Solution Paths to Limit Interferometric Noise Induced Performance Degradation in ASK/Direct Detection Lightwave Networks

Peter J. Legg, Moshe Tur, Senior Member, IEEE, and Ivan Andonovic, Member, IEEE

Abstract—Interferometric noise, arising on the optical interference of the desired information signal and parasitic crosstalk waveforms at the photodetector, afflicts practically all lightwave communication networks, inducing unacceptable power penalties and bit error rate floors. In this paper, the induced performance degradation is quantified, both experimentally and analytically, and solution paths are identified. It is concluded that the total crosstalk level of noise generating parasitics in a general optical network must be held below $-25 \text{ dB}$ for a penalty of less than $1 \text{ dB}$—a further 2 to 4 dB may lead to network failure; otherwise, means of suppressing the noise by RF rejection at the receiver must be invoked. A number of approaches to achieving a reduction in the level of interferometric noise are presented and contrasted.

I. INTRODUCTION

In the push to develop ever more powerful optical communication networks, interferometric noise, the result of data-crosstalk interference at the detector, has frequently been cited as a key performance-limiting factor—power penalties and bit-error-rate floors result [1]–[24]. The prevalence of interferometric noise is a consequence of the large number of generation mechanisms of parasitic crosstalk which follows multiple transparent paths before adding to the data; it is simply a requirement that crosstalk and data arise from the same source—the typical case, or from distinct sources closely aligned in wavelength. Levels of crosstalk thought to be innocuous with an internatural interference (ISI) mind-set may generate unacceptable quantities of interferometric noise because the crosstalk adds on a field amplitude basis as for other interference manifestations.

Consider the simplest optical network, an optical link comprising a laser connected to a fiber patchcord which in turn is connected to a photodetector. Light reflected at the connector nearest to the detector is partly reflected at the other connector and passes as parasitic crosstalk to the detector. On square-law detection the photocurrent is given by

$$i = P_d + P_c + 2\sqrt{P_d P_c} \cos(\text{relative phase}) P_d \cdot P_c \cdot P_e$$

where $P_d$ and $P_c$ are the instantaneous optical power, $P_d$ and $P_c$, the polarization vectors of the data and crosstalk, respectively. The data can be seen to be corrupted not only by the additive crosstalk $P_c$, as would be predicted by a sum of intensities (ISI) approach, but also by the mixing term that exhibits a cosinusoidal dependence on the relative phase of the data and crosstalk. When this relative phase fluctuates randomly (mechanisms for this are discussed below) interferometric noise arises. For example, in the worst-case of aligned polarizations (assumed throughout this paper), if $P_d = 10$ (arbitrary units), $P_c = 1$, the interferometric noise varies by $\pm 6.3$ (assuming a relative phase spanning $(0, 2\pi)$)—the eye opening is greatly reduced.

Sources of interferometric noise in optical networks employing (digital) ASK modulation and direct detection are summarized in Table I.

<table>
<thead>
<tr>
<th>NETWORK</th>
<th>CAUSE OF INTERFEROMETRIC NOISE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>general</td>
<td>non-specific</td>
<td>[1–5]</td>
</tr>
<tr>
<td>transport via cascaded optical components</td>
<td>multiple discrete reflections</td>
<td>[6–9]</td>
</tr>
<tr>
<td>transport via filter</td>
<td>Rayleigh backscatter</td>
<td>[10–13]</td>
</tr>
<tr>
<td>WDM/subcarrier</td>
<td>PMD in subcarrier channels at the same λ</td>
<td>[14–16]</td>
</tr>
<tr>
<td>fibre loop buffers and signal processors</td>
<td>crosstalk addition at the loop coupler</td>
<td>[17–19]</td>
</tr>
<tr>
<td>space switches</td>
<td>switch crosstalk</td>
<td>[20]</td>
</tr>
<tr>
<td>WDM transport network</td>
<td>switch crosstalk filter crosstalk</td>
<td>[21–23]</td>
</tr>
<tr>
<td>optical TDM switching node</td>
<td>switch crosstalk</td>
<td>[24]</td>
</tr>
</tbody>
</table>

In this paper, the performance degradation owing to interferometric noise in lightwave networks employing highly coherent sources, e.g., distributed feedback (DFB) lasers, is addressed and solution paths are explored. The DFB laser is a preferred source for high-bandwidth communications systems. Lower coherence sources, such as LED’s and multimode lasers, are less prone to interferometric noise which is strongly RF rejected at the receiver, and are not considered. In Section

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II, the different classes of interferometric noise resulting from the possible noise mechanisms governing the relative phase of data and crosstalk are introduced. Several important properties of the noise are summarized. The degradation due to the noise is quantified, experimentally and theoretically, for a single interferer (Section III) and multiple interferers (Section IV). Solution paths are explored (Section V) and conclusions are drawn.

II. INTERFEROMETRIC NOISE

The optical field of a DBF laser may be represented as

$$E(t) = E_0 \exp(j(\omega_0 t + \phi(t)))$$

where $\omega_0$ is the optical frequency and $\phi(t)$ is the phase noise, a random time varying component resulting from spontaneous emission events [25]. Considering the addition of CW data and crosstalk, the interferometric noise may be classified as follows (Fig. 1).

a) Data and crosstalk arise from the same laser source of coherence time $\tau_c$ and suffer a differential delay between source and detector of $\tau$.

$$\text{relative phase} = \omega_0 \tau + \phi(t) - \phi(t - \tau) = \omega_0 \tau + \Phi(t, \tau).$$

Coherent Crosstalk—$\tau$ is much smaller than $\tau_c$, resulting in an interference very close to the coherent limit ($\tau = 0$), characterized by an absence of laser phase noise (variance of $\Phi(t, \tau) \ll 2\pi$) [25], [26]. However, significant interferometric noise may arise from slow fluctuations in $\tau$ induced by temperature fluctuations and phonon excitations in optical fiber [27]—environmental phase noise. If $\tau$ is constant, the interferometric term in (3) is static and may be determined.

Incoherent Beat Noise Crosstalk (also called phase-induced intensity noise, PIIN)—$\tau$ is much greater than $\tau_c$, resulting in an interference at the so-called ‘incoherent limit,’ such that the variance of $\Phi(t, \tau) \gg 2\pi$ [25], [26].

Here the interferometric noise is driven by the laser phase noise which masks any influence of the (lower bandwidth) environmental phase noise.

Partially Coherent Crosstalk—this class falls between the two extremes of coherent and incoherent beat noise crosstalk.

Although a theory exists which simultaneously treats coherent, partially coherent and incoherent crosstalk [28], in experimentation employing directly modulated DBF lasers, partial coherence was not realized; this noise is not addressed further in this paper.

b) Data and crosstalk arise from distinct laser sources, giving

$$\text{relative phase} = \{(\omega_d - \omega_x)t + \phi_d(t) - \phi_x(t)\}.$$  

Incoherent Noise-Free Crosstalk—if the beat frequency of the two lasers, $(\omega_d - \omega_x)/2\pi$, exceeds the receiver bandwidth, $B$, then the interferometric noise is removed by electronic filtering following detection, and only additive crosstalk components remain.

Incoherent Beat Noise Crosstalk—if the beat frequency of the two lasers, $(\omega_d - \omega_x)/2\pi$, is smaller than the receiver bandwidth then the cyclic variation in phase due to $(\omega_d - \omega_x)t$, and the random variation due to the phase noise elements, generate interferometric noise. This is also called incoherent beat noise crosstalk because the mixing is incoherent.

The statistics of the interferometric noise, in particular the probability density function (pdf), are crucial in the determination of the BER. For a single interferer, in the coherent and incoherent limits, the pdf of the interferometric noise (iN) has a “two-pronged” shape (Fig. 2, [29])

$$p(i_N) = \frac{1}{\pi \sqrt{4R^2P_dP_x - i_N^2}}$$

where $R$ is the photodiode responsivity.

In the presence of RF filtering or multiple interferers the pdf becomes smoother and approaches a Gaussian dependency [29].
System performance is also dependent upon the (electrical) signal-to-interferometric noise power (SINR). For an idealised infinite bandwidth receiver

\[ \text{SINR} = \frac{1}{2P_x/P_d} = \frac{1}{2 \text{crosstalk level}(\xi)} \]  

Since the SINR is dependent upon the ratio of crosstalk and data powers (the crosstalk level), not on the data power (unlike the signal-to-thermal-noise ratio, STNR), the interferometric noise may dominate over the receiver thermal noise, giving a BER that may not be improved by increasing the incident optical power on the receiver—this is a BER floor. In practical scenarios, if the noise power spectrum extends beyond the receiver bandwidth the noise is filtered and its power falls. The noise spectrum may be determined by a convolution of the optical power spectra of the interfering waveforms [30]. Incoherent beat noise crosstalk derived from a single source is bursty [2] and baseband: no filtering is likely for externally modulated DFB lasers, while directly modulated DFB lasers, spectrally broadened by chirp, suffer less noise and give better performance [2], [12]. When there are two sources, the noise is centered at the beat frequency and is rejected unless the sources are very closely aligned in wavelength (e.g., @1.55 \mu m a beat frequency of less than 1 GHz requires wavelengths differing by less than 0.02 nm).

III. SINGLE CROSSTALK INTERFERER

The study of a single interferer is of more than academic interest; great insight into the nature and characteristics of interferometric noise may be gained without the added complexity of multiple beat components; simple experiments may be readily compared with theory.

Calculation of the mean BER for a balanced binary ASK transmission was made by integration of the detected photocurrent pdf between the limits of the decision threshold and \( \pm \infty \), for “zeros” and “ones,” respectively. The pdf of the interferometric noise is assumed to be either the theoretical bounded form (5), or to be Gaussian. The latter is only applicable to the single interferer problem (with suitable scaling of the crosstalk level) when the interferometric noise is strongly filtered at the receiver. However, the treatment offers an introduction to the later description of multiple interferers and serves to illustrate the importance of noise statistics in BER calculation. The Gaussian pdf of the thermal receiver noise is convolved with that of the interferometric noise to give the pdf of the net photocurrent noise.

It is assumed that the data and crosstalk bits are aligned and have equal polarizations (worst-case), there is no noise filtering, and the laser is biased precisely at threshold. Consideration of the four possible bit classes (data “one”-crosstalk “one,” data “one”-crosstalk “zero,” etc.) gives [31]

\[
\text{BER} = \frac{1}{4} \left( F(D) + \frac{1}{2} \text{erfc} \left( \frac{\sqrt{\text{STNR}(1-D)}}{\sqrt{2}} \right) \right) + \frac{1}{2} \text{erfc} \left( \frac{\sqrt{\text{STNR}(D-\xi)}}{\sqrt{2}} \right)
\]

where STNR is the (electrical) signal-to-thermal noise ratio, \( D \) is the decision threshold normalized to the data “one” photocurrent (0 < \( D < 1 \)), and \( \xi \) is the crosstalk level.

If the interferometric noise is taken to be Gaussian, calculation gives

\[
\text{BER} = \frac{1}{8} \left( \text{erfc} \left( \frac{1 + \xi - D}{\sqrt{4 \xi} + 2/\text{STNR}} \right) + \text{erfc} \left( \frac{\sqrt{\text{STNR}(1-D)}}{\sqrt{2}} \right) + \frac{1}{2} \text{erfc} \left( \frac{\sqrt{\text{STNR}(D-\xi)}}{\sqrt{2}} \right) + \frac{1}{2} \text{erfc} \left( \frac{\sqrt{\text{STNR}D}}{\sqrt{2}} \right) \right)
\]

Predictions from (7) and (8), for bounded and Gaussian statistics, are plotted in Fig. 3(a) and (b), respectively, for \( D = 0.5 \) (this represents an ac-coupled receiver with threshold set at 0). The Gaussian distributed noise pdf has a broad “skirt,” extending to \( \pm \infty \), giving a greater BER and a finite BER in the absence of thermal noise, i.e., there is always an error floor. In contrast, error floors arise with the bounded pdf for \( \xi > -10.6 \text{ dB} \) when the lower bound of the noise on the ‘one’ bits extends below the threshold.

The dependence of the optical power penalty at BER = 10\(^{-9}\) on the crosstalk level is depicted in Fig. 4. All interferometric noise curves demonstrate an asymptote where the power penalty goes rapidly to infinity, corresponding to the existence of an error floor at BER = 10\(^{-9}\). If the crosstalk is increased beyond the asymptotic value, the data may still be recovered but with a BER exceeding 10\(^{-9}\). The models employing the Gaussian approximation predict a greater penalty than the bounded approach. Threshold optimization gives a 5 dB better tolerance to crosstalk than the ac-coupled receiver (\( D = 0.5 \)). Surprisingly, the apparently simplistic eye-closure method (\( \Delta P = -10 \log (1 - 2/\xi) \)) closely follows the calculation assuming a bounded pdf and optimized threshold. In contrast, the curves for incoherent noise-free crosstalk demonstrate little performance degradation.

The experimental points were obtained from a test-bed comprising a directly modulated DFB laser @622 MHz feeding a fiber Mach-Zehnder interferometer with a 16 b differential path—this is sufficiently long to generate incoherent beat noise crosstalk. \( D \) was optimized. It was observed that some bits lacked the expected interferometric noise due to RF rejection. This has been shown to result from a pattern dependence in the center optical frequencies of the bits caused by intrabit frequency evolution in response to the carrier
Fig. 3. Theoretical BER curves for a single interferer calculated for (a) bounded and (b) Gaussian interferometric noise probability density functions (ac-coupled receiver).

Injection [32], [33]. However, this has negligible influence on the power penalty, for a single interferer [33], and discrepancies between theory and experiment are attributed to noise filtering from spectral broadening; the asymptote demonstrates the consequent deviation of the noise from a bounded form.

If the "zero" bits carry optical power, the BER in the absence of crosstalk is greater than the ideal case considered previously; given the same mean power the eye opening is smaller. Adding crosstalk now gives interferometric noise on all bits, the penalty is large, increasing as a greater share of the mean power is carried by the "zeros," Fig. 5. The experimental results were taken using an externally modulated DFB feeding a fiber Mach–Zehnder with a 10 km differential path to establish the incoherent limit. The modulation depth was limited to approximately 10:1 but deteriorated due to drift. In contrast to direct modulation all bits corrupted by noise were very similar showing the expected two-pronged bounded probability density function. The penalties are far greater than for the direct modulation case (Fig. 4) and are attributed to the nonideal modulation depth.

In conclusion, with an ac-coupled receiver, a single interferer of crosstalk level $<-22$ dB gives a penalty $<1$ dB assuming an infinite modulation depth. This crosstalk tolerance
are generated by chirp-free external modulation. The data signal has optical frequency \( \omega_d \), phase noise \( \phi_d(t) \) and instantaneous optical power \( P_d(t) \). The \( N \) crosstalk terms have optical frequency \( \omega_i \), phase noise \( \phi_i(t) \), instantaneous optical power \( P_i(t) \), and network transit delay relative to that of the data \( \tau_i \), where \( i = 1, \cdots, N \).

The total optical electric field is

\[
E(t) \propto \sqrt{P_d(t)} \exp\left( j(\omega_d t + \phi_d(t)) \right) + \sum_{i=1}^{N} \sqrt{P_i(t)} \exp\left( j(\omega_i(t - \tau_i) + \phi_i(t - \tau_i)) \right)
\]

(9)

The photocurrent on detection (responsivity = \( \Re \)) is shown in (10) at the bottom of the page. Note that the secondary crosstalk-crosstalk beat terms are smaller by \( O(\sqrt{\xi}) \) than the primary beating terms (\( \xi \) is the crosstalk level). If all crosstalk terms are of level \( \xi \) and all beating terms are in-band, the ratio of the variances of primary and secondary beat noise is \( 2/(N\xi) \). Since, as will be shown below, considering the primary terms alone, \( N\xi < 3 \times 10^{-3} \) for satisfactory performance, the secondary terms may be neglected in this case. However, secondary terms may be significant if there is greater RF filtering of the primary terms than the secondary. For example, if all the crosstalk terms arise from a single source at a different wavelength from that of the data, all primary terms, but no the secondary terms, will be RF rejected.

Beating terms that generate interferometric noise within the receiver bandwidth may be identified from the classification above, but further (tractable) analysis requires such terms to be statistically independent. Coherent crosstalk terms that traverse different optical fiber paths will experience statistically independent environmental phase fluctuations. In contrast, coherent crosstalk terms generated via multipaths in an integrated optical space switch do not suffer environmental phase noise, their phases relative to the data are time invariant albeit different. Incoherent beat noise crosstalk is statistically independent of coherent crosstalk but two such terms may be dependent on each other—two crosstalk elements derived from the same laser as the data and suffering the same transit delay as each other generate dependent primary beating components with the data. Partially coherent crosstalk is not permitted.

\[
i/R = P_d(t) + \sum_{i=1}^{N} P_i(t) + \sqrt{P_d(t)} \left\{ 2 \sum_{i=1}^{N} \sqrt{P_i(t)} \cos((\omega_i - \omega_d)t - \omega_i \tau_i + \phi_i(t - \tau_i) - \phi_d(t)) \right\}
\]

\[
+ \left\{ 2 \sum_{j=i+1}^{N} \sum_{i=1}^{N-1} \sqrt{P_i(t)P_j(t)} \cos((\omega_i - \omega_j)t - \omega_i \tau_i + \omega_j \tau_j + \phi_i(t - \tau_i) - \phi_j(t - \tau_j)) \right\}
\]

\[
N(N - 1)/2 \text{ secondary crosstalk—crosstalk beating terms}
\]

Fig. 4. Optical power penalty due to a single crosstalk interferer assuming infinite modulation depth and no noise filtering (incoherent noise-free crosstalk excepted).

Fig. 5. Power penalty versus crosstalk level for different values of the reciprocal modulation depth, alpha. The experimental points are for an externally modulated laser with imperfect extinction ratio.
Assuming statistical independence, the (electrical) signal-to-interferometric noise ratio (SINR) may be determined

\[
\text{SINR} = \frac{P_d^2}{2P_d \sum P_i + \sum P_i P_j}.
\]

(11)

The BER calculation, in addition, requires knowledge of the pdf of the noise. Here the central limit theorem, applicable to independent noise components and widely quoted in the literature [2], [3], [5], [20], is invoked to give a Gaussian pdf. It is assumed that there are \( N_b \) crosstalk terms, each of crosstalk level \( \xi \). Several worst-case conditions are also made: the \( N_b \) terms and the data have the same polarization, generate unfiltered interferometric noise, and have aligned bit-boundaries; furthermore, the decision threshold \( D = 0.5 \). However, the modulation depth is infinite (best-case); secondary crosstalk-crosstalk beating is neglected. The probability that \( m \) of the \( N_b \) number of crosstalk terms are simultaneously "ones" is given by the binomial distribution

\[
\begin{align*}
    p(m) &= \frac{N_b^m}{(N_b - m)! m! 2^{N_b}}.
\end{align*}
\]

(12)

this permits mean BER calculation by a statistically weighted average of the error probability for each value of \( m \).

The calculated BER curves show a similar behavior to the single interferer with Gaussian interferometric noise [cf. Fig. 4(b)]. The optical power penalty at BER = 10\(^{-9}\) is plotted in Fig. 6. The curve for a single crosstalk term (this is identical to the \( D = 0.5 \) curve of Fig. 4) in addition represents the worst-case for multiple interferers when all crosstalk bit sequences are identical. The system may tolerate more total crosstalk when the crosstalk is distributed over more terms; however, a limit is approached as the binomial distribution becomes narrower, and ultimately single-valued at \( m = N_b/2 \). Hence, the \( N_b = \infty \) curve is 3 dB displaced from the worst-case curve. In conclusion, the performance of a network may be estimated from the total crosstalk level of noise generating terms: for a penalty of \( < 1 \) dB the total crosstalk level must be held below \( -25 \) dB; a further 2 to 4 dB of total crosstalk may lead to network failure at the asymptote (error floor at BER = 10\(^{-9}\)).

A second, rigorous, approach determines the interferometric noise pdf by convolving the bounded "two-pronged" pdf's (5) of all in-band terms. Computation indicates that the Gaussian approximation gives an upper-bound on the BER but agreement is good when there are 10 or more in-band terms. Agreement improves with more terms (as anticipated from the central limit theorem).

Multiple crosstalk terms may be generated via a fiber coupler and a recirculating delay line (Fig. 7). The principle of operation is as follows: a repeating 64 b word sequence is fed to a 10:90 fiber coupler with a feedback loop delay equal to the word length. The first word enters the coupler and 90% of the signal is routed to the photodetector. Additionally, 10% of the signal is routed back to the coupler input and on subsequent passage through the coupler 10% of this feedback waveform is added (as crosstalk) to the second data word. The second word also sheds light into the loop but the majority reaches the detector together with the single added crosstalk term.

Light shed into the loop continues to circulate, its power falls due to splitting and propagation losses giving crosstalk addition of ever decreasing amounts to successive data words. Thus, for example, word number three suffers from two crosstalk terms, one due to light shed from word one (after two circulations) and one due to light shed from word two (after one circulation). The total crosstalk power saturates at a level of \( -14.7 \) dB contributed by approximately four or five significant terms.

The loop delay greatly exceeds the coherence time of the directly modulated DFB implying that all crosstalk terms are independent and constitute incoherent beat noise crosstalk. Interferometric noise is maximized by alignment of data and crosstalk polarizations. The lithium niobate modulator was gated every 16 words to permit the study of the development of interferometric noise. Fig. 8 shows the oscilloscope traces for the first four words while Fig. 9 shows the change in the noise pdf from the bounded form (one crosstalk term) toward the Gaussian form (fifteen crosstalk terms).

The BER characteristic (Fig. 10) gives a power penalty at BER = 10\(^{-9}\), corrected for the contribution of the crosstalk to
the mean optical power, of 2.8 dB. This value lies below that expected for Gaussian distributed noise of crosstalk = \(-14.7\) dB (error floor above \(10^{-9}\)), but is much higher than that of a single interferer (1.7 dB). The number of significant crosstalk terms is not sufficient to satisfy the Central Limit Theorem.

Performance degradation of optical TDM (OTDM) switching networks, constructed from \(-15\) dB isolated \(2 \times 2\) di-
rectional couplers and fiber delay lines, has been reported in detail elsewhere [24]. Time-slot interchangers requiring three crosspoints, \( T(1, 4) \) and \( T(1, 2) \), suffered worst-case penalties of approximately 1.0 and 1.75 dB respectively. A four crosspoint \( T(2, 2) \) network whose two inputs were fed by the same laser suffered from too much noise to permit BER measurement. The number of crosstalk terms is not sufficient to permit comparison with the theoretical predictions above.

V. SOLUTION PATHS

A bilateral strategy is proposed to combat crosstalk and interferometric noise comprising, first, minimization of the crosstalk optical power and, second, suppression of the interferometric noise owing to the remaining crosstalk.

Effective means of optical crosstalk power reduction in a network are summarized in Table II.

A switch architecture is dilated by adding \( 2 \times 2 \) crosspoints (the total crosspoint count is approximately doubled) to ensure that only one input of a crosspoint is ever "live," i.e., carrying a data signal, at any time. Crosstalk addition is thereby at most second order in the isolation of the crosspoint (undilated networks suffer first-order crosstalk). In the time compression technique [36], blocks of TDM data (i.e., many \( (p) \) successive bits from the same communication channel) are compressed in time at the network input, and suitably delayed to occupy a chosen subchannel within the original block period (Fig. 11). The compressed block is then transmitted through the network and crosstalk from other channels is added. However, crosstalk from channels that were time-compressed into different, nonoverlapping (termed "orthogonal") subchannels does
not induce degradation and is eliminated by the time decompression circuitry that reestablishes an uncompressed block at the network output. This scheme suffers from hardware complexity and pulse dispersion. The sparse coding method reduces the likelihood of data and crosstalk bits being simultaneously high [37]. The raw data is sampled via a time and is then transmitted as a symbol containing only a single high symbol. For example, in the precoding scheme for \( m = 2 \), 00 is transmitted as 0001, 01 as 0010, etc. The redundancy is equal to \( 2^m/m \). Given a single interferer the probability of a symbol being a “one” with noise (i.e., the crosstalk symbol is also a “one”) is reduced from 1/4 (no precoding) to 1/16. For many crosstalk terms the mean number of units of interferometric noise afflicting the “one” symbol in the transmitted word is inversely proportional to the redundancy. However, performance may not be improved indefinitely by increasing \( m \) since a point is reached where the interferometric noise reduction is offset by the increase in thermal noise within the necessarily broader receiver bandwidth. The method requires additional hardware at transmitter and receiver, operating at the symbol rate, and may give rise to additional dispersion penalties.

The magnitude of the interferometric noise that corrupts the detected data bit-sequence may be minimized by control of the polarization of the incident data and crosstalk waveforms, by minimization of the phase noise difference, and by RF rejection (Table III).

Methods that exploit the polarization dependence of the interference are only applicable to networks comprising polarization independent components; many integrated-optical switching technologies, for example, are polarization sensitive. The state of polarization of each laser may be scrambled by a lithium niobate integrated-optical device placed external to the source [38]. On the interference of crosstalk and data from two such scrambled sources, the scalar product of their polarizations, and the interferometric noise magnitude, will vary at a rate determined by the modulation rate of the scrambler. If lumped element electrodes are employed on the scrambler this is limited to about 1 MHz but may be extended to as great as 10 GHz by a coplanar travelling-wave electrode geometry [38]. The slow-speed scrambler is easy to drive and will give an effective crosstalk improvement of 3 dB in the above example with two sources.

If data and crosstalk arise from the same source, the modulation period must be smaller than the multipath differential delay. Slow scramblers are therefore suitable for managing interferometric noise due to reflections in long haul links but not for an OTDM crossconnect, for example. High-speed scramblers are suitable for small differential delays and, in addition, may be driven at rates exceeding the data bandwidth, thereby eliminating all interferometric noise by RF filtering. The drive signal must ensure that the polarization scalar product varies more rapidly that the transmission rate. Although expensive, and requiring large drive powers (~2 W), high-speed scramblers also combat polarization-dependent gain due to polarization hole burning in fiber amplified links [38]. The phase is also modulated although no dispersion penalty is found in practice [38].

The phase noise variation of phase-induced intensity noise (PIIN) may be reduced by selecting a source whose coherence

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**Table II**

**Means of reducing optical crosstalk power**

<table>
<thead>
<tr>
<th>Crosstalk source</th>
<th>Method to reduce crosstalk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space switch</td>
<td>ög idiosyncratic with better isolation</td>
</tr>
<tr>
<td>WDM MUX/DMUX filter</td>
<td>lower crosstalk components</td>
</tr>
<tr>
<td>Discrete reflections</td>
<td>low reflectivity elements (super PC connectors, angled or anti-reflection coated solid state devices)</td>
</tr>
<tr>
<td>Rayleigh backscatter</td>
<td>minimise fibre lengths (to less than half attenuation length)</td>
</tr>
<tr>
<td>Non-specific</td>
<td>time compression of TDM blocks</td>
</tr>
<tr>
<td></td>
<td>sparse coding</td>
</tr>
</tbody>
</table>

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**Fig. 10.** BER characterization of the recirculating loop experiment.

**Fig. 11.** Crosstalk elimination by the time compression method. Crosstalk is added, in this example, by an OTDM crossconnect; the method is applicable to other crosstalk sources too.


<table>
<thead>
<tr>
<th>Method</th>
<th>Noise suppression mechanism</th>
<th>Comments</th>
<th>RF effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>polarization scrambling</td>
<td>dependence, ( P_1, P_2 )</td>
<td>noise power reduced by NDF</td>
<td>[19]</td>
</tr>
<tr>
<td>rapid random polarization modulation</td>
<td>0-1 bit</td>
<td>modulated independent components</td>
<td>[19]</td>
</tr>
<tr>
<td>LED</td>
<td>noise RF filtered (scatter)</td>
<td>only suitable for short links</td>
<td>[40]</td>
</tr>
<tr>
<td>Fabry-Pérot and self-painting fiber (multi-</td>
<td>noise RF filtered (scatter)</td>
<td>only suitable for short links</td>
<td>[41-43]</td>
</tr>
<tr>
<td>mode)</td>
<td>dispersion difficulties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase modulation</td>
<td>noise RF filtered (scatter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity frequency manipulation</td>
<td>noise RF filtered (scatter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct modulation of DFB</td>
<td>normally-induced tone-bite frequency multiplication, noise RF filtered (multi-pulse)</td>
<td>no additional hardware, currently ineffective at Gbit rates</td>
<td>[12]</td>
</tr>
<tr>
<td>Employ multiple waveguides</td>
<td>optically filtered or noise RF filtered (multi-pulse)</td>
<td>no additional hardware, currently ineffective at Gbit rates</td>
<td>[36]</td>
</tr>
<tr>
<td>Employing a single waveguide</td>
<td>noise RF filtered (multi-pulse)</td>
<td>no additional hardware, currently ineffective at Gbit rates</td>
<td>[36]</td>
</tr>
<tr>
<td>Subcarrier combiner</td>
<td>noise RF filtered (multi-pulse)</td>
<td>no additional hardware, currently ineffective at Gbit rates</td>
<td>[36]</td>
</tr>
</tbody>
</table>

The table shows various methods for suppressing interferometric noise in optical networks, focusing on noise suppression mechanisms, RF effects, and applications.

Time is larger than the delays incurred by multipath crosstalk waveforms. The crosstalk becomes partially coherent. In typical optical networks, spanning many kms, sources developed for coherent communication, for example, the external cavity semiconductor laser, and low-chirp external modulation would be required. However, even if all laser phase noise is eliminated there remains coherent crosstalk, potentially problematic with or without environmental phase noise. In the baseband ASK modulation considered here, the coherent crosstalk falls in-band and is problematic; however, in subcarrier networks this is not necessarily the case and improvements are possible with higher coherent sources [39].

Techniques that exploit RF filtering of the noise at the coherent limit truly eliminate all interferometric noise, and are therefore preferred to the above coherent limit approach. Several methods engineer a modulated optical spectrum that is either broad or translated from baseband thereby suppressing the noise, albeit at the expense of increased dispersion. Low coherence sources [40]-[44] generate broad spectra and suffer less from interferometric noise than single frequency lasers (e.g., DFB). Phase modulation is a proven suppression technique [45]-[48] but requires additional hardware, comprising, in the simplest realization, a high-frequency single-tone laser driver.

The exploitation of the thermally induced intraband frequency evolution in directly modulated lasers requires no additional hardware and adds no dispersion penalty [32]. However, the suitability for high-speed (Gbit) transmission is limited by the small frequency change over a bit duration. This promising technique is a subject of on-going research with a multi-interferer test-bed.

Interference between NRZ waveforms, of bit-rate B bit/s separated by at least 2B Hz in optical frequency, may be eliminated by either optical filtering of the crosstalk, or by baseband RF filtering of the interferometric noise at the receiver. This suggests a technique for noise reduction whereby different optical channels are transmitted at different "orthogonal" wavelengths. For example, in an OTDM crossconnect [24] every input may be fed by a different laser; alternatively, wavelength converters may be placed at each input to tune the wavelength as appropriate [36]. The method is compatible with the time compression described above, and offers a 'bolt-on' upgrade strategy to combat ageing of the crossconnect components. In the MWTN crossconnect [21], wavelength converters could be located at the inputs (and outputs—to restore the correct wavelength) to the space switches. Note (as for time compression) coherent crosstalk is not suppressed.

In a similar strategy, with channels transmitted at a single wavelength but with different subcarriers located within a nonbaseband octave of frequency, for example, 2 to 4 GHz, interferometric noise generated between any two signals (including signals from the same channel) falls into the 0 to 2 GHz region of the RF spectrum and thus causes no degradation.

Finally, other approaches may be considered, including spread spectrum transmission [54], [55] and conventional error correction (hindered by the bursty nature of the noise). Modulation depth must also be maximized.

VI. CONCLUSION

Interferometric noise limits the performance of optical networks suffering a total noise-generating crosstalk level exceeding approximately -25 dB. Greater crosstalk may be tolerated by engineering interferometric noise suppression by RF rejection at the receiver.

REFERENCES

Peter J. Legg was born in Newcastle upon-Tyne, U.K., in 1966. He received the M.A. degree in physics from the University of Cambridge and the Ph.D. degree in electronic and electrical engineering from the University of Strathclyde in 1988 and 1995, respectively. From 1988 to 1991, he worked on the development of integrated optical components in lithium niobates and planar silicon technologies, for fiber-optic communication applications, at BT Laboratories and Alcatel FACE, respectively. In working towards the Ph.D. degree, he has addressed the nature of interferometric noise in optical communication networks, characterizing the performance degradation and identifying viable solution paths. In 1994, he was invited to attend Rank mini-Symposium on All-Optical Networks.

Dr. Legg is a member of the Optical Society of America (OSA) and an Associate Member of the IEE (U.K.).
Moshe Tur (M'87–SM'94) was born in Tel-Aviv, Israel, in 1948. He received the B.Sc. degree in mathematics and physics, from the Hebrew University, Jerusalem, Israel, in 1969, and the M.Sc. degree in applied physics from the Weizmann Institute of Science, Rehovot, Israel, in 1972, where he investigated electromagnetic wave propagation in cholesteric liquid crystals. He received the Ph.D. degree from the Faculty of Engineering of Tel-Aviv University, Tel-Aviv, Israel, in 1981.

He spent five years in the Israeli Defense Forces and later was with the Faculty of Engineering of Tel-Aviv University, where his research involved analytical, numerical, and experimental investigations of wave propagation through random media, as well as fiber optic communication systems. During the academic years 1981–1983, he was a Postdoctoral Fellow (1981–1982) and then a Research Associate (1982–1983) at the Information System Laboratory and the Edward L. Ginzton Laboratory of Stanford University, Stanford, CA. At the Information System Laboratory, he studied speckle phenomena, various theories of wave propagation in random media, and asymptotic solutions of the fourth-moment equation. At the Ginzton Laboratory, he participated in the development of new architectures for single-mode fiber optic signal processing and investigated the effect of laser phase noise on such processors. He is presently a Professor of Electrical Engineering in the Faculty of Engineering at Tel-Aviv University, Tel-Aviv, Israel, where he established a fiber-optic sensing laboratory. He has authored or coauthored more than 100 journal and conference technical papers with recent emphasis on fiber-optic bit rate limiters, fiber lasers, fiber-optic sensor arrays, the statistics of phase-induced intensity noise in fiber-optic systems, and fiber sensing in smart structures.

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Ivan Andonovic (M'79) received the B.Sc. degree with honors in electrical and electronic engineering from the University of Strathclyde in 1978. He also received the doctorate in optical waveguide modulator devices on LiNbO3 in collaboration with nearby Glasgow University.

Following a three-year period as a Research Scientist responsible for the design, manufacture, and test of guided-wave devices for a variety of applications, he joined the Electronic and Electrical Engineering Department at Strathclyde University in 1985. His main interests center on the development of guided-wave architectures for implementing optical signal processing and switching functions for optical networks. He has recently returned from a two-year Royal Society Industrial Fellowship in collaboration with BT Laboratories during which time he was investigating novel approaches to networking. He has edited two books and authored/coauthored four chapters in books and over 90 journal and conference papers.

Dr. Andonovic has been Chairman of the IEE Professional Group E13, has held a BT Short Term Fellowship, and is Editor of the International Journal of Optoelectronics. He is a member of the IEE and the Optical Society of America (OSA).