A Wavelength Encoded Multichannel Optical Bus for Local Area Networks

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***Abstract*— A scalable, high-speed, wavelength encoded multichannel optical bus (WEMCOB) employing the wavelength division multiplexing (WDM) technology is proposed to reduce the link speed requirement, the wiring complexity, and the number of optical amplifiers for local area networks. In this paper, a hierarchical network topology is adopted, in which a dual unidirectional WEMCOB with separate control and data channels composes the backbone network, and unidirectional tree-based WEMCOB's with centralized arbiters constitute the subnetworks. We perform a feasibility study on the implementation of a local area network based on the WEMCOB, discuss the related issues, and show that a total transmission capacity of several tens of gigabits per second (Gb/s) can be achieved to serve a large number of broadband users by utilizing today's optoelectronic technology.**

I. Introduction

RECENTLY, much attention has been paid to a promising technique for transferring and switching various types of information such as voice, data, and motion video in Broadband Integrated Service Digital Network (B-ISDN) [1]. In the meantime, with the advent of more complex and advanced broadband services and a continuous increase of users within a specific local area, the need for a universal high-speed local area network (LAN), with regard to the global telecommunication network, has become quite urgent. The broadband services, such as multimedia communication and high-definition television transmission, generally require the network be able to maintain high throughput among users located possibly several kilometers apart while still satisfying very tight delay constraints when real-time traffic is involved. To meet these demands, an appropriate choice should be made for each transmission technique, network topology, and access protocol being considered.

Among various transmission media, electrical connection links provided for these services are not capable of transmitting signals at Gb/s because of physical constraints such as power budget and crosstalk limitation. In contrast, optical fiber links can support data transmission over longer distance and consume less power than electrical links at such high data rates. Other attractive features of optical fiber links include immunity against electromagnetic interference, protection against signal leakage, and significantly more lightweighted and lower attenuation than coaxial cables.

Bit-serial multiplexing/demultiplexing technologies have been widely used in most digital transmission systems. In such systems, data rates increase with the number of nodes in a network. As transmission rates go higher than 10 Gb/s electronic control circuitry is quite involved and the related technologies are not yet fully matured. Even worse, additional framing and encoding required in a serial transmission link usually constitutes a large portion of overhead. Therefore, the serial transmission scheme is not practical in such high-speed data links. In most computer systems, data transfer is word-wide processed in parallel, owing to inherent design methodologies adopted in most CPU processor architectures. It is well known that the word-in-parallel communication can transfer data more efficiently than the word-in-serial communication. Multicopper is the traditional medium used in parallel transmission systems such as IEEE 488 or TCP/IP. Link speed, power consumption, and wiring complexity are, however, the major concerns when the multicopper is used as a long distance transmission medium. Multifiber has been used instead as a substitute since it offers advantages over multicopper in increasing link-speed and reducing power consumption [6], [7]. Other alternatives such as the *Wavelength Encoded Multichannel Optical Bus* (WEMCOB) which employs wavelength division multiplexing (WDM) to transfer data in parallel through a single fiber appears more attractive in reducing wiring complexity than the multi fiber. Some example works are the byte-wide WDM optical links [2], the interconnection switching network using bit-per-wavelength encoding [3], and the WDM-based Virtual Bus [4].

Many traditional networking topologies, such as basic ring, star, bus, or their combinations, can be configured to comprise a fiber-optics-based LAN. In particular, a dual bus renders itself three attractive features. First, it offers high-sharing bandwidth; second, all nodes which are sequentially connected can be easily added or dropped from the network; third, a number of standardized high-performance distributed protocols, such as IEEE 802.6 DQDB [5], can be implemented to maintain fairness access, high throughput, congestion free and priority controllability of the network. There are two major issues regarding dual bus topology. First, as the demand of broadband service increases, the total bandwidth must increase

Manuscript received December 29, 1994; revised November 20, 1995. This work was supported by the National Science Council, Taiwan, R.O.C., under Grants NSC 84-0408-E002-008 and NSC 83-0417-E002-005.

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Publisher Item Identifier S 0733-8724(96)02140-8.

proportionally resulting in a bottleneck of a serial optical link. Second, due to the distributive nature, the size of the network shall be limited by the power budget available when using existing optoelectronic devices.

In this paper, we propose a novel WEMCOB approach for a large number of users in a large spanned area such as a LAN. The wavelength-encoding scheme is based on the WDM technology in which separate low-speed control and high-speed data channels are transmitted in parallel to reduce the link speed requirement, the power consumption, and the wiring complexity. In addition, to solve the power budget issue, we propose a hierarchical architecture which consists of a main bus for backbone network and many scalable tree-based buses for subnetworks.

This paper is organized as follows. In Section II, we will first review several high-speed multichannel optical buses reported in the literature. The encoding technique of using separate control and data channels in our WEMCOB is described in Section III. In Section IV, a hierarchical WEMCOB LAN architecture cluster is proposed and discussed. The power budget and the complexity consideration in building a WEMCOB LAN are detailed in Section V. Finally, in Section VI we conclude our study.

II. High-Speed Multichannel Optical Buses

Two categories will be reviewed based on the processing technology: one is the multifiber optical bus (MFOB); the other is the WEMCOB.

A. MFOB

In this category two kinds of configurations have been studied. The first is a number of independent serial channels being transmitted simultaneously, but asynchronously, by multiple fibers, i.e., each channel has its own transmitter, receiver, and clock retiming devices [6]. The major research efforts and results of this configuration are technological developments for integrating multiple fibers with optoelectronic arrays and large reduction in interconnect volume, respectively.

The second is the parallel optical data links where data bits are transmitted in parallel and synchronously. An example is the MODLINK II developed by AT&T [7]. This system consists of eight synchronized data channels and is capable of transmitting data from dc to 500 Mb/s per channel in a continuous or burst mode. It can be implemented with low-speed optoelectronics, and is cheaper than the one utilizing multicopper. However, the transmission distance is limited to about 2.3 km due to the power budget and the speed constraints.

B. WEMCOB

In contrast to the multifiber approach, a wavelength encoded multichannel optical bus can have a big saving on fiber usage, since data bits are transmitted in parallel through a *single fiber.* Each bit of the parallel data (word or byte) is encoded with a distinct wavelength. These wavelengths are combined by a WDM multiplexer (mux), and then transmitted through a single-mode fiber. At the receiver end, a WDM demultiplexer (demux) separates the received signals by their wavelengths. These optical signals are then converted into electrical signals of a byte or a word.

Two examples were demonstrated for the WEMCOB's applications: one is for a computer interconnection network and the other is for a general interconnection network. Self-routing 2×2 photonic switches were used in the first example to implement a tightly coupled architecture, e.g., the Shuffle Net interconnect for a multiprocessor computing system [3]. Each bit of the routing and data information is encoded in a separate wavelength and transmitted within a packet period. However, like most multistage interconnection networks, such implementation would also face scalability problems as the number of nodes increase. Moreover, the number of wavelengths available from the current WDM technology is yet large enough to support a big data packet, e.g., a few hundred bits packet. The second example, which is a scalable interconnection network architecture called the Virtual Bus, an implementation approach resulted from early researches, exploited the feasibility of using WDM technology to reduce the wiring complexity and the power consumption [4]. The pipeline parallelism of the data path was maximized to reduce the control complexity of space division switching. The parallelism increased the speed of the time division bus, and reduced the number of ports in the space division switch which interconnected multiple time division buses. Based on this concept, the Virtual Bus consisted of a 3-D VLSI space division switch that connected multiple WDM bus clusters. The WDM bus clusters were further partitioned into multiple local buses to improve the pipeline parallelism. The local and cluster WDM buses were unidirectional such that high-speed pipelined arbitration and routing could be easily applied to both the transmitting and the receiving data paths. In each WDM bus, a big data packet was partitioned and simultaneously transmitted by a number of wavelengths sequentially. The Virtual Bus approach may solve the wavelength availability problem encountered by the system described in [3], particularly when a long-length packet is to be transmitted.

C. Comparisons between MFOB and WEMCOB

As mentioned above, in a high-speed network the parallel transmission technique is more attractive than the serial one. Multi fiber and multi wavelength are two major implementation techniques for a parallel transmission system. A common advantage for both the multifiber systems (MFOB) and the multiwavelength systems (WEMCOB) is the information transfer rates can be increased without increasing the terminal circuits' speed due to the fact that, as opposed to a serial transmission system, additional encoding and framing is not required [2], [7]. Since a WEMCOB encodes all the bits in wavelengths rather than in fibers, it offers the following unique advantages: a) reduced wiring complexity, b) reduced taper complexity, c) fewer dispersion compensators, and d) fewer optical amplifiers for loss compensation. The first three advantages are quite obvious due to the fact that a single fiber is used in a WEMCOB, while the last one will be discussed in detail in Section V. In contrast, there are two issues to be considered in a WEMCOB: one is the increased complexity of transceivers for multi wavelengths; the other is the increase

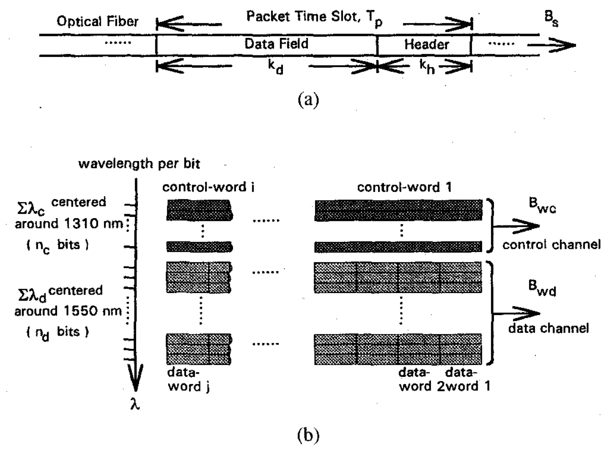


Fig. 1. Encoding techniques in a packet being transmitted.

of insertion loss caused by WDM multiplexers/demultiplexers. The former issue is expected to be relieved by the continuous improvement of the transceiver array technology, while the latter issue, which results in the power budget concern, will be discussed in Section V.

III. Novel Encoding Technique for WEMCOB

For most packet switching technologies, the format of a packet consists of two fields: a header field and a data field. The header field carries the control information such as the packet status, the routing destination, the priority level, and the error control code, etc., while the date field contains the packed data to be transmitted or received. In general, the bit length of a header field is much shorter than that of a data field. Moreover, in a switching node, the content to be processed is only in the header field, whereas the information in the data field is just for transportation. In a serial optical link, the switching node must be operated at the peak rate of a transmission line because the packets are transmitted bit-by-bit sequentially. As the transmission rate exceeds some value, say several tens Gb/s, electronics become very much involved, expensive, and not fully matured. Therefore, it becomes attractive and operationally efficient to divide the switching rate into two components: high-speed data rate and low-speed header rate. A similar concept called *field-coding* was proposed in a serial optical distribution channel [8]. However, in our WEMCOB, this separate field-encoding concept is to be used in a fully parallel form.

Each packet being transmitted in our WEMCOB is divided into a control channel and a data channel, as shown in Fig. 1. The control channel carries a pipelined control packet stream with n_c equally spaced wavelengths centered around 1310 nm. All bits in the control channel are transmitted at a low-speed bit rate B_{wc}. Similarly, the data channel contains a pipelined data packet stream with n_d wavelengths but centered around 1550 nm. All data bits are transmitted at a high-speed data bit rate B_{wd}.

We assume that a packet transmitted at bit rate B_s contains a k_h-bit header field and a k_d-bit data field as shown in Fig. 1(a). Thus, a packet time-slot T_p, i.e., the duration of a packet, can be expressed as:

$$T_p = (k_h + k_d) \cdot \left(\frac{1}{B_s}\right). \tag{1}$$

Suppose we encode the control channel and the data channel with n_c and n_d parallel bits, respectively, for the same packet time slot as that of a serial optical link, i.e., with the same transmission capacity, T_p can be rewritten as:

$$\begin{aligned} T_p &= \left(\frac{k_h}{n_c}\right) \cdot \left(\frac{1}{B_{wc}}\right) \\ &= \left(\frac{k_d}{n_d}\right) \cdot \left(\frac{1}{B_{wd}}\right) \end{aligned} \tag{2}$$

where B_{wc} and B_{wd} are control bit rate and data bit rate, respectively. From (1) and (2), B_{wc} and B_{wd} can also be expressed as:

$$B_{wc} = \left(\frac{k_h \cdot B_s}{k_h + k_d}\right) \cdot \left(\frac{1}{n_c}\right)$$

and

$$B_{wd} = \left(\frac{k_d \cdot B_s}{k_h + k_d}\right) \cdot \frac{1}{n_d}. \tag{3}$$

It is clear that both the control and the data rates are only a small portion of the total bit rate of a serial link. For example, a DQDB packet (with 5-octet header and 48-octet data) running at a bit rate of 2.488 Gb/s is hard to be implemented in a switching node using electrical processors directly. However, for the same transmission capacity, a WEMCOB encoded with 8 header wavelengths ($n_c = 8$ and 16 data wavelengths ($n_d = 16$ decreases its control channel bit rate B_{wc} and data channel bit rate B_{wd} to only 29.34 Mb/s and 140.83 Mb/s, respectively. It is apparent that at such rates a switching node can be easily implemented using commercial processors and electronic components. It is noted that a synchronous signal at a separate wavelength shall be embedded in the data channel to indicate packet boundary. However, the above analysis will still be applicable since the signal is not included in the useful data stream of a packet and used only for signal synchronization.

IV. Extension to Building a LAN Based on WEMCOB

In this section, we propose a hierarchical WEMCOB LAN to lift the network size limitation of a single-level bus network. In this hierarchical network, as shown in Fig. 2, the wavelength encoding technique as well as the distributive control scheme are employed to construct a dual unidirectional WEMCOB and tree-based WDM clusters. The dual unidirectional WEMCOB deals with backbone switching, while the clusters with the same function as proposed in the Virtual Bus serve as in-campus or in-building subnetworks [4]. The interconnection between the two distinct networks is performed by a cluster access node which deals with media access control (MAC) protocols, interworking interface, and data switching functions. The details of the building blocks are described in the following.

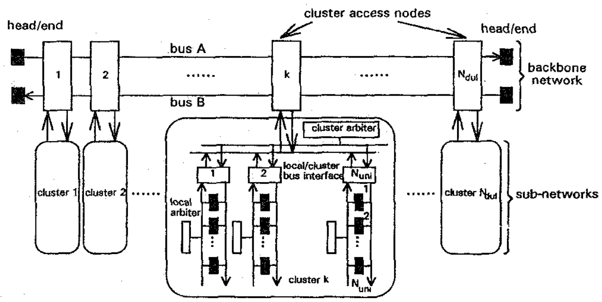


Fig. 2. A hierarchical WEMCOB architecture for a local area network.

A. Tree-Based WEMCOB Cluster

The functional block of the WEMCOB local/cluster bus networking is shown in Fig. 3. Each node consists of a transmitter module, a receiver module, optical multiplexers, and an electrical processing unit. Parallel data bits and control signals from the electronic processing unit can be multiplexed into a transmitter module. The transmitter module consists of an integrated multiwavelength laser array with electrical driving circuits. Control and data channels are transmitted in different wavelengths. These signals are combined by a WDM component and then coupled into an optical fiber using an optical tap. The protocol and routing control is completed by a fast tree VLSI arbiter, as shown in [9]. Fig. 4 shows the block diagram of a three-level tree arbiter. The header interpreter translates or decodes a control information specified in the packet header (e.g., VPI/VCI in an ATM cell header) to determine how to route the packet. The input packet is directed to an output port specified by the interpreted physical destination address. If it is a multicast or broadcast operation, the input packet will be directed to the related or all the output ports. Since multiple inputs may be directed to the same output port, the tree arbiter selects a winner based on a variable priority arbitration process with round-robin scheduling policy. The winner's address is then broadcasted to all the destined output ports through the control signal buses. However, the arbiter allows only one node at a time to upload on the "input" bus, but the data in the "output" bus can be broadcasted to all nodes. When data are downloaded from the "output" bus to a node, all parallel bits are simultaneously demultiplexed into a receiver module by a WDM demultiplexer. The receiver module, in the form of an optoelectronic integrated circuit (OEIC) chip composed of an array of photodetectors and integrated preamplifiers, detects and converts bit-representing optical signals into electrical signals. These electrical signals are then processed in an electronic processing unit. The details of a performance evaluation and a feasibility study are described in [4] and [9].

B. Dual Unidirectional WEMCOB

The encoding technique of the proposed WEMCOB is applied to a DQDB slot which contains a 5-octet header field and a 48-octet data field [5]. The data channels and the control channels are encoded in 16 and 8 wavelengths, respectively. For an equivalent transmission capacity, the packet time slot T_p of a WEMCOB shall be the same as that of a serial link. Thus, the data channel rate is $B_{wd} = 3/212 * B_s$, and the control channel rate is $B_{wc} = 5/424 * B_s$. It is apparent that the transmission rate of a WEMCOB is much smaller than that of a serial link. Moreover, the speed of a control channel is much slower than that of a serial link, facilitating the implementation by commercial devices.

The networking protocol of the WEMCOB is similar to that of the distributed queue dual bus (DQDB) which is one of the international standards for MAN [5], [10]. Fairness and bandwidth balancing are the most important issues when the DQDB is applied. Many techniques, such as the use of erasure nodes [11], or the bandwidth balancing scheme [12], have been proposed to implement a more efficient and fair networking protocol. It is expected that with some modifications many existing DQDB protocols can be implemented without reading in the dual unidirectional WEMCOB. The DQDB protocol and its control are handled by the MAC in a cluster access node. Fig. 5 depicts only a half portion of a cluster access node; the other half is identical but in the opposite direction. Empty slots generated sequentially by the head/end nodes will be detected and used by the following nodes. The input packet stream is tapped from a single mode fiber to a cluster access node. A 1.31/1.55 μm WDM-demux separates the input signal into control channels and data channels. These two separate channels, one at 1.31 μm and the other at 1.55 μm, are further divided into finer channels, i.e., with a narrower channel spacing, before being converted into electrical signals which are then processed by the MAC processor and the data queue unit. In the MAC processor, the slot information is detected and used to decide whether to receive a packet or to send a packet. The data queue and interface module is used a) to receive an incoming packet and to buffer the packet to be transmitted and b) to perform interworking functions between a dual WEMCOB and the clusters. Since 1.31 μm and 1.55 μm signals are multiplexed in a single fiber, depending on the node-to-node distance and the transmission speed, some dispersion compensators may be required to maintain an acceptable bit error rate for both channels.

V. Power Budget and Complexity Study

The number of nodes that a WEMCOB can support is determined by the emitting power of a transmitter, the minimum received optical power for an acceptable bit error rate, and any losses incurred between the transmitter and the receiver. In the following, the maximum number of nodes will be determined under the power budget of the transceiver in a node and the different link losses.

A. Power Budget Analysis

In our dual bus network, the worst power budget occurs in the last node after the signal power has been successively tapped out in the previous nodes. The optical power budget thus sets a limit on the maximum number of nodes that the network can have. For a unidirectional WEMCOB, the optical insertion loss at the tap (includes a splitter and a directional

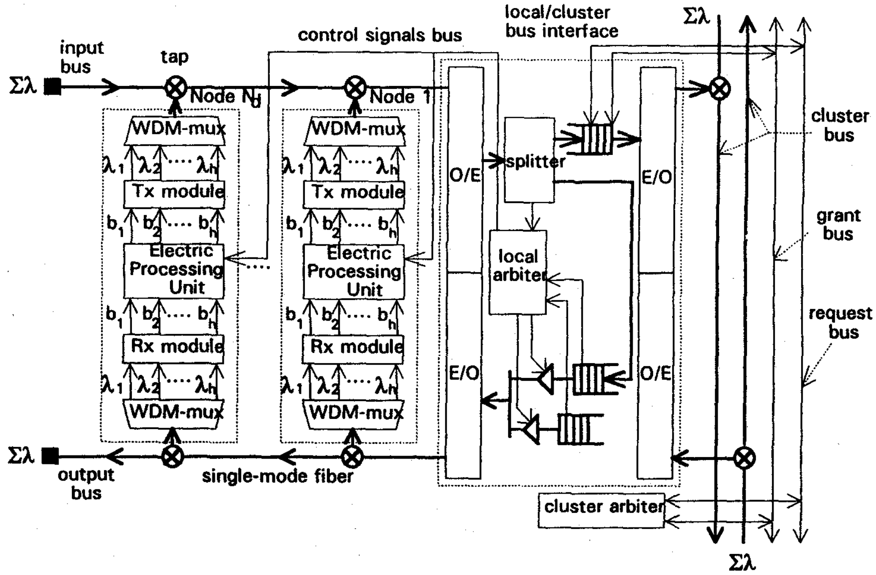


Fig. 3. One of the tree-based configurations of a WEMCOB cluster in the subnetwork.

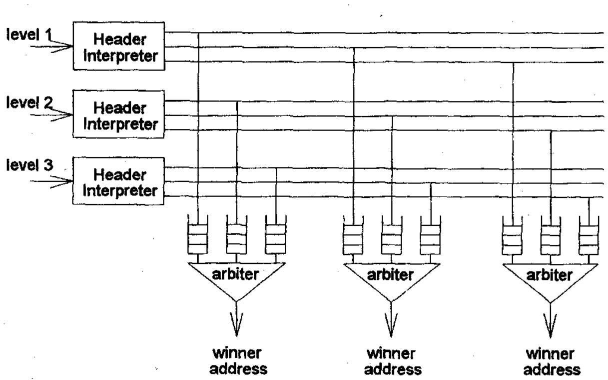


Fig. 4. A three-level tree arbiter.

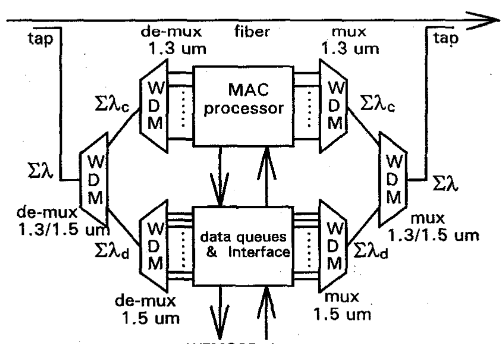


Fig. 5. Cluster access node structure of a dual unidirectional WEMCOB.

coupler) and the transceiver of each node can be modeled as shown in Fig. 6.

In this model, insertion loss of a splitter in the "bar" condition and the "cross" condition are denoted as L_{bar} and L_{cross}, respectively. L_c is the directional coupler insertion loss, and L_{WDM} is the total insertion loss of the WDM demultiplexers in the receiver side or the WDM multiplexers

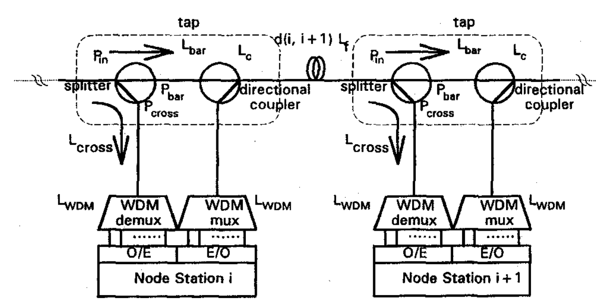


Fig. 6. Transmission loss model of a linear WEMCOB.

in the transmitter side of a node. All the losses are expressed in dB. The total transmission loss in an n-node WEMCOB, denoted as L_{total}, W can be therefore expressed as

$$L_{\text{total, W}} = (n-1)\cdot L_c + L_{\text{cross}} + (n-2)\cdot L_{\text{bar}} + \sum_{i}^{n-1} d(i, i+1)\cdot L_f + 2\cdot L_{\text{WDM}} \qquad (4)$$

where L_f is the fiber loss in dB/km and $d(i, i+1)$ is the fiber distance from node i to node $i+1$.

The insertion loss of a splitter defined as the sum of the excess loss and the coupling loss in each "bar" and "cross" condition can be expressed as

$$L_{\text{bar}} = \left(-10\log\frac{P_{\text{bar}}+P_{\text{cross}}}{P_{in}}\right) + \left(-10\log\frac{P_{\text{bar}}}{P_{\text{bar}}+P_{\text{cross}}}\right)$$

and

$$L_{\text{cross}} = \left(-10\log\frac{P_{\text{bar}}+P_{\text{cross}}}{P_{in}}\right) + \left(-10\log\frac{P_{\text{cross}}}{P_{\text{bar}}+P_{\text{cross}}}\right) \qquad (5)$$

where P_{in}, P_{bar}, and P_{cross} are the input power, the output power in the "bar" condition and in the "cross" condition, respectively.

Moreover, the splitting ratio α is defined as $P_{\text{bar}}/P_{\text{cross}}$. Therefore, (5) can be rewritten as

$$L_{\text{bar}} = L_{ex} + \left(-10 \log \frac{\alpha}{1+\alpha}\right)$$

and

$$L_{\text{cross}} = L_{ex} + \left(-10 \log \frac{1}{1+\alpha}\right) \tag{6}$$

where L_{ex} is the excess loss of a splitter. The quantity L_{total} can thus be minimized by optimizing the splitting ratio for a total number of n stations by substituting (6) into (4) and by differentiating (4) with respect to α. The optimum splitting ratio, α_{opt}, is found to be $\alpha_{opt} = n-2$. If every splitter has the same optimum splitting ratio α_{opt}, and the distance between every two adjacent nodes is equal to d, the minimum total transmission loss can be found as

$$\begin{aligned} L_{\text{total},\,W} = {} & (n-1) \cdot (L_{ex} + L_c) \\ & + \left[-10 \log \frac{(n-2)^{n-2}}{(n-1)^{n-1}}\right] \\ & + (n-1) \cdot d \cdot L_f + 2 \cdot L_{\text{WDM}}. \end{aligned} \tag{7}$$

Note that the first term of (7) represents the total insertion loss of tapers, the second term indicates the total splitting loss of tapers, and the third term denotes the sum of fiber losses. The total WDM insertion loss is independent of the number of nodes since the loss is incurred only at the transceiver ends. The dependence of the minimum total loss on the number of nodes can be found by differentiating (7), i.e.,

$$\begin{aligned} \frac{\Delta L_{\text{total},\,W}}{\Delta n} = {} & (L_{ex} + L_c) + d \cdot L_f \\ & + \log \frac{(n-1)}{(n-2)} + \frac{2}{(n-2)}. \end{aligned} \tag{8}$$

It is apparent that the insertion loss of a splitter and the attenuation loss of a fiber are two deciding factors when the number of nodes becomes large.

Fig. 7 shows the relationship between the power budget and the number of nodes that can be implemented for various insertion losses of splitters and fiber losses. The insertion loss of –7 dB for a WDM mux/demux [13], and a node-to-node distance of 100 m are assumed. We find from Fig. 7 that as the splitter insertion loss or fiber loss increases, the number of nodes that a WEMCOB can accommodate decreases dramatically. Also noted is that, although the total WDM mux/demux insertion loss does not depend on the number of nodes, the loss incurs a large decrease in power budget, 14 dB in Fig. 7. This suggests the significance of realizing a WDM mux/demux with low insertion loss, which may be feasible by employing an integrated grating [14]. Otherwise, optical amplifiers need to be installed for loss compensation. Depending on the working wavelength regions,

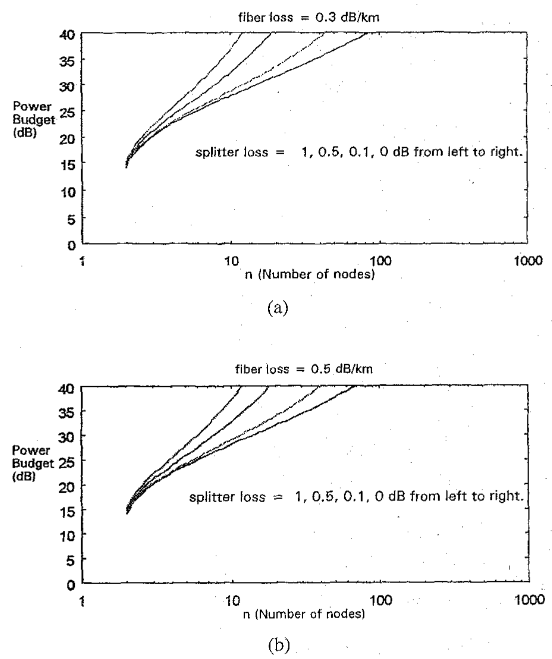


Fig. 7. The relationship between the power budget and the number of nodes as a function of splitter loss, where $L_{\text{WDM}} = 7$ dB and $d = 100$ m for L_f = (a) 0.3, and (b) 0.5 dB/km, respectively.

a possible candidate for optical amplifier may be an erbium-doped fiber amplifier (EDFA, $\sim 1.55 \mu$m), a praseodymium-doped fluoride fiber amplifier ($\sim 1.31 \mu$m), or a semiconductor amplifier (both 1.31 μm and 1.55 μm).

B. Consideration of Using Optical Amplifiers

Since the number of nodes in a bus-based network is limited by the transmission and the insertion losses, the use of optical amplifiers shall be considered in the network for loss compensation. Because using an optical amplifier is still relatively costly, it is important to estimate and compare the number of optical amplifiers required in an MFOB and in a WEMCOB. We assume that the EDFA's used in the MFOB and the WEMCOB have the same unsaturated and equalized gains over the wavelengths of interest. We also assume that all optical losses other than the WDM insertion loss in each channel of an MFOB are the same as those of a WEMCOB. The total loss in an MFOB denoted as $L_{\text{total},\,F}$ is therefore related to that in a WEMCOB, (7), by

$$L_{\text{total},\,F} = L_{\text{total},\,W} - 2 \cdot L_{\text{WDM}}. \tag{9}$$

Assume both the MFOB- and the WEMCOB-based LAN's which consist of k-bit signal channels transmitted in parallel are to be implemented with optical amplifiers for loss compensation. It is apparent that in an MFOB LAN a total of k optical amplifiers are required since k fibers are physically used for signal transmission. In contrast, a k-wavelength WEMCOB LAN only requires a *single* optical amplifier since k signal-encoded wavelengths are simultaneously amplified. Although each wavelength may have a different gain due to the nonuniform gain profile of an EDFA, significant achievements have been made by utilizing various techniques or algorithms for gain equalization [15]–[17]. In addition, unlike long-haul transmission, the spanned area of a LAN is typically within several kilometers, the number of cascaded optical amplifiers is generally quite limited, which simplifies gain equalization. As described at the beginning of this section, we can safely assume that each signal (or wavelength) in a WEMCOB will experience the same gain as in an MFOB. The number of nodes supported by a WEMCOB and an MFOB with optical amplifiers can therefore be calculated from (7) and (9) by replacing the total loss with the gain of an optical amplifier. Consider an N-node LAN spanned in a certain fixed geographical area the number of amplifiers required by a WEMCOB and an MFOB LAN can be expressed as

$$A_W = \left\lceil \frac{N - N_{TW}}{N_{GW}} \right\rceil$$

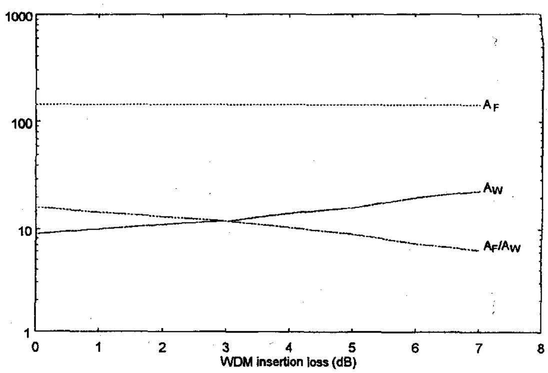
and

$$A_F = k \cdot \left\lceil \frac{N - N_{TF}}{N_{GF}} \right\rceil \tag{10}$$

where

- A_W: the number of optical amplifiers required for an N-node/k-channel WEMCOB LAN;
- A_F: the number of optical amplifiers required for an N-node/k-channel MFOB LAN;
- N_{TW}: the number of nodes supported by a WEMCOB without using an optical amplifier;
- N_{TF}: the number of nodes supported by an MFOB without using an optical amplifier;
- N_{GW}: the number of nodes that an optical amplifier can support in a WEMCOB;
- N_{GF}: the number of nodes that an optical amplifier can support in an MFOB.

For illustration, we now consider a numerical example in which a 1000-node LAN is to be built in a 16 parallel channel form. Each channel is operated at a speed of 622 Mb/s, and a power budget of 30 dB is assumed for each transceiver at this bit rate [18], [19]. We further assume that the distance between two adjacent nodes is 100 m and each optical amplifier has 40 dB gain (a number of optical amplifier studies have shown beyond this gain level such as [20]). Calculations show that the number of amplifiers required for WEMCOB is 23 and for MFOB is 144, assuming that the splitter loss, the fiber loss, and the WDM loss are 0.1 dB, 0.3 dB/km, and 7 dB, respectively (i.e., $L_{\text{total},W} = L_{\text{total},F} = 32$ dB, $N_{TW} = 16$, $N_{TF} = 71$, $G_W = G_F = 40$ dB, $N_{GW} = 43$, and $N_{GF} = 116$). It is clear from the calculated result that the total number of optical amplifiers required for an MFOB is greater than that for a WEMCOB. In addition, the difference is mainly caused by the WDM loss. Fig. 8 shows the effect of the WDM loss on the number of optical amplifiers in a WEMCOB. It is noted that as long as the WDM loss can be reduced below 4 dB, the number of amplifiers required in a WEMCOB LAN would be much smaller than that of an MFOB LAN (below a ratio of 1/10 as depicted in the figure), a clear economic advantage for a WEMCOB-based LAN over an MFOB-based LAN.



A_W: the number of optical amplifiers required in a WEMCOB;
A_F: the number of optical amplifiers required in an MFOB.

Fig. 8. The number of optical amplifiers required in a WEMCOB and an MFOB for different WDM insertion losses.

C. System Complexity

To determine the maximum number of nodes that can be supported by a WEMCOB LAN, we must calculate the power budget for each bus. Since the power budget decreases as the transmission speed increases, the power margin of the high-speed data channels in a WEMCOB, not the low-speed control channels, becomes the major concern in the analysis. Let the number of nodes connected to the dual unidirectional WEMCOB and the local bus of a cluster be N_{dul} and N_{uni}, respectively. These two numbers can be determined from the transceivers' power budget specified at a certain bit rate and from the total losses between a transmitter and a receiver. The total number of nodes that can be supported by the WEMCOB can therefore be expressed as

$$N_{\text{total}} = N_{dul} * (N_{uni})^L \tag{11}$$

where L is the level of the tree in a cluster bus. By tree level expanding, we can construct our WEMCOB LAN to be a network with high scalability.

Assuming that a single optical bus can support N nodes without using optical amplifiers, and all optical buses used in the hierarchical WEMCOB LAN are identical, the total number of nodes connected to the bus can reach N^3, if a dual unidirectional WEMCOB contains N two-level tree-based clusters (i.e., $N_{dul} = N_{uni} = N$, $L = 2$. If a WEMCOB LAN is operated at 1.25 Gb/s data-channel rate and at 260 Mb/s control-channel rate, the total bandwidth is equivalent to a serial dual bus of ~44 Gb/s (1.25 Gb/s $*16 * 53/48 * 2$ (dull)= 44.17 Gb/s). At these rates, 10 nodes can be supported by each bus using a typical transceiver-array with 29 dBm power margin [derived from Fig. 7(b) with splitter loss = 0.1 dB], and a 1000-node WEMCOB LAN can be built.

Aside from the power budget, a number of system issues, such as dispersion, crosstalk, interface power consumption, and bit error rate characteristics must also be considered. Most of these issues have been thoroughly investigated in a previous study on the technological feasibility of constructing a WEMCOB [4]. Among these issues, there is a unique problem to a WEMCOB, namely the bit-skewing caused by the relative time delay experienced by different wavelengths being transmitted because of a fiber's chromatic dispersion [2]. Dispersion generally sets limits for long-distance data transmission, particularly as speed goes high. However, many methods such as bit-skew correction algorithm [21], different kinds of dispersion-shifted fibers, and dispersion compensators [22]–[24] would be used to solve the bit-skewing problem.

VI. Conclusions

We have presented a scalable, high-speed wavelength encoded multichannel optical bus called WEMCOB, where data bits are transmitted in parallel through a single fiber. The WEMCOB not only reduces the link speed requirement and the wiring complexity, it also simplifies the complexity of the control circuitry. Moreover, a novel WEMCOB encoding technique has been proposed for packet switching in a LAN in which a packet is divided into control and data channels. The information of these two channels is transmitted in parallel at much lower bit-rate speeds than through a serial link. In particular, the control channel speed can be reduced significantly to facilitate a practical implementation. To meet the requirements for a LAN, we have proposed a hierarchical WEMCOB LAN with high scalability. In this architecture a dual WEMCOB with separate control and data channels composes the backbone network, while unidirectional tree-based WEMCOB clusters with centralized arbiters constitute the subnetwork. A power budget analysis has been performed on this tree-based hierarchical approach, and the results indicate that the tapping loss and fiber loss are the dominant factors in determining the number of nodes that can be attached to the bus. Optical amplifiers when employed are expected to effectively compensate for the losses in a WEMCOB-based LAN, and our calculation indicates that a WEMCOB-based LAN requires far less optical amplifiers than an MFOB-based LAN. We have also shown that the scalability of the WEMCOB-based LAN is high and estimated that a one-thousand-node WEMCOB-based LAN with a total transmission capacity of several tens of Gb/s can be efficiently implemented by utilizing today's commercial optoelectronic devices for broadband services.

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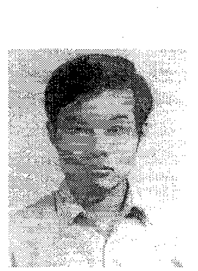

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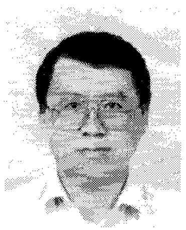
Lon A. Wang (M'95) photograph and biography not available at the time of publication.



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