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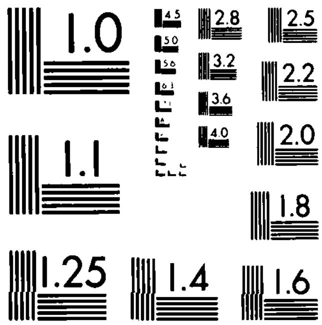

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A Comparison of Millimeter Wave, Direct Detect and Heterodyne Laser Intersatellite Links

THESIS

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Captain, USAF

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Wright-Patterson Air Force Base, Ohio

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

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Master of Science in Electrical Engineering

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Preface

The purpose of this study was to investigate the performance of four candidate technologies for intersatellite links under the tradeoffs of signalling scheme, energy per bit to noise ratio, probability of bit error and bandwidth requirements. State of the art and projected hardware capabilities were used to generate energy per bit to noise ratios and give a risk assessment for achieving a given error probability.

The results presented here can be used to evalute the relative risk and achievable error rates of proposed intersatellite links.

During the months in which this work was done I have had much support and guidance from others. I would like to thank Major K.G. Castor for his time, encouragement and technical assistance. The largest measure of thanks must go to my wife Sandra for her patience and understanding during many nights and weekends alone while I worked.

Marty J. Edmonds

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List of Symbols

A	amplitude
A	amperes
A_r	optical receiving area
A_d	detector area
A_m	amplitude of the mth signal
APD	avalanche photodiode
B	bandwidth
Be	bandwidth efficiency
B_{rf}	RF bandwidth
B_n	noise bandwidth
B_o	optical bandwidth
b_m	modulation index
B_m	amplitude of the mth signal
c	speed of light in a vacuum
CNR	carrier to noise power ratio
CO_2	carbon dioxide
d	cross sectional antenna diameter
dB	decibels
df	differential with respect to f
d_r	receive optics diameter
d_t	transmit optics diameter
Eb	energy per bit
E_{bav}	average energy per bit over the entire signal set

EHF	extremely high frequency
EIRP	effective isotropic radiated power
exp()	natural base e raised to the power of the argument
f	frequency
F	photodetector excess noise factor
FET	field effect transistor
F_i	noise figure of the ith element
F_n	noise figure
f_o	carrier or center frequency
F_s	system noise figure including antenna noise
FSK	frequency shift keying
GaAlAs	aluminuim gallium arssenide
GaAs	gallium arsenide
GaInAs	indium gallium arsenide
G_{AV}	time average photodetector gain
GBps	gigabits per second
GHz	gigahertz
G_i	gain of the ith element
G_r	receive antenna gain
G_t	transmit antenna gain
h	Planck's constant
HEMT	high electron mobility transistor
Hz	hertz
H(f)	impulse response
H_o	altitude above mean sea level
$H^*(f)$	complex conjugate of impulse response

In optical systems it is often advantageous to express receive power in terms of a receive photoelectron count rate, n_r.

$$n_r = P_r/h\ f_o \qquad (6)$$

h = Planck's constant, (6.63 X 10-34 J-s)

f_o = the optical frequency in Hz

(5:359-360)

In RF systems an antenna concentrates an electromagnetic field intensity at a field point where it is converted to an electronic signal. Optical systems use a lense (or lenses) to concentrate the field power at a detector. This photodetector has an efficiency, n. The relation for detected photoelectron count rate is then:

$$n_s = n\ n_r = n\ P_r/h\ f_o \qquad (7)$$

(5:393-365)

The photodectors most commonly used are avalanche photodiodes (APD) for direct detection receivers and silicon photodiodes for heterodyne receivers (see Chapter 3). APDs exhibit a random gain. The mean of this gain, G_{av}, becomes important in development of signal to noise relations.

Other losses which could be factors in the receive power equation are polarization loss and loss due to antenna pointing errors. Polarization refers to how energy is excited onto the antenna. Linear polarized (horizontal or vertical) antennas can

If the transmitted power (power available at the transmit antenna input) multiplied by the gain of the transmit antenna is defined as effective isotropic radiated power (EIRP) and the loss in receive power due to distance between receive and transmit antennas is defined as propagation loss (L_p) Equation 1 can be written in decibels as:

$$P_r = EIRP - L_p + G_r \quad (dB) \qquad (2)$$

where

$$L_p = 20 \log (4 \pi R/\lambda) = 20 \log (4 \pi Rf/c) \qquad (3)$$

$$\lambda = c/f$$

$$c = 2.997925 \times 10^8 \text{ meters per second}$$

Making the proper substitutions for frequency (f) in gigahertz, and separation distance (R) in kilometers the expression for propagation loss takes the form of Equation 4 (4:9). The choice of gigahertz and kilometers are best suited to the large distances and high frequencies typical of ISLs.

$$L_p = 92.447782 + 20 \log (Rf) \qquad (4)$$

As shown in Equation 5 receive power in an optical system is slightly different from that of the RF (millimeter wave) case.

$$P_r = \frac{P_t (d_t d_r)}{\lambda^2 R^2} \qquad [\text{ Optical System }] \qquad (5)$$

d_t, d_r = diameter of transmit/receive optics

ISLs will require high bit rates. To provide these bit rates, frequencies in the millimeter wave and optical regions are attractive. These two frequency/wavelength regions have different characteristics, advantages and disadvantages.

In this chapter the background theory necessary for modelling a millimeter wave and optical intersatellite links will be presented; the link equations to include received signal power, noise power due to circuitry, and noise due to background radiation; the signalling waveforms and the corresponding tradeoffs in energy per bit to noise power ratio, probability of error and bandwidth efficiency.

Link Equations

The link power equations for intersatellite links are free of the atmospheric attenuation present in up or downlinks. The relation for received power is given by (4:3):

$$P_r = \frac{P_t \; G_t \; G_r \; \lambda^2}{(4 \; \pi \; R)^2} \qquad [\text{ RF System }] \qquad (1)$$

P_t, P_r = Transmit and Receive Power

G_t, G_r = Transmit and Receive Antenna Gain

λ = Wavelength of the Carrier

R = Distance Between Receive and Transmit Antennas

II. Theoretical Background

In order to tap the benefits of intersatellite links the engineer must combine the techniques and theory of several areas of communication technology. First the linking satellites must be able to establish and maintain alignment of their antennas. This tracking and acquisition problem is not trivial when one considers that satellites have motion with respect to the earth, motion with respect to each other and random position within a defined volume. Solution to this problem will not be addressed here.

The second area of interest is link equations. ISL link equations describe the power received by one satellite from another and are simplified by the lack of atmospheric attenuation or rain induced fading. The overriding loss in ISL link equations is due to the great distances separating satellites. Once received power is well described the noise power must be determined. Noise power can be divided into the background noise seen by the antenna and noise generated by receiver circuitry (3:58).

Given the receive signal power and noise power the choice of signalling waveform may be investigated. Tradeoffs exist between probability of error, bandwidth and energy per bit to noise power ratio.

5. The channel is modelled as memoryless.

Approach

The first step is to determine the link equations governing millimeter wave and optical ISLs. Having identified these equations, the probability of bit error and bandwidth efficiency equations under M-ary Phase Shift Keying (PSK), M-ary Pulse Amplitude Modulation, M-ary Frequency Shift Keying and M-ary Pulse Position Modulation are presented.

Chapter 3 deals with the hardware dependent parameters needed to generate meaningful values for Eb/No. These values are presented to show the relative developmental risk for each link.

Chapter 4 describes the computer programming and verification of the equations of chapters 2 and 3. Results are presented in Chapter 5 and a collection of graphs in Appendix D.

The findings are analyzed in Chapter 6. Conclusions and recommendations for further research are included in this final chapter.

Scope

This research will present the link equations for intersatellite communication to include received signal power, background noise power and noise power due to circuitry; various signalling waveforms for millimeter wave and optical systems and their corresponding Eb/No, P_b, and Be.

Discussion of the mathematics of acquiring and tracking the antenna beam patterns between the two communicating satellites will not be included. Matching the communications system parameters (Eb/No, P_b, Be) to specific equipment currently available and analyzing power, weight and cube requirements of this equipment will not be accomplished here.

The intent of this thesis is not to design but to identify and investigate the theoretic limits and reasonable expectations of a millimeter wave and optical intersatellite communications link.

Assumptions

1. Satellites are assumed to be tracking each other within tolerable limits of antenna beamwidth.

2. The noise environment is assumed to be a gaussian random process.

3. The receive and transmit circuitry is phase and spatially (when appropriate) coherent.

4. Information is passed in a digital (one, zero) alphabet where a one and zero are equally probable events.

LES-9. These and other efforts proved the concept of ISLs and helped to define the requirements of intersatellite communication (2:1171). Among the major requirements is high data rate. The expected traffic loads of ISLs make the 100 megabit to 1 gigabit per second bit rates attractive. To supply such high data rates it is necessary to investigate the extremely high frequency (EHF) and above spectrum. Two promising technologies are millimeter wave and optical communications.

The special environment and characteristics of satellites influence the ISL. First, the near vacuum of space causes negligible atmospheric attenuation. Second, the great distances separating two satellites can approach twice geosynchronous orbit. Propagation loss at this distance is severe. Finally, satellites are size and power limited. This forces antennas to be small and power available for transmission to be low as compared to ground radio systems.

Problem

Due to the transmission data rate needed, the great distances separating satellites, and the limited transmit power and antenna gain available, millimeter wave and optical intersatellite links must be investigated to show the tradeoffs of energy per bit to noise power ratio (Eb/No), probability of bit error (P_b) and bandwidth efficiency (Be) for various signalling waveforms.

I. Introduction

Thesis Topic

This thesis is undertaken to formulate a performance analysis of millimeter wave and optical intersatellite links encompassing the engineering tradeoffs of energy per bit to noise ratio, probability of bit error and bandwidth requirements.

Background

The advantages of satellite-to-satellite communications over satellite-to-ground-to-satellite comunications have long been recognized. System connectivity is greatly improved. In some cases, regions of the globe otherwise unable to communicate could be served via satellite. By cross connecting satellites of different user communities communication between organizations which normally have little, but necessary, communication are enhanced. Intrasatellite links (ISL) decrease demands on satellite positioning and can reduce overall system cost by reducing the number of ground stations needed for global or hemispheric coverage (1:431).

In 1975 the first successful ISL was demonstrated between two amateur very high frequency band satellites, AMSAT/Oscar-6 and Oscar-7. Later that year a link between the SPACELAB and the ATS-6 satellite was established. In 1976 the Massachusetts Institute of Technology began a sustained investigation into ISLs with the Lincoln Laboratories experimental satellites LES-8 and

Abstract

This investigation determined the energy per bit to noise ratios which can be expected to be feasible in the near term (low risk), within five years and those foreseeable beyond five years (high risk) for intersatellite links (ISL). The ISLs considered are 60 and 90 gigahertz millimeter wave, 1064 nanometer direct detect Nd:YAG laser and 832 nanometer heterodyne GaAs laser. From these values the probability of bit error for various candidate signalling schemes can be determined. The required signalling bandwidth can also be evaluated.

The analysis showed that for low bit rate (1 MBps) ISLs, 60 GHz millimeter wave 16-ary pulse amplitude modulation is the least risk, most bandwidth efficient implementation of those investigated. For higher bit rates (100 MBps and 1 GBps) and separation angles of 120° or more current (low risk) technology is not sufficient. For ISL communication under these parameters heterodyne laser technology is the most promising.

List of Constants

c	speed of light	2.997925×10^{8} m/s
h	Planck's constant	6.63×10^{-34} Js
H_o	altitude above mean sea level	35784 km
k	Boltzmann's constant	1.38 X 10-23 J/°K
π	the number pi	3.1415926536
q	charge of one electron	1.602×10^{-19} coulombs
R_e	radius of the earth	6378.388 km

$\emptyset_b$	half power beamwidth
**	raised to the power

R	range
R_b	signalling rate, bit rate
Re	real part
R_e	radius of the earth
RF	radio frequency
R_1	impedance of load or photodetector
s	seconds
SNR	signal to noise power ratio
SNR_s	post detection signal to noise power ratio
s(t)	time varying signalling waveform
T	system noise temperature
t'	pulse time interval
Ta	antenna noise temperture
T_b	bit time
T_e	receiver noise equivalent temperature
T_p	waveform period
t_t	transit time for a photodiode
TWTA	travelling wave tube amplifier
u	receiver responsivity
um	micrometers
u(t)	unit rectangular pulse
w	radian frequency
W	Bandwidth when used in bit rate per hertz (Rb/W)
W	watts
λ	wavelength
Ø	satellite separation angle

nm	nanometers
N_o	bandwidth normalized noise power
N_O	combined shot, dark and thermal current spectra
n_r	received photoelectron count rate
n_s	detected photoelectron count rate
N_{sn}	shot noise current spectra
n_t	average thermal photoelectron count rate
N_t	thermal current spectra
O_{fv}	optical field of view
p_a	antenna efficiency
P_{av}	time average of received power
PAM	pulse amplitude modulation
P_b	background power
P_b	probability of bit error
P_L	local laser power
P_M	probability of word error
P_n	noise power
p_o	initial phase offset
PPM	pulse position modulation
P_r	receive power
$P_r(t)$	time varying receive power
P_s	signal power
PSK	phase shift keying
P_t	transmit power
q	quantum electron charge
Q	the gaussian Q function

IMPATT	impact avalanche transit time diode
ISL	intersatellite link
$i(t)$	time varying current
$i_{dc}(t)$	time varying dark current
$i_{sn}(t)$	time varying shot noise current
$i_t(t)$	time varying thermal current
j	square root of -1
J	joules
k	Boltzmann's constant
k	number of source letters per source symbol
km	kilometers
°K	degrees kelvin
log	base 10 logarithm
$\log_2$	base 2 logarithm
L_p	propagation loss
M	number of source symbols of words in the signalling set
m	the values of M, m = 1,2,...M or 0,1,2,...M-1
m	meters
MBps	million bits per second
$m(t)$	time varying message
n	photodetector efficiency
n_b	background photoelectron count rate
n_d	average dark current photoelectron count rate
N_{dc}	dark current spectra
Nd:YAG	neodynium yittrium aluminium garnet
$N(f)$	spectral radiance

suffer a loss due to misalignment of the receive energy with the receive antenna. Circularly polarized antennas are right hand (clockwise) or left hand (counter clockwise) polarized (5:86-88).

Polarization losses are usually associated with linear polarized antennas and atmospheric phenomenon. The atmosphere has the effect of rotating the axes of the propagating signal resulting in a net power loss. A horizontally polarized signal may therefore arrive at the receive antenna with a vertical component. Circular polarized antennas are less sensitive to this type of loss (5:88). In the environment of space with its rarified atmosphere polarization losses are not a concern.

Losses due to pointing errors occur when the beamwidth of the transmit and receive antennas do not optimally intersect. Equation 8 shows that RF frequency is inversely proportional to beamwidth (5:88).

$$\phi_b = \lambda / d\,(pa)^{\frac{1}{2}} \qquad (8)$$

ϕ_b = Half Power Beamwidth

P_a = antenna efficiency

d = cross sectional antenna diameter

As frequency increases wavelength (λ) decreases with a corresponding decrease in beamwidth. In the optical spectrum pointing error is much more severe due to the order of the parameter dimensions. The optical half power beamwidth is then given by:

$$\emptyset_b = \lambda / d_t \qquad (9)$$

where dt is the diameter of the transmitting laser optics. Consider a visible laser with wavelength on the order of 10^{-6} meters and a transmitting lense diameter of as little as 6 inches, the beamwidth produced is only 10×10^{-6} radians (17.5×10^{-3} radians = 1 degree) (5:359).

Pointing error can become a critical problem for ISLs. Typically a satellite subsystem for acquisition and tracking is used to maintain pointing error within tolerable limits. Discussion of the methods and mathematics of acquisition and tracking systems is not within the scope of this effort. It will be assumed the satellites have acquired and are maintaining track for the further development of the intersatellite link communications problem.

Noise Power - Millimeter Wave Systems

Equations 1 and 5 defined the received signal power for RF (milimeter wave) and optical systems respectively. The ratio of received power to the power in the noise and tolerance to this ratio is a prime factor in comparing and evaluating communication systems.

The noise power density of a system depends on the frequency (or wavelength) of the carrier and the in-band system noise temperature. From the theory of blackbody radiation, noise power can be written as (6:B5.3.2):

$$P_n = \frac{h\ f}{\exp\ [hf/kT] - 1} \qquad (10)$$

h = Planck's constant, (6.63 X 10-34 J-s)

k = Boltzmann's constant, (1.38 X 10^{-23} °K)

f = frequency in Hz

T = system noise temperature

Using the series expansion cf the exponential (Equation 11), noise power reduces to Equation 12 for hf<<kT.

$$\exp\ [x] = 1 + x + x^2/2! + x^3/3! + \ldots \qquad (11)$$

$$P_n = k\ T \qquad (12)$$

Substituting for h and k and choosing f = 60 or 90 GHz as a representative millimeter wave frequency equation 12 holds for a system with a noise temperatures on the order of 10 °K or more. For optical systems the simplified equation does not hold. Optical noise power and signal to noise ratio will be discussed later.

The remaining unknown in Equation 12 is system noise temperature, T. The system noise temperature is defined as the sum of equivalent receiver noise temperature (T_e) and antenna temperature (T_a) (7:345).

$$T = T_e + T_a = T_o F_s \tag{13}$$

F_s = System noise figure

T_o = 290 °K

The values for T_a are tabulated depending on the background observed by the antenna. T_e can be determined in two ways. If the noise temperatures of the cascaded elements of the receiver are known T_e is given by (7:347-348):

$$T_e = \frac{T_1}{G_1} + \frac{T_2}{G_2} + \frac{T_3}{G_3} + \ldots \tag{14}$$

G_i = gain of the ith element

T_i = noise temperature of the ith element

If the noise figure of the cascaded receiver elments is known T_e is given by Equation 15 (7:347-348).

$$T_e = (F_n - 1)\, T_o \tag{15}$$

$$F_n = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/(G_1 G_2) + \ldots \tag{16}$$

F_i = noise figure of the ith element

One remaining adjustment must be made to give the noise power generated over the receiver noise bandwidth, B_n, at temperature

T. The receiver noise bandwidth B_n, is given by:

$$B_n = \int \frac{H(f)\ H^*(f)}{H(f_o)\ H^*(f_o)}\ df \qquad (17)$$

For a superheterodyne type RF receiver, the noise bandwidth, B_n, is approximately equal to IF bandwidth (7:18). Using these results the equation for noise power in the millimeter wave case is given by Equations 18.

$$P_n = k\ T\ B_n \qquad (18)$$

<u>Signal to Noise Ratio - Millimeter Wave Systems</u>

For the millimeter wave system the carrier power to noise power ratio can now be written.

$$CNR = P_r/P_n \qquad (19)$$

$$CNR = \frac{EIRP\ L_p\ G_t}{k\ T_s\ B_{rf}} \qquad (20)$$

For digital communications it is useful to represent CNR as energy per bit to bandwidth normalized noise power ratio (15:158, 16:289-292).

$$E_b/N_o = CNR\ P_{rf}\ \frac{k}{R_b} \qquad (21)$$

R_b = bit rate

N_o = bandwidth normalized noise power

Noise Power - Optical Systems

Let us now turn our attention to the optical noise power case. The characteristics of photodetectors make the receiver model of Figure 1 a useful tool for determining the noise contributions in the optical receiver. First the equation for background noise power will be determined followed by the shot noise, detector dark current noise and receiver thermal noise contributions.

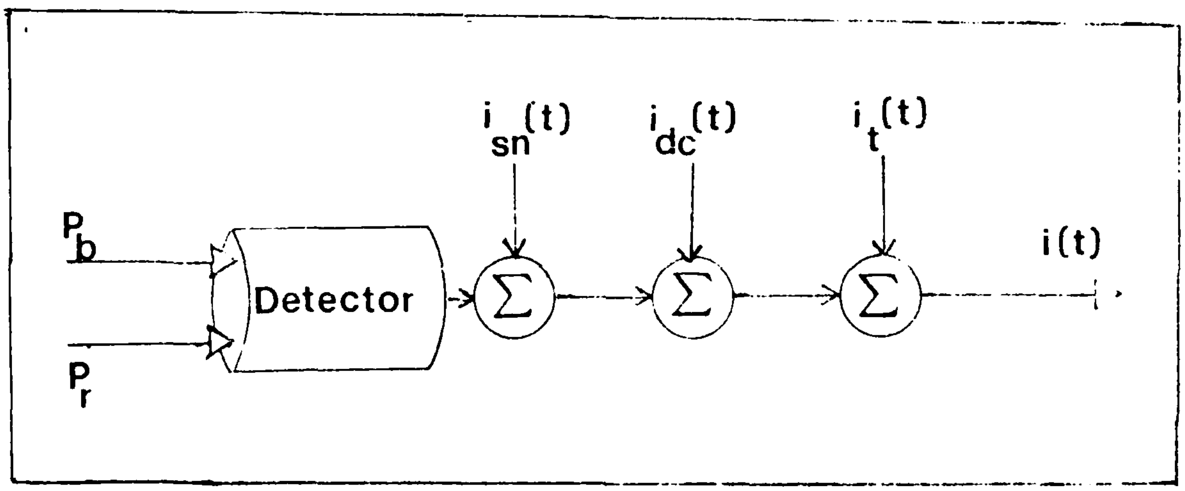

Figure 1: Optical Receiver Model
Source: (5:372)

Background noise in the optical environment is determined much as noise power is in the RF environment. Background noise power can be determined using the theory of blackbody radiation and an equivalent noise temperature for the heavens, T (see Equation 10). The choice of T depends heavily on whether a planet or the sun is in the view of the antenna.

To account for the high frequency and lensing systems of optical communications it is convenient to make several adjustments to the blackbody radiation equation. First we must define the spectral radiance function N(f) (8:37).

$$N(f) = \frac{h\,f^3}{c^2}\;\frac{1}{\exp[hf/kT] - 1} \tag{22}$$

Note that multiplying the spectral radiance by the wavelength squared yields the same value as Equation 10.

The second parameter necessary for the background power is the optical field of view O_{fv}. In RF systems the receiver field of view depends only on the receiving area, A_r. In an optical system the field of view depends on the detector area and the focal length of the receiving lense. The value of focal length is usually set to approximately the square root of detector area. With these assumptions the equation for optical field of view can be shown to be approximated by (5:364):

$$O_{fv} = A_d/A_r \tag{23}$$

We can now write the equation for optical system background radiation (see Equation 24)where B_o refers to the optical bandwidth in hertz. Optical bandwith is often given in wavelengths about the carrier wavelength and must therefore be converted to hertz to maintain consistent units.

$$P_b = N(f)\ B_o\ A_r\ O_{fv} \tag{24}$$

As with the received signal power it is convenient to express received background noise power in terms of photoelectrons detected. To do this an adjustment for photodetector efficiency, n, and energy per photoelectron is necessary (5:370).

$$n_b = \frac{n\ P_b}{h\ f_o} \tag{25}$$

Arriving at the detector is the time varying received signal and background noise powers. Given an ideal detector and constant field power the current i(t) would be constant (see Figure 1). In fact the detector gain is random and its variation about a mean creates a time varying current called shot noise, $i_{sn}(t)$ (5:367).

The photodetector itself produces a current called dark current, $i_{dc}(t)$. The dark current is caused by thermal emission of photoelectrons in the detector and modelled as a random process. There need not be radiation present at the reciever input to produce a dark current (5:367).

Thermal current, $i_t(t)$, is the current contributed by the noise equivalent temperature, T_e, of the receiver circuitry. T_e is computed as it is in the RF receiver.

If these three noise processes are combined into one receiver noise process its spectra (N_o) will be given by the sum of the shot noise spectra (N_{sn}), the dark current spectra (N_{dc}) and the thermal current spectra (N_t).

$$N_o = N_{sn} + N_{dc} + N_t \quad \text{amps}^2 \text{ per Hz} \qquad (26)$$

where N_{sn}, N_{dc} and N_t are defined below.

$$N_{sn}(w) = G_{av}^2 \, F \, q \, u \, P_{av} \quad \text{amps}^2 \text{ per Hz} \qquad (27)$$

G_{av} = time average of photodetector gain

F = 1 + Gain variance/G_{av}

= excess noise factor

q = 1.6×10^{-19} coulombs

= charge of one electron

u = $q \, n \, G_{av} / h \, f_o$

= receiver responsivity

P_{av} = time average of received power

$$N_{dc}(w) = q \, I_{dc} \quad \text{amps}^2 \text{ per Hz} \qquad (28)$$

q = 1.6×10^{-19} coulombs

= charge of one electron

I_{dc} = detector mean dark current

$$N_t(w) = 4 \, k \, T_e / R_1 \quad \text{amps}^2 \text{ per Hz} \qquad (29)$$

k = 1.38×10^{-23} °K

= Boltzmann's constant

T_e = receiver noise temperature

R_1 = impedance loading of photodetector

(5:365-638)

Signal to Noise Ratio - Optical Systems

To write the signal to noise ratio for an optical receiver the receiver structure must be considered. There are two types of optical receivers; the direct detection and heterodyne receivers. In direct detection a focusing lense, wavelength filter and photodetector demodulates the field intensity directly. Heterodyne receivers use a local laser to mix the received signal field before it is detected.

Direct Detection Laser Receivers. For direct detection receivers the message signal, m(t) is directly modulated onto the intensity of the laser field. The received field is then given by:

$$P_r(t) = P_r \left[1 + m(t)\, b_m \right] \qquad (30)$$

where

b_m = modulation index << 1

m(t) is normalized to unit amplitude

P_r is defined in Equation 5

The current i(t) in Figure 1, for receiver responsivity u, can now be written as:

$$i(t) = u \left[P_r(t) + P_b \right] + i_{sn}(t) + i_{dc}(t) + i_t(t) \qquad (31)$$

which expands to

$$i(t) = (u[\, P_r + P_b \,]) + [\, u\, P_r\, b_m\, m(t) \,] + i_{sn}(t) + i_{dc}(t) + i_t(t) \qquad (32)$$

If the message bandwidth is B_m and the signal power is given by:

$$P_s = (u\ P_r\ b_m)^2\ P_m \quad (33)$$

then noise power is given by Equation 34 (5:373-374).

$$P_n = 2\ B_m\ N_o \quad (34)$$

If the postdetection signal to noise ratio is defined as P_s divided by P_n, the results of Equations 7 and 25 through 34 can be combined to give:

$$SNR_s = \frac{(b_m\ n_s)^2}{[F(n_s + n_b) + n_d + n_t]2B_m} \quad (35)$$

where

$$n_d = \frac{I_{dc}}{(G_{av})^2\ q} \quad (36)$$

= average number of dark current photoelectrons per second

$$n_t = \frac{4\ k\ T_e}{(G_{av})^2\ q^2\ R_1} \quad (37)$$

= average number of thermal photoelectrons per second

q = the charge of one electron = 1.6×10^{-19} coulombs

Analyzing Equation 35 we see that a high gain photomultiplier would decrease the effect of post detection (thermal and dark current) noise by making n_s and n_b the dominant factors. As a tradeoff, increasing photomultiplier gain increases the excess noise factor, F (5:374).

<u>Heterodyne Laser Receivers</u>. Heterodyne laser systems mix a very strong and very stable local field with the received field before it encounters the photodetector to generate an IF signal. Mixing in this way offers several advantages. First the IF signal strength is proportional to the product of the local field and the receive field so an effective amplification of the received bsignal occurs. Secondly, avalanche photodiodes with their temperature dependent operation and noisy electron multiplication process are not necessary in heterone lasers. Third, the bandwidth of the received field is determined by the IF filter, not the laser optics and can be made as narrow as the information bandwidth (9:2-114). Fourth, since the signal field and local field are detected as a product, information can be modulated onto the signal field by any means which allows it to be recovered in a mixing process (e.g. AM, FM, PM) (5:377).

For a heterodyne laser crosslink the received laser power is given by (5:377):

$$P_s = (2\ u)^2\ P_L\ P_r \tag{38}$$

where

P_L = the local laser field power

P_r = received power over the receiving photodetector area

u = the photodetector responsivity

As with the direct detector, the heterodyne receiver noise contributions are due to background, shot noise, detector dark current and thermal current. Local field power being much greater than the background and signal field powers is the dominant field driving shot noise. Since high gain photomultipliers are not needed in heterodyne detection, F and G_{AV} are given a unity value. With these simplifications the equation for detected signal to noise ratio becomes

$$SNR_s = \frac{4\ u^2\ P_L\ P_r}{[quP_L + 4quP_L N_b/2 + qI_{dc} + 4kT/R_L]2B} \qquad (39)$$

where B is the IF bandwidth and $N_b = n\ N(f)\lambda^2/hf$. If n_L is defined as $n_L = n\ P_L/hf$ the SNR_s can be written as (5:377-378)

$$SNR_s = \frac{4n_s/2B}{1 + 2N_b + n_d/n_L + n_t/n_L} \qquad (40)$$

Signal to noise ratio can be converted to the more useful E_b/N_o ratio by evaluating SNR_s at bandwidth equal to bit rate (5:386).

$$Eb/No = SNR_s \text{ for } B = 1/T_b = R_b/k \qquad (41)$$

Digital Communications Signalling

A digital communications system accepts a continuous waveform from a source. This waveform is source coded (sampled and quantized) into a set of discrete letters called an alphabet. Often the source alphabet is the binary digits one and zero.

Source coded information is then passed to the digital modulator where a waveform is assigned to each letter or groups of letters of the source alphabet. In the receiver a demodulator looks at the received waveform and makes decisions as to which source sequence corresponds to the received waveform. If the transmitted waveform has been corrupted by noise an incorrect decision is possible.

The different digital modulators, and hence signalling methods, are characterized by probability of bit error and bandwidth requirements. Probability of bit error is dependent on the energy per bit to noise ratio and the number of distinct signals in the signal set, M. For a binary source alphabet groups of k source letters (ones and zeroes) are modulated into one of the M signals. In this way there are $2^k = M$ signals (see the example below) (10).

Given: A binary source alphabet, [0,1]

$M = 4$ Phase shift keyed signalling (4-ary PSK)

Then: $M = 2^k \quad k = 2$

2 bits of source data (00, 01, 10, 11) are assigned to one of 4 phases of a carrier frequency

Phase Shift Keying (PSK). The first signalling waveform to be discussed is M-ary phase shift keying (MPSK). The equation describing the MPSK waveform is given by Equation 42 (10).

numbers given by Equation 13.3.3 of Gowar's text (Equation 61 below). The bandwidth values in ref. 9 (when given) are in conflict with those indicated by Gowar.

Table VI.

Characteristics of APDs

	λ (nm)	G_{av}	F (dB)	I_{dc} (nA)	n	t_t (ns)	B (MHz)
Low risk	700-1700	100	14	10	.80	1	440
High risk	700-1700	100	0	0	.80	<.1	4400
Mean*	700-1700	100	10.9	5	.80	<.55	800
5-year	700-1700	100	6	1	.80	<.1	4400

Source: (9:2-107 to 109,13:393-394 and 371-374)

Note: * mean of high and low transit times and Equ. 61 below are used to compute mean bandwidth, not mean of the bandwidths.

$$f = \frac{.44}{t_t} \qquad (61)$$

The detection area, A_d, has been chosen to have a 130 um diameter as indicated in ref. 13 page 391. This seems consistent with the ref. 9 comment that a good silicon APD would generate approximately 1 nanoampere of dark current. Ref. 9, Figure 2.4-1 list a GaAlAs APD with 4800 nA/cm^2. The resulting dark current would be I_{dc} = .64 nA. Also from Figure 2.4-1 a silicon APD with 20,000 nA/cm^2 yields I_{dc} = 2.65 nA.

uses high electron mobility transistors (HEMT) instead of GaAs FETs for amplfiers. Currently not available in the 60 or 90 GHz frequencies HEMTs could provide 3.0 dB noise figure at 60 dB in the future (9:2-87).

Table V.

RF Receiver Noise Figure / Bandwidth

	60 GHz	90 GHz
Low risk	6.5 dB / 2 GHz	7.0 dB / 2 GHz
High risk	2.5 dB / 2 GHz	3.0 dB / 2 GHz
Mean*	4.9 dB / 2 GHz	5.4 dB / 2 GHz
5-year	3.0 dB / 2 GHz	3.5 dB / 2 GHz

Optical Receivers

Direct Detection. Avalanche photodiodes (APD) are currently the best way to detect optical signals intensity modulated on an optical carrier. APDs are currently available in silicon, gallium aluminium arsenide and indium gallium arsenide (InGaAs). InGaAs currently offer good operating characteristics and show promise for future improvements. In five years a silicon APD may match the InGaAs better excess noise factor performance (6 dB) (9:2-108).

Values given in Table 6 are based on information in Figure 2.4-1 of ref. 9 and the reading in the few pages prior. Bandwidth values are not those given in ref. 9 but are the within 5 years and 1 W in a few more years (9:2-90,2-91). Also within a five year view is a viable heterodyned laser system. Laboratory experiments have used GaAa laser with coherent beam combining techniques to produce a 90 mW near diffraction limited beam and 3 W in a multimode beam (9:2-96).

Table IV.

Optical Sources

	Direct Detection Nd:YAG	Heterodyne GaAs
Low risk	200 mW	20 mW
High Risk	1 W	90 mW
Mean	600 mW	55 mW
5-year	500 mW	25 mW

RF Receiver Noise

For satellite crosslinks at 60 and 90 GHz two receiver technologies offer the best current and prospectivce noise performance. The first is a Mixer/IF Amplifier. Current capabilities allow a 60 GHz carrier system with a noise figure of 6.5 dB at 290 °K and 7.0 dB at 290 °K for a 90 GHz carrier system. A factor of 2 to 3 (3.0 to 4.7 dB) noise figure improvement in future systems could be achieved by cooling to 150 °K. An additional improvement of 1 to 2 dB is possible with development of better filters for high frequency image enhanced mixers (9:2-83 to 87;2-69 to 72). The second receiver structure

State of the art in satellite qualified optics is 8 inch optics. A 20 inch tel .cope is feasible but weight for this device using advanced construction techniques would be 42 lbs (9:3-42).

Half power beamwidth is easily obtained from optics diameter and the wavelength of the laser source (see Equation 9).

Table III.

Optical Antennas - Lense Diameter

Low risk	8 inch
High risk	20 inch
Mean	14 inch
5-year	10 inch

Laser Source. Relatively few wavelengths are currently being considered for laser communications. CO_2 lasers operate at 9 to 11 um but are seen unlikely as ISL carriers due to limitations on lifetime. The other candidates are GaAlAs, GaInAsP and Nd:YAG. The gallium arsenide (800-900 nm) diode lasers generate output powers of 20 mW. Operating at a 1064 nm Nd:YAG source (laser diode excited) is capable of 200 mW output power. A frequency doubled, diode pumped, slab Nd:YAG laser can generate over 400 mW (9:2-90 to 2-98).

It is clear advances in laser technology are necessary before laser crosslinks are feasible. These advances are not unreasonable. A Nd:YAG laser can be expected to supply .5 W program is underway within NASA to develop a 75 W, 60 GHz coupled cavity tube with 5 GHz bandwidth. At 90 GHz the five year projection for TWTAs is 40 W (9:7-4,2-3). The alternative to TWTAs is the impact avalanche transit time diode (IMPATT). Available technology can produce 5 W and 2 GHz bandwidth at 60GHz power combined IMPATT amplifiers. Five year projections (1988) for IMPATT amplifiers show 10 to 12 W and 2 GHz bandwidth. In the 90 GHz region .5 W, 2 GHz is achievable with 4 W, 2 GHz projected for 1988 (9:2-35).

Table II.

Transmit Power and Amplifier Bandwidth

	60 GHz	90GHz
Low risk	10 W / 2 GHz	.5 W / 2 GHz
High risk	75 W / 5 GHz	40 W / 2 GHz
Mean	42.5 W / 3.5 GHz	20.25 W / 2 GHz
5-year	60 W / 2 GHz	4 W / 2 GHz

<u>Optical Receive Power</u>

As evident in Equation 5, to determine transmit power for optical systems, the diameter of transmit and receive optics, the half power beamwidth and transmit power are needed. As with the RF case the satellites are assumed to be identical (have the same optics) thus $d_t = d_r$.

Current limitations maximize lense diameter at 30 inches (9:7-19). A realistic expectation prior to 1989 is 10 inches.

Separation Angle	Range (km)
160°	83043.693
120°	73027.398
60°	42162.388

Millimeter Wave Receive Power

RF Antenna Gain. The two linking satellites are assumed to be identical with equal transmit and receive antenna gain. At 60 and 90 GHz a parabolic dish of between 4 and 16 feet can reasonably be expected to achieve gains of 48 to 58 dB. Projected capabilities reach 60 dB (9:3-16,3-24).

Table I.

RF Antenna Gain

Low risk	48 dB
High risk	60 dB
Mean	56 dB
5-year	53 dB

Transmit Power - Millimeter Wave System. Currently at 60 GHz a 10 W output power travelling wave tube amplifier (TWTA) has been achieved in a laboratory model with a five year projection for 60 W (9:2-3). The TRW corporation has reported TWTAs with 50 W output power at 60 GHz as feasible (12:7-6). A medium risk numbers will be given. An example is the range between satellites.

Range

The range between geosynchronous satellites is largely dependent on the operational requirements of the satellite constellation. If the radius of the earth (modelled as a sphere) is taken as 6378.388 km and geosynchrouous altitude as 35784 km above mean sea level the maximum line of sight distance between two satellites occurs when the satellites are separated by 162.6° (see development below).

$$R = 2(R_e + H_o) \sin \frac{\emptyset}{2} \tag{60}$$

$$R_e = 6378.388 \text{ km}$$

$$H_o = 35784 \text{ km}$$

The maximum separation angle occurs when the line of sight between two satellites first intersects the surface of the earth. Allowing for atmosphere the maximum allowable separation will be approximated by 160°. For the purposes of this effort three separations of 160°, 120° and 60° for long, medium and short range will be used.

Using Equation 60 the range values corresponding to 160°, 120° and 60° are given below:

III. Approach to the Problem

Chapter 2 identified the equations which yield Eb/No, P_b and Be for optical and millimeter wave ISLs. To give a range of these parameters which is physically realizable within the next five to ten years the projected capabilities of space qualifiable hardware must be investigated.

Link parameters are directly dependent on hardware design research and development. As an example, a link's energy per bit to noise ratio is directly dependent on transmit power, receiver noise characteristics and antenna design. Transmit power, receiver noise characteristics and antenna design are all based on the state of the art. The choice for values of this type are presented in a low risk, high risk, five year expectation and mean format. Low risk values reflect current state of the art technology. High risk values are the goals, expectations or reasonable hopes of research not expected to be completed within five years (prior to 1989). Five year expectation values are those which current research efforts expect to achieve for space qualifiable hardware within five years. Mean values are simply the numerical average of the low and high risk values and presented only to allow a fourth data point for comparison.

Some parameters most dependent on operational requirements than on state of the art technology can be given a fixed value. For this type of parameter a single number or a set of reasonable

In this way there can be $M = T/t' = 2BT$ pulse positions per period each representing $\log_2 M$ bits.

As is the case in M-ary FSK, M-ary PPM signals have equal energy, are equiprobable and orthogonal. Under these conditions the probability of bit error can be upper bounded by the union bound and given by Equations 50 and 51.

The bit rate for PPM can be evaluated several ways, based on pulse repetition frequency, based on quantum efficiency and bits per detected photoelectron or by pulse width and M as is done in Equation 58 (8:264).

$$R_b = \frac{\log_2 M}{T_p} = \frac{\log_2 M}{Mt'} \quad \text{bits per second} \tag{58}$$

Since $t' = 1/2B$ the bandwidth efficiency is given by:

$$Be = Rb/W = \frac{2 \log_2 M}{M} \tag{59}$$

As was the case for PSK, PAM probability of bit error is independent of the choice of assignment of k bit words to each of the M symbols. The decision regions for PAM, like PSK, are gaussian distributed but in amplitude instead of phase. If a Gray code is used to make the k bit word assignments, the same relation for P_b and P_M given in Equation 46 for PSK can be argued for PAM.

Two equally bandwidth efficient methods of transmitting PAM signals are single sideband PAM and quadrature PAM. In both methods the source sequence is broken into two parallel sequences and modulated onto the quadrature components of the carrier (sine and cosine). The bandwith required is approximately equal to $1/2T_p$. Bandwidth efficiency is given below (10,11:182).

$$Be = Rb/W = 2 \log_2 M \qquad (56)$$

It is significant to note that the bandwidth efficiency of PAM is twice that of PSK.

Pulse Position Modulation (PPM). This modulation technique positions a pulse into one of M time intervals. The general equation for the signalling waveform is given by Equation 57.

$$s(t) = \text{rect}\left[\frac{t - mt' + t'/2}{t'}\right] \quad 0 < t' < T_p \qquad (57)$$

where

$t' = 1/2B$ (B = the bandwitdh of the pulse)

$m = 0, 1, 2, \ldots, M - 1$

$T_p = Mt'$ = period of the signal

The bandwidth required for MFSK can be computed by using the required separation $1/2T_p$.

$$W = [f_c + (M + 1)/2T_p] - [f_c - 1/2T_p]$$
$$= \frac{(M + 3)}{2T_p} = \frac{(2^{**}RT + 3)}{2T_p} \qquad (52)$$

Bandwidth can be approximated as $(2^{**}RT)/(2T_p) = M/(2T_p)$ for large M. The bandwidth efficiency is then given by (10):

$$Be = Rb/W = (2 \log_2 M)/(M + 3) \qquad (53)$$

<u>Pulse Amplitude Modulation (PAM)</u>. A third method of signalling is the use of discrete levels of amplitude difference to distinguish source symbols. Equation 54 holds frequency and phase constant giving the waveform equation for M-ary PAM (10).

$$s(t) = \mathrm{Re}\,[A_m\, u(t) \exp(2j\, \pi\, f_c\, t)] \qquad (54)$$

where

$A_m = 2m - 1 - M$ for $m = 1, 2, 3, \ldots M$

$0 <= t <= T_p$

In terms of average energy per bit to noise ratio, Equation 55 gives the probability of symbol error for PAM.

$$P_M = \frac{2}{M(M - 1)} Q[(6k\, (E_{bav}/N_o)/(M^2 - 1))^{\frac{1}{2}}] \qquad (55)$$

amplitude and phase with discrete carrier frequencies. Individual source symbols are distinguished by frequency. The frequencies must be separated by $1/2T_p$ hertz to maintain orthogonality of the signal set. The equation defining the MFSK waveform is (10):

$$s(t) = \mathrm{Re}[A\ u(t)\ \exp(2j\ \pi\ (m-1)t/2T_p)\ \exp(2j\ \pi\ f_c t)] \qquad (49)$$

where

A = amplitude

$m = 1,2,3,\ \ldots\ M$

T_p = pulse period

f_c = a constant frequency

The equation for probability of bit error for MFSK is also an involved integral equation which can be approximated by an upper bound of probability of bit error. The union bound offers a reasonable bound for FSK signals. Although other bounds exist they are not defined over all the values of Eb/No. The union bound is given by Equation 50 (16:264-266). Equation 51 is used to convert the probability of symbol error to bit error (10, 11:152).

$$P_b < (M-1)\ Q\ [(E_b/N_o)] \qquad (50)$$

$$P_b = \frac{P_M\ (2^{k-1})}{(2^k - 1)} \qquad (51)$$

consecutive words differ only by one bit, a Gray code. The decision region corresponding to 8-ary PSK will be gaussian distributed about eight phases 45 degrees apart (equal variances, different means). The probability of the receiver choosing the symbol corresponding to m=2 or 4 (45° or 135° for zero initial offset) when the m=3 siganl is sent (90°) is much greater than if choosing for m=1 or 5 (2 phases away). In this way the probability of bit error is approximately equal to the probability of symbol error divided by k.

$$P_b = 1/k \; P_M \tag{46}$$

The bandwidth required for multiphase signalling is given by $W = 1/T_p$ where T_p is the duration of the pulse u(t). If R_b is the source rate in bits per second then T_p is also given by Equation 47. Using these relations the bandwidth efficiency, Be, is defined as Rb/W and has units of bits per second per hertz (11:177).

$$T_p = k/R_b = (\log_2 M)/R_b \tag{47}$$

$$Be = R_b/W = \log_2 M \tag{48}$$

Frequency Shift Keying (FSK). MPSK signals are generated by transmitting a constant amplitude, constant frequency pulse at discrete phases. Individual source symbols are distinguished by the phase of the signal. In M-ary frequency shift keying (MFSK) signals are generated by transmitting a pulse at constant

$$s(t) = Re\,[u(t)\,exp(j\,(2\pi\ f_c\ t + 2\pi\ (m-1)/M + p_o))] \qquad (42)$$

where

Re = the real part of

$u(t) = A$ for $0 <= t <= T_p$

$m = 1, 2, 3, \ldots M$

p_o = an initial phase

The probability of symbol error for M-ary PSK is given by an involved integral equation without closed form solution (See reference 11 page 168). Analysis of the equation under the individual cases of M=2 and M=4 (quadrature PSK) gives Equations 43 and 44 as approximations of P_M. For M = 8 or more and with large signal to noise ratio (>> 1) Equation 45 holds (11:169, 10).

$$\text{For } M = 2, \qquad P_M = Q\,[(2\ E_b/N_o)^{\frac{1}{2}}] \qquad (43)$$

$$\text{For } M = 4, \qquad P_M = Q\,[(2\ E_b/N_o)^{\frac{1}{2}}] - [Q\,[(2\ E_b/N_o)^{\frac{1}{2}}]]^2 \qquad (44)$$

For M large and E_b/N_o large,

$$P_M = 2\ Q\,[(2k\ E_b/N_o)^{\frac{1}{2}}\ \sin\ \pi/M] \qquad (45)$$

In order to convert probability of symbol error to bit error one must consider the assignment of k bit words to each symbol. In order to keep bit error due to incorrect receiver decisions to a minimum this assignment is made in such a way that any two

Direct Detect Front End. The current signal from the APD must be converted into a useable form. To do this a receiver front end converts to voltage and amplifies the APD current with as little additive noise as possible. The noise added by the front end is characterized by a thermal noise current, $i_t(t)$.

Several possibilities for front end design exist. First a terminating resistor of a standard value (e.g. 50 ohms) and a voltage amplifier. This design contributes the largest additive noise of the three alternatives. The second design is an integrating amplifier. Integrating amplifiers provide the greatest low noise amplification but lack dynamic range and are susceptible to pulse distortion (9:2-114). The third and possibly most advantageous design for ISLs is the transimpedance amplifier. Transimpedance amplifiers have poorer noise performance than integrating amplifiers but greater dynamic range (14:126-128).

Actual state of the art hardware characteristics are not available on the noise equivalent temperature and impedance loading of transimpedance amplifiers. As an alternative Ref. 14 gives experimental results for thermal noise current density of various semiconductors, bit rates and bandwidths. At 274 MBps the measured current density normalized to bandwidth for a GaAs FET was 6.2×10^{-15} A^2 (14:129).

Optical Background Power. To determine P_b for the direct detect optical system the noise temperature of the space seen by the optical antenna is of primary concern. The optical bandwith will be assumed to be the range of frequencies / wavelengths for which the APD was designed (e.g. 700-1700 nm or 1000 nm optical bandwidth). The worst case background noise temperature occurs when the sun is in the antenna field of view. If T = 6000 °K is used for solar noise temperature (6:B5.3.3) the background noise power is given by Equation 24.

Background power for heterodyne systems is not dependent on optical bandwidth but on IF bandwidth and the spectral radiance function (Equ. 22). Again the worst case occurs for T = 6000 °K.

Heterodyne Optical Receiver. Gain in heterodyne receiver is acheived by the multiplication of the local laser field power with the receive laser field power. This eliminates the need for high gain photomultipliers or avalanche photodiodes. For this reason the gain and excess noise factor of heterodyne system detectors are considered to equal one with negligible dark current. The only parameters needed to characterize heterodyne receivers for Eb/No, P_b and Be comparisons are local oscillator power, detector efficieny and detector bandwidth.

Development of detectors for GaAs heterodyne lasers system seems to be the lowest risk technology for ISL (9:2-120). The local laser power is therefore given by Table 4. Ref 9 discusses several detectors suitable for this type of system. This information is summarized in Table 7.

Table VII.

Heterodyne Receiver Parameters

	P_L (mW)	n	B (MHz)
Low risk	20	.62	440
High risk	90	.70	1000
Mean*	50	.66	600
5-year	25	.50	1000

Source (9:2-90 to 100, 105 to 106, 109, 114 to 120)

Note: * mean bandwith is computed from the mean of the high and low risk transit times given by Equation 61 not the mean of the bandwidths.

For receivers in the 800-900 nm wavelengths photodiode technology is fairly mature. Improvements will be difficult to achieve and may come with the tradeoff of increased dark current (13:360). Table 8 outlines currently realizable photodiode characteristics in the 800-900 nm range.

Table VIII.

Photodiode Detectors for the Heterodyne Receiver

λ (nm)	n	min. detectable signal (w)	B (MHz)
830	.70	10^{-16}	4000

Source (9:2-109,2-120)

In the absence of actual data for thermal current of heterodyne optical receivers the values for noise figure for the

90 GHz millimeter wave receiver will be used. These values are chosen as the post detection circuitry of the heterodyne receiver can be considered a conventional IF system. As the heterodyne receiver will have a smaller bandwidth than the 90 GHz receiver it is reasonable to assume the noise figure for the heterodyne receiver would be approximately equal to or less than the 90 GHz receiver.

IV. Computer Aids

Hardware Assistance

Computer programming in support of this study was done in the Pascal language on a 16 bit personal computer. Data files were then transfered to a PDP 11/70 mainframe and processed using the S data manipulation language. Graphs of probability of bit error (P_b) versus energy per bit to noise power ratio (Eb/No) were drawn on a Hewlett Packard 7220 plotter.

The Software Modules

Three major programs were needed to complete the effort. The first uses the hardware and operational parameter of Chapter 3 to generate a range of values for Eb/No. Stored in a 1 by 4 dimensional array the four values represent the low risk, high risk, expected five year and high/low risk average for each link, data rate and M-ary combination. For example, using Appendix A for a 60 GHz millimeter wave link, at 100 Mbps, and M=2 the low risk Eb/No is 9.75 dB. The high risk, 5-year and average values for this combination follow the low risk entry.

The other two programs generate the P_b over a given range of Eb/No and bandwidth efficiency for the selected signalling waveforms; PSK, PAM, and orthogonal, equiprobable, equienergy waveforms (FSK and PPM).

Coding for Eb/No

In order to generate the link, bit rate, and M-ary dependent energy per bit to noise ratio it is first convienient to find the signal to noise power ratio for the link. In this way only four array variables, one each for the 60 GHz or 90 GHz millimeter wave and Nd:Yag or GaAs laser, need to be maintained. Multiplying these values by the bandwidth of their respective receivers give the signal power to bandwidth normalized noise power ratio. From this Eb/No can be found by multiplying by the bit time, T_b (see Equation 38).

Procedures used to generate interim results include millimeter wave noise and signal power; heterodyne and direct detect optical receiver thermal, dark and shot noise photoelectron count rates, background noise count rate and receive signal count rate.

Verification of Coding for Eb/No. The correctness of the Eb/No coding was verified at each procedure and for the entire program by input of known data values and comparison of the results with pencil and paper calculations. The program computations, although lengthy, involve only the four basic mathematical operators (+, -, x, ÷) and are therfore easily checked for correctness. The results cannot be compared to existing equipment for authenticity as they are based on projections for future component technology. The actual Eb/No for future systems should be bracketed within the low to high risk range.

Coding for Probability of Bit Error

Of the four signalling waveforms selected for comparison two, Pulse Position Modulation and Frequency Shift Keying, posess certain common and useful characteristics. PPM and FSK yield orthogonal, equiprobable and equienergy signal sets. P_b for such signal sets can be upper bounded by the union bound. Other equations for approximating probability of error are available and give tighter bounds over regions but are unreliable for the low signal to noise ratio case (give probabilities greater than 1) and contain discontinuities at their upper and lower limits. For high signal to noise ratio the union bound for a given P_b was found to require approximately 1 dB more energy per bit to noise than the best approximation available in reference 11. The union bound is also everywhere continuous and gives consistent values of probability of error in the low signal to noise ratio case.

Using the Union Bound for the orthogonal signalling schemes and two other equations for PSK and PAM, three major procedures give probability of bit error. Central to these procedures is the use of the gaussian Q function defined below.

$$Q(a) = \int_a^{\infty} \frac{1}{(2\pi)^{\frac{1}{2}}} \exp[x^2/2]\, dx \qquad (59)$$

Although well tabulated the solution to this equation is completed by numerical integration. Methods of numerical integration usually involve using a small increments of the independent variable, calculating area under the curve and summing these incremental areas. With this method extremely high accuracy can be obtained at the expense of computaion time.

A second method uses a series expansion to iteratively approximate the function. Again accuracy is increased at the expense of computation time by increasing the number of terms in the expansion. This method for the Q function is reliable for small arguments but introduces increasing error for large arguments.

The method which was used is a combination of a 12th order polynomial approximation of the Q function for large arguments (a greater than 1.5) and a 12 term series expansion for small arguments (see ref. 17 and Appendix E).

Verification Probability of Bit Error Results. The values for P_b over the range of -10 to 20 dB and for M=2, 4, 8, and 16 are tabulated in Appendix B and in graphical form throughout Appendix D. These results were compared against the graphical results of reference 11 and found consistent. In the worst case for a given value of P_b, Eb/No differs by no more than 1 to 2 dB between the two sets of results.

The accuracy of the Q function was verified to four decimal places by comparison of calculated results to the tabulated results of reference 18.

Coding for Bandwidth Efficiency

The third major program evaluates the required signalling bandwidth and bandwidth efficiency of the four signalling schemes at various values of M. The equations for signalling bandwidth and bandwidth efficiency are well defined in Chapter 2 and easily coded. The results of this program are presented in Appendix C and verified by pencil and paper calculation.

V. Presentation of Results

Overview

The numerical values for probability of bit error discussed in Chapter 4 and tabulated in Appendix B were used to create a set of graphs for 2-ary, 4-ary, 8-ary and 16-ary signalling. On each graph the range of energy per bit to noise ratio for a given bit rate and receiver/transmitter type corresponding to low and high risk, high/low average and five year projection are indicated with an L, H, A, or F respectively. Eb/No values are tabulated in Appendix A. From these graphs, included as Appendix D, and the bandwidth calculations of Appendix C, the link performance, risk and bandwidth requirements for each M, bit rate and receiver/transmitter combination can be described and compared.

Bandwidth Requirements

Appendix C gives the set of numbers for bandwidth efficiency and required signalling bandwidth for the four signalling schemes at various values of M (or equivalently K). Bandwidth efficiency as determined by the equations of Chapter 2 has the units of bits per second per hertz. It can be used to give a measure of the bit rate supported by a given bandwidth or inversely the bandwidth expended to provide a specified bit rate. A large Rb/W is desirable. The larger the bandwidth efficiency the more information can be conveyed over a fixed bandwidth.

Comparing Rb/W (see Appendix C) one sees that the most efficient of the four signalling schemes is PAM. Pulse Amplitude Modulation is twice as bandwidth efficient as PSK with efficiency increasing (as does PSK) as M increases. As a tradeoff the probabability of bit error versus energy per bit to noise ratio curve for PAM does not drop off as quickly as does the PSK curve for the higher values of M. The orthogonal signalling waveforms (FSK and PPM) are the least bandwidth efficient with decreasing efficiency for increasing M. Orthogonal signalling schemes exhibit a more favorable P_b vs. Eb/No curve than do PSK or PAM. With increasing M bit error probability for FSK/PPM drops off faster than PSK or PAM. or PAM curves.

Link Bit Error Performance

Bit error performance is evaluated from the graphs of Appendix D and the criteria of Table 9.

Table 9

Performance Criteria for Link P_b

P_b	Performance
$x > 10^{-4}$	poor
$10^{-4} => x => 10^{-8}$	marginal
$10^{-8} > x$	good

The first system to be discussed is the millimeter wave 60 GHz link at the low bit rate (1 MBps) progressing to the higher rates (100 and 1000 MBps). After the 60 GHz links, the millimeter wave 90 GHz, direct detect optical Nd:YAG laser and heterodyne optical GaAs laser links are presented.

Millimeter Wave 60 GHz ISL. Sixty gigahertz intersatellite links offer technically feasible communications through 1000 MBps. Figures 2 through 13 plot the probability of bit error versus energy per bit to noise ratio for 60 GHz links at 160° separation, 1 MBps to 1000 MBps and M=2, 4, 8 and 16.

Consider first the four figures (Figs. 2 to 5) for 1 MBps communications. At this bit rate the low risk Eb/No is approximately 10 dB for M=2 (see Fig. 2) and 16 dB for M=16. Achieving an error probability of 10^{-8} at or slightly above the low risk level for one or more signalling schemes is reasonable.

For communication at 100 MBps and 160° separation (Figs. 6 to 9) the risk increases but again good performance can be obtained. Five year projections of current technology would allow good performance for 2, 4 or 8-ary PSK, FSK or PPM. PAM signalling for M greater than 4 requires high risk Eb/No to achieve 10^{-8} probability of bit error. For M=16 only FSK/PPM can give good performance within five year projections of Eb/No.

Achieving 10^{-8} performance at 1000 MBps and 160° is less likely. Frequency Shift Keyed or Pulse Position Modulation M=16 systems with Eb/No of 8 to 9 dB could give this performance at slightly higher than current five year projections (see Figs. 10

to 13). For values of M less than 16 or other signalling schemes high risk Eb/No of 13 dB or more would approach good performance. Marginal (10^{-4}) performance can be obtained for M=8 and M=16 orthogonal signalling with five year Eb/No projections.

Referring to Appendix A the energy per bit to noise ratio values for 120° or less separation show that performance of 10^{-8} bit error probability or smaller is low risk for all signalling schemes.

Millimeter Wave 90 GHz ISL. Good performance at 90 gigahertz, 160° separation and 1 MBps is feasible (see Figs. 14 to 17). Eb/No at the high/low risk average value gives a bit error probability of 10^{-8} or smaller for nearly all signalling schemes and M combinations. The exceptions are 8-ary and 16-ary PAM. High/low risk average Eb/No will only provide marginal or poor performance for 8-ary and 16-ary PAM. Note that the high/low average is smaller and therefore a lower risk than the five year projection. The orthogonal schemes for M=2 require approximately 3 dB more Eb/No for equivalent performance. Risk in achieving this Eb/No is low to moderate and less than five year projections.

Stepping the bit rate up to 100 MBps shows a significant increase in development risk. For M=2 and M=4 (see Figs. 18 and 19) the five year projections of 5.55 and 8.56 dB allow only poor performance. Good performance at these values of M occurs with high risk development. If M is increased to 8 or 16 (see Figs. 20 and 21) the orthogonal signalling schemes offer marginal to good performance at five year projected Eb/No. PSK and PAM for M=8 or M=16 require high risk state of the art advancements to provide P_b of 10^{-6} or better.

At 1 GBps and 160° separation (see Figs. 22 to 25) M=2 and M=4 signalling exceed the high risk Eb/No projections for 10^{-5} bit error probability. With high risk, M=8 and M=16 FSK or PPM will provide good performance at Eb/No of 10.0 and 9.0 dB respectively.

If angular separation is decreased to 120° (see Appendix A) five year Eb/No projections provide for good performance at 1 and 100 MBps. At 1 GBps five year values give poor performance. High risk development does allow good performance at 1 GBps. Decreasing angular separation to 60° will give good performance at the high/low average value of Eb/No for 1 MBps. Bit error of 10^{-8} or smaller is achievable for 100 MBps with five year projections. At 500 or 1000 MBps the risk for good performance is high.

Direct Detect Nd:YAG Laser. A direct detection Nd:YAG laser ISL has considerably higher risk for a given level of performance than do the millimeter wave systems. At 1 MBps and 160° separation (see Figs. 26 to 29) 10^{-8} bit error performance is achievable with high risk advances of the state of the art. Signalling schemes which yield this performance are 4-ary PSK and 4, 8, or 16-ary FSK and PPM. Higher bit rates at this separation are not feasible with forseeable technology.

RANGE OF Eb/No FOR MILLIMETER WAVE 60 GHZ

RANGE = 42162.388 Km SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	7.3314878384E-02	-1.1348078815E+01	LOW RISK
	1.5542044798E+02	2.1915081564E+01	HIGH RISK
	1.3154293227E+01	1.1190675186E+01	5-YEAR
	4.9003785136E+00	6.9022962697E+00	AVERAGE
M = 4	1.4662975677E-01	-8.3377788584E+00	LOW RISK
	3.1084089596E+02	2.4925381521E+01	HIGH RISK
	2.6308586453E+01	1.4200975143E+01	5-YEAR
	9.8007570272E+00	9.9125962263E+00	AVERAGE
M = 8	2.1994463515E-01	-6.5768662679E+00	LOW RISK
	4.6626134394E+02	2.6686294111E+01	HIGH RISK
	3.9462879680E+01	1.5961887733E+01	5-YEAR
	1.4701135541E+01	1.1673508817E+01	AVERAGE
M = 16	2.9325951354E-01	-5.3274789018E+00	LOW RISK
	6.2168179193E+02	2.7935681478E+01	HIGH RISK
	5.2617172906E+01	1.7211275100E+01	5-YEAR
	1.9601514054E+01	1.2922896183E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	3.6657439192E-02	-1.4358378772E+01	LOW RISK
	7.7710223991E+01	1.8904781608E+01	HIGH RISK
	6.5771466133E+00	8.1803752296E+00	5-YEAR
	2.4501892568E+00	3.8919963131E+00	AVERAGE
M = 4	7.3314878384E-02	-1.1348078815E+01	LOW RISK
	1.5542044798E+02	2.1915081564E+01	HIGH RISK
	1.3154293227E+01	1.1190675186E+01	5-YEAR
	4.9003785136E+00	6.9022962697E+00	AVERAGE
M = 8	1.0997231758E-01	-9.5871662245E+00	LOW RISK
	2.3313067197E+02	2.3675994155E+01	HIGH RISK
	1.9731439840E+01	1.2951587777E+01	5-YEAR
	7.3505677704E+00	8.6632088602E+00	AVERAGE
M = 16	1.4662975677E-01	-8.3377788584E+00	LOW RISK
	3.1084089596E+02	2.4925381521E+01	HIGH RISK
	2.6308586453E+01	1.4200975143E+01	5-YEAR
	9.8007570272E+00	9.9125962263E+00	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 60 GHZ

RANGE = 42162.388 Km SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	3.6657439192E+01	1.5641621228E+01	LOW RISK
	7.7710223991E+04	4.8904781608E+01	HIGH RISK
	6.5771466133E+03	3.8180375230E+01	5-YEAR
	2.4501892568E+03	3.3891996313E+01	AVERAGE
M = 4	7.3314878384E+01	1.8651921185E+01	LOW RISK
	1.5542044798E+05	5.1915081564E+01	HIGH RISK
	1.3154293227E+04	4.1190675186E+01	5-YEAR
	4.9003785136E+03	3.6902296270E+01	AVERAGE
M = 8	1.0997231758E+02	2.0412833775E+01	LOW RISK
	2.3313067197E+05	5.3675994155E+01	HIGH RISK
	1.9731439840E+04	4.2951587777E+01	5-YEAR
	7.3505677704E+03	3.8663208860E+01	AVERAGE
M = 16	1.4662975677E+02	2.1662221141E+01	LOW RISK
	3.1084089596E+05	5.4925381521E+01	HIGH RISK
	2.6308586453E+04	4.4200975143E+01	5-YEAR
	9.8007570272E+03	3.9912596226E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	3.6657439192E-01	-4.3583787717E+00	LOW RISK
	7.7710223991E+02	2.8904781608E+01	HIGH RISK
	6.5771466133E+01	1.8180375230E+01	5-YEAR
	2.4501892568E+01	1.3891996313E+01	AVERAGE
M = 4	7.3314878384E-01	-1.3480788151E+00	LOW RISK
	1.5542044798E+03	3.1915081564E+01	HIGH RISK
	1.3154293227E+02	2.1190675186E+01	5-YEAR
	4.9003785136E+01	1.6902296270E+01	AVERAGE
M = 8	1.0997231758E+00	4.1283377548E-01	LOW RISK
	2.3313067197E+03	3.3675994155E+01	HIGH RISK
	1.9731439840E+02	2.2951587777E+01	5-YEAR
	7.3505677704E+01	1.8663208860E+01	AVERAGE
M = 16	1.4662975677E+00	1.6622211416E+00	LOW RISK
	3.1084089596E+03	3.4925381521E+01	HIGH RISK
	2.6308586453E+02	2.4200975143E+01	5-YEAR
	9.8007570272E+01	1.9912596226E+01	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 60 GHZ

RANGE = 73027.398 Km   SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	2.4438292794E-02	-1.6119291362E+01	LOW RISK
	5.1806815994E+01	1.7143869017E+01	HIGH RISK
	4.3847644088E+00	6.4194626390E+00	5-YEAR
	1.6334595046E+00	2.1310837226E+00	AVERAGE
M = 4	4.8876585588E-02	-1.3108991406E+01	LOW RISK
	1.0361363199E+02	2.0154168974E+01	HIGH RISK
	8.7695288176E+00	9.4297625956E+00	5-YEAR
	3.2669190091E+00	5.1413836792E+00	AVERAGE
M = 8	7.3314878382E-02	-1.1348078815E+01	LOW RISK
	1.5542044798E+02	2.1915081564E+01	HIGH RISK
	1.3154293226E+01	1.1190675186E+01	5-YEAR
	4.9003785137E+00	6.9022962698E+00	AVERAGE
M = 16	9.7753171176E-02	-1.0098691449E+01	LOW RISK
	2.0722726398E+02	2.3164468930E+01	HIGH RISK
	1.7539057635E+01	1.2440062552E+01	5-YEAR
	6.5338380182E+00	8.1516836358E+00	AVERAGE
	BIT RATE = 1 GBps		
M = 2	1.2219146397E-02	-1.9129591319E+01	LOW RISK
	2.5903407997E+01	1.4133569060E+01	HIGH RISK
	2.1923822044E+00	3.4091626824E+00	5-YEAR
	8.1672975228E-01	-8.7921623406E-01	AVERAGE
M = 4	2.4438292794E-02	-1.6119291362E+01	LOW RISK
	5.1806815994E+01	1.7143869017E+01	HIGH RISK
	4.3847644088E+00	6.4194626390E+00	5-YEAR
	1.6334595046E+00	2.1310837226E+00	AVERAGE
M = 8	3.6657439191E-02	-1.4358378772E+01	LOW RISK
	7.7710223991E+01	1.8904781608E+01	HIGH RISK
	6.5771466132E+00	8.1803752296E+00	5-YEAR
	2.4501892568E+00	3.8919963131E+00	AVERAGE
M = 16	4.8876585588E-02	-1.3108991406E+01	LOW RISK
	1.0361363199E+02	2.0154168974E+01	HIGH RISK
	8.7695288176E+00	9.4297625956E+00	5-YEAR
	3.[illegible]9190091E+00	5.1413836792E+00	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 60 GHZ

RANGE = 73027.398 Km   SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	1.2219146397E+01	1.0870408681E+01	LOW RISK
	2.5903407997E+04	4.4133569060E+01	HIGH RISK
	2.1923822044E+03	3.3409162682E+01	5-YEAR
	8.1672975228E+02	2.9120783766E+01	AVERAGE
M = 4	2.4438292794E+01	1.3880708638E+01	LOW RISK
	5.1806815994E+04	4.7143869017E+01	HIGH RISK
	4.3847644088E+03	3.6419462639E+01	5-YEAR
	1.6334595046E+03	3.2131083723E+01	AVERAGE
M = 8	3.6657439191E+01	1.5641621228E+01	LOW RISK
	7.7710223991E+04	4.8904781608E+01	HIGH RISK
	6.5771466132E+03	3.8180375229E+01	5-YEAR
	2.4501892568E+03	3.3891996313E+01	AVERAGE
M = 16	4.8876585588E+01	1.6891008594E+01	LOW RISK
	1.0361363199E+05	5.0154168974E+01	HIGH RISK
	8.7695288175E+03	3.9429762596E+01	5-YEAR
	3.2669190091E+03	3.5141383679E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	1.2219146397E-01	-9.1295913190E+00	LOW RISK
	2.5903407997E+02	2.4133569060E+01	HIGH RISK
	2.1923822044E+01	1.3409162682E+01	5-YEAR
	8.1672975228E+00	9.1207837659E+00	AVERAGE
M = 4	2.4438292794E-01	-6.1192913624E+00	LOW RISK
	5.1806815994E+02	2.7143869017E+01	HIGH RISK
	4.3847644088E+01	1.6419462639E+01	5-YEAR
	1.6334595046E+01	1.2131083723E+01	AVERAGE
M = 8	3.6657439191E-01	-4.3583787718E+00	LOW RISK
	7.7710223991E+02	2.8904781608E+01	HIGH RISK
	6.5771466132E+01	1.8180375230E+01	5-YEAR
	2.4501892568E+01	1.3891996313E+01	AVERAGE
M = 16	4.8876585588E-01	-3.108991405[illegible]E+00	LOW RISK
	1.0361363199E+03	3.0154168974E+01	HIGH RISK
	8.7695288176E+01	1.9429762596E+01	5-YEAR
	3.2669190091E+01	1.5141383679E+01	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE60 GHZ

RANGE = 83043.693 Km SEPARATION ANGLE = 160°

BIT RATE = 500 MBps

	Eb/No	Eb/No (dB)	
M = 2	1.8898581558E-02	-1.7235707908E+01	LOW RISK
	4.0063164214E+01	1.6027452472E+01	HIGH RISK
	3.3908190106E+00	5.3030460936E+00	5-YEAR
	1.2631842956E+00	1.0146671771E+00	AVERAGE
M = 4	3.7797163116E-02	-1.4225407951E+01	LOW RISK
	8.0126328428E+01	1.9037752428E+01	HIGH RISK
	6.7816380212E+00	8.3133460502E+00	5-YEAR
	2.5263685912E+00	4.0249671337E+00	AVERAGE
M = 8	5.6695744674E-02	-1.2464495361E+01	LOW RISK
	1.2018949264E+02	2.0798665019E+01	HIGH RISK
	1.0172457032E+01	1.0074258641E+01	5-YEAR
	3.7895528867E+00	5.7858797243E+00	AVERAGE
M = 16	7.5594326232E-02	-1.1215107995E+01	LOW RISK
	1.6025265686E+02	2.2048052385E+01	HIGH RISK
	1.3563276042E+01	1.1323646007E+01	5-YEAR
	5.0527371823E+00	7.0352670903E+00	AVERAGE

BIT RATE = 1 GBps

	Eb/No	Eb/No (dB)	
M = 2	9.4492907790E-03	-2.0246007864E+01	LOW RISK
	2.0031582107E+01	1.3017152515E+01	HIGH RISK
	1.6954095053E+00	2.2927461369E+00	5-YEAR
	6.3159214779E-01	-1.9956327796E+00	AVERAGE
M = 4	1.8898581558E-02	-1.7235707908E+01	LOW RISK
	4.0063164214E+01	1.6027452472E+01	HIGH RISK
	3.3908190106E+00	5.3030460936E+00	5-YEAR
	1.2631842956E+00	1.0146671771E+00	AVERAGE
M = 8	2.8347872337E-02	-1.5474795317E+01	LOW RISK
	6.0094746321E+01	1.7788365062E+01	HIGH RISK
	5.0862285159E+00	7.0639586841E+00	5-YEAR
	1.8947764434E+00	2.7755797676E+00	AVERAGE
M = 16	3.7797163116E-02	-1.4225407951E+01	LOW RISK
	8.0126328428E+01	1.9037752428E+01	HIGH RISK
	6.7816380212E+00	8.3133460502E+00	5-YEAR
	2.5263685912E+00	4.0249671337E+00	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE60 GHZ

RANGE = 83043.693 Km SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	9.4492907790E+00	9.7539921355E+00	LOW RISK
	2.0031582107E+04	4.3017152515E+01	HIGH RISK
	1.6954095053E+03	3.2292746137E+01	5-YEAR
	6.3159214779E+02	2.8004367220E+01	AVERAGE
M = 4	1.8898581558E+01	1.2764292092E+01	LOW RISK
	4.0063164214E+04	4.6027452471E+01	HIGH RISK
	3.3908190106E+03	3.5303046094E+01	5-YEAR
	1.2631842956E+03	3.1014667177E+01	AVERAGE
M = 8	2.8347872337E+01	1.4525204683E+01	LOW RISK
	6.0094746321E+04	4.7788365062E+01	HIGH RISK
	5.0862285159E+03	3.7063958684E+01	5-YEAR
	1.8947764434E+03	3.2775579768E+01	AVERAGE
M = 16	3.7797163116E+01	1.5774592049E+01	LOW RISK
	8.0126328428E+04	4.9037752428E+01	HIGH RISK
	6.7816380212E+03	3.8313346050E+01	5-YEAR
	2.5263685912E+03	3.4024967134E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	9.4492907790E-02	-1.0246007864E+01	LOW RISK
	2.0031582107E+02	2.3017152515E+01	HIGH RISK
	1.6954095053E+01	1.2292746137E+01	5-YEAR
	6.3159214779E+00	8.0043672204E+00	AVERAGE
M = 4	1.8898581558E-01	-7.2357079078E+00	LOW RISK
	4.0063164214E+02	2.6027452472E+01	HIGH RISK
	3.3908190106E+01	1.5303046094E+01	5-YEAR
	1.2631842956E+01	1.1014667177E+01	AVERAGE
M = 8	2.8347872337E-01	-5.4747953173E+00	LOW RISK
	6.0094746321E+02	2.7788365062E+01	HIGH RISK
	5.0862285159E+01	1.7063958684E+01	5-YEAR
	1.8947764434E+01	1.2775579768E+01	AVERAGE
M = 16	3.7797163116E-01	-4.2254079512E+00	LOW RISK
	8.0126328428E+02	2.9037752428E+01	HIGH RISK
	6.7816380212E+01	1.8313346050E+01	5-YEAR
	2.5263685912E+01	1.4024967134E+01	AVERAGE

Appendix A:

Energy Per Bit to Bandwidth Normalized Noise Power Ratio Values

produces a beam of the same phase, wavelength and wavefront profile as the first. The major design problem in beam combining is achieving and maintaining precise alignment of the optical elements (9:2-94 to 2-97).

Another area of concern is performance of ISLs in a burst error environment. Bit interleaving and coding provide performance protection in this type of environment.

Aside from the advantage of using coding in the bursty error environment the use of coding provides a coding gain resulting in reducing the Eb/No necessary to achieve a specified probability of bit error. As coding is routinely used on up and downlinks it may be feasible to use these same processors for crosslink coding without an increase in satellite cube, weight, or power consumption.

As has been stated several times in this report the acquisition and tracking problem for laser intersatellite links is particularly sensitive due to the small beamwidth, and the spatial and frequency acquisition necessary. Before the risk of implementing a laser ISL can be determined fully this problem must be thoroughly analyzed.

Examining the denominator of Equation 35 reveals that for separations of 160° the value of $F(n_s + n_b)$ is on the order of 10^{15}. Dark current photoelectron count rate (n_d) is negligible and thermal current photoelectron count rate (n_t) is on the order of 10^{19}. Any order of magnitude decrease in n_t down to 10^{15} will result in a order of magnitude increase in signal to noise ratio.

Thermal current count rate is inversely dependent on photodiode gain and directly on thermal current (see Equation 37). As increases in photodiode gain are expected to come with increases in shot noise current (9:2-107) the likely place for improvements in thermal current is in amplifier design. Reduction in receiver thermal current also has application to heterodyne laser receivers (see Equation 40) but not to the same extent. An order of magnitude decrease in thermal count rate will only create a 3 dB increase in signal to noise ratio.

Included in the values presented in Chapter 3 for laser source power are some state of the art advances in laser power combining techniques. Further research and advancements in this area will improve the feasibility of laser ISLs. Two approaches to this end are optical combining and beam combining. In optical combining 25 to 50 single mode laser diodes of 20 milliwatts are fabricated on one substrate to give a combined output power of .5 to 1 watt. Current limitations are proper alignment and shock, vibration and thermal distortion requirements. Beam combining differs from optical combining in that the laser light of one diode is injected into a second diode. The second diode then more difficult for laser link than the millimeter wave case. Finding the solutions to these problems may delay the development of a space qualifiable heterodyne ISL package.

Choosing the best signalling scheme for heterodyne links at 160° and 1 GBps results in several options. For M=2 or 4 PAM will provide performance equivalent to PSK but at a smaller required signalling bandwidth, 500MHz. At M=8 PSK or PPM allow good performance however PSK uses only 333 MHz signalling bandwidth against 1.833 GHz for PPM. Sixteen-ary communication is limited to PPM at 2 GHz signalling bandwidth for good bit error performance. If receiver/transmitter bandwidth constraints are not a factor PPM is the best choice at all values of M.

Comparing all four link types for the one most favorable is a difficult and perhaps improper comparison. A selection can be made however over a desired bit rate. If 1 MBps is an acceptable bit rate, designers should persue a millimeter wave 60 GHz 16-ary PAM link as the most bandwidth efficient and least risk technology. For application requiring higher bit rates at 120° or more separation, heterodyne lasers are the most likely technology to deliver this capability.

<u>Areas Which Merit Further Investigation</u>

As mentioned in discussion of the direct detection laser link, reduction in receiver thermal current has the promise of significant increase in signal to noise power ratio. Under the component performance parameters used here (see Chapter 3) receiver thermal current is the dominant noise source.

reason 90 GHz links are not recommended where frequency allocations allow a 60 GHz link to be used.

Direct Detection Nd:YAG laser systems will not deliver sufficient signal to noise power ratio at the receiving satellite to make them viable for ISLs over 120° or 160° separations with current projection of the state of the art. Performance of direct detection laser systems may be improved by advancements in minimizing thermal current. Rationale for this conclusion follows in the recommendations section.

The only feasible direct detection Nd:YAG ISL is a 60° or smaller separation, 1 MBps PPM link. For M=16 the necessary signalling bandwidth is 2 MHz.

Heterodyne GaAs laser ISLs show the most favorable Eb/No of the four link types investigated. At low risk this type of laser link seems capable of delivering good bit error performance at 160° separation and 1 GBps. Although development of the necessary components to generate these links are low risk extensions of the current state of the art this risk level is deceiving. The fabrication of the receiver within the very strict alignment tolerance required for the receive wavefront and local laser wavefront has not been demonstrated in a space qualifiable receiver. Lasing frequency of the diodes must be stable to within 1 MHz which requires millidegree accuracy of the semiconductor laser temperature and microampere accuracy of the laser diode drive current (9:2-119). As was pointed out in Chapter 2 the tracking and acquisition problem is significantly

VI. Analysis, Recommendations and Conclusions

Chapter 5 identifies the various combinations of bit rate, satellite separation, receiver/transmitter type, and signalling scheme provide good performance at low risk or within five year projections for Eb/No. The bandwidth requirements of the signalling schemes were also shown to vary with M and bit rate. Comparing the bit error performance and bandwidth requirements one can make system recommendations for inclusion in design concepts, statements of work and/or performance criteria of future ISLs.

Recommmended Links

At 60 GHz a pulse amplitude modulated 1 MBps link is the best choice of signalling scheme. An M=16 link would require a signalling bandwidth of 125 KHz. For 100 Mbps PAM performance degrades making Phase Shift Keying the best choice. Sixteen-ary PSK requires a signalling bandwidth of 25 MHz, two and one half times less than FSK or PPM. Sixty gighertz links are not recommended for bit rates nearing 1 GBps. Only high risk advancements of current technology would approach good performance at 60° separation. Higher separation of 120° and 160° are at or beyond even high risk levels of Eb/No.

Recommendation for 90 GHz links follow exactly those of 60 GHz but come at higher risk. Low risk Eb/No at 60 GHz is 16 dB below the corresponding value of Eb/No at 90 GHz. For this the risk in developing circuit components with given performance parameters (see Chapter 3). This risk does not include the very strict spatial alignment of the receive and local laser fields. Discussion of of this risk is included in Chapter 6.

Decreasing the angular separation to 120° does not offer a significant risk reduction over the 160° case. Good performance for 1 MBps is again limited to high risk Eb/No values and 4-ary PSK and 4-ary, 8-ary or 16-ary FSK and PPM (see Figs. 30 to 33).

A noticeable decrease in risk occurs at separations of 60° and 1 MBps (see Figs. 34 to 37). Under these conditions five year projections give bit error probabilities of 10^{-5} for 8-ary orthogonal signallling and 10^{-8} for 16-ary. In order to achieve higher bit rates the separation must be decreased further. High risk values of Eb/No which allow good performance at 100 MBps occur at separations of 30°. Separation must be decreased to 15° for 10^{-8} bit error probability and 1 GBps (see Figs. 38 to 45).

<u>Heterodyne GaAs Laser</u>. Heterodyne laser communications links have two advantages which give them much greater Eb/No than comparable direct detect Nd:YAG laser links. First, the IF signal strength is proportional to the product of the local field and the receive field. Secondly, background power is dependent on the IF bandwidth not the larger, optical bandwidth.

These two characteristics combine for favorable low risk performance of heterodyne GaAs links (see Figs. 46 to 49). At 160° separation and 1000 MBps a bit error probability of 10^{-8} or lower is acheivable at low risk with PSK and PAM for M=2, with PSK, PAM, FSK and PPM for M=4 and with PSK, FSK and PPM for M=8 or 16.

The risk assessment for heterodyne laser Eb/No is based on

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 83043.693 Km SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	2.1000583989E-01	-6.7776862814E+00	LOW RISK
	4.7487764907E+03	3.6765817292E+01	HIGH RISK
	3.5906705989E+02	2.5551755656E+01	5-YEAR
	1.8715985907E+01	1.2722127095E+01	AVERAGE
M = 4	4.2001167978E-01	-3.7673863248E+00	LOW RISK
	9.4975529814E+03	3.9776117249E+01	HIGH RISK
	7.1813411978E+02	2.8562055613E+01	5-YEAR
	3.7431971814E+01	1.5732427052E+01	AVERAGE
M = 8	6.3001751967E-01	-2.0064737342E+00	LOW RISK
	1.4246329472E+04	4.1537029840E+01	HIGH RISK
	1.0772011797E+03	3.0322968203E+01	5-YEAR
	5.6147957721E+01	1.7493339642E+01	AVERAGE
M = 16	8.4002335956E-01	-7.5708636813E-01	LOW RISK
	1.8995105963E+04	4.2786417206E+01	HIGH RISK
	1.4362682396E+03	3.1572355570E+01	5-YEAR
	7.4863943628E+01	1.8742727008E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	2.1000583989E-03	-2.6777686281E+01	LOW RISK
	4.7487764907E+01	1.6765817292E+01	HIGH RISK
	3.5906705989E+00	5.5517556562E+00	5-YEAR
	1.8715985907E-01	-7.2778729050E+00	AVERAGE
M = 4	4.2001167978E-03	-2.3767386325E+01	LOW RISK
	9.4975529814E+01	1.9776117249E+01	HIGH RISK
	7.1813411978E+00	8.5620556129E+00	5-YEAR
	3.7431971814E-01	-4.2675729484E+00	AVERAGE
M = 8	6.3001751967E-03	-2.2006473734E+01	LOW RISK
	1.4246329472E+02	2.1537029840E+01	HIGH RISK
	1.0772011797E+01	1.0322968203E+01	5-YEAR
	5.6147957721E-01	-2.5066603578E+00	AVERAGE
M = 16	8.4002335956E-03	-2.0757086368E+01	LOW RISK
	1.8995105963E+02	2.2786417206E+01	HIGH RISK
	1.4362682396E+01	1.1572355570E+01	5-YEAR
	7.4863943628E-01	-1.2572729917E+00	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 83043.693 Km SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	4.2001167978E-04	-3.3767386325E+01	LOW RISK
	9.4975529814E+00	9.7761172491E+00	HIGH RISK
	7.1813411978E-01	-1.4379443871E+00	5-YEAR
	3.7431971814E-02	-1.4267572948E+01	AVERAGE
M = 4	8.4002335956E-04	-3.0757086368E+01	LOW RISK
	1.8995105963E+01	1.2786417206E+01	HIGH RISK
	1.4362682396E+00	1.5723555695E+00	5-YEAR
	7.4863943628E-02	-1.1257272992E+01	AVERAGE
M = 8	1.2600350393E-03	-2.8996173778E+01	LOW RISK
	2.8492658944E+01	1.4547329796E+01	HIGH RISK
	2.1544023593E+00	3.3332681601E+00	5-YEAR
	1.1229591544E-01	-9.4963604012E+00	AVERAGE
M = 16	1.6800467191E-03	-2.7746786411E+01	LOW RISK
	3.7990211925E+01	1.5796717162E+01	HIGH RISK
	2.8725364791E+00	4.5826555262E+00	5-YEAR
	1.4972788726E-01	-8.2469730351E+00	AVERAGE
	BIT RATE = 1 GBps		
M = 2	2.1000583989E-04	-3.6777686281E+01	LOW RISK
	4.7487764907E+00	6.7658172925E+00	HIGH RISK
	3.5906705989E-01	-4.4482443438E+00	5-YEAR
	1.8715985907E-02	-1.7277872905E+01	AVERAGE
M = 4	4.2001167978E-04	-3.3767386325E+01	LOW RISK
	9.4975529814E+00	9.7761172491E+00	HIGH RISK
	7.1813411978E-01	-1.4379443871E+00	5-YEAR
	3.7431971814E-02	-1.4267572948E+01	AVERAGE
M = 8	6.3001751967E-04	-3.2006473734E+01	LOW RISK
	1.4246329472E+01	1.1537029840E+01	HIGH RISK
	1.0772011797E+00	3.2296820345E-01	5-YEAR
	5.6147957721E-02	-1.2506660358E+01	AVERAGE
M = 16	8.4002335956E-04	-3.0757086368E+01	LOW RISK
	1.8995105963E+01	1.2786417206E+01	HIGH RISK
	1.4362682396E+00	1.5723555695E+00	5-YEAR
	7.4863943628E-02	-1.1257272992E+01	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 73027.398 Km   SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	2.7156451864E-01	-5.6612697359E+00	LOW RISK
	6.1407778112E+03	3.7882233838E+01	HIGH RISK
	4.6431981762E+02	2.6668172202E+01	5-YEAR
	2.4202173170E+01	1.3838543641E+01	AVERAGE
M = 4	5.4312903728E-01	-2.6509697792E+00	LOW RISK
	1.2281555622E+04	4.0892533794E+01	HIGH RISK
	9.2863963524E+02	2.9678472158E+01	5-YEAR
	4.8404346340E+01	1.6848843597E+01	AVERAGE
M = 8	8.1469355592E-01	-8.9005718869E-01	LOW RISK
	1.8422333434E+04	4.2653446385E+01	HIGH RISK
	1.3929594529E+03	3.1439384749E+01	5-YEAR
	7.2606519510E+01	1.8609756188E+01	AVERAGE
M = 16	1.0862580746E+00	3.5933017740E-01	LOW RISK
	2.4563111245E+04	4.3902833751E+01	HIGH RISK
	1.8572792705E+03	3.2688772115E+01	5-YEAR
	9.6808692680E+01	1.9859143554E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	2.7156451864E-03	-2.5661269736E+01	LOW RISK
	6.1407778112E+01	1.7882233838E+01	HIGH RISK
	4.6431981762E+00	6.6681722017E+00	5-YEAR
	2.4202173170E-01	-6.1614563595E+00	AVERAGE
M = 4	5.4312903728E-03	-2.2650969779E+01	LOW RISK
	1.2281555622E+02	2.0892533795E+01	HIGH RISK
	9.2863963524E+00	9.6784721583E+00	5-YEAR
	4.8404346340E-01	-3.1511564028E+00	AVERAGE
M = 8	8.1469355592E-03	-2.0890057189E+01	LOW RISK
	1.8422333434E+02	2.2653446385E+01	HIGH RISK
	1.3929594529E+01	1.1439384749E+01	5-YEAR
	7.2606519510E-01	-1.3902438123E+00	AVERAGE
M = 16	1.0862580746E-02	-1.9640669823E+01	LOW RISK
	2.4563111245E+02	2.3902833751E+01	HIGH RISK
	1.8572792705E+01	1.2688772115E+01	5-YEAR
	9.6808692680E-01	-1.4085644621E-01	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 73027.398 Km   SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	5.4312903728E-04	-3.2650969779E+01	LOW RISK
	1.2281555622E+01	1.0892533795E+01	HIGH RISK
	9.2863963524E-01	-3.2152784166E-01	5-YEAR
	4.8404346340E-02	-1.3151156403E+01	AVERAGE
M = 4	1.0862580746E-03	-2.9640669823E+01	LOW RISK
	2.4563111245E+01	1.3902833751E+01	HIGH RISK
	1.8572792705E+00	2.6887721150E+00	5-YEAR
	9.6808692680E-02	-1.0140856446E+01	AVERAGE
M = 8	1.6293871118E-03	-2.7879757232E+01	LOW RISK
	3.6844666867E+01	1.5663746342E+01	HIGH RISK
	2.7859189057E+00	4.4496847055E+00	5-YEAR
	1.4521303902E-01	-8.3799438556E+00	AVERAGE
M = 16	2.1725161491E-03	-2.6630369866E+01	LOW RISK
	4.9126222490E+01	1.6913133708E+01	HIGH RISK
	3.7145585410E+00	5.6990720716E+00	5-YEAR
	1.9361738536E-01	-7.1305564896E+00	AVERAGE
	BIT RATE = 1 GBps		
M = 2	2.7156451864E-04	-3.5661269736E+01	LOW RISK
	6.1407778112E+00	7.8822338380E+00	HIGH RISK
	4.6431981762E-01	-3.3318277983E+00	5-YEAR
	2.4202173170E-02	-1.6161456359E+01	AVERAGE
M = 4	5.4312903728E-04	-3.2650969779E+01	LOW RISK
	1.2281555622E+01	1.0892533795E+01	HIGH RISK
	9.2863963524E-01	-3.2152784166E-01	5-YEAR
	4.8404346340E-02	-1.3151156403E+01	AVERAGE
M = 8	8.1469355592E-04	-3.0890057189E+01	LOW RISK
	1.8422333434E+01	1.2653446385E+01	HIGH RISK
	1.3929594529E+00	1.4393847489E+00	5-YEAR
	7.2606519510E-02	-1.1390243812E+01	AVERAGE
M = 16	1.0862580746E-03	-2.9640669823E+01	LOW RISK
	2.4563111245E+01	1.3902833751E+01	HIGH RISK
	1.8572792705E+00	2.6887721150E+00	5-YEAR
	9.6808692680E-02	-1.0140856446E+01	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 42162.388 Km   SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	8.1469355591E-01	-8.9005718874E-01	LOW RISK
	1.8422333433E+04	4.2653446385E+01	HIGH RISK
	1.3929594529E+03	3.1439384749E+01	5-YEAR
	7.2606519509E+01	1.8609756188E+01	AVERAGE
M = 4	1.6293871118E+00	2.1202427679E+00	LOW RISK
	3.6844666866E+04	4.5663746342E+01	HIGH RISK
	2.7859189058E+03	3.4449684706E+01	5-YEAR
	1.4521303902E+02	2.1620056144E+01	AVERAGE
M = 8	2.4440806677E+00	3.8811553585E+00	LOW RISK
	5.5267000299E+04	4.7424658932E+01	HIGH RISK
	4.1788783587E+03	3.6210597296E+01	5-YEAR
	2.1781955853E+02	2.3380968735E+01	AVERAGE
M = 16	3.2587742236E+00	5.1305427245E+00	LOW RISK
	7.3689333732E+04	4.8674046298E+01	HIGH RISK
	5.5718378116E+03	3.7459984662E+01	5-YEAR
	2.9042607804E+02	2.4630356101E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	8.1469355591E-03	-2.0890057189E+01	LOW RISK
	1.8422333433E+02	2.2653446385E+01	HIGH RISK
	1.3929594529E+01	1.1439384749E+01	5-YEAR
	7.2606519509E-01	-1.3902438123E+00	AVERAGE
M = 4	1.6293871118E-02	-1.7879757232E+01	LOW RISK
	3.6844666866E+02	2.5663746342E+01	HIGH RISK
	2.7859189058E+01	1.4449684706E+01	5-YEAR
	1.4521303902E+00	1.6200561443E+00	AVERAGE
M = 8	2.4440806677E-02	-1.6118844642E+01	LOW RISK
	5.5267000299E+02	2.7424658932E+01	HIGH RISK
	4.1788783587E+01	1.6210597296E+01	5-YEAR
	2.1781955853E+00	3.3809687349E+00	AVERAGE
M = 16	3.2587742236E-02	-1.4869457275E+01	LOW RISK
	7.3689333732E+02	2.8674046298E+01	HIGH RISK
	5.5718378116E+01	1.7459984662E+01	5-YEAR
	2.9042607804E+00	4.6303561009E+00	AVERAGE

RANGE OF Eb/No FOR MILLIMETER WAVE 90 GHZ

RANGE = 42162.388 Km SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	1.6293871118E-03	-2.7879757232E+01	LOW RISK
	3.6844666866E+01	1.5663746342E+01	HIGH RISK
	2.7859189058E+00	4.4496847057E+00	5-YEAR
	1.4521303902E-01	-8.3799438557E+00	AVERAGE
M = 4	3.2587742236E-03	-2.4869457275E+01	LOW RISK
	7.3689333732E+01	1.8674046298E+01	HIGH RISK
	5.5718378116E+00	7.4599846623E+00	5-YEAR
	2.9042607804E-01	-5.3696438991E+00	AVERAGE
M = 8	4.8881613354E-03	-2.3108544685E+01	LOW RISK
	1.1053400060E+02	2.0434958889E+01	HIGH RISK
	8.3577567174E+00	9.2208972528E+00	5-YEAR
	4.3563911705E-01	-3.6087313085E+00	AVERAGE
M = 16	6.5175484473E-03	-2.1859157319E+01	LOW RISK
	1.4737866746E+02	2.1684346255E+01	HIGH RISK
	1.1143675623E+01	1.0470284619E+01	5-YEAR
	5.8085215607E-01	-2.3593439424E+00	AVERAGE
	BIT RATE = 1 GBps		
M = 2	8.1469355591E-04	-3.0890057189E+01	LOW RISK
	1.8422333433E+01	1.2653446385E+01	HIGH RISK
	1.3929594529E+00	1.4393847490E+00	5-YEAR
	7.2606519509E-02	-1.1390243812E+01	AVERAGE
M = 4	1.6293871118E-03	-2.7879757232E+01	LOW RISK
	3.6844666866E+01	1.5663746342E+01	HIGH RISK
	2.7859189058E+00	4.4496847057E+00	5-YEAR
	1.4521303902E-01	-8.3799438557E+00	AVERAGE
M = 8	2.4440806677E-03	-2.6118844642E+01	LOW RISK
	5.5267000299E+01	1.7424658932E+01	HIGH RISK
	4.1788783587E+00	6.2105972962E+00	5-YEAR
	2.1781955853E-01	-6.6190312652E+00	AVERAGE
M = 16	3.2587742236E-03	-2.4869457275E+01	LOW RISK
	7.3689333732E+01	1.8674046298E+01	HIGH RISK
	5.5718378116E+00	7.4599846623E+00	5-YEAR
	2.9042607804E-01	-5.3696438991E+00	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 83043.693 Km SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	1.8133376059E-04	-3.7415213317E+01	LOW RISK
	6.9173453685E+00	8.3993945963E+00	HIGH RISK
	1.4355711460E-01	-8.4297527927E+00	5-YEAR
	6.7551895946E-03	-2.1703624573E+01	AVERAGE
M = 4	3.6266752118E-04	-3.4404913361E+01	LOW RISK
	1.3834690737E+01	1.1409694553E+01	HIGH RISK
	2.8711422920E-01	-5.4194528361E+00	5-YEAR
	1.3510379189E-02	-1.8693324617E+01	AVERAGE
M = 8	5.4400128177E-04	-3.2644000770E+01	LOW RISK
	2.0752036105E+01	1.3170607143E+01	HIGH RISK
	4.3067134380E-01	-3.6585402456E+00	5-YEAR
	2.0265568784E-02	-1.6932412026E+01	AVERAGE
M = 16	7.2533504236E-04	-3.1394613404E+01	LOW RISK
	2.7669381474E+01	1.4419994510E+01	HIGH RISK
	5.7422845840E-01	-2.4091528795E+00	5-YEAR
	2.7020758378E-02	-1.5683024660E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	1.8133376059E-06	-5.7415213317E+01	LOW RISK
	6.9173453685E-02	-1.1600605404E+01	HIGH RISK
	1.4355711460E-03	-2.8429752793E+01	5-YEAR
	6.7551895946E-05	-4.1703624573E+01	AVERAGE
M = 4	3.6266752118E-06	-5.4404913361E+01	LOW RISK
	1.3834690737E-01	-8.5903054471E+00	HIGH RISK
	2.8711422920E-03	-2.5419452836E+01	5-YEAR
	1.3510379189E-04	-3.8693324617E+01	AVERAGE
M = 8	5.4400128177E-06	-5.2644000770E+01	LOW RISK
	2.0752036105E-01	-6.8293928565E+00	HIGH RISK
	4.3067134380E-03	-2.3658540246E+01	5-YEAR
	2.0265568784E-04	-3.6932412026E+01	AVERAGE
M = 16	7.2533504236E-06	-5.1394613404E+01	LOW RISK
	2.7669381474E-01	-5.5800054904E+00	HIGH RISK
	5.7422845840E-03	-2.2409152879E+01	5-YEAR
	2.7020758378E-04	-3.5683024660E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE =83043.693 Km SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	3.6266752118E-07	-6.4404913361E+01	LOW RISK
	1.3834690737E-02	-1.8590305447E+01	HIGH RISK
	2.8711422920E-04	-3.5419452836E+01	5-YEAR
	1.3510379189E-05	-4.8693324617E+01	AVERAGE
M = 4	7.2533504236E-07	-6.1394613404E+01	LOW RISK
	2.7669381474E-02	-1.5580005490E+01	HIGH RISK
	5.7422845840E-04	-3.2409152879E+01	5-YEAR
	2.7020758378E-05	-4.5683024660E+01	AVERAGE
M = 8	1.0880025635E-06	-5.9633700814E+01	LOW RISK
	4.1504072211E-02	-1.3819092900E+01	HIGH RISK
	8.6134268760E-04	-3.0648240289E+01	5-YEAR
	4.0531137567E-05	-4.3922112070E+01	AVERAGE
M = 16	1.4506700847E-06	-5.8384313447E+01	LOW RISK
	5.5338762948E-02	-1.2569705534E+01	HIGH RISK
	1.1484569168E-03	-2.9398852923E+01	5-YEAR
	5.4041516757E-05	-4.2672724703E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	1.8133376059E-07	-6.7415213317E+01	LOW RISK
	6.9173453685E-03	-2.1600605404E+01	HIGH RISK
	1.4355711460E-04	-3.8429752793E+01	5-YEAR
	6.7551895946E-06	-5.1703624573E+01	AVERAGE
M = 4	3.6266752118E-07	-6.4404913361E+01	LOW RISK
	1.3834690737E-02	-1.8590305447E+01	HIGH RISK
	2.8711422920E-04	-3.5419452836E+01	5-YEAR
	1.3510379189E-05	-4.8693324617E+01	AVERAGE
M = 8	5.4400128177E-07	-6.2644000770E+01	LOW RISK
	2.0752036105E-02	-1.6829392857E+01	HIGH RISK
	4.3067134380E-04	-3.3658540246E+01	5-YEAR
	2.0265568784E-05	-4.6932412026E+01	AVERAGE
M = 16	7.2533504236E-07	-6.1394613404E+01	LOW RISK
	2.7669381474E-02	-1.5580005490E+01	HIGH RISK
	5.7422845840E-04	-3.2409152879E+01	5-YEAR
	2.7020758378E-05	-4.5683024660E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 73027.398 Km   SEPARATION ANGLE = 120°

BIT RATE = 1 MBps

	Eb/No	Eb/No (dB)	
M = 2	3.0322286902E-04	-3.5182380474E+01	LOW RISK
	1.1567049020E+01	1.0632225761E+01	HIGH RISK
	2.4005330431E-01	-6.1969231163E+00	5-YEAR
	1.1295899709E-02	-1.9470791722E+01	AVERAGE
M = 4	6.0644573804E-04	-3.2172080517E+01	LOW RISK
	2.3134098040E+01	1.3642525717E+01	HIGH RISK
	4.8010660862E-01	-3.1866231597E+00	5-YEAR
	2.2591799418E-02	-1.6460491765E+01	AVERAGE
M = 8	9.0966860706E-04	-3.0411167927E+01	LOW RISK
	3.4701147060E+01	1.5403438308E+01	HIGH RISK
	7.2015991293E-01	-1.4257105691E+00	5-YEAR
	3.3887699127E-02	-1.4699579175E+01	AVERAGE
M = 16	1.2128914761E-03	-2.9161780561E+01	LOW RISK
	4.6268196080E+01	1.6652825674E+01	HIGH RISK
	9.6021321724E-01	-1.7632320306E-01	5-YEAR
	4.5183598836E-02	-1.3450191808E+01	AVERAGE

BIT RATE = 100 MBps

	Eb/No	Eb/No (dB)	
M = 2	3.0322286902E-06	-5.5182380474E+01	LOW RISK
	1.1567049020E-01	-9.3677742392E+00	HIGH RISK
	2.4005330431E-03	-2.6196923116E+01	5-YEAR
	1.1295899709E-04	-3.9470791722E+01	AVERAGE
M = 4	6.0644573804E-06	-5.2172080517E+01	LOW RISK
	2.3134098040E-01	-6.3574742825E+00	HIGH RISK
	4.8010660862E-03	-2.3186623160E+01	5-YEAR
	2.2591799418E-04	-3.6460491765E+01	AVERAGE
M = 8	9.0966860706E-06	-5.0411167927E+01	LOW RISK
	3.4701147060E-01	-4.5965616920E+00	HIGH RISK
	7.2015991293E-03	-2.1425710569E+01	5-YEAR
	3.3887699127E-04	-3.4699579175E+01	AVERAGE
M = 16	1.2128914761E-05	-4.9161780561E+01	LOW RISK
	4.6268196080E-01	-3.3471743259E+00	HIGH RISK
	9.6021321724E-03	-2.0176323203E+01	5-YEAR
	4.5183598836E-04	-3.3450191808E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 73027.398 Km SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	6.0644573804E-07	-6.2172080517E+01	LOW RISK
	2.3134098040E-02	-1.6357474283E+01	HIGH RISK
	4.8010660862E-04	-3.3186623160E+01	5-YEAR
	2.2591799418E-05	-4.6460491765E+01	AVERAGE
M = 4	1.2128914761E-06	-5.9161780561E+01	LOW RISK
	4.6268196080E-02	-1.3347174326E+01	HIGH RISK
	9.6021321724E-04	-3.0176323203E+01	5-YEAR
	4.5183598836E-05	-4.3450191808E+01	AVERAGE
M = 8	1.8193372141E-06	-5.7400867970E+01	LOW RISK
	6.9402294120E-02	-1.1586261735E+01	HIGH RISK
	1.4403198259E-03	-2.8415410613E+01	5-YEAR
	6.7775398254E-05	-4.1689279218E+01	AVERAGE
M = 16	2.4257829522E-06	-5.6151480604E+01	LOW RISK
	9.2536392160E-02	-1.0336874369E+01	HIGH RISK
	1.9204264345E-03	-2.7166023246E+01	5-YEAR
	9.0367197672E-05	-4.0439891852E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	3.0322286902E-07	-6.5182380474E+01	LOW RISK
	1.1567049020E-02	-1.9367774239E+01	HIGH RISK
	2.4005330431E-04	-3.6196923116E+01	5-YEAR
	1.1295899709E-05	-4.9470791722E+01	AVERAGE
M = 4	6.0644573804E-07	-6.2172080517E+01	LOW RISK
	2.3134098040E-02	-1.6357474283E+01	HIGH RISK
	4.8010660862E-04	-3.3186623160E+01	5-YEAR
	2.2591799418E-05	-4.6460491765E+01	AVERAGE
M = 8	9.0966860706E-07	-6.0411167927E+01	LOW RISK
	3.4701147060E-02	-1.4596561692E+01	HIGH RISK
	7.2015991293E-04	-3.1425710569E+01	5-YEAR
	3.3887699127E-05	-4.4699579174E+01	AVERAGE
M = 16	1.2128914761E-06	-5.9161780561E+01	LOW RISK
	4.6268196080E-02	-1.3347174326E+01	HIGH RISK
	9.6021321724E-04	-3.0176323203E+01	5-YEAR
	4.5183598836E-05	-4.3450191808E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 42162.388 Km SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	2.7290044471E-03	-2.5639957566E+01	LOW RISK
	1.0410303368E+02	2.0174633855E+01	HIGH RISK
	2.1604647507E+00	3.3454718492E+00	5-YEAR
	1.0166304786E-01	-9.9283687428E+00	AVERAGE
M = 4	5.4580088942E-03	-2.2629657610E+01	LOW RISK
	2.0820606736E+02	2.3184933812E+01	HIGH RISK
	4.3209295014E+00	6.3557718059E+00	5-YEAR
	2.0332609572E-01	-6.9180687862E+00	AVERAGE
M = 8	8.1870133413E-03	-2.0868745019E+01	LOW RISK
	3.1230910104E+02	2.4945846402E+01	HIGH RISK
	6.4813942521E+00	8.1166843964E+00	5-YEAR
	3.0498914358E-01	-5.1571561956E+00	AVERAGE
M = 16	1.0916017788E-02	-1.9619357653E+01	LOW RISK
	4.1641213472E+02	2.6195233769E+01	HIGH RISK
	8.6418590028E+00	9.3660717625E+00	5-YEAR
	4.0665219144E-01	-3.9077688296E+00	AVERAGE
	BIT RATE = 100 MBps		
M = 2	2.7290044471E-05	-4.5639957566E+01	LOW RISK
	1.0410303368E+00	1.7463385525E-01	HIGH RISK
	2.1604647507E-02	-1.6654528151E+01	5-YEAR
	1.0166304786E-03	-2.9928368743E+01	AVERAGE
M = 4	5.4580088942E-05	-4.2629657610E+01	LOW RISK
	2.0820606736E+00	3.1849338119E+00	HIGH RISK
	4.3209295014E-02	-1.3644228194E+01	5-YEAR
	2.0332609572E-03	-2.6918068786E+01	AVERAGE
M = 8	8.1870133413E-05	-4.0868745019E+01	LOW RISK
	3.1230910104E+00	4.9458464024E+00	HIGH RISK
	6.4813942521E-02	-1.1883315604E+01	5-YEAR
	3.0498914358E-03	-2.5157156196E+01	AVERAGE
M = 16	1.0916017788E-04	-3.9619357653E+01	LOW RISK
	4.1641213472E+00	6.1952337685E+00	HIGH RISK
	8.6418590028E-02	-1.0633928237E+01	5-YEAR
	4.0665219144E-03	-2.3907768830E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 42162.388 Km SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	5.4580088942E-06	-5.2629657610E+01	LOW RISK
	2.0820606736E-01	-6.8150661881E+00	HIGH RISK
	4.3209295014E-03	-2 3644228194E+01	5-YEAR
	2.0332609572E-04	-3.6918068786E+01	AVERAGE
M = 4	1.0916017788E-05	-4.9619357653E+01	LOW RISK
	4.1641213472E-01	-3.8047662315E+00	HIGH RISK
	8.6418590028E-03	-2.0633928237E+01	5-YEAR
	4.0665219144E-04	-3.3907768830E+01	AVERAGE
M = 8	1.6374026683E-05	-4.7858445062E+01	LOW RISK
	6.2461820208E-01	-2.0438536409E+00	HIGH RISK
	1.2962788504E-02	-1.8873015647E+01	5-YEAR
	6.0997828716E-04	-3.2146856239E+01	AVERAGE
M = 16	2.1832035577E-05	-4.6609057696E+01	LOW RISK
	8.3282426944E-01	-7.9446627483E-01	HIGH RISK
	1.7283718006E-02	-1.7623628281E+01	5-YEAR
	8.1330438288E-04	-3.0897468873E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	2.7290044471E-06	-5.5639957566E+01	LOW RISK
	1.0410303368E-01	-9.8253661447E+00	HIGH RISK
	2.1604647507E-03	-2.6654528151E+01	5-YEAR
	1.0166304786E-04	-3.9928368743E+01	AVERAGE
M = 4	5.4580088942E-06	-5.2629657610E+01	LOW RISK
	2.0820606736E-01	-6.8150661881E+00	HIGH RISK
	4.3209295014E-03	-2.3644228194E+01	5-YEAR
	2.0332609572E-04	-3.6918068786E+01	AVERAGE
M = 8	8.1870133413E-06	-5.0868745019E+01	LOW RISK
	3.1230910104E-01	-5.0541535976E+00	HIGH RISK
	6.4813942521E-03	-2.1883315604E+01	5-YEAR
	3.0498914358E-04	-3.5157156196E+01	AVERAGE
M = 16	1.0916017788E-05	-4.9619357653E+01	LOW RISK
	4.1641213472E-01	-3.8047662315E+00	HIGH RISK
	8.6418590028E-03	-2.0633928237E+01	5-YEAR
	4.0665219144E-04	-3.3907768830E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 21824.858 Km SEPARATION ANGLE = 30°

BIT RATE = 1 MBps

	Eb/No	Eb/No (dB)	
= 2	3.8010050141E-02	-1.4201015575E+01	LOW RISK
	1.4499449515E+03	3.1613515142E+01	HIGH RISK
	3.0090536658E+01	1.4784299334E+01	5-YEAR
	1.4159807659E+00	1.5105735412E+00	AVERAGE
= 4	7.6020100282E-02	-1.1190715618E+01	LOW RISK
	2.8998899030E+03	3.4623815098E+01	HIGH RISK
	6.0181073316E+01	1.7794599290E+01	5-YEAR
	2.8319615318E+00	4.5208734978E+00	AVERAGE
= 8	1.1403015042E-01	-9.4298030278E+00	LOW RISK
	4.3498348545E+03	3.6384727689E+01	HIGH RISK
	9.0271609974E+01	1.9555511881E+01	5-YEAR
	4.2479422977E+00	6.2817860884E+00	AVERAGE
= 16	1.5204020056E-01	-8.1804156617E+00	LOW RISK
	5.7997798060E+03	3.7634115055E+01	HIGH RISK
	1.2036214663E+02	2.0804899247E+01	5-YEAR
	5.6639230636E+00	7.5311734544E+00	AVERAGE

BIT RATE = 100 MBps

	Eb/No	Eb/No (dB)	
= 2	3.8010050141E-04	-3.4201015575E+01	LOW RISK
	1.4499449515E+01	1.1613515142E+01	HIGH RISK
	3.0090536658E-01	-5.2157006665E+00	5-YEAR
	1.4159807659E-02	-1.8489426459E+01	AVERAGE
= 4	7.6020100282E-04	-3.1190715618E+01	LOW RISK
	2.8998899030E+01	1.4623815098E+01	HIGH RISK
	6.0181073316E-01	-2.2054007098E+00	5-YEAR
	2.8319615318E-02	-1.5479126502E+01	AVERAGE
= 8	1.1403015042E-03	-2.9429803028E+01	LOW RISK
	4.3498348545E+01	1.6384727689E+01	HIGH RISK
	9.0271609974E-01	-4.4448811927E-01	5-YEAR
	4.2479422977E-02	-1.3718213912E+01	AVERAGE
= 16	1.5204020056E-03	-2.8180415662E+01	LOW RISK
	5.7997798060E+01	1.7634115055E+01	HIGH RISK
	1.2036214663E+00	8.0489924681E-01	5-YEAR
	5.6639230636E-02	-1.2468826546E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 21824.858 Km SEPARATION ANGLE = 30°

BIT RATE = 500 MBps

	Eb/No	Eb/No (dB)	
= 2	7.6020100282E-05	-4.1190715618E+01	LOW RISK
	2.8998899030E+00	4.6238150982E+00	HIGH RISK
	6.0181073316E-02	-1.2205400710E+01	5-YEAR
	2.8319615318E-03	-2.5479126502E+01	AVERAGE
= 4	1.5204020056E-04	-3.8180415662E+01	LOW RISK
	5.7997798060E+00	7.6341150548E+00	HIGH RISK
	1.2036214663E-01	-9.1951007532E+00	5-YEAR
	5.6639230636E-03	-2.2468826546E+01	AVERAGE
= 8	2.2806030085E-04	-3.6419503071E+01	LOW RISK
	8.6996697090E+00	9.3950276454E+00	HIGH RISK
	1.8054321995E-01	-7.4341881626E+00	5-YEAR
	8.4958845954E-03	-2.0707913955E+01	AVERAGE
= 16	3.0408040113E-04	-3.5170115705E+01	LOW RISK
	1.1599559612E+01	1.0644415011E+01	HIGH RISK
	2.4072429326E-01	-6.1848007965E+00	5-YEAR
	1.1327846127E-02	-1.9458526589E+01	AVERAGE

BIT RATE = 1 GBps

	Eb/No	Eb/No (dB)	
= 2	3.8010050141E-05	-4.4201015575E+01	LOW RISK
	1.4499449515E+00	1.6135151416E+00	HIGH RISK
	3.0090536658E-02	-1.5215700666E+01	5-YEAR
	1.4159807659E-03	-2.8489426459E+01	AVERAGE
= 4	7.6020100282E-05	-4.1190715618E+01	LOW RISK
	2.8998899030E+00	4.6238150982E+00	HIGH RISK
	6.0181073316E-02	-1.2205400710E+01	5-YEAR
	2.8319615318E-03	-2.5479126502E+01	AVERAGE
= 8	1.1403015042E-04	-3.9429803028E+01	LOW RISK
	4.3498348545E+00	6.3847276888E+00	HIGH RISK
	9.0271609974E-02	-1.0444488119E+01	5-YEAR
	4.2479422977E-03	-2.3718213912E+01	AVERAGE
= 16	1.5204020056E-04	-3.8180415662E+01	LOW RISK
	5.7997798060E+00	7.6341150548E+00	HIGH RISK
	1.2036214663E-01	-9.1951007532E+00	5-YEAR
	5.6639230636E-03	-2.2468826546E+01	AVERAGE

AD-A151 964 A COMPARISON OF MILLIMETER WAVE DIRECT DETECT AND HETERODYNE LASER INTERS..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI.. M J EDMONDS 2/2

UNCLASSIFIED DEC 84 AFIT/GE/ENG/84D-27 F/G 17/2 NL

END

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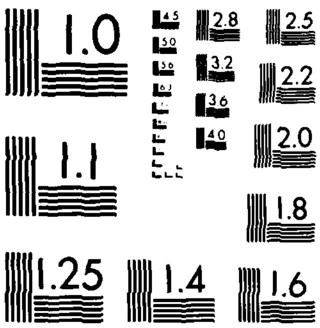


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 11006.592 Km SEPARATION ANGLE = 15°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	5.8760989657E-01	-2.3091089840E+00	LOW RISK
	2.2413922303E+04	4.3505178621E+01	HIGH RISK
	4.6513041183E+02	2.6675747361E+01	5-YEAR
	2.1890119398E+01	1.3402481304E+01	AVERAGE
M = 4	1.1752197931E+00	7.0119097263E-01	LOW RISK
	4.4827844606E+04	4.6515478578E+01	HIGH RISK
	9.3026082366E+02	2.9686047318E+01	5-YEAR
	4.3780238796E+01	1.6412781261E+01	AVERAGE
M = 8	1.7628296897E+00	2.4621035632E+00	LOW RISK
	6.7241766909E+04	4.8276391168E+01	HIGH RISK
	1.3953912355E+03	3.1446959908E+01	5-YEAR
	6.5670358194E+01	1.8173693851E+01	AVERAGE
M = 16	2.3504395863E+00	3.7114909293E+00	LOW RISK
	8.9655689212E+04	4.9525778535E+01	HIGH RISK
	1.8605216473E+03	3.2696347274E+01	5-YEAR
	8.7560477592E+01	1.9423081217E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	5.8760989657E-03	-2.2309108984E+01	LOW RISK
	2.2413922303E+02	2.3505178621E+01	HIGH RISK
	4.6513041183E+00	6.6757473611E+00	5-YEAR
	2.1890119398E-01	-6.5975186960E+00	AVERAGE
M = 4	1.1752197931E-02	-1.9298809027E+01	LOW RISK
	4.4827844606E+02	2.6515478578E+01	HIGH RISK
	9.3026082366E+00	9.6860473177E+00	5-YEAR
	4.3780238796E-01	-3.5872187394E+00	AVERAGE
M = 8	1.7628296897E-02	-1.7537896437E+01	LOW RISK
	6.7241766909E+02	2.8276391168E+01	HIGH RISK
	1.3953912355E+01	1.1446959908E+01	5-YEAR
	6.5670358194E-01	-1.8263061488E+00	AVERAGE
M = 16	2.3504395863E-02	-1.6288509071E+01	LOW RISK
	8.9655689212E+02	2.9525778535E+01	HIGH RISK
	1.8605216473E+01	1.2696347274E+01	5-YEAR
	8.7560477592E-01	-5.7691878273E-01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 11006.592 Km SEPARATION ANGLE = 15°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	1.1752197931E-03	-2.9298809027E+01	LOW RISK
	4.4827844606E+01	1.6515478578E+01	HIGH RISK
	9.3026082366E-01	-3.1395268227E-01	5-YEAR
	4.3780238796E-02	-1.3587218739E+01	AVERAGE
M = 4	2.3504395863E-03	-2.6288509071E+01	LOW RISK
	8.9655689212E+01	1.9525778535E+01	HIGH RISK
	1.8605216473E+00	2.6963472744E+00	5-YEAR
	8.7560477592E-02	-1.0576918783E+01	AVERAGE
M = 8	3.5256593794E-03	-2.4527596480E+01	LOW RISK
	1.3448353382E+02	2.1286691125E+01	HIGH RISK
	2.7907824710E+00	4.4572598649E+00	5-YEAR
	1.3134071639E-01	-8.8160061922E+00	AVERAGE
M = 16	4.7008791726E-03	-2.3278209114E+01	LOW RISK
	1.7931137842E+02	2.2536078491E+01	HIGH RISK
	3.7210432946E+00	5.7066472310E+00	5-YEAR
	1.7512095518E-01	-7.5666188261E+00	AVERAGE
	BIT RATE = 1 GBps		
M = 2	5.8760989657E-04	-3.2309108984E+01	LOW RISK
	2.2413922303E+01	1.3505178621E+01	HIGH RISK
	4.6513041183E-01	-3.3242526389E+00	5-YEAR
	2.1890119398E-02	-1.6597518696E+01	AVERAGE
M = 4	1.1752197931E-03	-2.9298809027E+01	LOW RISK
	4.4827844606E+01	1.6515478578E+01	HIGH RISK
	9.3026082366E-01	-3.1395268227E-01	5-YEAR
	4.3780238796E-02	-1.3587218739E+01	AVERAGE
M = 8	1.7628296897E-03	-2.7537896437E+01	LOW RISK
	6.7241766909E+01	1.8276391168E+01	HIGH RISK
	1.3953912355E+00	1.4469599083E+00	5-YEAR
	6.5670358194E-02	-1.1826306149E+01	AVERAGE
M = 16	2.3504395863E-03	-2.6288509071E+01	LOW RISK
	8.9655689212E+01	1.9525778535E+01	HIGH RISK
	1.8605216473E+00	2.6963472744E+00	5-YEAR
	8.7560477592E-02	-1.0576918783E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 3678.195 Km   SEPARATION ANGLE = 5°

	Eb/No	Eb/No (dB)	
BIT RATE = 1 MBps			
M = 2	4.7111101027E+01	1.6731232542E+01	LOW RISK
	1.7959439795E+06	6.2542927857E+01	HIGH RISK
	3.7249467174E+04	4.5711200649E+01	5-YEAR
	1.7550259123E+03	3.2442835330E+01	AVERAGE
M = 4	9.4222202054E+01	1.9741532499E+01	LOW RISK
	3.5918879590E+06	6.5553227813E+01	HIGH RISK
	7.4498934348E+04	4.8721500605E+01	5-YEAR
	3.5100518246E+03	3.5453135287E+01	AVERAGE
M = 8	1.4133330308E+02	2.1502445089E+01	LOW RISK
	5.3878319385E+06	6.7314140404E+01	HIGH RISK
	1.1174840152E+05	5.0482413196E+01	5-YEAR
	5.2650777369E+03	3.7214047877E+01	AVERAGE
M = 16	1.8844440411E+02	2.2751832455E+01	LOW RISK
	7.1837759180E+06	6.8563527770E+01	HIGH RISK
	1.4899786870E+05	5.1731800562E+01	5-YEAR
	7.0201036492E+03	3.8463435244E+01	AVERAGE
BIT RATE = 100 MBps			
M = 2	4.7111101027E-01	-3.2687674581E+00	LOW RISK
	1.7959439795E+04	4.2542927857E+01	HIGH RISK
	3.7249467174E+02	2.5711200649E+01	5-YEAR
	1.7550259123E+01	1.2442835330E+01	AVERAGE
M = 4	9.4222202054E-01	-2.5846750145E-01	LOW RISK
	3.5918879590E+04	4.5553227813E+01	HIGH RISK
	7.4498934348E+02	2.8721500605E+01	5-YEAR
	3.5100518246E+01	1.5453135287E+01	AVERAGE
M = 8	1.4133330308E+00	1.5024450891E+00	LOW RISK
	5.3878319385E+04	4.7314140404E+01	HIGH RISK
	1.1174840152E+03	3.0482413196E+01	5-YEAR
	5.2650777369E+01	1.7214047878E+01	AVERAGE
M = 16	1.8844440411E+00	2.7518324552E+00	LOW RISK
	7.1837759180E+04	4.8563527770E+01	HIGH RISK
	1.4899786870E+03	3.1731800562E+01	5-YEAR
	7.0201036492E+01	1.8463435244E+01	AVERAGE

RANGE OF Eb/No FOR DIRECT DETECT OPTICAL

RANGE = 3678.195 Km SEPARATION ANGLE = 5°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	9.4222202054E-02	-1.0258467501E+01	LOW RISK
	3.5918879590E+03	3.5553227813E+01	HIGH RISK
	7.4498934348E+01	1.8721500605E+01	5-YEAR
	3.5100518246E+00	5.4531352871E+00	AVERAGE
M = 4	1.8844440411E-01	-7.2481675448E+00	LOW RISK
	7.1837759180E+03	3.8563527770E+01	HIGH RISK
	1.4899786870E+02	2.1731800562E+01	5-YEAR
	7.0201036492E+00	8.4634352437E+00	AVERAGE
M = 8	2.8266660616E-01	-5.4872549542E+00	LOW RISK
	1.0775663877E+04	4.0324440361E+01	HIGH RISK
	2.2349680304E+02	2.3492713152E+01	5-YEAR
	1.0530155474E+01	1.0224347834E+01	AVERAGE
M = 16	3.7688880821E-01	-4.2378675882E+00	LOW RISK
	1.4367551836E+04	4.1573827727E+01	HIGH RISK
	2.9799573739E+02	2.4742100519E+01	5-YEAR
	1.4040207298E+01	1.1473735200E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	4.7111101027E-02	-1.3268767458E+01	LOW RISK
	1.7959439795E+03	3.2542927857E+01	HIGH RISK
	3.7249467174E+01	1.5711200649E+01	5-YEAR
	1.7550259123E+00	2.4428353304E+00	AVERAGE
M = 4	9.4222202054E-02	-1.0258467501E+01	LOW RISK
	3.5918879590E+03	3.5553227813E+01	HIGH RISK
	7.4498934348E+01	1.8721500605E+01	5-YEAR
	3.5100518246E+00	5.4531352871E+00	AVERAGE
M = 8	1.4133330308E-01	-8.4975549109E+00	LOW RISK
	5.3878319385E+03	3.7314140404E+01	HIGH RISK
	1.1174840152E+02	2.0482413196E+01	5-YEAR
	5.2650777369E+00	7.2140478776E+00	AVERAGE
M = 16	1.8844440411E-01	-7.2481675448E+00	LOW RISK
	7.1837759180E+03	3.8563527770E+01	HIGH RISK
	1.4899786870E+02	2.1731800562E+01	5-YEAR
	7.0201036492E+00	8.4634352437E+00	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE = 83043.693 KM SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
BIT RATE = 1 MBps			
M = 2	1.8253624094E+04	4.2613491026E+01	LOW RISK
	6.5367375085E+06	6.8153610456E+01	HIGH RISK
	7.8528288250E+05	5.8950261308E+01	5-YEAR
	6.7596575915E+04	4.8299246974E+01	AVERAGE
M = 4	3.6507248188E+04	4.5623790983E+01	LOW RISK
	1.3073475017E+07	7.1163910413E+01	HIGH RISK
	1.5705657650E+06	6.1960561265E+01	5-YEAR
	1.3519315183E+05	5.1309546931E+01	AVERAGE
M = 8	5.4760872282E+04	4.7384703573E+01	LOW RISK
	1.9610212525E+07	7.2924823003E+01	HIGH RISK
	2.3558486475E+06	6.3721473856E+01	5-YEAR
	2.0278972774E+05	5.3070459522E+01	AVERAGE
M = 16	7.3014496376E+04	4.8634090940E+01	LOW RISK
	2.6146950034E+07	7.4174210369E+01	HIGH RISK
	3.1411315300E+06	6.4970861222E+01	5-YEAR
	2.7038630366E+05	5.4319846888E+01	AVERAGE
BIT RATE = 100 MBps			
M = 2	1.8253624094E+02	2.2613491026E+01	LOW RISK
	6.5367375085E+04	4.8153610456E+01	HIGH RISK
	7.8528288250E+03	3.8950261308E+01	5-YEAR
	6.7596575915E+02	2.8299246974E+01	AVERAGE
M = 4	3.6507248188E+02	2.5623790983E+01	LOW RISK
	1.3073475017E+05	5.1163910413E+01	HIGH RISK
	1.5705657650E+04	4.1960561265E+01	5-YEAR
	1.3519315183E+03	3.1309546931E+01	AVERAGE
M = 8	5.4760872282E+02	2.7384703574E+01	LOW RISK
	1.9610212525E+05	5.2924823003E+01	HIGH RISK
	2.3558486475E+04	4.3721473856E+01	5-YEAR
	2.0278972774E+03	3.3070459522E+01	AVERAGE
M = 16	7.3014496376E+02	2.8634090940E+01	LOW RISK
	2.6146950034E+05	5.4174210370E+01	HIGH RISK
	3.1411315300E+04	4.4970861222E+01	5-YEAR
	2.7038630366E+03	3.4319846888E+01	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE = 83043.693 KM SEPARATION ANGLE = 160°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	3.6507248188E+01	1.5623790983E+01	LOW RISK
	1.3073475017E+04	4.1163910413E+01	HIGH RISK
	1.5705657650E+03	3.1960561265E+01	5-YEAR
	1.3519315183E+02	2.1309546931E+01	AVERAGE
M = 4	7.3014496376E+01	1.8634090940E+01	LOW RISK
	2.6146950034E+04	4.4174210370E+01	HIGH RISK
	3.1411315300E+03	3.4970861222E+01	5-YEAR
	2.7038630366E+02	2.4319846888E+01	AVERAGE
M = 8	1.0952174456E+02	2.0395003530E+01	LOW RISK
	3.9220425051E+04	4.5935122960E+01	HIGH RISK
	4.7116972950E+03	3.6731773812E+01	5-YEAR
	4.0557945549E+02	2.6080759478E+01	AVERAGE
M = 16	1.4602899275E+02	2.1644390896E+01	LOW RISK
	5.2293900068E+04	4.7184510326E+01	HIGH RISK
	6.2822630600E+03	3.7981161178E+01	5-YEAR
	5.4077260732E+02	2.7330146844E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	1.8253624094E+01	1.2613491026E+01	LOW RISK
	6.5367375085E+03	3.8153610456E+01	HIGH RISK
	7.8528288250E+02	2.8950261308E+01	5-YEAR
	6.7596575915E+01	1.8299246974E+01	AVERAGE
M = 4	3.6507248188E+01	1.5623790983E+01	LOW RISK
	1.3073475017E+04	4.1163910413E+01	HIGH RISK
	1.5705657650E+03	3.1960561265E+01	5-YEAR
	1.3519315183E+02	2.1309546931E+01	AVERAGE
M = 8	5.4760872282E+01	1.7384703574E+01	LOW RISK
	1.9610212525E+04	4.2924823003E+01	HIGH RISK
	2.3558486475E+03	3.3721473856E+01	5-YEAR
	2.0278972774E+02	2.3070459521E+01	AVERAGE
M = 16	7.3014496376E+01	1.8634090940E+01	LOW RISK
	2.6146950034E+04	4.4174210370E+01	HIGH RISK
	3.1411315300E+03	3.4970861222E+01	5-YEAR
	2.7038630366E+02	2.4319846888E+01	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE = 73027.398 KM   SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	2.3604279973E+04	4.3729907572E+01	LOW RISK
	8.4528410063E+06	6.9270027002E+01	HIGH RISK
	1.0154716083E+06	6.0066677854E+01	5-YEAR
	8.7411052998E+04	4.9415663520E+01	AVERAGE
M = 4	4.7208559946E+04	4.6740207529E+01	LOW RISK
	1.6905682013E+07	7.2280326958E+01	HIGH RISK
	2.0309432166E+06	6.3076977811E+01	5-YEAR
	1.7482210600E+05	5.2425963477E+01	AVERAGE
M = 8	7.0812839919E+04	4.8501120119E+01	LOW RISK
	2.5358523019E+07	7.4041239549E+01	HIGH RISK
	3.0464148249E+06	6.4837890401E+01	5-YEAR
	2.6223315899E+05	5.4186876067E+01	AVERAGE
M = 16	9.4417119892E+04	4.9750507485E+01	LOW RISK
	3.3811364025E+07	7.5290626915E+01	HIGH RISK
	4.0618864332E+06	6.6087277767E+01	5-YEAR
	3.4964421199E+05	5.5436263433E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	2.3604279973E+02	2.3729907572E+01	LOW RISK
	8.4528410063E+04	4.9270027002E+01	HIGH RISK
	1.0154716083E+04	4.0066677854E+01	5-YEAR
	8.7411052998E+02	2.9415663520E+01	AVERAGE
M = 4	4.7208559946E+02	2.6740207529E+01	LOW RISK
	1.6905682013E+05	5.2280326958E+01	HIGH RISK
	2.0309432166E+04	4.3076977811E+01	5-YEAR
	1.7482210600E+03	3.2425963477E+01	AVERAGE
M = 8	7.0812839919E+02	2.8501120119E+01	LOW RISK
	2.5358523019E+05	5.4041239549E+01	HIGH RISK
	3.0464148249E+04	4.4837890401E+01	5-YEAR
	2.6223315899E+03	3.4186876067E+01	AVERAGE
M = 16	9.4417119892E+02	2.9750507485E+01	LOW RISK
	3.3811364025E+05	5.5290626915E+01	HIGH RISK
	4.0618864332E+04	4.6087277767E+01	5-YEAR
	3.4964421199E+03	3.5436263433E+01	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE = 73027.398 KM SEPARATION ANGLE = 120°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	4.7208559946E+01	1.6740207529E+01	LOW RISK
	1.6905682013E+04	4.2280326958E+01	HIGH RISK
	2.0309432166E+03	3.3076977811E+01	5-YEAR
	1.7482210600E+02	2.2425963477E+01	AVERAGE
M = 4	9.4417119892E+01	1.9750507485E+01	LOW RISK
	3.3811364025E+04	4.5290626915E+01	HIGH RISK
	4.0618864332E+03	3.6087277767E+01	5-YEAR
	3.4964421199E+02	2.5436263433E+01	AVERAGE
M = 8	1.4162567984E+02	2.1511420076E+01	LOW RISK
	5.0717046038E+04	4.7051539506E+01	HIGH RISK
	6.0928296498E+03	3.7848190358E+01	5-YEAR
	5.2446631799E+02	2.7197176024E+01	AVERAGE
M = 16	1.8883423978E+02	2.2760807442E+01	LOW RISK
	6.7622728050E+04	4.8300926872E+01	HIGH RISK
	8.1237728664E+03	3.9097577724E+01	5-YEAR
	6.9928842398E+02	2.8446563390E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	2.3604279973E+01	1.3729907572E+01	LOW RISK
	8.4528410063E+03	3.9270027002E+01	HIGH RISK
	1.0154716083E+03	3.0066677854E+01	5-YEAR
	8.7411052998E+01	1.9415663520E+01	AVERAGE
M = 4	4.7208559946E+01	1.6740207529E+01	LOW RISK
	1.6905682013E+04	4.2280326958E+01	HIGH RISK
	2.0309432166E+03	3.3076977811E+01	5-YEAR
	1.7482210600E+02	2.2425963477E+01	AVERAGE
M = 8	7.0812839919E+01	1.8501120119E+01	LOW RISK
	2.5358523019E+04	4.4041239549E+01	HIGH RISK
	3.0464148249E+03	3.4837890401E+01	5-YEAR
	2.6223315899E+02	2.4186876067E+01	AVERAGE
M = 16	9.4417119892E+01	1.9750507485E+01	LOW RISK
	3.3811364025E+04	4.5290626915E+01	HIGH RISK
	4.0618864332E+03	3.6087277767E+01	5-YEAR
	3.4964421199E+02	2.5436263433E+01	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE =42162.388 KM   SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 1 MBps		
M = 2	7.0812839916E+04	4.8501120119E+01	LOW RISK
	2.5358523018E+07	7.4041239549E+01	HIGH RISK
	3.0464148248E+06	6.4837890401E+01	5-YEAR
	2.6223315898E+05	5.4186876067E+01	AVERAGE
M = 4	1.4162567983E+05	5.1511420076E+01	LOW RISK
	5.0717046036E+07	7.7051539505E+01	HIGH RISK
	6.0928296496E+06	6.7848190358E+01	5-YEAR
	5.2446631796E+05	5.7197176023E+01	AVERAGE
M = 8	2.1243851975E+05	5.3272332666E+01	LOW RISK
	7.6075569054E+07	7.8812452096E+01	HIGH RISK
	9.1392444744E+06	6.9609102948E+01	5-YEAR
	7.8669947694E+05	5.8958088614E+01	AVERAGE
M = 16	2.8325135966E+05	5.4521720032E+01	LOW RISK
	1.0143409207E+08	8.0061839462E+01	HIGH RISK
	1.2185659299E+07	7.0858490314E+01	5-YEAR
	1.0489326359E+06	6.0207475980E+01	AVERAGE
	BIT RATE = 100 MBps		
M = 2	7.0812839916E+02	2.8501120119E+01	LOW RISK
	2.5358523018E+05	5.4041239549E+01	HIGH RISK
	3.0464148248E+04	4.4837890401E+01	5-YEAR
	2.6223315898E+03	3.4186876067E+01	AVERAGE
M = 4	1.4162567983E+03	3.1511420076E+01	LOW RISK
	5.0717046036E+05	5.7051539505E+01	HIGH RISK
	6.0928296496E+04	4.7848190358E+01	5-YEAR
	5.2446631796E+03	3.7197176024E+01	AVERAGE
M = 8	2.1243851975E+03	3.3272332666E+01	LOW RISK
	7.6075569054E+05	5.8812452096E+01	HIGH RISK
	9.1392444744E+04	4.9609102948E+01	5-YEAR
	7.8669947694E+03	3.8958088614E+01	AVERAGE
M = 16	2.8325135966E+03	3.4521720032E+01	LOW RISK
	1.0143409207E+06	6.0061839462E+01	HIGH RISK
	1.2185659299E+05	5.0858490314E+01	5-YEAR
	1.0489326359E+04	4.0207475980E+01	AVERAGE

RANGE OF Eb/No FOR HETERODYNE OPTICAL

RANGE =42162.388 KM   SEPARATION ANGLE = 60°

	Eb/No	Eb/No (dB)	
	BIT RATE = 500 MBps		
M = 2	1.4162567983E+02	2.1511420076E+01	LOW RISK
	5.0717046036E+04	4.7051539505E+01	HIGH RISK
	6.0928296496E+03	3.7848190358E+01	5-YEAR
	5.2446631796E+02	2.7197176024E+01	AVERAGE
M = 4	2.8325135966E+02	2.4521720032E+01	LOW RISK
	1.0143409207E+05	5.0061839462E+01	HIGH RISK
	1.2185659299E+04	4.0858490314E+01	5-YEAR
	1.0489326359E+03	3.0207475980E+01	AVERAGE
M = 8	4.2487703949E+02	2.6282632623E+01	LOW RISK
	1.5215113811E+05	5.1822752053E+01	HIGH RISK
	1.8278488949E+04	4.2619402905E+01	5-YEAR
	1.5733989539E+03	3.1968388571E+01	AVERAGE
M = 16	5.6650271933E+02	2.7532019989E+01	LOW RISK
	2.0286818414E+05	5.3072139419E+01	HIGH RISK
	2.4371318598E+04	4.3868790271E+01	5-YEAR
	2.0978652718E+03	3.3217775937E+01	AVERAGE
	BIT RATE = 1 GBps		
M = 2	7.0812839916E+01	1.8501120119E+01	LOW RISK
	2.5358523018E+04	4.4041239549E+01	HIGH RISK
	3.0464148248E+03	3.4837890401E+01	5-YEAR
	2.6223315898E+02	2.4186876067E+01	AVERAGE
M = 4	1.4162567983E+02	2.1511420076E+01	LOW RISK
	5.0717046036E+04	4.7051539505E+01	HIGH RISK
	6.0928296496E+03	3.7848190358E+01	5-YEAR
	5.2446631796E+02	2.7197176024E+01	AVERAGE
M = 8	2.1243851975E+02	2.3272332666E+01	LOW RISK
	7.6075569054E+04	4.8812452096E+01	HIGH RISK
	9.1392444744E+03	3.9609102948E+01	5-YEAR
	7.8669947694E+02	2.8958088614E+01	AVERAGE
M = 16	2.8325135966E+02	2.4521720032E+01	LOW RISK
	1.0143409207E+05	5.0061839462E+01	HIGH RISK
	1.2185659299E+04	4.0858490314E+01	5-YEAR
	1.0489326359E+03	3.0207475980E+01	AVERAGE

Appendix B:

Eb/No vs. Probability of Bit Error Tables

M-ary PSK

Eb/No	M = 2	M = 4	M = 8	M = 16
-1.0000E+01	3.27360E-01	2.73778E-01	2.55635E-01	2.15369E-01
-9.5000E+00	3.17852E-01	2.67337E-01	2.51176E-01	2.13340E-01
-9.0000E+00	3.07910E-01	2.60506E-01	2.46480E-01	2.11194E-01
-8.5000E+00	2.97531E-01	2.53269E-01	2.41537E-01	2.08927E-01
-8.0000E+00	2.86715E-01	2.45612E-01	2.36339E-01	2.06531E-01
-7.5000E+00	2.75464E-01	2.37524E-01	2.30876E-01	2.04000E-01
-7.0000E+00	2.63790E-01	2.28997E-01	2.25142E-01	2.01328E-01
-6.5000E+00	2.51704E-01	2.20027E-01	2.19129E-01	1.98507E-01
-6.0000E+00	2.39229E-01	2.10614E-01	2.12832E-01	1.95531E-01
-5.5000E+00	2.26391E-01	2.00765E-01	2.06246E-01	1.92392E-01
-5.0000E+00	2.13228E-01	1.90495E-01	1.99368E-01	1.89083E-01
-4.5000E+00	1.99784E-01	1.79827E-01	1.92199E-01	1.85598E-01
-4.0000E+00	1.86114E-01	1.68795E-01	1.84740E-01	1.81930E-01
-3.5000E+00	1.72283E-01	1.57442E-01	1.76998E-01	1.78071E-01
-3.0000E+00	1.58368E-01	1.45828E-01	1.68979E-01	1.74015E-01
-2.5000E+00	1.44456E-01	1.34022E-01	1.60699E-01	1.69757E-01
-2.0000E+00	1.30644E-01	1.22110E-01	1.52174E-01	1.65291E-01
-1.5000E+00	1.17040E-01	1.10191E-01	1.43428E-01	1.60612E-01
-1.0000E+00	1.03759E-01	9.83761E-02	1.34490E-01	1.55717E-01
-5.0000E-01	9.09212E-02	8.67879E-02	1.25396E-01	1.50604E-01
0.00000E+00	7.86496E-02	7.55567E-02	1.16188E-01	1.45272E-01
5.00000E-01	6.70652E-02	6.48163E-02	1.06916E-01	1.39722E-01
1.00000E+00	5.62819E-02	5.46981E-02	9.76371E-02	1.33958E-01
1.50000E+00	4.64013E-02	4.53247E-02	8.84154E-02	1.27986E-01
2.00000E+00	3.75061E-02	3.68028E-02	7.93214E-02	1.21815E-01
2.50000E+00	2.96553E-02	2.92156E-02	7.04313E-02	1.15458E-01
3.00000E+00	2.28786E-02	2.26169E-02	6.18251E-02	1.08931E-01
3.50000E+00	1.71734E-02	1.70259E-02	5.35847E-02	1.02255E-01
4.00000E+00	1.25009E-02	1.24227E-02	4.57909E-02	9.54558E-02
4.50000E+00	8.79383E-03	8.75516E-03	3.85208E-02	8.85645E-02
5.00000E+00	5.95387E-03	5.93615E-03	3.18433E-02	8.16171E-02
5.50000E+00	3.86223E-03	3.85478E-03	2.58158E-02	7.46552E-02
6.00000E+00	2.38829E-03	2.38544E-03	2.04799E-02	6.77260E-02
6.50000E+00	1.39980E-03	1.39883E-03	1.58586E-02	6.08813E-02
7.00000E+00	7.72675E-04	7.72376E-04	1.19532E-02	5.41775E-02
7.50000E+00	3.98796E-04	3.98717E-04	8.74142E-03	4.76742E-02
8.00000E+00	1.90908E-04	1.90890E-04	6.18107E-03	4.14325E-02
8.50000E+00	8.39995E-05	8.39960E-05	4.20914E-03	3.55135E-02
9.00000E+00	3.36272E-05	3.36267E-05	2.74814E-03	2.99758E-02
9.50000E+00	1.21089E-05	1.21088E-05	1.71170E-03	2.48725E-02

Appendix C: Bandwidth Efficiency and Required Signalling Bandwidth

Bandwidth Efficiency

M	K	PSK	FSK	PAM	PPM
2	1	1.0000E+00	4.0000E-01	2.0000E+00	1.0000E+00
4	2	2.0000E+00	5.7143E-01	4.0000E+00	1.0000E+00
8	3	3.0000E+00	5.4545E-01	6.0000E+00	7.5000E-01
16	4	4.0000E+00	4.2105E-01	8.0000E+00	5.0000E-01
32	5	5.0000E+00	2.8571E-01	1.0000E+01	3.1250E-01

16-ary Signalling Comparisons (continued)

Eb/No	PSK	PAM	UNION BOUND
1.00000E+01	2.02488E-02	7.78067E-02	1.01585E-09
1.05000E+01	1.61385E-02	7.12794E-02	8.37631E-11
1.10000E+01	1.25618E-02	6.47734E-02	5.12684E-12
1.15000E+01	9.52321E-03	5.83368E-02	2.24622E-13
1.20000E+01	7.00961E-03	5.20215E-02	6.76337E-15
1.25000E+01	4.99245E-03	4.58829E-02	1.33699E-16
1.30000E+01	3.42730E-03	3.99782E-02	1.64839E-18
1.35000E+01	2.25799E-03	3.43649E-02	1.19664E-20
1.40000E+01	1.42069E-03	2.90984E-02	4.79493E-23
1.45000E+01	8.49005E-04	2.42299E-02	9.86362E-26
1.50000E+01	4.78936E-04	1.98033E-02	9.60301E-29
1.55000E+01	2.53281E-04	1.58528E-02	4.03890E-32
1.60000E+01	1.24600E-04	1.23999E-02	6.62422E-36
1.65000E+01	5.65251E-05	9.45180E-03	1.00000E-37
1.70000E+01	2.34169E-05	6.99961E-03	1.00000E-37
1.75000E+01	8.76221E-06	5.01937E-03	1.00000E-37
1.80000E+01	2.92515E-06	3.47210E-03	1.00000E-37
1.85000E+01	8.59265E-07	2.30705E-03	1.00000E-37
1.90000E+01	2.18681E-07	1.46545E-03	1.00000E-37
1.95000E+01	4.73845E-08	8.85130E-04	1.00000E-37
2.00000E+01	8.57259E-09	5.05307E-04	1.00000E-37
2.05000E+01	1.26681E-09	5.77752E-04	1.00000E-37
2.10000E+01	1.49190E-10	2.88507E-04	1.00000E-37
2.15000E+01	1.36207E-11	1.33095E-04	1.00000E-37
2.20000E+01	9.34594E-13	5.61837E-05	1.00000E-37
2.25000E+01	4.65477E-14	2.14706E-05	1.00000E-37
2.30000E+01	1.61833E-15	7.33895E-06	1.00000E-37
2.35000E+01	3.75928E-17	2.21367E-06	1.00000E-37
2.40000E+01	5.55464E-19	5.80352E-07	1.00000E-37
2.45000E+01	4.94042E-21	1.30010E-07	1.00000E-37
2.50000E+01	2.48624E-23	2.44159E-08	1.00000E-37
2.55000E+01	6.60435E-26	3.76240E-09	1.00000E-37
2.60000E+01	8.56599E-29	4.64409E-10	1.00000E-37
2.65000E+01	4.97057E-32	4.46942E-11	1.00000E-37
2.70000E+01	1.16978E-35	3.25352E-12	1.00000E-37
2.75000E+01	1.00000E-37	1.73156E-13	1.00000E-37
2.80000E+01	1.00000E-37	6.48525E-15	1.00000E-37
2.85000E+01	1.00000E-37	1.63766E-16	1.00000E-37
2.90000E+01	1.00000E-37	2.65738E-18	1.00000E-37
2.95000E+01	1.00000E-37	2.62544E-20	1.00000E-37
3.00000E+01	1.00000E-37	1.48658E-22	1.00000E-37

16-ary Signalling Comparisons

Eb/No	PSK	PAM	UNION BOUND
-1.0000E+01	2.15369E-01	2.16261E-01	5.00000E-01
-9.5000E+00	2.13340E-01	2.15192E-01	5.00000E-01
-9.0000E+00	2.11194E-01	2.14059E-01	5.00000E-01
-8.5000E+00	2.08927E-01	2.12861E-01	5.00000E-01
-8.0000E+00	2.06531E-01	2.11592E-01	5.00000E-01
-7.5000E+00	2.04000E-01	2.10249E-01	5.00000E-01
-7.0000E+00	2.01328E-01	2.08829E-01	5.00000E-01
-6.5000E+00	1.98507E-01	2.07325E-01	5.00000E-01
-6.0000E+00	1.95531E-01	2.05735E-01	5.00000E-01
-5.5000E+00	1.92392E-01	2.04052E-01	5.00000E-01
-5.0000E+00	1.89083E-01	2.02273E-01	5.00000E-01
-4.5000E+00	1.85598E-01	2.00391E-01	5.00000E-01
-4.0000E+00	1.81930E-01	1.98402E-01	5.00000E-01
-3.5000E+00	1.78071E-01	1.96299E-01	5.00000E-01
-3.0000E+00	1.74015E-01	1.94077E-01	5.00000E-01
-2.5000E+00	1.69757E-01	1.91730E-01	5.00000E-01
-2.0000E+00	1.65291E-01	1.89251E-01	4.48552E-01
-1.5000E+00	1.60612E-01	1.86635E-01	3.69663E-01
-1.0000E+00	1.55717E-01	1.83874E-01	2.98670E-01
-5.0000E-01	1.50604E-01	1.80962E-01	2.36039E-01
0.00000E+00	1.45272E-01	1.77892E-01	1.82003E-01
5.00000E-01	1.39722E-01	1.74658E-01	1.36535E-01
1.00000E+00	1.33958E-01	1.71253E-01	9.93205E-02
1.50000E+00	1.27986E-01	1.67671E-01	6.98157E-02
2.00000E+00	1.21815E-01	1.63906E-01	4.72294E-02
2.50000E+00	1.15458E-01	1.59952E-01	3.06088E-02
3.00000E+00	1.08931E-01	1.55804E-01	1.89078E-02
3.50000E+00	1.02255E-01	1.51457E-01	1.10691E-02
4.00000E+00	9.54558E-02	1.46908E-01	6.10204E-03
4.50000E+00	8.85645E-02	1.42155E-01	3.14480E-03
5.00000E+00	8.16171E-02	1.37197E-01	1.50298E-03
5.50000E+00	7.46552E-02	1.32034E-01	6.60095E-04
6.00000E+00	6.77260E-02	1.26670E-01	2.63709E-04
6.50000E+00	6.08813E-02	1.21109E-01	9.47403E-05
7.00000E+00	5.41775E-02	1.15360E-01	3.02171E-05
7.50000E+00	4.76742E-02	1.09434E-01	8.43356E-06
8.00000E+00	4.14325E-02	1.03345E-01	2.02665E-06
8.50000E+00	3.55135E-02	9.71119E-02	4.11773E-07
9.00000E+00	2.99758E-02	9.07585E-02	6.93094E-08
9.50000E+00	2.48725E-02	8.43125E-02	9.44573E-09

8-ary Signalling Comparisons (continued)

Eb/No	PSK	PAM	UNION BOUND
1.00000E+01	1.01140E-03	2.65326E-02	8.64093E-08
1.05000E+01	5.63359E-04	2.14022E-02	1.31236E-08
1.10000E+01	2.93729E-04	1.68836E-02	1.59376E-09
1.15000E+01	1.42219E-04	1.29921E-02	1.50607E-10
1.20000E+01	6.33788E-05	9.72406E-03	1.07413E-11
1.25000E+01	2.57371E-05	7.05610E-03	5.58682E-13
1.30000E+01	9.41726E-06	4.94600E-03	2.03922E-14
1.35000E+01	3.06593E-06	3.33537E-03	5.00270E-16
1.40000E+01	8.75633E-07	2.15400E-03	7.85868E-18
1.45000E+01	2.15926E-07	1.32534E-03	7.48677E-20
1.50000E+01	4.51609E-08	7.72472E-04	4.06959E-22
1.55000E+01	7.85243E-09	4.23736E-04	1.17868E-24
1.60000E+01	1.10987E-09	2.17174E-04	1.68455E-27
1.65000E+01	1.24342E-10	1.03151E-04	1.08992E-30
1.70000E+01	1.07337E-11	4.49889E-05	2.89828E-34
1.75000E+01	6.91650E-13	1.78336E-05	2.84192E-38
1.80000E+01	3.21032E-14	6.35115E-06	1.00000E-37
1.85000E+01	1.03127E-15	2.00592E-06	1.00000E-37
1.90000E+01	2.19220E-17	5.53735E-07	1.00000E-37
1.95000E+01	2.93225E-19	1.31437E-07	1.00000E-37
2.00000E+01	2.33243E-21	2.63389E-08	1.00000E-37
2.05000E+01	1.03555E-23	7.48315E-09	1.00000E-37
2.10000E+01	2.39004E-26	1.00226E-09	1.00000E-37
2.15000E+01	2.64759E-29	1.05707E-10	1.00000E-37
2.20000E+01	1.28713E-32	8.52761E-12	1.00000E-37
2.25000E+01	2.48363E-36	5.09293E-13	1.00000E-37
2.30000E+01	1.00000E-37	2.17077E-14	1.00000E-37
2.35000E+01	1.00000E-37	6.33742E-16	1.00000E-37
2.40000E+01	1.00000E-37	1.21012E-17	1.00000E-37
2.45000E+01	1.00000E-37	1.43509E-19	1.00000E-37
2.50000E+01	1.00000E-37	9.97330E-22	1.00000E-37
2.55000E+01	1.00000E-37	3.80543E-24	1.00000E-37
2.60000E+01	1.00000E-37	7.40993E-27	1.00000E-37
2.65000E+01	1.00000E-37	6.78315E-30	1.00000E-37
2.70000E+01	1.00000E-37	2.66238E-33	1.00000E-37
2.75000E+01	1.00000E-37	4.04076E-37	1.00000E-37
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37

8-ary Signalling Comparisons

Eb/No	PSK	PAM	UNION BOUND
-1.0000E+01	2.55635E-01	2.52517E-01	5.00000E-01
-9.5000E+00	2.51176E-01	2.50221E-01	5.00000E-01
-9.0000E+00	2.46480E-01	2.47794E-01	5.00000E-01
-8.5000E+00	2.41537E-01	2.45228E-01	5.00000E-01
-8.0000E+00	2.36339E-01	2.42516E-01	5.00000E-01
-7.5000E+00	2.30876E-01	2.39652E-01	5.00000E-01
-7.0000E+00	2.25142E-01	2.36626E-01	5.00000E-01
-6.5000E+00	2.19129E-01	2.33432E-01	5.00000E-01
-6.0000E+00	2.12832E-01	2.30061E-01	5.00000E-01
-5.5000E+00	2.06246E-01	2.26505E-01	5.00000E-01
-5.0000E+00	1.99368E-01	2.22755E-01	5.00000E-01
-4.5000E+00	1.92199E-01	2.18804E-01	5.00000E-01
-4.0000E+00	1.84740E-01	2.14643E-01	5.00000E-01
-3.5000E+00	1.76998E-01	2.10265E-01	4.94050E-01
-3.0000E+00	1.68979E-01	2.05661E-01	4.40248E-01
-2.5000E+00	1.60699E-01	2.00825E-01	3.87987E-01
-2.0000E+00	1.52174E-01	1.95749E-01	3.37757E-01
-1.5000E+00	1.43428E-01	1.90428E-01	2.90046E-01
-1.0000E+00	1.34490E-01	1.84857E-01	2.45326E-01
-5.0000E-01	1.25396E-01	1.79032E-01	2.04030E-01
0.00000E+00	1.16188E-01	1.72953E-01	1.66529E-01
5.00000E-01	1.06916E-01	1.66618E-01	1.33106E-01
1.00000E+00	9.76371E-02	1.60031E-01	1.03938E-01
1.50000E+00	8.84154E-02	1.53196E-01	7.90773E-02
2.00000E+00	7.93214E-02	1.46124E-01	5.84378E-02
2.50000E+00	7.04313E-02	1.38825E-01	4.18067E-02
3.00000E+00	6.18251E-02	1.31317E-01	2.88433E-02
3.50000E+00	5.35847E-02	1.23621E-01	1.91086E-02
4.00000E+00	4.57909E-02	1.15764E-01	1.20979E-02
4.50000E+00	3.85208E-02	1.07779E-01	7.28023E-03
5.00000E+00	3.18433E-02	9.97042E-02	4.13904E-03
5.50000E+00	2.58158E-02	9.15849E-02	2.20809E-03
6.00000E+00	2.04799E-02	8.34727E-02	1.09694E-03
6.50000E+00	1.58586E-02	7.54249E-02	5.03112E-04
7.00000E+00	1.19532E-02	6.75046E-02	2.11002E-04
7.50000E+00	8.74142E-03	5.97793E-02	8.00485E-05
8.00000E+00	6.18107E-03	5.23198E-02	2.71389E-05
8.50000E+00	4.20914E-03	4.51976E-02	8.11126E-06
9.00000E+00	2.74814E-03	3.84830E-02	2.10476E-06
9.50000E+00	1.71170E-03	3.22419E-02	4.66102E-07

4-ary Signalling Comparisons (continued)

Eb/No	PSK	PAM	UNION BOUND
1.00000E+01	3.87210E-06	1.75415E-03	7.74422E-06
1.05000E+01	1.08385E-06	1.02573E-03	2.16770E-06
1.10000E+01	2.61307E-07	5.64706E-04	5.22614E-07
1.15000E+01	5.32866E-08	2.90605E-04	1.06573E-07
1.20000E+01	9.00601E-09	1.38659E-04	1.80120E-08
1.25000E+01	1.23303E-09	6.07856E-05	2.46606E-09
1.30000E+01	1.33293E-10	2.42338E-05	2.66586E-10
1.35000E+01	1.10546E-11	8.68609E-06	2.21092E-11
1.40000E+01	6.81019E-13	2.76321E-06	1.36204E-12
1.45000E+01	3.00555E-14	7.68967E-07	6.01110E-14
1.50000E+01	9.12396E-16	1.84186E-07	1.82479E-15
1.55000E+01	1.82023E-17	3.72859E-08	3.64047E-17
1.60000E+01	2.26740E-19	6.25020E-09	4.53479E-19
1.65000E+01	1.66510E-21	8.47883E-10	3.33020E-21
1.70000E+01	6.75897E-24	9.07163E-11	1.35179E-23
1.75000E+01	1.41073E-26	7.43684E-12	2.82145E-26
1.80000E+01	1.39601E-29	4.52231E-13	2.79203E-29
1.85000E+01	5.97978E-33	1.96695E-14	1.19596E-32
1.90000E+01	1.00107E-36	5.87418E-16	2.00215E-36
1.95000E+01	1.00000E-37	1.15059E-17	1.00000E-37
2.00000E+01	1.00000E-37	1.40404E-19	1.00000E-37
2.05000E+01	1.00000E-37	1.34338E-21	1.00000E-37
2.10000E+01	1.00000E-37	5.31350E-24	1.00000E-37
2.15000E+01	1.00000E-37	1.07724E-26	1.00000E-37
2.20000E+01	1.00000E-37	1.03179E-29	1.00000E-37
2.25000E+01	1.00000E-37	4.26076E-33	1.00000E-37
2.30000E+01	1.00000E-37	6.84588E-37	1.00000E-37
2.35000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.40000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.45000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.50000E+01	1.00000F-37	1.00000E-37	1.00000E-37
2.55000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.60000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.65000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.70000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.75000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37

4-ary Signalling Comparisons

Eb/No	PSK	PAM	UNION BOUND
-1.0000E+01	2.73778E-01	2.91487E-01	5.00000E-01
-9.5000E+00	2.67337E-01	2.86680E-01	5.00000E-01
-9.0000E+00	2.60506E-01	2.81615E-01	5.00000E-01
-8.5000E+00	2.53269E-01	2.76282E-01	5.00000E-01
-8.0000E+00	2.45612E-01	2.70668E-01	5.00000E-01
-7.5000E+00	2.37524E-01	2.64766E-01	5.00000E-01
-7.0000E+00	2.28997E-01	2.58565E-01	5.00000E-01
-6.5000E+00	2.20027E-01	2.52056E-01	5.00000E-01
-6.0000E+00	2.10614E-01	2.45233E-01	4.78457E-01
-5.5000E+00	2.00765E-01	2.38089E-01	4.52783E-01
-5.0000E+00	1.90495E-01	2.30619E-01	4.26456E-01
-4.5000E+00	1.79827E-01	2.22821E-01	3.99568E-01
-4.0000E+00	1.68795E-01	2.14695E-01	3.72228E-01
-3.5000E+00	1.57442E-01	2.06244E-01	3.44566E-01
-3.0000E+00	1.45828E-01	1.97475E-01	3.16737E-01
-2.5000E+00	1.34022E-01	1.88398E-01	2.88912E-01
-2.0000E+00	1.22110E-01	1.79030E-01	2.61289E-01
-1.5000E+00	1.10191E-01	1.69391E-01	2.34081E-01
-1.0000E+00	9.83761E-02	1.59509E-01	2.07518E-01
-5.0000E-01	8.67879E-02	1.49419E-01	1.81842E-01
0.00000E+00	7.55567E-02	1.39160E-01	1.57299E-01
5.00000E-01	6.48163E-02	1.28783E-01	1.34130E-01
1.00000E+00	5.46981E-02	1.18346E-01	1.12564E-01
1.50000E+00	4.53247E-02	1.07913E-01	9.28025E-02
2.00000E+00	3.68028E-02	9.75593E-02	7.50122E-02
2.50000E+00	2.92156E-02	8.73645E-02	5.93107E-02
3.00000E+00	2.26169E-02	7.74154E-02	4.57573E-02
3.50000E+00	1.70259E-02	6.78027E-02	3.43468E-02
4.00000E+00	1.24227E-02	5.86184E-02	2.50017E-02
4.50000E+00	8.75516E-03	4.99533E-02	1.75877E-02
5.00000E+00	5.93615E-03	4.18923E-02	1.19077E-02
5.50000E+00	3.85478E-03	3.45111E-02	7.72447E-03
6.00000E+00	2.38544E-03	2.78713E-02	4.77658E-03
6.50000E+00	1.39883E-03	2.20161E-02	2.79961E-03
7.00000E+00	7.72376E-04	1.69669E-02	1.54535E-03
7.50000E+00	3.98717E-04	1.27207E-02	7.97593E-04
8.00000E+00	1.90890E-04	9.24725E-03	3.81816E-04
8.50000E+00	8.39960E-05	6.49534E-03	1.67999E-04
9.00000E+00	3.36267E-05	4.39034E-03	6.72545E-05
9.50000E+00	1.21088E-05	2.84267E-03	2.42178E-05

2-ary Signalling Comparisons (continued)

Eb/No	PSK	PAM	UNION BOUND
1.00000E+01	3.87211E-06	3.87211E-06	7.82701E-04
1.05000E+01	1.08385E-06	1.08385E-06	4.04562E-04
1.10000E+01	2.61307E-07	2.61307E-07	1.93985E-04
1.15000E+01	5.32866E-08	5.32866E-08	8.55105E-05
1.20000E+01	9.00601E-09	9.00601E-09	3.43026E-05
1.25000E+01	1.23303E-09	1.23303E-09	1.23806E-05
1.30000E+01	1.33293E-10	1.33293E-10	3.96925E-06
1.35000E+01	1.10546E-11	1.10546E-11	1.11426E-06
1.40000E+01	6.81019E-13	6.81019E-13	2.69515E-07
1.45000E+01	3.00555E-14	3.00555E-14	5.51612E-08
1.50000E+01	9.12396E-16	9.12396E-16	9.36104E-09
1.55000E+01	1.82023E-17	1.82023E-17	1.28753E-09
1.60000E+01	2.26740E-19	2.26740E-19	1.39903E-10
1.65000E+01	1.66510E-21	1.66510E-21	1.16699E-11
1.70000E+01	6.75897E-24	6.75897E-24	7.23598E-13
1.75000E+01	1.41073E-26	1.41073E-26	3.21675E-14
1.80000E+01	1.39601E-29	1.39601E-29	9.84500E-16
1.85000E+01	5.97978E-33	5.97978E-33	1.98212E-17
1.90000E+01	1.00107E-36	1.00107E-36	2.49452E-19
1.95000E+01	1.00000E-37	1.00000E-37	1.85310E-21
2.00000E+01	1.00000E-37	1.00000E-37	7.61985E-24
2.05000E+01	1.00000E-37	1.00000E-37	1.61362E-26
2.10000E+01	1.00000E-37	1.00000E-37	1.62296E-29
2.15000E+01	1.00000E-37	1.00000E-37	7.07987E-33
2.20000E+01	1.00000E-37	1.00000E-37	1.20974E-36
2.25000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.30000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.35000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.40000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.45000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.50000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.55000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.60000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.65000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.70000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.75000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37

2-ary Signalling Comparisons

Eb/No	PSK	PAM	UNION BOUND
-1.0000E+01	3.27360E-01	3.27360E-01	3.75915E-01
-9.5000E+00	3.17852E-01	3.17852E-01	3.68826E-01
-9.0000E+00	3.07910E-01	3.07910E-01	3.61365E-01
-8.5000E+00	2.97531E-01	2.97531E-01	3.53519E-01
-8.0000E+00	2.86715E-01	2.86715E-01	3.45276E-01
-7.5000E+00	2.75464E-01	2.75464E-01	3.36623E-01
-7.0000E+00	2.63790E-01	2.63790E-01	3.27552E-01
-6.5000E+00	2.51704E-01	2.51704E-01	3.18053E-01
-6.0000E+00	2.39229E-01	2.39229E-01	3.08120E-01
-5.5000E+00	2.26391E-01	2.26391E-01	2.97749E-01
-5.0000E+00	2.13228E-01	2.13228E-01	2.86942E-01
-4.5000E+00	1.99784E-01	1.99784E-01	2.75700E-01
-4.0000E+00	1.86114E-01	1.86114E-01	2.64034E-01
-3.5000E+00	1.72283E-01	1.72283E-01	2.51957E-01
-3.0000E+00	1.58368E-01	1.58368E-01	2.39489E-01
-2.5000E+00	1.44456E-01	1.44456E-01	2.26659E-01
-2.0000E+00	1.30644E-01	1.30644E-01	2.13502E-01
-1.5000E+00	1.17040E-01	1.17040E-01	2.00063E-01
-1.0000E+00	1.03759E-01	1.03759E-01	1.86397E-01
-5.0000E-01	9.09212E-02	9.09212E-02	1.72569E-01
0.00000E+00	7.86496E-02	7.86496E-02	1.58655E-01
5.00000E-01	6.70652E-02	6.70652E-02	1.44742E-01
1.00000E+00	5.62819E-02	5.62819E-02	1.30927E-01
1.50000E+00	4.64013E-02	4.64013E-02	1.17318E-01
2.00000E+00	3.75061E-02	3.75061E-02	1.04029E-01
2.50000E+00	2.96553E-02	2.96553E-02	9.11804E-02
3.00000E+00	2.28786E-02	2.28786E-02	7.88959E-02
3.50000E+00	1.71734E-02	1.71734E-02	6.72961E-02
4.00000E+00	1.25009E-02	1.25009E-02	5.64953E-02
4.50000E+00	8.79383E-03	8.79383E-03	4.65951E-02
5.00000E+00	5.95387E-03	5.95387E-03	3.76790E-02
5.50000E+00	3.86223E-03	3.86223E-03	2.98063E-02
6.00000E+00	2.38829E-03	2.38829E-03	2.30074E-02
6.50000E+00	1.39980E-03	1.39980E-03	1.72803E-02
7.00000E+00	7.72675E-04	7.72675E-04	1.25871E-02
7.50000E+00	3.98796E-04	3.98796E-04	8.86107E-03
8.00000E+00	1.90908E-04	1.90908E-04	6.00439E-03
8.50000E+00	8.39995E-05	8.39995E-05	3.89863E-03
9.00000E+00	3.36272E-05	3.36272E-05	2.41331E-03
9.50000E+00	1.21089E-05	1.21089E-05	1.41612E-03

M-ary Orthogonal Signalling, Union Bound (continued)

Eb/No	M = 2	M = 4	M = 8	M = 16
1.00000E+01	7.82701E-04	7.74422E-06	8.64093E-08	1.01585E-09
1.05000E+01	4.04562E-04	2.16770E-06	1.31236E-08	8.37631E-11
1.10000E+01	1.93985E-04	5.22614E-07	1.59376E-09	5.12684E-12
1.15000E+01	8.55105E-05	1.06573E-07	1.50607E-10	2.24622E-13
1.20000E+01	3.43026E-05	1.80120E-08	1.07413E-11	6.76337E-15
1.25000E+01	1.23806E-05	2.46606E-09	5.58682E-13	1.33699E-16
1.30000E+01	3.96925E-06	2.66586E-10	2.03922E-14	1.64839E-18
1.35000E+01	1.11426E-06	2.21092E-11	5.00270E-16	1.19664E-20
1.40000E+01	2.69515E-07	1.36204E-12	7.85868E-18	4.79493E-23
1.45000E+01	5.51612E-08	6.01110E-14	7.48677E-20	9.86362E-26
1.50000E+01	9.36104E-09	1.82479E-15	4.06959E-22	9.60301E-29
1.55000E+01	1.28753E-09	3.64047E-17	1.17868E-24	4.03890E-32
1.60000E+01	1.39903E-10	4.53479E-19	1.68455E-27	6.62422E-36
1.65000E+01	1.16699E-11	3.33020E-21	1.08992E-30	1.00000E-37
1.70000E+01	7.23598E-13	1.35179E-23	2.89828E-34	1.00000E-37
1.75000E+01	3.21675E-14	2.82145E-26	2.84192E-38	1.00000E-37
1.80000E+01	9.84500E-16	2.79203E-29	1.00000E-37	1.00000E-37
1.85000E+01	1.98212E-17	1.19596E-32	1.00000E-37	1.00000E-37
1.90000E+01	2.49452E-19	2.00215E-36	1.00000E-37	1.00000E-37
1.95000E+01	1.85310E-21	1.00000E-37	1.00000E-37	1.00000E-37
2.00000E+01	7.61985E-24	1.00000E-37	1.00000E-37	1.00000E-37
2.05000E+01	1.61362E-26	1.00000E-37	1.00000E-37	1.00000E-37
2.10000E+01	1.62296E-29	1.00000E-37	1.00000E-37	1.00000E-37
2.15000E+01	7.07987E-33	1.00000E-37	1.00000E-37	1.00000E-37
2.20000E+01	1.20974E-36	1.00000E-37	1.00000E-37	1.00000E-37
2.25000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.30000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.35000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.40000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.45000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.50000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.55000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.60000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.65000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.70000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.75000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.00000E-37

M-ary Orthogonal Signalling, Union Bound

Eb/No	M = 2	M = 4	M = 8	M = 16
-1.0000E+01	3.75915E-01	5.00000E-01	5.00000E-01	5.00000E-01
-9.5000E+00	3.68826E-01	5.00000E-01	5.00000E-01	5.00000E-01
-9.0000E+00	3.61365E-01	5.00000E-01	5.00000E-01	5.00000E-01
-8.5000E+00	3.53519E-01	5.00000E-01	5.00000E-01	5.00000E-01
-8.0000E+00	3.45276E-01	5.00000E-01	5.00000E-01	5.00000E-01
-7.5000E+00	3.36623E-01	5.00000E-01	5.00000E-01	5.00000E-01
-7.0000E+00	3.27552E-01	5.00000E-01	5.00000E-01	5.00000E-01
-6.5000E+00	3.18053E-01	5.00000E-01	5.00000E-01	5.00000E-01
-6.0000E+00	3.08120E-01	4.78457E-01	5.00000E-01	5.00000E-01
-5.5000E+00	2.97749E-01	4.52783E-01	5.00000E-01	5.00000E-01
-5.0000E+00	2.86942E-01	4.26456E-01	5.00000E-01	5.00000E-01
-4.5000E+00	2.75700E-01	3.99568E-01	5.00000E-01	5.00000E-01
-4.0000E+00	2.64034E-01	3.72228E-01	5.00000E-01	5.00000E-01
-3.5000E+00	2.51957E-01	3.44566E-01	4.94050E-01	5.00000E-01
-3.0000E+00	2.39489E-01	3.16737E-01	4.40248E-01	5.00000E-01
-2.5000E+00	2.26659E-01	2.88912E-01	3.87987E-01	5.00000E-01
-2.0000E+00	2.13502E-01	2.61289E-01	3.37757E-01	4.48552E-01
-1.5000E+00	2.00063E-01	2.34081E-01	2.90046E-01	3.69663E-01
-1.0000E+00	1.86397E-01	2.07518E-01	2.45326E-01	2.98670E-01
-5.0000E-01	1.72569E-01	1.81842E-01	2.04030E-01	2.36039E-01
0.00000E+00	1.58655E-01	1.57299E-01	1.66529E-01	1.82003E-01
5.00000E-01	1.44742E-01	1.34130E-01	1.33106E-01	1.36535E-01
1.00000E+00	1.30927E-01	1.12564E-01	1.03938E-01	9.93205E-02
1.50000E+00	1.17318E-01	9.28025E-02	7.90773E-02	6.98157E-02
2.00000E+00	1.04029E-01	7.50122E-02	5.84378E-02	4.72294E-02
2.50000E+00	9.11804E-02	5.93107E-02	4.18067E-02	3.06088E-02
3.00000E+00	7.88959E-02	4.57573E-02	2.88433E-02	1.89078E-02
3.50000E+00	6.72961E-02	3.43468E-02	1.91086E-02	1.10691E-02
4.00000E+00	5.64953E-02	2.50017E-02	1.20979E-02	6.10204E-03
4.50000E+00	4.65951E-02	1.75877E-02	7.28023E-03	3.14480E-03
5.00000E+00	3.76790E-02	1.19077E-02	4.13904E-03	1.50298E-03
5.50000E+00	2.98063E-02	7.72447E-03	2.20809E-03	6.60095E-04
6.00000E+00	2.30074E-02	4.77658E-03	1.09694E-03	2.63709E-04
6.50000E+00	1.72803E-02	2.79961E-03	5.03112E-04	9.47403E-05
7.00000E+00	1.25871E-02	1.54535E-03	2.11002E-04	3.02171E-05
7.50000E+00	8.86107E-03	7.97593E-04	8.00485E-05	8.43356E-06
8.00000E+00	6.00439E-03	3.81816E-04	2.71389E-05	2.02665E-06
8.50000E+00	3.89863E-03	1.67999E-04	8.11126E-06	4.11773E-07
9.00000E+00	2.41331E-03	6.72545E-05	2.10476E-06	6.93094E-08
9.50000E+00	1.41612E-03	2.42178E-05	4.66102E-07	9.44573E-09

M-ary PAM (continued)

Eb/No	M = 2	M = 4	M = 8	M = 16
1.00000E+01	3.87211E-06	1.75415E-03	2.65326E-02	7.78067E-02
1.05000E+01	1.08385E-06	1.02573E-03	2.14022E-02	7.12794E-02
1.10000E+01	2.61307E-07	5.64706E-04	1.68836E-02	6.47734E-02
1.15000E+01	5.32866E-08	2.90605E-04	1.29921E-02	5.83368E-02
1.20000E+01	9.00601E-09	1.38659E-04	9.72406E-03	5.20215E-02
1.25000E+01	1.23303E-09	6.07856E-05	7.05610E-03	4.58829E-02
1.30000E+01	1.33293E-10	2.42338E-05	4.94600E-03	3.99782E-02
1.35000E+01	1.10546E-11	8.68609E-06	3.33537E-03	3.43649E-02
1.40000E+01	6.81019E-13	2.76321E-06	2.15400E-03	2.90984E-02
1.45000E+01	3.00555E-14	7.68967E-07	1.32534E-03	2.42299E-02
1.50000E+01	9.12396E-16	1.84186E-07	7.72472E-04	1.98033E-02
1.55000E+01	1.82023E-17	3.72859E-08	4.23736E-04	1.58528E-02
1.60000E+01	2.26740E-19	6.25020E-09	2.17174E-04	1.23999E-02
1.65000E+01	1.66510E-21	8.47883E-10	1.03151E-04	9.45180E-03
1.70000E+01	6.75897E-24	9.07163E-11	4.49889E-05	6.99961E-03
1.75000E+01	1.41073E-26	7.43684E-12	1.78336E-05	5.01937E-03
1.80000E+01	1.39601E-29	4.52231E-13	6.35115E-06	3.47210E-03
1.85000E+01	5.97978E-33	1.96695E-14	2.00592E-06	2.30705E-03
1.90000E+01	1.00107E-36	5.87418E-16	5.53735E-07	1.46545E-03
1.95000E+01	1.00000E-37	1.15059E-17	1.31437E-07	8.85130E-04
2.00000E+01	1.00000E-37	1.40404E-19	2.63389E-08	5.05307E-04
2.05000E+01	1.00000E-37	1.34338E-21	7.48315E-09	5.77752E-04
2.10000E+01	1.00000E-37	5.31350E-24	1.00226E-09	2.88507E-04
2.15000E+01	1.00000E-37	1.07724E-26	1.05707E-10	1.33095E-04
2.20000E+01	1.00000E-37	1.03179E-29	8.52761E-12	5.61837E-05
2.25000E+01	1.00000E-37	4.26076E-33	5.09293E-13	2.14706E-05
2.30000E+01	1.00000E-37	6.84588E-37	2.17077E-14	7.33895E-06
2.35000E+01	1.00000E-37	1.00000E-37	6.33742E-16	2.21367E-06
2.40000E+01	1.00000E-37	1.00000E-37	1.21012E-17	5.80352E-07
2.45000E+01	1.00000E-37	1.00000E-37	1.43509E-19	1.30010E-07
2.50000E+01	1.00000E-37	1.00000E-37	9.97330E-22	2.44159E-08
2.55000E+01	1.00000E-37	1.00000E-37	3.80543E-24	3.76240E-09
2.60000E+01	1.00000E-37	1.00000E-37	7.40993E-27	4.64409E-10
2.65000E+01	1.00000E-37	1.00000E-37	6.78315E-30	4.46942E-11
2.70000E+01	1.00000E-37	1.00000E-37	2.66238E-33	3.25352E-12
2.75000E+01	1.00000E-37	1.00000E-37	4.04076E-37	1.73156E-13
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37	6.48525E-15
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.63766E-16
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37	2.65738E-18
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37	2.62544E-20
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.48658E-22

M-ary PAM

Eb/No	M = 2	M = 4	M = 8	M = 16
-1.0000E+01	3.27360E-01	2.91487E-01	2.52517E-01	2.16261E-01
-9.5000E+00	3.17852E-01	2.86680E-01	2.50221E-01	2.15192E-01
-9.0000E+00	3.07910E-01	2.81615E-01	2.47794E-01	2.14059E-01
-8.5000E+00	2.97531E-01	2.76282E-01	2.45228E-01	2.12861E-01
-8.0000E+00	2.86715E-01	2.70668E-01	2.42516E-01	2.11592E-01
-7.5000E+00	2.75464E-01	2.64766E-01	2.39652E-01	2.10249E-01
-7.0000E+00	2.63790E-01	2.58565E-01	2.36626E-01	2.08829E-01
-6.5000E+00	2.51704E-01	2.52056E-01	2.33432E-01	2.07325E-01
-6.0000E+00	2.39229E-01	2.45233E-01	2.30061E-01	2.05735E-01
-5.5000E+00	2.26391E-01	2.38089E-01	2.26505E-01	2.04052E-01
-5.0000E+00	2.13228E-01	2.30619E-01	2.22755E-01	2.02273E-01
-4.5000E+00	1.99784E-01	2.22821E-01	2.18804E-01	2.00391E-01
-4.0000E+00	1.86114E-01	2.14695E-01	2.14643E-01	1.98402E-01
-3.5000E+00	1.72283E-01	2.06244E-01	2.10265E-01	1.96299E-01
-3.0000E+00	1.58368E-01	1.97475E-01	2.05661E-01	1.94077E-01
-2.5000E+00	1.44456E-01	1.88398E-01	2.00825E-01	1.91730E-01
-2.0000E+00	1.30644E-01	1.79030E-01	1.95749E-01	1.89251E-01
-1.5000E+00	1.17040E-01	1.69391E-01	1.90428E-01	1.86635E-01
-1.0000E+00	1.03759E-01	1.59509E-01	1.84857E-01	1.83874E-01
-5.0000E-01	9.09212E-02	1.49419E-01	1.79032E-01	1.80962E-01
0.00000E+00	7.86496E-02	1.39160E-01	1.72953E-01	1.77892E-01
5.00000E-01	6.70652E-02	1.28783E-01	1.66618E-01	1.74658E-01
1.00000E+00	5.62819E-02	1.18346E-01	1.60031E-01	1.71253E-01
1.50000E+00	4.64013E-02	1.07913E-01	1.53196E-01	1.67671E-01
2.00000E+00	3.75061E-02	9.75593E-02	1.46124E-01	1.63906E-01
2.50000E+00	2.96553E-02	8.73645E-02	1.38825E-01	1.59952E-01
3.00000E+00	2.28786E-02	7.74154E-02	1.31317E-01	1.55804E-01
3.50000E+00	1.71734E-02	6.78027E-02	1.23621E-01	1.51457E-01
4.00000E+00	1.25009E-02	5.86184E-02	1.15764E-01	1.46908E-01
4.50000E+00	8.79383E-03	4.99533E-02	1.07779E-01	1.42155E-01
5.00000E+00	5.95387E-03	4.18923E-02	9.97042E-02	1.37197E-01
5.50000E+00	3.86223E-03	3.45111E-02	9.15849E-02	1.32034E-01
6.00000E+00	2.38829E-03	2.78713E-02	8.34727E-02	1.26670E-01
6.50000E+00	1.39980E-03	2.20161E-02	7.54249E-02	1.21109E-01
7.00000E+00	7.72675E-04	1.69669E-02	6.75046E-02	1.15360E-01
7.50000E+00	3.98796E-04	1.27207E-02	5.97793E-02	1.09434E-01
8.00000E+00	1.90908E-04	9.24725E-03	5.23198E-02	1.03345E-01
8.50000E+00	8.39995E-05	6.49534E-03	4.51976E-02	9.71119E-02
9.00000E+00	3.36272E-05	4.39034E-03	3.84830E-02	9.07585E-02
9.50000E+00	1.21089E-05	2.84267E-03	3.22419E-02	8.43125E-02

M-ary PSK (continued)

Eb/No	M = 2	M = 4	M = 8	M = 16
1.00000E+01	3.87211E-06	3.87210E-06	1.01140E-03	2.02488E-02
1.05000E+01	1.08385E-06	1.08385E-06	5.63359E-04	1.61385E-02
1.10000E+01	2.61307E-07	2.61307E-07	2.93729E-04	1.25618E-02
1.15000E+01	5.32866E-08	5.32866E-08	1.42219E-04	9.52321E-03
1.20000E+01	9.00601E-09	9.00601E-09	6.33788E-05	7.00961E-03
1.25000E+01	1.23303E-09	1.23303E-09	2.57371E-05	4.99245E-03
1.30000E+01	1.33293E-10	1.33293E-10	9.41726E-06	3.42730E-03
1.35000E+01	1.10546E-11	1.10546E-11	3.06593E-06	2.25799E-03
1.40000E+01	6.81019E-13	6.81019E-13	8.75633E-07	1.42069E-03
1.45000E+01	3.00555E-14	3.00555E-14	2.15926E-07	8.49005E-04
1.50000E+01	9.12396E-16	9.12396E-16	4.51609E-08	4.78936E-04
1.55000E+01	1.82023E-17	1.82023E-17	7.85243E-09	2.53281E-04
1.60000E+01	2.26740E-19	2.26740E-19	1.10987E-09	1.24600E-04
1.65000E+01	1.66510E-21	1.66510E-21	1.24342E-10	5.65251E-05
1.70000E+01	6.75897E-24	6.75897E-24	1.07337E-11	2.34169E-05
1.75000E+01	1.41073E-26	1.41073E-26	6.91650E-13	8.76221E-06
1.80000E+01	1.39601E-29	1.39601E-29	3.21032E-14	2.92515E-06
1.85000E+01	5.97978E-33	5.97978E-33	1.03127E-15	8.59265E-07
1.90000E+01	1.00107E-36	1.00107E-36	2.19220E-17	2.18681E-07
1.95000E+01	1.00000E-37	1.00000E-37	2.93225E-19	4.73845E-08
2.00000E+01	1.00000E-37	1.00000E-37	2.33243E-21	8.57259E-09
2.05000E+01	1.00000E-37	1.34338E-21	7.48315E-09	5.77752E-04
2.10000E+01	1.00000E-37	5.31350E-24	1.00226E-09	2.88507E-04
2.15000E+01	1.00000E-37	1.07724E-26	1.05707E-10	1.33095E-04
2.20000E+01	1.00000E-37	1.03179E-29	8.52761E-12	5.61837E-05
2.25000E+01	1.00000E-37	4.26076E-33	5.09293E-13	2.14706E-05
2.30000E+01	1.00000E-37	6.84588E-37	2.17077E-14	7.33895E-06
2.35000E+01	1.00000E-37	1.00000E-37	6.33742E-16	2.21367E-06
2.40000E+01	1.00000E-37	1.00000E-37	1.21012E-17	5.80352E-07
2.45000E+01	1.00000E-37	1.00000E-37	1.43509E-19	1.30010E-07
2.50000E+01	1.00000E-37	1.00000E-37	9.97330E-22	2.44159E-08
2.55000E+01	1.00000E-37	1.00000E-37	3.80543E-24	3.76240E-09
2.60000E+01	1.00000E-37	1.00000E-37	7.40993E-27	4.64409E-10
2.65000E+01	1.00000E-37	1.00000E-37	6.78315E-30	4.46942E-11
2.70000E+01	1.00000E-37	1.00000E-37	2.66238E-33	3.25352E-12
2.75000E+01	1.00000E-37	1.00000E-37	4.04076E-37	1.73156E-13
2.80000E+01	1.00000E-37	1.00000E-37	1.00000E-37	6.48525E-15
2.85000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.63766E-16
2.90000E+01	1.00000E-37	1.00000E-37	1.00000E-37	2.65738E-18
2.95000E+01	1.00000E-37	1.00000E-37	1.00000E-37	2.62544E-20
3.00000E+01	1.00000E-37	1.00000E-37	1.00000E-37	1.48658E-22

Required Signalling Bandwidth

BIT RATE = 1.0 MBps

	PSK	FSK	PAM	PPM
M = 2	1.0000E+06	2.5000E+06	5.0000E+05	1.0000E+06
M = 4	5.0000E+05	1.7500E+06	2.5000E+05	1.0000E+06
M = 8	3.3333E+05	1.8333E+06	1.6667E+05	1.3333E+06
M = 16	2.5000E+05	2.3750E+06	1.2500E+05	2.0000E+06
M = 32	2.0000E+05	3.5000E+06	1.0000E+05	3.2000E+06

BIT RATE = 100 MBps

	PSK	FSK	PAM	PPM
M = 2	1.0000E+08	2.5000E+08	5.0000E+07	1.0000E+08
M = 4	5.0000E+07	1.7500E+08	2.5000E+07	1.0000E+08
M = 8	3.3333E+07	1.8333E+08	1.6667E+07	1.3333E+08
M = 16	2.5000E+07	2.3750E+08	1.2500E+07	2.0000E+08
M = 32	2.0000E+07	3.5000E+08	1.0000E+07	3.2000E+08

BIT RATE = 500 MBps

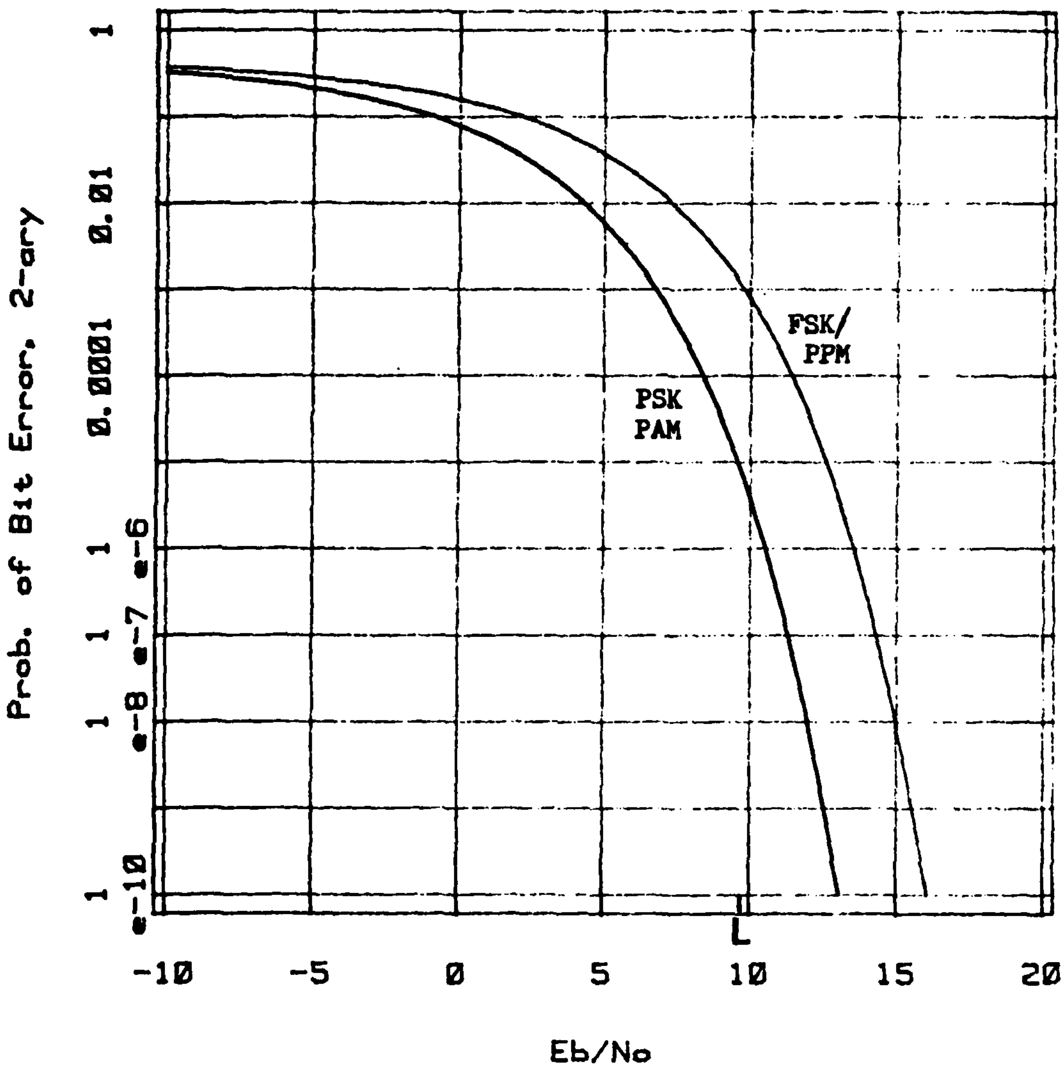
	PSK	FSK	PAM	PPM
M = 2	5.0000E+08	1.2500E+09	2.5000E+08	5.0000E+08
M = 4	2.5000E+08	8.7500E+08	1.2500E+08	5.0000E+08
M = 8	1.6667E+08	9.1667E+08	8.3333E+07	6.6667E+08
M = 16	1.2500E+08	1.1875E+09	6.2500E+07	1.0000E+09
M = 32	1.0000E+08	1.7500E+09	5.0000E+07	1.6000E+09

BIT RATE = 1.0 GBps

	PSK	FSK	PAM	PPM
M = 2	1.0000E+09	2.5000E+09	5.0000E+08	1.0000E+09
M = 4	5.0000E+08	1.7500E+09	2.5000E+08	1.0000E+09
M = 8	3.3333E+08	1.8333E+09	1.6667E+08	1.3333E+09
M = 16	2.5000E+08	2.3750E+09	1.2500E+08	2.0000E+09
M = 32	2.0000E+08	3.5000E+09	1.0000E+08	3.2000E+09

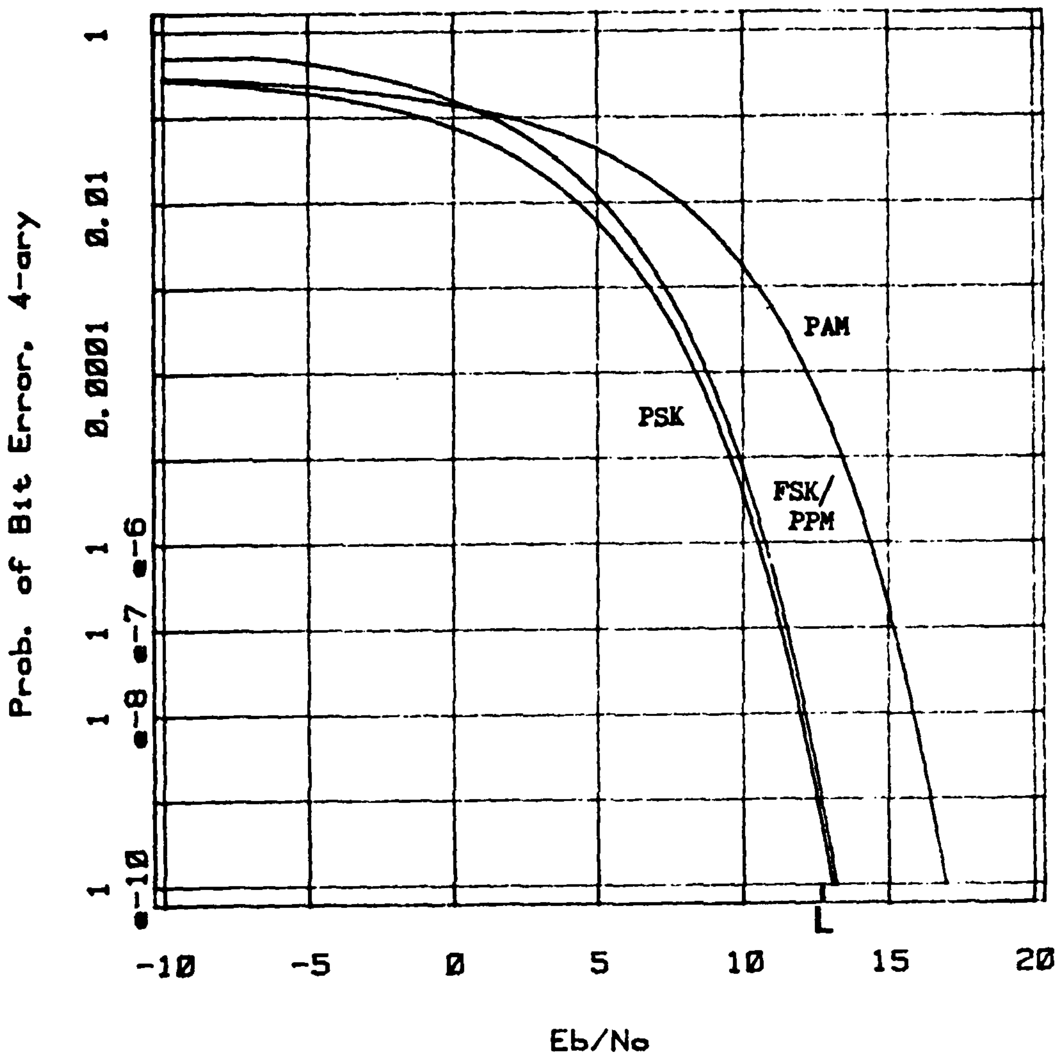
Appendix D:

Graphs of P_b vs. Eb/No



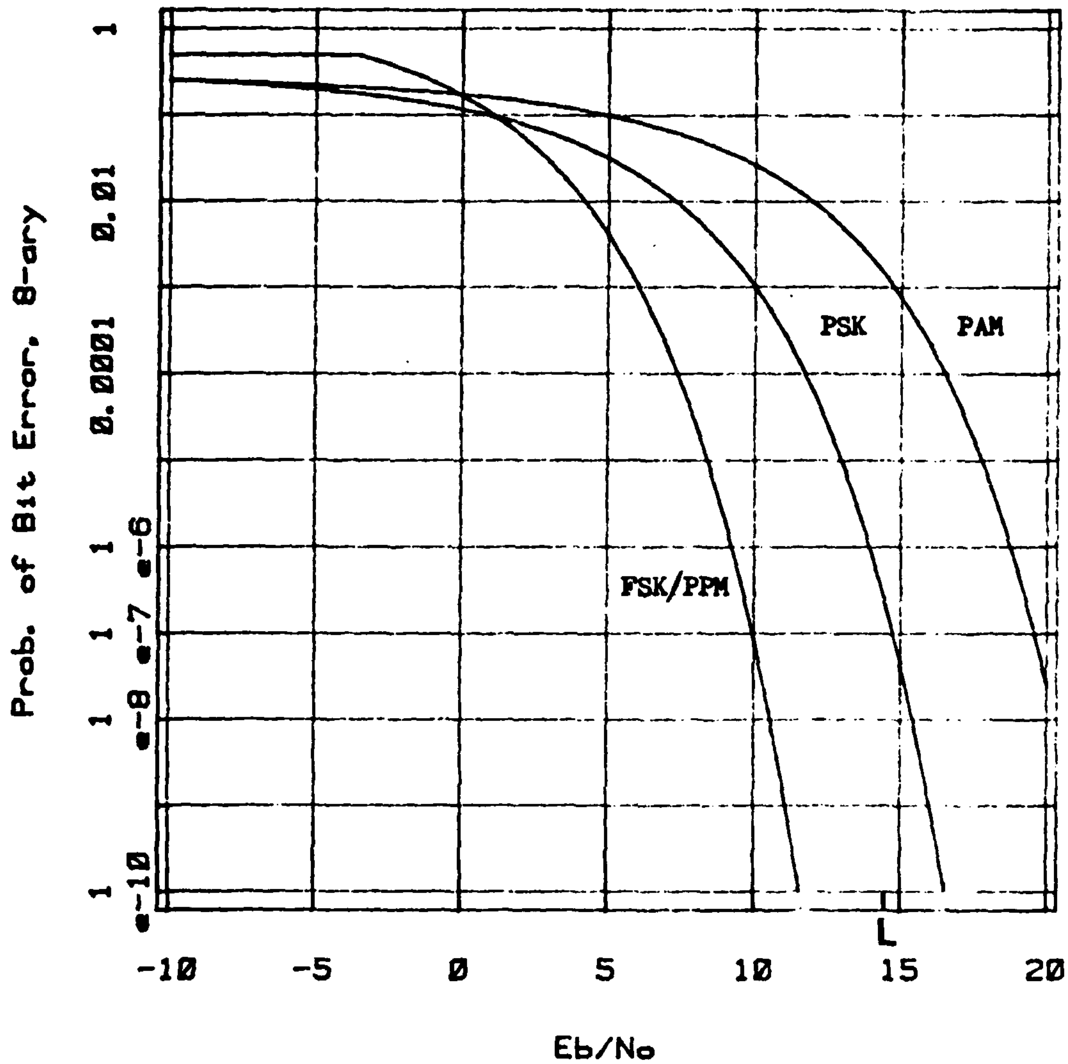
Low Risk Eb/No	9.75 dB
High/Low Risk Average Eb/No	28.00 dB
Five Year Projected Eb/No	32.29 dB
High Risk Eb/No	43.02 dB

Figure 2. Millimeter Wave 60 GHz, 1 MBps, 160° Separation, M=2



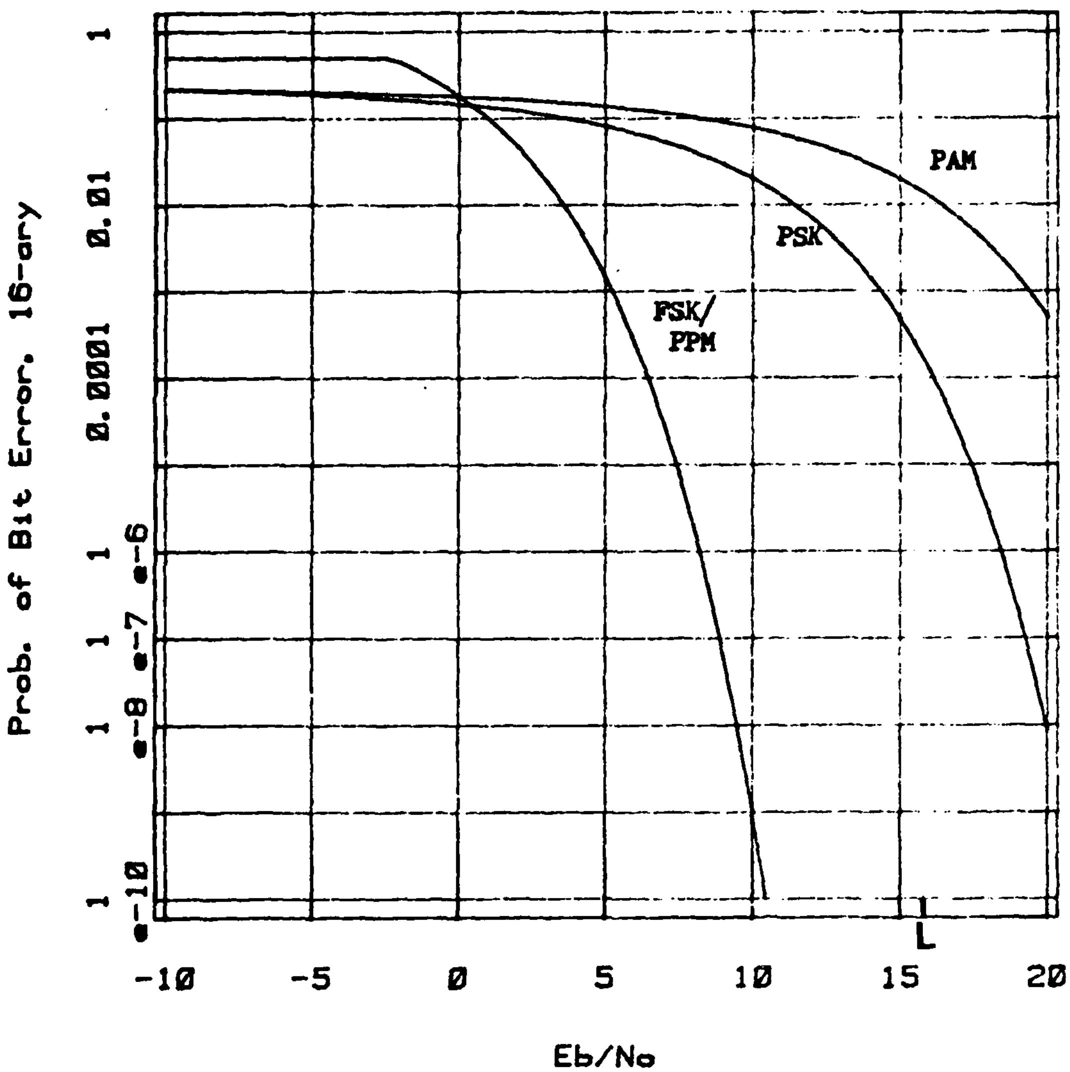
Low Risk Eb/No	12.76 dB
High/Low Risk Average Eb/No	31.01 dB
Five Year Projected Eb/No	35.30 dB
High Risk Eb/No	46.03 dB

Figure 3. Millimeter Wave 60 GHz, 1 MBps, 160° Separation, M=4



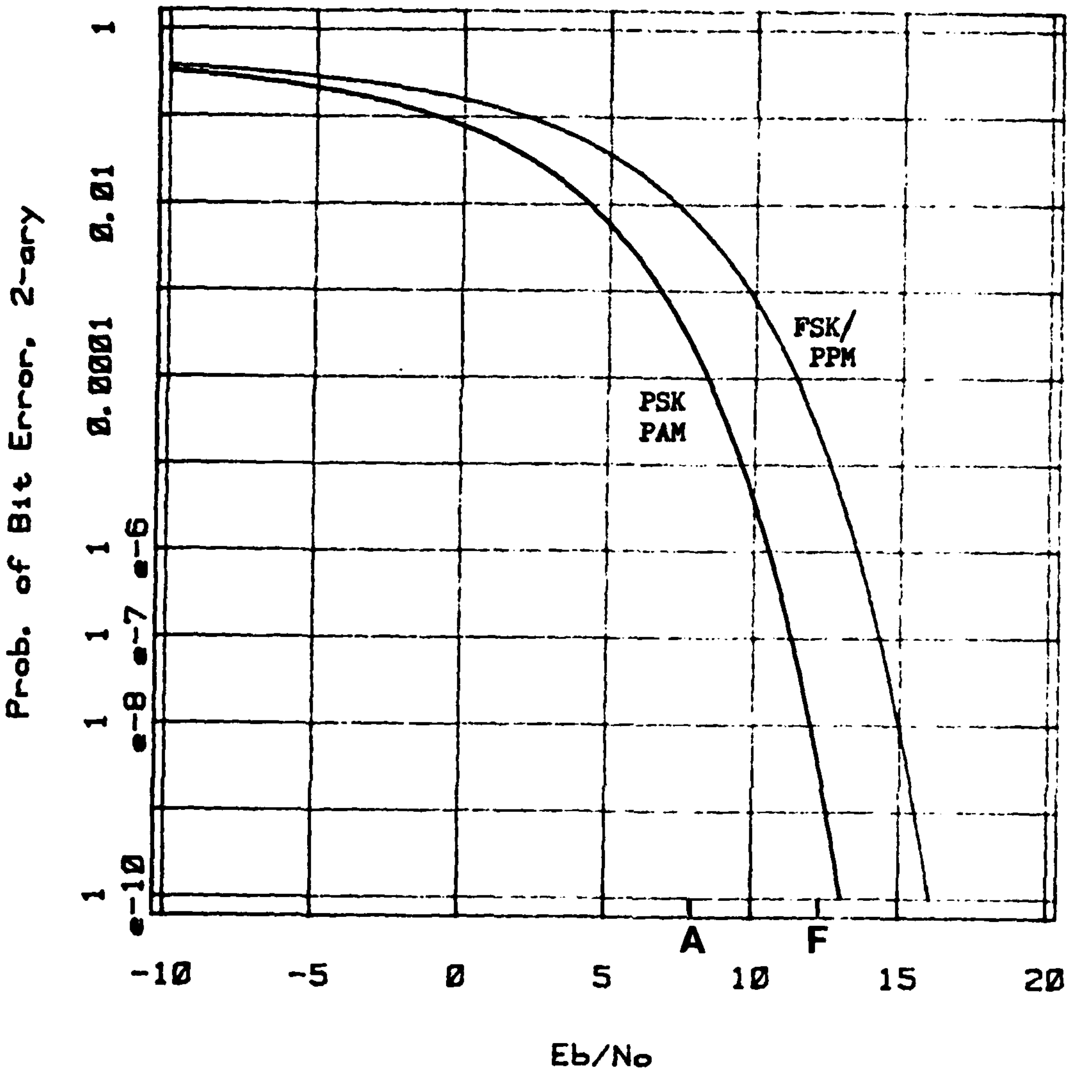
Low Risk Eb/No	14.53 dB
High/Low Risk Average Eb/No	32.78 dB
Five Year Projected Eb/No	37.06 dB
High Risk Eb/No	47.78 dB

Figure 4. Millimeter Wave 60 GHz, 1 MBps, 160° Separation, M=8



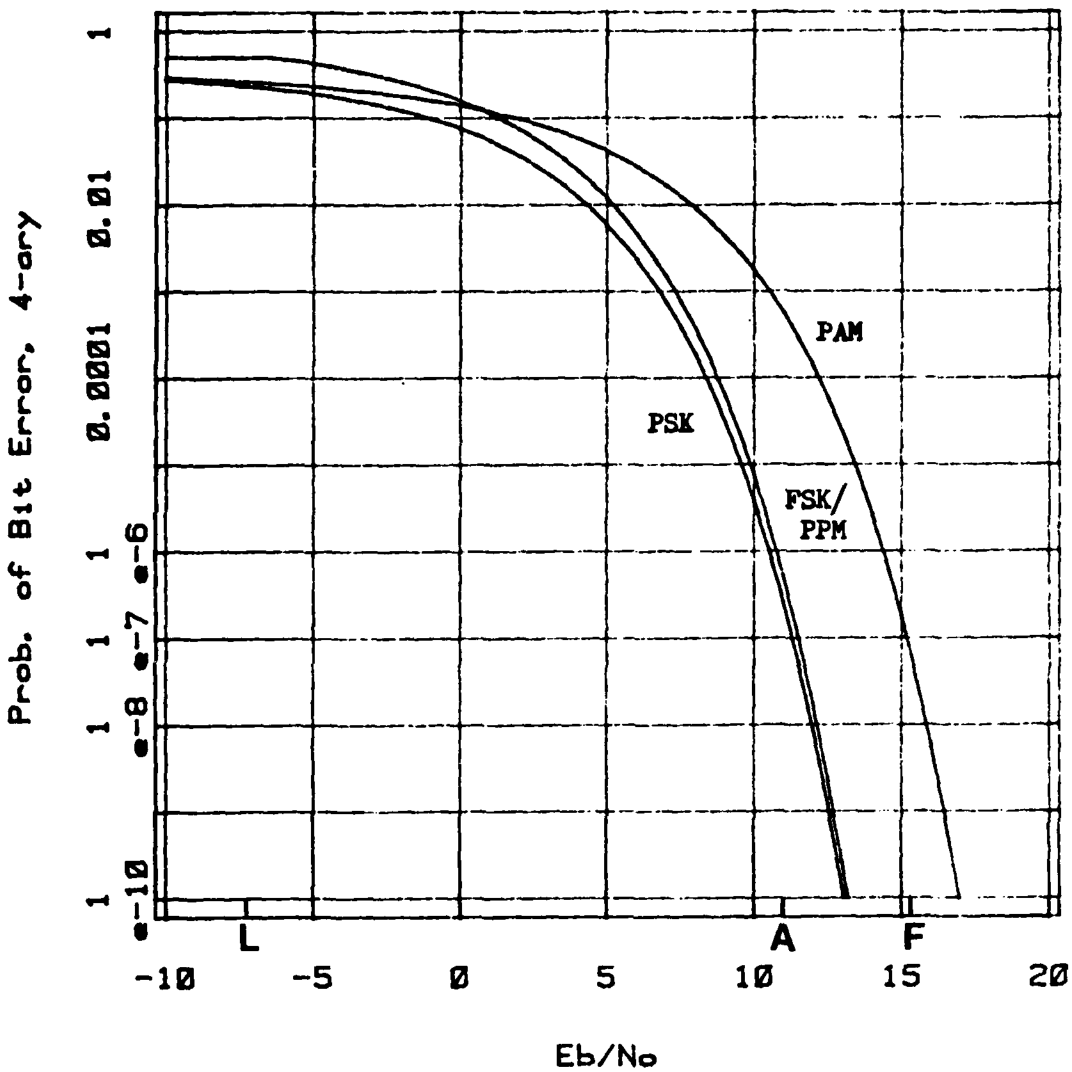
Low Risk Eb/No	15.77 dB
High/Low Risk Average Eb/No	34.02 dB
Five Year Projected Eb/No	38.31 dB
High Risk Eb/No	49.04 dB

Figure 5. Millimeter Wave 60 GHz, 1 MBps, 160° Separation, M=16



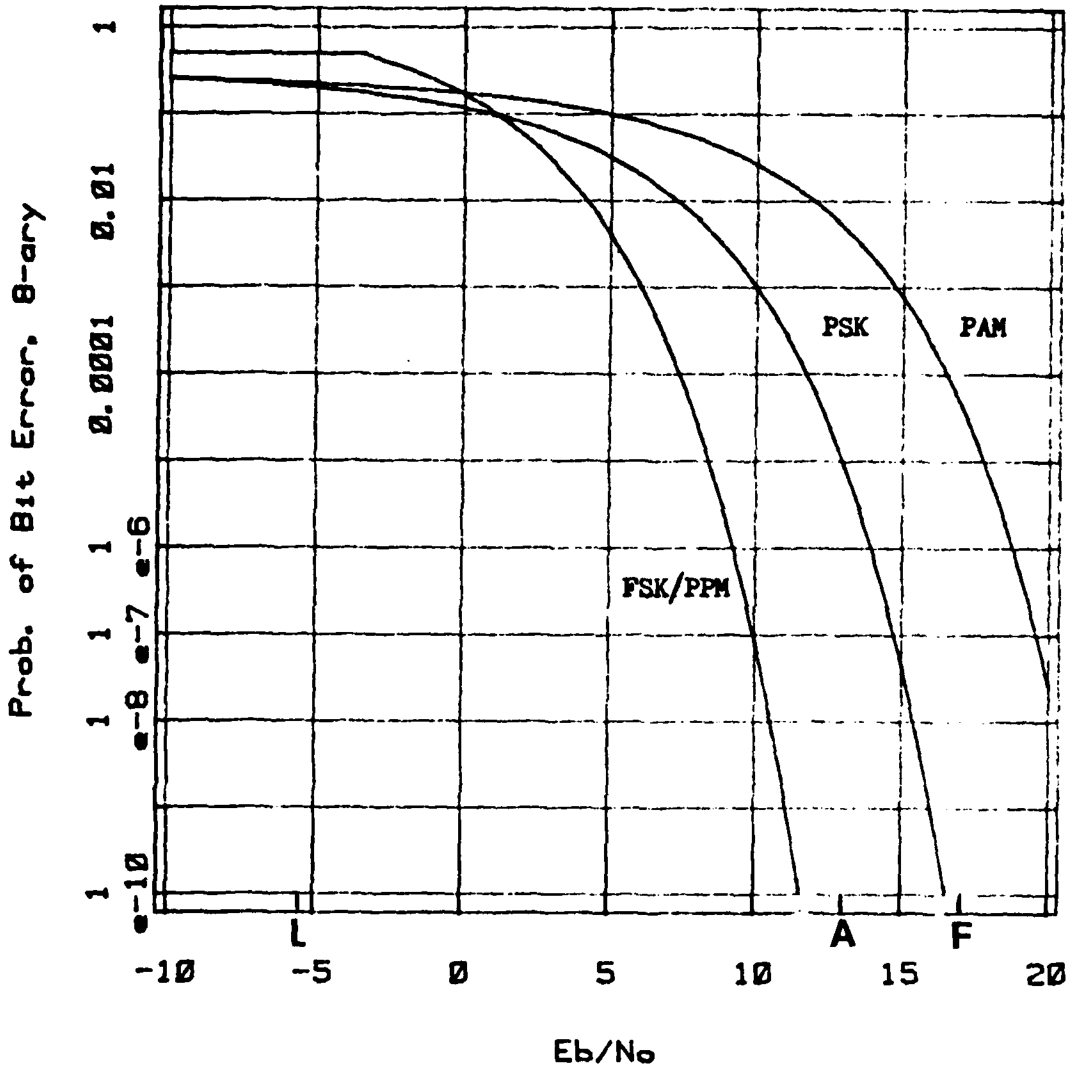
Low Risk Eb/No	-10.24 dB
High/Low Risk Average Eb/No	8.00 dB
Five Year Projected Eb/No	12.29 dB
High Risk Eb/No	23.02 dB

Figure 6. Millimeter Wave 60 GHz, 100 MBps, 160° Separation, M=2



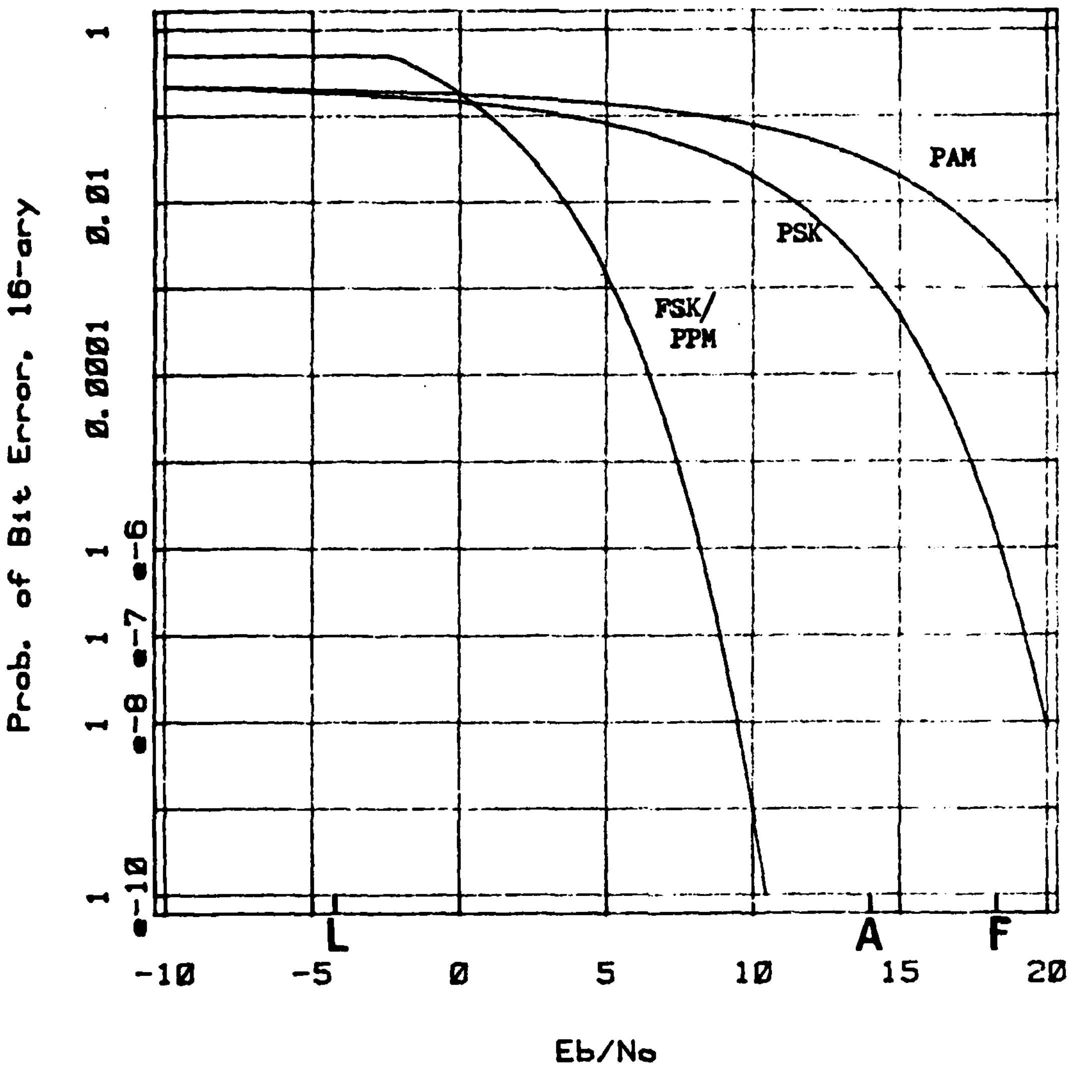
Low Risk Eb/No	-7.24 dB
High/Low Risk Average Eb/No	11.01 dB
Five Year Projected Eb/No	15.30 dB
High Risk Eb/No	26.03 dB

Figure 7. Millimeter Wave 60 GHz, 100 MBps, 160° Separation, M=4



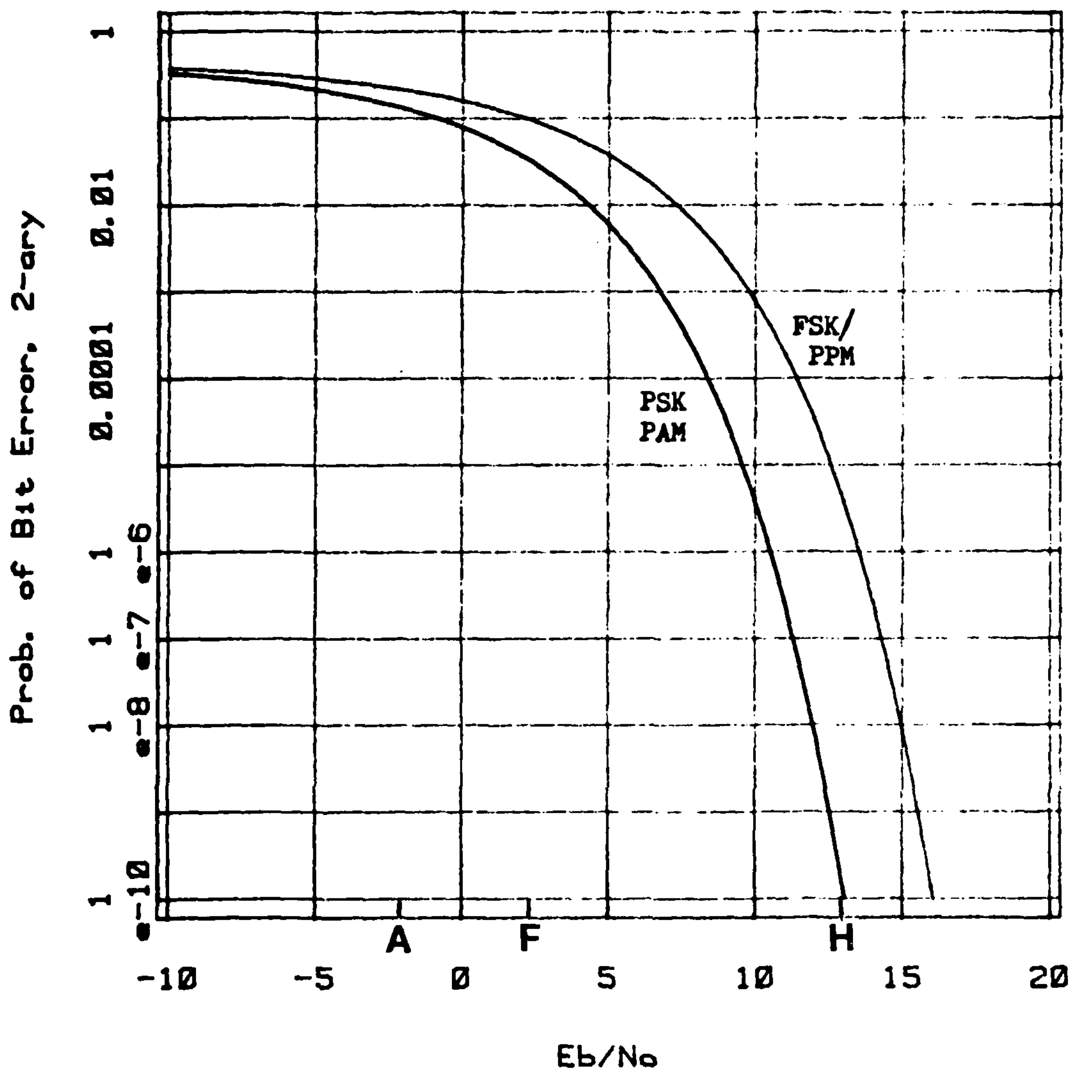
Low Risk Eb/No	-5.47 dB
High/Low Risk Average Eb/No	12.78 dB
Five Year Projected Eb/No	17.06 dB
High Risk Eb/No	27.79 dB

Figure 8. Millimeter Wave 60 GHz, 100 MBps, 160° Separation, M=8



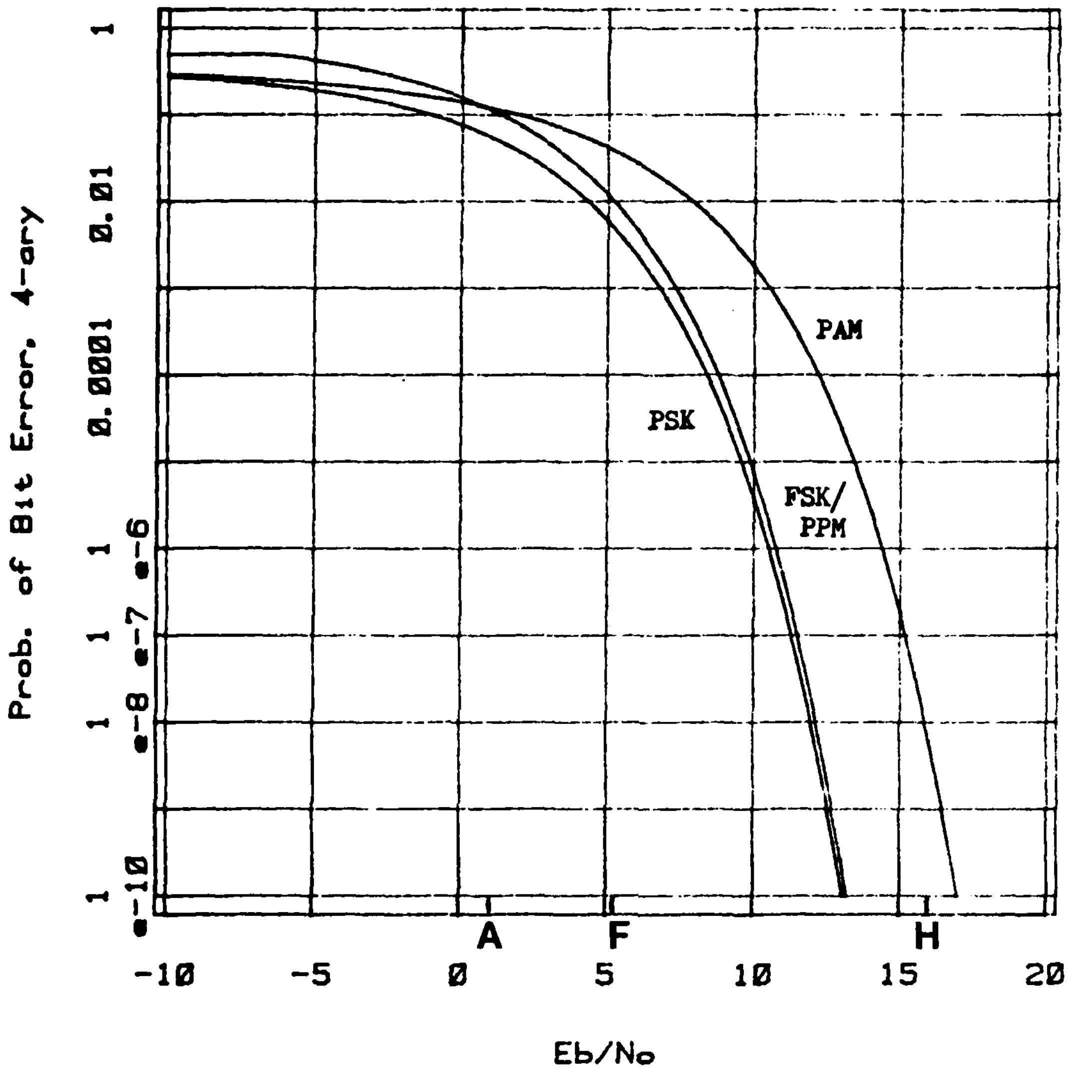
Low Risk Eb/No	-4.23 dB
High/Low Risk Average Eb/No	14.02 dB
Five Year Projected Eb/No	18.31 dB
High Risk Eb/No	29.04 dB

Figure 9. Millimeter Wave 60 GHz, 100 MBps, 160° Separation, M=16



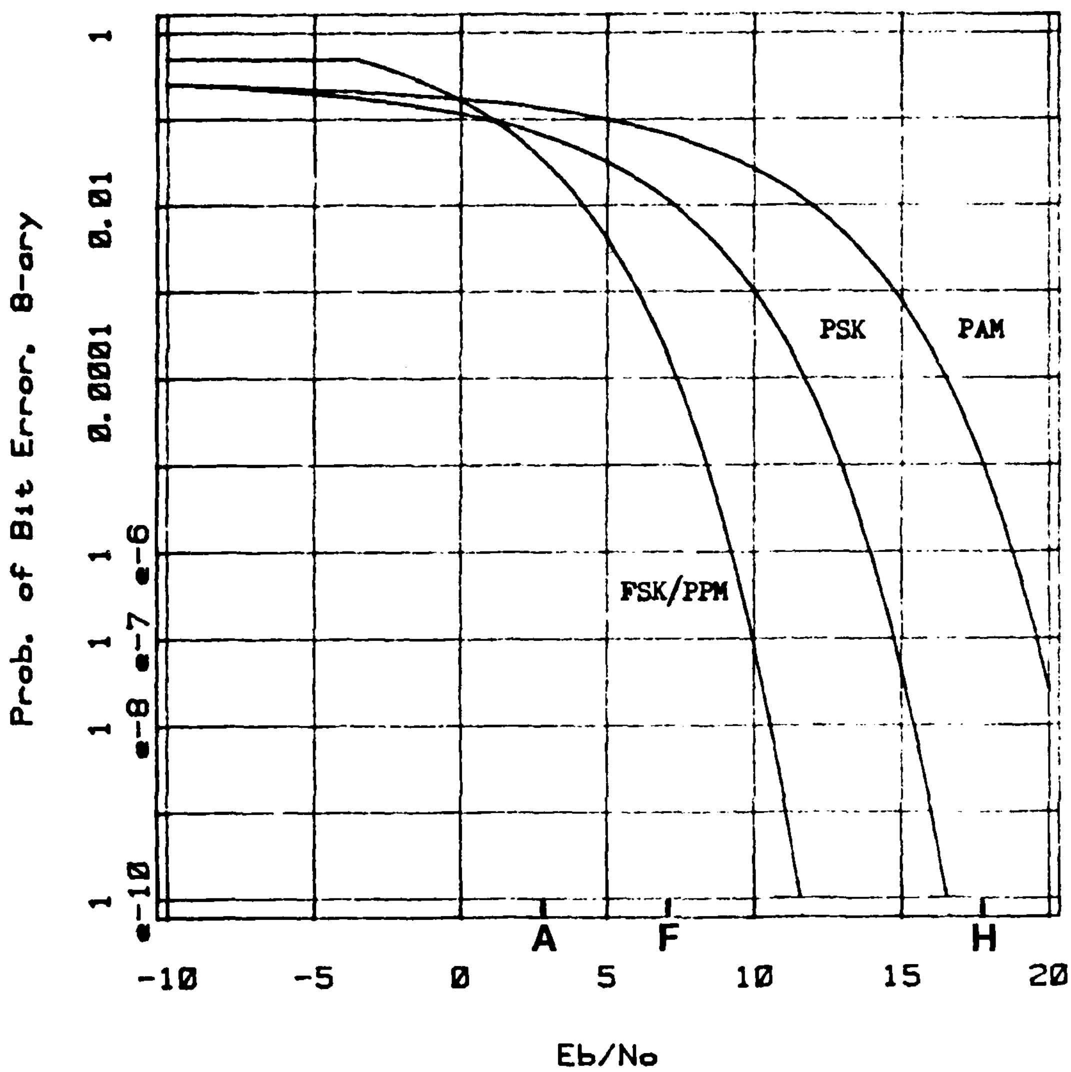
Low Risk Eb/No	-20.24 dB
High/Low Risk Average Eb/No	-2.00 dB
Five Year Projected Eb/No	2.29 dB
High Risk Eb/No	13.02 dB

Figure 10. Millimeter Wave 60 GHz, 1 GBps, 160° Separation, M=2



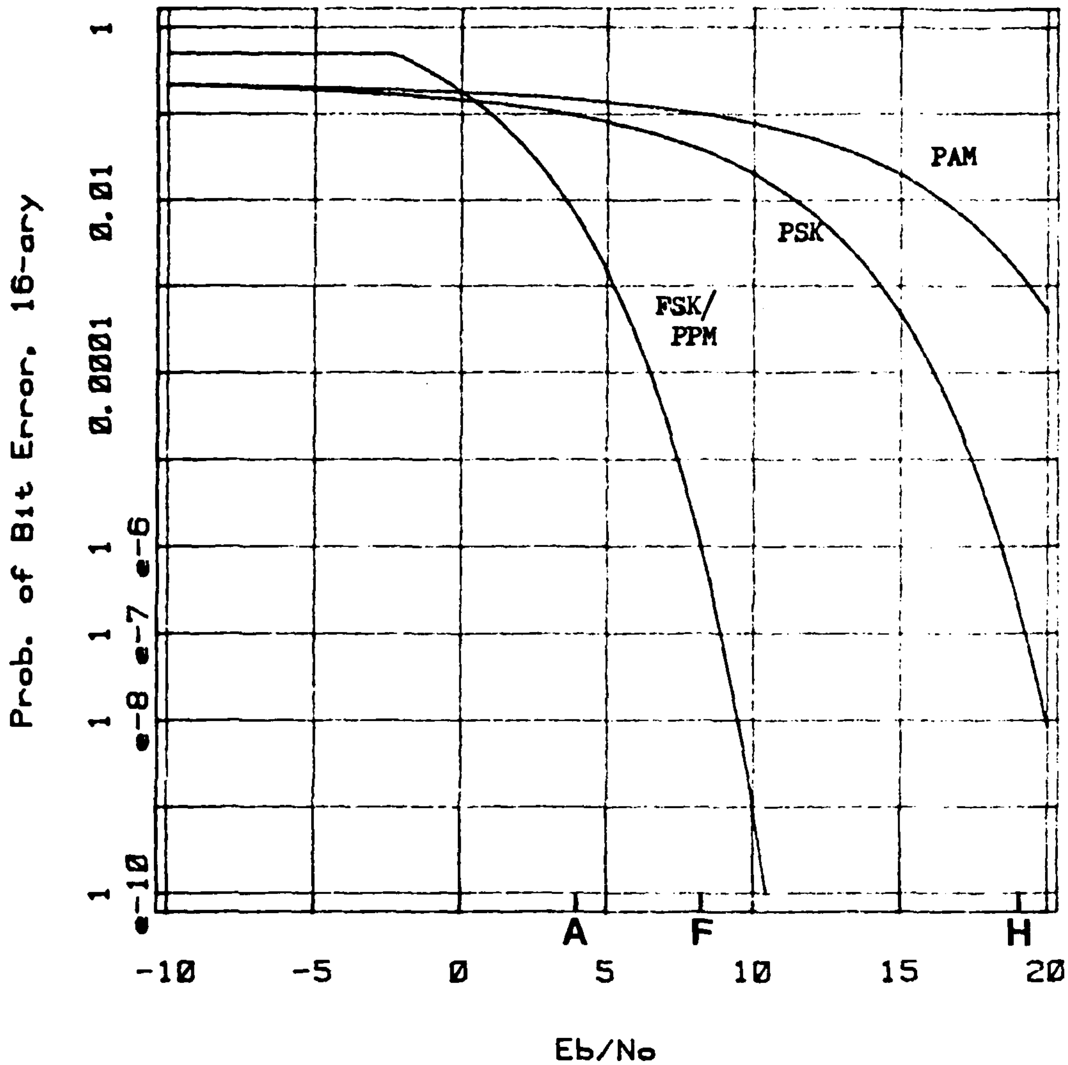
Low Risk Eb/No	-17.24 dB
High/Low Risk Average Eb/No	1.01 dB
Five Year Projected Eb/No	5.30 dB
High Risk Eb/No	16.03 dB

Figure 11. Millimeter Wave 60 GHz, 1 GBps, 160° Separation, M=4



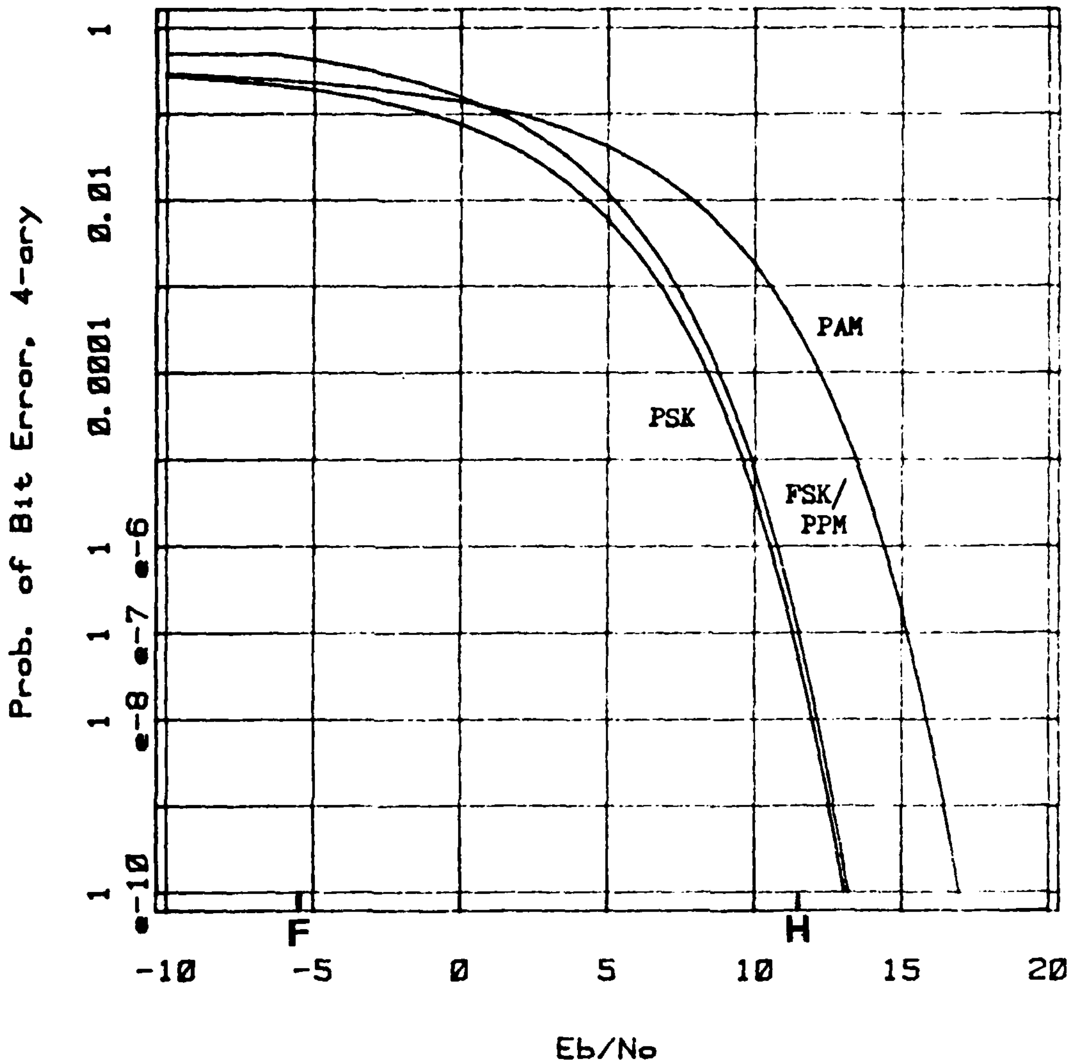
Low Risk Eb/No	-15.47 dB
High/Low Risk Average Eb/No	2.78 dB
Five Year Projected Eb/No	7.06 dB
High Risk Eb/No	17.79 dB

Figure 12. Millimeter Wave 60 GHz, 1 GBps, 160° Separation, M=8



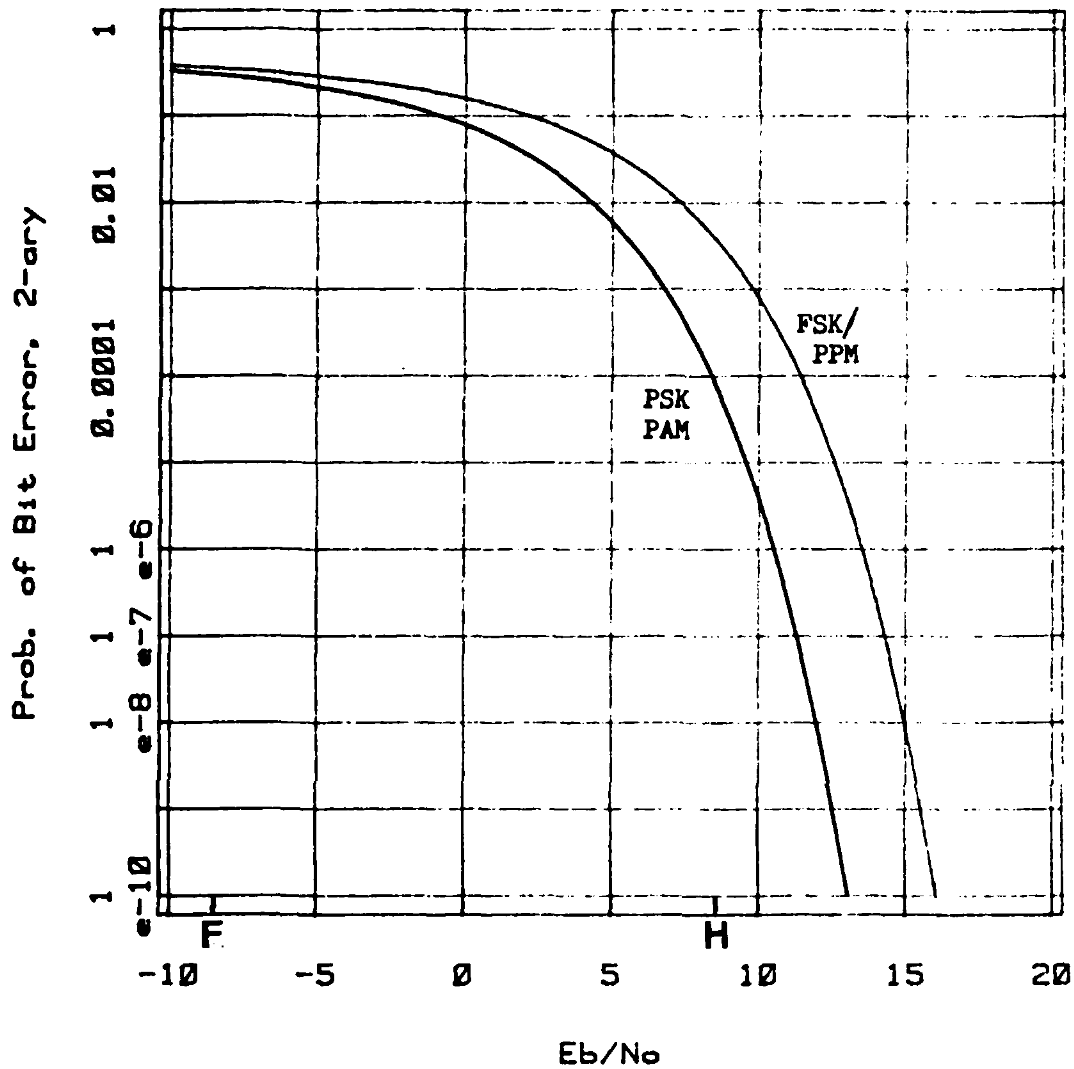
Low Risk Eb/No	-14.23 dB
High/Low Risk Average Eb/No	4.02 dB
Five Year Projected Eb/No	8.31 dB
High Risk Eb/No	19.04 dB

Figure 13. Millimeter Wave 60 GHz, 1 GBps, 160° Separation, M=16



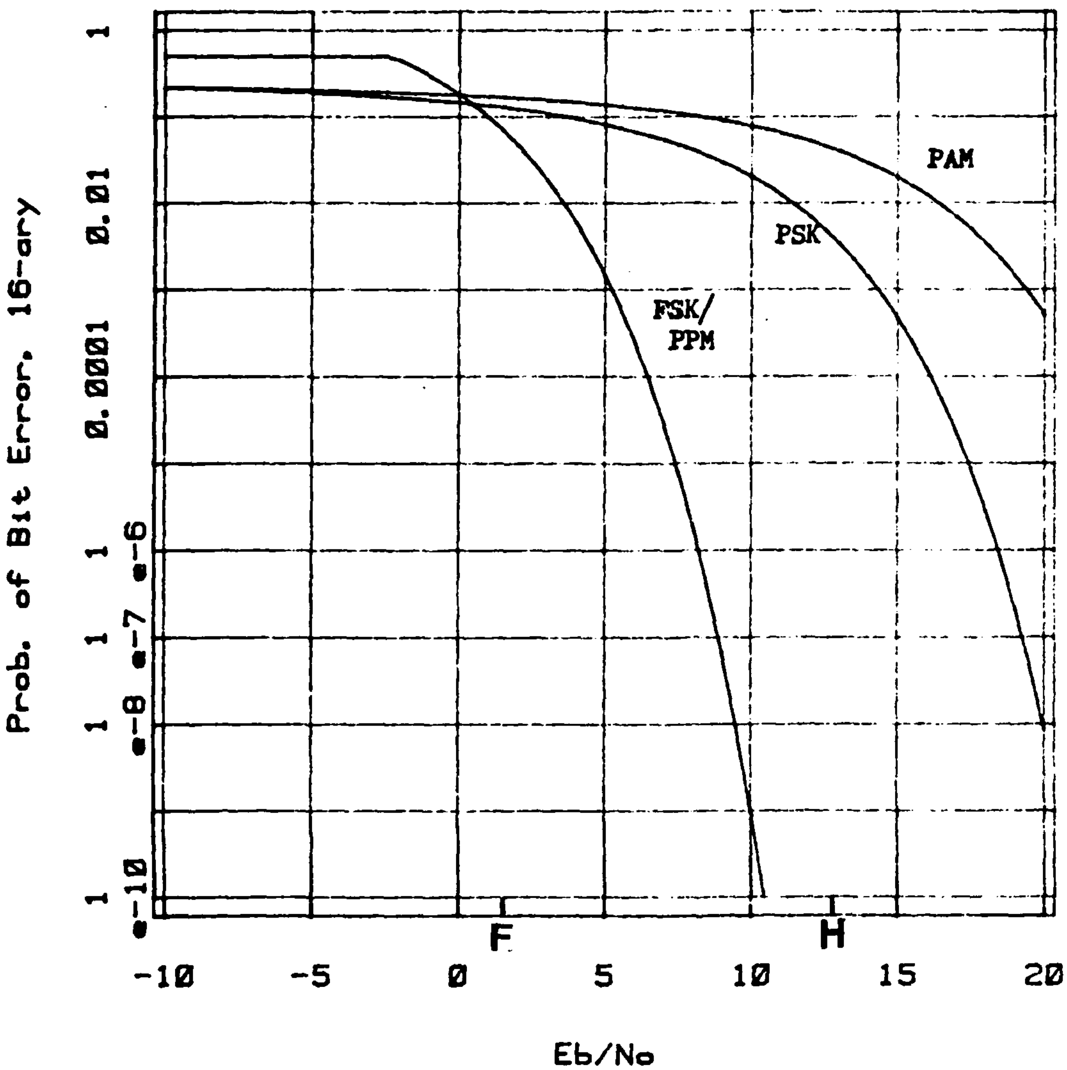
Low Risk Eb/No	-34.40 dB
High/Low Risk Average Eb/No	-18.69 dB
Five Year Projected Eb/No	-5.42 dB
High Risk Eb/No	11.41 dB

Figure 27. Direct Detect Nd:YAG, 1 MBps, 160° Separation, M=4



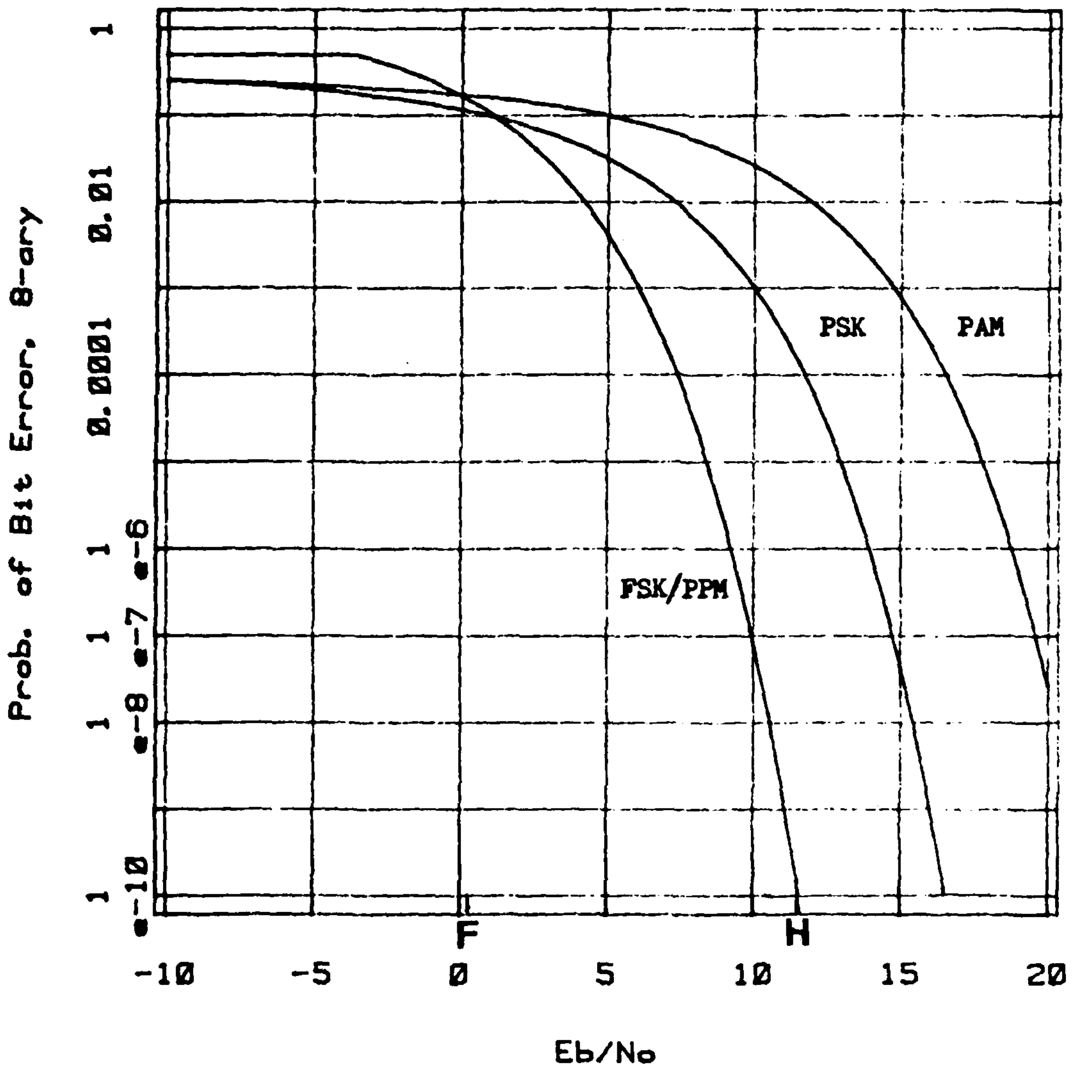
Low Risk Eb/No	-37.42 dB
High/Low Risk Average Eb/No	-21.70 dB
Five Year Projected Eb/No	-8.43 dB
High Risk Eb/No	8.40 dB

Figure 26. Direct Detect Nd:YAG, 1 MBps, 160° Separation, M=2



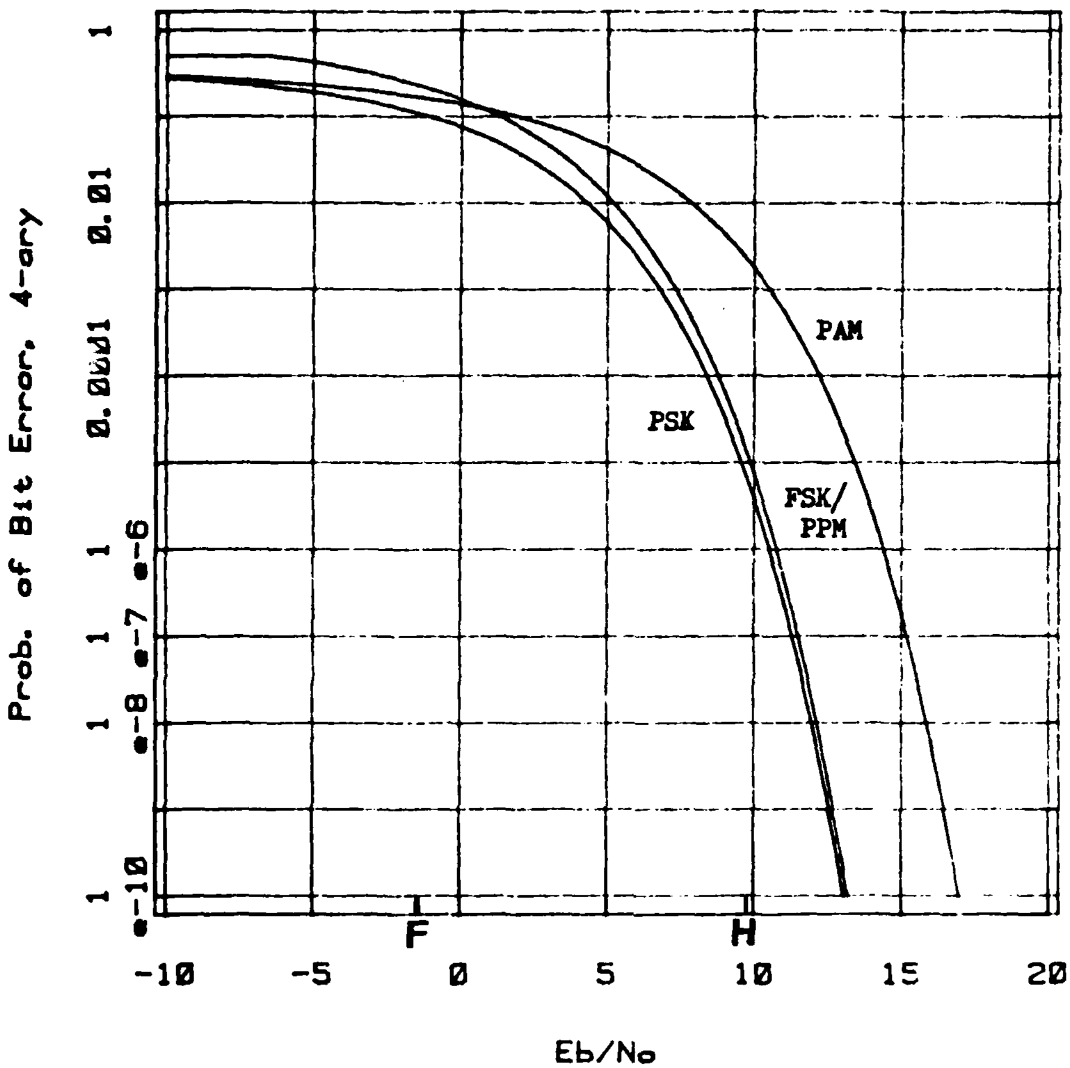
Low Risk Eb/No	-30.76 dB
High/Low Risk Average Eb/No	-11.26 dB
Five Year Projected Eb/No	1.57 dB
High Risk Eb/No	12.79 dB

Figure 25. Millimeter Wave 90 GHz, 1 GBps, 160° Separation, M=16



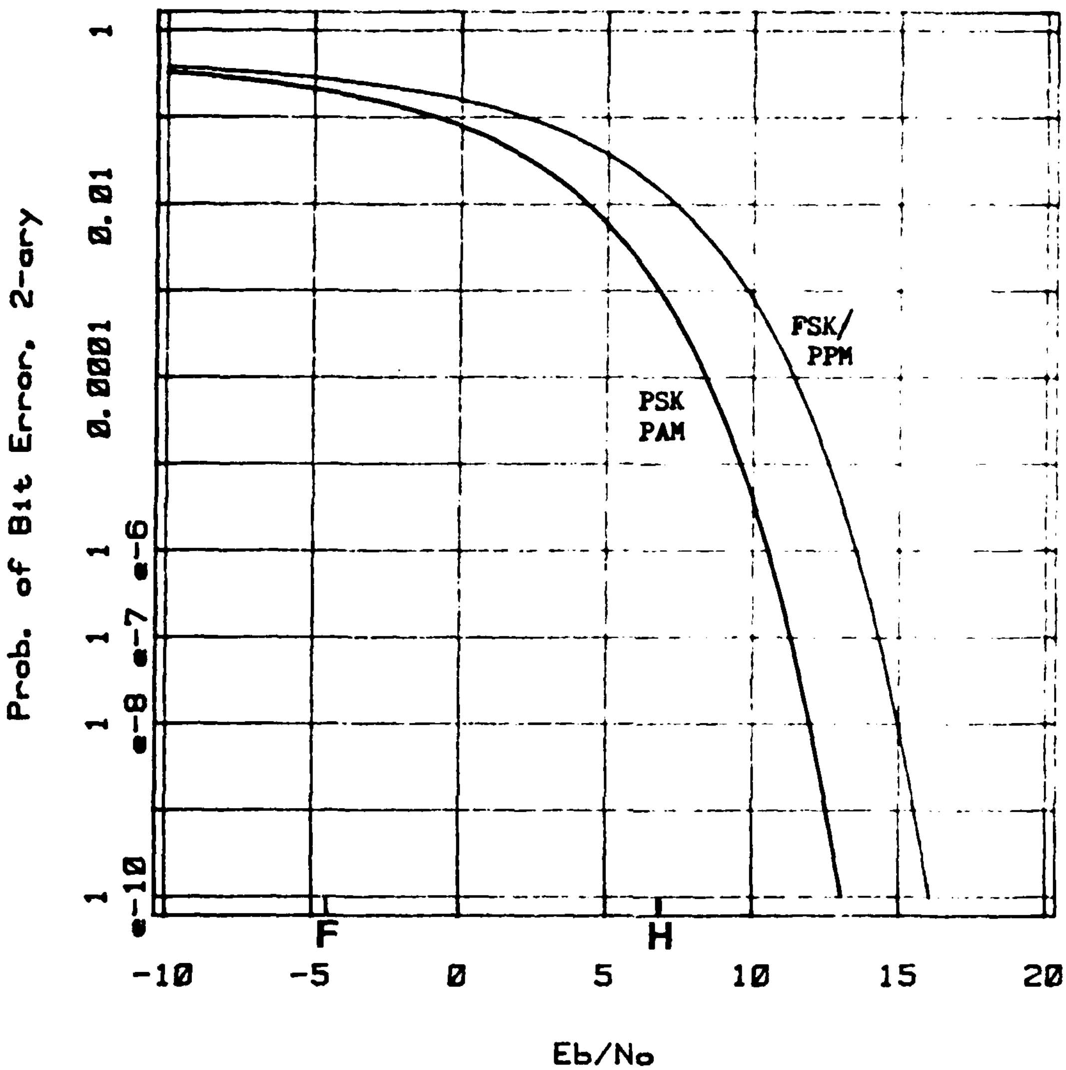
Low Risk Eb/No	-32.01 dB
High/Low Risk Average Eb/No	-12.51 dB
Five Year Projected Eb/No	0.32 dB
High Risk Eb/No	11.54 dB

Figure 24. Millimeter Wave 90 GHz, 1 GBps, 160° Separation, M=8



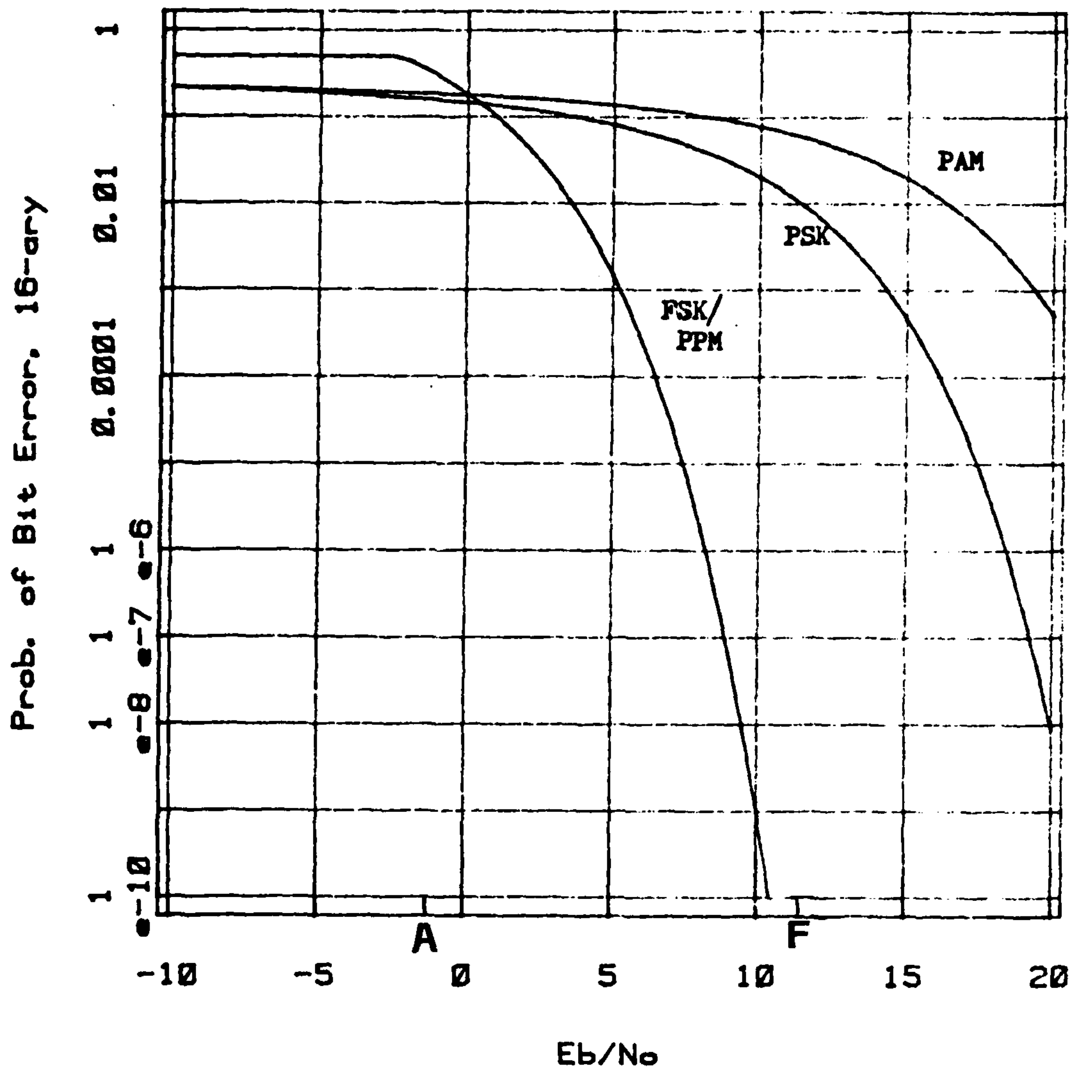
Low Risk Eb/No	-33.77 dB
High/Low Risk Average Eb/No	-14.27 dB
Five Year Projected Eb/No	-1.44 dB
High Risk Eb/No	9.78 dB

Figure 23. Millimeter Wave 90 GHz, 1 GBps, 160° Separation, M=4



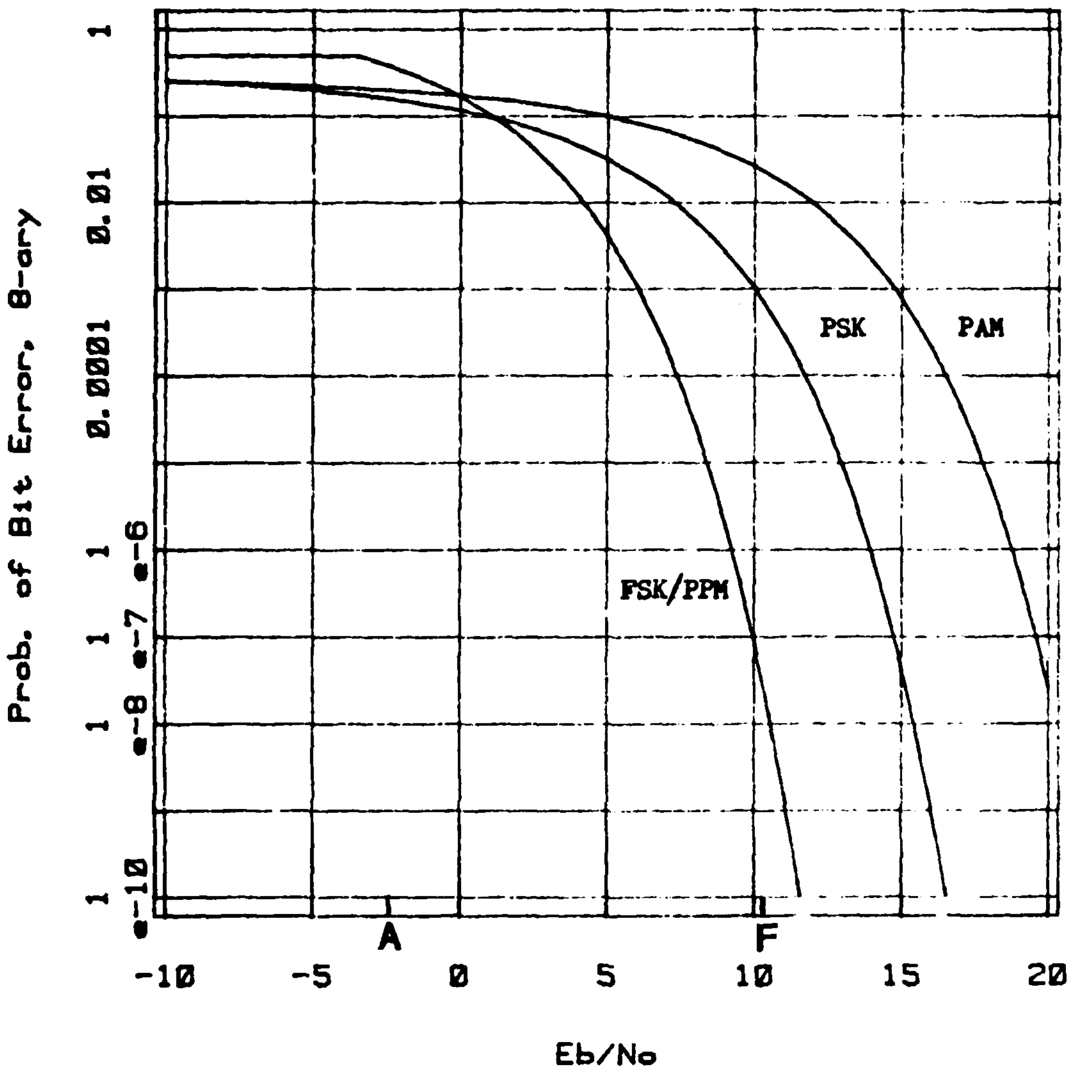
Low Risk Eb/No	-36.78 dB
High/Low Risk Average Eb/No	-17.28 dB
Five Year Projected Eb/No	-4.45 dB
High Risk Eb/No	6.76 dB

Figure 22. Millimeter Wave 90 GHz, 1 GBps, 160° Separation, M=2



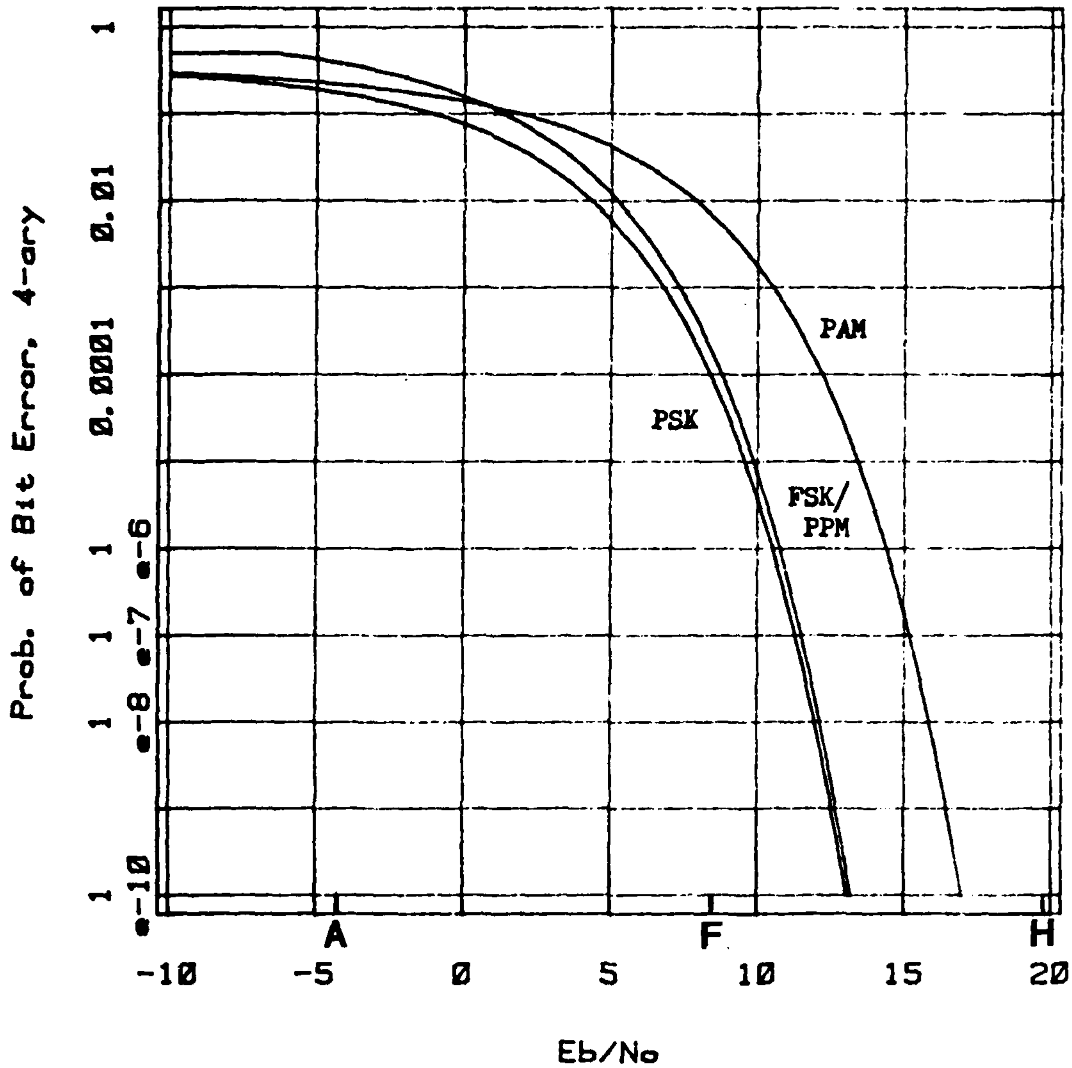
Low Risk Eb/No	-20.76 dB
High/Low Risk Average Eb/No	-1.26 dB
Five Year Projected Eb/No	11.57 dB
High Risk Eb/No	22.79 dB

Figure 21. Millimeter Wave 90 GHz, 100 MBps, 160° Separation, M=16



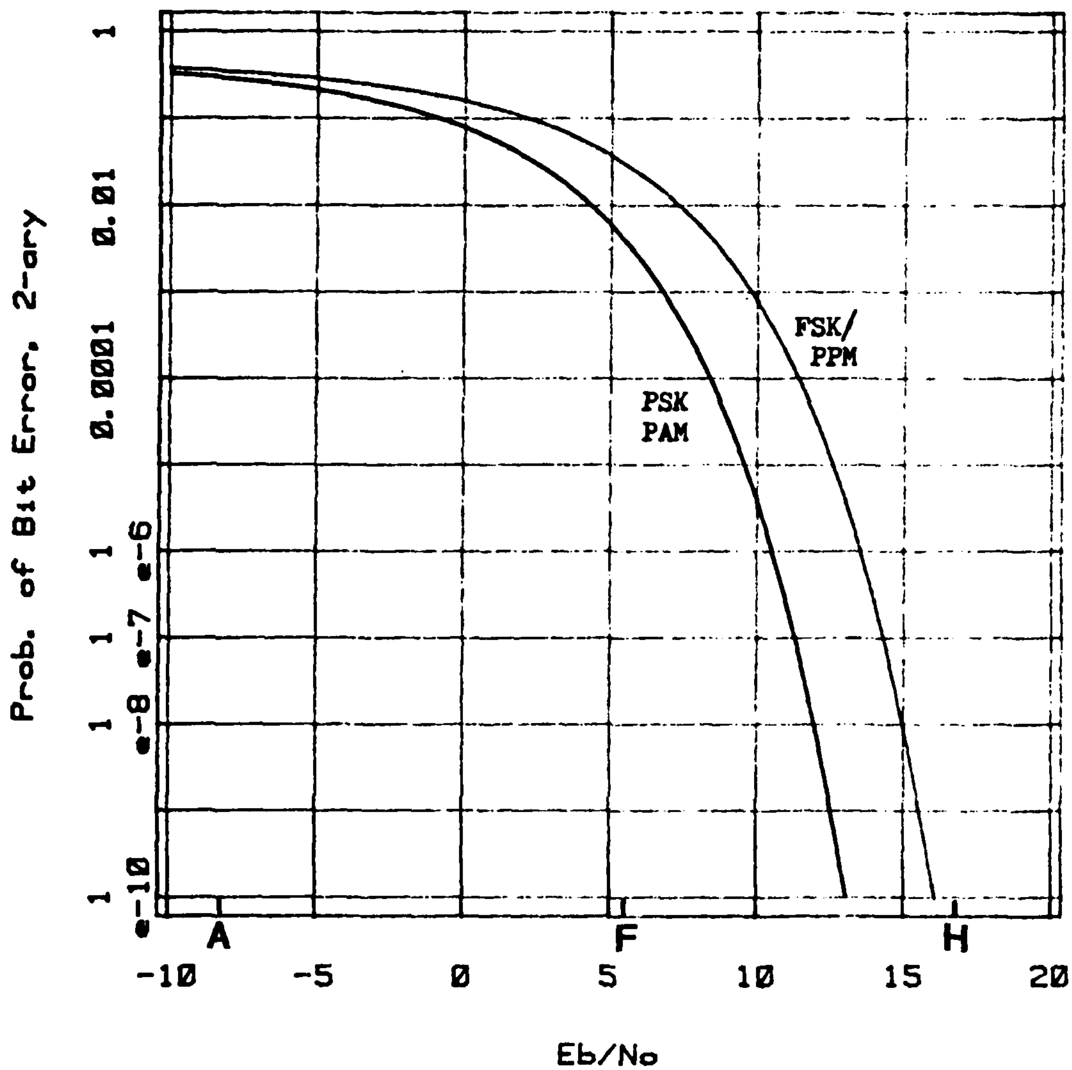
Low Risk Eb/No	-22.01 dB
High/Low Risk Average Eb/No	-2.51 dB
Five Year Projected Eb/No	10.32 dB
High Risk Eb/No	21.54 dB

Figure 20. Millimeter Wave 90 GHz, 100 MBps, 160° Separation, M=8



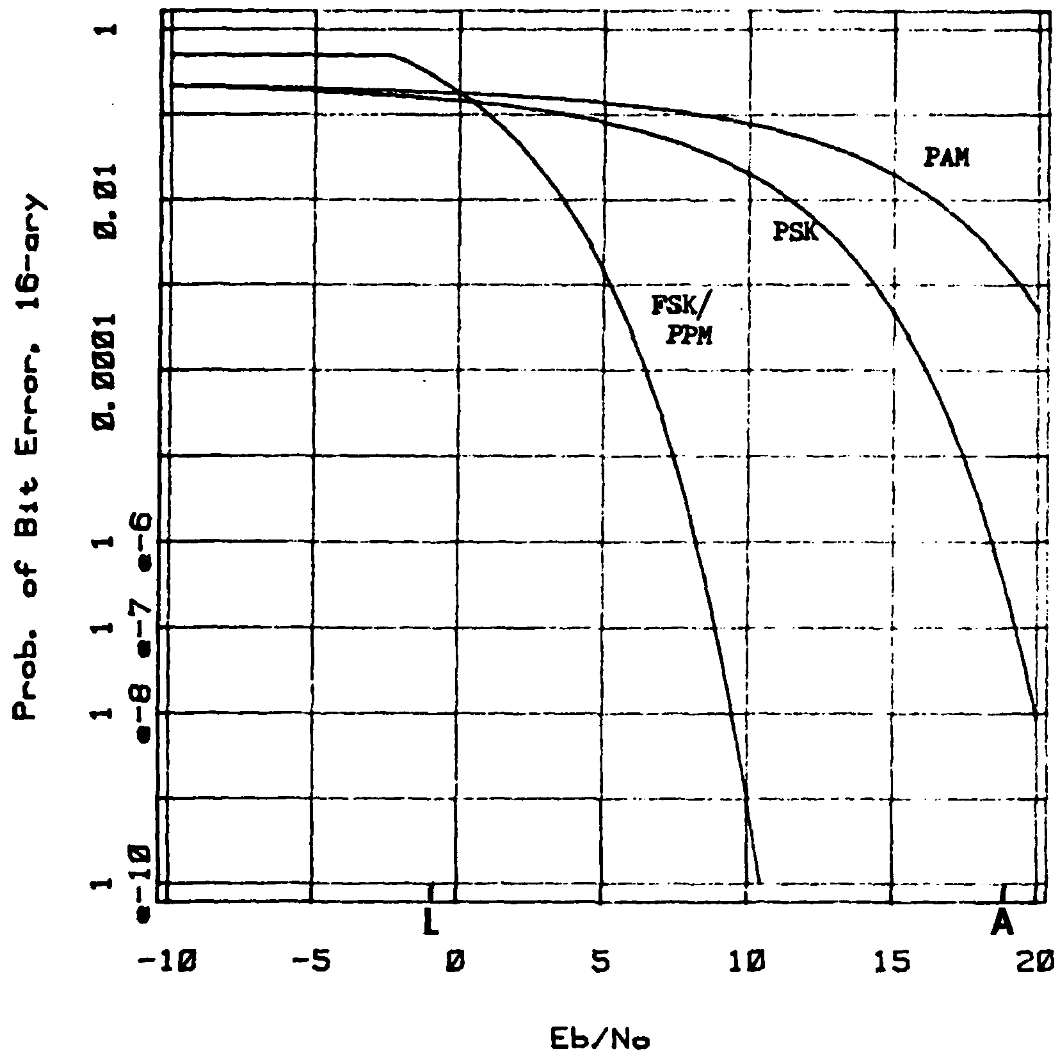
Low Risk Eb/No	-23.77 dB
High/Low Risk Average Eb/No	-4.27 dB
Five Year Projected Eb/No	8.56 dB
High Risk Eb/No	19.78 dB

Figure 19. Millimeter Wave 90 GHz, 100 MBps, 160° Separation, M=4



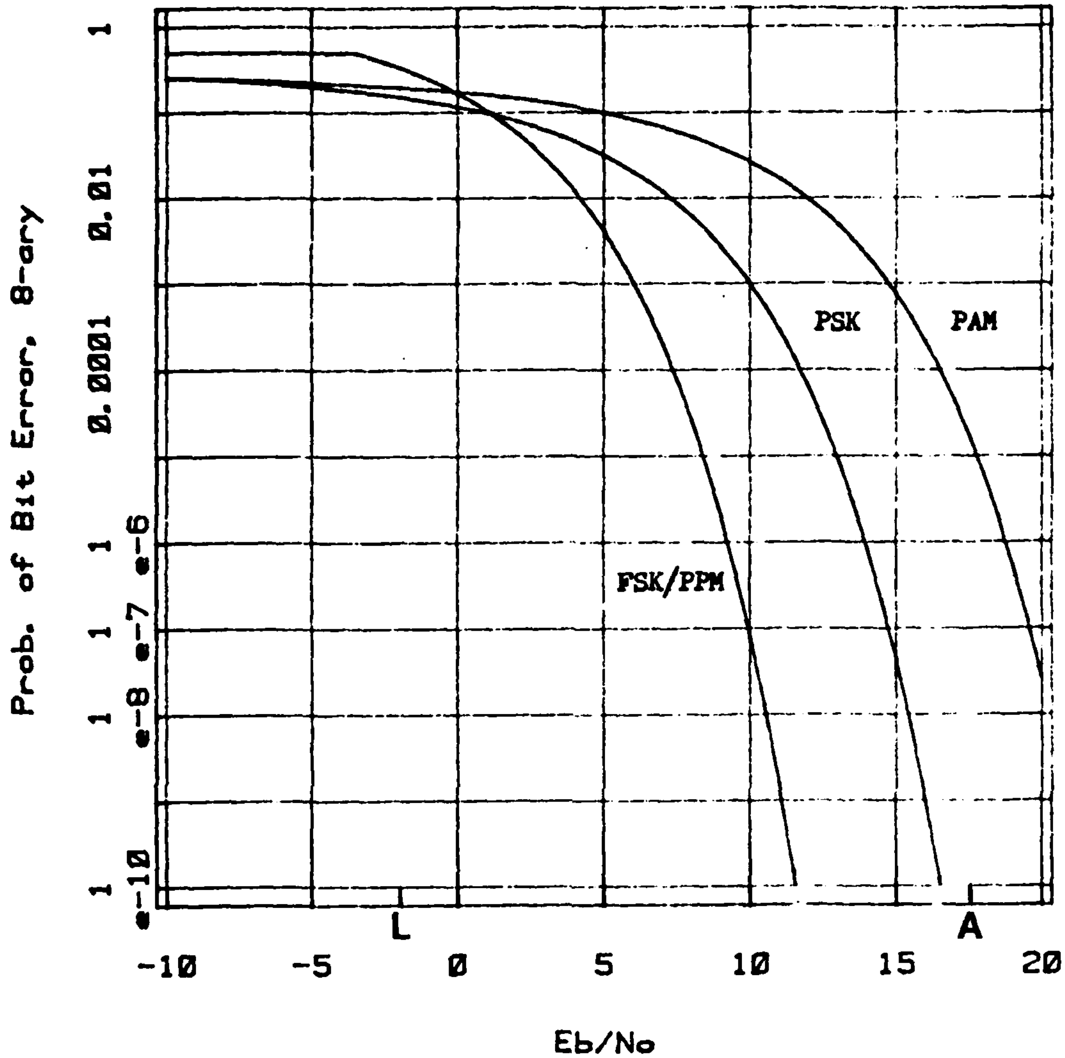
Low Risk Eb/No	-26.78 dB
High/Low Risk Average Eb/No	-7.28 dB
Five Year Projected Eb/No	5.55 dB
High Risk Eb/No	16.77 dB

Figure 18. Millimeter Wave 90 GHz, 100 MBps, 160° Separation, M=2



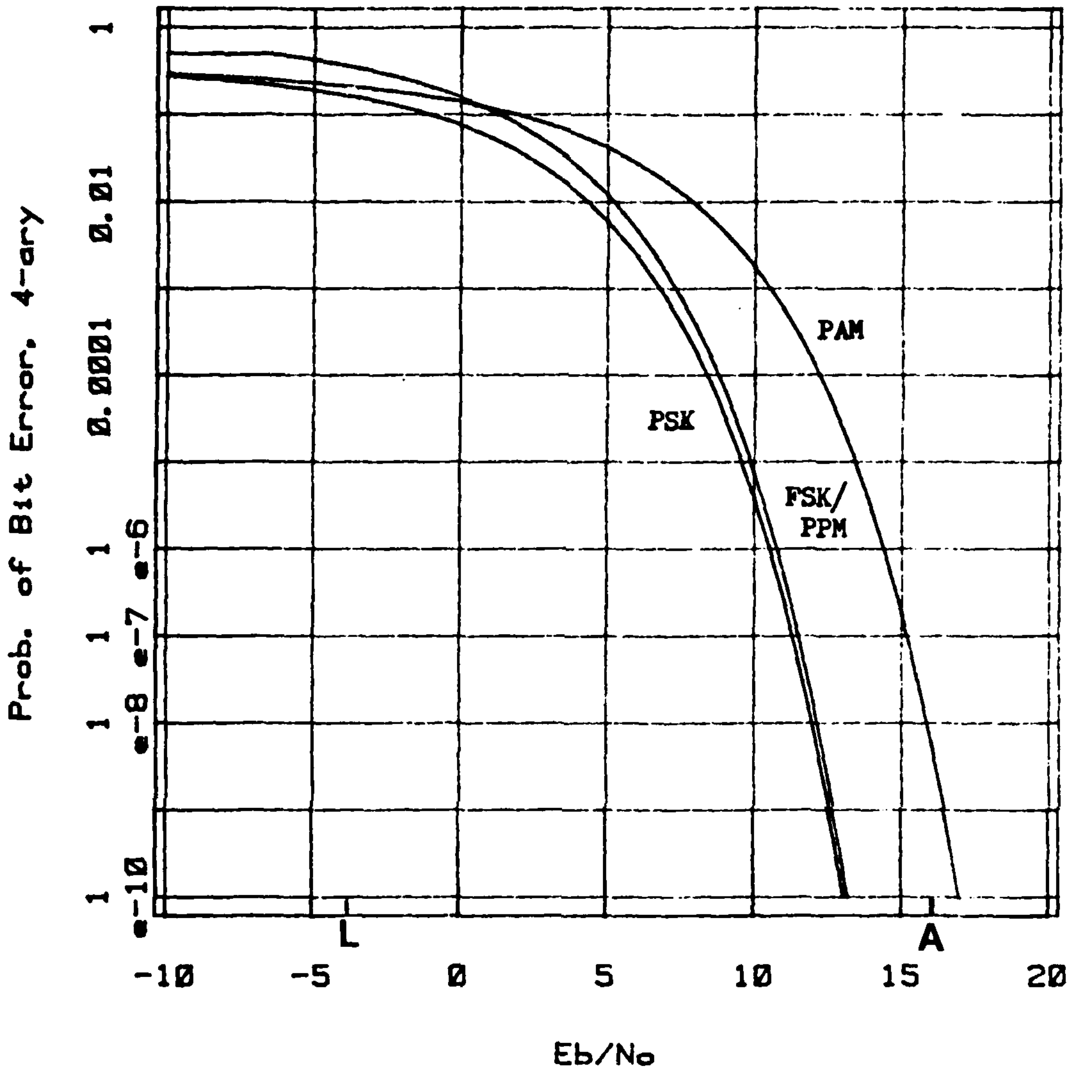
Low Risk Eb/No	-0.76 dB
High/Low Risk Average Eb/No	18.74 dB
Five Year Projected Eb/No	31.57 dB
High Risk Eb/No	42.79 dB

Figure 17. Millimeter Wave 90 GHz, 1 MBps, 160° Separation, M=16



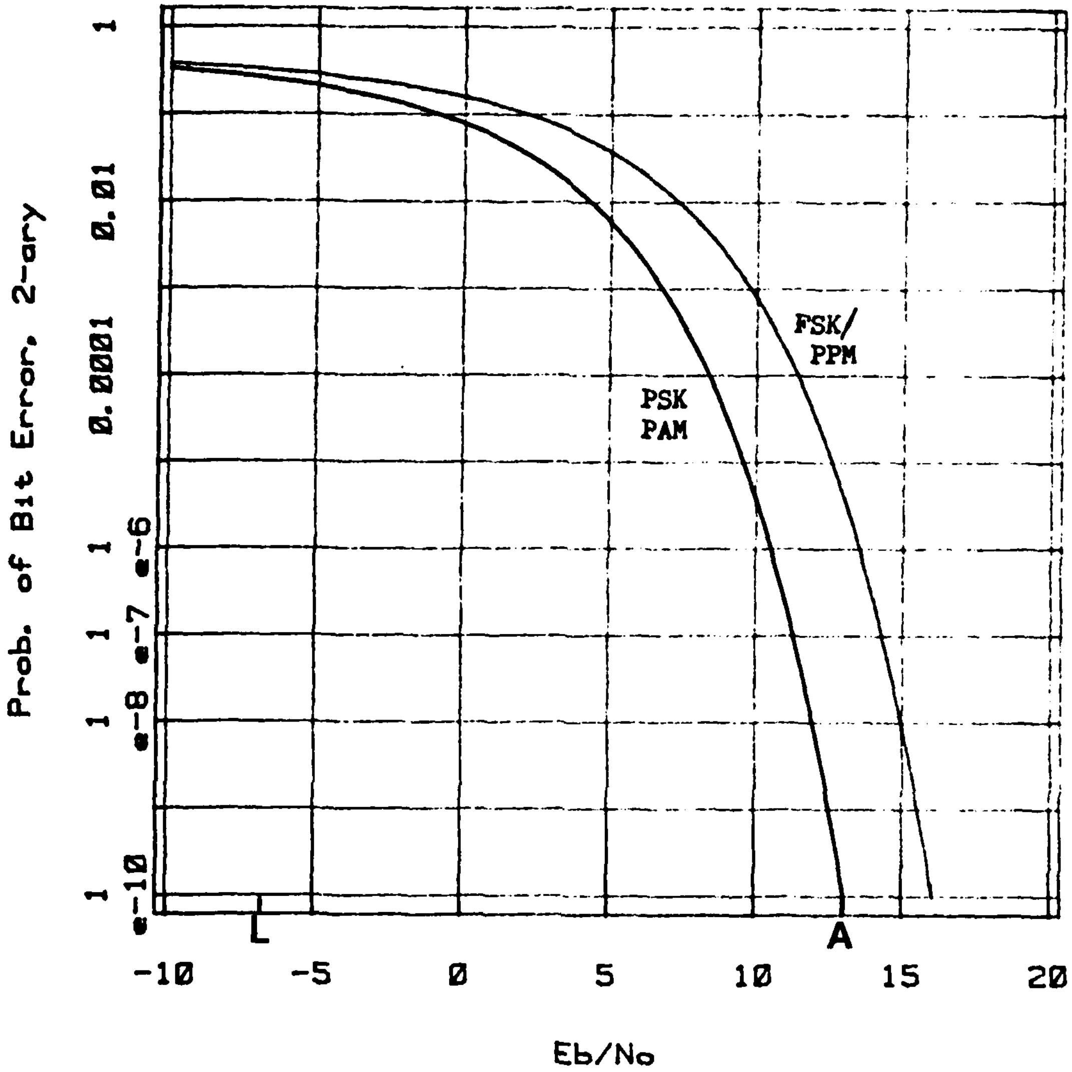
Low Risk Eb/No	-2.01 dB
High/Low Risk Average Eb/No	17.49 dB
Five Year Projected Eb/No	30.33 dB
High Risk Eb/No	41.54 dB

Figure 16. Millimeter Wave 90 GHz, 1 MBps, 160° Separation, M=8



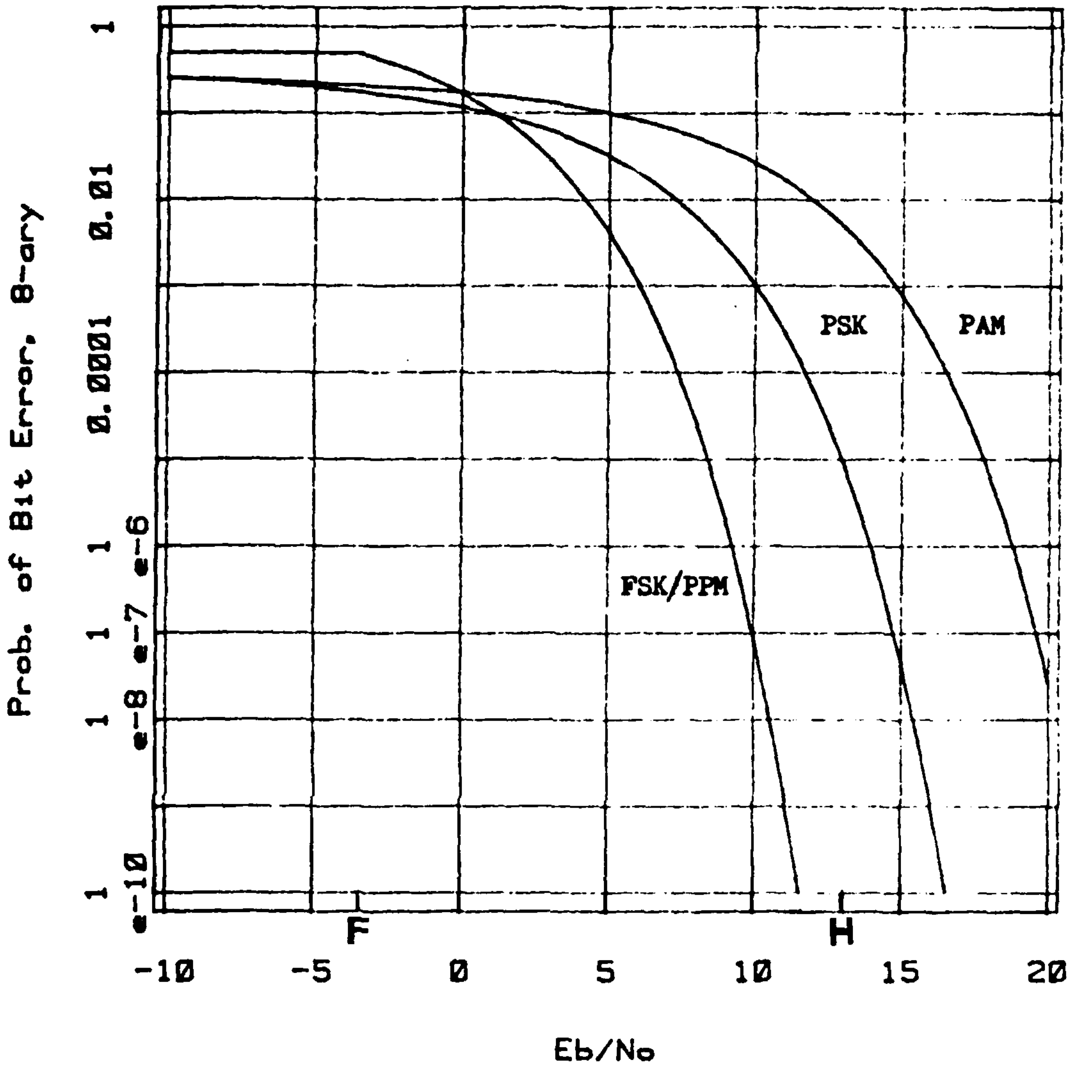
Low Risk Eb/No	-3.77 dB
High/Low Risk Average Eb/No	15.73 dB
Five Year Projected Eb/No	28.56 dB
High Risk Eb/No	39.78 dB

Figure 15. Millimeter Wave 90 GHz, 1 MBps, 160° Separation, M=4



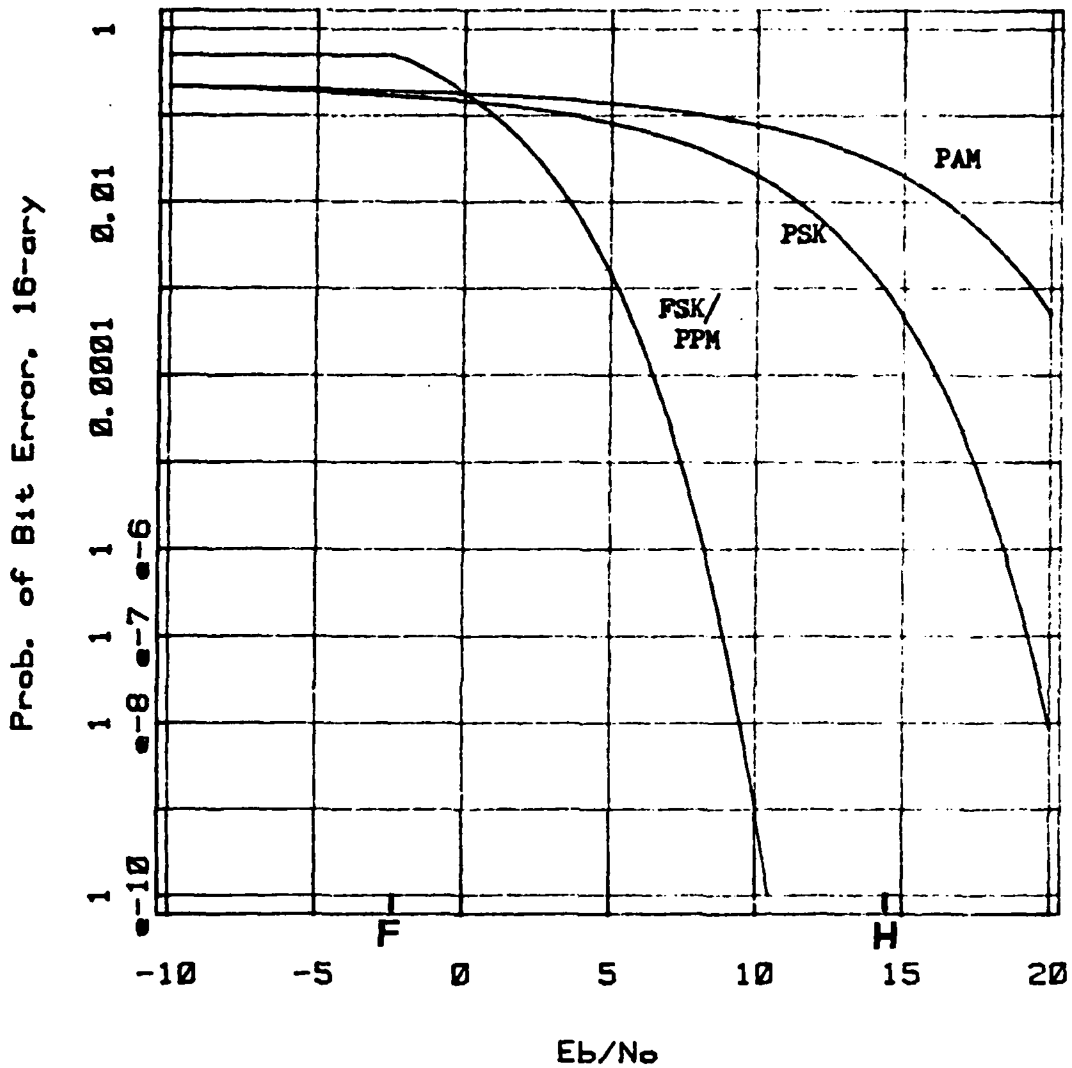
Low Risk Eb/No	-6.78 dB
High/Low Risk Average Eb/No	12.72 dB
Five Year Projected Eb/No	25.55 dB
High Risk Eb/No	36.77 dB

Figure 14. Millimeter Wave 90 GHz, 1 MBps, 160° Separation, M=2



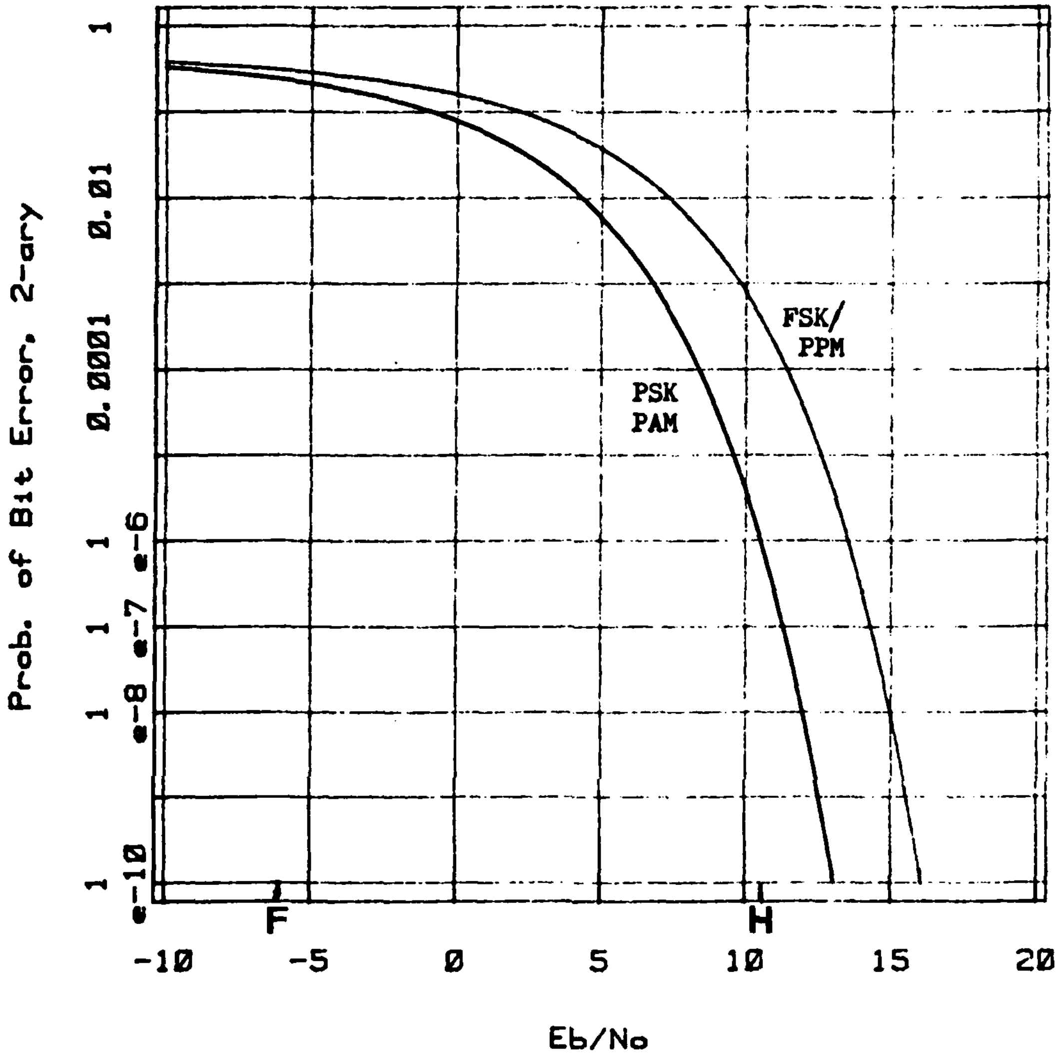
Low Risk Eb/No	-32.64 dB
High/Low Risk Average Eb/No	-16.93 dB
Five Year Projected Eb/No	-3.66 dB
High Risk Eb/No	13.17 dB

Figure 28. Direct Detect Nd:YAG, 1 MBps, 160° Separation, M=8



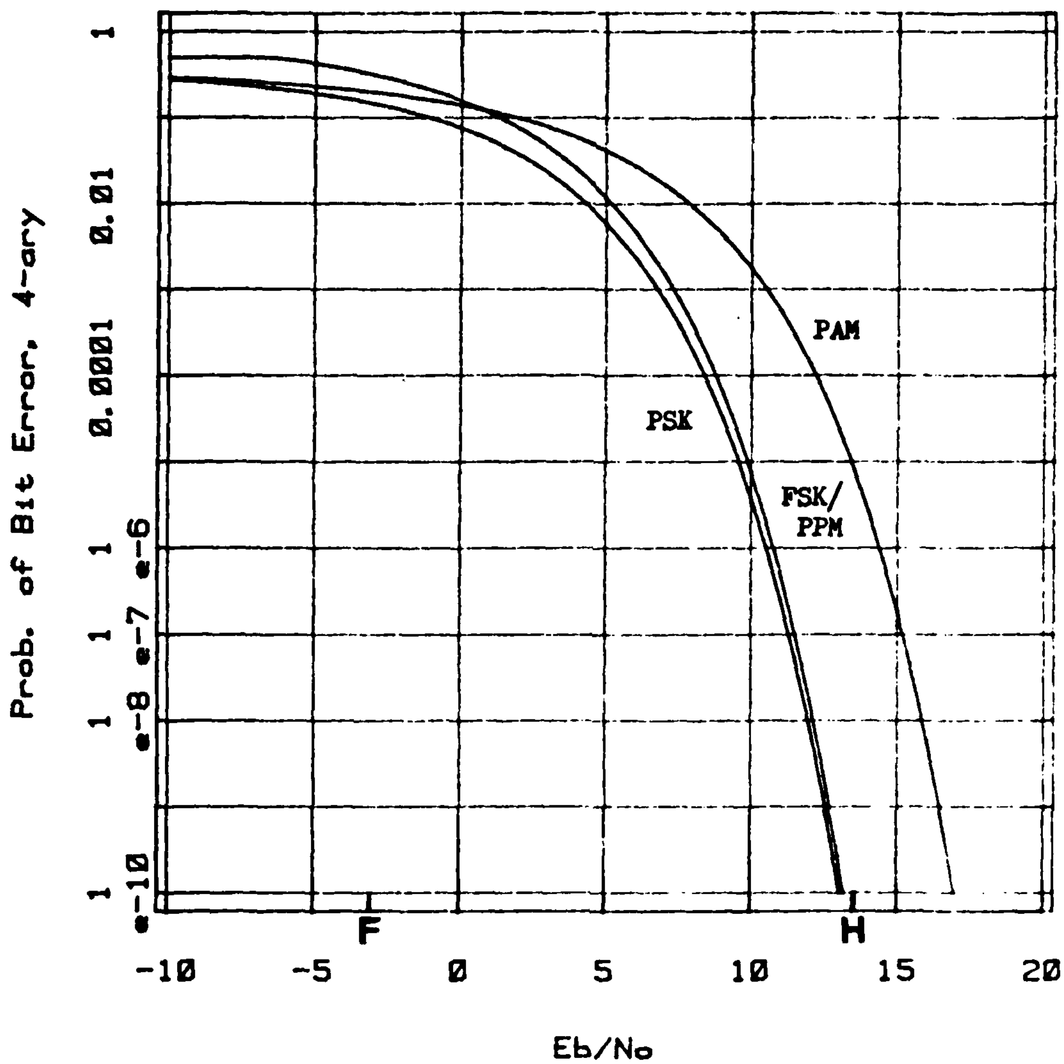
Low Risk Eb/No	-31.39 dB
High/Low Risk Average Eb/No	-15.68 dB
Five Year Projected Eb/No	-2.41 dB
High Risk Eb/No	14.42 dB

Figure 29. Direct Detect Nd:YAG, 1 MBps, 160° Separation, M=16



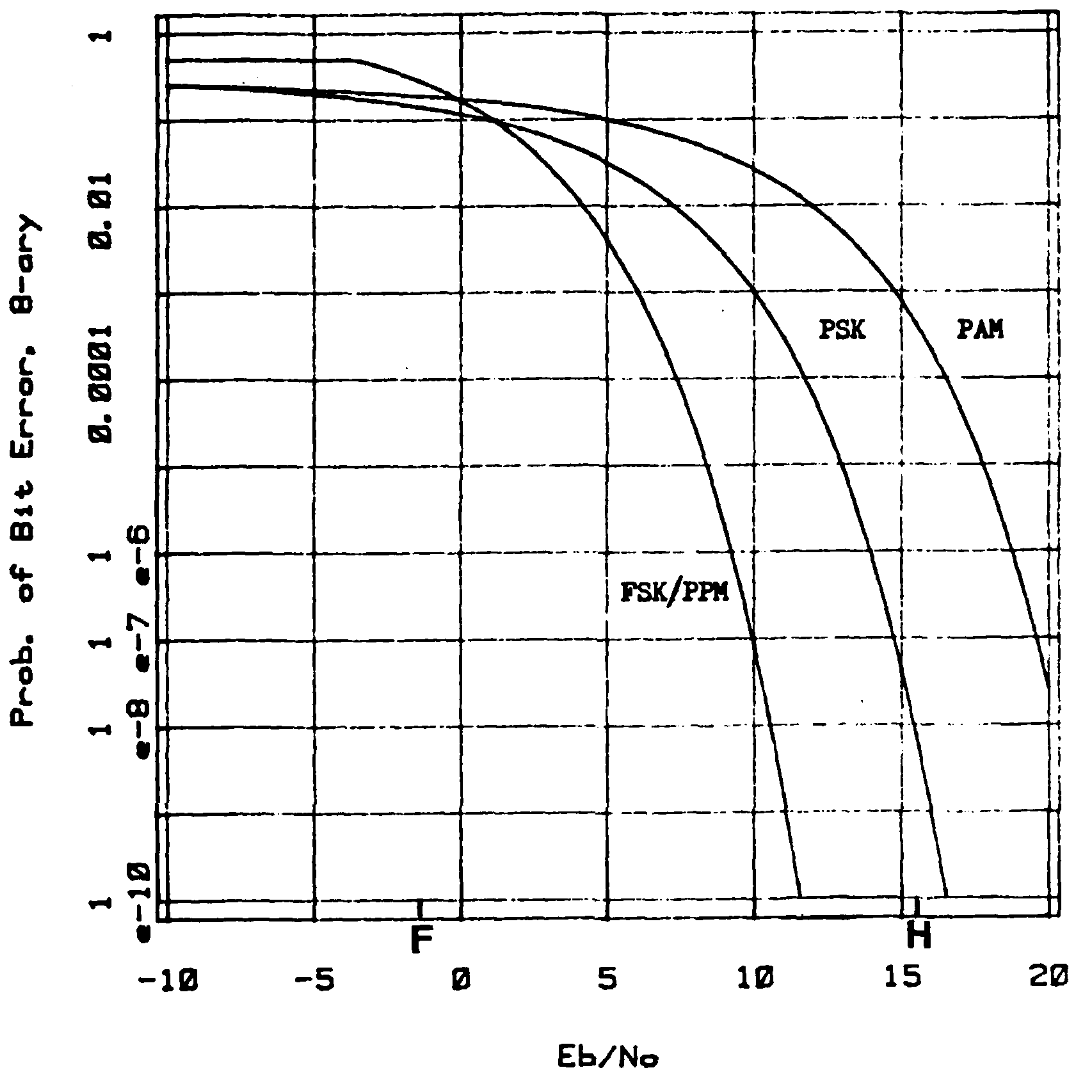
Low Risk Eb/No	-35.18 dB
High/Low Risk Average Eb/No	-19.47 dB
Five Year Projected Eb/No	-6.20 dB
High Risk Eb/No	10.63 dB

Figure 30. Direct Detect Nd:YAG, 1 MBps, 120° Separation, M=2



Low Risk Eb/No	-32.17 dB
High/Low Risk Average Eb/No	-16.46 dB
Five Year Projected Eb/No	-3.19 dB
High Risk Eb/No	13.64 dB

Figure 31. Direct Detect Nd:YAG, 1 MBps, 120° Separation, M=4



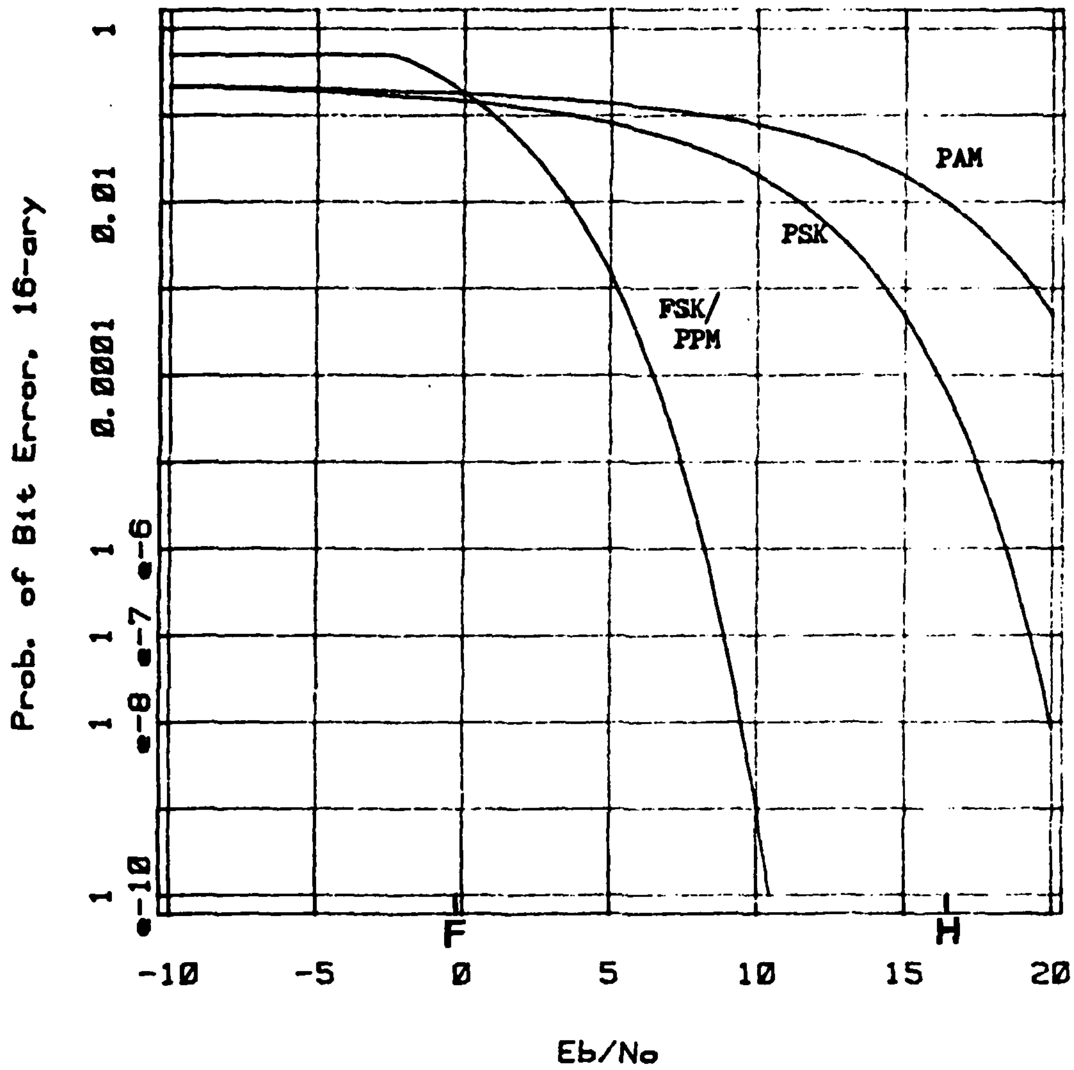
Low Risk Eb/No -30.41 dB

High/Low Risk Average Eb/No -14.70 dB

Five Year Projected Eb/No -1.42 dB

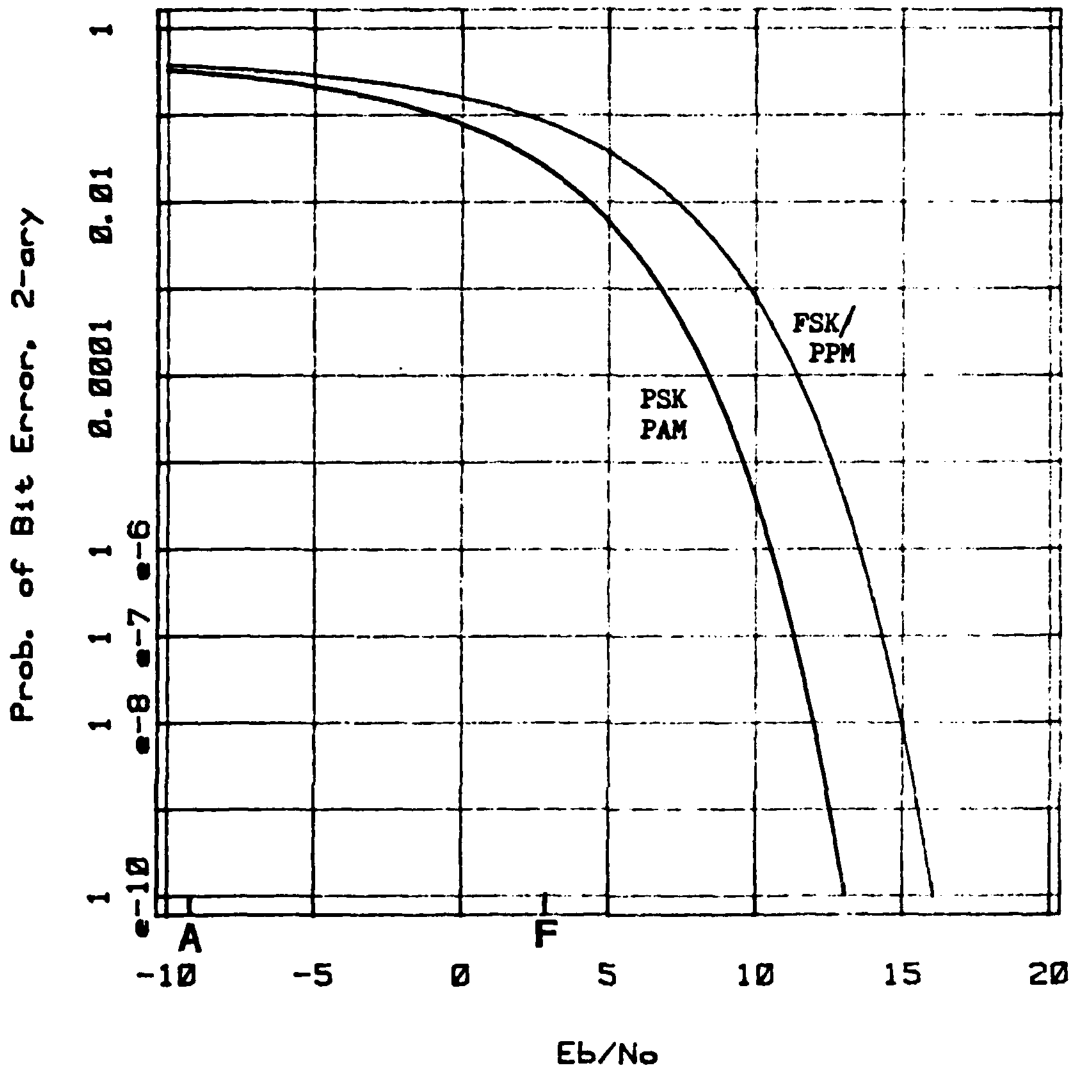
High Risk Eb/No 15.40 dB

Figure 32. Direct Detect Nd:YAG, 1 MBps, 120° Separation, M=8



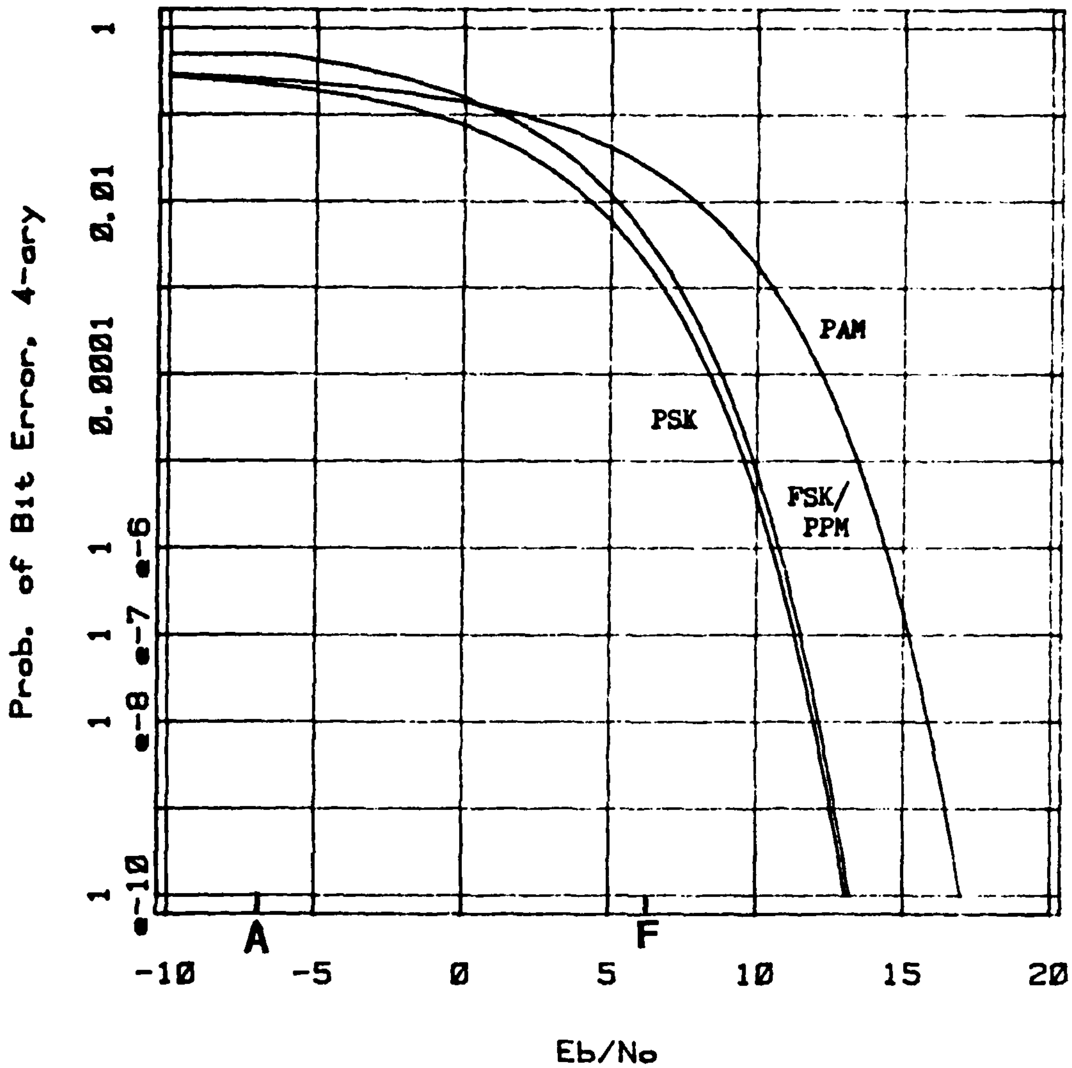
Low Risk Eb/No	-29.16 dB
High/Low Risk Average Eb/No	-13.45 dB
Five Year Projected Eb/No	-0.18 dB
High Risk Eb/No	16.65 dB

Figure 33. Direct Detect Nd:YAG, 1 MBps, 120° Separation, M=16



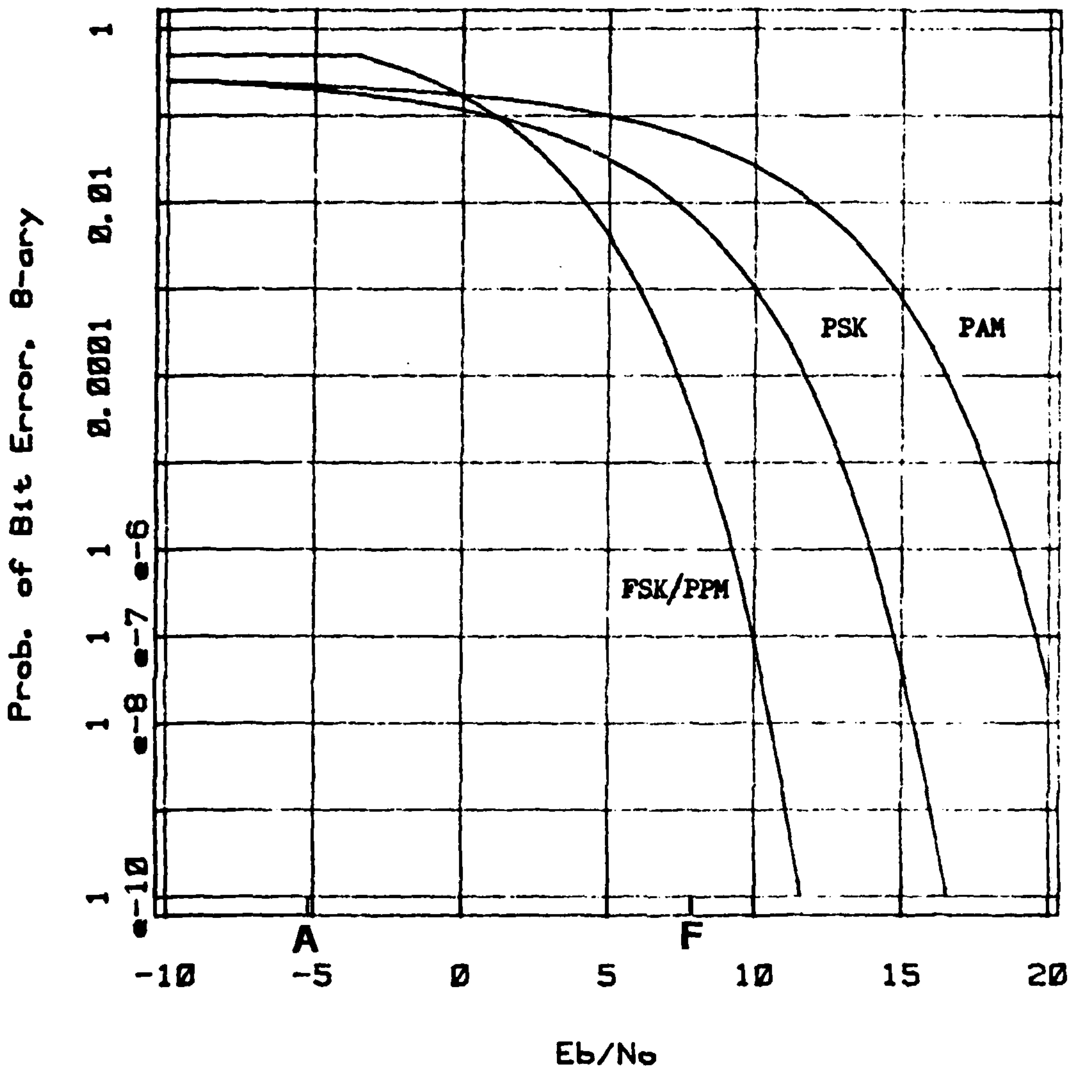
Low Risk Eb/No	-25.64 dB
High/Low Risk Average Eb/No	-9.93 dB
Five Year Projected Eb/No	3.35 dB
High Risk Eb/No	20.17 dB

Figure 34. Direct Detect Nd:YAG, 1 MBps, 60° Separation, M=2



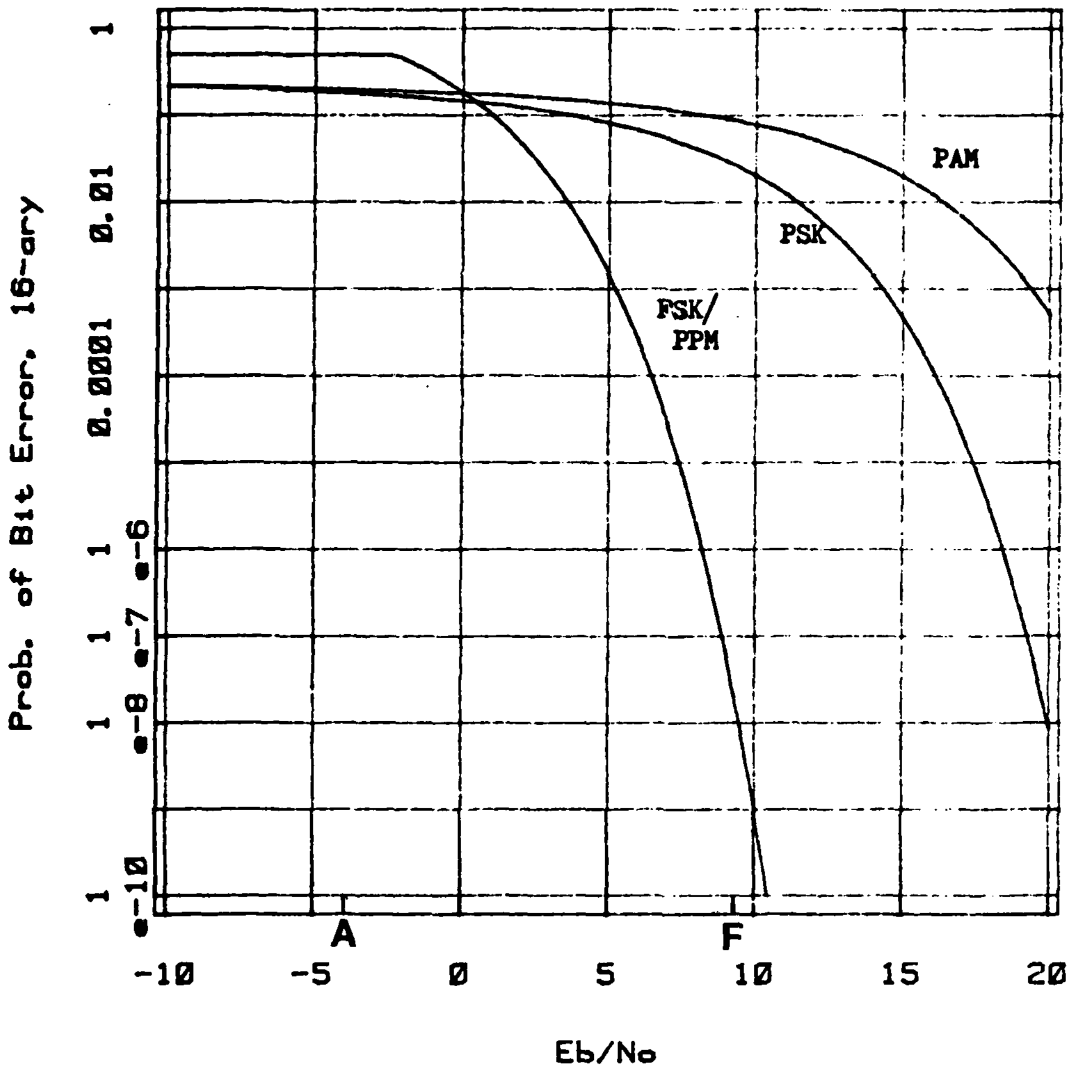
Low Risk Eb/No	-22.63 dB
High/Low Risk Average Eb/No	-6.92 dB
Five Year Projected Eb/No	6.36 dB
High Risk Eb/No	23.18 dB

Figure 35. Direct Detect Nd:YAG, 1 MBps, 60° Separation, M=4



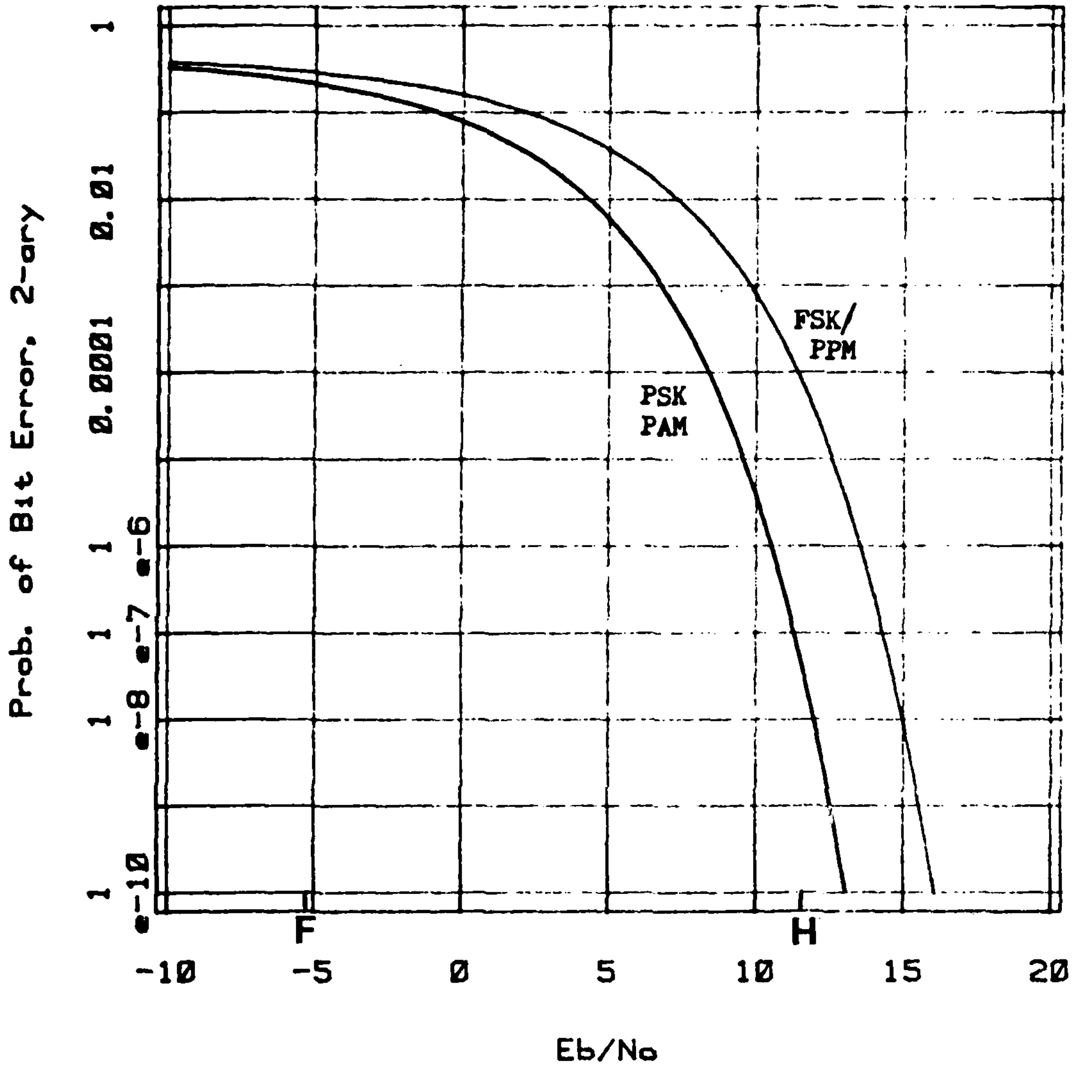
Low Risk Eb/No	-20.87 dB
High/Low Risk Average Eb/No	-5.16 dB
Five Year Projected Eb/No	8.12 dB
High Risk Eb/No	24.95 dB

Figure 36. Direct Detect Nd:YAG, 1 MBps, 60° Separation, M=8



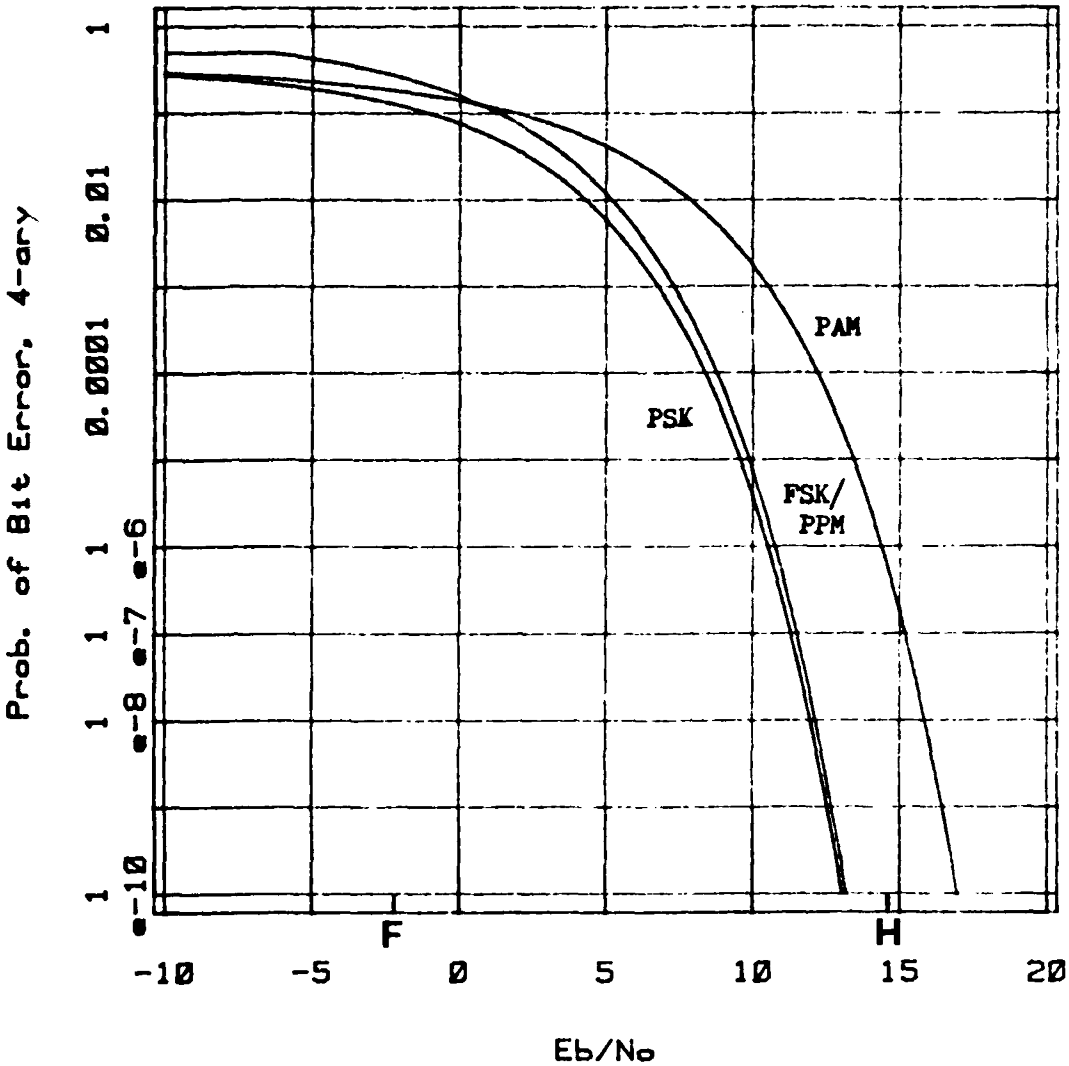
Low Risk Eb/No	-19.62 dB
High/Low Risk Average Eb/No	-3.91 dB
Five Year Projected Eb/No	9.37 dB
High Risk Eb/No	26.20 dB

Figure 37. Direct Detect Nd:YAG, 1 MBps, 60° Separation, M=16



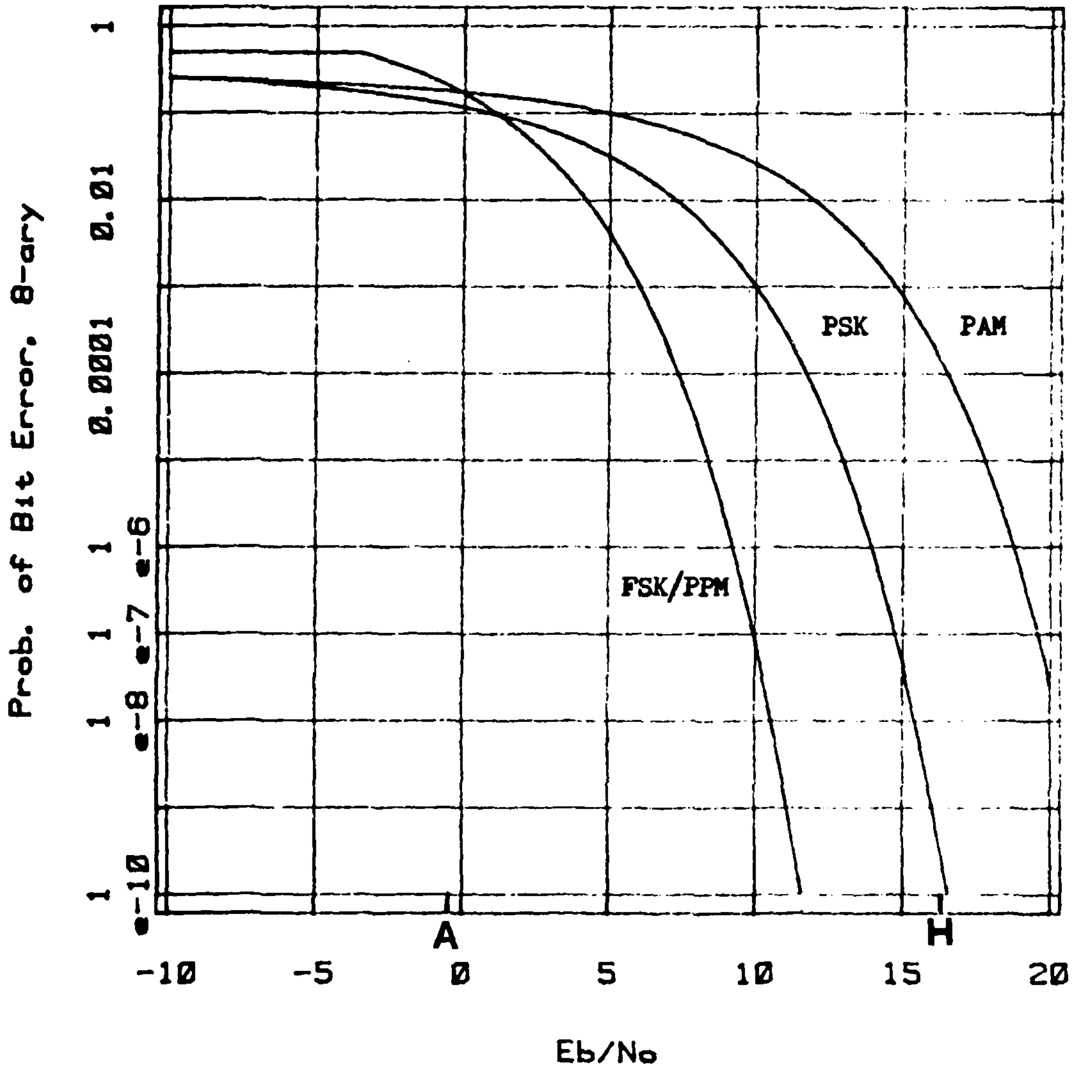
Low Risk Eb/No	-34.20 dB
High/Low Risk Average Eb/No	-18.49 dB
Five Year Projected Eb/No	-5.22 dB
High Risk Eb/No	11.61 dB

Figure 38. Direct Detect Nd:YAG, 100 MBps, 30° Separation, M=2



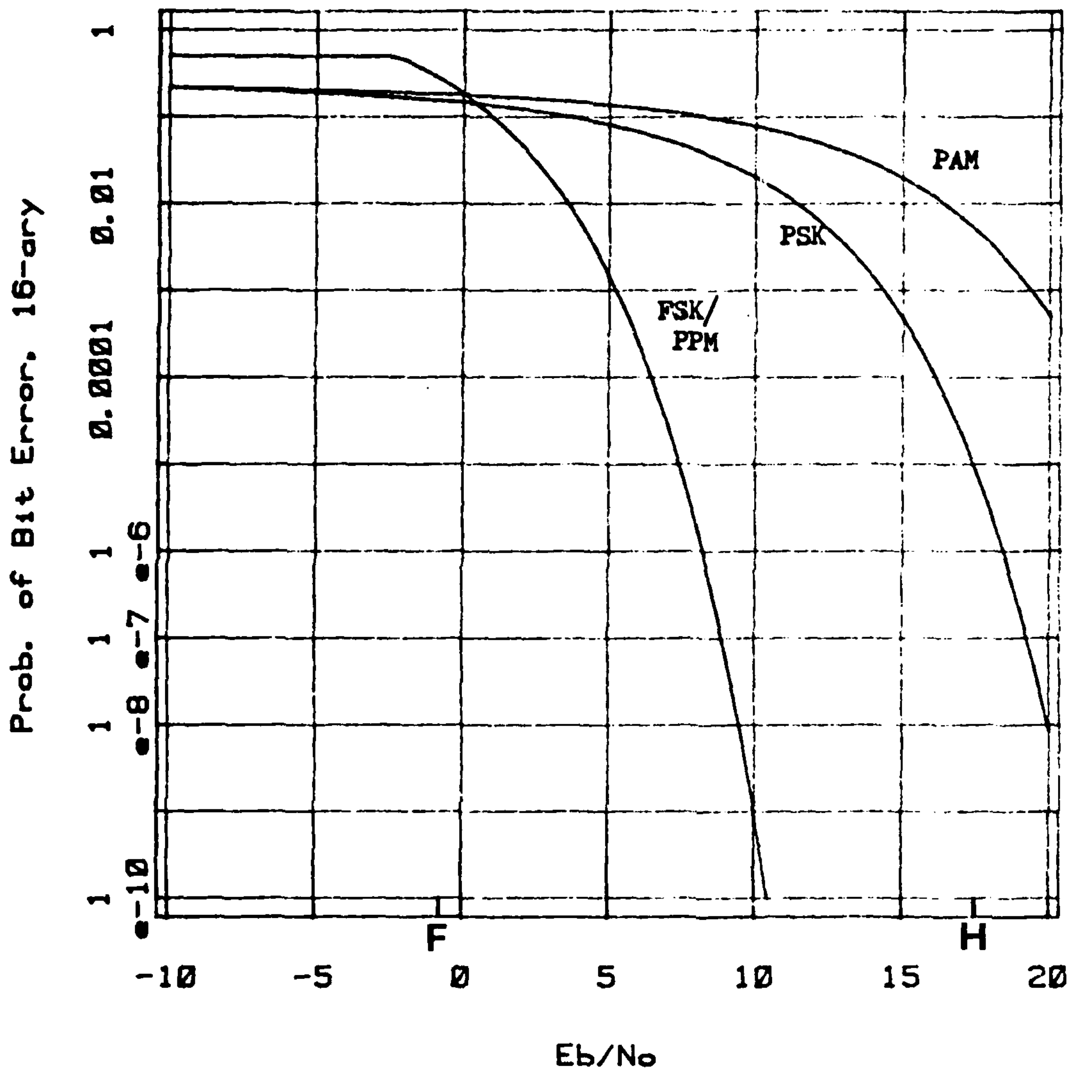
Low Risk Eb/No	-31.19 dB
High/Low Risk Average Eb/No	-15.48 dB
Five Year Projected Eb/No	-2.21 dB
High Risk Eb/No	14.62 dB

Figure 39. Direct Detect Nd:YAG, 100 MBps, 30° Separation, M=4



Low Risk Eb/No	-29.43 dB
High/Low Risk Average Eb/No	-13.72 dB
Five Year Projected Eb/No	-0.44 dB
High Risk Eb/No	16.38 dB

Figure 40. Direct Detect Nd:YAG, 100 MBps, 30° Separation, M=8



Low Risk Eb/No	-28.18 dB
High/Low Risk Average Eb/No	-12.47 dB
Five Year Projected Eb/No	-0.80 dB
High Risk Eb/No	17.63 dB

Figure 41. Direct Detect Nd:YAG, 100 MBps, 30° Separation, M=16

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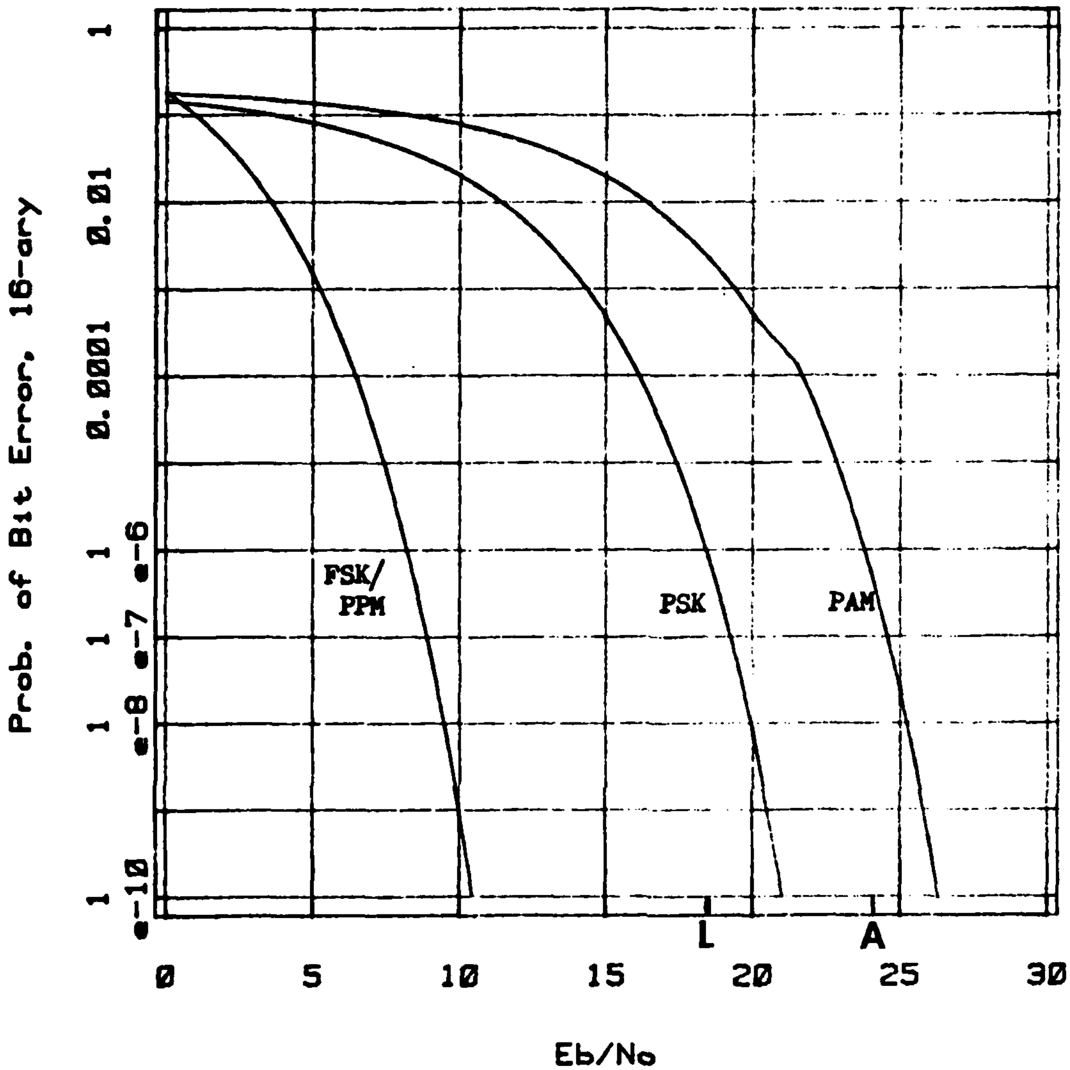
```
    BEGIN
      V:=1.0/(2.0*X2);
      SUM:=V/(1+8*V/(1+9*V/(1+10*V/(1+11*V/(1+12*V)))));
      SUM:=V/(1+3*V/(1+4*V/(1+5*V/(1+6*V/(1+7*SUM)))));
      EC:=1.0/(EXP(X2)*W*SQRTPI*(1+V/(1+2*SUM)));
      QQ:=0.5*EC;
    END;
  IF X<0.0 THEN
    QQ:=1.0-QQ;
  Q:=QQ;
END (* Q FUNCTION *);
```

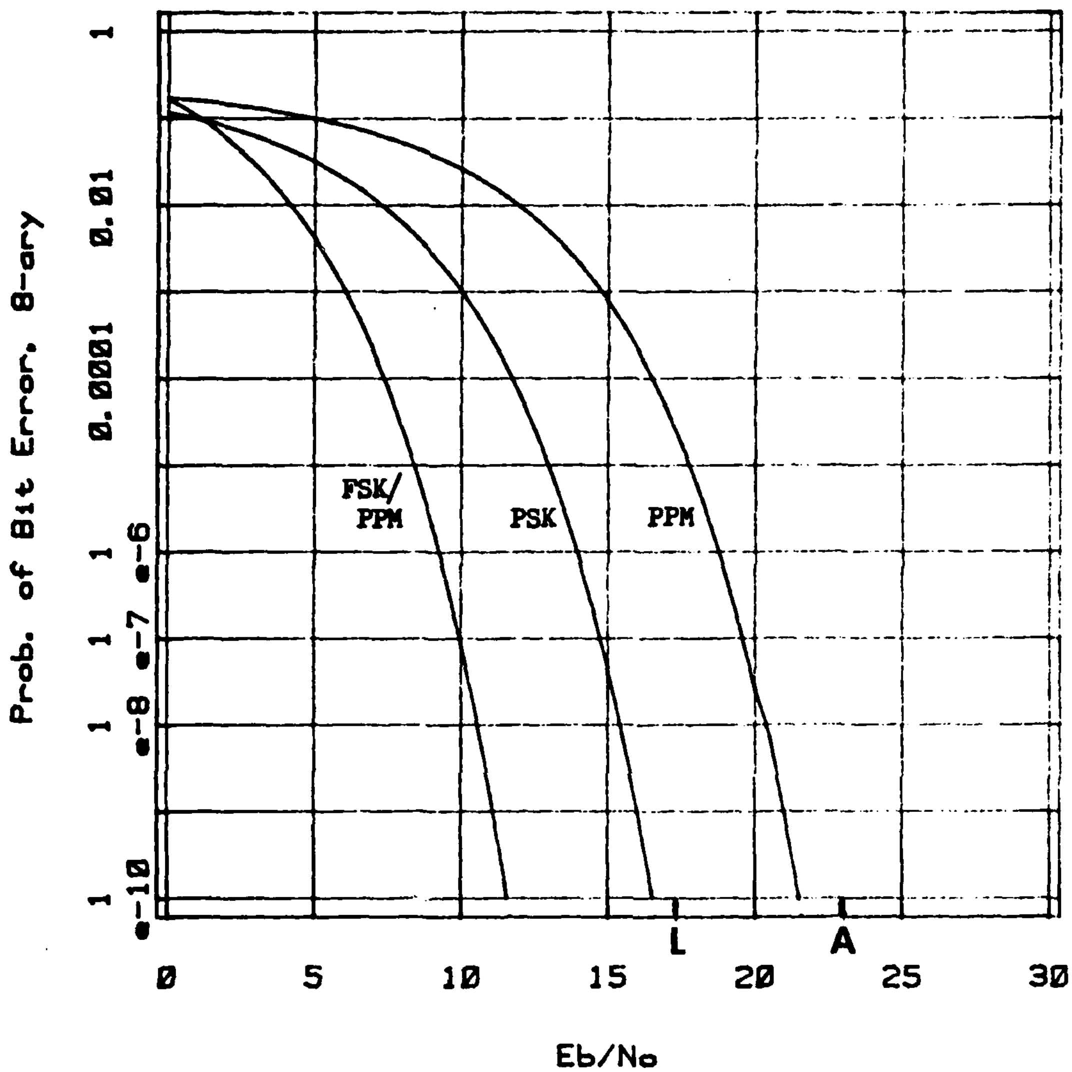
Appendix E: Gaussian Q Function

```
FUNCTION Q(Y:REAL):REAL;

(* 12 TH ORDER POLYNOMIAL USED TO GENERATE VALUES *)
(* OF THE GAUSSIAN Q FUNCTION FOR ARGUMENTS GREATER THAN *)
(* OR EQUAL TO 1.5 *)
(* SERIES EXPANSION OF 12 TERMS USED TO GENERATE VALUES *)
(* OF THE GAUSSIAN Q FUNCTION FOR ARGUMENTS LESS THAN 1.5 *)


CONST
  T2=0.6666667;
  T3=0.2666667;
  T4=0.07619048;
  T5=0.01693122;
  T6=3.078403E-3;
  T7=4.736005E-4;
  T8=6.314673E-5;
  T9=7.429027E-6;
  T10=7.820028E-7;
  T11=7.447646E-8;
  T12=6.476214E-9;

VAR
  V,QQ,W,ER,EC,X,X2,SUM:REAL;
  SQRTPI:REAL;

BEGIN
  SQRTPI:=SQRT(PI);
  IF Y=0.0 THEN
    BEGIN
      Q:=0.5;
    END;
  X:=Y/SQRT(2);
  X2:=X*X;
  W:=ABS(X);
  IF W<1.5 THEN
    BEGIN
      SUM:=T5+X2*(T6+X2*(T7+X2*(T8+X2*(T9+X2*(T10+X2*(T11+X2*T12))))));
      ER:=2.0*EXP(-X2)/SQRTPI*(W*(1+X2*(T2+X2*(T3+X2*(T4+X2*SUM)))));
      QQ:=0.5*(1-ER);
    END
  ELSE
```



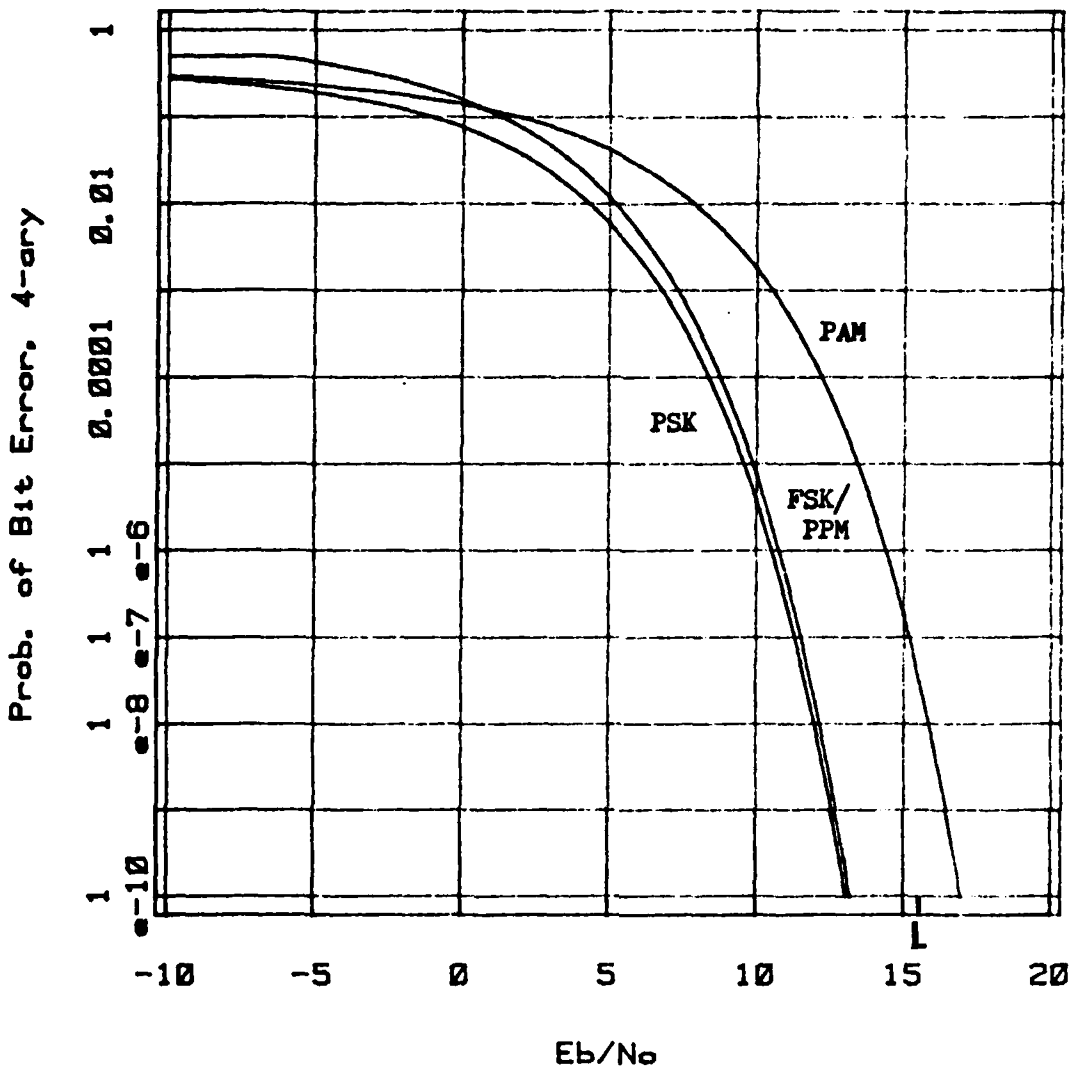
Low Risk Eb/No	18.63 dB
High/Low Risk Average Eb/No	24.32 dB
Five Year Projected Eb/No	34.97 dB
High Risk Eb/No	44.17 dB

Figure 49. Heterodyne GaAs, 1000 Mps, 160° Separation, M=16



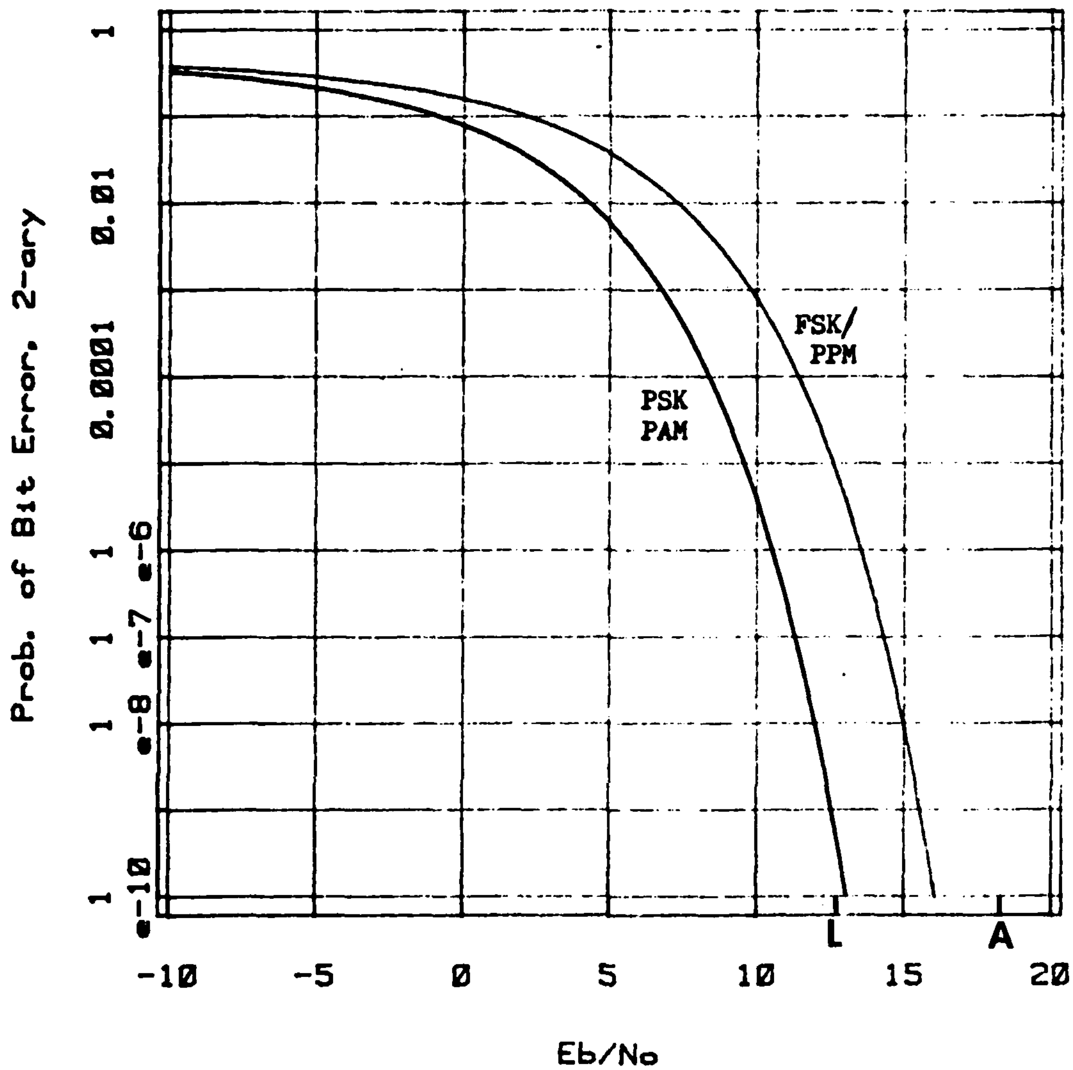
Low Risk Eb/No	17.38 dB
High/Low Risk Average Eb/No	23.07 dB
Five Year Projected Eb/No	33.72 dB
High Risk Eb/No	42.92 dB

Figure 48. Heterodyne GaAs, 1000 Mps, 160° Separation, M=8



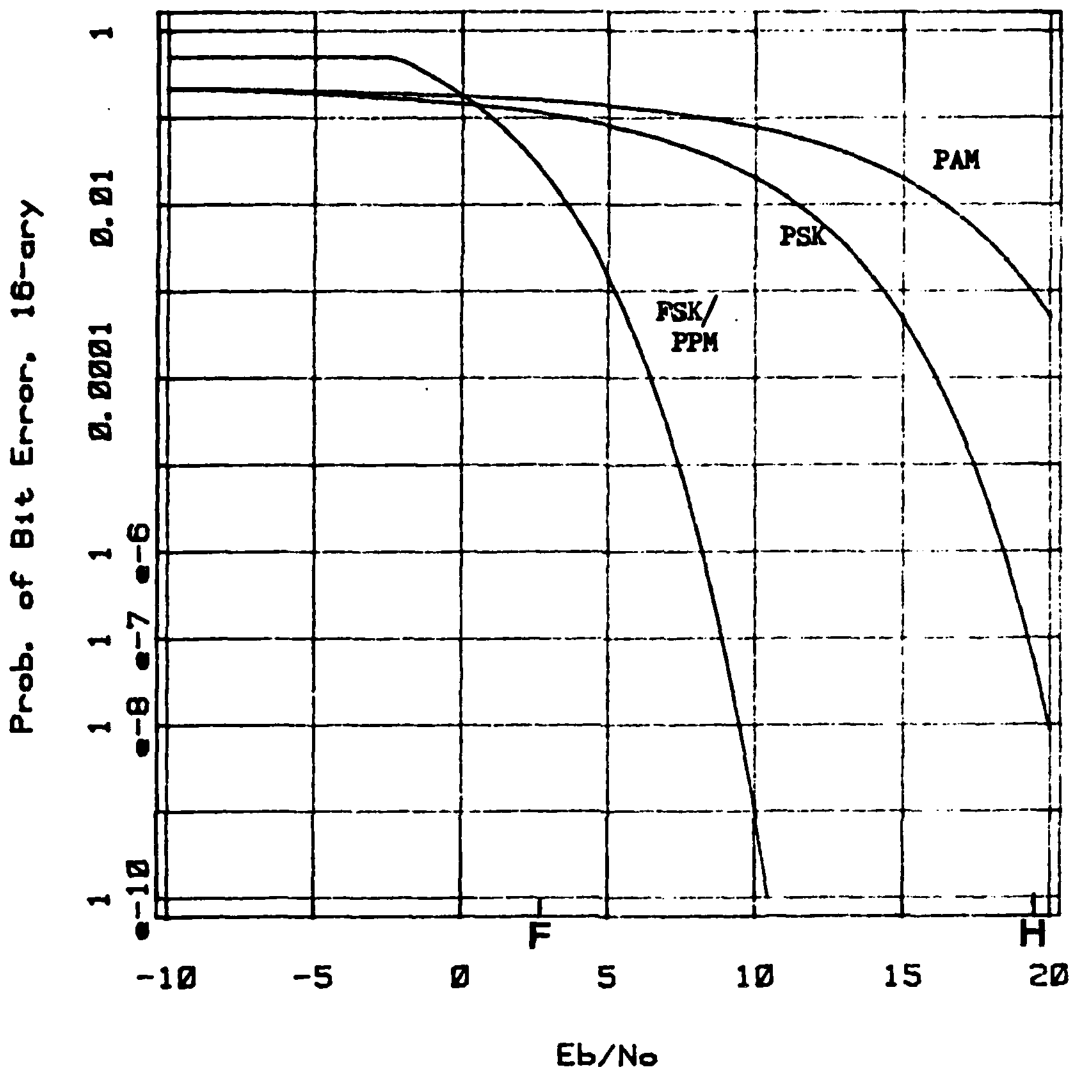
Low Risk Eb/No	15.62 dB
High/Low Risk Average Eb/No	21.31 dB
Five Year Projected Eb/No	31.96 dB
High Risk Eb/No	41.16 dB

Figure 47. Heterodyne GaAs, 1000 Mps, 160° Separation, M=4



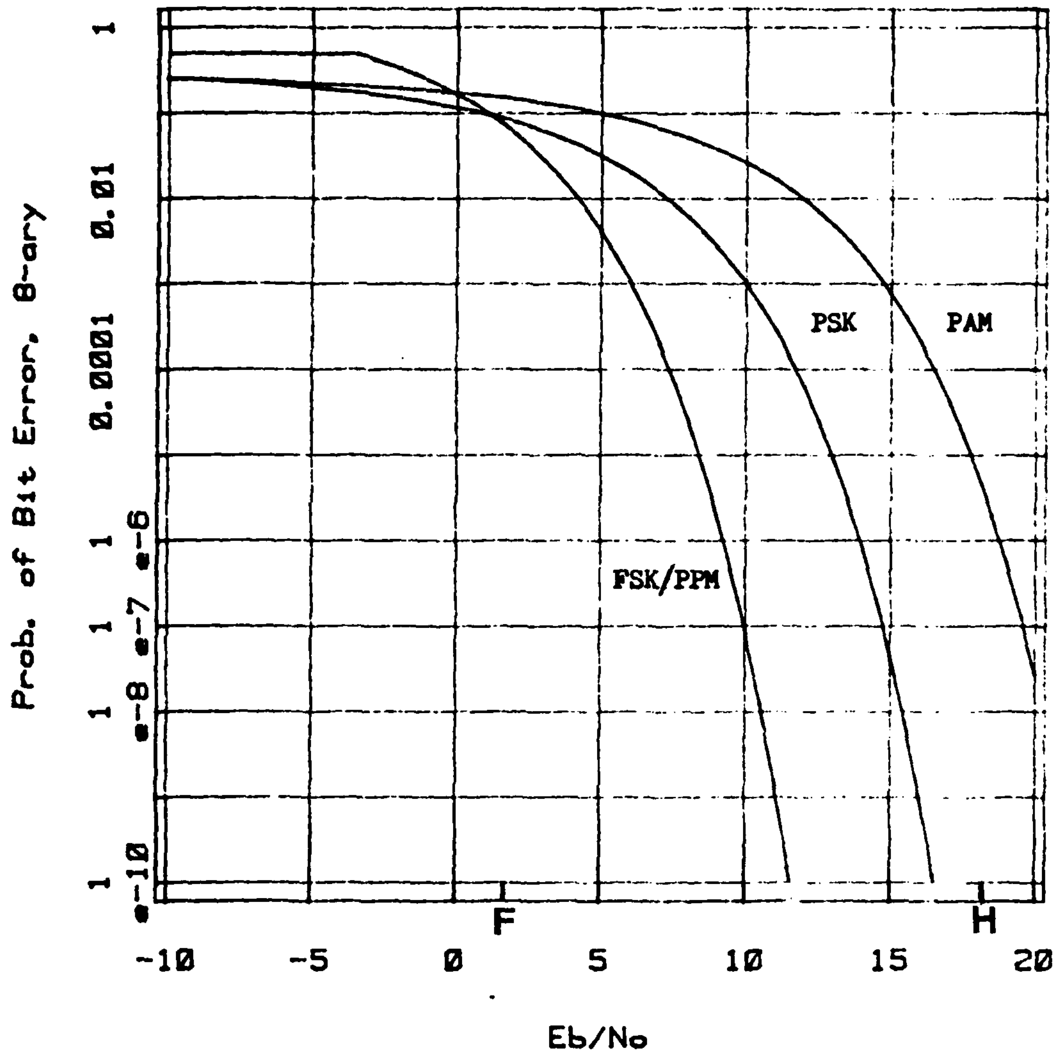
Low Risk Eb/No	12.61 dB
High/Low Risk Average Eb/No	18.30 dB
Five Year Projected Eb/No	28.95 dB
High Risk Eb/No	38.15 dB

Figure 46. Heterodyne GaAs, 1000 Mps, 160° Separation, M=2



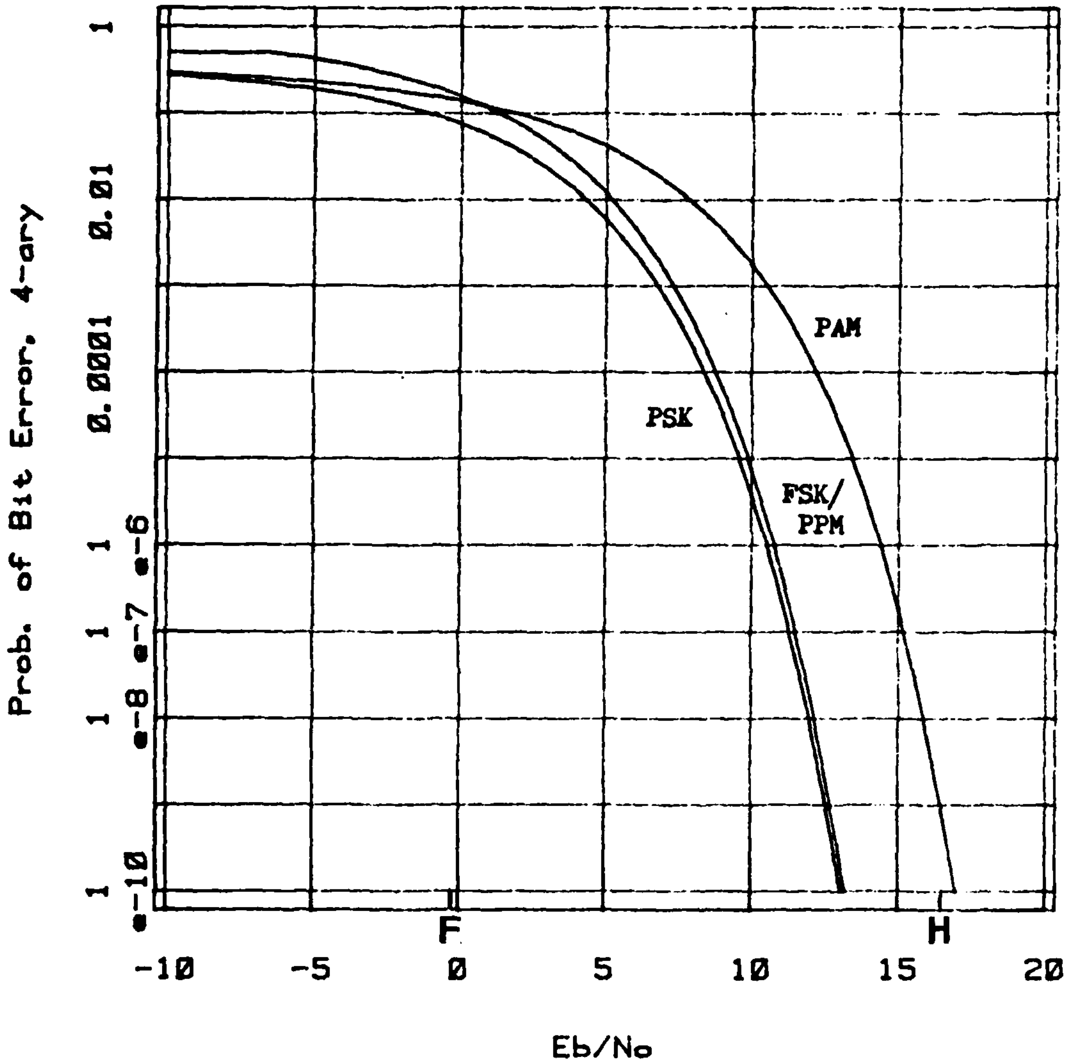
Low Risk Eb/No	-26.29 dB
High/Low Risk Average Eb/No	-10.58 dB
Five Year Projected Eb/No	2.70 dB
High Risk Eb/No	19.53 dB

Figure 45. Direct Detect Nd:YAG, 1 GBps, 15° Separation, M=16



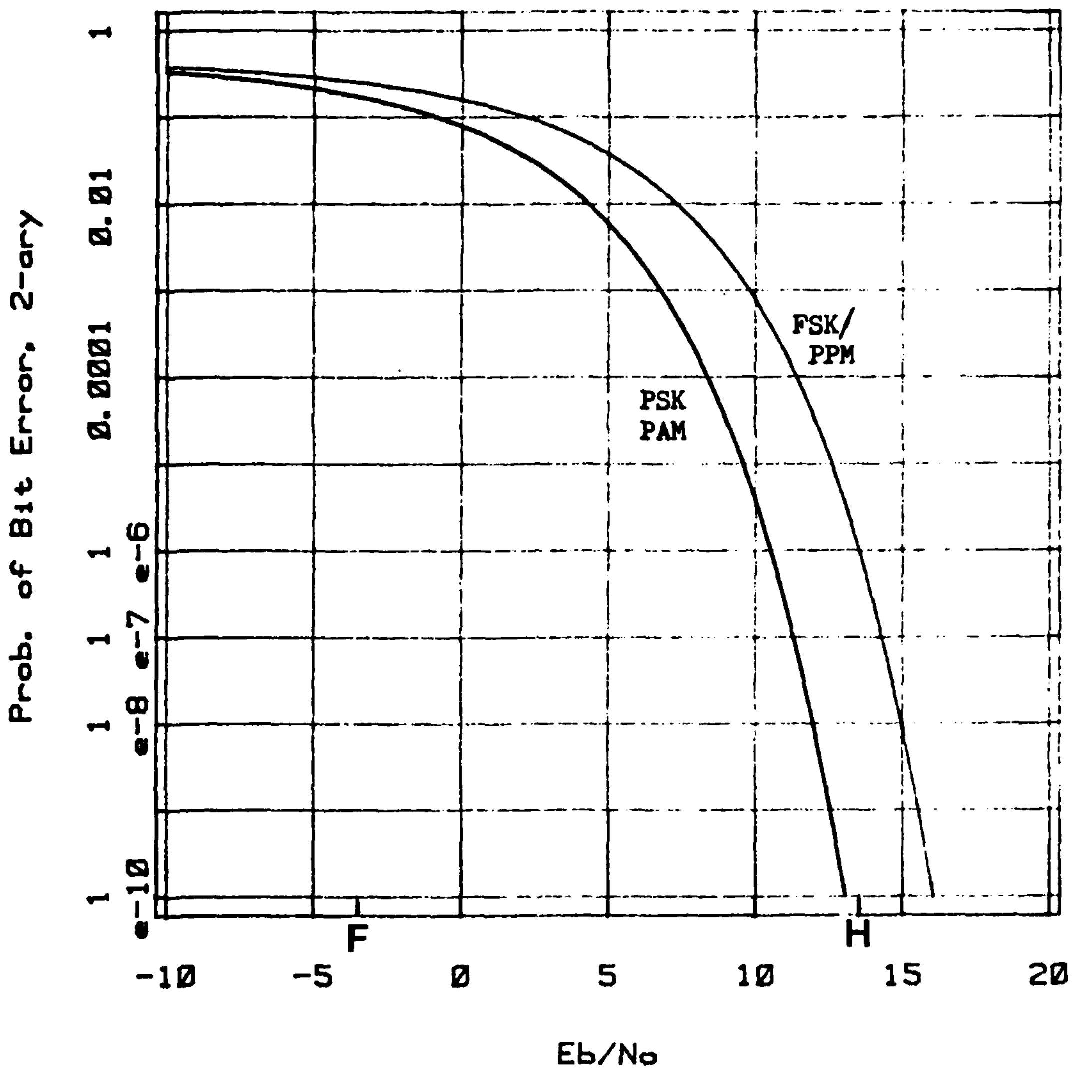
Low Risk Eb/No	-27.54 dB
High/Low Risk Average Eb/No	-11.83 dB
Five Year Projected Eb/No	1.45 dB
High Risk Eb/No	18.28 dB

Figure 44. Direct Detect Nd:YAG, 1 GBps, 15° Separation, M=8



Low Risk Eb/No	-29.30 dB
High/Low Risk Average Eb/No	-13.59 dB
Five Year Projected Eb/No	-0.31 dB
High Risk Eb/No	16.52 dB

Figure 43. Direct Detect Nd:YAG, 1 GBps, 15° Separation, M=4



Low Risk Eb/No	-32.31 dB
High/Low Risk Average Eb/No	-16.60 dB
Five Year Projected Eb/No	-3.32 dB
High Risk Eb/No	13.51 dB

Figure 42. Direct Detect Nd:YAG, 1 GBps, 15° Separation, M=2

Abstract

This investigation determined the energy per bit to noise ratios which can be expected to be feasible in the near term (low risk), within five years and those foreseeable beyond five years (high risk) for intersatellite links (ISL). The ISLs considered are 60 and 90 gigahertz millimeter wave, 1064 nanometer direct detect Nd:YAG laser and 832 nanometer heterodyne GaAs laser. From these values the probability of bit error for various candidate signalling schemes can be determined. The required signalling bandwidth can also be evaluated.

The analysis showed that for low bit rate (1 MBps) ISLs, 60 GHz millimeter wave 16-ary pulse amplitude modulation is the least risk, most bandwidth efficient implementation of those investigated. For higher bit rates (100 MBps and 1 GBps) and separation angles of 120° or more current (low risk) technology is not sufficient. For ISL communication under these parameters heterodyne laser technology is the most promising.

ORIGINATOR - SUPPLIED KEY WORDS INCLUDE:-

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