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Fail-Safe Nodes for Lightguide Digital Networks

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Lightguide digital networks that use fail-safe nodes made of an optical regenerator and optical couplers are described and analyzed. Every node in the network can regenerate or overwrite information traveling in a ring or bus network, and in the case of a power failure at one of the nodes, the network continues to function because the coupler keeps the continuity at the failing node. Fail-safe nodes that operate at 16 Mb/s were built to implement a digital network of ring architecture. A description of the components is presented, together with an analysis of the design constraints of the different parts of the fail-safe nodes.

I. INTRODUCTION

The use of regenerators at the nodes of a lightwave network introduces a reliability problem when the power at one node fails. Optical passive couplers solve this problem, but the number of passive couplers in a network is limited by the maximum insertion loss that can be tolerated between a transmitter and the receiver farthest away from it.[1]

This paper describes a new arrangement for a lightguide digital network built with fail-safe nodes and with the characteristics that the number of stations is independent of the coupler insertion loss, and that the network keeps functioning when the power at one or more nodes fails. A fail-safe node consists of a lightguide receiver and a lightguide transmitter electrically connected by a regenerator and optically connected by a directional coupler. Figure 1 shows a configuration for a fail-safe node consisting of a lightwave receiver and transmitter pair connected by a regenerator and a directional coupler that provides optical continuity when the power at the node fails. The feasibility of the network was tested using lightwave transmitters

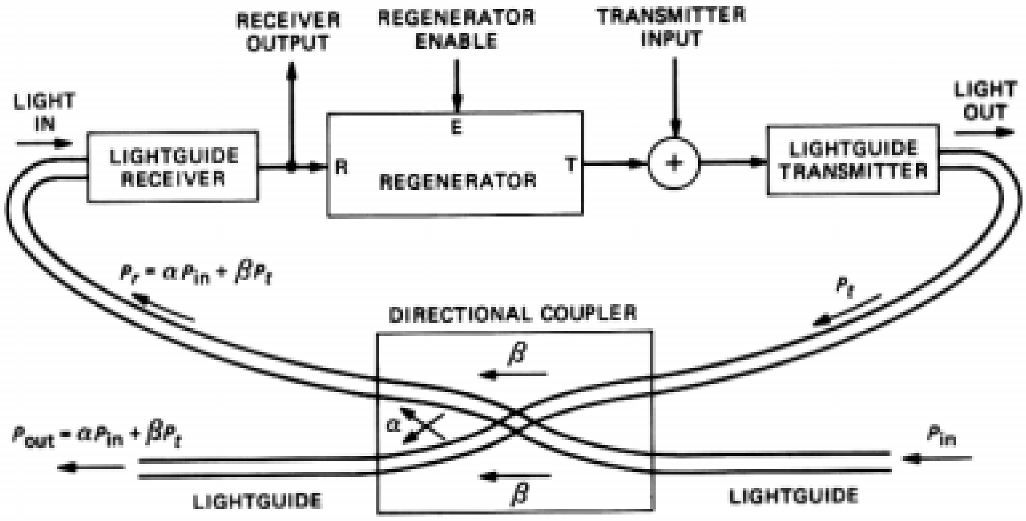

Fig. 1—Fail-safe node.

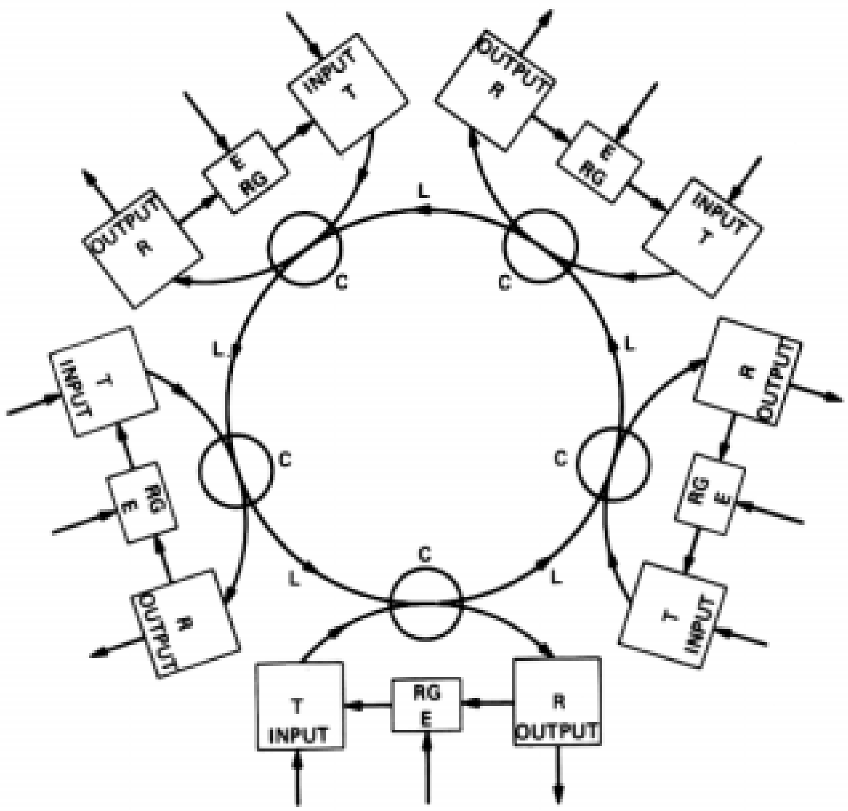

Fig. 2—Ring-type lightguide network.

(GaAlAs LED, $\lambda = 0.8\ \mu m$) and lightwave, avalanche photodiode (APD) receivers made by Western Electric. The repeaters were built using transistor-transistor logic (TTL) integrated circuits, and the network was operated with 16 Mb/s digital signals.

A node can regenerate, overwrite, or be off, depending on whether

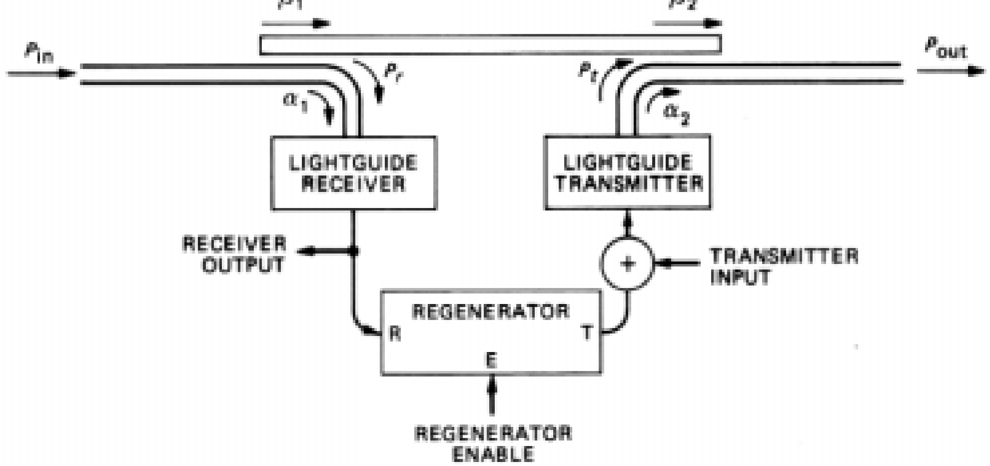

Fig. 3—A two-coupler node.

the regenerator is operating. In the regenerating configuration, the transmitter is controlled by the receiver, while in the overwriting state, the transmitter is independent of the receiver.

II. FAIL-SAFE NETWORKS

Fail-safe nodes can be connected together by a lightguide to form a ring-type network as shown in Fig. 2. Each node consists of a coupler, C, a receiver, R, a regenerator, RG, and a transmitter, T. The nodes are connected by lightguides, L. The E input disables the regenerator. The ring architecture was selected as an example; fail-safe nodes may also be used in other optical bus-type networks.[1] The nodes in the network are normally regenerating; that is, each node listens and regenerates the information flowing in the network. When a node wants to transmit, it turns its regenerator off and the information is inserted in the network by the lightguide transmitter. If the power at one node fails, or if the electronic components are removed for maintenance, the node is in the off state, and the optical coupler provides the continuity needed for the operation of the network. An additional advantage is that all the signals from different stations arrive with the same intensity at every receiver.

For proper operation of the fail-safe network, every node in the network must meet the three following constraints:

(*i*) *Sensitivity constraint*—The receiver of any node must be sensitive enough to receive the signal from a preceding transmitter when several nodes between the transmitter and the receiver are off.

(*ii*) *Interference constraint*—When two nodes are transmitting simultaneously, a node down the line should receive the signal from the closer node. This discrimination between the two transmitters is

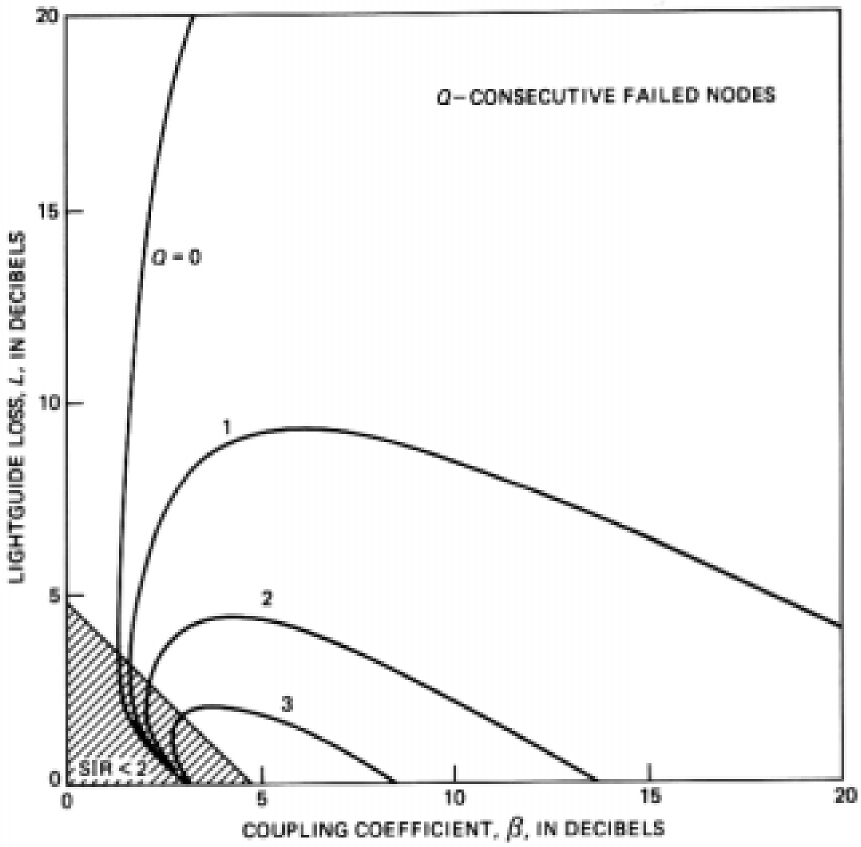

Fig. 4—Feasibility graph for one-coupler nodes.

achieved by the automatic gain control (AGC) of the receiver that adjusts the gain so the comparator circuit can detect only the stronger signal, while the less intense signal is below the threshold level.

(*iii*) *Automatic gain control response time*—In the case of a ring-type network, the sending node should be prevented from regenerating its own pulses to avoid having pulses traveling around the ring forever. This constraint is satisfied when the response time of the AGC in the lightguide receiver is longer than the time it takes a pulse to go around the ring once.

III. ANALYSIS

Each fail-safe node in the network may have one or two couplers, depending on whether the network uses return-to-zero or nonreturn-to-zero formats. Figure 1 shows the case where one coupler is used. The receiver has to be off during the time the transmitter is on to avoid saturation. This is achieved using a signal with a duty ratio less than 50 percent, and having the transmitter operating out of phase from the receiver. Figure 3 shows the coupler arrangement when two couplers are used.[2] In this case, the receiver can always be on because it does not receive light from the transmitter.

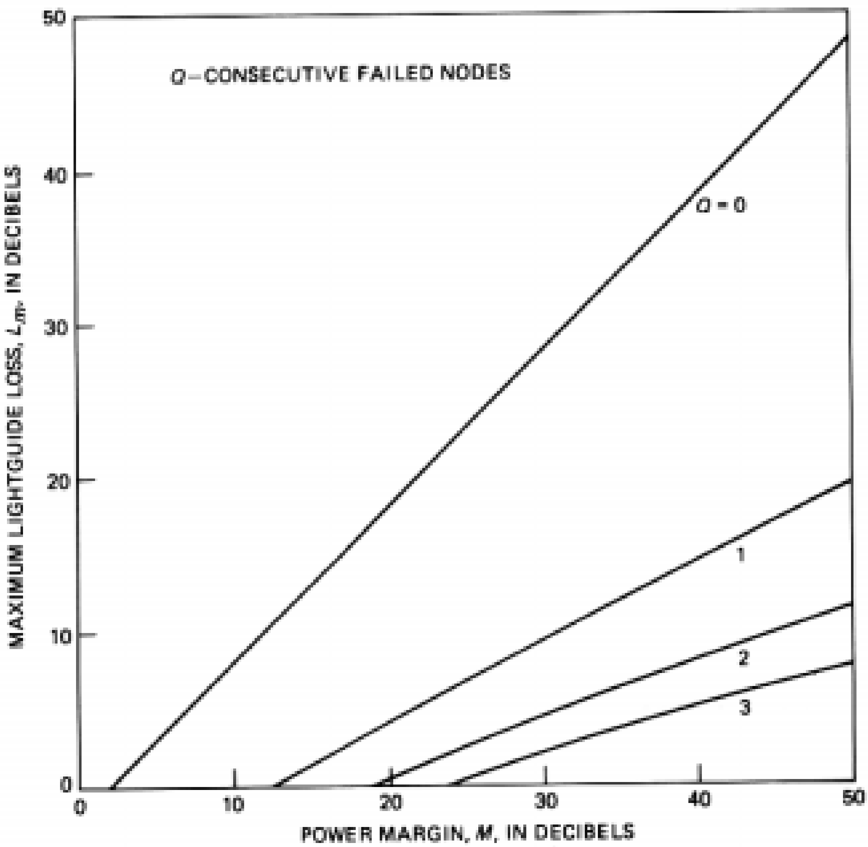

Fig. 5—Maximum lightguide loss for one-coupler nodes.

The coupler used in both cases can be characterized by a four-port device with a transmission coefficient α, a coupling coefficient β, and an excess loss coefficient $\gamma = \alpha + \beta$. Couplers with γ better than -1 dB have been reported in the literature.[3]

In the case of Fig. 1, P_{in} is the light entering the coupler from the ring; P_t is the light entering the coupler from the transmitter; $\alpha P_{\text{in}} + \beta P_t$ is the amount of light entering the receiver, P_r; $\alpha P_t + \beta P_{\text{in}}$ is the amount of light leaving the coupler and going into the ring, P_{out}. And in the case of Fig. 3, $P_r = \alpha_1 P_{\text{in}}$, and $P_{\text{out}} = \alpha_2 P_t + \beta_1 \beta_2 P_{\text{in}}$. These two node configurations will be analyzed next.

3.1 One-coupler nodes

Let us consider first the case of one-coupler node and analyze a hypothetical network where Q adjacent nodes have failed and they are off. The power received after Q failed nodes is $P_s + P_i$; P_s is the power received from the closest active transmitter:

$$P_s = P_t L^{Q+1} \beta^Q \alpha^2, \tag{1}$$

and P_i the sum of all the powers received from all the other previous active transmitters that may cause interference:

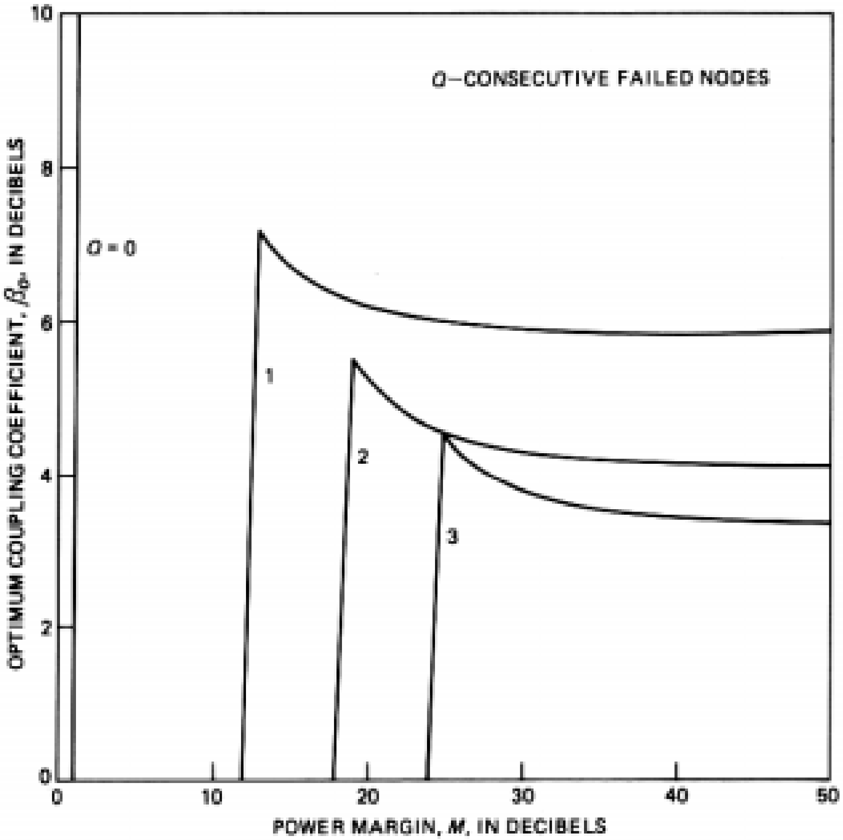

Fig. 6—Optimum coupling coefficient for one-coupler nodes.

$$P_i = \sum_{i=Q}^{i=\infty} P_t \alpha^2 L^{i+2} \beta^{i+1} = \frac{P_t L^{Q+2} \beta^{Q+1} \alpha^2}{1 - \beta L}. \tag{2}$$

In eqs. (1) and (2), L is the average lightguide attenuation between two adjacent nodes, and the infinite summation accounts for the worst case of interference.

The sensitivity and the interference constraints are satisfied when the effective received power, $P_{re}(Q)$, is larger than the sensitivity of the receiver, S,

$$P_{re}(Q) = P_s - P_i \geq S; \tag{3}$$

the minus sign accounts for the reduction in the opening of the eye diagram caused by the interference.

Equations 1 and 2, and $\alpha = \gamma - \beta$ are used to rewrite eq. 3 as

$$L^{Q+1} \beta^Q (\gamma - \beta)^2 \left| \frac{1 - 2\beta L}{1 - \beta L} \right| \geq \frac{S}{P_t} = M^{-1}, \tag{4}$$

which limits the values of β and L that satisfy the network constraints. In eq. 4, M is the optical power margin between the transmitter and the receiver.

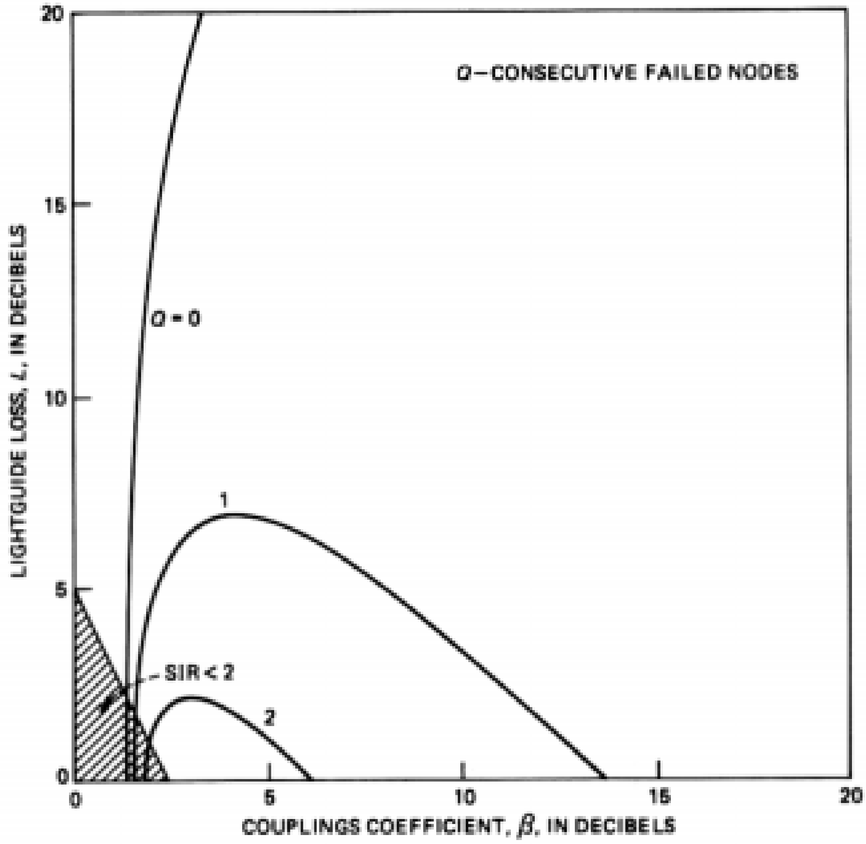

Fig. 7—Feasibility graph for two-coupler nodes.

The interference is deterministic, and it will not be seen by the comparator in the receiver because the AGC circuit sets the threshold automatically to one half of the peak amplitude which is precisely in the middle of the eye pattern. In addition to satisfying the sensitivity constraint expressed by eq. 3, one should have a signal-to-interference ratio (SIR) greater than 2 to eliminate any possible error caused by variations in the pulse amplitude,

$$\text{SIR} = \frac{P_s}{P_i} = \frac{1 - \beta L}{\beta L} \geq 2. \tag{5}$$

The SIR value of 2 was selected experimentally as the value where the error rate doubles.

Equations 4 and 5 are used to find the minimum value of L for a given β. This is done by defining a variable $V = \beta L$ that allows us to express L and β as a function of V:

$$L = \frac{V}{\gamma} + F(V) + [F^2(V) + 2VF(V)/\gamma]^{1/2}$$

$$\beta = \frac{V}{L}, \tag{6}$$

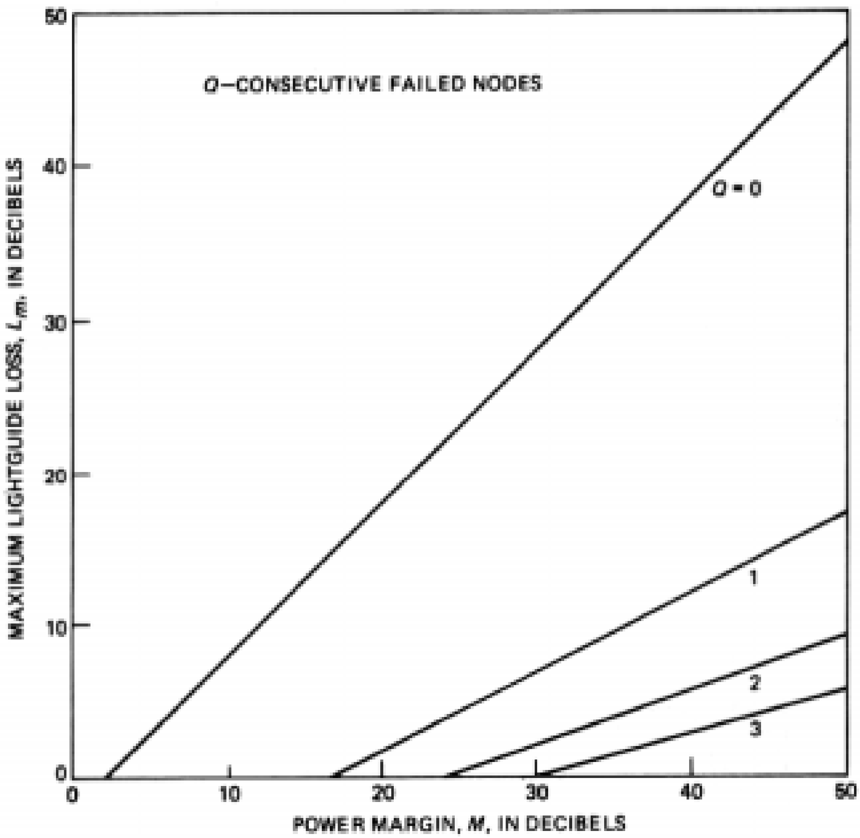

Fig. 8—Maximum lightguide loss for two-coupler nodes.

where

$$F(V) = \frac{1 - V}{2M\gamma^2(1 - 2V)V^Q}.$$

Equation 5 restricts the possible values of V to be within the range from 0 to 0.33.

Figure 4 shows a relation between L and β as given by eq. 6 for values of $Q = 0$, 1, 2, and 3, $\gamma = -1$ dB, and $M = 30$ dB. Values L and β are generally expressed in decibels, and L is commonly called the lightguide loss.

We can define an optimum coupling, β_o, as the value of β that allows the maximum lightguide loss, L_m, for a given power margin M. Figures 5 and 6 show the values of maximum L_m, and β_o as a function of M, and for a $\gamma = -1$ dB.

Figures 4 and 5 also show that the use of the fail-safe nodes in the network reduces the maximum lightguide loss between repeaters. This fact cannot be tolerated in transmission systems, but it may be possible in local area networks where the lightguide loss may not be a limiting factor.

Figure 4 shows that the maximum lightguide loss L_m is not sensitive

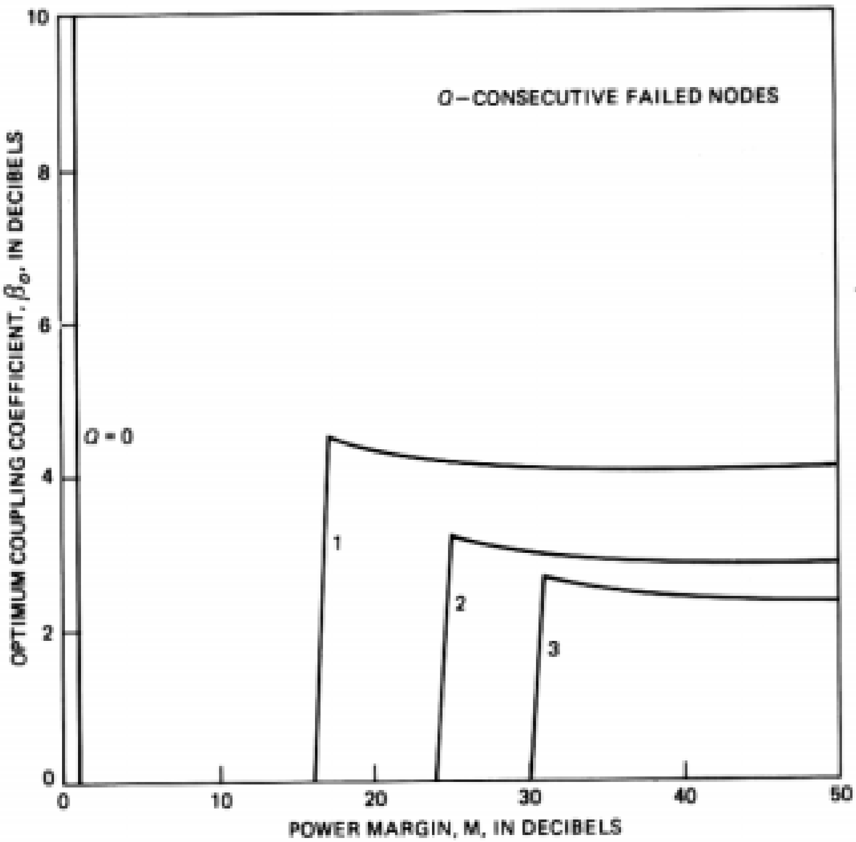

Fig. 9—Optimum coupler coefficient for two-coupling nodes.

to variations of β within ±1 dB from the optimum value of β, β_o. From Fig. 6, one could establish that a coupler with β between 4 and 6 dB is adequate for different values of M and Q.

3.2 Two-coupler nodes

The analysis of a network with two-coupler nodes is similar to the case of one-coupler nodes substituting β by β^2 in eqs. 1, 2, and 5. Note that the expression of $\alpha = \gamma - \beta$ remains the same for both cases. In this case, β and L are related by the expression

$$L^{Q+1}\beta^{2Q}(\gamma - \beta)^2 \left|\frac{1 - 2\beta^2 L}{1 - \beta^2 L}\right| \geq \frac{S}{P_t} \tag{7}$$

for the sensitivity constraint, and

$$\text{SIR} = \frac{1 - \beta^2 L}{\beta^2 L} = 2 \tag{8}$$

for the interference constraint. Figure 7 shows a relation between L and β as given by eqs. (7) and (8) for values of $Q = 0$, 1, and 2, $\gamma = -1$ dB, and $M = 30$ dB. Figures 8 and 9 show the values of L_m and β_o as a function of M when $\gamma = -1$ dB.

A comparison of Figs. 7, 8, and 9 against Figs. 4, 5, and 6 indicates that there is a 3-dB penalty when using nodes made of two couplers instead of one.

IV. CONCLUSIONS

Two configurations of optical couplers were analyzed to provide continuity in an optical network in the case of a power failure at several consecutive nodes. The analysis determines the optimum coupling coefficient, and the maximum lightguide loss that a network can have. Optical networks with fail-safe nodes are of interest in local area networks where the lightguide transmission loss is substantially less than the optical power margin between the transmitter and the receiver.

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