A Broad-Band Optical Network Based on Hierarchical Multiplexing of Wavelengths and RF Subcarriers

SOUNG C. LIEW, MEMBER, IEEE, AND KWOK-WAI CHEUNG, MEMBER, IEEE

***Abstract*—We propose a multiwavelength local-access optical network that is capable of supporting multiple services with diverse requirements. Integral to the network is an acoustooptic tunable filter, which has the unique capability of selecting multiple, but not necessarily adjacent, wavelengths simultaneously. The use of multiwavelength selectivity, together with subcarrier multiplexing in the electronic domain, suggests simple solutions to many transmission and switching problems in a multiservice setting. An important conclusion is that multiwavelength selectivity can be used to implement many networking functions not easily realized otherwise.**

I. INTRODUCTION

WITH THE recent rapid advances in fiber-optic technologies, people have begun to envision a future all-optical network that is capable of supporting multiple services with differing transmission rates. This paper deals with an alternative approach for the local-access network, which includes the subscriber loop as well as local switching between subscribers of a common remote multiplexing node. Although the network proposed here is targeted toward broad-band applications envisioned by the telephone companies, in many ways the network structure logically resembles a large local area network. Unlike a local area network, however, the physical locations of the different parts in our network could be separated relatively far apart. The network we propose thus is like a future metropolitan area network [1].

Among various approaches and technologies suitable for a broad-band optical network [2]–[8], wavelength-division multiplexing [2], [3] and subcarrier multiplexing [4] appear to be very promising because they are less demanding technologically than other alternatives. To date, direct-detection wavelength-division multiplexing has been successfully demonstrated both in high bit rate transmission [9] and in network applications [2], [3]. Optical filtering for selection of channels separated by 2 nm is currently achievable, and narrower channel separations may be possible as filter technologies improve. This would give more than a hundred broad-band channels in the entire low-loss fiber transmission region (from 1.2 to 1.7 μm with the exception of the high loss region around 1.4 μm), with each wavelength channel having a transmission bandwidth of several gigahertz [10].

Microwave subcarrier multiplexing has also been successfully demonstrated using commercially available microwave components [11], [12]. Not only can narrow electronic channel separations be achieved, but an entire microwave spectrum as broad as several gigahertz can also be used. In fact, channel separations in the megahertz range are much easier in the electronic domain than in the optical domain using coherent technologies. Most of the recent subcarrier multiplexing approaches [12]–[14] use multimode lasers to distribute a large number of video channels (e.g., 90 channels were demonstrated in [14]). Considering that optical fiber has tens of terahertz of inherent transmission bandwidth, however, the subcarrier multiplexing approaches pursued to date have certainly not taken full advantage of this high potential bandwidth. Thus, we propose to combine wavelength-division multiplexing with subcarrier multiplexing in a novel way that permits each customer to have simultaneous access to multiple wavelengths and subcarriers, hence access to a large number of broad-band channels. By making many broad-band channels available to each individual user, we also achieve increased flexibility in switching as well as simplicity in service provisioning.

Before we present the network architecture, let us emphasize several points of interest about our proposal.

1) The subcarrier multiplexing approach can provide multiple services with only one optical transmitter and receiver per user, thus lowering the cost of terminal equipment relative to approaches that use one wavelength per service for each customer.

2) Very narrow channel spacing can be achieved in the RF domain, and RF frequency stabilization is not as difficult as optical frequency stabilization in coherent optical systems [6] or direct detection FDM systems [7].

3) Unlike many other approaches in which the transmission medium is time shared (e.g., [5]), the transmission of different services to different subscribers does not have to be synchronized and coordinated. Many services can proceed at the same time, since they are separated in the optical as well as electronic frequency domain.

4) Signals on RF carriers can be manipulated and processed easily using electronic components.

5) A wavelength filter that can select multiple, nonadjacent wavelengths simultaneously is a very desirable device. Acoustooptic tunable filters are capable of achieving that [15]–[17]. To date, simultaneous selection of five wavelengths have been demonstrated [17].

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The authors are with Bell Communications Research, Morristown, NJ 07960-1910.

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6) As far as we know, this is the first proposal that integrates wavelength tuning (selection) and RF subcarrier tuning into a single framework, achieving switching as well as simultaneous transmission and reception of multiple services. Reference [4] proposes a multiaccess network based on subcarrier multiplexing and RF tuning alone. Every user in the network receives all information transmitted, since no switching is done internally. Thus, security and privacy are intrinsic problems if one implements a public network as such. The entire usable bandwidth is also limited to a few gigahertz in the RF spectrum. References [2] and [3] consider static wavelength multiplexing, while [7] and [18] assume dynamic wavelength tunability. For these pure WDM systems, simultaneous reception of information streams from more than one user is impossible since the filters reject all but one wavelength. Simple extension to allow each wavelength to contain multiple subcarrier channels does not solve the problem since subcarrier channels on different wavelengths cannot be received simultaneously. In fact, straightforward combination of WDM and SCM only serves to increase the number of channels for cases in which the wavelength separation is large, and does not offer system or functionality advantages over very dense wavelength-multiplexed networks [7]. In order to combine WDM and SCM in a way that allows switching and multiaccessibility, we believe that multiwavelength selectivity is required. This can be achieved either through an AOTF, as assumed in this paper, or through multiple parallel single-wavelength filters that emulate the function of an AOTF.

7) Many network architectures are designed to support either purely broadcast services or purely point-to-point switched services [3], [19]. In order to provide both broadcast and switched services cost effectively, multiple physical networks are overlaid. In our approach, we have only a single physical network upon which multiple logical subnetworks can be overlaid to support different service types. As a result, network reconfiguration can be achieved without significant physical modifications.

In short, wavelength-division multiplexing with RF subcarriers 1) increases the usable bandwidth of optical fibers; 2) is technologically feasible; and 3) uses the two degrees of freedom in optical and electronic subcarrier frequencies to provide the network with new capabilities in services, switching, and distribution.

Section II of this paper describes our vision of a future network. This discussion outlines the network characteristics desired. Section III presents the general structure of the multiwavelength subcarrier network. We show how multiple logical networks, each providing different services, can be overlaid on the basic network architecture. In Section IV we consider the flow of control information. Detailed discussions on control protocols and blocking probabilities are relegated to Appendices A, B, and C. In Section V we present a physical network realization and consider the related technological issues. A receiver sensitivity analysis is presented in Appendix D. Section VI, the concluding section, summarizes the network issues and key technologies that call for further investigations and studies.

II. A Vision of a Future Multiservice Local Access Network

The figures of merit most often used to compare different networks are throughput and delay, in the case of packet-switched networks, and blocking probability, in the case of circuit-switched networks. But in a multiservice environment, consideration should also be given to an architecture in which the logical network structure and connectivity can be reconfigured easily, since services may be added and removed over time. Preferably, the reconfiguration should be achieved logically without substantial modifications to the physical network. A given user should also be able to transmit distinct signals to several other users simultaneously, and at the same time, be able to receive information or services from the same users or other sources.

The following summarizes the properties that are critical or desirable in a future network.

1) *Multiple concurrent services:* A subscriber must be able to transmit and receive multiple services concurrently. Fig. 1 shows a scenario in which a subscriber is engaged in a telephone conversation, while simultaneously receiving a TV broadcast and communicating with a computer network for other services. All of these services are to be supported by a single physical network.

2) *Introduction of new services:* From the perspective of the network provider, it is desirable that any future, and perhaps unforeseen, services can be introduced without modifying the basic network structure. In this way, the network can evolve from a narrow-band network to a broad-band network gracefully.

3) *Support of heterogeneous users:* Heterogeneous users with different demands must be supported by the network. For example, in an ideal situation, each user would need only one optical transmitter and one optical receiver, through which multiple signals could be transmitted and received concurrently. Upgradability is achieved by introducing additional electronic components at the subscriber premises.

4) *Independence of noninteracting users:* For simplicity and privacy, activities of users who are not communicating with each other should be invisible to each other. The setup and the teardown of noninteracting services should be independent of each other. In addition, privacy and security requirements dictate that unintended users not receive unauthorized information.

5) *Technological feasibility:* The technologies used to implement the network must be simple, inexpensive, and realizable as part of an overall communications network.

III. A Multipurpose Logical Network Structure

In view of the small transmission loss of the relatively short fiber spans in local networks, a wide optical spec-

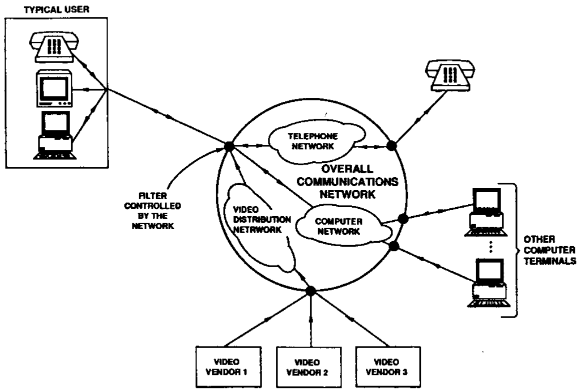

Fig. 1. A multipurpose network from a subscriber's viewpoint.

trum, say from 1.2 to 1.7 μm (with the exception of the high loss region around 1.4 μm), may be exploited to accommodate a large number of subscribers, using wavelength-division multiplexing with channel spacings of approximately 1-2 nm. Together with the bandwidth in the electronic domain for each wavelength (e.g., a baseband channel occupying frequencies from 0-2 GHz plus RF subcarrier channels from 2 to 8 GHz), this represents a very large aggregate transmission capacity.

To exploit the high capacity of the optical medium, we propose a network with the logical network structure depicted in Fig. 2. Given the logical network structure, there are many possible physical realizations. One specific physical realization and the locations of the different parts or functions in the network will be discussed in Section V. We postpone this discussion because the physical details are irrelevant to the logical relationship between the different network parts.

Functionally, the network can be considered as consisting of two layers, as shown in Fig. 2. The inner layer is a purely broadcast network in which input signals are distributed among all outputs. Each user has an associated wavelength filter which is located at the boundary of this inner layer. Thus, depending on the wavelengths selected by the wavelength filter, each user has a different view of the outer network layer, as if the network is tailored to his or her own individual needs.

Each user and each service vendor in the network is assigned a unique wavelength for transmission. To increase the number of users beyond the number of available wavelengths, more than one user can share the same wavelength. For simplicity, this paper will concentrate on the case with unique wavelength assignments. Each wavelength may contain many subchannels at different subcarrier frequencies, each subcarrier channel transmitting a different service. Thus, a user or vendor can transmit multiple information streams to different destinations using only a single optical transmitter of a specific wavelength. The optical filter mentioned above is under the control of a central network controller. The optical filter we assume here is a multiwavelength filter that can select a combination wavelengths which are not necessarily adjacent to each other. In general, multiple wavelengths, and therefore all the subcarrier subchannels that they carry, would reach a given user. Without further wavelength demultiplexing, the selected wavelengths are detected by a single optical detector. The user then selects the desired subcarriers using tunable electronic filters. In this way, the combination of subcarrier multiplexing and wavelength multiplexing allows the user to transmit multiple information streams to, and receive multiple information streams from, several other users simultaneously.

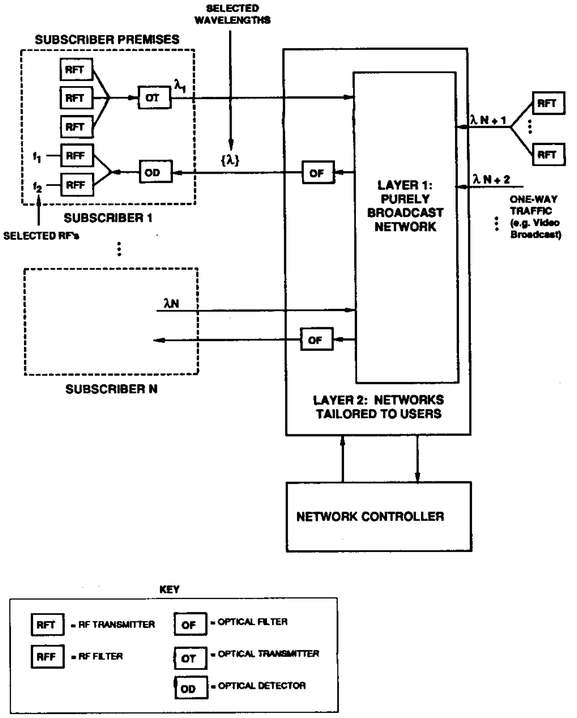

Fig. 2. A multipurpose logical network structure.

The network controller monitors and provides multiple services on multiple overlaid subnetworks. For instance, the network controller can establish the circuit-switched telephone connection between two subscribers or one-to-many connectivity in the case of broadcast services. However, the overall logical structure of the network is independent of other network attributes such as the specific services supported, switching methods used (packet or circuit), or signal formats employed. Consequently, we could overlay multiple, application-specific subnetworks on one basic network structure and simultaneously support widely varying service requests from different subscribers. Furthermore, the network controller can set up new subnetworks and tear down unused subnetworks dynamically in order to utilize the available bandwidth efficiently.

The two-level signal selection or filtering process provides a certain level of flexibility for the network con-

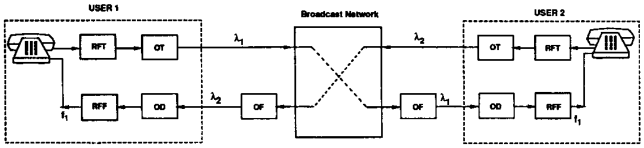

Fig. 3. An overlaid telephone connection. (Point-to-point telephone communication.)

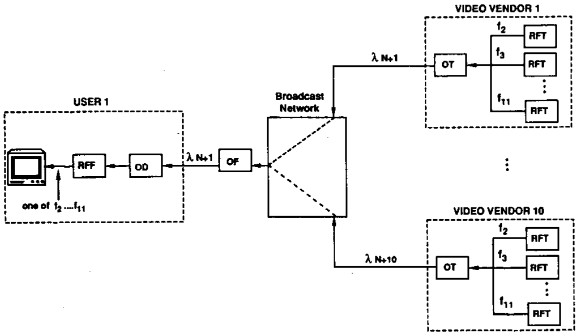

Fig. 4. An overlaid video distribution network. (Video broadcast.)

troller as well as the user. Since the filtering of wavelengths is performed by the network controller, the network controller can prevent unauthorized users from gaining access to certain private wavelengths. The subcarrier filtering at the subscriber's premises allow the subscriber to receive multiple services simultaneously. In general, a range of selective broadcast (or multicast) services is possible, with point-to-point communication at one extreme and pure broadcasting at the other extreme.

A. Examples of Overlaid Networks

To illustrate the versatility of the network structure, we consider the examples depicted in Figs. 3, 4, and 5. It should be emphasized that these are only specific examples, and other ways of assigning wavelength and subcarrier to individual services are certainly possible. An important feature is that the logical subnetworks in these examples can coexist simultaneously within the general network structure.

1. Point-to-Point Telephone Service: Independent of wavelength, a particular RF subcarrier f_1 can be dedicated to the transmission of telephone signals. As illustrated in Fig. 3, if node 1 wants to talk to node 2, then the network controller tunes the optical filters (OF's) of nodes 1 and 2 to let λ_2 and λ_1 through, respectively. At the subscribers' premises, RF filters (RFF's) associated with telephone service would be tuned to f_1. The multiwavelength nature of the network is totally transparent to the subscribers, since wavelength selectivity is controlled by the network controller. Although both subscribers transmit on subcarrier f_1, there is no signal collision at the receiver end, since the optical carriers are at different wavelengths and a subscriber does not receive his or her own wavelength.

Multiparty conversation can be established easily with the same scheme. The OF of a participant is tuned simultaneously to the wavelengths of all the other participants. If the voice signals are in baseband and not digitized, the sum of the voices of the other participants would be available after demodulation. Of course, additional processing at the subscriber premises can be employed to select the loudest speaker and make only that signal audible to each subscriber, thereby making the multiparty conversation more intelligible.

2. Selective Video Broadcast: Again independent of wavelength, a set of subcarrier RF's f_2 to f_{11} could be dedicated to selective video broadcast or video on demand, providing ten possible video channels to each subscriber. In addition, ten wavelengths, λ_{N+1} to λ_{N+10}, could be assigned to ten video vendors for a total of 10 × 10 = 100 channels. As shown in Fig. 4, if a subscriber wants to use one of the ten vendors, say the first vendor, then his or her OF would allow only λ_{N+1} to be received. If the subscriber uses more than one vendor, the network controller would retune the OF whenever the user wishes to switch channels between vendors.

To allow a viewer to watch programs from more than one vendor simultaneously, a different RF subcarrier allocation scheme is required. For instance, each vendor could be allocated only a subset of the overall video RF subcarriers. As long as the video channels of two vendors are nonoverlapping in RF, their optical wavelengths can be tuned in simultaneously by the OF, and the video channels separated electronically thereafter. In general, the subcarriers can be assigned to the vendors with only partial overlap so that the nonoverlapping channels of more than one vendor can still be viewed simultaneously.

If the aim is to conserve wavelengths, different vendors could use the same wavelength but transmit their signals on different RF subcarriers. As long as their optical sources are incoherent with each other and the number of vendors sharing the same wavelength is small, there will be no significant interference between their signals.

3. Multiaccess Local Area Network (LAN): A LAN with collision detection can be implemented on two RF subcarriers, say f_{12} and f_{13}, and a dedicated wavelength λ_{LAN}. As shown in Fig. 5, all participating users, regardless of their wavelength assignments, would transmit outgoing data on f_{12} and receive incoming data of f_{13} at λ_{LAN}. An OF at the controller admits the wavelengths of all participating nodes and the composite signal is then detected. The controller then frequency translates the composite signal from subcarrier f_{12} to subcarrier f_{13} in the elec-

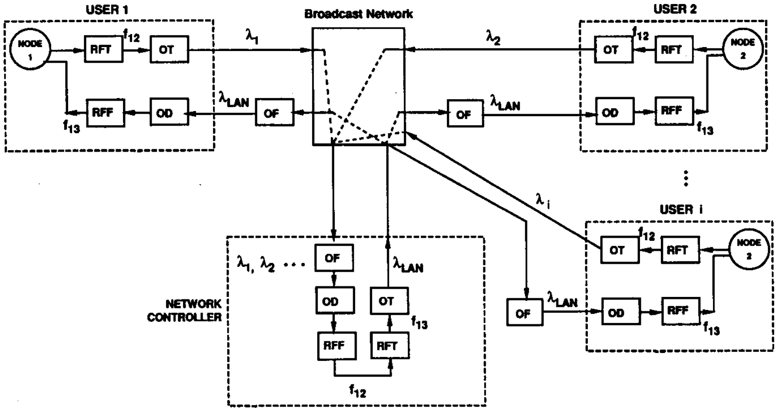

Fig. 5. An overlaid local area network.

tronic domain, and sends it out optically on λ_{LAN}. The wavelength translation process is transparent to the participating users in the sense that they do not need to be aware of λ_{LAN}; their corresponding OF's are tuned by the controller to select λ_{LAN}. Other than the fact that transmission and reception are on different subcarriers, it is as if the users were connected to an Ethernet-type LAN that is separate from the other network services. An interesting point to note is that a multiparty telephone conversation could also be established using a similar logical setup. As an alternative, a "distributed" collision-free packet switch similar to HYPASS [18] could be implemented. Instead of wavelength tuning, as in HYPASS, a set of subcarrier RF's would be used to achieve any tuning functions required [4].

IV. Flow of Control Information

Since different application-specific control protocols may be needed for different logical networks, one must be careful in considering the flow of control information so that new services (or logical subnetworks) can be introduced without disrupting the operation of existing services. We propose to overlay a separate control network on top of the communication network using a different wavelength. Fig. 6 depicts the network from the viewpoint of an arbitrary user node i. Since a given user transmits at only one wavelength, that wavelength must be shared between communication with the controller and communication with the other users. Again, subcarrier multiplexing can be used to transmit both control information and data on the same wavelength.

Control information from all users to the controller is carried on a dedicated subcarrier RF f_u. When the controller wishes to receive from node i, it simply listens to f_u on wavelength λ_i. The downstream information from the controller to all the users in the network is transmitted on subcarrier RF f_d on wavelength λ''. At any instant, to prevent control information from reaching any unintended users, the controller makes sure that only the OF's of the intended users choose λ'' as one of the selected wavelengths.

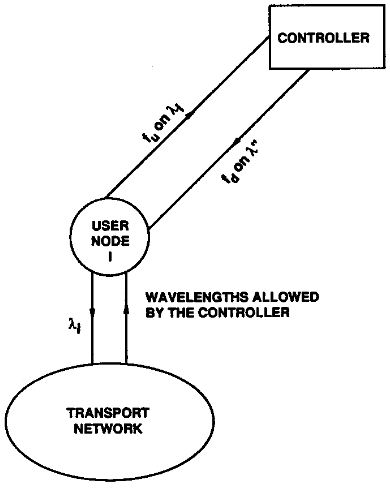

Fig. 6. Logical separation of control and transport networks.

In general, the wavelengths selected by an OF may contain services occupying overlapped subcarrier RF's. Thus, whenever a new service is set up it is important for the controller to assign the service a subcarrier RF that will not result in conflicts with existing services. This issue is treated in Appendices A and B. The general problem of determining the blocking probability in a multiservice setting is difficult and is dependent on several parameters such as the traffic patterns of the services, the priorities of the services, the numbers of wavelengths and subcarriers available, and the way in which they are partitioned and assigned to the services, etc. Although this problem is beyond the scope here, the advantage of this network over a pure WDM network is obvious. In a pure WDM network with N user and N wavelengths, a user can receive only one wavelength at a time. The blocking probability is certainly high if one uses the pure WDM network to support multiple services, since reception of more than one service is intrinsically impossible without additional multiplexing.

V. A Physical Network Architecture

There are many physical realizations for the logical network structure in the previous section. Here, we propose a physical network that relies on two-stage star couplers for signal distribution and acoustooptic tunable filters (AOTF's) for wavelength filtering [15], [16]. The internal broadcast network is implemented as a two-stage star because of its desirable power-division loss characteristic. The AOTF is chosen because it is capable of filtering out an arbitrary combination of its input wavelengths without requiring the selected wavelengths to be adjacent to each other.

Figures 7, 8, and 9 depict the physical details of the broadcast network, the network controller, and the optical filters and their associated local controller, respectively. With respect to Fig. 2, these are the realizations of the "internal" portion of the network. Two indices are used to label the network parameters associated with the users. Thus, λ_{ij}, T_{ij}, and R_{ij} represent the transmitted wavelength, transmitter, and receiver of user ij, respectively. The next subsection gives an example on the control of this network. First, we describe the network in general.

As illustrated in Fig. 7, subscribers transmit signals to the broadcast network via the first-stage couplers (i.e., the left-hand column of $N \times N$ couplers), and receive signals via the second-stage couplers. Each first-stage coupler has one output leading to the central controller's location and one output leading to every second-stage coupler. The central controller is also connected to an input port of every second-stage coupler, so that signals from the controller and the outside world (e.g., video vendors and other subscribers not within the local network) can reach the subscribers. For wavelength filtering of signals received by the users, AOTF arrays are located at the outputs of the second-stage couplers, and each AOTF in an array is assigned to a unique user. Thus, the two stages of couplers perform signal splitting and combining so that the inputs to all AOTF's contain signals from all users.

Each coupler at the first stage serves N subscribers. Although each coupler has only one fiber leading to the central controller, more than one user can communicate with the central controller at the same time because the signals are wavelength and subcarrier multiplexed. So, by splitting the composite signal power, individual channels can be isolated by performing wavelength and subcarrier filtering. As illustrated in Fig. 8, $1 \times M$ couplers are used for signal splitting, and AOTF arrays are used to select the wavelengths carrying signals going to the controller and the outside world. Correspondingly, $M' \times 1$ couplers are used to combine signals from the outside world and the controller to the local users. For each AOTF array at the central controller, an AOTF is used for scanning purposes. By repeatedly scanning all wavelengths, the controller can detect any newly active users or new requests for services. To set up a service requested, the participants' AOTF's need to be controlled, and the control information for tuning the remote OF's is transmitted on a fixed wavelength channel, λ'. This is a wavelength distinct from λ'' described in the previous section; λ'' carries control information to the subscribers rather than to their AOTF's.

The outputs from each second-stage $N \times N$ coupler are connected to an array of AOTF's, depicted in Fig. 9. Associated with each remote AOTF array is a local controller which tunes the AOTF's according to the directions it receives from the central controller. To receive this control information, one of the AOTF's is assigned to the local controller, and it is permanently tuned to control channel λ'.

At the central controller, AOTF sharing (or concentration) for the outbound traffic can be achieved by letting $(M - 1) < N$. Through subcarrier multiplexing, however, the actual number of users communicating with the outside could be larger than $(M - 1)$, since each AOTF is capable of selecting multiple wavelengths.[1] Thus, through intelligent assignment of subcarrier frequencies to active subscribers, the network controller can achieve $N:(M - 1)$ concentration without constraining the number of users that route traffic via each AOTF array to be less than or equal to $(M - 1)$. As long as the wavelengths selected by an AOTF contain only signals on separate RF subcarriers, no collision will result. In general, for a given blocking probability requirement and some assumed underlying traffic patterns, there is a minimum M. A detailed performance analysis relating to this parameter is beyond the scope here. Also, it should be noted that the power loss for the signal paths from the subscribers to the central controller is no worse than that of the direct signal paths between the subscribers since $M, M' < N$. Signals with destinations outside the network are passed on to the inter-network interface, which then transforms and transmits the signals in the format desired by the external network. A different set of wavelengths (in addition to $\lambda_{11}, \ldots, \lambda_{N-1,N}$) is used to carry information from the outside world to the local network.

In practice, the central controller could be located at a central office, and the users' AOTF's and the two-stage star could be located at either the central office or a remote multiplexing node between the central office and the users. In the latter case the number of feeder fibers between the central office and the remote node is reduced N-fold, since only one branch out of each $N \times N$ coupler extends to the central controller. The penalty for the pair gain achieved in this case is that the remote node needs to be powered for AOTF tuning.

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[1] Given n wavelengths, an "ideal" AOTF which can select any combination of the n wavelengths has $\Sigma_{i=1}^{n} \binom{n}{i} = 2^n$ possible states. An $n \times 1$ switch (or a wavelength filter capable of selecting only one wavelength), on the other hand, has only n states. The proposal here makes use of this fact to achieve network flexibility.

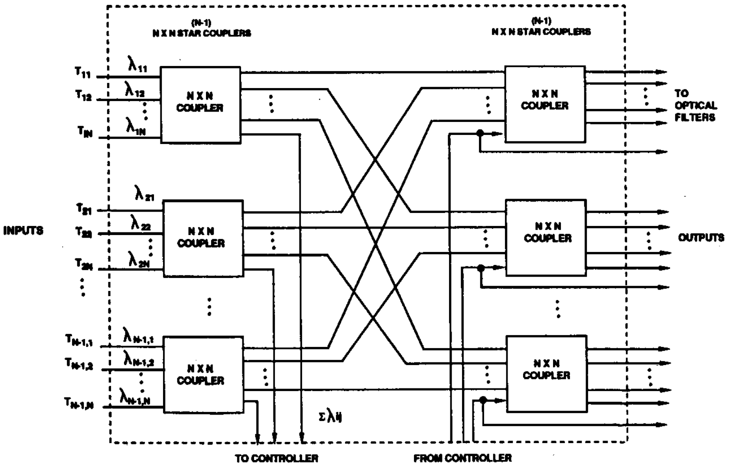

Fig. 7. A physical implementation of broadcast network.

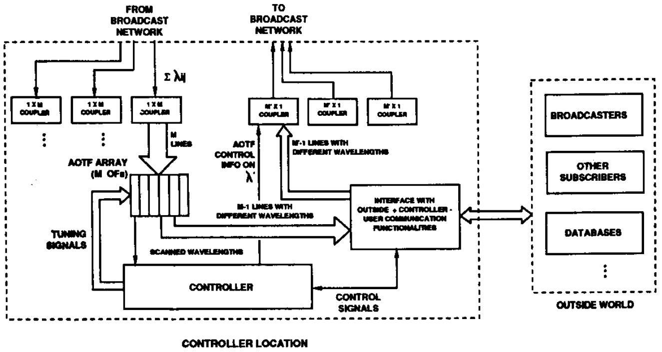

Fig. 8. A physical implementation of controller.

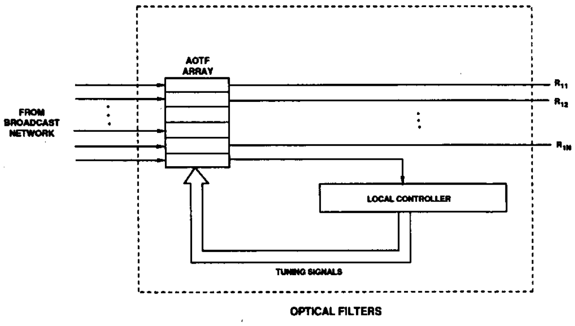

Fig. 9. A physical implementation of an array of optical filters.

A. Flow of Signals

For illustration, we consider the problem of setting up a communication path from subscriber ij to subscriber pq, assuming the architecture in Figs. 7, 8, and 9. The reader is referred to Appendix D for a more complete description of the control protocol. The following sequences are depicted in Fig. 10.

1) Subscriber ij transmits to the central controller a request to establish a connection with subscriber pq. This request is carried on RF subcarrier f_u on wavelength λ_{ij}, which we denote as (f_u, λ_{ij}). When the controller's AOTF scans to λ_{ij}, this information gets through to the controller.

2) The controller then transmits on (f_d, λ') information for tuning the AOTF of subscriber pq. After receiving this information, the local controller tunes the AOTF of subscriber pq to admit both λ_{ij} and λ''. The central controller sends an alerting signal to subscriber pq on (f_d, λ''). If the connection can be established without interfering with the currently active services of subscriber pq, subscriber pq will send a positive acknowledgement to the controller. Otherwise, the connection will be denied and subscriber ij will receive a busy signal from the controller.

3) After tuning the remote AOTF of subscriber pq to admit λ_{ij}, the connection is established. Subscriber ij can transmit to subscriber pq without any further intervention from the controller.

B. Possible Network Parameter Values

We now consider some specific examples in order to develop some idea on the possible network parameter val-

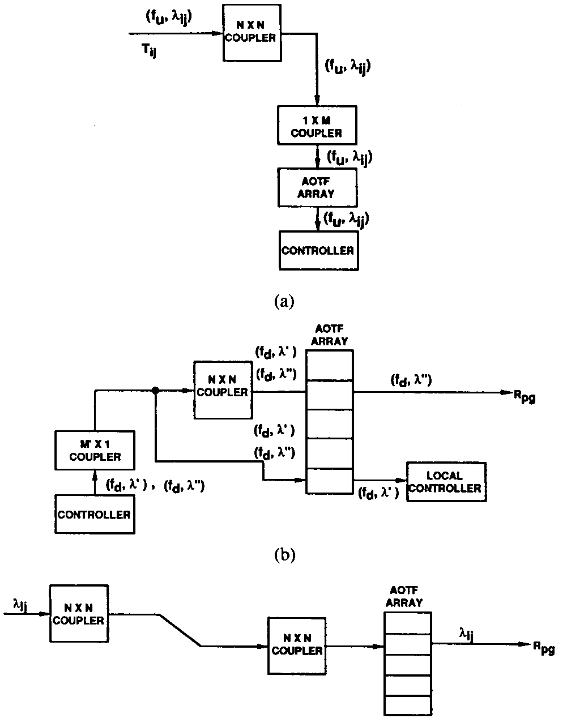

Fig. 10. An example of call setup. (a) Upstream control signal. (b) Downstream control signal. (c) User-to-user communication path.

TABLE I
CHARACTERISTICS OF AOTF'S

Device	*Bulk* (INRAD)	*Integrated* (BELLCORE)
Optical Tuning Range $\Delta\lambda_T$	1.2-1.6 μm	1.2-1.6 μm
Resolution $\Delta\lambda$	33 Å	10 Å
No. of Channels	~100	~400
Access Time τ	3 μs	10 μs
Drive Frequency Range	50-80 MHz	170-230 MHz
RF Drive Power for 100% Deflection	5 W	250 mW
Max Tolerable RF Drive Power	3 W	1 W
Max Deflection Efficiency	~50 %	98%
Optical Insertion Loss	~5.0 %	~30%
Fiber Coupling Loss	~1 dB	~ 3 dB

TABLE II
POWER BUDGET ESTIMATES

Component	*Power Budget* (Present)		*Power Budget* (Future)	
Transmitter Power		13dBm		20dBm
Input Star Coupler Loss	(16 × 16)	< 14.5dB	(64 × 64)	< 22dB
Output Star Coupler Loss	(16 × 16)	< 14.5dB	(64 × 64)	< 22dB
Filter Loss		5dB		5dB
Fiber Loss	(< 10km)	4dB	(< 20km)	8dB
Connector loss		2dB		4dB
Optical Preamp		None		15dB
Receiver Sensitivity		−32dBm		−35dBm
Total Power Loss		< 40dB		< 61dB
Power Margin		5dB		9dB

ues, such as bit rates, number of users, etc. The reader is referred to Appendix C for an analytical discussion of the relationship between the network size, the individual channel bandwidths, the number of RF's transmitted by each user, and the number of wavelengths selected by each AOTF.

Table I lists for reference some of the properties of AOTF's demonstrated to date. Table II summarizes some power budget estimates, based on the following assumptions:

- A receiver sensitivity of −32 dBm is possible for the transmission of 50 Mbit/s FSK binary data with an optical modulation depth of less than 0.2. The same sensitivity can be obtained for the simultaneous transmission of 500 Mbit/s baseband data. The assumed receiver is a high-speed p-i-n/FET baseband receiver *not* customized for RF reception.
- There are no additional power penalties due to the introduction of multiple subcarriers and wavelengths in the system. Crosstalk penalties between channels are ignored in this paper. Note that any power penalties could be included by simply allowing a bigger power margin.

Based on the above assumptions, it should be possible to build a network with thirty-two 16 × 16 couplers using technologies demonstrated to date. There would be 240 subscriber nodes, each capable of transmitting at 4 subcarrier channels at 50 Mbit/s. In the future, it may also be possible to allow users to transmit high bit rate data, say at 500 Mbit/s, via a baseband channel. With four 50 Mbit/s subcarrier channels per subscriber, the total traffic generated by the internal users, not including the traffic from the central office, is 48 Gbit/s. In the above example, we assume the wavelengths are spaced about 1 nm apart. In general, to increase the number of users or to allow a larger wavelength spacing with the same number of users, one could let several users transmit on the same wavelength. One then has to increase the bandwidth in the subcarrier domain so that they do not transmit on the same subcarriers. By using optical amplifiers as preamps [20], an additional 15-20 dB of power margin could be expected. Based on the power budget alone, this would increase the number of users by about 30 times. Another way to increase the network size and throughput is to improve receiver sensitivity and customize the receiver for RF reception [21].

In the second column of Table II, we estimate that in the future, about 4000 users can be supported. The underlying assumptions are: 1) there are 200 available wavelengths; 2) for transmission, 20 users share a single wavelength; 3) the available RF bandwidth is from 4 to 8 GHz. Thus, in the worst case when all 20 users in the same wavelength are transmitting, each user is still guaranteed a capacity of 200 Mbit/s.

The above assumes all channels have the same bit rate. A mixture of bit rates (e.g., from 10 to 155 Mbit/s) is certainly possible by adjusting the optical modulation depths of the channels in proportion to their bandwidths. In addition, the concurrent transmission of analog channels and digital channels is certainly possible.

Whereas the number of channels transmitted by a single laser is limited by power sharing between the subcarriers and laser nonlinearity [22], the number of channels received is limited by shot noise from multiple sources (see Appendix D for an analysis). To the extent that the number of simultaneously received wavelengths is not too large, and the receiver's thermal noise is the dominant noise, the number of received wavelengths is not limited, since thermal noise is independent of the optical power falling on the photodetector. In this case, one would be able to receive more channels than transmit. This happens to coincide with many practical situations in which the predominant traffic is asymmetric (e.g., a network with broadcast traffic).

VI. CONCLUSIONS

A novel network architecture based on hierarchical multiplexing of optical wavelengths and RF subcarriers has been presented. Among the strengths of this network are the following.

1) Multiple services can be supported by a physical network, with noninteracting services transparent to each other. Synchronization and coordination of transmission times between subscribers and between independent services are unnecessary.

2) Multiple application-specific logical subnetworks can be set up on the same physical network through wavelength and subcarrier assignments. Broadcast, multicast, or dedicated point-to-point logical subnetworks can be established.

3) New services can be introduced easily without disrupting the existing services. Reconfiguration of the connectivities among the users is achieved by wavelength tuning and RF subcarrier tuning.

4) Only a single optical transmitter and a single optical receiver are necessary for each subscriber. Multiple services are made possible by multiple *electronic* components (RF receiver and transmitter circuits), which are less expensive than corresponding optical components. A user would require as many of these electronic components as the number of services desired. Thus, users with different service requirements can be supported without penalizing the less demanding users.

This work raises many questions and issues that call for further investigation. Many key technologies remain to be demonstrated and understood more fully. They are summarized as follows.

1) The use of AOTF's for multiwavelength selection need to be understood more fully. What is the maximum number of wavelengths that can be selected simultaneously? What are the performance penalties associated with their use? How are these penalties related to the number of selected wavelengths? How do other multiwavelength filter technologies compare with AOTF's?

2) Since DFB lasers are essential for dense wavelength multiplexing, RF modulation of these lasers and the performance penalties due to laser nonlinearity need to be investigated. The maximum tolerable total optical modulation depth of DFB lasers needs to be established. The optimal receiver structure and the corresponding sensitivity for FSK signals must be studied.

3) Taking technology and device limitations into account, what is the best way to partition the RF spectrum among different services? Control protocols for setting up and removing services must be studied in more detail.

4) On a network-theoretic level, it is important to establish a quantitative measure of the flexibility of the proposed network in terms of the number of different network configurations that are possible, a notion related to the "entropy" of the system [23]. As a switching system, this network goes beyond point-to-point switching and multicasting; multiple inputs can also be connected to the same output. Thus, this network has more possible "states" than many other switching systems. Appendices A and B may serve as a good starting point for this study.

APPENDIX A

A GENERAL SUBCARRIER RF SELECTION RULE

This Appendix develops a general rule for selecting the RF subcarrier to carry a service. Consider the wavelengths selected by the optical filter (OF) of an arbitrary node n. Each of these wavelengths contains a set of RF subcarriers, and since the same RF may be used on different wavelengths, there could be overlapping of RF's. The signals on the overlapped RF's are not separable once they are detected and converted into electrical signals. Thus, it is important to make sure that an RF being listened to contains only signals from one source (wavelength). We could either statically preassign RF subcarriers to users and services in such a way that RF collisions are impossible, or assign RF's dynamically based on demand. In general, a combination is desired in a multiservice network.

For dynamic assignment, we present a rule to eliminate the RF's that cannot be used. The *optimal* rule as to which of the allowed RF's is the best choice will not be addressed here. The state of the network can be represented by a graph which keeps track of the relationship between receiver nodes, transmitter nodes (wavelengths) and RF subcarriers. The example in Fig. 11 will be used throughout this discussion for illustration purposes. To avoid confusion of this graph with the communication network, the terms "vertex" and "edge" (as opposed to "node" and "link") are used when referring to entities in the graph.

The graph is related to the network state as follows. Addition or deletion of a number of edges, corresponding to addition and completion of services, is performed each time the network changes state.

- Vertices of stage 1, stage 2, and stage 3 correspond to the RF subcarriers, the transmitters (wavelengths), and the receivers, respectively. The baseband could be treated as one of the subcarriers as far as the problem here is concerned.
- An edge is incident from transmitter vertex λ_j to receiver vertex n if and only if the OF of node n allows λ_j to pass through.
- An edge exists between transmitter vertex λ_j and RF vertex f_i if and only if the transmitter of node j carries a signal on f_i. A label n is attached to this edge if and only if node n is listening to f_i on λ_j. Physically, the OF of

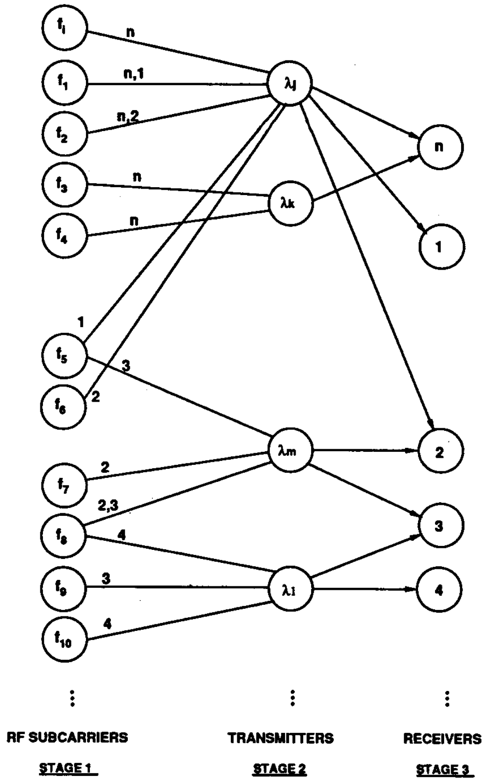

Fig. 11. Graphical representation of network state.

node n allows λ_j to go through, and an RF receiver of node n is tuned to f_i.

Suppose we want to establish a new signal path from an arbitrary node m to an arbitrary node n. An RF subcarrier must be selected to carry the signal on λ_m.

1) Rule out the "RF leaves" of the tree rooted at vertex n (from right to left), regardless of the labels of their adjacent edges. In Fig. 11, the RF's ruled out are f_i, f_1, f_2, f_3, f_4, f_5, and f_6. This eliminates conflicts with the RF's already reaching the detector of node n.

2) If node m is transmitting to some other node on an RF subcarrier that is listened to by node n, the communication path from node m to node n cannot be established. This is because if λ_m is let in by the OF of node n, an RF collision will result, since the same RF is used to carry signals from two sources. In Fig. 11, there is no such collision, since node n listens to f_i, f_1, f_2, f_3, and f_4 while node m transmits on f_5, f_7, and f_8. Note that even though there is a signal on f_5 of λ_j, which is allowed in by the OF of node n, there is no RF collision since node n is not listening to f_5 (vertex f_5 does not have an adjacent edge labeled n).

3) Eliminate all RF leaves adjacent to vertex λ_m, regardless of the edge labels. In Fig. 11 these are f_5, f_7, and f_8. These RF's are already used by node m for transmission of other signals.

4) Consider each and every node listening to λ_m. This corresponds to the receiver vertices that are adjacent to vertex λ_m; i.e., vertices 2 and 3 in Fig. 11. Eliminate the RF vertices with an adjacent edge labeled by these receiver vertices. These are vertices f_2, f_5, f_6, f_7, f_8, and f_9 in Fig. 11. This is to avoid RF conflicts in the nodes that are already listening to λ_m. For instance, establishing the communication path from node m to node n on f_9 results in an RF collision in node 3, even though node n is collision free.

5) Any of the remaining RF's can be used. In Fig. 11, the only remaining RF is f_{10}.

For multicast setup, from λ_m to node 1, node 2 . . . , the above steps are run through for node 1, node 2, ... Any of the common remaining RF's can be used. Similarly, this can be done for multipoint-to-multipoint situation, such as the initial setting up of a multiaccess network.

In general, blocking can occur due to one or a combination of the above conditions. Some of the blocking situations can be eliminated by switching through the controller. This will be detailed in Appendix B.

APPENDIX B
PERFORMANCE ANALYSIS

This Appendix establishes a bound for the blocking probability in order to compare the performance of this network with other networks. The mathematical problem of finding the blocking probability under very general conditions is difficult and will not be treated here. The following assumptions are adopted.

- Only point-to-point traffic between the internal nodes are considered. Analytically, the traffic between the internal nodes and the outside world can be taken into account by introducing "virtual" nodes to represent the information sources and sinks of the outside world.
- Traffic between users is uniform, and the number of users n is large. Thus, new requests to establish connection with a particular user follow Poisson arrival process. For a particular receiver or transmitter, the new requests for connection arrive with rate λ. Furthermore, the states of two arbitrary nodes, in terms of the number of existing ongoing services, are approximately independent.
- The holding time of all connections is assumed to be exponentially distributed with average $1/\mu$.
- Subcarriers are assigned in a random fashion. That is, there is no optimization as far as which wavelengths should carry which subcarriers other than the requirement that the assignments should not result in RF collisions.
- For simplicity in analysis, we do not consider rearrangement of existing connections.
- We consider only the establishing of a unidirectional link from a transmitting node to a receiving node here.

Suppose we want to establish a connection between the transmitting node T and the receiving node R. There are several conditions under which blocking can occur.

1) T is currently transmitting to a node other than R on RF f. But R is also currently receiving from a node other than T on f. Thus, the OF of R could not possibly select the wavelength of T without creating a collision of the two

signals carried on f. Fortunately, this situation can be eliminated by routing and switching the connection through the central controller (see Section V). Specifically, if the above situation occurs, then T first transmits the signal to the central controller. The central controller detects the signal and convert (switch) the subcarrier, if necessary, to a subcarrier not currently reaching the detector of R. The central controller then transmits the signal on a wavelength assigned to the controller for such switching purposes. Thus, we will assume blocking under this condition is insignificant in the following analysis.

2) A set of RF's is currently reaching the detector of R. Only some of the RF's are of interest to R; the rest are selected by its OF simply because the wavelengths carrying them also contain the actual RF's of interest to R. If the set of RF's reaching R already contains all the RF's available in the network, then blocking occurs.

3) A set of nodes is currently listening to T. These receiving nodes are also currently connected to other nodes through some RF's. If the set of RF's of interest to these nodes contains all the available RF's in the network, then blocking occurs. This is because T could not possibly choose an RF for the new request without creating conflicts in the nodes currently listening to T.

4) If the union of the set of RF's in conditions 2 and 3 above contains all the available RF's, blocking also occurs. Fortunately, if neither set contains all the RF's, blocking under this condition can be eliminated by switching through the central controller, as in 1) above.

Only conditions 2 and 3, C_2 and C_3, are of interest to us. By symmetry, the blocking probabilities under these conditions are equal. Thus, the overall blocking probability is

$$P_b = Pr[C_2 \cup C_3] \leq 2Pr[C_2]. \tag{1}$$

Suppose there are m subcarriers, as $M/M/m/m$ queueing model [24] can be used to model the number of connections (ongoing services) for a particular transmitter or receiver. The probability of finding the system in state i is simply

$$P_i = \frac{\rho^i/i!}{\sum_{k=0}^{k=m} \rho^k/k!} \tag{2}$$

where $\rho = \lambda/\mu$. The model will be accurate if blocking due to conditions 2 and 3 above are small. In any case, the model will only result in an overestimate of the blocking probability calculated later. Thus, as far as establishing an upper bound for the blocking probability is concerned, the model is valid.

When m is sufficiently is large, the $M/M/m/m$ model is well approximated by an $M/M/m$ model. In this case, the probability of finding a receiver with i connections or ongoing services is simply

$$P_i = \frac{\rho^i}{i!} e^{-\rho}. \tag{3}$$

The expected number of services in progress is $\Sigma\, iP_i = \rho$ and its moment generating function is

$$P(z) = \sum_{i=0}^{\infty} z^i P_i = e^{\rho(Z-1)}. \tag{4}$$

Again, going from the $M/M/m/m$ model to the $M/M/m$ model will only overestimate the blocking probability.

We will obtain an upper bound for $Pr[C_2]$ by considering the worst case scenario. That is, suppose there are currently j ongoing services for receiver R. Then we assume all j services are carried on different wavelengths. Given j, we have

$$\begin{aligned} Pr[C_2 \mid j] &\leq Pr[\text{the } j \text{ wavelengths contain all the } m \text{ subcarriers}] \\ &< Pr\left[\sum_{k=1}^{j} \text{number of subcarriers in the } k\text{th wavelength} \geq m\right]. \end{aligned} \tag{5}$$

Let $q = \Sigma_{k=1}^{j} q_k$ where q_k = number of subcarriers in the kth wavelength. Then, $Pr[q_k = i] = P_i$, where P_i is given in (3) and its moment generating function given in (4). Under the assumption that the numbers of subcarriers in the wavelengths are independent (which will be valid if the total number of users in the network is large), the moment generating function of $Pr[q \mid j]$ is simply the product of the moment generating functions of $Pr[q_k]$ for k = 1 to j. Specifically

$$P_{q|j}(z) = P^j(z) = e^{j\rho(z-1)}. \tag{6}$$

But the probability of R having j services also obey (3). Thus, we have

$$\begin{aligned} P_q(z) &= \sum_{j=0}^{\infty} \frac{\rho^j}{j!} e^{-\rho} P_{q|j}(z) = \sum_{j=0}^{\infty} \frac{\rho^j}{j!} e^{-\rho} e^{j\rho(z-1)} \\ &= \exp\left[\rho(e^{\rho(z-1)} - 1)\right]. \end{aligned} \tag{7}$$

Now, continuing from (5)

$$\begin{aligned} Pr[C_2] &< \sum_{i \geq m} Pr[q = i] \\ &\leq \sum_{i \geq m} Pr[q = i] z^{i-m}, \qquad z \geq 1 \\ &< z^{-m} P_q(z). \end{aligned} \tag{8}$$

To obtain a good bound, we minimize (8) over all $z \geq 1$. After performing the minimization, the optimal z, z', obeys the following nonlinear equation:

$$z' e^{\rho(z'-1)} = m/\rho^2. \tag{9}$$

Substituting the above into (8) and then into (1), we have

$$P_b < \frac{2e^{-\rho} e^{m/z'\rho}}{z'^m} \tag{10}$$

where z' can be obtained from (9) numerically.

For comparison purposes, consider a network with n users, each has a unique wavelength for transmission, and a filter capable of filtering out any wavelength for reception. All signals are in baseband. A request is blocked if either the transmitter or the receiver involved is already connected. Specifically, the blocking probability is

$$P_b' = 2P_1 - P_1^2 \tag{11}$$

where P_1 is given in (2) with $m = 1$.

Next, we consider a network with nm wavelengths. Each user has m transmitters transmitting at m unique wavelength, and m receivers, each capable of tuning over the nm wavelengths in the network. Blocking occurs if either all the transmitters of the transmitting node or all the receivers of the receiving node are currently occupied. Specifically, the blocking probability is

$$P_b'' = 2P_m - P_m^2 \tag{12}$$

where P_m is given in (2).

In Fig. 12, P_b (solid lines), P_b' (dashed line), and P_b'' (dotted line) are plotted against ρ for various m values. Recall that ρ can be interpreted as the average number of ongoing services per node when the blocking probability is small. For instance, for a telephone network, ρ should be much less than 0.5. For a multiservice network, we do not expect ρ to be more than 2 (unless each node actually represents many users). If we look at values of ρ around 1.5, twenty subcarriers ($m = 20$) will yield an acceptable value for P_b, which is about one in 10 000 (note that actual P_b is lower than indicated by the curve, which shows an upper bound for P_b). As expected, without multiple subcarrier channels, the blocking probability P_b' is unacceptably high. On the other hand, even without subcarrier channels, if each user has ten unique wavelengths for transmission, as shown by P_b'', the grade of service should be good enough. In practice, however, it is unlikely that one would implement a large network this way because a large number of wavelengths will be required. Furthermore, additional costs are incurred since each user require multiple transmitters and receivers

APPENDIX C
A CONTROL PROTOCOL FOR TWO-WAY POINT-TO-POINT COMMUNICATION

This Appendix outlines the control protocol for establishing a two-way point-to-point connection.

1. Source Node i

1) Send request-for-service (RS) signal on f_u continuously until acknowledged by the controller. An RF filter on the receiver is permanently tuned to f_d to receive control information from the controller.

2) Upon being acknowledged (ACK1) by the controller, transmit on f_u specific information on the service required and the destination.

3) Wait for acknowledgement (ACK2) from the controller.

4) Upon receiving acknowledgement, tune an RF filter to the subcarrier on which the service type is assigned (could be assigned dynamically by the controller or fixed as a standard).

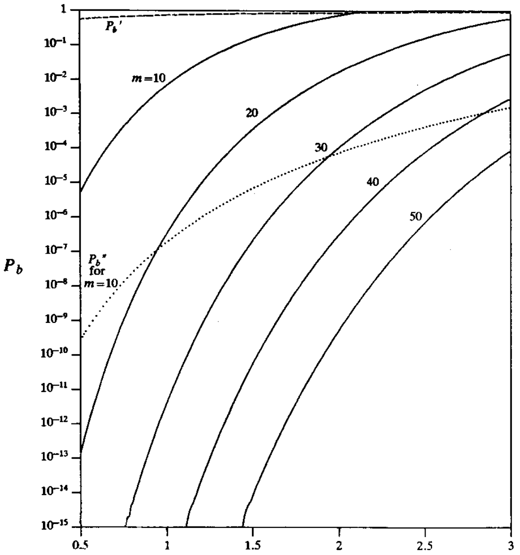

Fig. 12. Blocking probabilities versus offered load per user.

2. Controller

1) The controller has a scanner which detects new requests for service. In a round robin fashion, an optical filter (OF) of the scanner scans through the incoming wavelengths, selecting one wavelength at a time. The selected wavelength is detected and an RF filter, fixed at f_u, is used to filter out the control signal from the corresponding user. The wavelength scanning sequence is repeated until an RS signal transmitted on subcarrier f_u is detected.

2) Upon detecting an RS signal from node i on wavelength λ_i, the controller tunes the OF of node i to let through λ''. Send an ACK1 to node i, prompting it for further detail (e.g., destination, etc.).

3) Upon receiving the required information, and if the service can be established, the OF of destination node j is tuned to let through λ_i and λ''. The OF of the controller is tuned to filter out λ_i and let through λ_j.

4) On subcarrier RF f_d of λ'', information is sent to the destination node to inform the destination of an incoming service request.

5) If approved by the receiver, tune the OF of node j to filter out λ'' and filter through λ_i. The OF of node i will be tuned to let through λ'' and λ_j.

6) An acknowledgement (ACK2) will be sent to the source node on f_d of λ''. The OF of node i is tuned to let through λ_j.

7) Connection established.

3. Destination Node j

1) An RF filter here is always tuned to f_d.

2) Upon receiving a request for establishing service,

decide if service can be established or whether the receiver wants to set up the connection.

3) If yes, tune another RF filter to filter through the subcarrier of the new service.

4) Acknowledge the controller on f_u of λ_j.

APPENDIX D
INTERDEPENDENCE OF NETWORK PARAMETERS

This Appendix investigates the interdependence of the attenuation of the signal path (including the splitting loss), the transmitter power, the number of transmitted channels per laser, the number of received channels, and the bit rates of the channels. The analysis is based on a modification of [4] to take into account the multiwavelength and wavelength selectivity capability of our system. In particular, the detection of channel i on transmitter j by receiver k is analyzed, where i, j, and k are arbitrary. The following notation will be used.

A_{jk}	optical power attenuation for signal path from laser j to receiver k,
B_{ij}	signal bandwidth of channel i on laser (transmitter) j,
CNR_{ijk}	carrier-to-noise ratio of channel i on laser j at receiver k,
F	noise factor (figure) due to noise contributed by receiver circuitry,
I_k	average optical power falling on detector k,
i_{ijk}	RMS current detected by receiver k attributed to channel i on laser j,
k_B	Boltzmann constant,
$L^{(k)}$	set of lasers selected by the AOTF of receiver k,
L_j	optical power launched by laser j,
m_{ij}	optical modulation index of channel i on laser j,
N_s	shot noise,
N_t	thermal noise of receiver circuitry,
q	charge of an electron,
$\Re$	responsivity of the photodetector,
R_L	load resistance of photodetector,
T	temperature in kelvin.

Using the above notation, the average optical power falling on detector k is

$$I_k = \sum_{j \in L^{(k)}} A_{jk} \overline{L_j}. \tag{13}$$

The corresponding shot noise is therefore

$$N_s = 2qI_k B_{ij} R_L = 2qB_{ij} R_L \Re \sum_{j \in L^{(k)}} A_{jk} \overline{L_j}. \tag{14}$$

The thermal noise is

$$N_t = 4Fk_B T B_{ij}. \tag{15}$$

The RMS signal current for channel i on laser j detected by receiver k, given that laser j is one of the lasers selected by the AOTF of k, is

$$i_{ijk} = A_{jk} \Re m_{ij} \overline{L_j} / \sqrt{2}. \tag{16}$$

From the above, the carrier-to-noise ratio is therefore

$$\mathrm{CNR}_{ijk} = \frac{A_{jk}^2 \Re^2 m_{ij}^2 \overline{L_j}^2 R_L / 2}{2qR_L B_{ij} A_{jk} \Re \sum_{j \in L^{(k)}} \overline{L_{jk}} + 4Fk_B T B_{ij}}. \tag{17}$$

Rearranging

$$\mathrm{CNR}_{ijk} B_{ij} / m_{ij}^2 = \frac{A_{jk}^2 \Re^2 \overline{L_j}^2 R_L / 2}{2qR_L A \Re \sum_{j \in L^{(k)}} \overline{L_{jk}} + 4Fk_B T}. \tag{18}$$

Some observations can be made from the above. 1) Given a constant RHS and a minimum required CNR (16 dB for a BER of 10^{-9} [4]), there is a tradeoff between the optical modulation index and the signal bandwidth. The higher the bandwidth, the higher the required modulation index. But the number of channels that can be multiplexed onto a single transmitter decreases with the increase in the modulation indices of the individual channels. 2) The number of users is approximately inversely proportional to A_{jk}, considering the splitting loss in a star network. Keeping all other factors constant, m_{ij} is inversely proportional to A_{jk}, or proportional to the number of users. 3) Assuming the number of channels per laser is inversely proportional to m_{ij}^2 (so that the total modulation index, $\sqrt{\#\ \text{channels}} \times m_{ij}$ is constant), the number of channels per user is inversely proportional to the square of the number of users.

If the receiver is thermal-noise limited (i.e., the second term of the denominator is much greater than the first term), then there is no significant limit on the number of channels let through by the AOTF of receiver k. In other words, there is no limit on the size of the set $L^{(k)}$. In this case, there is no limit on the number of receivable channels (so long as the first term is kept much smaller than the second term).

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Soung C. Liew (S'84-M'87) was born in Malaysia in 1960. He received the S.B., S.M., E.E., and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1984, 1986, 1986, and 1988, respectively.

From 1984 to 1988 he was a Research Assistant in the Local Communication Networks Group at the M.I.T. Laboratory for Information and Decision Systems, where he investigated fundamental problems in high-capacity fiber-optic networks. Since 1988, he has been with Bell Communications Research, Morristown, NJ. His current research interests include fiber-optic subscriber loops and local area networks, and broad-band circuit and packet switching architectures.

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Kwok-wai Cheung (S'82-M'86) was born in Hong Kong in 1956. He received the B.S.E.E. degree from the University of Hong Kong, and the M.S. and Ph.D. degrees in physics from Yale and the California Institute of Technology, respectively. His Ph.D. dissertation was on the design of an acoustooptic correlation spectrometer.

Immediately after he graduated he joined Bell Communications Research as a Member of the Technical Staff, doing research on optical networks. His primary interest is in the application of acoustooptics in multiwavelength optical networks.

Dr. Cheung is a member of OSA and SPIE.