WDM signals} \tag{17}$$

and

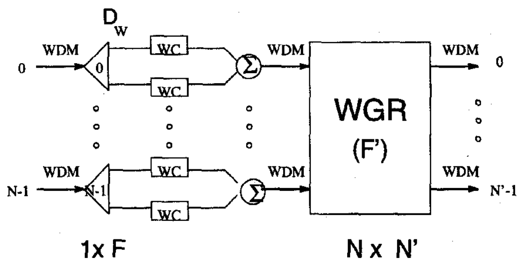
$$C = NN'TT' \quad \text{for the T-S switch with TDM signals.} \tag{18}$$

Recall that the array of space switches S's in Figs. 3(b), 4(b), and 6(b) can be replaced by a single time-multiplexed space switch (TMS). In a TMS, the crosspoint settings are dynamically changed for each of the T time slots. It is worthwhile, therefore, to consider what we may call a WMS (wavelength-multiplexed space switch), i.e., a wavelength counterpart of TMS. We can view it as an integrated space switch, whose crosspoint settings are selected separately for different wavelengths. Note that this space switch need not change dynamically in time, because the input signals considered here are WDM signals, and carrier wavelengths correspond to time slots.

Let us consider a limited special case of WMS, where the space switch matrices in Fig. 6(a) are set according to the



(a)



(b)

Fig. 7. (a) Wavelength switches followed by WGR and (b) actual implementation of (a).

connection pattern of the static WGR. For the special case $N' = N$, the connections are given by (8)

$$\mathbf{S}_F = \mathbf{D}^f, \quad f = 0, 1, 2, \cdots, F-1. \tag{19}$$

For $N' \neq N$, the matrices $\mathbf{S}_f$ are not square, but the structure are almost identical to (19). We then modify the structure of Fig. 6(a) by inserting an array of wavelength multiplexers M_w in series with wavelength demultiplexers D_w at the output side of each wavelength switch W. Since D_w is inverse to M_w, this modification will not affect the functional properties of the system. Now by noting that the dynamic router of Fig. 2 with the fixed switch settings given above reduces to the WGR, the modified structure becomes equivalent to Fig. 7(a). Then applying the equivalence between Fig. 5(a) and (c), we obtain Fig. 7(b), i.e., an array of wavelength converters (WC's) and combiners, followed by the WGR. This configuration is a generalization of the structure (where $F' = F$, $N' = N$) discussed by Sasayama *et al.* [13] as a possible ATM switch.

The degree of connectivity is

$$C = \min\{N, N'\} FF', \quad \text{for the W-WGR structure with WDM signals.} \tag{20}$$

IV. WDM/TDM Signals and Optical Routers and Switches

In the preceding sections, we discussed wavelength routers, both static and dynamic, and derived a wavelength interchanger (or array of wavelength converters plus combiner) as the wavelength counterpart of TSI. We assumed throughout that the input signals are WDM signals, and analyzed these wavelength devices by identifying their time-domain counterparts, where the input signals are all TDM.

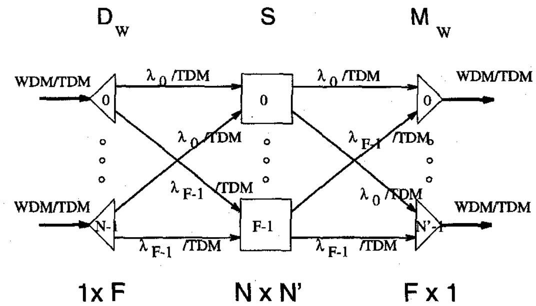


Fig. 8. Wavelength router with S switches (or TMS switches) for WDM/TDM signals.

In this section, we extend the above results and discuss a case, where information is carried by combination of TDM and WDM. What are termed as "Type-B services" in the AON discussed by Alexander *et al.* [1] correspond to this case, whereas the wavelength devices presented in Section III are applicable to what are called "Type-A services." It is rather straightforward to consider appropriate versions of the router/switches of the previous sections for the case in which input signals are WDM/TDM.

In Fig. 8, we show a wavelength router with space switches ($N \times N'$) only, and in Fig. 9, one with both space and wavelength switches. The inputs to all the switches are TDM signals. Therefore, we can consider different cases, depending on whether each of the space switches (denoted S) and the wavelength interchangers (denoted W) may be time-multiplexed or not. If S is a time multiplexed switch, and can change its connection patterns at different time slots, it corresponds to the TMS (time multiplexed space switch) discussed in the previous section: each TMS is equivalent to T copies of the $N \times N$ space switches as shown in Fig. 3(b). Similarly, if a wavelength switch (or equivalently it WC components) can tune to different wavelengths at different time slots, then we can construct what may be termed a TMW (time-multiplexed wavelength switch), which is schematically shown in Fig. 10(b). The degree of connectivity of the dynamic wavelength router of Fig. 8 for WDM/TDM signals is given by

$$C = NN'FT, \quad \text{for the dynamic router with } F \text{ TMS switches, and WDM/TDM inputs} \tag{21}$$

where the space switch is dynamically set. Similarly, for the router of Fig. 9 we have

$$C = NN'FF'T, \quad \text{for the TMW-TMS-TMW switch with WDM/TDM inputs.} \tag{22}$$

Each of the F space switches, denoted S, in the middle stage of Fig. 8 could be replaced with the T-S-T switch of Fig. 4(b). Similarly, we could replace each S switch of Fig. 9 with the T-S-T switch of Fig. 4(b). Then we would have the W-T-S-T-W switch instead of the W-S-T switch between D_w and M_w, allowing complete switching capability in each of the space, wavelength, and time domains. This of course

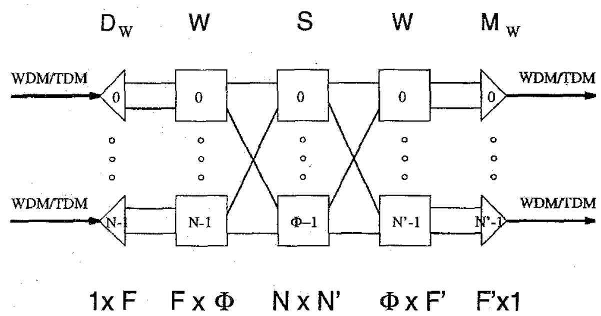


Fig. 9. Wavelength router with W-S-W switches (or TMW-TMS-TMW switches) for WDM/TDM signals.

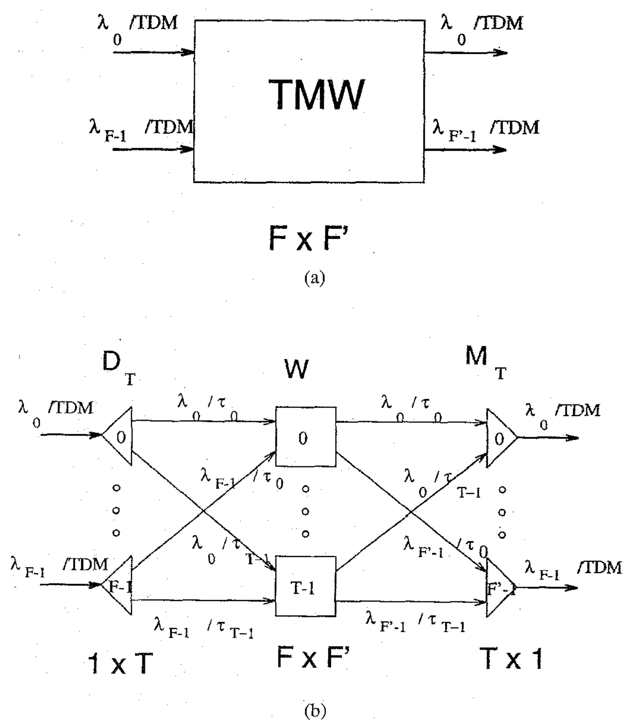


Fig. 10. (a) Time-multiplexed wavelength (TMW) switches and (b) its equivalent representation.

would require the full TSI capability, a major difficulty in the photonic switching technology today, as we remarked earlier.

V. Concluding Remarks

We have discussed various forms of optical routers, which include combinations of space-division, wavelength-division, and time-division switches. We also considered the cases where input signals are combinations of space division with wavelength-division and/or time-division. We exploited the duality relationships among wavelength, time, and space, and explored a number of possible routing and switching devices that could be used in all-optical networks. We also derived the necessary and sufficient conditions for nonblocking and rearrangeably nonblocking.

In this paper, we have been primarily concerned with structures that provide a large number of simultaneous connections among a set of nodes. The performance of such connecting structures can be characterized in terms of blocking probabilities. In a separate paper [11], we report a blocking analysis of these optical devices using recent results in loss network theory, which builds on classical Erland and Engset loss models.

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Hisashi Kobayashi (S'66–M'68–SM'76–F'77) was born in Tokyo, Japan, on June 13, 1938. He received the B.S.E. in 1961 and M.S.E in 1963 from the University of Tokyo, and the M.A. and Ph.D. degrees in 1967 from Princeton University, all in electrical engineering.

He was a radar engineer at Toshiba Electric Co., Kawasaki, Japan, from 1963 to 1965, prior to coming to Princeton as an Orson Desaix Munn Fellow. From 1967 to 1982 he was with IBM T. J. Watson Research Center, Yorktown Heights, NY, where he worked on data transmission, seismic signal processing, digital magnetic recording, image compression, performance modeling of computers and communication systems, and queueing network theory. He is the inventor (1971) of a high-density magnetic recording method, now widely known as PRML (partial-response, maximum- likelihood decoding) scheme, a co-inventor (in 1974) of relative address coding for image compression, which formed a basis for the international standard for facsimile compression algorithm. He also developed the convolutional algorithm (in 1975) for a multiclass queueing network, and the diffusion approximation method for a general queueing network (in 1974). He served as Senior Manager of Systems Analysis and Algorithms (from 1974 to 1980), and Department Manager of VLSI Design (from 1981 to 1982). From 1982 to 1986 he was the Founding Director of the IBM Tokyo Research Laboratory. In 1986 he joined Princeton University as Dean of Engineering and Applied Science (from 1986 to 1991),

and as the Sherman Fairchild University Professor of Electrical Engineering and Computer Science. He held visiting professorships at UCLA (from 1969 to 1970), University of Hawaii (in 1975), Stanford University (in 1976), Technical University of Darmstadt, West Germany (from 1979 to 1980), Free University of Brussels, Belgium (in 1980), and the University of Tokyo (from 1991 to 1992). His current research interest includes performance analysis of ATM and optical networks; wireless CDMA and coherent optical CDMA; and teletraffic theory. He is the author of *Modeling and Analysis: An Introduction to System Performance Evaluation Methodology* (New York: Addison-Wesley, 1978), and has authored more than 120 technical papers.

Dr. Kobayashi is the recipient of the Humboldt Prize from Germany (1979), IFIP (International Federation of Information Processing)'s Silver Core Award (1980); IBM Outstanding Contribution Awards (1975 and 1984) and IBM Invention Achievement Awards (1971 and 1973). He was elected a Member of the Engineering Academy of Japan (1992). He has served as a scientific advisor of many organizations, including NASA, Washington DC; SRI International, Menlo Park, CA; the Institute of Systems Science at the National University of Singapore; the Advanced Systems Institute of British Columbia, Canada; and the Information Technology Research Center, Ont. Canada.

Ivan P. Kaminow (A'54–M'59–SM'73–F'74–LF'95) was born in Union City, NJ, on March 3, 1930. He received the B.S.E.E. degree from Union College, Schenectady, NY, in 1952, the M.S.E. degree from the University of California, Los Angeles in 1954, and the A.M. and Ph.D. degrees in applied physics from Harvard University in 1957 and 1960, respectively.

He was a Hughes Fellow at UCLA (from 1952 to 1954) and a Bell Laboratories CDTP Fellow at Harvard (from 195 to 1960). From 1952 to 1954 he worked on microwave antennas at Hughes Aircraft Company, Culver City, CA. Since 1954, he has been at AT&T Bell Laboratories in Whippany and Holmdel, NJ, and has done research on antenna arrays, ferrite devices, electrooptic modulators, ferroelectrics, nonlinear optics, Raman scattering, integrated optics, semiconductor lasers, optical fibers, and lightwave networks. He was appointed Head of the Broadband Networks Research Department in 1984. He has been a Visiting Lecturer at Princeton University in 1968 and at the University of California Berkeley in 1977, an Adjunct Professor at Columbia University in 1986, and Visiting Professor at the University of Tokyo from 1990 to 1991. He has published 203 papers and received 39 patents. He is the author of *An Introduction to Electrooptic Devices* (1974), co-editor (with A. E. Siegman) of the book *Laser Devices and Applications* (New York: IEEE Press, 1972), and co-editor (with S. E. Miller) of *Optical Fiber Telecommunications II* (1988).

Dr. Kaminow is a Fellow of the American Physical Society and the Optical Society of America. He is a recipient of the Bell Laboratories Distinguished Member of Technical Staff Award, the IEEE Quantum Electronics Award, and the OSA Charles Townes Award. He is a member of the National Academy of Engineering and a Diplomate of the American Board of Laser Surgery. He is spending 1996 as IEEE Congressional Fellow on the staff of the House Science Committee.