A Broadband Optical Local Network Based on Multiple Wavelengths and Multiple RF Subcarriers

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Abstract

We propose a multi-wavelength local-access optical network that is capable of supporting multiple services with diverse requirements. Integral to the network is an acousto-optic tunable filter which can select multiple non-adjacent wavelengths simultaneously. The use of multi-wavelength selectivity, together with subcarrier multiplexing in the electronic domain, results in simple solutions to many transmission and switching problems in a multi-service setting. An important conclusion is that multi-wavelength selectivity can be used to implement many networking functions not easily realized otherwise.

I. Introduction

With the recent dramatic advances of fiber-optic technologies, many people have begun to envision a future broadband optical network that is capable of supporting multiple services with differing transmission rates. This paper deals with the local-access network, which includes the subscriber loop as well as local switching between subscribers of a common remote multiplexing node. Among various approaches and technologies for realizing such a network [1] – [6], wavelength-division multiplexing and subcarrier multiplexing appear to be very promising because they are less demanding technologically than other alternatives.

To date, wavelength-division multiplexing has been successfully demonstrated both in high bit rate transmission [7] and in network applications [2], [3]. Filtering or selection of channels separated by 2nm is currently achievable, and narrower channel separations may be possible as filter technologies improve. This gives more than a hundred broadband channels in the entire low loss fiber transmission region (from $1.2\mu m$ to $1.7\mu m$ with the exception of the high loss region around $1.4\mu m$), with each wavelength channel having a transmission bandwidth of several GHz.

Subcarrier multiplexing in the GHz region uses commercially available microwave components which can be manufactured inexpensively [8],[9]. Not only can narrow electronic channel separations be achieved, but an entire microwave spectrum as broad as several GHz can also be used. In fact, channel separations in the MHz range is much easier in the electronic domain than in the optical domain using coherent technologies. Most of the recent subcarrier multiplexing approaches [9],[10] use multi-mode lasers to distribute a large number of video channels (e.g., 90 channels was demonstrated in [11]). 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 so that narrow channel separations and efficient fiber bandwidth utilization can be achieved at the same time. By making many broadband channels available to each individual user, we also achieve increased flexibility in switching as well as simplicity in service provisioning.

Many network architectures are designed to support either purely broadcast services or purely point-to-point switched services [3],[15]. In order to provide both broadcast and switched services cost-effectively, multiple physical networks are overlaid. In our approach, transmission and switching are considered together. We describe 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.

II. A Multi-Purpose Logical Network Structure

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 multi-service network, consideration should also be given to an architecture in which the network structure and connectivity can be reconfigured easily, since services may be added and removed over time. A 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. An example of the scenario from a subscriber's viewpoint is depicted in Fig. 1.

To exploit the high capacity of the optical medium, we propose a general network structure depicted in Fig. 2. We first describe the logical relationship between the different network parts and functions. Physical details, such as the locations of the functions, the technologies employed, will be presented in Section IV. Each user (subscriber or vendor) is assigned a unique wavelength for transmission. A single wavelength may contain many subchannels at different subcarrier frequencies, each carrying a different

CH2655-9/89/0000-0162 $1.00 © 1989 IEEE

service or information stream. Two levels of signal filtering are associated with the receiving end. A central network controller tunes an optical filter within the network to select the desired wavelengths for a given subscriber. At the subscriber premises, the desired subcarrier channels are selected by electronic filtering.

Logically, 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. The wavelength filters at the boundary of this inner layer allow only wavelengths permitted by the controller to pass on to the users. Thus, each user has a different view of the outer network layer, as if the network is tailored to his or her own individual needs. The wavelength filter we assume here is a "random-access" multi-wavelength selector; in other words, the selected wavelengths need not be adjacent to each other [13]. Note that a user will only require a single fixed-wavelength transmitter and a broadband optical receiver capable of detecting all optical carrier frequencies in the network.

The network controller monitors and provides multiple services over simultaneously overlaid logical subnetworks. For instance, the network controller can establish circuit-switched connectivity 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 physical network and thus 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 filtering process provides a certain level of flexibility for the network controller as well as the user. Since wavelength filtering is performed under the direction of a network controller, the controller can prevent unauthorized users from gaining access to certain private wavelengths. Thus, 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.

Examples of Overlaid Networks

To illustrate the versatility of the network structure, consider the examples depicted in Figures 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 co-exist simultaneously within the general network structure.

(a) 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 would tune the Optical Filters (OFs) of nodes 1 and 2 to let λ_2 and λ_1 through, respectively. At the subscribers' premises, RF Filters (RFFs) associated with telephone service would be tuned to f_1. The multi-wavelength 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.

Multi-party 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, the sum total 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 that signal audible to each subscriber, thereby making the multi-party conversation more intelligible.

(b) Video Broadcast

Again independent of wavelength, a set of subcarrier RFs, f_2 to f_{32}, could be dedicated to video broadcast, providing thirty-one possible video broadcast 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 $31 \times 10 = 310$ channels. As shown in Fig. 4, if a subscriber uses 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, an RF subcarrier allocation scheme different from the above 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 non-overlapping in the RF domain, their optical wavelengths can be tuned in simultaneously by the OF, and the video channels can be separated electronically thereafter. Note that if the vendor subcarrier frequencies are totally disjoint, then their optical sources could be of the same wavelength, so long as the light sources are incoherent with each other and the total number vendors sharing the same wavelength is small.

(c) Multiaccess Local Area Network (LAN)

A LAN with collision detection can be implemented on two RF subcarriers, say f_{33} and f_{34}, 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_{33} and receive incoming data on f_{34} at λ_{LAN}. An OF at the controller admits the wavelengths of all participating nodes and detects the composite signal. The controller then frequency-translates the composite signal from subcarrier f_{33} to subcarrier f_{34} in the electronic 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 OFs 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 a "real" Ethernet-type LAN that is separate from the other network services. An interesting point to note is that a multi-party telephone conversation could also be established using a similar logical setup.

III. 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 the existing services. The strategy that we propose is to overlay a separate control network on top of the communication network, using a different wavelength. Figure 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 that 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 OFs of the intended users choose λ'' as one of the selected wavelengths.

IV. A Physical Network Architecture

There are many ways to physically realize the network structure described in the previous sections. Here, we propose a physical network that relies on two-stage star couplers for signal distribution and Acousto-Optic Tunable Filters (AOTF) [12],[13] for wavelength filtering. 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.

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) 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 AOTFs contain signals from all users.

At the central controller's location (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 changing the selected wavelength of this filter, the controller can detect any newly active users or new requests for services. To set up the network connectivity requested, the wavelengths selected by the participants' AOTFs need to be controlled. The control information for tuning the remote AOTFs 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 AOTFs.

The outputs from a second-stage $N \times N$ coupler are connected to an array of AOTFs, depicted in Fig. 9. Associated with each remote AOTF array is a local controller which tunes the AOTFs according to the directions it receives from the central controller. To receive this control information, one of the AOTFs 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 if $(M-1) < N$. 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. Thus, we 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. 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 network.

In practice, the central controller could be located at a central office, and the users' AOTFs 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. Note from Figures 7 and 8 that 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.

Possible Network Parameter Values

We now consider some specific examples in order to develop some idea of possible network parameter values, such as bit rates, number of users etc. Table 1 summarizes some power budget estimates based on the following assumptions:

- A receiver sensitivity of −30 dBm is possible for the transmission of 20 Mb/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 Mb/s baseband data. The assumed receiver is a high-speed PIN-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 between channels can be ignored.

Based on the above assumptions, it should be possible to build a demonstration network with eight 4×4 couplers. There would be 12 subscriber nodes, each capable of transmitting at 4 subcarrier channels at 20 Mb/s and 1 baseband channel at 500 Mb/s. The total traffic generated by the internal users, not including the traffic from the central office, in this case is 6.96 Gb/s. In this example, the number of users and transmission throughput is bounded by the limited optical power rather than the available optical spectrum. In the future, with a transmitter power of 12 dBm, 240 users and a total user-generated traffic of 139.2 Gb/s can be supported. Other ways to increase the network size and throughput include improving receiver sensitivity, customizing the receiver for RF reception [4], and using an optical amplifiers to boost the pre-detection optical power [11].

The above assumes all channels have the same bit rate. A mixture of bit rates (e.g., from 10 to 155 Mb/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 non-linearity [16], the number of channels received is limited by the shot-noise from multiple sources. For a thermal-noise-limited receiver, this is not a problem, since receiver thermal noise is independent of the optical power falling on the photodetector. Thus, in practice we expect the number of receivable RF channels to be larger than the number of transmittable channels. This means a subscriber could receive more traffic than he would be able transmit, a common situation in networks with asymmetric traffic patterns.

V 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:

1. Multiple services can be supported by a physical network, with non-interacting services transparent to each other. Unlike a time-division approach, synchronization and coordination of transmission times between subscribers and between services (for 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 user connectivity 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 (electronic receiver and transmitter circuitries), which are less expensive than the 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 capability of AOTFs to select multiple wavelengths needs to be demonstrated and its limitations understood. What is the maximum number of wavelengths that can be selected simultaneously? What are the performance penalties associated with their use? How are they related to the number of selected wavelengths?

2. RF Modulation of DFB lasers and the performance penalties due to laser nonlinearity need to be investigated; most of the recent investigations on subcarrier multiplexing use Fabry-Perot lasers. The maximum tolerable total optical modulation depth of DFB lasers, which are essential for dense-wavelength multiplexing, needs to be established. The optimal receiver structure and the corresponding sensitivity for FSK signal must be studied more carefully.

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 also 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 [17]. 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.

Acknowledgements

We would like to thank C. Brackett, H. Lemberg, R. Menendez, P. Shumate, and W. Way for their suggestions and comments.

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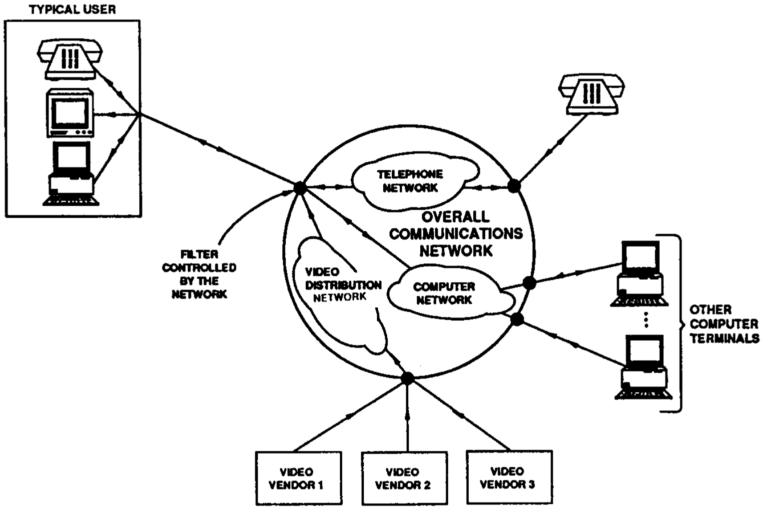

Fig. 1 A Multi-Purpose Network from a Subscriber's Viewpoint.

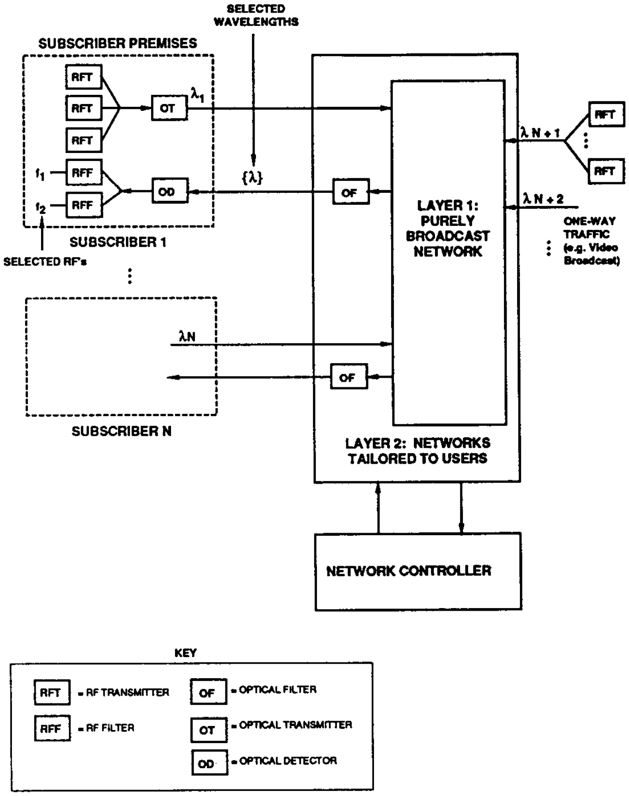

Fig. 2 A Multi-Purpose Logical Network Structure.

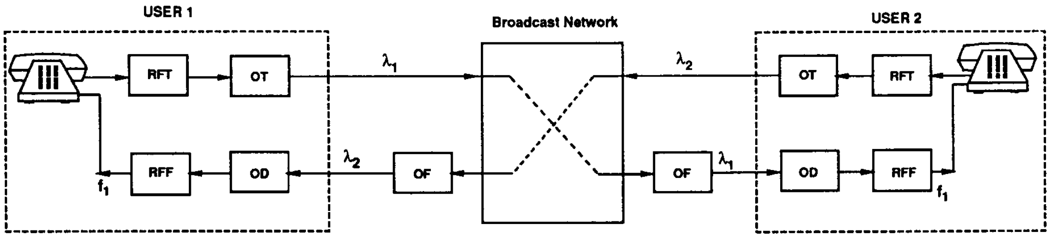

Fig. 3 An Overlaid Telephone Connection.

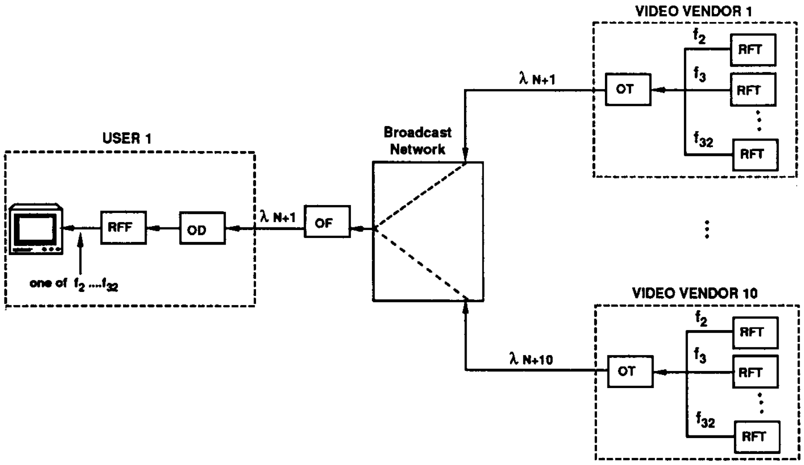

Fig. 4 An Overlaid Video Distribution Network.

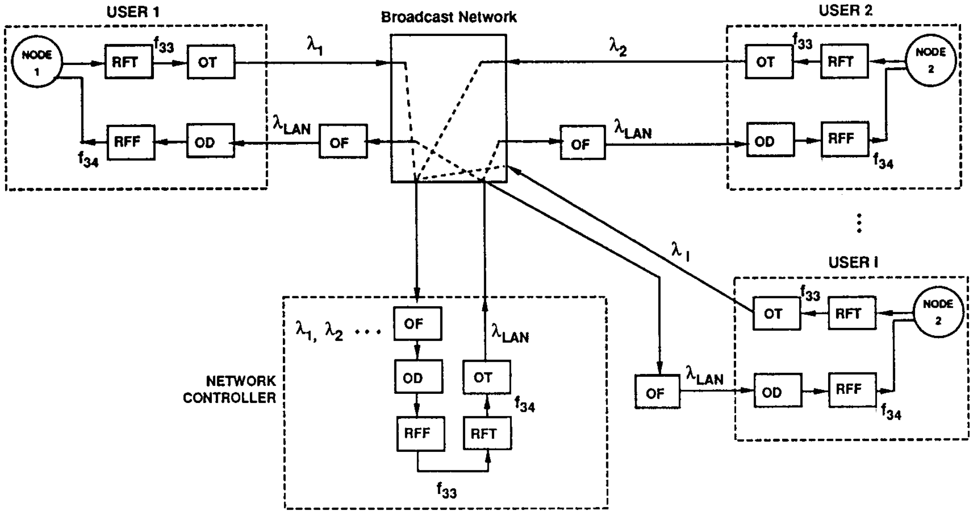

Fig. 5 An Overlaid Local Area Network.

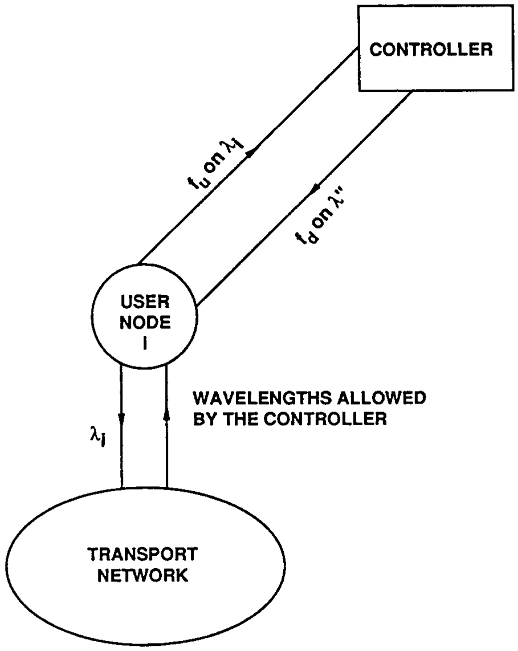

Fig. 6 Logical Separation of Control and Transport Networks.

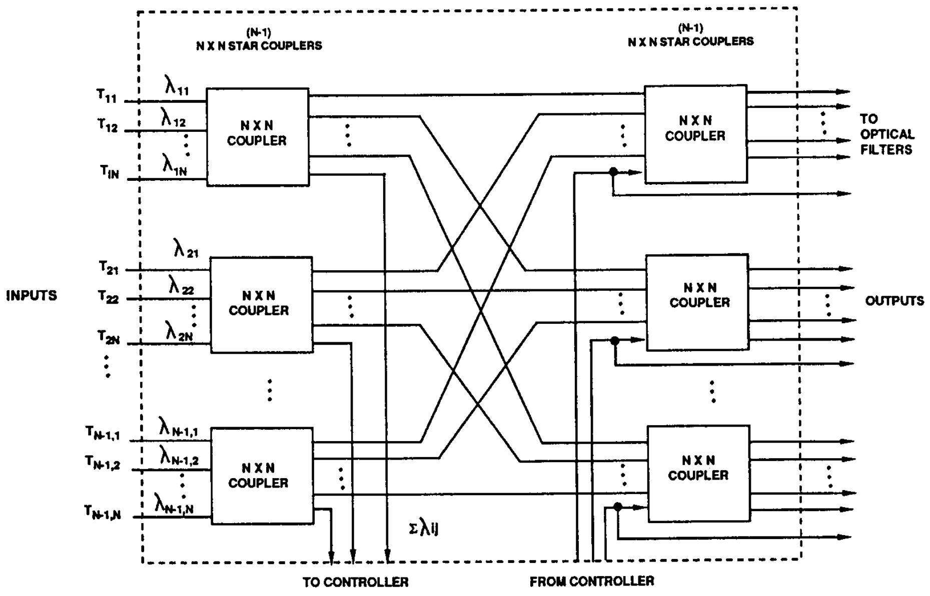

Fig. 7 A Physical Implementation of Broadcast Network.

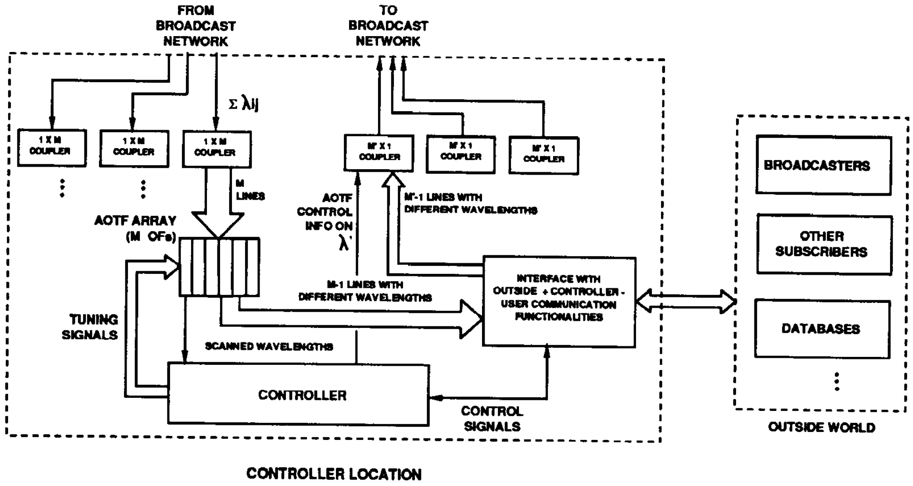

Fig. 8 A Physical Implementation of Controller.

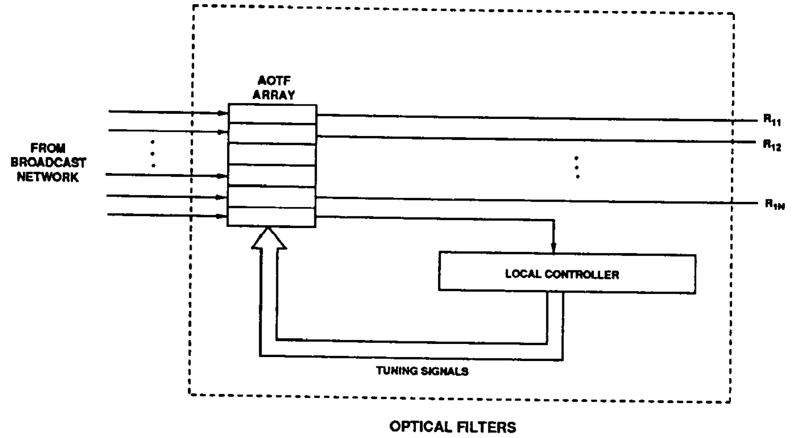

Fig. 9 A Physical Implementation of an Array of Optical Filters.

Component	*Power Budget* (Present)		*Power Budget* (Near-future)	
Transmitter Power		0dBm		12dBm
Input Star Coupler Loss	(4 × 4)	< 8dB	(16 × 16)	< 14.5dB
Output Star Coupler Loss	(4 × 4)	< 8dB	(16 × 16)	< 14.5dB
Filter Loss		7dB		7dB
Fiber Loss	(< 10km)	4dB	(< 10km)	4dB
Connector loss		2dB		2dB
Receiver Sensitivity		−30dBm		−32dBm
Total Power Loss		< 29dB		< 42dB
Power Margin		1dB		2dB

Table 1. Power Budget Estimates.