Abstract—The crosstalk and interference penalty in an all-optical network using static wavelength routers is analyzed in this paper. A worst case methodology is used to derive the upper bound of the penalty. We show that the penalty strongly depends on the linewidth of the laser source. Up to $-20\,\text{dB}$ in crosstalk can be tolerated in a moderate-size network ($\approx 10^2$ nodes), with the ratio of the laser linewidth to the electrical bandwidth less than or equal to unity. Larger linewidth has the advantage of reducing the power penalty incurred by phase-to-amplitude noise conversion. However, the number of wavelength channels will be reduced as well. The maximum tolerable component crosstalk for a network with arbitrary size is reduced to $-30\,\text{dB}$.

I. INTRODUCTION

WAVELENGTH routing for all-optical networks using WDMA has received increasing attention recently [1]–[4]. In a wavelength-routing network, shown in Fig. 1, wavelength-selective elements are used to route different wavelengths to their corresponding destinations. Compared to a network using only star couplers, a network with wavelength routing capability can avoid the splitting loss incurred by the broadcasting nature of a star coupler [5]. Furthermore, the same wavelength can be used simultaneously on different links of the same network and reduce the total number of required wavelengths [1].

The routing mechanism in a wavelength router can either be static, in which the wavelengths are routed using a fixed configuration [6], or dynamic, in which the wavelength paths can be reconfigured [7]. The common feature of these multiprotocol devices is that different wavelengths from each individual input port are spatially resolved and permuted before they are recombined with wavelengths from other input ports. These wavelength routers, however, have imperfections and nonideal filtering characteristics which give rise to signal distortion and crosstalk.

Crosstalk phenomena in wavelength routers have previously been studied [8]–[11]. It was shown in [8] that the maximum allowable crosstalk in each grating (grating as optical demultiplexers and multiplexers in the wavelength router) is $-15\,\text{dB}$ in an all-optical network with moderate size (say 20 wavelengths and 10 routers in cascade). The results are based on using a 1 dB power penalty criterion and only considering the power addition effect of the crosstalk. Crosstalk can also arise from beating between the data signal and the leakage signal (from imperfect filtering) at the same output.

Fig. 1. Topology of a wavelength routing network.

channel. The beating of these uncorrelated signals converts the phase noise of the laser sources into the amplitude noise and corrupts the received signals [12] when the linewidths of the laser sources are smaller than the electrical bandwidth of the receiver. Coherent beating, in which the data signal beats with itself, can occur as a result of the beatings among the signals from multiple paths or loops caused by the leakage in the wavelength routers in the system. It was shown in [10] that the component crosstalk has to be less than $-20, -30, \text{and} -40\,\text{dB}$ in order to achieve satisfactory performance for a system consisting of a single, ten, and hundred leakage sources, respectively. However, the authors only considered the case for narrow linewidth sources (using external modulation) and with destructive interference. In [11], the authors simulated the theoretical results reported in [12] with experiments, again, using externally modulated source of 40 MHz linewidth. The situation in which the dominant noise arises from phase-to-intensity noise conversion for different laser linewidths is yet to be studied.

In this paper, we investigate the maximum allowable component crosstalks in optical networks using static wavelength routers. The component crosstalk is a major system issue as the network size can be limited by the crosstalk accumulated through these routers. Apart from what had previously been published, we concentrate our study on crosstalk arising from phase-to-intensity-noise conversion due to the beating between the interfering channels and the data channel. A worst-case methodology, in which the data pattern sent in the crosstalk channels is chosen so that the system penalty is

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maximized, is used to evaluate the upper bound of the system penalty for a given crosstalk level. Using this methodology, we found that the crosstalk penalty heavily depends on the linewidth and the difference in deviation from the assigned wavelength of the laser sources. We found that the maximum tolerable component crosstalk is $-20$ dB (or $-40$ dB when a demultiplexer/multiplexer pair is considered) for a network of moderate size when both the laser linewidth and the difference in deviation from the assigned wavelength are less than or comparable to the electrical bandwidth of the receiver, since most of the noise power falls within of the receiver bandwidth. Conversely, the system penalty becomes negligible when either of the laser linewidth or this difference in deviation from the assigned wavelength is much larger than the electrical bandwidth of the receiver. This implies that the crosstalk penalty is reduced when the frequency chirping from direct modulation of the laser is also considered. For a small number of wavelengths (say, 4–6), our model predicts that the maximum tolerable component crosstalk is $-16.75$ dB (or $-33.5$ dB for a demultiplexer/multiplexer pair) to achieve a power penalty less than 1 dB. This number matches the experimental data reported in [11].

The organization of the rest of the paper is as follows. Section II presents the crosstalk formulation for a static wavelength router. Power penalty of single- and multiple-stage optical networks using static wavelength routers are evaluated in Sections III and IV, respectively. Several numerical examples are given in Section V. This paper is summarized in Section VI.

II. CROSSTALK FORMULATION

A. Wavelength Router Structure

Fig. 2 shows the structure of a static wavelength router which consists of $K$ optical demultiplexers and multiplexers. Each input fiber to an optical demultiplexer is assumed to contain up to $M$ different wavelengths where $M \leq K$. However, we only consider the case where $M = K$. The optical demultiplexer spatially separates the incoming wavelengths into $M$ paths. Each of these paths is then combined at an optical multiplexer with the outputs from the other $M - 1$ optical demultiplexers.

The wavelength routing configuration in Fig. 2 is fixed permanently. The optical data at wavelength $\lambda_j$ entering the $i$th demultiplexer exit at the $[(j - i) \mod M]$th output of that demultiplexer. That output is connected to the $i$th input of the $[(j - i) \mod M]$th multiplexer.

Because of the imperfections and nonideal filtering characteristics of the optical multiplexers and demultiplexers, crosstalks occurs in the wavelength routers. On the demultiplexer side, each output contains both the signals from the desired wavelength and that from the other $M - 1$ crosstalk wavelengths. From reciprocity, both the desired wavelength and the crosstalk signals exit at the output on the multiplexer side. Thus, each wavelength at every multiplexer contains $M - 1$ crosstalk signals originating from all demultiplexers.

B. Crosstalk Evaluation

The crosstalk effects can be formulated as follows. We assume each end node in Fig. 1 has a fixed-tuned or tunable single-mode laser transmitter (such as a distributed feedback laser) and a fixed-tuned or tunable optical receiver. The optical power for the logical ONE's and ZERO's at the output of the transmitter are $P_{ON}$ and $P_{OFF}$, respectively, and can be related to the average output power, $P_{av}$, and extinction ratio, $r$, as

$$P_{ON} = \frac{2r}{r + 1} P_{av}$$
$$P_{OFF} = \frac{2}{r + 1} P_{av}$$ (1)

for nonreturn-to-zero (NRZ) data. The electric field of a laser output during a bit can be expressed as

$$E(t) = \sqrt{2P} \cos(\omega t + \Phi(t) + \Theta)$$ (2)

where $P$ can be either $P_{ON}$ or $P_{OFF}$, $\omega$ is the angular laser frequency, $\Phi(t)$ is the phase noise process, and $\Theta$ is the initial phase of the laser. We only consider the phase-to-intensity noise as all other noise sources (such as the relative intensity noise and the mode-partition noise) are negligible as compared to the phase-to-intensity noise conversion. We denote the input electric field of the $j$th wavelength at the $i$th optical demultiplexer in Fig. 2 as $E_{i,j}^{in}$; the power attenuation of wavelength $\lambda_j$ at the $i$th output channel of the $i$th optical demultiplexer as $\alpha_{i,i-j}$; and the power attenuation of wavelength $\lambda_j$ at the $l$th input channel of the $i$th optical multiplexer as $\beta_{i,i-l}$. The output electric field of the $j$th wavelength at the $i$th optical multiplexer $E_{i,j}^{out}$ thus equals

$$E_{i,j}^{out}(t) = \sum_{l=0}^{M-1} \sqrt{\beta_{i,i-l}} \sqrt{\alpha_{i,i-j}} E_{i,j}^{in}(t)$$ (3)

It can be found from Fig. 2 that for an ideal demultiplexer, we have $\alpha_{i,i-i-j} \equiv 1$ (no attenuation) and $\alpha_{i,i,j} = 0$ for $j \neq (i - l) \mod M$ (full attenuation). Similarly, for an ideal multiplexer, we have $\beta_{i,i-l} \equiv 1$ and $\beta_{i,i,j} = 0$ for $j \neq (i - l) \mod M$. For nonideal demultiplexers and multiplexers, we have $0 < \alpha_{i,i,j} < 1$ and $0 < \beta_{i,i,j} < 1$. 

Fig. 2. Structure of a static wavelength routing mode using 3 wavelengths as an example. Calculation of total crosstalk for a wavelength router is also indicated in the figure.
To evaluate the worst case scenario (upper-bound in system penalty), we assume that all of the optical multiplexers and demultiplexers have identical characteristics, and that the crosstalk introduced for each channel is also identical. That is, we have \( \alpha_{j,i,(l-i) \mod M} = \alpha, \beta_{i,l,(l-i) \mod M} = \beta = \alpha, \beta_{i,l,(l-i) \mod M} = C\beta = C\alpha \) for \( j \neq (i - l) \mod M \) where \( C \) is the ratio of the intensity of a crosstalk channel to that of the signal channel. Typically, a flat \(-30\) dBc crosstalk across the bandwidth can be observed in planar waveguide demultiplexer devices [13]. From reciprocity, we have \( \beta_{i,l,(l-i) \mod M} = \beta = \alpha, \beta_{i,l,(l-i) \mod M} = C\beta = C\alpha \) for \( j \neq (l - i) \mod M \). Equation (3) can then be simplified to

\[
E_{i,j}^{out} = \alpha \left( E_{i,(j-i) \mod M}^{in} + C \sum_{l \in \mathcal{X}_{ij}} E_{l,j}^{in} \right)
\]

(4)

where \( X_{ij} = \{0, \ldots, M - 1\} - \{j - i \mod M\} \). The output intensity of wavelength \( \lambda_j \) at the output of the \( i \)th wavelength demultiplexer can then be computed:

\[
P_{i,j}^{out}(t) = \alpha^2 \left( p_{(j-i) \mod M,j}^{in} + C^2 \sum_{l \in \mathcal{X}_{ij}} p_{l,j}^{in} \right)
+ 2C \sum_{l \in \mathcal{X}_{ij}} \gamma_{kl}(t) \sqrt{p_{l,j}^{in} p_{l,j}^{in}}
+ \alpha^2 C^2 \sum_{k \in \mathcal{X}_{ik}} \sum_{l \in \mathcal{X}_{il}} \gamma_{kl}(t) \sqrt{p_{k,j}^{in} p_{l,j}^{in}}
\]

(5)

In (5), \( \gamma_{kl}(t) \) is defined as

\[
\gamma_{kl}(t) = \cos \left( \Delta \omega_{kl} t + \Phi_k(t) - \Phi_l(t) + \Theta_k - \Theta_l \right)
\]

(6)

where \( \Delta \omega_{kl} = \omega_k - \omega_l \) is the frequency difference between the \( k \)-th and \( l \)-th laser sources. The first, second, third and fourth terms on the right-hand side of (5) represent the signal, the dc crosstalk, the signal-crosstalk beating and crosstalk-crosstalk beating, respectively. While the dc crosstalk adds directly to the signal, the beatings arising from the signal-crosstalk and crosstalk-crosstalk generate the phase-to-intensity noise.

The phase-to-intensity noise at the fixed-tuned or tunable receiver (only a single wavelength is selected) can be computed as follows. Assuming that a transimpedance preamplifier with transimpedance \( R_F \), the output voltages for the ONE's and ZERO's from the preamplifier are

\[
V_{ON} = \frac{\eta_e}{h u} S_{ON} R_F
\]

\[
V_{OFF} = \frac{\eta_e}{h u} S_{OFF} R_F
\]

(7)

where \( \eta \) is the photodetector quantum efficiency, \( \nu \) is the optical frequency, and \( h \) is the Planck's constant. \( S_{ON} \) and \( S_{OFF} \) are the respective expectation values of (5) for receiving a ONE and ZERO

\[
S_{ON,xtalk} = \alpha^2 \left( P_{ON} + C^2 \sum_{l \in \mathcal{X}_{ij}} P_l \right)
\]

\[
S_{OFF,xtalk} = \alpha^2 \left( P_{OFF} + C^2 \sum_{l \in \mathcal{X}_{ij}} P_l \right)
\]

(8)

where \( P_l \) instead of \( P_{l,j} \) is used since only one wavelength is considered here. The subscript \( xtalk \) denotes the bit pattern \( (b_0, b_1, \ldots, b_{M-1}) \) sent on the crosstalk channels: \( P_l = P_{ON} \) if \( b_l = 1 \) and \( P_l = P_{OFF} \) if \( b_l = 0 \). The total noise power of the received logical ONE's and ZERO's equals [14]

\[
V_{N,i,xtalk} = \left( \frac{1}{2} \right)^2 \left( 1 + \frac{R_F}{R} \right)^2 \frac{4\pi T}{3} B_c C^2 R_F^2 + R_F^2 \left( \frac{4kT}{R} + (I_A^2) \right) + 4kT R_F B_c
+ R_F^2 \int_{-B_c}^{B_c} S_{i,xtalk}(f) df \quad i \in \{ON, OFF\}
\]

(9)

where \( R \), and \( C_n \) are the preamplifier input resistance, and input capacitance, respectively, \( k \) is the Boltzmann’s constant, and \( T \) is the temperature. \( S_{i,xtalk}(f) \) is the two-sided noise spectral density of the photodetector current, given as

\[
S_{i,xtalk}(f) = \frac{\eta e^2}{h v} S_i f + \left( \frac{\eta e}{h v} \right)^2 S_{P,i,xtalk}(f) \quad i \in \{ON, OFF\}
\]

(10)

where \( S_{P,i,xtalk}(f) \) is the optical intensity noise spectral density (see next section). This intensity-related noise comes from the signal and the dc crosstalks (first term), and the beatings between the signal and crosstalks as well as among the crosstalks (second term). The latter is greatly affected by the laser linewidth and the difference in the deviation from the assigned wavelength, as will be fully discussed in the next section.

Assuming Gaussian receiver noise, the bit-error rate at a receiver output is

\[
P_e = \frac{1}{4} \sum_{j=0}^{1} \sum_{j'=0}^{1} \text{Prob}[xtalk = j]
\]

\[
\times \left( \text{erfc} \left( \frac{th_{opt} - V_{OFF,xtalk}}{\sqrt{2V_{N,OFF,xtalk}}} \right) + \text{erfc} \left( \frac{V_{ON,xtalk} - th_{opt}}{\sqrt{2V_{N,ON,xtalk}}} \right) \right)
\]

(11)

where \( th_{opt} \) is the optimal decision threshold that minimizes the bit-error rate.

III. SYSTEM PEnALTY IN SINGLE-STAGE CONFIGURATION

In this section, the system penalty caused by the crosstalk in a single-stage wavelength router will be derived for the following cases.

1) Noncoinciding uncorrelated sources, in which the independent laser sources have slightly different wavelengths of \( \leq 10 \) GHz.

2) Coinciding uncorrelated sources, in which the independent laser sources have identical wavelengths. Note that this is a special case of (1).
The coinciding correlated case (such as that arises from loops in the network) is not considered here, as it is network-structure-dependent and has to be addressed individually for each specific configuration.

A. Noncoinciding Uncorrelated Sources

Using the approach similar to [14], the noise spectral density $S_{i,talk}^p(f)$ can be derived from the autocovariance, $L_P(\tau)$, of (5)

$$L_P(\tau) = \mathbb{E}[(P(t+\tau) - \mathbb{E}[P(t+\tau)])(P(t) - \mathbb{E}[P(t)])]$$

$$= 4C^2 \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{im}(t+\tau)\gamma_{in}(t)]$$

$$\cdot \sqrt{P_i P_m} \sqrt{P_i P_n}$$

$$+ 2C^3 \sum_{l \in \mathbb{X}_i} \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{il}(t+\tau)\gamma_{mn}(t)]$$

$$\cdot \sqrt{P_l P_i} \sqrt{P_m P_n}$$

$$+ 2C^3 \sum_{l \in \mathbb{X}_i} \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{mn}(t+\tau)\gamma_{il}(t)]$$

$$\cdot \sqrt{P_l P_i} \sqrt{P_m P_n}$$

$$+ C^4 \sum_{k \in X_i} \sum_{l \in \mathbb{X}_i} \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{kl}(t+\tau)\gamma_{mn}(t)]$$

$$\cdot \sqrt{P_k P_l} \sqrt{P_i} \sqrt{P_m P_n}.$$  \hspace{1cm} (12)

This equation can further be simplified by keeping only the $C^2$ term (i.e., ignoring those terms arising from the beatings among the crosstalks) since $C \ll 1$ in most multiplexers and demultiplexers reported. That is,

$$L_P(\tau) \approx 4C^2 \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{mn}(t+\tau)\gamma_{mn}(t)]$$

$$\cdot \sqrt{P_i P_m} \sqrt{P_i P_n}$$

$$= 4C^2 \left( \sum_{m \in X_i} \mathbb{E}[\gamma_{im}(t+\tau)\gamma_{im}(t)] P_i P_m ight)$$

$$+ \sum_{m \in X_i} \sum_{n \in X_i} \mathbb{E}[\gamma_{im}(t+\tau)\gamma_{in}(t)] P_i \sqrt{P_m P_n}.$$  \hspace{1cm} (13)

By substituting (6) in (13), the first term can be expanded into

$$\mathbb{E}[\gamma_{im}(t+\tau)\gamma_{im}(t)]$$

$$= \mathbb{E}[\cos(\Delta \omega_{im}(t+\tau) + \Phi_{i}(t+\tau) - \Phi_{m}(t+\tau) + \Phi_{i} - \Phi_{m})]$$

$$= \frac{1}{2} \cos(\Delta \omega_{im}(\tau)e^{-2\pi \Delta \nu |\tau|}$$  \hspace{1cm} (14)

while the second term in (13) can be shown to reduce to zero [14]. Therefore,

$$L_P(\tau) \approx 2C^2 P_i \sum_{m \in X_i} \cos(\Delta \omega_{im}(\tau)e^{-2\pi \Delta \nu |\tau|} P_m$$

$$i \in \{ON, OFF\}$$  \hspace{1cm} (15)

and the spectral density is the Fourier transformation of (15):

$$S_i^p(f) = \frac{2\Delta \nu C^2 P_i}{\pi} \sum_{m \in X_i} \frac{P_m}{(\Delta \nu)^2 + (f - \Delta f_{im})^2}$$

$$i \in \{ON, OFF\}$$  \hspace{1cm} (16)

where $\Delta \nu$ is the linewidth of the laser, and $\Delta f_{im}$ is the frequency separation between the $m$th crosstalk and the signal.

Total noise power due to phase-to-intensity noise conversion can then be found

$$N_{total, i, xtalk} = \int_{-B_e}^{B_e} S_i^p(f) \, df$$

$$= \frac{2C^2}{\pi} \sum_{m \in X_i} P_m \left( \tan^{-1} \frac{B_e - \Delta f_{im}}{\Delta \nu} + \tan^{-1} \frac{B_e + \Delta f_{im}}{\Delta \nu} \right)$$  \hspace{1cm} (17)

where $B_e$ is the electrical bandwidth of the receiver. This equation implies that the phase-to-intensity noise conversion can be ignored when $\Delta f_{im} \gg B_e$ or $\Delta \nu \gg |B_e \pm \Delta f_{im}|$.

B. Coinciding Uncorrelated Sources

For the coinciding-uncorrelated-sources case, we have $\Delta f_{im} = 0$ for all $m \neq j$. Equation (17) can thus be further reduced to

$$N_{total, i, xtalk} = \int_{-B_e}^{B_e} S_i^p(f) \, df$$

$$= \frac{4C^2}{\pi} P_i (L_i, OFF P_{OFF} + L_i, ON P_{ON})$$

$$\cdot \tan^{-1} \frac{B_e}{\Delta \nu}$$  \hspace{1cm} \forall i \in \{ON, OFF\}$$  \hspace{1cm} (18)

and (8) is reduced to

$$S_i, xtalk = P_i + C^2 (L_i, OFF P_{OFF} + L_i, ON P_{ON})$$  \hspace{1cm} (19)

The parameter $L_{i,j}$ describes the number of crosstalk channels that are transmitting the symbol $j$ while the signal channel is transmitting the symbol $i$. Note that $L_i, OFF + L_i, ON = M - 1$.

The power penalty can be computed by taking the logarithm of the ratio of the required signal level to achieve a specific bit error rate with a crosstalk level of $C, P_{av,c}, C$, to that of the required signal level to achieve the same bit error rate with zero crosstalk, $P_{av}, i.e., \log_{10} (P_{av,c} / P_{av})$. A worst-case methodology, in which the crosstalk channels are assumed to transmit bit patterns that maximize the bit error rate, is used to evaluate the system penalty. In this methodology, the crosstalk channels are assumed to transmit a bit pattern that maximizes the system penalty or effectively, minimizes the eye-opening in the eye-diagram analysis. Due to our pessimistic assumptions, the derived results yield the upper bound of the maximum allowable component crosstalk in the system.

The worst case crosstalk can be analyzed in two categories. First, when the data channel is transmitting a ZERO, the worst case degradation on the signal occurs when all crosstalk channels are transmitting ONE’s. Note that the total noise is also maximized [see (18)], resulting in the worst case power penalty. When the data channel is transmitting a ONE, the worst case power penalty could occur at $L_{ON, OFF} = 0, 0 < L_{ON, OFF} < M - 1$, or $L_{ON, OFF} = M - 1$, as illustrated.
in Fig. 4. In this figure, we choose $M = 60$ to illustrate a broad range of possible worst case scenarios. Here, the power penalty is plotted as a function of $L_{\text{ON,OFF}}$ with zero $L_{\text{OFF,OFF}}$. When $\Delta \nu/B_e < 50$, the noise contributed by phase-to-amplitude conversion is the dominant source and the worst case occurs where all of the crosstalk channels are transmitting ONE’s. The power penalty becomes almost independent of the number of crosstalk channels transmitting ONE’s or ZERO’s when $\Delta \nu/B_e \sim 50$. When $\Delta \nu/B_e > 50$, the noise contributed by phase-to-amplitude conversion becomes insignificant and the worst case occurs where all of the crosstalk channels are transmitting ZERO’s.

The phase-to-amplitude noise contributed by noncoincident uncorrelated sources is always smaller than coinciding uncorrelated sources, as shown in (17) and (18). Therefore, we restrict our attention to those situations with coinciding uncorrelated sources for the rest of the paper.

**IV. System Penalty in Multistage Configuration**

Crosstalk power can accumulate as wavelength routers are cascaded, as shown in Fig. 3. In this section, we evaluate the system penalty in a multistage configuration consisting of coinciding uncorrelated sources as this case represents an upper bound on the system penalty. The constraint set by the accumulated signal-to-noise ratio degradation caused by the crosstalk limits the size of the network to $M^H$, assuming a fully populated $M$-ary tree configuration.

Assuming all of the wavelength channels of each fiber are fully populated, we can categorize signal paths as low-attenuation and high-attenuation crosstalk paths. Each stage of wavelength router only allows one low-attenuation path (which is the intended signal path) and $M - 1$ high-attenuation paths. In a network consisting of multiple stages of wavelength routers, we only need to consider crosstalk signals going through low-attenuation crosstalk path, as the relatively weak contribution from the high-attenuation paths can be ignored. Each additional stage of wavelength router will increase the number of low-attenuation paths by $M - 1$. Therefore, the total number of crosstalk paths after $H$ stages of wavelength routers is $H(M - 1)$.

Taking into the consideration of multiple stages, (19) is modified to

$$S_{i,\text{xtalk}} = P_i + C^2(L_{i,\text{OFF}}P_{\text{OFF}} + L_{i,\text{ON}}P_{\text{ON}})$$

$$= P_i + C^2(L_{i,\text{OFF}}P_{\text{OFF}} + (H(M - 1) - L_{i,\text{OFF}})P_{\text{ON}})$$

$$i \in \{\text{ON, OFF}\}$$

(20)

where $L_{i,\text{ON}}$ and $L_{i,\text{OFF}}$ are constrained by $H(M - 1)$, the total number of possible crosstalk paths. That is, $L_{i,\text{OFF}} + L_{i,\text{ON}} = H(M - 1)$. Equation (18) is modified to

$$N_{\text{total},i,\text{xtalk}} = \int_{-B_e}^{B_e} S_{i,\text{xtalk}}(f) \, df$$

$$= \frac{4C^2}{\pi} P_i(L_{i,\text{OFF}}P_{\text{OFF}} + L_{i,\text{ON}}P_{\text{ON}}) \tan^{-1} \frac{B_e}{\Delta \nu}$$

$$= \frac{4C^2}{\pi} P_i(L_{i,\text{OFF}}P_{\text{OFF}} + (H(M - 1) - L_{i,\text{OFF}})P_{\text{ON}})$$

$$\cdot \tan^{-1} \frac{B_e}{\Delta \nu}$$

$$i \in \{\text{OFF, ON}\}.$$  

(21)

The bit error rate at a receiver output of the entire network can be obtained by evaluating (11).

For a specific $(H, M, C)$, the total noise power can be calculated from (20) and (21). The bit error rate can be computed by substituting the signal and noise power into (11). The power penalty can then be obtained by using the same procedure as outlined at the end of the previous section.

**V. Numerical Results**

Fig. 5 shows crosstalk penalty as a function of crosstalk level $C$ for various values of network size parameters $H(M - 1)$. The maximum tolerable component crosstalk level at $-16.75$ dB (or $-33.5$ dB when a demultiplexer/multiplexer pair is considered) for $H(M - 1) = 5$ in this figure matches the experimental results obtained in [11]. System penalty increases rapidly with the increase of $C$, and linearly increases...
with $H(M-1)$ (see Fig. 6). As shown in Fig. 6 the network can tolerate a crosstalk level $C$ of $-30$ dB, independent of the network size. This assumes a typical laser linewidth of 50 MHz and using a bit error rate of $10^{-9}$. The network size is severely limited ($H(M-1) < 100$) as the crosstalk level $C$ approaches $-20$ dB. Using a 1-dB crosstalk penalty criterion, the maximum achievable network size ($M^H$) is plotted in Fig. 7 as a function of crosstalk level $C$ for various values of linewidth $\Delta \nu$. For each given crosstalk level, the values in $(M, H)$ have been chosen so that $M^H$ is maximized. Note that the tolerable crosstalk level $C$ is $-20$ dB for a network size of $10^3$. The difference in this value as opposed to the results ($-30$ dB) generated earlier is because of the optimum network tree configuration, allowing more crosstalk to the same constraint of $H(M-1)$.

The dependency of the crosstalk penalty on the linewidth of a laser sources is shown in Fig. 8 for $H(M-1) = 50$ and $B_e = 500$ MHz. For a given crosstalk level $C$, there exists a dc crosstalk at large laser-linewidth regime ($\Delta \nu/B_e > 50$) and phase-to-amplitude crosstalk at narrow laser-linewidth regime ($\Delta \nu/B_e < 0.5$). The apparent saturation of the crosstalk penalty in these regimes arises from (18), in which $N_{\text{total},i}$ is determined by the $\tan^{-1}(B_e/\Delta \nu)$. The crosstalk penalty is significantly reduced for systems using lasers with larger linewidth, which could result from the chirp introduced by directly modulating DFB lasers [15]. However, increasing the laser linewidth reduces the number of wavelength channels that can be accommodated by the 30 nm ($\sim 3.7$ THz) transmission window of the Er-doped fiber amplifier. Furthermore, as a result of the increased laser linewidth, additional power penalty is introduced by the intersymbol interference caused by the fiber dispersion. A trade-off exists and the laser linewidth should be controlled such that the total power penalty is minimized. This is illustrated in Fig. 9, in which the dispersion penalties are plotted as a function of $\Delta \nu/B_e$ for propagation distances of 100, 200, and 500 km, respectively. The dispersion penalty is calculated based on the analytical model described in [16]. For comparison, the power penalty from phase-to-amplitude noise conversion at a crosstalk level of $-20$ dB with $H(M-1) = 50$ is also shown in the same figure. As an example in Fig. 9, the power penalty from dispersion (propagation distance of 500 km) and from crosstalk intersects at $\Delta \nu/B_e \sim 5$, suggesting an optimal linewidth of 2.5 GHz for the system. In this calculation, the crosstalk power penalty from adjacent channels (due to increased linewidth) is not considered as it has been shown in [15] that the crosstalk with a channel separation of 0.6 nm (at a bit rate less than 1 Gb/s) is negligible.

VI. SUMMARY AND DISCUSSION

In this paper, the crosstalk penalties in an all-optical network consisting of single or multiple stages of static wavelength routers are evaluated. A worst-case methodology is adopted in which all of the crosstalk channels are assumed to transmit
Fig. 9. Comparison of system penalty due to crosstalk and dispersion as a function of linewidth.

data patterns that maximize system penalty. This methodology allows us to derive an upper bound of the crosstalk penalty. Using this methodology and assuming that the laser linewidth is smaller than the receiver bandwidth, we show that the maximum allowable crosstalk for each device is \( -20 \) dB in order to achieve a network with moderate size, and \(-30 \) dB for a network with arbitrary size.

REFERENCES


Chung-Sheng Li (S’87–M’91–SM’95) received the B.S.E.E. degree from National Taiwan University, Taiwan, R.O.C., in 1984, and the M.S. and Ph.D. degree in electrical engineering and computer science from the University of California, Berkeley in 1989 and 1991, respectively.

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