FIBER OPTIC
RF LINK ANALYSIS

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ABSTRACT

The key system design parameters for analog fiber optic systems are their noise and distortion specifications. Both the optical transmitter and optical receiver have the potential to significantly limit the link's noise and distortion performance. A thorough system analysis first requires establishing the individual noise and distortion parameters for the laser transmitter and optical receiver, and secondly, examining the complete link's (noise and distortion) performance over the required range of optical loss budgets.

Noise performance of an RF optical link may be limited by either the transmitter (laser noise) or the optical receiver noise depending on the optical loss budget. Additionally, there are several independent noise sources contributing to the optical receiver noise. These are referred to as the "quantum" and "circuit" noise.

Distortion is introduced primarily in the optical source (laser). However, when high optical powers are delivered into the optical receiver, the receiver may also generate significant distortion.

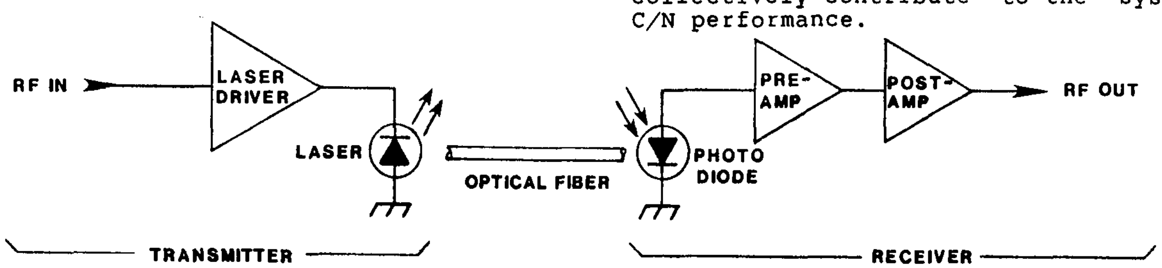
The focus of this paper will be to 1) quantify these noise and distortion parameters for the laser transmitter and optical receiver; and then, 2) apply these system performance parameters by analyzing an optical link over a range of optical loss budgets.

LINK PERFORMANCE PARAMETERS

The key performance parameters used to characterize any multi-channel RF optical link are its carrier/noise ratio (C/N) and intermodulation distortion (C/IMD). Although there are currently many types of optical sources and fiber available, this analysis will deal exclusively with 1300 nm single mode lasers and optical fiber. Single-mode technology provides the essential performance requirements with manageable costs; thus, it is becoming the defacto standard for high performance RF optical link applications.

A block diagram of a typical RF optical link is illustrated in Fig. 1. The main system components are: 1) a laser transmitter, 2) the fiber-optic cable and, 3) the optical receiver. As in conventional RF link analysis, one analyzes the link by first establishing the contribution for each of the individual (transmitter and receiver) components. Then, a complete system analysis can be performed using optical loss as a system variable.

The optical link's C/N performance is highly dependent upon the actual optical loss budget. For low loss budgets (distances < 10 km), the inherent noise of the laser transmitter will generally establish the upper limit on C/N performance. However, as the optical loss increases (high loss budgets), the optical receiver will takeover and limit the optical link's C/N performance. At intermediate loss budgets, both the laser transmitter and optical receiver will collectively contribute to the system's C/N performance.



RF OPTICAL LINK

FIG. 1

Similarly, the distortion performance of the RF optical link may vary as a function of the optical-loss budget. The laser's inherent linearity (or nonlinearity), in conjunction with system reflections, normally determines the intermodulation distortion for the optical link. However, at very low optical-loss budgets, the optical receiver may overload; and thus, the receiver may actually limit the link's distortion performance.

Since both of these key system performance parameters are highly dependent on optical loss budgets, it is important to perform a system analysis over an application's "relevant" loss-budget range. Spreadsheets have proven to be a powerful tool in supporting this type of analysis. DEC's 20/20 spreadsheet software has been utilized to perform the system analyses that are illustrated in this paper.

The required performance for any RF optical link is dependent on the form of modulation (AM or FM) used to modulate the individual carriers. For example, AM modulation is less expensive to utilize; however, it is the most demanding on the link's noise and distortion performance. FM modulation is more costly; however, bandwidth is traded off for a substantial "signal-to-noise" enhancement (typically > 25dB). Additionally, an FM-modulated carrier has a much greater tolerance for "in channel" distortions (typically also > 25dB).

LASER TRANSMITTER NOISE

LASER "RELATIVE INTENSITY NOISE" (RIN)

RIN defines the inherent noise power of the semiconductor laser diode. Minute fluctuations in optical emission are exhibited when the laser is biased above threshold. This intensity noise is neither thermal nor strictly shotnoise in nature. The noise is related to the response of the laser to modulation caused by the intrinsic shotnoise which is present in the laser. This phenomena results from the granular nature of light and electricity.

Analog lasers are currently available (specified) with RIN performance of (-135 dB/Hz) to (-155 dB/Hz). Carrier/noise is calculated from the RIN specification by subtracting 3 dB (for a 100% modulation index and a single carrier). This factor of 3 dB results from RIN being defined as the ratio of average (dc) light power [rather than (rms) signal power] to the (rms) noise power. For other modulation indexes and multiple channels, the carrier/noise (per channel) may be determined using the following equation.

C/N(1) =-RIN-10 LOG (2n*Bw/m^2) (1)

where;

C/N(1) =transmitter C/N (per ch.) (dB)
m = composite modulation index (%)
n = number of carriers
Bw = noise (channel) bandwidth (Hz)
RIN = laser noise (dB/Hz)

It should be emphasized that it is essential to control the fiber and/or connector related back reflections (interactions) to the laser (40 dB typical) in order to preserve consistent, low noise results from the laser transmitter. Laser diode noise significantly increases when there are reflected waves created from the discontinuities of the refractive index in the optical transmission path. Optical isolators are now being introduced, either integral to the laser package or externally, to provide this important isolation.

LASER MODULATION

Referring to equation (1), one can see that the laser's noise performance is highly dependent on its modulation index. This modulation index (m) is defined as the ratio of the peak laser current excursion about the laser's normalized (dc) bias current (Fig. 2). The equation which defines the laser's modulation index is:

m = (delta-I)/Ib' (2)

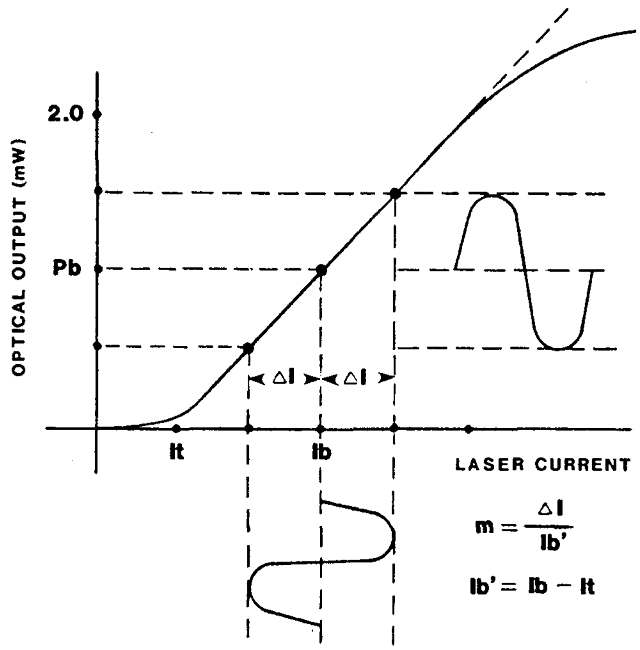
where;

Ib = (bias current)
Ib' = Ib-It (normalized bias)
It = (threshold current)
delta-I = (RF peak current)

Using a higher modulation index (m) provides a greater C/N ratio since the signal detected in the optical receiver is directly proportional to (m) squared. However, a higher modulation index requires operating the laser over a wider range of its light-current (LI) characteristic curve which also results in higher distortion levels. Typically, a laser's modulation index is set at 50 to 70% as the best tradeoff for transmitter noise versus distortion performance.

LASER TRANSMITTER DISTORTION

The laser transmitter is generally the



LASER LI CURVE

FIG. 2

distortion limiting component in high-performance RF optical links. Lasers generate harmonic and intermodulation distortion as a result of their nonlinear (LI) transfer characteristics and sensitivity to system reflections.

As can be seen from Fig. 2, the laser's (LI) curve exhibits nonlinear characteristics (especially at the extremes). Laser threshold determines the lower limit, while the instantaneous rise in laser temperature (as current is increased) causes the upper portion of the (LI) curve to saturate. Thus, for linear operation, it is important to bias the laser in the center of its linear region and to limit the amplitude of the modulation consistent with achieving the required distortion performance. High performance lasers are currently available which provide (specify) third-order intermodulation distortion levels of (> 60 dB) when operating at a 1 mW bias (50% modulation index).

An approach which is currently used to characterize the transmitter's distortion performance is to define its input "Intercept Point" (IP). The expression which defines the three-tone, 3rd-order (3-o) input (IP) is:

$$IP(3\text{-}o) = Pt + (IMD/2);(dBm) \qquad (3)$$

where;
Pt = composite RF input (dBm)
IMD = three-tone, (3-o) laser intermodulation ratio (dBl)

Second-order (2-o) distortion performance of a laser transmitter is generally (10-15 dB) poorer than its third-order performance. The equation which defines the transmitter's two-tone, (2-o) input (IP) is:

$$IP(2\text{-}o) = Pt + (IMD); (dBm) \qquad (4)$$

where;
Pt = composite RF input (dBm)
IMD = two-tone, (2-o) laser intermodulation ratio (dBl)

When possible, the RF optical links should attempt to limit the transmission bandwidth to a single octave. This avoids having the second-order distortion products fall within the desired transmission bandwidth.

When transmitting more than (3) carriers, the carrier-to-intermodulation ratio (C/IMD) will not necessarily degrade as rapidly as one might first expect. The reason for this is due to the laser requiring a constant (average) modulation index (independent of the number of channels transmitted). Otherwise, the transmitter's RF modulation peaks would overload the laser and perhaps might subject the laser to destructive current levels.

Thus, as more channels are loaded onto the transmitter, the individual carrier levels are lowered in amplitude (as required to maintain constant (composite) input power). For example, as the number of channels are increased to 10 channels, the amplitude for each of the individual carriers is lowered by 10 dB (constant RF power loading).

In the following analysis, it will be assumed that the C/IMD ratio is independent of the number of channels transmitted, (contingent on the composite modulation index also being maintained at a constant value).

OPTICAL RECEIVER NOISE

The optical receiver configuration reviewed in this analysis is an avalanche (APD) photodiode driving a low-noise, 50-ohm preamplifier. Although there are alternative front end designs available, this is a competitive (and representative) high performance front end receiver configuration.

There are two major sources of noise present in optical receivers. They are referred to as "quantum" noise and the receiver "circuit" noise.

QUANTUM NOISE

Quantum noise results from the statistical nature of the production and collection of photo-electrons when an optical signal (photon) is incident on a photodetector. Since fluctuations in the number of photocarriers created from the photoelectric effect are a fundamental property of the photodetection process, they set the ultimate "quantum limit" on receiver sensitivity when all other conditions are optimized. The quantum noise current has a mean square value, in a bandwidth (B), which is proportional to the average value of photocurrent.

Although quantum noise theoretically limits the link's ultimate C/N performance; in practice, laser noise usually limits the link's C/N performance first.

The C/N expression for "quantum" limited performance is:

$$C/N(q) = \frac{[(m*M*Re*Pb)\hat{}2/(2*n)]}{[2q(Re*Pb + Id)(M\hat{}(2+x))Bw]} \qquad (5)$$

where;
m = modulation index (%)
M = gain value (APD)
Re = responsivity (A/W)
Pb = average optical power (W)
n = number of channels
q = electron charge
Id = dark current (A)
M^x = excess noise factor (APD)
x = excess noise exponent
Bw = noise bandwidth (Hz)

CIRCUIT NOISE

There are two main constituents of the optical receiver's "circuit" noise. The first is due to the total equivalent resistance (Req) which is reflected back to the input node of the optical preamplifier (Fig. 3). This resistance constitutes a thermal noise source at the receiver's input. The second component is related to the "noise factor" (Ft) of the preamplifier.

The C/N expression for an optical link limited by the receiver's "circuit" noise is:

$$C/N(c) = \frac{[(m*M*Re*Pb)\hat{}2/(2*n)]}{(4*K*T*Bw/Req)Ft} \qquad (6)$$

where;
K = Boltzmann's constant
T = temperature (degrees K)
Ft = preamplifier noise factor
Req = equivalent resistance reflected at receiver's input node (ohm)

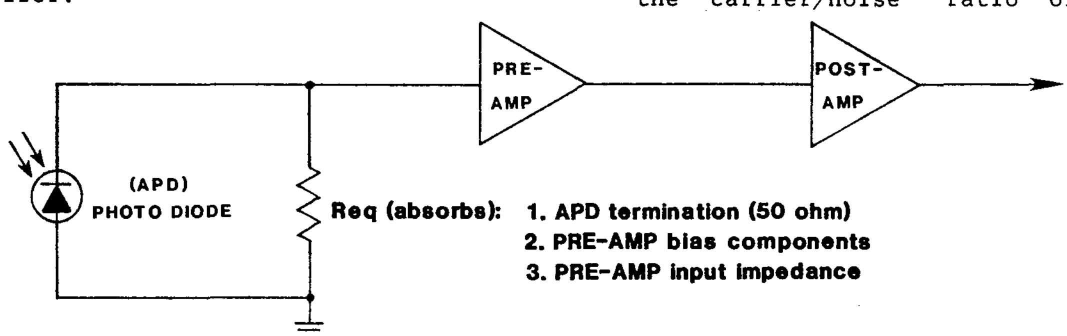
Combining the "quantum" and "circuit" noise components, the equation for the complete C/N performance of the optical receiver is:

$$C/N(r) = \frac{(m*M*Re*Pb)\hat{}2/(2*n)}{[N(q) + N(c)]} \qquad (7)$$

where;
N(q) = 2q(Re*Pb + Id)(M^(2+x))Bw
N(c) = (4K*T*Bw/Req)Ft

Referring to this equation, one may draw the following conclusions:

- At low signal levels and with low-gain (M) values, the circuit noise term dominates.
- At a fixed low signal level, as the gain (M) is increased from a low value, the carrier/noise ratio increases with gain until the quantum noise term becomes comparable to the circuit noise term.
- As the gain is increased further beyond this point, the carrier/noise ratio decreases (due to the APD's excess noise (M^x).
- Thus, for a given set of operating conditions, there exists an optimum gain value (M) of the APD for which the carrier/noise ratio of the



OPTICAL RECEIVER

FIG. 3

receiver is a maximum.

The expression which determines this optimum (M) value for optimum C/N of the link is:

$$Mopt = [A/(q*Req(B)x]\hat{}(1/(2+x)) \quad (8)$$

where;
A = 4K*T*Ft
B = (Re*Pb)+Id

The C/N performance for the complete RF optical link may then be obtained by summing the C/N ratios of the transmitter and optical receiver on a power basis.

$$C/N(s)=-10\log(10\hat{}(-Tx)+10\hat{}(-Rx)) \quad (9)$$

where;
Tx=C/N(l)/10
Rx=C/N(r)/10
C/N(l)=C/N of transmitter (dB)
C/N(r)=C/N of receiver(dB)
C/N(s)=C/N of the link (dB)

OPTICAL RECEIVER DISTORTION

The optical receiver's distortion performance is generally negligible (relative to the laser transmitter). However, at high optical input powers, the optical receiver's output amplifier may overload and begin to introduce substantial distortion. Even at high input powers, photodetectors normally contribute a negligible portion of the total optical receiver's output distortion. Thus, in this analysis, their contribution is ignored.

The preamplifier and post-amplifier distortions are determined from their respective output "Intercept Point" specifications. Cumulative receiver distortion levels are then determined by combining "voltage summing" these resultant independent C/IMD ratios of the preamplifier and post-amplifier. Similarly, the composite distortion of the complete RF optical link may be determined by combining "voltage summing" the C/IMD ratios of the laser transmitter and optical receiver. The equations which define these C/IMD ratios for both second and third-order distortions of the optical receiver and complete link are summarized below.

$$C/IMD(3\text{-}o) = 2(IP(3\text{-}o) - RF\ out) \quad (10)$$

$$C/IMD(2\text{-}o) = (IP(2\text{-}o) - RF\ out) \quad (11)$$

$$C/IMD(Rx) = -20*\log(A + B) \quad (12)$$

$$A = 10\hat{}-(G1/20) \quad (13)$$
$$B = 10\hat{}-(G2/20) \quad (14)$$

$$C/IMD(Link) = -20*\log(C + D) \quad (15)$$

$$C = 10\hat{}-(Tx/20) \quad (16)$$
$$D = 10\hat{}-(Rx/20) \quad (17)$$

where;
IP(3-o)=(3-o) output IP (dBm)
IP(2-o)=(2-o) output IP (dBm)
G1 = IMD ratio of preamp (dB)
G2 = IMD ratio of post-amp (dB)
Tx = IMD ratio of Tx (dB)
Rx = IMD ratio of Rx (dB)

Equations (10 & 11) are used to determine the C/IMD ratios out of the receiver pre-amp and post-amplifier, given their respective output (IP) specifications.

Equations (12 & 15) are "voltage summing" the C/IMD ratios for two independent C/IMD ratios in order to obtain a combined C/IMD ratio.

OPTICAL LINK ANALYSIS

Having defined the noise and distortion parameters for the optical transmitter and receiver, one may now analyze the link's total performance over a range of optical loss budgets. The analysis which follows is modeled onto a DEC 20/20 spreadsheet which provides one with a very powerful tool for evaluating "what if" results when alternative system variables are selected.

The optical link's performance model, illustrated in Tables (1 and 2), actually consists of two sub-models. Table 1 illustrates the C/N performance model exercised over a range of optical loss budgets; whereas, Table 2 illustrates the link's distortion performance model for the same range of optical loss budgets.

Each of these sub-models consists of three subsections. In the upper portion of each model is a list of the system parameters which must be quantified. These parameters are either the fixed or variable parameters used in the model's analysis equations. The model's equations are written to the right of the parameter list to provide a convenient reference for the user.

The lower portion of the model is where the system analysis is actually performed using optical loss budget as an additional variable parameter. Basically, the system analysis is performed by evaluating the optical link's noise and distortion performance at various optical losses using the analysis equations which have been referred to in this paper.

An illustrative RF optical link performance analysis is shown in Tables

(1 & 2). This example analyzes the performance of a 20 channel RF optical link over an optical loss budget range of 12 dB. In this example, the laser RIN noise is specified at -145 dB/Hz with an optical output power of 1mW (50% modulation). The transmitter and receiver distortion components are determined from their respective "Intercept Point" specifications.
Plots of the system's C/N and IMD performance are conveniently displayed with this spreadsheet software. This is especially useful when evaluating which of the system's components are the most dominant at specific loss budgets. For example, Fig. 4 is a plot of the system's C/N performance used in this example. Individual C/N components of the transmitter and receiver are also plotted enabling one to examine which component is most dominant in determining the link's C/N performance. As seen from the curves (Fig. 4), the C/N performance is mainly laser limited at very low optical losses to a limit of 55 dB. At 6 dB of optical loss, the optical receiver is the dominant C/N contributor limiting the link's performance to 51 dB.

Distortion performance for this example is displayed in Fig. 5. These curves reveal the contribution of the laser transmitter versus the optical receiver in determining the link's total distortion performance. In this example, the laser limits the third-order distortion performance of the link to -65 dBc. However, the receiver will degrade this performance to -61 dBc at the maximum available optical input power.

RF OPTICAL LINK PERFORMANCE MODEL

(LASER/APD-PHOTODIODE)

Parameters			Model Equations
n=	20	ch	C/N(1-laser)=-RIN-10Log(2*n*Bw/m^2)
m=	0.5		
M=	var		C/N(q)=10Log(m*M*RePb)^2/(4nq(RePb+Id)(M^2+x)Bw)
Re=	0.7	A/W	
Pb=	var		C/N(circuit)=10Log(m*M*RePb)^2/(8nK*T*Bw*Ft/Req)
q=	1.6e-19		
Id=	1.0e-06	A	C/N(rec'r)=10Log[((m*M*RePb)^2/(2*n))/
M^x	var		(2q(RePb+Id)BwM^(2+x))+(4KTBwFt/Req)]
K=	1.4e-23		C/N(s)=-10Log(10^(-C/N(1)/10)+10^(-C/N(r)/10))
			= System Carrier/Noise Performance
T=	300	K	
Ft=	4.0		M(opt)=((4K*T*Ft)/(q*Req(Re*Pb+Id)x))^(1/(2+x))
Req=	50	ohm	
Bw=	4.0e+06	Hz	
x=	0.95		
RIN=	-145	dB/Hz	

(Carrier / Noise)

(Watts)	Ptx out	1.0e-03	6.3e-04	4.0e-04	2.5e-04	1.6e-04	1.0e-04	6.3e-05
(dB/div)	2							
(dB)	Opt Loss	0	-2	-4	-6	-8	-10	-12
	C/N(c)=	65	62	60	57	54	52	49
	C/N(q)=	62	59	57	54	51	49	46
	C/N(r)=	60	57	55	52	50	47	44
	C/N(l)=	57	57	57	57	57	57	57
	C/N(s)=	55	54	53	51	49	46	44
	M(opt)=	2	3	3	4	4	5	6
	M^x =	2	3	3	4	4	5	5

TABLE 1

(Distortion Performance)

(Laser Transmitter)

Parameters		Model Equations
Pn=	-5 dBm	Pn=per/channel input power
Pt=	8.5 dBm	Pt=total input power
i(1)p/p=	33 mA	i(1)=(((10^(Pt/10))*10^-3/50)^0.5)(2.8)
n%=	3 W/A	n=laser quantum efficiency
Pb=	1 mW	Pb=optical bias power
deltaPo=	0.50 mW	Po=(1/2)(i(1))*10^3*n%/100; (delta Popt)
m=	0.50	m=Po/Pb (modulation index)
IP(3o)=	41 dBm	IP=input intercept point(3rd order)
IP(2o)=	64 dBm	IP=input intercept point(2nd order)
(dBl)=	65(3o)	(dBl laser-3o IMD)=2*(IP(3o)-Pt)
(dBl)=	55(2o)	(dBl laser-2o IMD)=(IP(2o)-Pt)

(Optical Receiver)

Parameters		Model Equations
m=	0.50	i(pd-RMS)=((m*M*Re*Pb)/(2^(1/2)))
M=	var	AMP-3o=2*(3oIP-(Amp Out)):3oG1;3oG2
Re=	0.7 A/W	AMP-2o=(2oIP-(Amp Out)):2oG1;2oG2
Pb=	var	Rec'r-3o=-20Log(10^-(3oG1)/20)+10^-(3oG2/20))
Ft=	4.0	Rec'r-2o=-20Log(10^-(2oG1/20)+10^-(2oG2/20))
Req=	50 ohm	Link-3o=-20Log(10^-(3oTx/20)+10^-(3oRx/20))
BW=	4.0e+06 Hz	Link-20=-20Log(10^-(2oTx/20)+10^-(2oRx/20))
G1-db=	8(pre-amp)	
IP-dBm=	31(output 3o-IP(G1))	
IP-dBm=	55(output 2o-IP(G1))	
G2-db=	8(post-amp	
IP-dBm=	31(output 3o-IP(G2))	
IP-dBm=	55(output 2o-IP(G2))	

(watts)Opt Pwr	1.0e-03	6.3e-04	4.0e-04	2.5e-04	1.6e-04	1.0e-04	6.3e-05
(dB) Opt Loss	0	-2	-4	-6	-8	-10	-12
(RMS) i(pd)=	5.9e-04	4.3e-04	3.2e-04	2.4e-04	1.7e-04	1.3e-04	9.4e-05
(dBm) 50ohms=	-18	-20	-23	-26	-28	-31	-34
Pre-Amp(G1)							
(dB) Gain=	8	8	8	8	8	8	8
(dBm) AMP-OUT=	-10	-12	-15	-18	-20	-23	-26
(dB) AMP-3o=	87	93	98	103	108	114	119
(dB) AMP-2o=	68	70	73	76	78	81	84
Post-Amp(G2)							
(dB) Gain=	8	8	8	8	8	8	8
(dBm) AMP-OUT=	-2	-4	-7	-10	-12	-15	-18
(dB) AMP-3o=	71	77	82	87	92	98	103
(dB) AMP-2o=	60	62	65	68	70	73	76
Optical Receiver	(Composite Receiver Distortion)						
(dBr) Rec'r-3o	70	75	81	86	91	96	102
(dBr) Rec'r-2o	57	59	62	65	67	70	73
Optical Link	(Total Link Distortion)						
(dBc) Link-3o=	61	63	64	64	65	65	65
(dBc) Link-2o=	50	51	52	53	53	54	54

TABLE 2

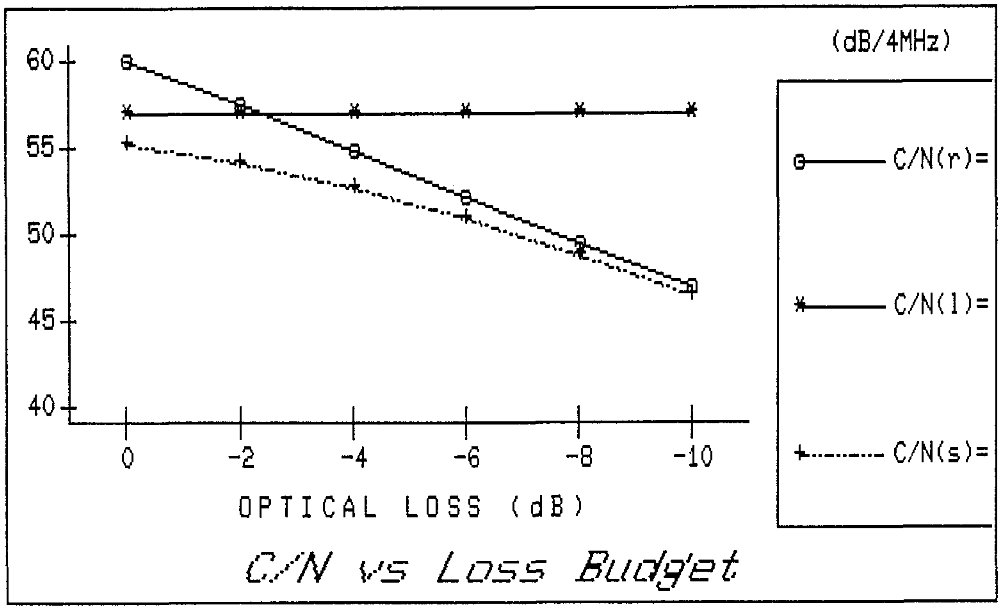


FIG. 4

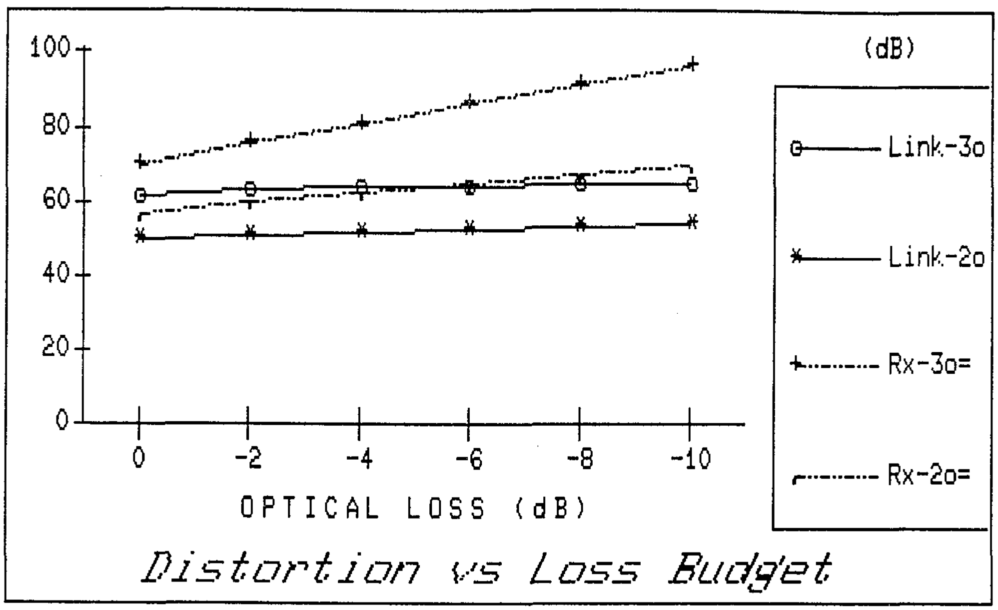


FIG. 5

SUMMARY

A comprehensive RF optical link analysis requires analyzing the C/N and C/IMD performance of the optical link over a range of optical loss budgets. The equations which characterize the optical link's noise and distortion performance have been reviewed and modeled onto a spreadsheet.

In addition to analyzing the optical link's system performance, this analysis technique also enables one to specify the essential performance parameters of the optical transmitter and receiver in order to satisfy specific system design requirements.