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OPTICAL DISTRIBUTION CHANNEL: AN *ALMOST-ALL* OPTICAL LAN BASED ON THE *FIELD-CODING* TECHNIQUE

Zygmunt Haas and Richard D. Gitlin
AT&T Bell Laboratories
Room 4F-501, Crawfords Corner Rd
Holmdel, NJ 07733, USA

Abstract
The very high-speed access requirement that characterizes interactive and real-time high-performance applications like parallel processing, compressed video, or high-quality imaging, initiated a considerable interest in networks that provide a single user with a very high-speed network access. Coupled with this effort is the belief that optical networking can provide very high speed access, in addition to already utilized large aggregated bandwidth. In this paper, we examine the possibility of harvesting the optical spectrum to provide high-speed access networking capability in local-area environment in a way that is economically justifiable. In particular, we describe a design of the physical layer of an "almost-all" optical local-area network that is capable of providing gigabit per second network access. The network design is based on the dual-bus topology, the *field-coding* technique that was reported by us earlier (in which the *header* and the *data* fields are encoded at different rates), and the principle of "almost-all" optical switching. The *field-coding* technique allows integration of several subnets on the same physical medium. Moreover, we show that because of the *field-coding* technique, the maximal number of stations on the bus before signal amplification is required is doubled in the limit. Furthermore, we discuss various implementation issues in the design of ODC, like opto-electronic amplification, clock distribution and clock-data synchronization, and reduction in the receiver dynamic range.
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1. Introduction and Motivation

Providing a single user with a very high (on the order of gigabit per second) access is a challenge that the research community is trying to address these days. Considerable number of optical network architectures capable of supporting such high-speed access were proposed in technical literature. However, many of these proposals rely on "experimental" photonic technologies, that are as yet immature and quite expensive. The purpose of this work is to describe the design of the physical layer of an "almost-all" optical local-area network, termed the *Optical Distribution Channel* (ODC), that is capable of providing Gbps directly to the user, and that can be commercially justified today. The network design is based on the dual-bus topology, the *field-coding* technique that was reported by us earlier [1] (in which the header and the data fields are encoded in different rates), and the principle of "almost-all" optical switching.

As we intended to provide a "commercially sound" solution, we could not justify use of some optical devices (such as optical amplifiers, $LiNbO_3$ switches, etc.) in our design, unless their cost could be amortized over several stations.[1] This is the reason why we discarded the ring topology, since there is a need for an optical switching element to remove a packet from the ring,[2] and optical switches are considerably more expensive than passive devices. However, we note that optical switches provide additional capability of removing the optical transmission from the medium, and they may be a viable alternative as their prices decline in the future. An optical bus, in spite of the fact that it has some disadvantages (such as limited number of taps without regeneration/amplification), can be implemented relatively cost-effectively, by using optical couplers.

There were other considerations, besides cost, that guided us in our design, of which traffic integration was the major one. The wide range of applications and equipment dictate diverse network requirements. Moreover, users that require some level of service will not, in general, agree to pay more so that other users may utilize the same network with higher service requirements. In other words, user that requires access of only 100 Mbps will be ready to pay only the cost of an FDDI attachement and will not support a network that provides access of 1 Gbps to satisfy other users' requirements. This is why we have decided to use the *field-coding* technique, which supports different subnetworks on the same physical media by using different bit rates for the header and the data fields. Through the use of gateways, connectivity between the various subnets is provided.

Further considerations were flexibility and possible compatibility with current standards. Thus node design and network access and routing algorithms should be essentially independent of the number of active stations and their attachment position.

2. The *Field-coding* Technique: a Short Overview

In *optical* high-speed time division multiplexing of packetized traffic, it is required for the switching node to operate at the peak transmission rate. If, for example, the transmission bit rate is 10 Gbps, the line cards in the switching node are also required to operate at this rate; this is in spite of the fact that the switching node may not actually need to access the data at this rate. Electronics operating at 10 Gbps are quite expensive and the technology is not yet fully developed. Thus separation of the switching rate from the transmission rate is of great advantage.

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[1] In the today's market, a semiconductor optical amplifier costs about 8 k$. Obviously, use of an optical amplifier in each station would result in an unreasonable price of a switching node.

[2] Note that our assumption was that the data path is fully photonic. This is also required, if the *field-coding* technique [1] is to be used.

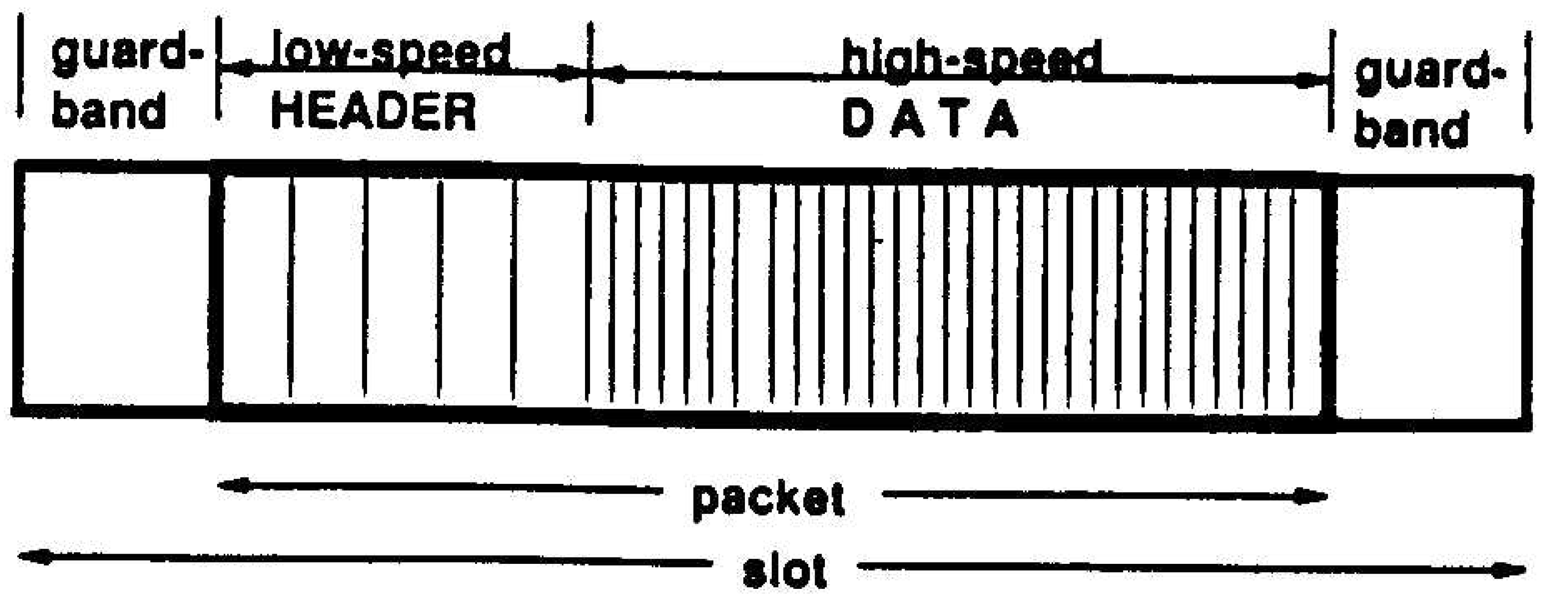

Fig. 1. Different encoding rates of header and payload: the *field-coding* technique

Moreover, such separation permits independent changes in the switching (processing) or in the transmission facilities. For example, increasing the data rate to 100 Gbps requires virtually no changes in the switching node, except possibly the changes in the hardware required for local input/output traffic.

In the *field-coding* technique, the separation is done by using *different* bit rates for the header and the data *fields* of the optical packets,[3] as illustrated in Fig. 1 (hence the name *field-coding*). Since, to perform the switching operation, the switching node does not need to process the data portion of the packet, the switching node can operate at the lower header rate, and the fast-rate data field can pass transparently through the switching node. Thus, in the case of the bus topology, the "switching" element is a splitter, while in the case of a multihop network, a switch can be made out of Lithium Niobate ($LiNbO_3$) elements, for example. Therefore, we assume that the data portion of the packet is not optically-to-electrically converted at the switching node and the configuration is that of an *almost-all* optical network. (In an *almost-all* optical network, the data-path is optical, but the Control is electrical. This is in contrast with *all* optical networks, in which all the components are photonic. The *almost-all* optical principle was used in previous designs, [2], for example.) The principle of operation is shown in Fig. 2. A small portion of the optical signal is extracted, and serves to detect the header. The header information is then read from the packet at the lower header rate and passed to the switch Control. The Control then decides whether to receive the packet or not. The "reception" of a packet can be performed by simply extracting the optical transmission at the correct time, as is the case in optical power splitters, or by setting a correct transmission path through the switch fabric, as in the case of an optical switching element. The packet is temporary delayed in a *delay line* to compensate for the electrical control processing time (and for the time to activate the switching fabric, if such exists). The high-rate data signal is not processed at any time during the switching operation. Thus the switching process is "transparent" as far as the data field is concerned.

For additional information on the performance of the *field-coding* technique, the reader is referred to [1].

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[3] The separation of transmission from processing could be accomplished in other ways, for example, by using different (WDM) channels for the data and control information.

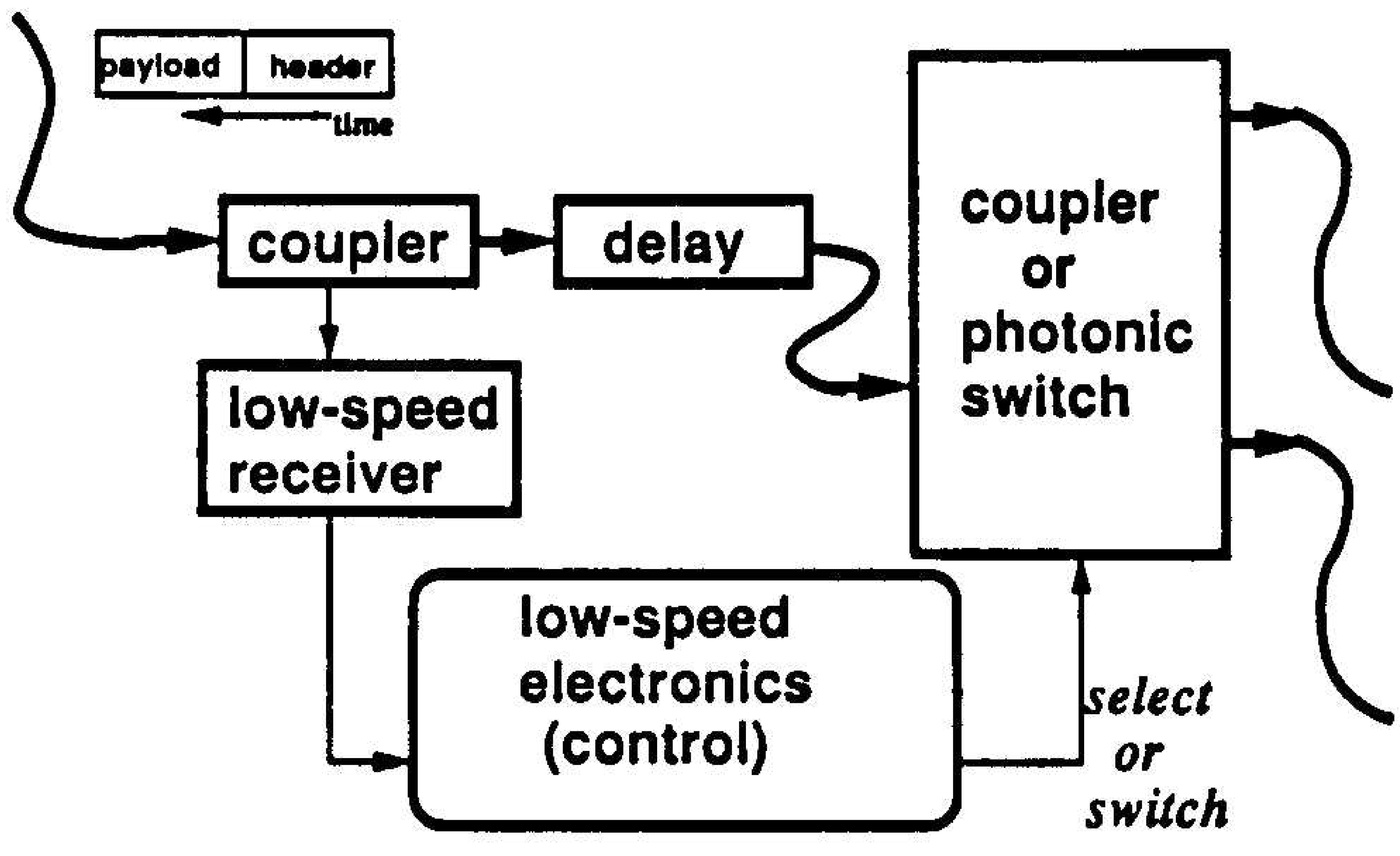

Fig. 2. Principle of design of an "almost-all" optical node

3. The Optical Distribution Channel

3.1. *The Network Architecture*

The ODC described in this section serves as a physical layer for high-speed LAN or MAN; it facilitates high-speed access (on the order of several gigabits per second) between "relatively" closely spaced nodes, at most on the order of 1–2 km. The network uses the *field-coding* technique to integrate several subnets on the same media.

ODC is based on the dual-bus topology (similar to the IEEE 802.6 standard), shown in Fig. 3. If information is to be sent from node i to node j and $i < j$ then it will travel on the lower bus, and when $i > j$, it will be transmitted on the upper bus. The *Slot Generator* (SG) is placed at the head of each bus.[4] The node connection to each bus is shown in Fig. 4. A station has two connections to each one of the buses: the first connection is the *sense* and the second is the

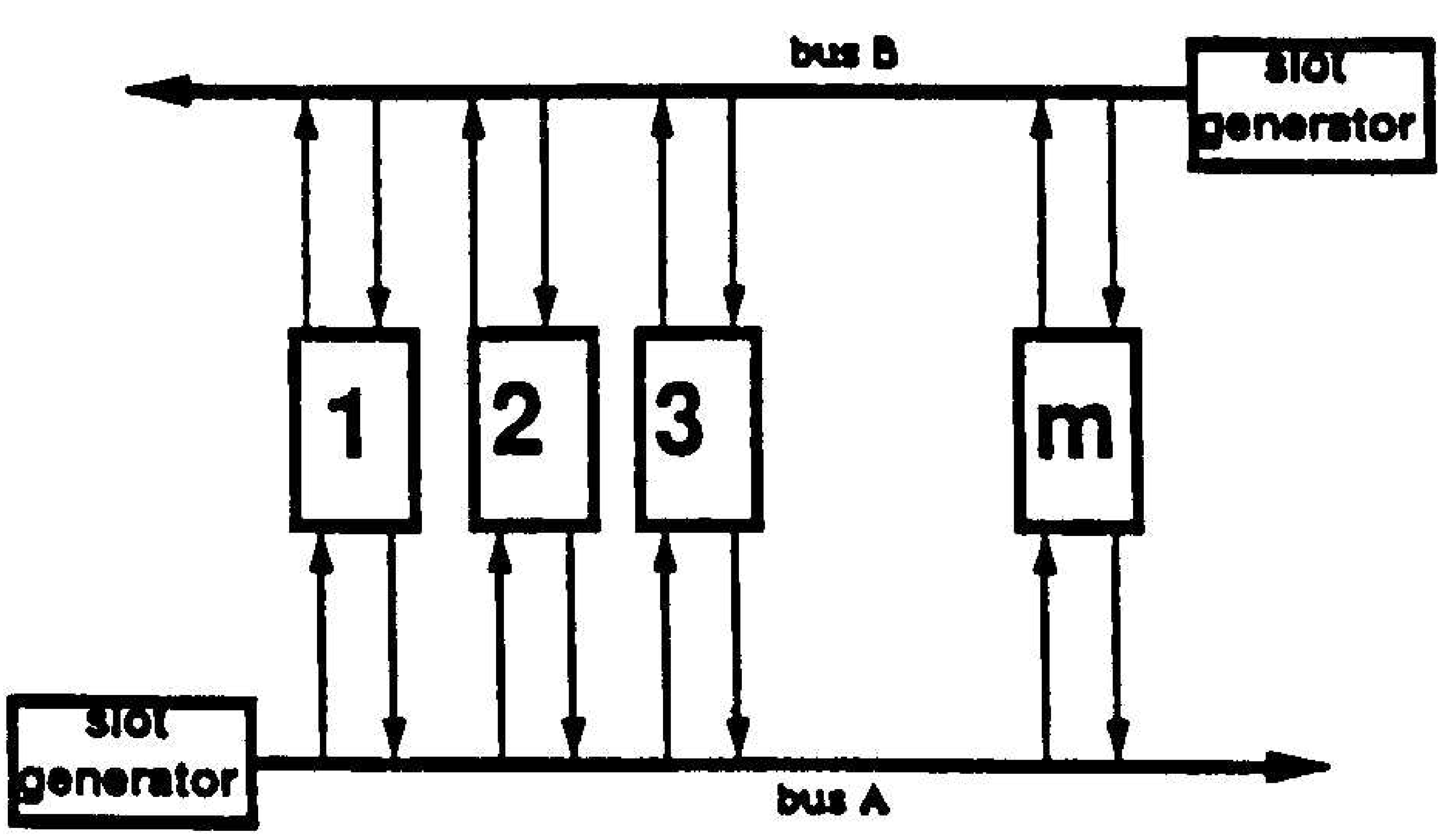

Fig. 3. The dual-bus ODC topology

[4] The slot generation function could be integrated into the design of the first node. However, since we insisted that all the station have the same design, the SG was introduced.

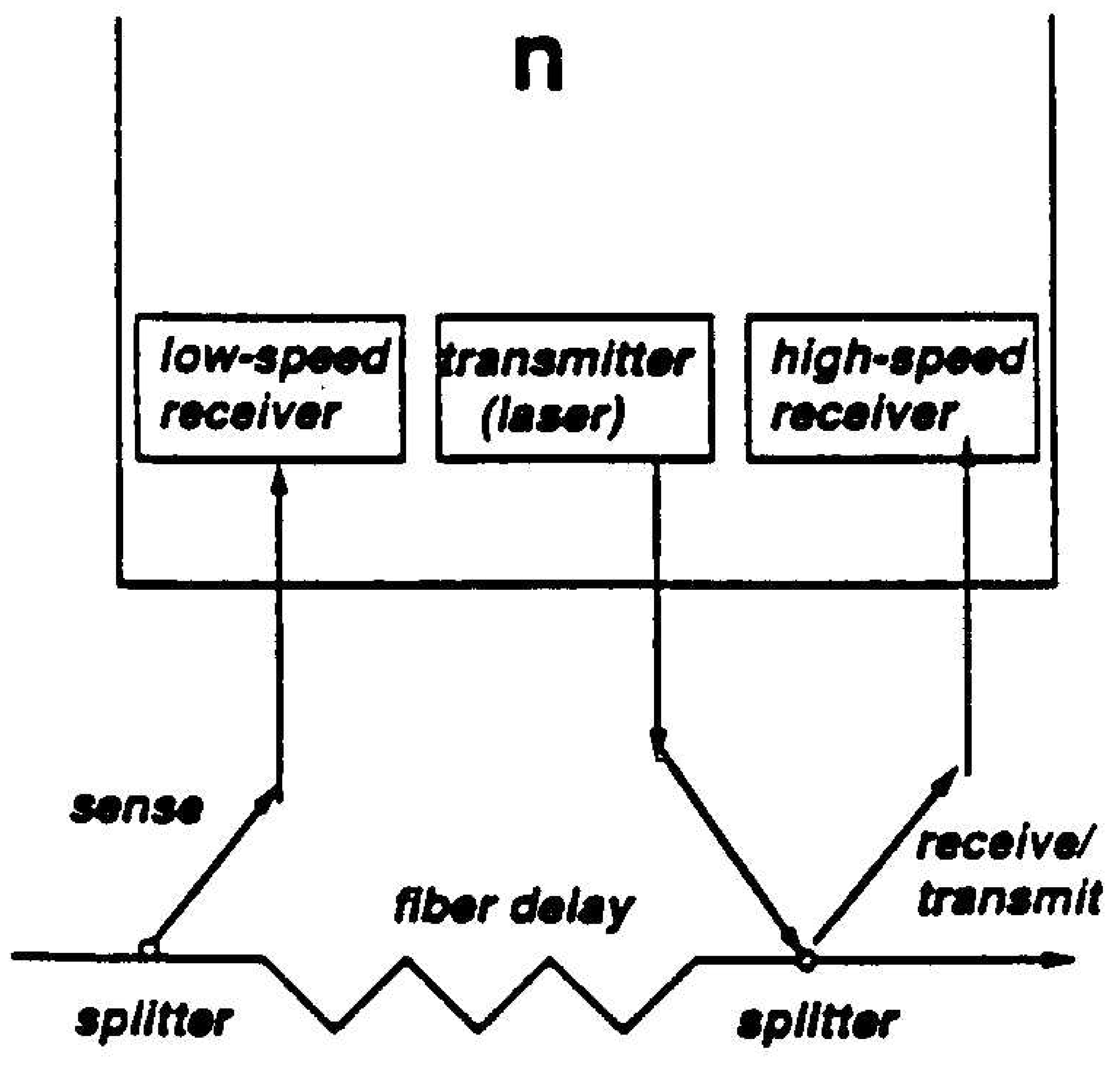

Fig. 4. Node connection to a bus

receive/transmit. Each connection is made through a 2 × 2 splitter with some splitting ratio. We label the splitting ratios of the *sense* and the *receive/transmit* splitters with $\alpha : (1-\alpha)$ and $\beta : (1-\beta)$, respectively. A segment of optical fiber that serves as a *delay line* is placed between the two connections. The length of this fiber is determined so that its delay corresponds to the time required by the node to perform (electronically) the Media Access Control (MAC) protocol. The transmission on the buses is synchronized to slots, generated by the SG. Slots contain packets, generated by the stations. When transmitted on the optical bus, the packets "float" within the slots, with the restriction that the packet is not too close to the beginning or the end of the slot; i.e., the band guards are enforced. An example of a format of a packet, shown in Fig. 5, consists of the following fields:[5]

- **Access**
  - *busy-bit*
  - 3 reserved bits
  - 4 *request* bits
- **Header**
  - *destination-address:* 20 bits
    - SID: 8 bits
    - VCI: 12 bits
  - *payload-type:* 2 bit
  - *segment-priority:* 2 bits
  - *header-crc:* 8 bits
- **Data**

[5] This example of the packet structure is somewhat analogous, to the 802.6 standard.

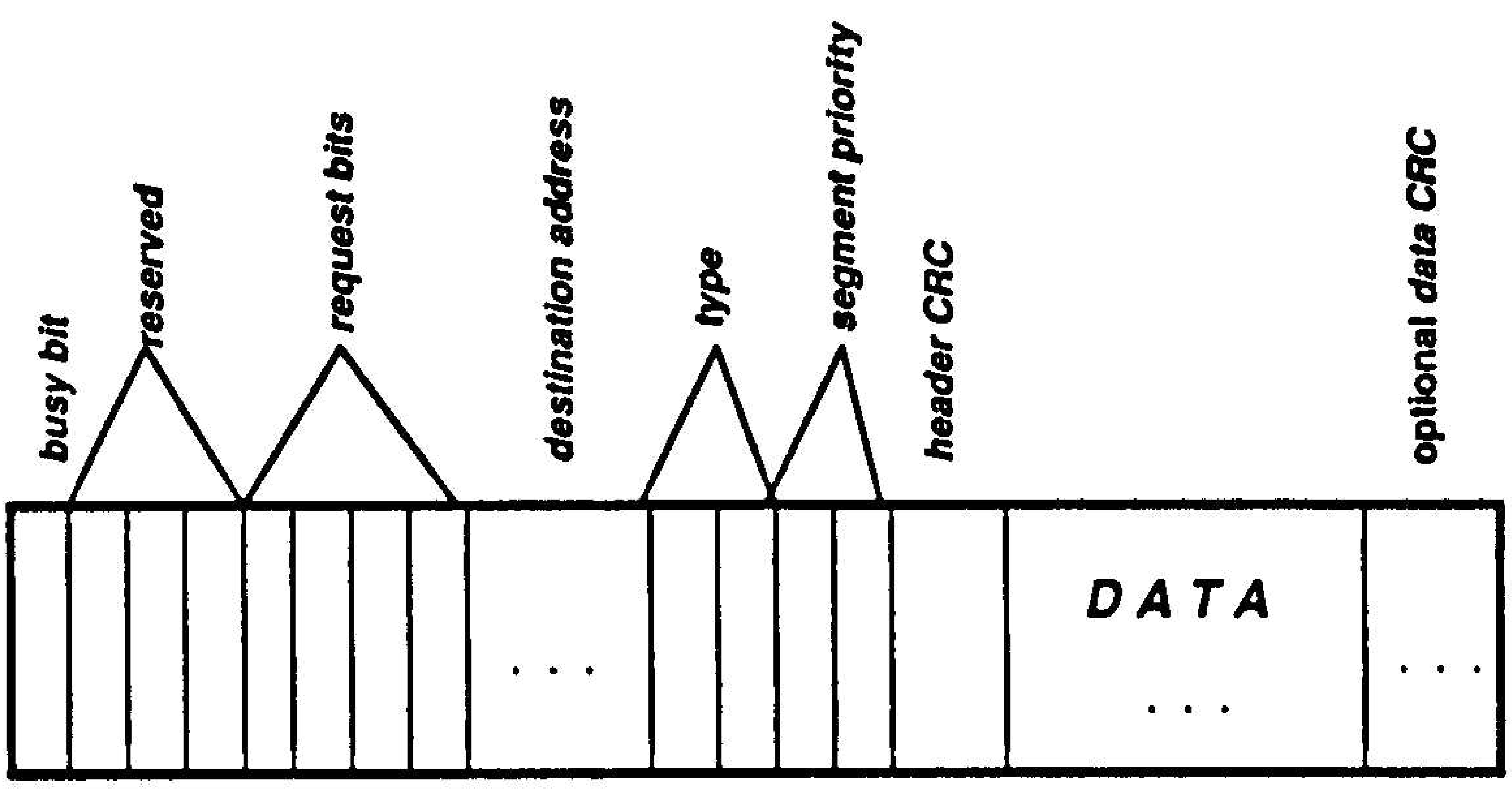

Fig. 5. An example of packet format

The *busy-bit* indicates the status of the slot: whether its data-field is occupied or not. The four *request* bits may serve to implement priorities in the system. Thus, for example, as in the case of the 802.6 network, these bits may be used to reserve slots for the four priorities for traffic in the opposite direction ([3] and [4]). Besides defining the station number, the *destination-address* determines the subnet that the packet belongs to. In other words, the *destination-address* field is divided into two subfields, the first subfield (*Subnet IDentifier* or SID) identifies the number of subnet (and thus the speed of the *data* field), while the second subfield (*Virtual Circuit Identifier* or VCI) identifies the virtual circuit the packet belongs to. In this sense, the *destination-address* field is somewhat similar to the *Virtual Path* and *Virtual Circuit* identifiers of the ATM standard. A station can determine whether the packet is destinated to itself by comparing the VCI to its own address. If more than one bit-rate is allowed on the same subnet, a station may learn what the actual bit-rate of the packet *data* field is from the SID.[6] Two *payload-type* bits define whether the slot is a regular data slot or a supervisory (control) one, and the *segment-priority* bits define the priority of the current slot. The priority bits allow to assign higher priority to more latency sensitive traffic, thus supporting different traffic classes. The *header-crc* is the Cyclic Redundancy Code (CRC) computed on the header information. The CRC does not cover the *access* portion of the slot. The *data* field is encoded with the speed indicated by the SID and may, optionally, be protected by CRC, whose function may include error detection and error correction. The interpretation of the *data* field is the responsibility of the source and destination stations, and intermediate stations need not be able to decode the *data* field information. It is envisioned that the *access* and the *header* portion of the packet is encoded at a single lower bit-rate, while the *data* field bit-rate is station dependent. Consequently, each station may read the *access* and the *header* fields, but should be capable of accessing the *data* field only in the frames destinated to it. Nevertheless, it is assumed that the slot (which encapsulates the

[6] SID also plays an important role in the design of a gateway that filters traffic between subnetworks, as is described later.

packet) is of fixed time duration. Thus, the amount of data in the *data* field varies, according to the *data* field bit-rate.

Since the header is encoded at a lower bit-rate than the data field, there is some lost capacity due to the fact that more date could be placed in the header, if the header were to be encoded at the higher bit-rate. This penalty was investigated in [1]. In the case presented here, where the duration of the header and the data field are constant, this lost capacity is bounded by the ratio of the header to the total packet durations. Taking as an example the numbers from an ATM packets, the loss is 9.5% in the worst case.

The design of the switching node is shown in Fig. 6; it is based on the "almost-all" optical switching principle. A slot generated by the SG travels through the bus, visiting each one of the nodes. Each node receives the slot header by the *sense* connection, and detects whether or not the slot is destinated to the node and whether or not the slot is reserved for transmission by the node. Since the header bits are low-rate, the *sense* detector needs to detect low-rate transmission only. During the time the header is processed, the optical transmission is delayed in the *delay line*, so that the processing of the header is completed by the time the optical header reaches the *receive/transmit* splitter. If the packet in the slot is destinated to the current switching node, the data field is received by the high-speed receiver through the *receive/transmit* connection. If the slot is reserved for the current switching node, the transmitter writes into the data field of the slot through the *receive/transmit* connection.[7] In this case, the *busy-bit* is also rewritten into the

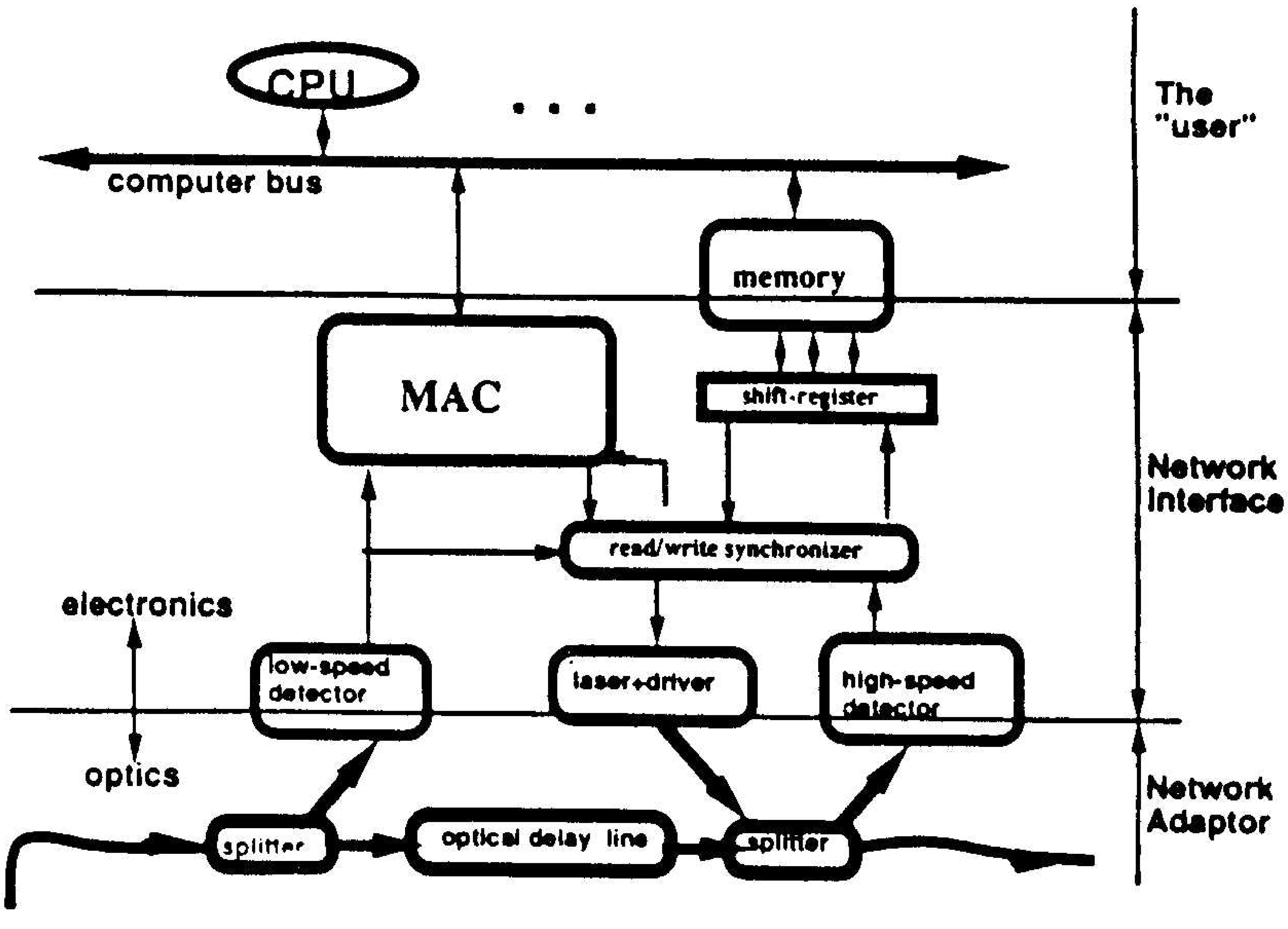

Fig. 6. The ODC switching node design

[7] Note that while the receiver/transmitter is reading/writing from/into the data field of the current slot, the header of a new slot can be examined by the *sense* mechanism. This, however, requires that the *delay line* be of the length of at least the whole slot. If there is a large number of stations on the bus, this may result in too long a delay for some systems.

slot's header, indicating that the slot is now occupied. The slot travels along the bus and is examined by each station. As the slot reaches the end of the bus, it is "drained" by optical termination. ODC consists of the physical layer only and is independent of the actual MAC protocol implemented on top of it. An example of a MAC that could be implemented on top of ODC is the DQDB algorithm ([3] and [4]).

By the virtue of the *field-coding* technique, ODC can accommodate several parallel subnets on the same media. Consider, for example, three types of nodes requiring three different transmission speeds: 155 Mbps (802.6- or ATM-type), 600 Mbps, and 1 Gbps. Assume that the header is encoded at 155 Mbps. The 155 Mbps stations require **only** 155 Mbps detection capability. The 600 Mbps and 1 Gbps stations require 155 Mbps detection capability in the *sense* receiver and 600 Mbps and 1 Gbps detection capability in the *receive* receiver, respectively. Thus, the cost of the station is determined by the level of service required and not by the level of service of the most sophisticated equipment on the network.

In the next subsections, we discuss some practical considerations of the ODC design.

3.2. *Power Budget Design*

In the ODC design, each station on a bus extracts a small portion of the optical energy through its two splitters coupled to the bus. Obviously, this limits the maximum number of station on the bus, before the amplification of the optical signal is needed. This maximum number of stations depends on the optical transmission and detection schemes, and on the loss of the optical splitters, fiber, and splices/connectors. The loss of optical splitters comes from the loss due to power division of the optical splitters and from the excess loss. Assuming other parameters constant, the splitting ratios of the splitters can be optimized to maximize the number of stations on the network. This optimization can be done either by assuming only two types of splitter ratios (the *sense* and the *receive/transmit* splitters), or by assuming that each splitter may have its own ratio optimized. Since we assume that the splitter ratios are fixed and that any station may be attached at any position on the buses,[8] we require the same design of all the stations. Thus we optimize the splitting ratio assuming only two splitter types.[9] In this section, unless otherwise noted, we assume that the header portion of the packet is encoded at a constant lower-bit rate, while the higher bit-rate encoding the data field may vary.

Consider the network in Fig. 7. The splitting ratios of the *sense* and the *transmit/receive* splitters of each station are labeled $\alpha : (1-\alpha)$ and $\beta : (1-\beta)$, respectively.[10] Moreover, we label x as the ratio of the highest to the lowest bit-rate. In particular, since we assume that the header is encoded at the lowest bit-rate, x is the ratio of the highest speed data-rate to the header bit-rate. We also assume that the required header field Bit-Error-Rate (BER) is equal to that of the data field.

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[8] In practice, the station attachements may be limited to preexisting sockets.

[9] For additional discussion on optimization of the splitter ratios under different set of assumptions see [5].

[10] Which means that the *bar* and the *cross* coupling values are $(1-\alpha)$ and α, respectively.

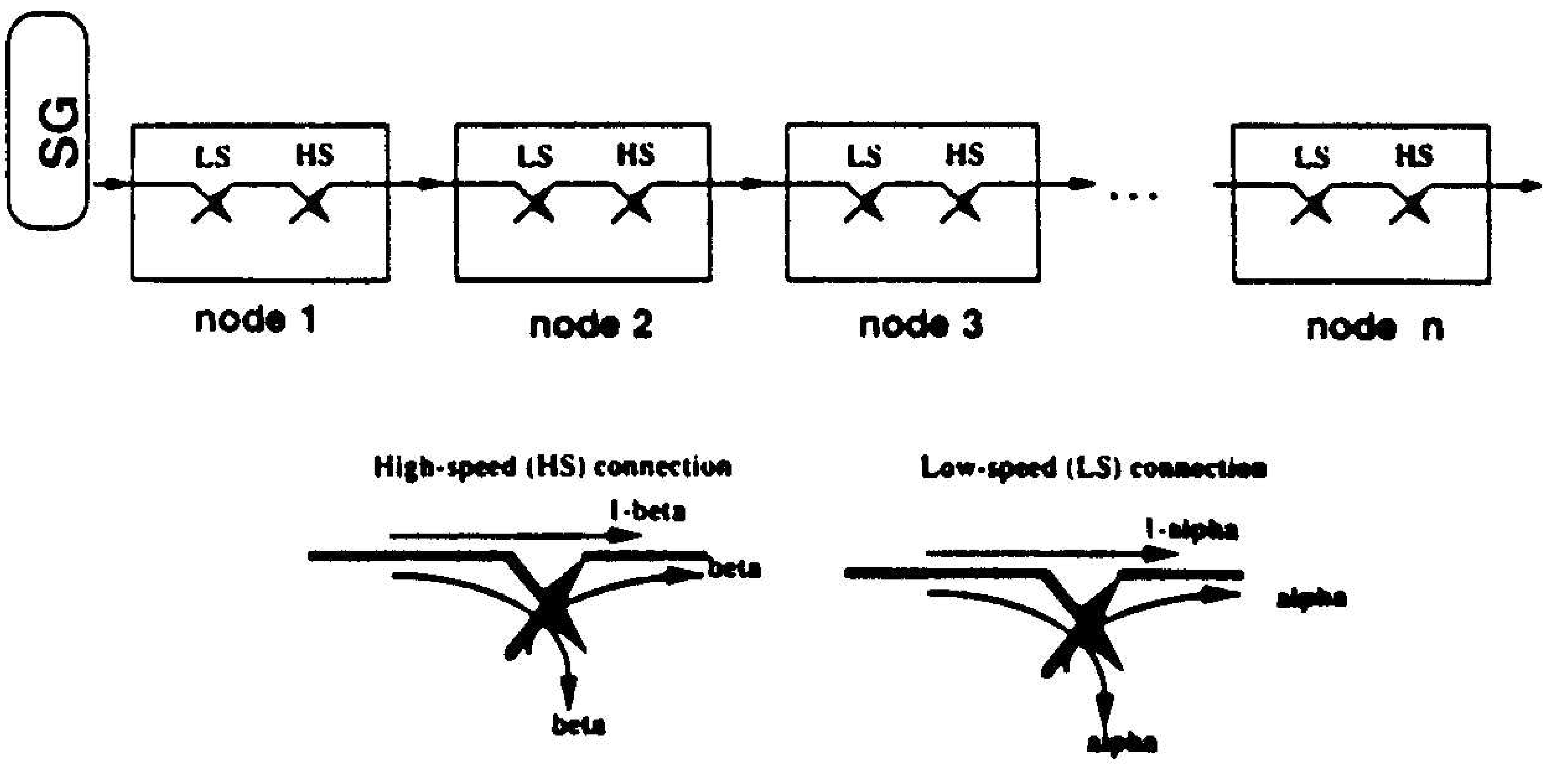

Fig. 7. Model for splitter ratio optimization

This implies that the minimal required received power of the high-speed detector is x times the power of the low-speed detector and, neglecting the attenuation of a single station attachement, $\beta = x\alpha$. We now define the maximal attenuation of any high-speed transmission, $A_{\text{hs}}^{\text{max}}$, and low-speed transmission, $A_{\text{ls}}^{\text{max}}$, to be the ratio of the power transmitted from station 1 to the power received at station n, for the high-speed and the low-speed transmitter/receiver pairs.

$$A_{\text{hs}}^{\text{max}} = -10\log\left(\beta^2(1-\beta)^{n-2}(1-\alpha)^{n-1}\right)[\text{dB}] \tag{1}$$

$$A_{\text{ls}}^{\text{max}} = -10\log\left(\alpha^2(1-\alpha)^{n-2}(1-\beta)^{n-1}\right)[\text{dB}] \tag{2}$$

Since we assume that the received power of the high-speed transmission is x times the received power of the low-speed transmission, thus,

$$A_{\text{hs}}^{\text{max}} = A_{\text{ls}}^{\text{max}} - 10\log x \tag{3}$$

Solving (1), (2), and (3) yields

$$\alpha \approx \frac{\beta}{\sqrt{x}} \tag{4}$$

where we assumed that $\alpha \approx \beta$.

Now, differentiating the equation (1) with respect to β after substituting (4), results in an equation for optimal value of β, β_{opt}, that corresponds to minimal attenuation:

$$\beta_{\text{opt}}^2(2n-1) - \beta_{\text{opt}}\left(1 + n\sqrt{x} + n\right) + 2\sqrt{x} = 0 \tag{5}$$

After solving (5) for β_{opt}, substituting into (4) gives α_{opt}, and into (1) and (2) gives $A_{\text{hs}}^{\text{max}}$ and $A_{\text{ls}}^{\text{max}}$.

The attenuations $A_{\text{hs}}^{\text{max}}$ and $A_{\text{ls}}^{\text{max}}$ are plotted in Fig. 8 for $x = 2$, 10, and 20, as a function of the number of stations, n. The case of $x = 1$ (i.e., single bit rate for the header and the data fields) is also shown in these graphs for comparison. Thus, for example, if the sensitivity at 1 Gbps can be achieved with 30 dB splitting loss, then for $x = 10$, the maximum number of stations on the bus is 18. In this

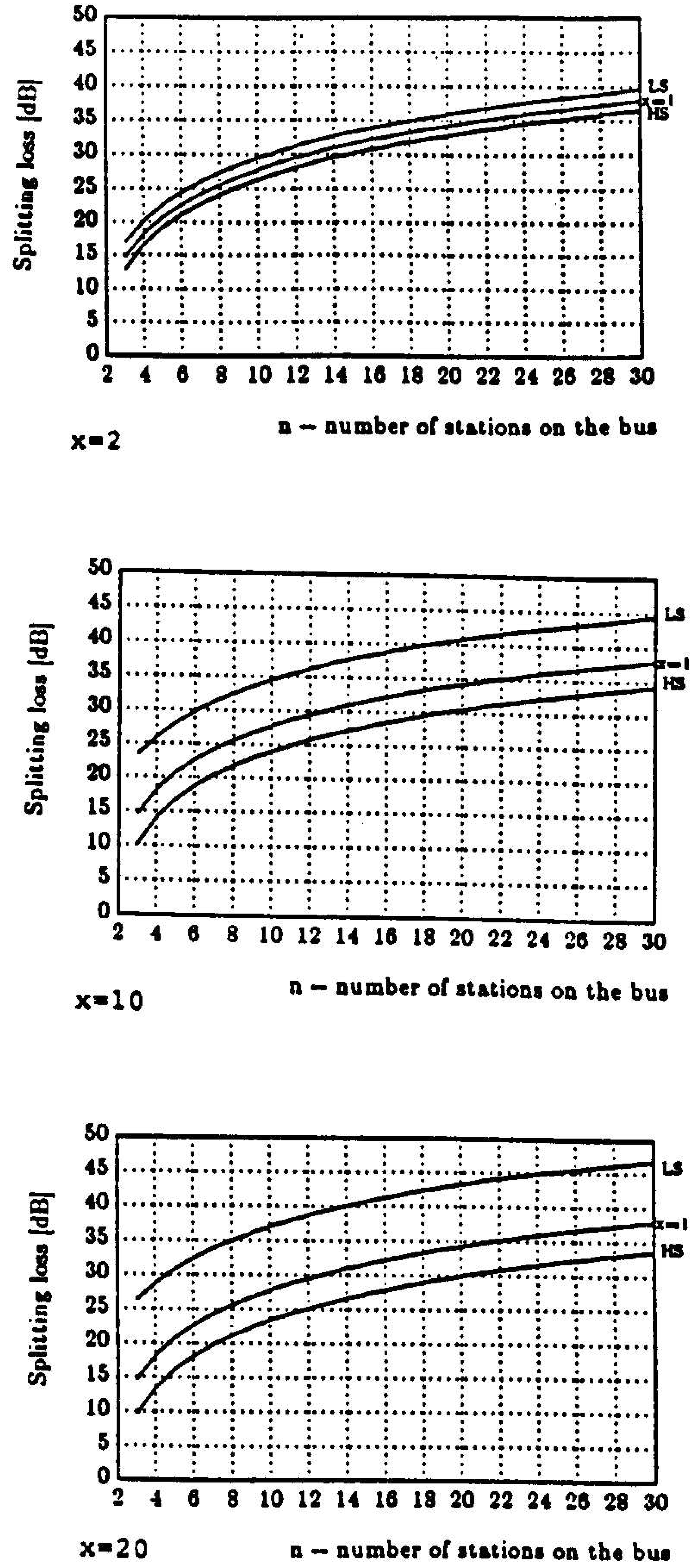

Fig. 8. Attenuation of the high-speed (HS) and the low-speed (LS) transmissions

case, the low-speed bit-rate is 100 Mbps, with sensitivity that corresponds to 40 dB splitting loss. If, on the other hand, the header would also be encoded at 2 Gbps, then the maximum number of stations would be 12. It should be noted that for any value of x, the maximum number of stations decrease as the high-speed bit rate increases. This is the direct consequence of the fact that the power required for high-speed bit-rate is larger by the factor of the rate increase. Assume, for example,

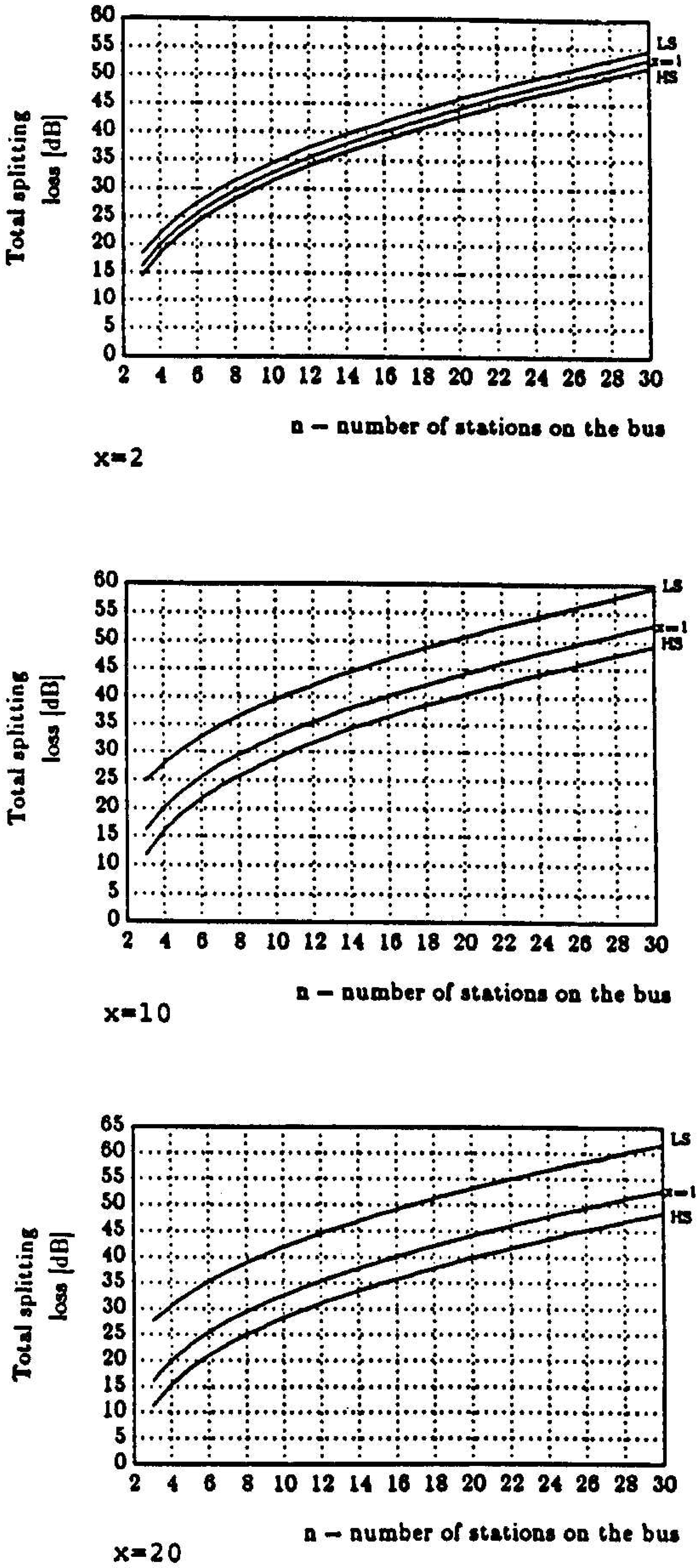

Fig. 9. Total attenuation of the high-speed (HS) and the low-speed (LS) transmissions

that the bit-rate (HS = LS) is 1 Gbps, with detection sensitivity that corresponds to −35 dB splitting loss. If the high-speed bit-rate is increased to 10 Gbps, the number of stations that can be accommodated on the bus is decreased from 22 to 7; i.e., third of the initial value (the $x = 1$ curve in Fig. 8 at splitting loss of −35 dBm and −25 dBm). However, this decrease is reduced when the *field-coding*

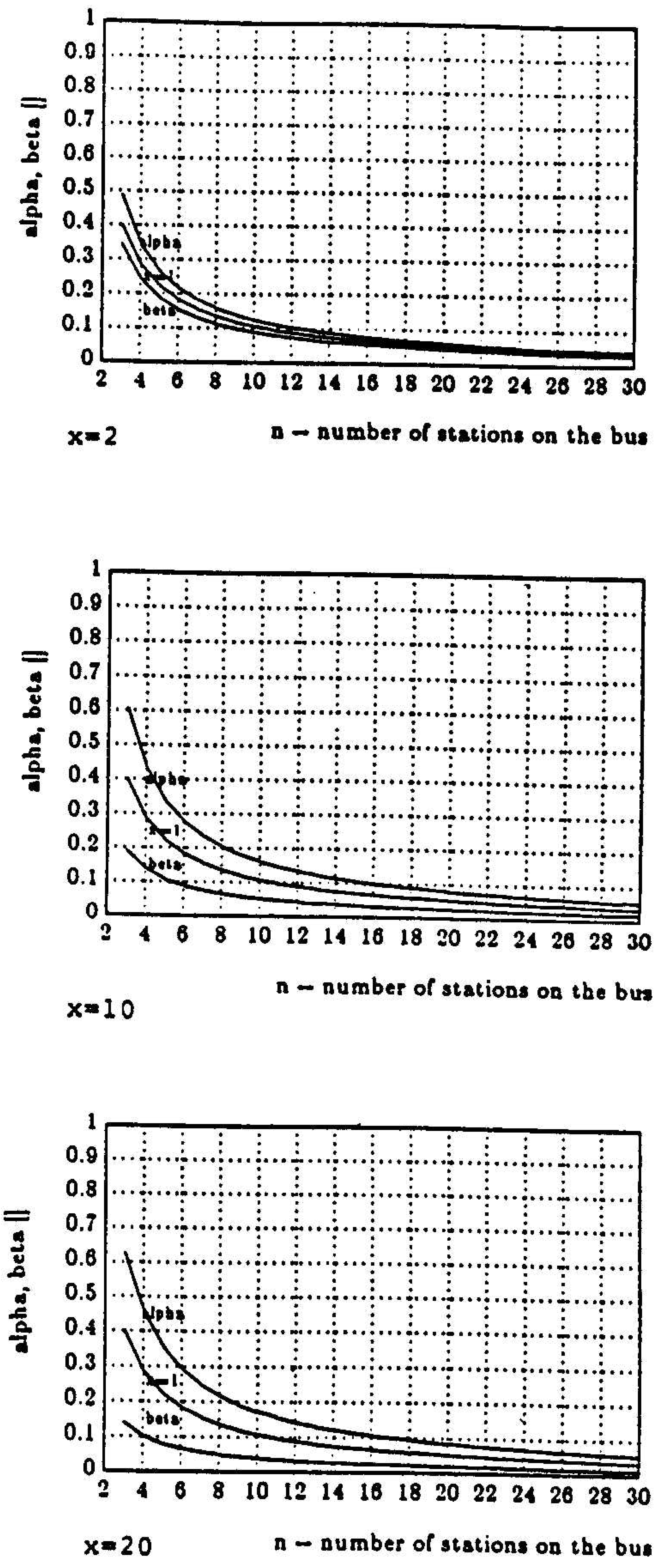

Fig. 10. Optimal values of α and β as a function of n

technique is used. For example, assume that the low-speed bit-rate is 500 Mbps, resulting in $x = 2$. If the high-speed bit-rate is increased now to 10 Gbps (keeping the low-speed bit-rate constant; i.e., $x = 20$), the number of stations that can be accommodated on the bus is decreased from 26 to 12; i.e., decrease by half only (the $x = 2$ curve at 35 dBm and the $x = 20$ curve at 25 dBm in Fig. 8). Larger values of x lead to even more significant effect. The total attenuation is larger than that displayed in Fig. 8, because of the excess loss of splitters, fiber loss, and the loss of optical splices. Assuming additional 0.5 dB loss per switching node (0.05 dB excess loss of splitters [6], 0.2 dB loss of 1 km of fiber, and 0.05 dB loss per splice $\times$ 4 splices = 0.2 dB), the total attenuation as a function of n for x = 2, 10, and 20 is displayed in Fig. 9. The comparative case of $x = 1$, which is shown in this figure, was also adjusted for the additional loss per station. Comparing the case of $x = 1$ with $x > 1$, one may learn on the actual amount of gain resulting from the *field-coding* technique. For example, for $x = 20$ and total allowed HS-loss of 40 dB, without the *field-coding* technique 16 stations can coexist on the bus, while with the technique 20 stations may be used; i.e., 25% increase in the number of stations. The advantage becomes more significant as x increases. In the limit, for very large values of x, twice as many stations can be placed on the bus by using the *field-coding* technique. From Fig. 9, one may conclude that, for example, for $x = 10$, +3 dBm laser output power, −35 dBm sensitivity at the high-speed rate, and 3 dB power margin, the number of stations that can be supported on ODC is 15. (As a point of reference, 1306AA receiver has sensitivity of −32 dBm at 1.7 Gbps [7], and 215 series laser may supply +3 dBm output power [8].) Thus, 15-node ODC design with HS = 1 Gbps and LS = 100 Mbps is feasible.

In Fig. 10, there are shown the optimal values of α and β as a function of the number of stations on the bus, for x = 2, 10, and 20. Interestingly, the optimal values of the splitting ratios become weakly dependent on the number of stations when the number of stations is large (i.e., larger than 20). This may have significance if an ODC needs to be redesigned (for example, to include more powerful lasers and larger number of stations), since a practical implementation will probably quantize the splitting ratios. Thus increasing the number of stations may not, necessarily, need replacement of the splitters.

Figure 11 demonstrates how the HS- and LS-attenuations depend on the value of x for $n = 15$. The HS-attenuation is quite constant with x. This may have an important implication when a system needs to be redesigned to allow reduction in x. (This could be the case, for example, when lower bit-rate stations are phased out.) In this case, changes in the low-speed splitting ratio result in minor changes

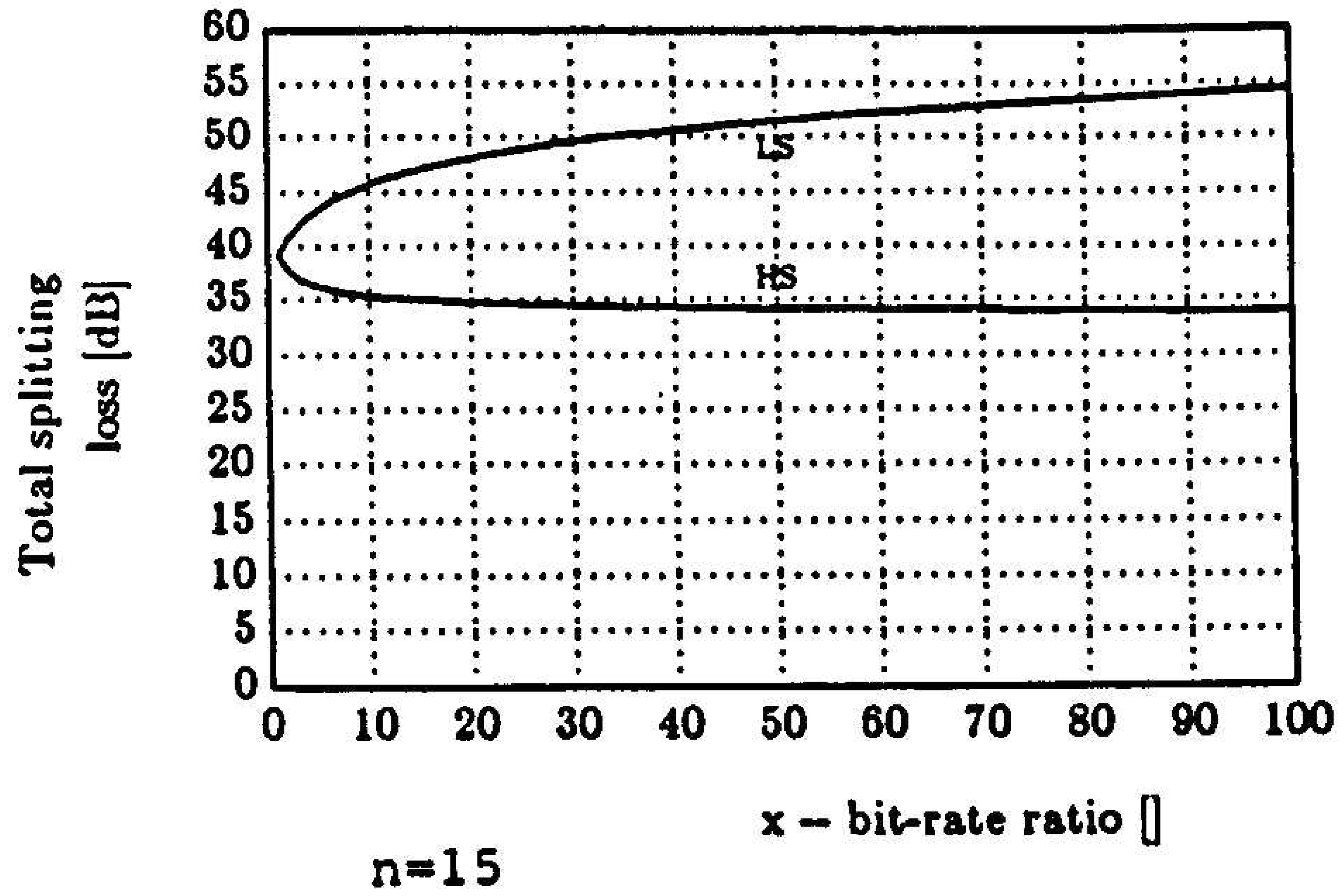

Fig. 11. Attenuations as a function of parameter x

to the high-speed attenuation; i.e., there is no need to redesign the high-speed components.

If a 15-station system is designed to support a particular HS-rate (that corresponds to the 35 dB loss, in this case), the attenuation of any LS-rate is automatically optimized. This is the direct outcome of the optimization process.

Figure 12 shows the maximum number of stations as a function of x, when the $A_{hs}^{max} = 35$ dBm. The maximum number of stations is quite constant for wide range of x. This, again, is of significance for the design process, since several bit-rates may be accommodated on the same ODC, without violating the optimality of the network design. Moreover, high-bit rate may be increased without decreasing the number of stations, assuming no change in HS sensitivity is required; e.g., for small increase in x.

Finally, we have investigated the effect of an increase in x in an already existing design. Suppose an ODC was designed for $x = 10$ as the maximal number of stations. Increasing x, will turn the design into an unoptimal. In Fig. 13, we plot the maximal number of stations that can be placed when the splitter ratio is

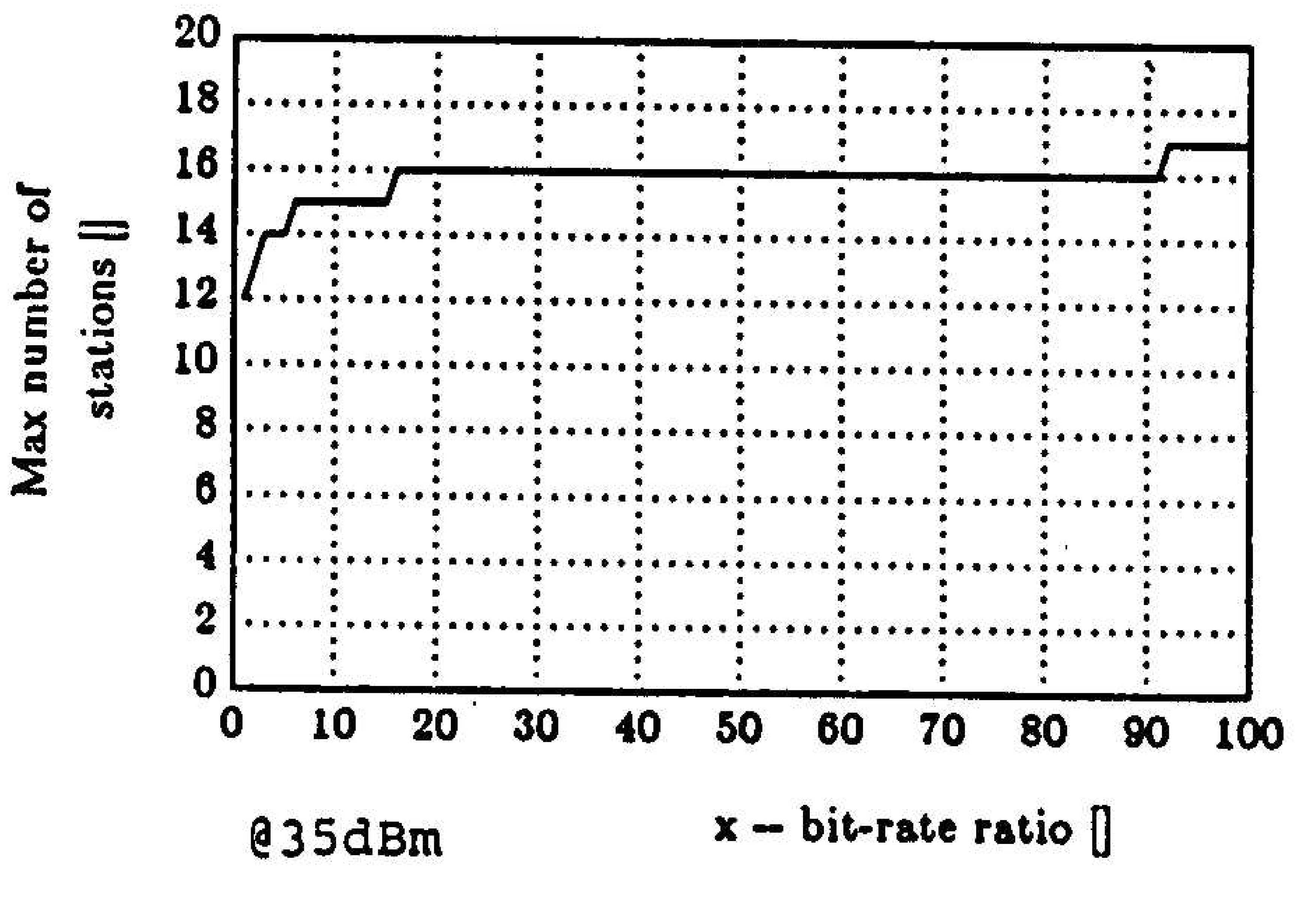

Fig. 12. Maximum number of stations as a function of parameter x

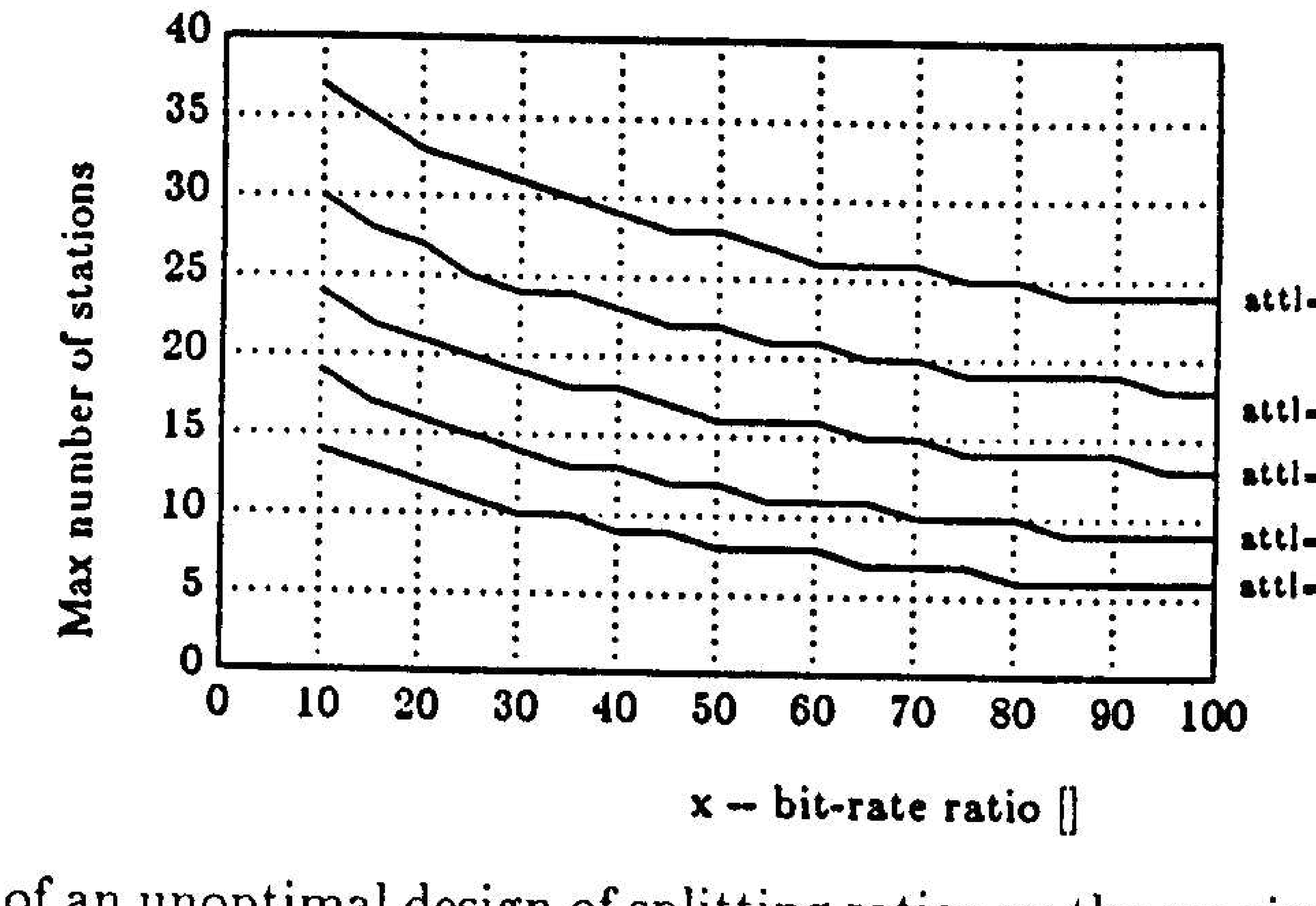

Fig. 13. Effect of an unoptimal design of splitting ratios on the maximum number of stations

optimized for $x = 10$. The required $A_{\mathrm{ls}}^{\mathrm{max}}$ ($\triangleq$ attl) is a parameter. Thus one design strategy would be to take into account possible future upgrades.

As mentioned, the realistic number of stations that may be expected to be placed on an ODC with the standard ("of-the-shelf") lightwave components is in the vicinity of 15. If the number of stations on the network exceeds the above limit, amplification is required. Optical signal amplification can be performed by optical amplifiers, [9], or by the *electro-optical amplification* technique described in Section 3.7.

In case of several data-field bit-rates that coexist on the same ODC, the optimization should be based on the highest bit-rate as the value of the HS parameter.

3.3. *Receiver Dynamic Range*

Because of the large attenuation of the optical path, the power level of the optical signal may have large dynamic range; i.e., the power level depends on the source of the transmission. This may be quite undesirable, leading to required large dynamic range of the receivers. We show here how to ensure that the power delivered to each receiver is independent of the source of the transmission; i.e.,

$$P_{(i,j)} = P_j \tag{6}$$

where $P_{(i,j)}$ denotes power at the node j from transmitter at node i. We achieve this requirement by tuning the transmission power of the transmitter in such a way, that the further a station is down the bus, the lower its injected power is. This is illustrated in Fig. 14. The attenuation placed on the *transmitter* input of the *receiver/transmitter* splitter is determined according to the station number. For example, if the total loss of a station is γ (which includes the total loss of the splitters (i.e., $\gamma = (1-\alpha)(1-\beta) +$ splitter excess loss), fiber loss, and connectors and splices losses), then the required attenuation of the station j ($j > 1$), A_j, is given by

$$A_j = \frac{\gamma^{j-1}}{1-\beta} \tag{7}$$

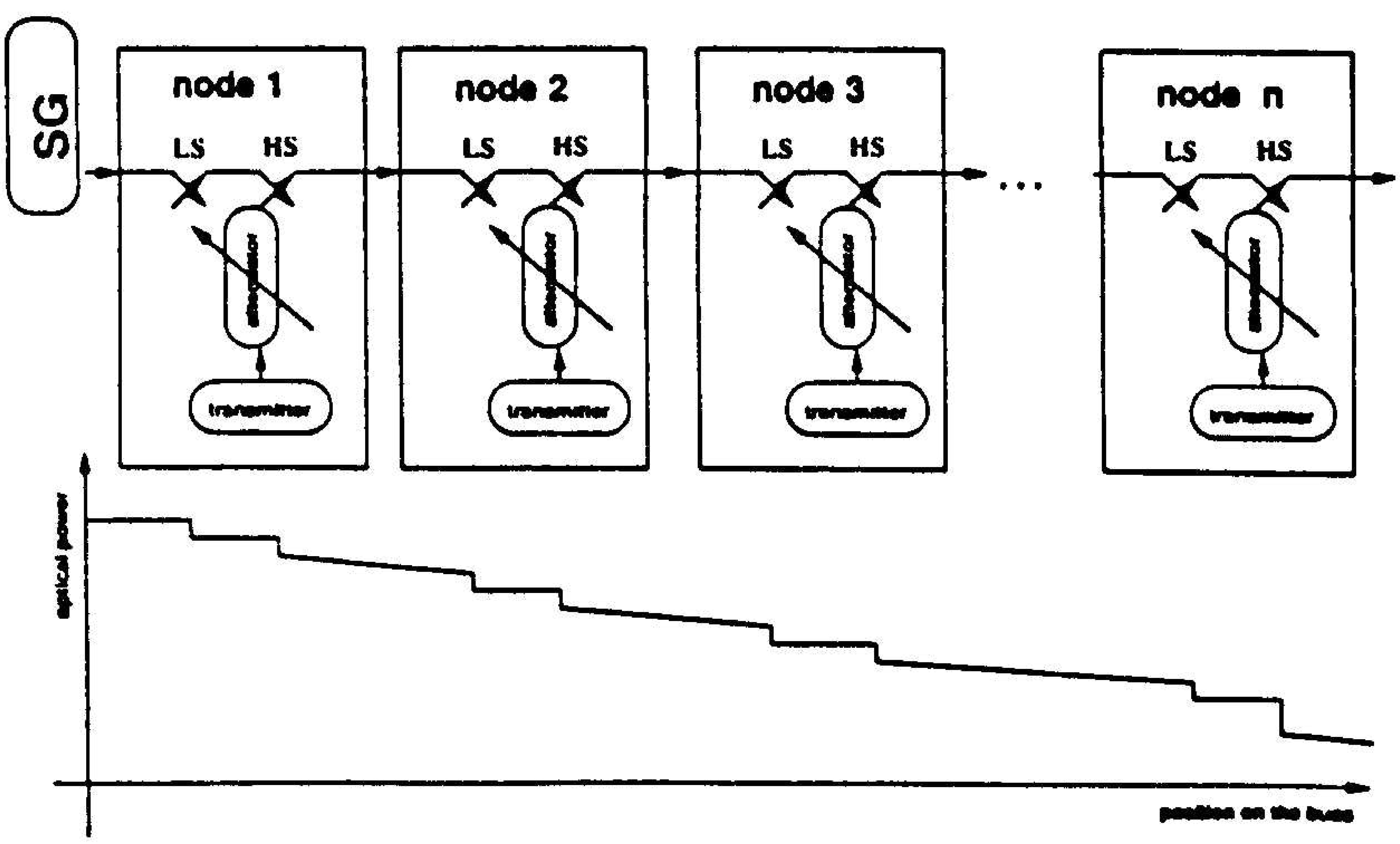

Fig. 14. Reducing the dynamic range of the detectors

This ensures that the power level at the input to any high-speed receiver on the bus is constant, irrelevant of the transmission source.

Note that since the attenuation can be automatically adjusted by the station (i.e., using controllable attenuators), we have not violated the principle of the node design being independent of its location. In other words, the splitter ratio must be designed to be fixed, since it cannot be easily automatically controlled, while the attenuation can.

Because of the fact that the transmission on the bus comes in bursts, the receiver design should be DC coupled. For an example of such a design see [10]. However, in our case, since the dynamic range of the receiver is small, the problem of threshold placement in DC coupled receivers is essentially eliminated.

3.4. *Line Coding and Clock Recovery*

The ODC clock system is based on three clocks sets: the *master clock*, the *frame clock*, and the *station clocks*. The *master clock* and the *frame clock* are generated in the *slot generator*. All transmissions in the system are synchronized to the *master clock*, which is the fastest running clock in the whole system (see Fig. 15). The *frame clock* synchronizes slot events. The *station clocks* synchronize the transmission/reception of data into/from slots. The *station clocks* and the *frame clock* are derived from the *master clock* by division. The *frame clock* is used by the station to initiate and synchronize processing of a new slot.

Since clock information is usually recovered from data bit stream, line coding and clock recovery are intimately related issues. Several line codes that are widely used, have increased bandwidth to accommodate more clocking information (e.g., Manchester coding). The clock is usually recovered from the bit stream by high-pass filtering, assuming that there are "enough" data transitions so that the probability of incorrect timing is small.

In very high-speed local environment, the approach of extracting a clock from data stream may carry a large price due to the relatively high cost of the bit synchronizer for high-speed burst transmission. An alternative approach for providing clock to the network stations is the direct clock distribution method; i.e., the clock is sent on a separate channel. We propose that all the network clocks be generated

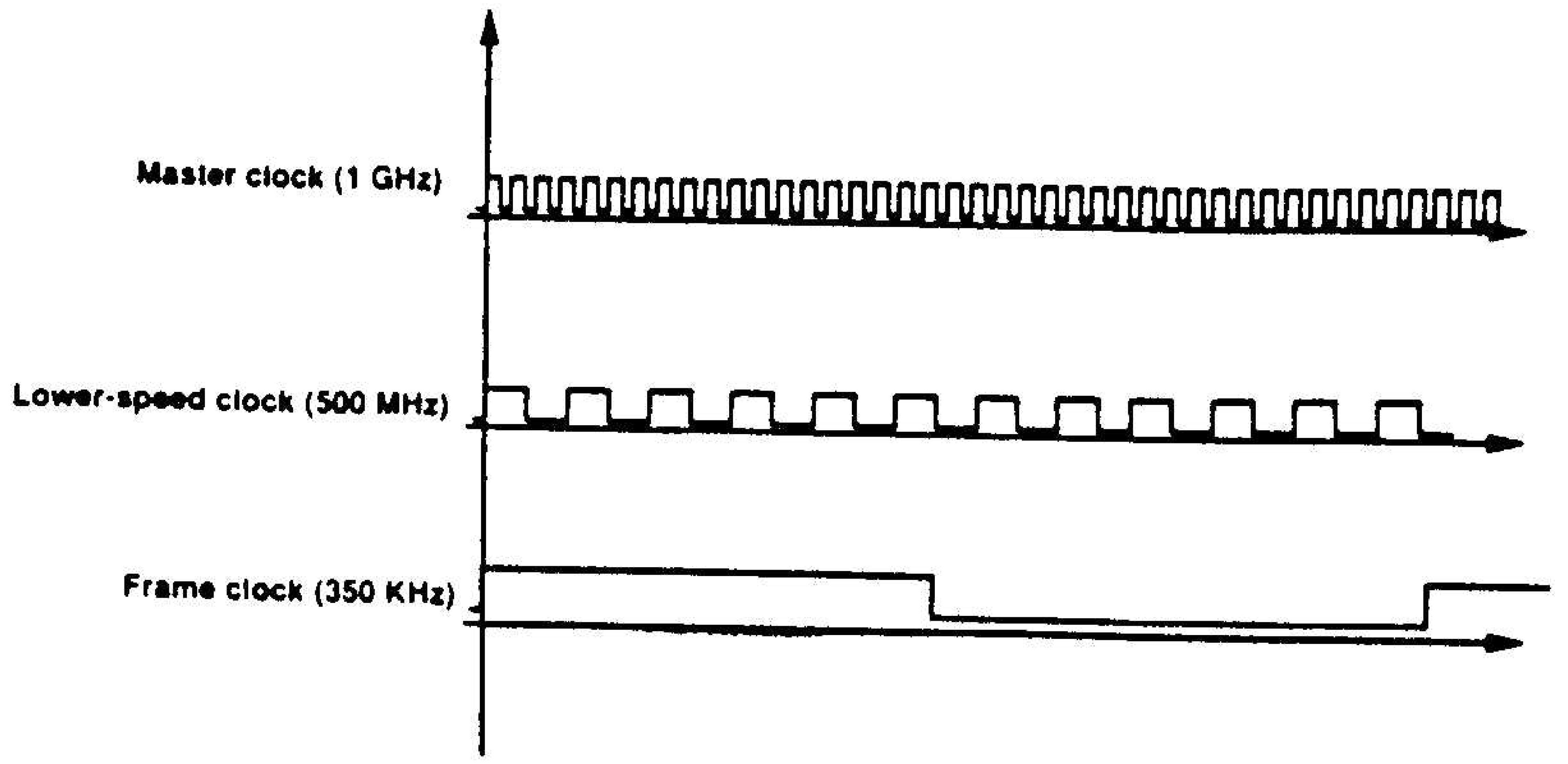

Fig. 15. The design of system clocks

at the SG, added together to create the *clock composite signal*, and transmitted over a separate optical channel. Each station, then, recovers its clock by **band-passing** the *clock composite signal* after local detection. Thus, the stations that require only low-rate clock, need only low-speed detector. This scheme is illustrated in Fig. 16. Consequently, the derivation of the various *station clocks* is done in a centralized manner at the SG, as opposed to being derived locally either by division of the *master clock* or by recovery of the clock from the bit-streams. The distribution of the *composite signal* to the stations can be done either on a separate fiber or on another color on the same fiber. This approach has the disadvantage of increased bandwidth and additional detector per station, but overall reduction in complexity, since no clock recovery from burst bit stream is needed. Moreover, simpler, more efficient, and lower bandwidth line-coding technique may be used, since there is no need to increase the clock component in the data signal. Additional requirement for the direct clock distribution scheme is clock and data synchronization. Depending on the actual network parameters (type of glass, changes in temperature, maximum data rate, etc), data and clock synchronization circuitry may be required. This is discussed in the Appendix.

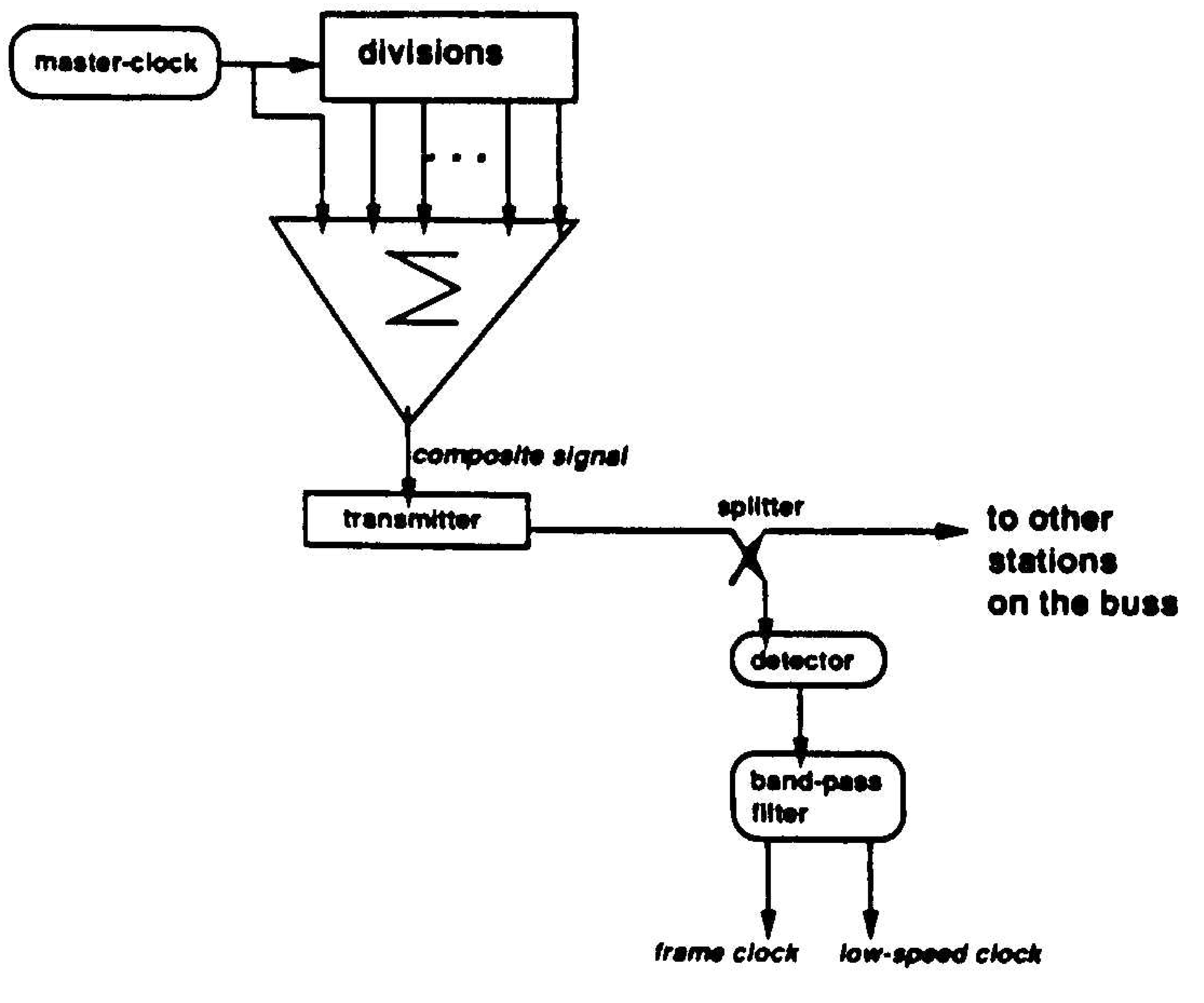

Fig. 16. The distribution scheme of system clocks

3.5. *Isochronous Services*

Isochronous traffic may be accommodated in ODC by reservations. However, when the *field-coding* technique is used, a new and interesting use of the isochronous traffic is created; an application can be periodically served by the reservation scheme, yet the amount of traffic may vary, depending on the level of activity of the application. The variation of the amount of traffic translates into variation in the bit rate. Thus in the periods of higher activity the data-rate increases, reducing the quality of transmission; i.e., increasing the bit-error rate, or requiring to use more complex error detection/correction algorithm. On the other hand, when the level of the connection activity is low, the bit rate is decreased and simpler and faster error control algorithm may be used. This mode of operation may be of particular interest in compressed video transmission, where the amount of traffic varies in time, yet some amount of errors is permissible. This operation requires the station clock to be per-packet adjustable. This is performed by switching clocks to the receiver/transmitter, as explained in the next subsection.

3.6. *Interconnection Between Subnets*

Interconnection between the subnetworks is created by gateway nodes that are capable of receiving more than one data rate. This capability of "listening" to more than one station is achieved by switching the clock rate to the detection circuit (see Fig. 17), and does not require a separate receiver for each subnet in question. The appropriate clock is selected based on the SID value. Thus the *delay-line* latency includes also SID decoding and clock selection time. The gateway detects transmission on one subnet (one bit-rate), buffers the received packets and retransmit them on a different subnet. Thus the gateway provides speed-translation

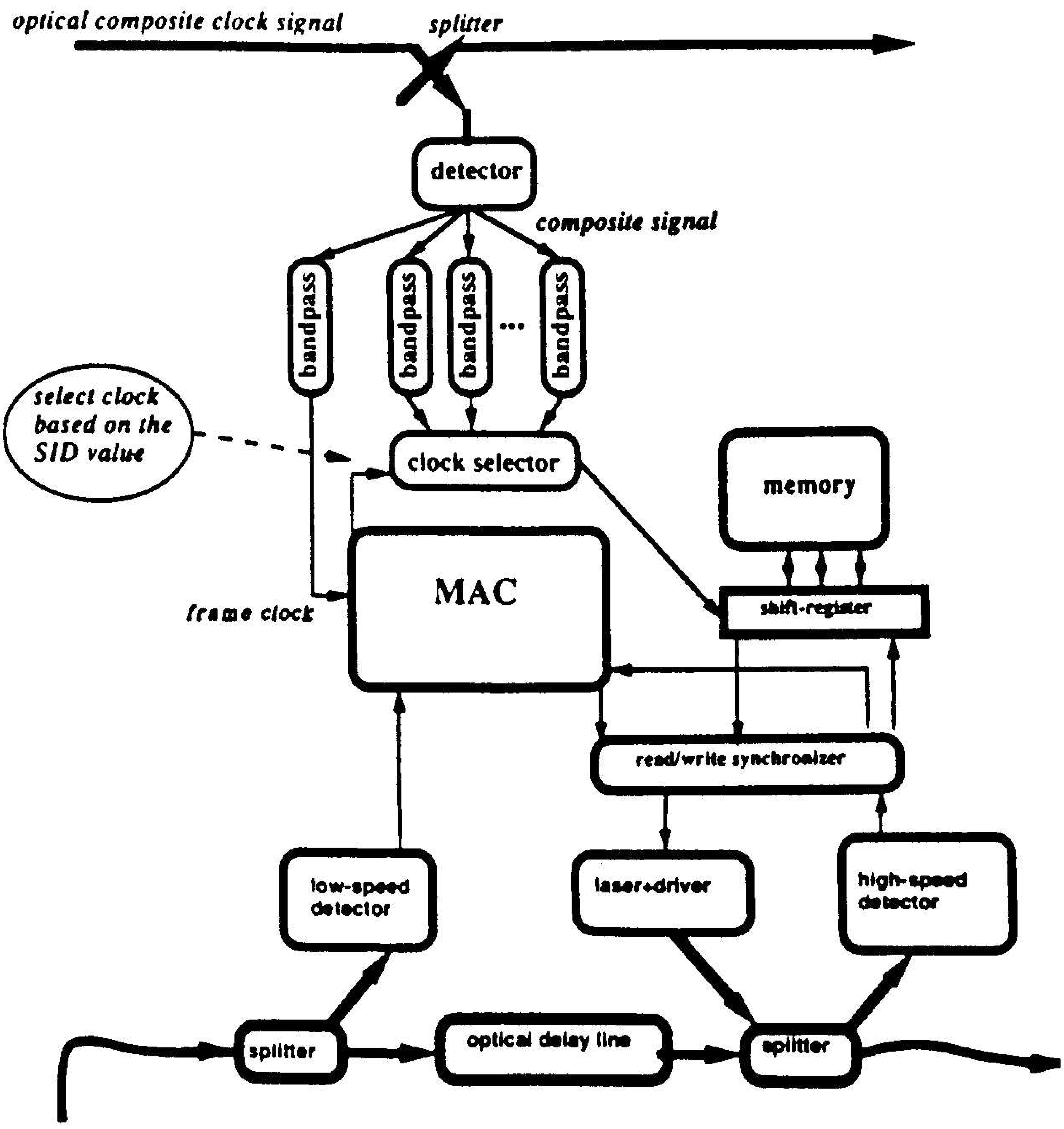

Fig. 17. The gateway design

service. Gateways residing on several subnets may provide connectivity between these subnets.

3.7. *Expansibility and Growability*

Growability and expansibility of a local-area network is an important issues, since typical research-based installations change quite frequently. As discussed in Section 3.2, the maximum number of stations that can be used in the proposed design before the attenuation of the optical signal requires amplification is approximately 15.[11]

Increasing the size of the network is done by providing amplification of the optical path. There are three possible approaches: optical amplification, full regeneration, and *electro-optical amplification*. Optical amplification, although possibly the most straight forward approach, is also the most expensive one.[12] Full regeneration may also be quite expensive for high-speed rates. In the *electro-optical amplification* approach, the optical signal is detected, electronically amplified, and modulates a laser (see Fig. 18). There is no clock detection and the optical signal is, in fact, treated as analog signal. The *electro-optical* amplification scheme may be used in applications, in which the optical signal is confined to a single color, which is the case in the basic ODC design. By the virtue of the *electro-optical amplification* technique, several segments of the ODC can be interconnected in the manner shown in Fig. 19. In order to ensure low jitter (that may affect the BER), the rise times of the detector, the laser, and the electronic amplifiers in the *electro-optical amplification* scheme need to be faster than the rise times of the original signal. The rise times add according to the square-law:

$$\tau_{\text{total}} = \sqrt{\tau^2_{\text{signal}} + \sum_i \tau^2_{\text{amplifier}_i}} = \sqrt{\tau^2_{\text{signal}} + m\tau^2_{\text{amplifier}}} \tag{8}$$

where m is the number of amplifiers (i.e., one less the number of ODC segments). Thus if it is required that $\tau_{\text{total}} \approx \tau_{\text{signal}}$, then $\tau_{\text{amplifier}} \ll \frac{1}{\sqrt{m}}\tau_{\text{signal}}$. Assuming

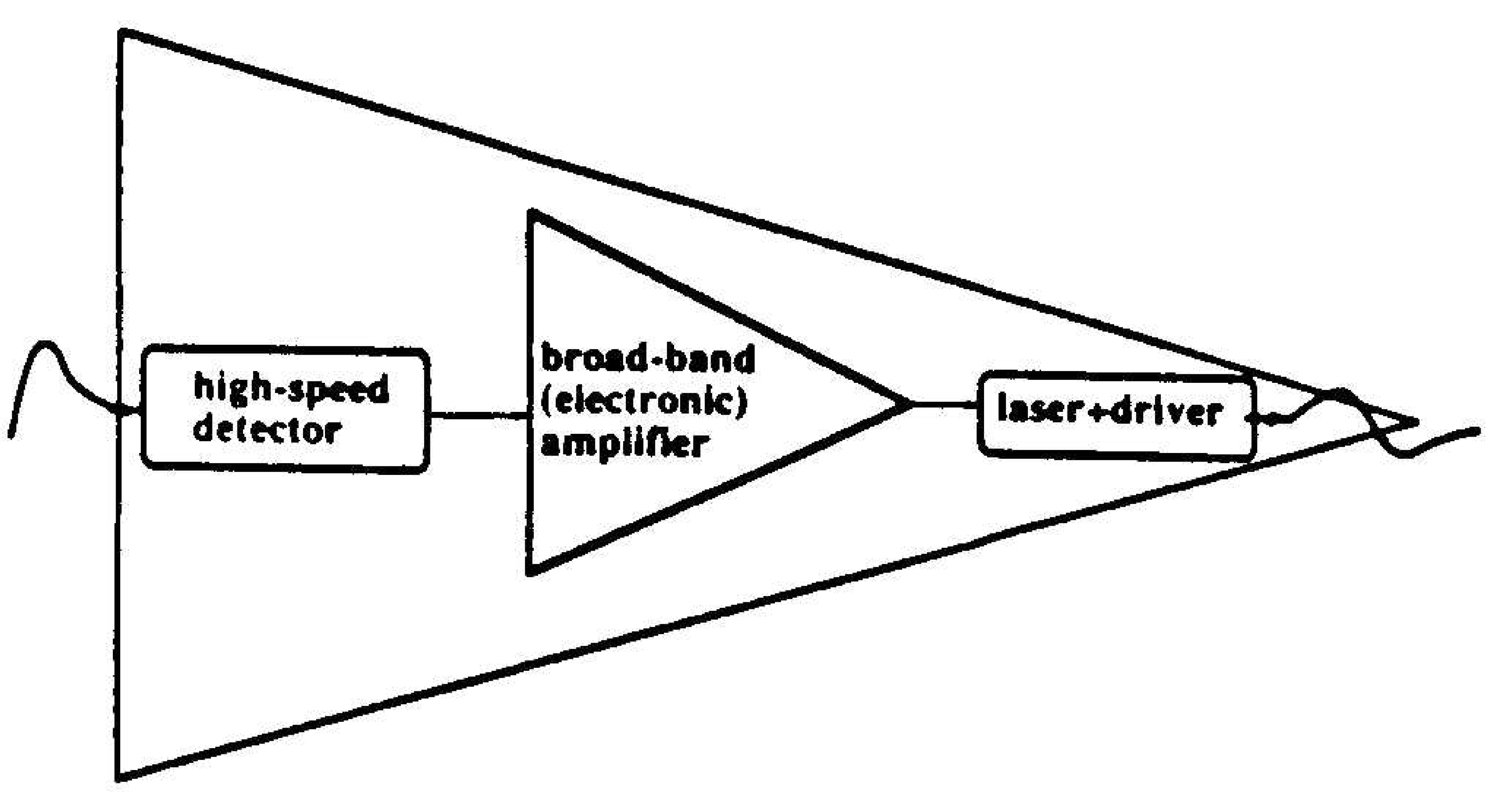

Fig. 18. The *electro-optical amplification* scheme

[11] This number could be substantially increased by "customizing" the optical coupler ratio. However, by doing so, the station design is not independent of location.

[12] Note, however, that since the cost of the amplification spreads over fifteen stations, it may still be an economical solution.

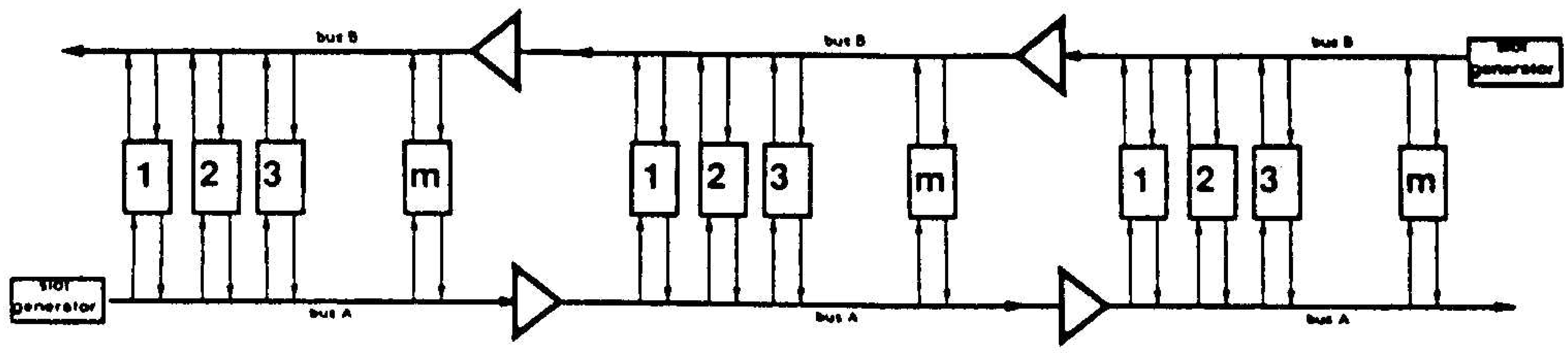

Fig. 19. Growing ODC

rise time of the signal to be 100 ps and 10 ODC segments, the required amplifier rise time should be less than 30 ps. Amplifiers with fast rise/falltime on the order of 15 ps are commercially available today (for an example see [11]). The amount of amplification provided by each electro-optical amplifier in Fig. 18 is designed to compensate for the losses in each ODC segment.

If full optical amplification is used, ODC can be further expanded by use of the WDM technique; i.e., the optical spectrum can be divided into WDM channels, each carrying a TDM transmission with rate that correspond to the maximum rate required by any station. However, because of the use of the *field-coding* technique, lower-rate stations are required to detect transmission at the lower rate only. Thus, the WDM channels are used to increase the number of TDM channels, where each TDM channel implements a subnetwork. Additionally, the WDM technique could be used to implement the *field-coding* technique, by dedicating a separate, low-speed channel for the control (headers) information.

4. Concluding Remarks

In this paper, we have introduced the design of ODC, the Optical Distribution Channel, which can serve as the physical layer for high-speed access optical local-area network. ODC facilitates high-speed interconnection among heterogeneous machines by the central feature of its design — the use of the *field-coding* technique. The *field-coding* technique enables to integrate several subnetworks on the same physical media. These subnetworks may provide different quality of service or different traffic attributes. Thus, for example, use of different transmission rates, different line encoding technique, and different error-detection/correction techniques may be easily integrated. Moreover, the cost of an attachement of a station to the network depends on the actual set of attributes required, and not on the maximal performance of all the attachements. The topology of ODC is based on the dual-bus architecture, and the attachement of stations to the optical bus is based on the "almost-all" optical network principle, that facilitate the *field-coding* scheme. We've demonstrated that by using the *field-coding* technique, the maximal number of stations can be doubled in the limit. Furthermore, we have addressed the growability issue by the use of the *electro-optical amplification* method, the clock distribution by the use of the clock composite signal, the reduction in the dynamic range of the receivers, and integration with the WDM approach that increases the total network capacity.

The main purpose of this paper is to investigate the feasibility of an "almost-all" optical network with the currently available optical components. Several other considerations (besides cost) guided us in our design, among them: traffic integration, and flexibility. By providing all of the above attributes, the Optical Distribution Channel may be an example of the physical layer of future high-speed local area networks, in line with the FDDI-Follow On (FDDI-FO) effort, [12] and [13].

5. Appendix: Clock and Data Synchronization

In this Appendix, we demonstrate the effect of temperature on the synchronization of two optical transmissions (clock and data, in particular), when the two transmissions are: (1) on the same wavelength but on different fiber, and (2) on the same fiber but on different wavelength.

First, we consider the change in time-synchronization, Δt, of two colors as a function of temperature changes, T. The time delay t of optical signal propagating with velocity v on a fiber with length L and refractive index n is

$$t = \frac{L}{v} = \frac{Ln(\lambda)}{c} \tag{9}$$

where c is the speed of light. Thus the time difference between two wavelength is

$$\Delta t = \frac{L}{c} \Delta n(\lambda) \tag{10}$$

where Δn is the difference in the refractive index between the two wavelengths. Differentiating with respect to changes in temperature, results in

$$\frac{\Delta(\Delta t)}{\Delta T} = \frac{L}{c} \frac{\Delta[n(\lambda_1) - n(\lambda_2)]}{\Delta T} \tag{11}$$

The values of $\Delta n(\lambda)/\Delta T$ are in the range of $- 10 \cdot 10^{-6}$ to $+ 10 \cdot 10^{-6}$ [1/°K], depending on the type of the optical glass used, and are relatively constant with wavelength above 800 nm, [14]. For example, changes in $\Delta n/\Delta T$ between 800 nm and 1100 nm are at most $1 \cdot 10^{-6}$ for most materials. This, assuming 50° changes in temperature and 10 km fiber, results in $\Delta(\Delta t) = 1.5$ nsec. This is a considerable change even for transmissions at 150 Mbps (bit duration = 6 nsec).

Next, we consider the case of two different fibers transmitting at the same wavelength. The thermal expansion coefficient of glass in the +20 to 300°C range, $\alpha_{20-300°C}$, is in the range of $4 \cdot 10^{-6}$ to $16 \cdot 10^{-6}$ [15]. Thus assuming that the network span may be on the order of 10 km and the temperature difference between the two fibers on the order of several degrees (we assume pessimistic case of 5°C), the differential changes in the fiber length may be as large as 0.8 m, which corresponds to $\Delta(\Delta t)$ of approximately 4 nsec.

We have demonstrated that if two optical signals are transmitted either using SDM[13] or WDM, loss of synchronization between the clock and data can occur.

[13] Space Division Multiplexing

Therefore, clock and data synchronization circuitry may be required[14] in the direct clock distribution systems, to prevent loss of synchronization. However, there is no loss of synchronization between the system clocks, since all the clock information is sent on the same channel by the *composite signal.*

References

[1] Z. Haas and R. D. Gitlin, "*Field Coding:* A High-Speed 'Almost-all' Optical Interconnect", in *Proceedings of the Twenty Fifth Annual Conference on Information Sciences and Systems,* Baltimore, Maryland, Mar. 20–22, 1991.

[2] Z. Haas and D. R. Cheriton, "Blazenet: A Packet-Switched Wide-Area Network with Photonic Data Path", *IEEE Trans. Comm.* **COM-38**, (Jun. 1990).

[3] M. Jinno, T. Morioka, T. Matsumoto and M. Saruwatari, "Ultrafast all-optical cell expander for photonic asynchronous transfer-mode networks", in *OFC '91,* San Diego, CA, Feb. 18–22, 1991.

[4] IEEE, *P802.6/D6, Proposed Standard. Distributed Queue Dual Bus (DQDB) Metropolitan Area Network (MAN),* IEEE, (Nov. 15, 1988).

[5] IEEE, *IEEE 802.6 Standard. Distributed Queue Dual Bus (DQDB) Subnetwork of a Metropolitan Area Network (MAN),* IEEE 802.6, (Feb. 7, 1990).

[6] John O. Limb, "On Fiber Optic Taps for Local Area Networks", in *Science, Systems & Services in Communications,* 1984.

[7] Gould Inc., *Fiber Optic Components,* 1310-AOS-XX/XX-02x02, Data Sheet, (Oct. 1986).

[8] AT&T Microelectronics, *ASTROTEC(R) 1306AA Lightwave Receiver,* Data Sheet, (Oct. 1986).

[9] AT&T Microelectronics, *215-Type ASTROTEC(R) Thermoelectrically Cooled 1.3μm and 1.56μm Injection Laser Modules,* Data Sheet, (Sep. 1989).

[10] M. J. O'Mahoney, "Semiconductor Laser Optical Amplifier for Use in Future Fiber Systems", *IEEE J. Lightwave Techn.* **6** (4), (Apr. 1988).

[11] Y. Ota and R. G. Swartz, "DC — 1 Gb/s burst mode receiver for optical bus applications", in *SPIE OE/Fibers '91,* Boston, MA, Sep. 3–6, 1991.

[12] B&H Electronics Corporation, *Amplifiers,* Data Sheets, (Apr. 1991).

[13] X3T9.5 Committee, *Project Proposal,* FOL-019, (Aug. 22, 1990).

[14] R. M. Grow, "FDDI-Follow On Status", in 15*th Conference on Local Computer Networks,* Mineapolis, MN, Sep. 30–Oct. 3, 1990.

[15] Solomon Musikant, *Optical Materials, An Introduction to Selection and Application,* Marcel Dekker, Inc., 1985, p. 41.

[16] Solomon Musikant, *Optical Materials, An Introduction to Selection and Application,* Marcel Dekker, Inc., 1985, pp. 45–46.

[14] However, since more and more local-area networks are implemented in the centralized manner, the *clock skew* problems when two separate fibers are used in the direct clock distribution method are largely eliminated. Furthermore, the cost for the additional bandwidth for the direct clock distribution in such a centralized design is minimal.