METHOD FOR INCLUDING CTBR, CSO, AND CHANNEL ADDITION COEFFICIENT IN MULTICHANNEL AM FIBER OPTIC SYSTEM MODELS

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ABSTRACT

A model of multichannel fiber optic AM CATV links is presented. The analysis yields the worst case Carrier-to-Noise Ratios (CNRs) as a function of average received optical power for desired Composite Triple-Beat Ratios (CTBR) and Composite Second Order (CSO) ratios. A method for determining the required Optical Modulation Index (OMI) per channel for desired CTBRs and CSOs, and number of transmitted channels is included.

The overall OMI is related to the per-channel OMI for given numbers of channels.

INTRODUCTION

Publications to date on multichannel AM fiber optic system models have concentrated on yielding the CNRs as a function of average received optical power without explicitly including OMI related distortion or the appropriate channel power addition coefficients [1, 2, 3]. In this paper, we propose a model in which the laser diode OMI is specifically related to the desired CSO and CTBR.

The per-channel OMI, (OMI/ch), to distortion relationship is derived from two figures of merit for laser diodes. The new parameters are the Optical Second Order Intercept Point (OIP2) and Optical Third Order Intercept Point (OIP3). Similar to radio frequency (RF) amplifier intercept points [4], multichannel composite distortions for a given channel input power at a specific average launched optical power, may be estimated using the simple two-tone measurement method of characterizing the laser diode optical output distortion. The relationship between the two-tone measurements and desired CTBRs and CSOs for given numbers of channels is presented.

Using OIP2 and OIP3, OMI/ch can be determined. Then, the CNR as a function of average received optical powers can be computed by using the receiver noise, shot noise, photodetector responsivity, and channel bandwidth for desired CTBRs and CSOs. The overall (total) statistical OMI, OMIt, can be calculated to confirm that the quasi-linear assumptions of this model are not violated. Comparisons of the projected performance through the use of the model to experimental results at four different channel loadings are included. The comparison showed excellent correlation.

For multichannel AM CATV systems OMIt is related to OMI/ch by [1]

$$\mathrm{OMI/ch} = \mathrm{OMIt}/N^{\zeta}, \qquad (1)$$

where N is the number of channels and ζ is the multichannel addition coefficient used to combine the multiple carriers. A simple graph and chart is presented which allows AM CATV fiber optic designers to find the appropriate ζ factor.

MODEL

There are several steps included in the model. They are:

1. Determine the number and type of distortion products falling into the frequency band of interest. Determine "penalty" numbers.

2. Determine the fiber optic receiver noise sources. The required parameters are: amplifier noise figure in dB (Ft), effective receiver load impedance in (R_L), photodiode dark current in amperes (Id), operating temperature in Kelvins (T), and photodetector responsivity in amperes/watt (η).

3. Using the two-tone test, determine the third order intermodulation distortion IMD3 and second order intermodulation distortion IMD2 of the laser diode at the desired average launched optical power.

Using data from the first three steps, the projected performance can be calculated.

Distortion Products

The determination of the number of intermodulation distortion products falling into the channels of interest is a critical step in the model. All calculations are performed with unmodulated channels, consistent with the measurement procedure used when MATRIX type systems are utilized.

To see the effect of a multichannel load, it is instructive to consider an input of three sinusoids of frequencies , and α,β and γ because the form of all modulation products can be found from a three-frequency input. If we assume a quasi-linear transfer function, the output eout is a function of the input ein,

$$\mathrm{eout} = a_1\mathrm{ein} + a_2\mathrm{ein}^2 + a_3\mathrm{ein}^3 \qquad (2)$$

where ein is made up of the three sinusoids. The resulting eout is presented in Table 1 for the three frequencies at three phases [5]. The output then contains modulation products at all possible sums and differences of all multiples of the input frequencies, up to order three. The products of interest are;

$$\begin{aligned}&\alpha - \beta,\\ &\alpha + \beta,\\ &\alpha - 2\beta,\\ &2\alpha - \beta,\\ &2\alpha + \beta,\\ &\alpha - \beta - \gamma,\\ &\alpha + \beta - \gamma,\\ &\text{and } \alpha + \beta + \gamma.\end{aligned} \qquad (3)$$

CSO is primarily caused by the second order sum beats [6]. The reason being that the permissible limits for interfering signals in relation to visual carriers indicate that the sum beats (which falls at fc + 1.25 MHz, where fc is a visual carrier frequency), the carrier-to-beat ratio is approximately 52 dB. For the second order difference beats (which falls at fc - 1.25 MHz), the visually limiting carrier-to-beat ratio is approximately 30 dB. Therefore, we calculate the CSO from the sum beats since the difference beats will not have a significant effect on the picture quality.

Although the calculation of the beats is complex, a simple graphical method can be employed using figure 1. The graphs show normalized numbers of products of a given type as a function of normalized channels. The number of products outside the limits of the curves is zero.

In Figure 1,

U =
Total possible products of a given type.

N =
Number of channels transmitted with carriers n_1f to n_2f inclusive, where f is the base frequency in Hz (6 MHz in CATV) and n_1 and n_2 are integers $n_2 > n_1$.

k =
Channel of interest associated with carrier kf_o within the fundamental band $n_1 < k < n_2$.

M =
Channel of interest associated with carrier Mf_o where;
$M = k - n_1 + 1$.

To clarify the above, a 40 channel example is given. For simplicity, we are assuming consecutive channel loading (i.e. no FM radio channels).

f = 6 [MHz]
f_1 = 55.25 [MHz]
f_2 = 289.25 [MHz]

n_1 = integer_truncate (f_1/f_o)
= 9

n_2 = integer_round up (f_2/f_o)
= 49

$N = n_2 - n_1$
= 40

$k = f_1/f_o, f_1/f_o + f_o, \ldots, f_2/f_o$
= 55.25/289.25, 55.25/289.25 + 6, ... , 289.25/6

Therefore, Channel 2 at 55.25 MHz is designated as

M = 55.25/6 - 9 + 1
= 1.208

Referring to figure 1 at M = 1.208 (Channel 2), for the $2\alpha - \beta$ distortion products we see that at M/N (1.208/40) is 0.03. Using the graph, we find that U/N is 0.5. Knowing that the number of channels, N, is 40, U is found to be 20; corresponding to 20 intermodulation distortion of this type falling into Channel 2.

Table 2 provides the maximum number of beats of each kind observed over the total channel capacity of interest. The calculations are for consecutive channels without dead bands. If there is an FM band, the beats are worse than experimentally observed for low channel counts (up to about 20) and approximately correct for 30 channels and up.

The intermodulation "penalties" are correction factors to desired CTBRs or CSOs used to determine OMI/ch after finding the laser diode OIP3 and OIP2. They are dependent only on the channel loading and products found from calculations using figure 1. The second order penalty correction factor uses the number of sum beats,

$$P2 = 10\log[U(\alpha + \beta)]. \qquad (4)$$

The third order penalties are more complex. The penalties must be made in terms of the triple beat components. From Table 1, we observe that the triple beat products are twice the amplitude of the other non-harmonic third order intermodulation distortion. Knowing that the triple beats are twice the amplitude of the other third order intermodulation products, the penalty P3 is,

$$P3 = 10\log\{1^2[U(2\alpha + \beta) + U(\alpha - 2\beta)] + 2^2U(\alpha + \beta + \alpha)\}. \qquad (5)$$

<u>Laser Two-Tone Test</u>

The distortion characteristics of the optical source must then be quantified. The laser diode of interest is tested with the two-tone method at the desired average launched optical power. The measurement set-up is shown in figure 2. Each tone is set at 0.4 OMI/ch, where Pmod is the optical modulation of each carrier, Pav is the average optical power, and

$$OMI/ch = Pmod/Pav. \qquad (6)$$

The measurement is made over the entire frequency range of interest. A typical laser diode two-tone measurement result at 2.73 dBm optical is shown in Table 3.

The second order (a) and third order distortion (b) ratios, in dB, measured from the two-tone test are used to determine OIP2 and OIP3. Since the laser diode at total modulation indices less than 0.8 follow approximately (less than 10% deviation) the polynomial rule for quasi-linear systems, RF intercept point concepts can be used. The intercept points are,

$$OIP2 = rms(OMI/ch) + a,$$

$$\text{and } OIP3 = rms(OMI/ch) + b/2. \qquad (7)$$

The relationship between CTBR and CSO to OIP2 and OIP3 for given channel loading are defined as,

$$CTBR = b - P3, \qquad (8)$$

$$\text{and } CSO = a - P2.$$

Using equations 7 and 8, the required OMI/ch for given numbers of channels can be calculated for desired CTBRs and CSOs. The expressions are,

$$\mathrm{rms(OMI/ch)} = \mathrm{OIP2} - (\mathrm{CSO} + \mathrm{P2}), \qquad (9)$$

$$\text{and } \mathrm{rms(OMI/ch)} = \mathrm{OIP3} - (\mathrm{CTBR} + \mathrm{P3})/2.$$

As an example, for the characteristics of the Distributed Feedback (DFB) laser diode, with integrated optical isolator shown in Table 3, with 40 consecutive channel loading,

OIP2 = 39 dBm,

OIP3 = 19 dBm.

From table 1 the penalties for CSO = 60 dB and CTBR = 65 dB found by computing the number and types of distortion products, using equations 4 and 5 are;

P2 = 10 dB,

P3 = 33.9 dB.

The peak OMI/ch can then be calculated from equation 9,

OMI/CH = 0.04.

Channel Addition Coefficient

Knowing the OMI/ch, it is sometimes useful to determine the overall OMI (OMIt) to make certain that we do not exceed 100% modulation. If we approach 100% OMIt, the quasi-linear assumptions do not hold.

The relationship of OMI/ch and OMIt is dependent on the number of channels and the channel addition coefficient ζ. ζ can be determined either experimentally or through statistical analysis. We chose to experimentally determine ζ.

The measurements indicated that, as expected, for low channel counts (e.g. 2), ζ is 1. For large channel counts, ζ approaches 0.5. The later condition is approached as a result of the averaging effect produced by a large number of subcarriers with random phases.

The results are shown in figure 3 and presented in tabular form in Table 4. Using Table 4 (or figure 3) and equation 1, a solution to OMIt can be found. To maintain the integrity of the model, OMIt must be less than 1 (preferably less than 0.9). If OMIt is greater than or equal to 1, the assumption of a quasi-linear system is violated, and the model is invalid. If the computation yields an OMIt of greater than 1, the OMI/ch must be reduced such that OMIt is within the bounds required for the quasi-linear assumption of the model.

Model Development

Many authors have developed equations for analog fiber optic systems to determine CNR. A concise equation for PIN photodetector receiver systems is given by Koscinski [2] in linear CNR:

$$\mathrm{CNR} = 1/2\,\frac{(\mathrm{OMI/CH})^2\,\eta^2 \cdot P_{AV}^2}{[(\mathrm{RIN})\eta^2 \cdot P_{AV}^2 B) + 2q(\eta P_{AV} + I_d)B + (4kTB/R_L)Ft} \qquad (10)$$

$$\text{LET } Ns = \mathrm{RIN}\eta^2 P_{AV}^2 B + 2q(\eta + P_{AV} I_d)B + (4kTB/R_L)Ft$$

where
q = electron charge[C]
k = Boltzmann's Constant [J/K]
B = bandwidth of channel [4 MHz]

RIN = laser relative intensity noise [dB/Hz]
= 148 dB/Hz for the laser diode of Table 2
RL = 470 Ω, I_d = 0.5 nA, η = 0.75 A/W, T = 290K, Ft = 4dB

Substituting the expressions for rms(OMI/ch) we arrive at;

$$\mathrm{CNR\ [dB]} = \mathrm{OIP3} - \frac{(\mathrm{CTBR} + \mathrm{P3})}{2} + 20\log[\eta P_{AV}] - 10\log Ns \qquad (11)$$

for the desired CSO for N channels, and;

$$\mathrm{CNR[dB]} = \mathrm{OIP2} - (\mathrm{CSO} + \mathrm{P2}) + 20\log[\eta P_{AV}] - 10\log Ns \qquad (12)$$

for the desired CTBR for N channels.

The CNR as a function of average received optical power is shown in figure 4a for desired CTBRs and figure 4b for desired CSOs for 40 channel loading. For a CTBR of 65 and CSO of 60, the required OMI/ch is approximately 0.04.

Note that the linearity of the receiver is not included. The receiver in question was tested with the two-laser, two-tone measurement and exhibited acceptably high linearity and wide bandwidth.

COMPARISON TO EXPERIMENTAL DATA

A comparison between the model and experimental data was made with the laser diode and receiver exhibiting the behavior above. The measurements were taken with a MATRIX Multiple Frequency Signal Generator and R-75 Signal Analyzer. The output from the receiver/AGC was set at +30 dBmV +/-1 dB over the channels of interest.

Comparisons were made for four channel loadings: 10, 20, 30, and 40 channels. In the first case, a comparison was made for consecutive channel loading from Channel 14. There were no second order products for the 10 and 20 channel case. The second case was that in which the model was run for consecutive channel loading from channel 2 in 6 MHz increments without a dead band for the FM channels. The experiment, however, did include an unused FM band. The results are shown in Table 5 exhibiting the differences between the model and experimental CNR, CTBR, and CSO. The + in the CTB and CSO columns indicate higher ratios found in experimental results than that of the model.

CNR difference between the model and the experiment agreed to within 2 dB. The CNR difference was equal to the expected CNR calculated by the model for 65 dB CTBR and 60 dB CSO to that of the experimental results. For the most part, the CTBR differences were within 2 dB. Notable exceptions were for the 30 channel consecutive from Channel 14 case. At -2 dBm average received optical power, the CTBR differed by as much as 3.8 dB and CSO by as much as 3.0 even though the CNR results were excellent. Another notable deviation were the CSO differences for the 20 and 30 channel cases for consecutive loading from Channel 2. The large deviations are indicative of beat stacking at the higher frequencies not accounted for in the model beyond the calculated maximum carrier.

CONCLUSIONS

Fiber optic multichannel AM CATV links are being developed and deployed in increasing numbers. Enhancements of the analytical tools which will aid in the design of fiber optic AM CATV systems is becoming ever more important.

In this paper, a model was presented which yields the CNR as a function of average received optical power, and desired CTBR and CSO. By characterizing a semiconductor laser diode using the two-tone method, projected multichannel distortion performance can be calculated. Those calculations involve the determination of the numbers and types of intermodulation distortion products, and the computation of intermodulation "penalties". The "penalties", P2 and P3, are used in conjunction with the optical intercept points, OIP2 and OIP3, found from two-tone measurements of the laser diode and the desired CTBR and CSO to find the appropriate OMI/ch. The resulting OMI/ch is used in conjunction with the intrinsic noise of the laser diode (RIN) and receiver parameters to calculate the expected CNR as a function of average received power at desired CTBR and CSO under specific channel loading.

The channel addition coefficient as a function of the number of channels has been tabulated. OMIt can then be determined from the OMI/ch. By limiting the OMIt to 0.9 or less (and the corresponding OMI/ch), the quasi-linear assumptions of this model can be maintained.

The results of the model was compared to experimental data under various channel loading conditions. The comparison produced favorable correspondence.

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TABLE 1

Terms in $e_{out} = a_1 e_{in} + a_2 e_{in}{}^2 + a_3 e_{in}{}^3$ for $e_{in} = A\cos(\alpha t + \phi_1) + B\cos(\beta t + \phi_2) + C\cos(\gamma t + \phi_3)$

dc

$$\frac{1}{2}a_2(A^2 + B^2 + C^2)$$

First order

$$\begin{aligned}
&a_1 A\cos(\alpha t + \phi_1) + a_1 B\cos(\beta t + \phi_2) + a_1 C\cos(\gamma t + \phi_3)\\
&+ \frac{3}{4}a_3 A(A^2 + 2B^2 + 2C^2)\cos(\alpha t + \phi_1)\\
&+ \frac{3}{4}a_3 B(B^2 + 2C^2 + 2A^2)\cos(\beta t + \phi_2)\\
&+ \frac{3}{4}a_3 C(C^2 + 2A^2 + 2B^2)\cos(\gamma t + \phi_3)
\end{aligned}$$

Second order

$$\begin{aligned}
&\frac{1}{2}a_2\left[A^2\cos(2\alpha t + 2\phi_1) + B^2\cos(2\beta t + 2\phi_2) + C^2\cos(2\gamma t + 2\phi_3\right]\\
&+ a_2 AB\left\{\cos\left[(\alpha + \beta)t + \phi_1 + \phi_2\right] + \cos\left[(\alpha - \beta)t + \phi_1 - \phi_2\right]\right\}\\
&+ a_2 BC\left\{\cos\left[(\beta + \gamma)t + \phi_2 + \phi_3\right] + \cos\left[(\beta - \gamma)t + \phi_2 - \phi_3\right]\right\}\\
&+ a_2 AC\left\{\cos\left[(\alpha + \gamma)t + \phi_1 + \phi_3\right] + \cos\left[(\alpha - \gamma)t + \phi_1 - \phi_3\right]\right\}
\end{aligned}$$

Third order

$$\frac{1}{4}a_3\left[A^3\cos(3\alpha t + 3\phi_1) + B^3\cos(3\beta t + 3\phi_2) + C^3\cos(3\gamma t + 3\phi_3)\right]$$

$$+\frac{3}{4}a_3\left\{\begin{aligned}
&A^2B\left\{\cos\left[(2\alpha + \beta)t + 2\phi_1 + \phi_2\right] + \cos\left[(2\alpha - \beta)t + 2\phi_1 - \phi_2\right]\right\}\\
&+ A^2C\left\{\cos\left[(2\alpha + \gamma)t + 2\phi_1 + \phi_3\right] + \cos\left[(2\alpha - \gamma)t + 2\phi_1 - \phi_3\right]\right\}\\
&+ B^2A\left\{\cos\left[(2\beta + \alpha)t + 2\phi_2 + \phi_1\right] + \cos\left[(2\beta - \alpha)t + 2\phi_2 - \phi_1\right]\right\}\\
&+ B^2C\left\{\cos\left[(2\beta + \gamma)t + 2\phi_2 + \phi_3\right] + \cos\left[(2\beta - \gamma)t + 2\phi_2 - \phi_3\right]\right\}\\
&+ C^2A\left\{\cos\left[(2\gamma + \alpha)t + 2\phi_3 + \phi_1\right] + \cos\left[(2\gamma - \alpha)t + 2\phi_3 - \phi_1\right]\right\}\\
&+ C^2B\left\{\cos\left[(2\gamma + \beta)t + 2\phi_3 + \phi_2\right] + \cos\left[(2\gamma - \beta)t + 2\phi_3 - \phi_2\right]\right\}
\end{aligned}\right\}$$

$$\begin{aligned}
+\frac{3}{2}a_3 ABC\Big\{&\cos\left[(\alpha + \beta + \gamma)t + \phi_1 + \phi_2 + \phi_3)\right] + \cos\left[(\alpha + \beta - \gamma)t + \phi_1 + \phi_2 - \phi_3\right]\\
&+ \cos\left[(\alpha - \beta + \gamma)t + \phi_1 - \phi_2 + \phi_3\right]\\
&+ \cos\left[(\alpha - \beta - \gamma)t + \phi_1 - \phi_2 - \phi_3)\right\}
\end{aligned}$$

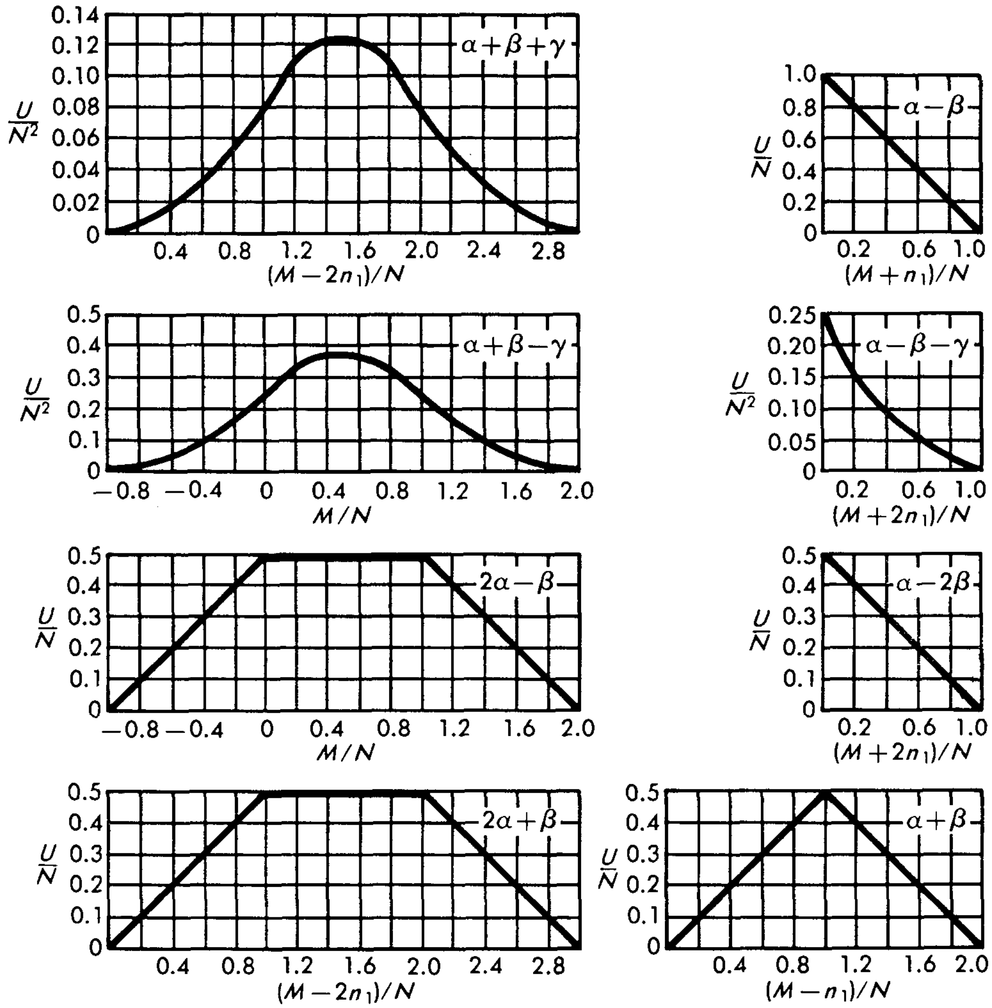

Figure 1 Spectral Distribution of Various Types of Imtermodulation Products

INTERMOD. TYPE	No. CONSECUTIVE CHANNELS FROM Ch. 2: 10	20	30	40
$\alpha-\beta$	0	9.8	19.7	29.8
$\alpha+\beta$	0.6	5.6	10.6	15.6
$\alpha-2\beta$	0.2	5.2	10.2	15.2
$2\alpha-\beta$	5	10	15	20
$2\alpha+\beta$	5	10	15	20
$\alpha-\beta-\gamma$	0	2.3	56.6	158.4
$\alpha-\beta-\gamma$	37.5	150	337.5	600
$\alpha+\beta+\gamma$	0	1.2	11.3	35.8

TABLE 2 Number of Intermodulation Distortion Products

Fundamental Freq's in MHZ	IMD3 [dB] $2f_1-f_2$	IMD3 [dB] $2f_2-f_1$	IMD2 [dB] f_2-f_1	IMD2 [dB] f_2+f_1
55.25 61.25	58	58	49	49
199.25 205.25	60	60	50	45
301.25 307.25	62	62	50	39
445.25 451.25	63	63	49	31

TABLE 3 Typical Laser-Diode Two-tone Measurement Result At +2.73 dBm Optical Power And 0.4 OMI/ch

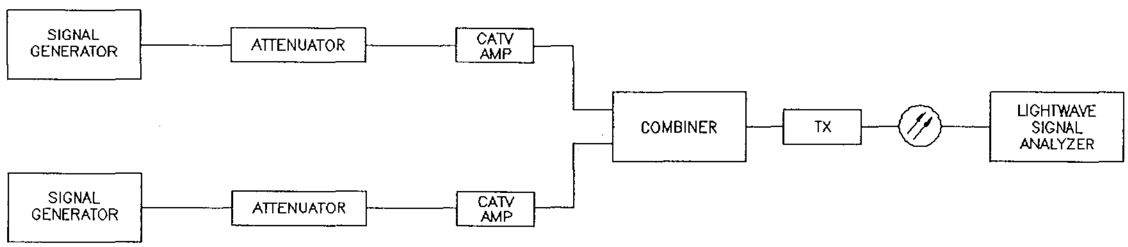

FIGURE 2:
TWO-TONE LASER DIODE MEASUREMENT SETUP

NUMBER OF CHANNELS	ζ
10	0.7
20	0.67
30	0.62
40	0.59
50	0.57
60	0.55
70	0.54
80	0.53

TABLE 4 Channel Addition Coefficient, ζ, for Given Channel Loading

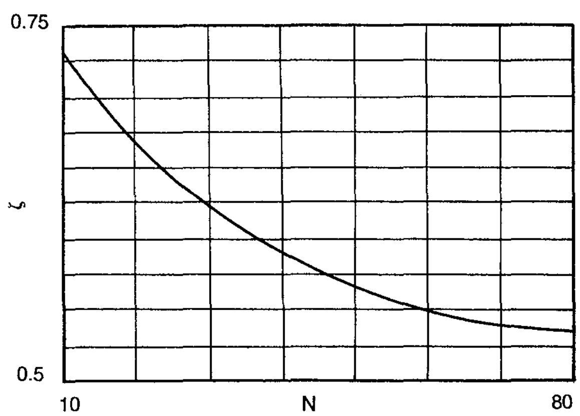

Figure 3 Channel Addition Coefficient ζ for 10 to 80 Channels

No. of Channels	Avg. Opt. Pwr [dBm]	ΔCNR	ΔCSO[dB]	ΔCTBR[dB]
10	-1	1	N/A	+1.6
From Ch14	-2	<1	N/A	+1.4
20	-1	1	N/A	-1.1
From Ch14	-2	1	N/A	+1.1
30	-1	1	+1.1	-1.4
From Ch14	-2	<1	+3.0	-3.8
40	-1	1	+1.1	-0.4
From Ch14	-2	1	+1.1	-1.7
10	-1	1	N/A	+1.6
From Ch 2	-2	<1	+4.7	+2.4
20	-1	2	-1.6	-0.2
From Ch2	-2	<1	+4.7	+2.4
30	-1	2	+2.7	-0.8
From Ch2	-2	1	-4.7	+2.4
40	-1	1	-1	-2
From Ch2	-2	1	+2.3	-0.3

TABLE 5 Comparison of the Model Results to Experimental Data

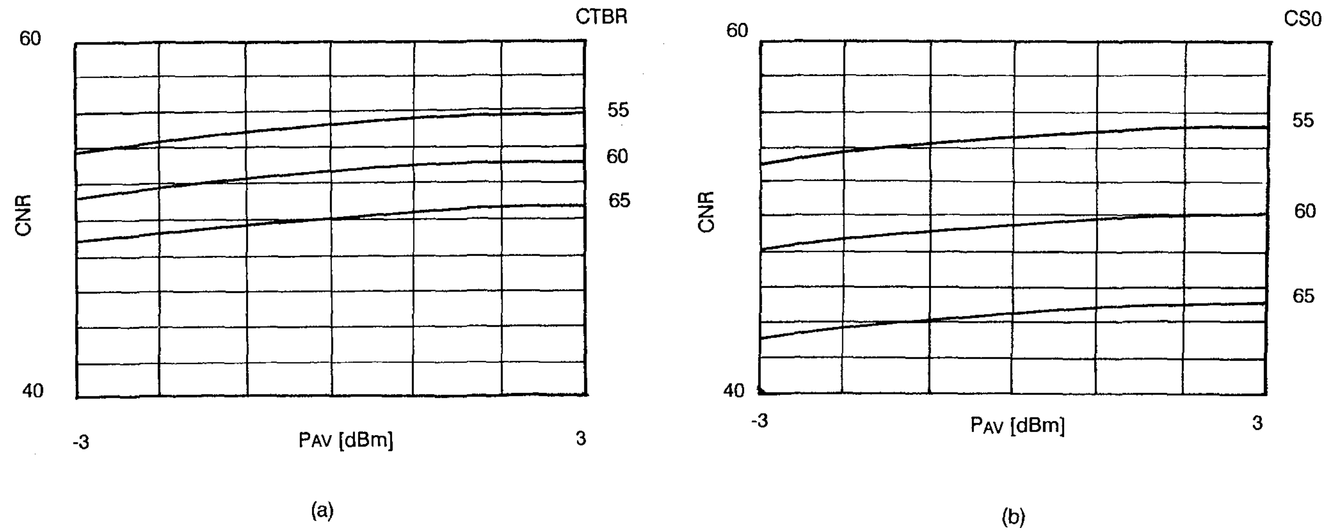

Figure 4 Results of the Model for a 40 Channel System
CNR as a function of average optical power for desired (a) CTBR and (b) CSO