DATA TRANSMISSION OVER FDM/FM TROPOSCATTER SYSTEMS

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ABSTRACT

There are more than one hundred troposcatter systems of various sizes in existence all over the world.[1] As the transmission of computer data becomes more and more in common and popular demand, such systems are certain to be involved in these services.

Two methods are generally used for transmitting data over troposcatter channels: direct transmission and FDM/FM technique. In the latter, the individual data channels are combined into an FDM baseband to frequency or phase modulate a common radio carrier--the same technique used conventionally for the carrier transmission of multiplex telephone channels.

In this study, only FDM/FM techniques are investigated as it is of immediate and primary interest. It was found that both theoretically and experimentally, troposcatter systems can support data transmission of various rates from 2.4 to 40.8 kbps for path lengths of nominally from 100 to 400 statute miles in smooth earth geometry with diversity reception, if proper path and equipment parameters were chosen.

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1. INTRODUCTION

Data transmission through troposcatter channels requires the considerations of their transmittance (amplitude or attenuation and phase) characteristics. These characteristics are not only time-variant, but also frequency-variant. They are, therefore, statistical functions. In addition, random noise must also be considered as in conventional stable channels as well as in fading channels.

Typical examples of transmittance characteristics varying with time at a fixed frequency are the expected average attenuation (called path loss in more familiar terms) and systematic seasonal variations form the average, together with the probability distributions of slow and fast fading or fluctuations from the mean. Other important characteristics are the distribution of duration and fading rate of fast fades.

A typical example of transmittance characteristics varying with frequency as a fixed time is the fluctuation of amplitude and phase with frequency, usually called selective fading in more familiar terms.

At sufficiently low rate of data transmission, the frequency-variant transmittance may be assumed as such that the attenuation characteristics is constant and the phase characteristics linear over the narrow band of the pulse spectra. In this particular case, only time-variant transmittance may be considered.

On the other hand, at sufficiently high rate of data transmission, the reverse is true. This is because of the fact that the duration of the pulse is so short that the time variations in both amplitude and phase may be disregarded.

Instead, it now becomes necessary to take into account the pulse distortion and resultant intersymbol interference caused by the selective fading or the erratic variations with the frequency at a fixed instant in amplitude and phase.

In general, when the data transmission rate is neither low nor high, both time and frequency-variant transmittances must be considered.

From the above discussion, it can be seen that the performance of tropo-scatter data transmission, in terms of probability of errors, is derived from three basic sources, namely:

a. Error resulting from random noise in the presence of Rayleigh nonselective fading.

b. Errors resulting from frequency selective fading in the absence of noise (which puts an upper bound on the transmission rate for a specified error probability, but only in cases when pulses are transmitted in a continuous pulse train).

c. Errors resulting from time variations in amplitude, phase, and frequency in the absence of noise (which is important at low bit rates).

The above discussion applies to direct data transmission through the tropo-scatter channel. As discussed by Sunde,[2] when the individual data channels are combined into an FDM baseband to frequency or phase modulate a common radio carrier, usually called FDM/FM transmission as in the present case, intersymbol interference due to selective fading is avoided. Instead, mutual interference between the various data channels owing to intermodulation distortion caused by frequency selective fading, generally called path intermodulation, must be considered.

Therefore, errors due to random noises -- the thermal noise of the receiver front-end (especially below the FM threshold region) and the path intermodulation noise due to multipath delay or frequency selective fading -- need special consideration.

In the following discussion, appropriate systems parameters are first established to restrict the theoretical analysis to the area of interest. From these parameters, data channel noise performances are obtained. Using the methods of theoretical analysis the bit error rates to be expected are calculated from the data channel noise performances and evaluated on the basis of diversity reception. These calculated error rates are compared with experimental results.

2. THEORETICAL ANALYSIS

2.1 System Parameters

2.1.1 Propagation Model[3]

The propagation model shown in Figure 1 and advocated by the Bell System is used here. This is a conventional simple smooth earth without obstruction with a symmetrical antenna beamwidth at both terminals. Since optimum troposcatter performance is generally achieved with the antenna axis aimed at the horizon, the effective beamwidth forming the common volume are taken here to be half of the 3 dB values.

2.1.2 Path Parameters

The detailed path parameters are shown in Table 1. Three paths with lengths of 86.7, 168.4 and 381.5 statute miles were used. The two shorter paths are over land while the longer one is over water. The path geometry of all three paths are fairly representative of the propagation model chosen.

2.1.3 Equipment Parameters and Configurations

The detailed equipment parameters and configurations are shown in Table 2. The radio equipment is frequency modulated, and has 10 kW of transmitter power operating at 882 MHz. The multiplex equipment is SSB/FDM with 24 and 120 equivalent voice channels. The modem equipment uses 4-phase differential phase shift keying (4ϕ DPSK) with data transmission rates of 2.4 kbps (one equivalent voice channel) and 40.8 kbps (12 equivalent voice channels).

2.1.4 Transmission and Modulation Technique

The digital transmission technique to be used is FDM/FM. Each individual data channel first modulates a subcarrier. These modulated subcarriers are then multiplexed into a baseband for radio transmission by frequency modulation; 4-phase differential phase shift keying (4ØDPSK) is used for the individual data channel.

2.1.5 Diversity and Combining

Several orders of diversity (1, 2 and 4) and maximum ratio (also known as ratio-square) baseband combining were used.

2.2 System Calculation

2.2.1 Differential Time Delays

Using the propagation model of Figure 1, the worst differential time delay (between the maximum and minimum path lengths), may be expressed as:[2]

$$\Delta_o = \frac{\alpha' d}{2C}\left(\theta' + \frac{\alpha'}{2}\right) \tag{1}$$

where Δ_o = worst differential time delay in seconds

d = path length in miles

C = velocity of propagation in free space in miles per second

θ' = half of the scattering angle = $d/2R$ in radians

R = effective earth radius in miles = $K R_o$

R_o = real earth radius in miles

K = effective earth radius factor usually taken as 4/3

α' = half of 3 dB antenna beamwidth in radians

The differential time delays for the test paths are shown in Table 3. Due to the beam broadening effect, the time delay for long path with high gain antennas, such as path A, tends to be optimistic.

Sunde[2] suggested that in order to account for this broadening effect, a factor expressed as the ratio of broadened antenna beamwidth to free space antenna beamwidth may be used to adjust the calculated differential time delay.

The broadened antenna beamwidth may be indirectly obtained from the path antenna gain, which is the free space antenna gain minus the aperture coupling loss. The adjusted differential time delay is also shown in Table 3.

2.2.2 Noise Performance

The total noise power present in a voice channel is equal to the sum of the noise power from the thermal and intermodulation noise components. The individual noise components which are treated in the analysis in this report are as follows:

N_r - residual noise power due to random current variations in the radio equipment

N_t - thermal noise power due to the receiver input circuits and effective antenna temperature

N_{ie} - intermodulation noise power due to radio equipment alone, as measured on a back-to-back basis

N_{if} - intermodulation noise associated with feeder echoes

N_{ip} - intermodulation noise power associated with multipath effects in scatter propagation

Since each component is associated with a separate and independent source, the total noise power in the channel, N, may be expressed as the sum of the individual noise components:

$$N = N_r + N_t + N_{ie} + N_{if} + N_{ip} \quad (2)$$

The residual noise component, N_r, and intermodulation noise due to equipment, N_{ie} (generally specified as the noise power ratio NPR), are functions of the equipment, and for good quality systems are usually on the order of -70 dBm0. The intermodulation noise due to feeder echo, N_{if}, is a function of feeder length, baseband width, impedance matching, etc., and is even less when the test set-up is carefully controlled. These three components can therefore be neglected.

2.2.2.1 Thermal Noise at Receiver Input - (N_t) - No Diversity. The noise performance (thermal noise at receiver input) of a voice channel in an FDM/FM system on a fading carrier has been treated rather extensively by Barrow,[6] and followed by Johansen[7] and Smith.[8] Barrow's treatment will be used here.

Above FM threshold, the signal-to-thermal noise ratio of the top voice channel with preemphasis, but without diversity, is linearly related to the carrier-to-thermal noise ratio as follows: [Equation (67) of Barrow[6]]

$$\text{Above threshold: } \frac{S}{N_t} = \frac{C}{N_t} + 20 \log \left(\frac{F_{ch}}{f_m}\right) + 10 \log \frac{B_{if}}{b} + P \text{ in dB} \tag{3}$$

where $\frac{S}{N_t}$ = the ratio of test load to the flat weighted thermal noise in the highest (top) voice channel in dB

$\frac{C}{N_t}$ = the carrier-to-thermal noise ratio in dB

B_{if} = the IF frequency bandwidth in Hz

b = the voice channel bandwidth in Hz

F_{ch} = the rms test load deviation per channel in Hz

f_m = the mid-frequency of the highest (top) channel in Hz

P = the preemphasis improvement factor in dB

A carrier-to-thermal noise ratio of 10 dB is taken as the FM threshold

Below FM threshold, two models are assumed - the "abrupt" model and the "smooth" model. For the "abrupt" model, the signal-to-thermal noise ratio is assumed to be zero: [Equation (9_a) of Barrow[6]].

$$\text{Below threshold abrupt model: } \frac{S}{N_t} = 0 \tag{4}$$

For the "smooth" model, the signal-to-thermal noise ratio is proportional to the square of the carrier-to-thermal noise ratio: [Equation (70) of Barrow[6]].

Below threshold smooth model:

$$\frac{S}{N_t} = 2\left(\frac{C}{N_t}\right) + 20 \log F_{ch} + 10 \log \left(\frac{1}{B_{if}b}\right) + 10 \log \frac{(2\pi)^2}{11.5} + P \tag{5}$$

$$= 2\left(\frac{C}{N_t}\right) + 20 \log F_{ch} + 10 \log \left(\frac{1}{B_{if}b}\right) + 5.4 + P \quad \text{in dB} \tag{6}$$

All notations are the same as before. It is interesting to note that S/N_t is independent of the channel modulating frequency. In Barrow's equation (70), peak channel deviation is used, while in equation (4), rms channel deviation is used. A factor of 2 is involved in this change. This is accomplished by changing the constant from 23 to 11.5. The "smooth" model will be used here.

2.2.2.2 Intermodulation Noise Due to Multipath -(N_{ip}) - No Diversity. Intermodulation due to multipath, N_{ip}, has been extensively treated by Beach et al,[4] Sunde,[5] and Bello.[9] The former uses two-path model and the latter two use multipath model. According to Sunde,[5] the median* (50%) path intermodulation noise to average signal ratio for the top voice channel with preemphasis but without diversity may be expressed as: [Equation (18) of Sunde[5]] .

$$N_{ip}/S = 10 \log_{10} \left[\left(\frac{f_m}{\Delta F_r} \right)^2 \quad 0.192\ H \left| 8\Delta_a{}^2 \Delta F_r{}^2 \right| \right] \quad \text{in dB} \tag{7}$$

where f_m = top baseband frequency in Hz

ΔF_r = rms multiplex deviation in Hz

Δ_a = adjusted differential time delay in seconds

H ( ) = analytical function of $\Delta_a{}^2 \Delta F_r{}^2$ in ratios (Figure 10 of Sunde[5])

2.2.3 Channel Loading and Frequency Deviation

2.2.3.1 One Equivalent Voice Channel (for 2.4 kbps Data Operation). The loading per equivalent 4 kHz voice channel is -5 dBm0. The rms multiplex loading L_{nr}, assuming activity factor of 100% becomes:

24 channels: $L_{nr} = -5 + 10 \log\ 24 = \ 8.8$ dBm0 (ratio of 7.6) (8)

120 channels: $L_{nr} = -5 + 10 \log 120 = 15.8$ dBm0 (ratio of 38.0) (9)

The peak-to-rms multiplex loading, (sometimes called peak factor) according to Holbrook and Dixon,[10] is 15.2 dB for 24 channels and 13.5 dB for 120 channels. However, for the convenience of theoretical analysis, a peak factor of 12 dB (a ratio of 16) is proposed to be used here as Sunde[5] and others also use this value. The peak multiplex loading L_{np} is thus:

24 channels: $L_{np} = L_{nr} + 12.0 = 20.8$ dBm0 (ratio of 120) (10)

120 channels: $L_{np} = L_{nr} + 12.0 = 27.8$ dBm0 (ratio of 600) (11)

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*Median to Time Block 2.

On site, for a 24 channel test, a 0 dBm0 test tone was measured and seen to produce a peak frequency deviation of 75.4 kHz. The rms frequency deviation is 3 dB (ratio of 2) down and equal to $75.4/\sqrt{2}$ or 53.2 kHz. For -5 dBm0 test channel loading, the rms frequency deviation is $53.2/\sqrt{3.16}$ or 30.0 kHz.

The rms multiplex frequency deviation ΔF_r is thus:

$$\text{24 channels: } \Delta F_r = 53.2 \times \sqrt{7.6} = 146 \text{ kHz} \tag{12}$$

The peak multiplex frequency deviation ΔF_p is thus:

$$\text{24 channels: } \Delta F_p = 146 \times \sqrt{16} = 584 \text{ kHz} \tag{13}$$

The deviation ratio m_p is thus:

$$\text{24 channels: } m = \Delta F_p/f_m = 584/156 = 3.8 \tag{14}$$

Another test for 24 channels was made by amplification of 7 dB (a ratio of 5.0) in the drive to the exciter. In this case, the frequency deviation was not measured but the deviation ratio may be calculated as $3.8 \times \sqrt{5}$ or 8.5.

For the 120 channel test, a peak 0 dBm0 test tone frequency deviation at 42 and 137 kHz were used, giving ratios of 1.4 and 4.4, respectively. Channel loading and frequency deviation are shown in Table 4.

2.2.3.2 Twelve Equivalent Voice Channels (for 40.8 kbps Data Operation). The loading for 12 equivalent voice channels is 10.8 dB (a ratio of 12) higher than one equivalent voice channel. The frequency deviation is $\sqrt{12}$ or 3.5 times higher.

2.2.4 Calculated Results

The carrier-to-thermal noise ratio (C/N_t) at median of Time Block 2 can be expressed as:

$$C/N_t = P_t - L_{bsr} + G_p - L_a - F - 10 \log_{10} K T_o - 10 \log_{10} B_{if} \qquad (15)$$

where
P_t = transmitter power in dBw
L_{bsr} = basic transmission loss (median Time Block 2) in dB
G_p = path antenna gain in dB
L_a = line losses, etc., in dB
F = receiver noise figure in dB
K = Boltzmann's constant = 1.38×10^{-23} joules/^{o}K
T_o = ambient temperature = 290^{o}K
KT_o = 4×10^{-21} (-204 dBw)
B_{if} = IF bandwidth in Hz

Using data in Tables 1, 2, and 4 and equations (3), (6) and (15), the thermal noise performance above and below FM threshold are calculated and shown in Tables 5 and 6. The performance for one or twelve equivalent voice channels is the same. These calculated results are also plotted in Figures 2 and 3. In the above FM threshold region, the signal-to-thermal noise ratio S/N_t is linearly related to the carrier-to-thermal noise ratio C/N_t, dB for dB; while in the below FM threshold region, the relationship is non-linear. A one dB change in C/N_t results in 2 dB change in S/N_t.

Using data in Tables 1, 2, 3, and 4, and equation (7), the path intermodulation noise performances are calculated and shown in Table 7. The performance of one or twelve equivalent voice channels is the same. These calculated results are also plotted in Figures 4 and 5. In the above FM threshold region, according to Beach et al,[4] one dB change in path loss (which is equivalent to change in carrier-to-noise ratio C/N_t) results in 0.7 dB change in signal-to-intermodulation noise ratio S/N_{ip}.* In the below FM threshold region, no relationship was mentioned. In the present case, same relationship for thermal noise below FM threshold will be used.

2.3 Probability of Bit Error

The relationship between probability of bit error versus data channel signal energy-to-noise power diversity ratio for non-diversity reception and Rayleigh fading has been given by Voelcker[11] [Equation (21) of Voelcker]:

For two-phase differential phase shift keying:

$$(Pe, 1) \approx \frac{1}{2}\ \bar{N}_o/\bar{E} \tag{16}$$

where $(Pe, 1)$ = probability of bit error

$\bar{E}/\bar{N}_o$ = average data channel signal energy-to-noise power density in ratios

$\bar{E}$ = average signal energy per bit

$\bar{N}_o$ = average noise power density per Hz

*Private communication from J. Elliott of Page indicates that for short paths the change of S/N_{ip} is about 0.4 - 0.5 dB per dB change of path loss.

For four-phase differential phase shift keying (Figure 3 of Cahn[12]):

$$(Pe, 1) \approx \frac{3}{2} \bar{N}_o / \bar{E} \tag{17}$$

The data channel signal energy-to-noise power density ratios are generally given in median values, which are about 1.6 dB (a ratio of 1.44) above the average for Rayleigh distribution. If the median values are used, equation (17) becomes:

non diversity: $(Pe, 1) \approx N_o / E$ (18)

E/N_o = median data channel signal energy-to-noise power density ratio

For diversity reception and maximum ratio baseband combining, Barrow[6] gave the following expressions [equation (32) of Barrow[6]]:

Dual diversity: $(Pe, 2) = 2\ (Pe, 1)^2$ (19)

Quadruple diversity: $(Pe, 4) = 8\ (Pe, 1)^4 = 2\ (Pe, 2)^2$ (20)

It must be cautioned that equations (16), (17) and (18) are applicable only when the signal energy-to-noise power density ratio is large (in the order of 10 or higher) and that equations (19) and (20) are applicable only when the probability of bit error is small (in the order of 10^{-1} or smaller) and when the median data channel signal energy-to-noise power density ratios from all the diversity branches are equal.

The median data channel signal energy-to-noise power density ratio (E/N_o) is related to the median voice channel signal-to-noise ratio (S/N) as follows:

For 2.4 kbps transmission (one equivalent voice channel):

$$S/N = (E \times 2400) / (N_o \times 4000) = 0.6\ E/N_o \text{ in ratios} \quad (21)$$
$$= E/N_o - 2.2 \text{ in dB}$$

For 40.8 kbps transmission (12 equivalent voice channels):

$$S/N = (E \times 40800) / (N_o \times 48000) = 0.85\ E/N_o \text{ in ratios} \quad (22)$$
$$= E/N_o - 0.7 \text{ in dB}$$

The probability of error for various orders of diversity due to thermal and intermodulation noises combined can now be calculated using the equations (18) to (22). The results are shown in Table 8. A few typical curves are shown in Figures 6 to 10. Use of the carrier-to-thermal noise ratios instead of data channel signal energy-to-noise power density ratio is for the convenience of comparing the predicted bit error with measured results.

3. MEASURED RESULTS AND OBSERVATIONS

Some of the measured results are superimposed on Figures 6 to 10. Each measured point represents a test sample from 5 to 20 minutes. The following observations may be made:

a. For non-diversity operations, calculated values check closely with measured results.

b. For diversity operations, the calculated results are always optimistic, especially the 400-mile path. This may be explained as either the order of diversity is not fully realized or the median data channel signal energy-to-noise power density ratios of the diversity branches are not equal. For the 400-mile path another reason may be the insufficient margin above threshold at 99.9% of Time Block 2.

c. For the 100-mile path, when the system is operated with both 24 and 120 equivalent voice channel capacity, and for 200 mile path, when the system is operated with 24 equivalent voice channel capacity, it is possible to transmit up to 40.8 kbps data with bit error probability of 10^{-6} for 99.9% of Time Block 2. These are considered acceptable standard performances.

d. For the 400-mile path, when the system is operated on 24 equivalent voice channel capacities, it is possible to transmit 2.4 kbps with bit error probability of 10^{-4} for 99.9% and 10^{-5} for median of Time Block 2. This performance is below the standard. It may be improved by the use of a large antenna in order to provide more margin above threshold and to reduce the path intermodulation (through the effect of smaller differential multipath time delay due to smaller antenna beamwidth), which requires further experimental study.

4. CONCLUSIONS AND ACKNOWLEDGEMENTS

As shown in Table 1, the channel total noise performance of the three test paths with parameters as indicated, are way below the DCS noise objectives (varying from 14 to 27 dB).

Therefore, the test results suggest that troposcatter circuits designed to meet the DCS FDM/FM standards will provide an error rate of 10^{-6} or better during a large part of the time, and an error rate of 10^{-3} or better during 99.9% of the time block 2 period.

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Table 1. Path Parameters

Path	A	B		C	
Path length (statute miles)	381.5	168.4		86.7	
Basic trans. loss, L_{bsr} (dB)*	231.9	206.5		196.5	
N_s used (units)	350	310		310	
Frequency used (MHz)	882	882		882	
Antenna size (ft.)	60	28		28	
Transmitter power (kW)	10	10		10	
Antenna gain G, each end (dB)	41.8	35.2		35.2	
Antenna coupling loss G_L (dB)	7.7	1.9		1.1	
Path antenna gain = $2G - G_L = G_p$ (dB)	75.9	68.5		69.3	
No. voice channels	24	24		120	
Carrier-to-noise ratio (dB):					
Median Time Block 2	21.7	39.7		42.3	
99.9%, Time Block 2	11.7	24.2		17.8	
Deviation ratio, m	3.8	3.8	8.5	1.4	4.4
Voice channel total noise (dBm0):					
Median, TB2, m = 1	-25.0	-40.6	-33.8	-44.3	-37.6
99.9%, TB2, m = 1	-18.0	-29.7	-22.6	-33.5	-21.0
Median TB2, m = 4 (dBm0)	-31.0	-46.6	-39.8	-50.3	-43.6
(dba)	(51.0)	(35.4)	(42.2)	(31.7)	(38.4)
99.9%, TB2, m = 4 (dBm0)	-24.0	-35.7	-28.6	-39.5	-27.0
(dba)	(58.0)	(46.3)	(53.4)	(42.5)	(55.0)
DCS total noise objective (dBa0)					
Median TB2, m = 4	24.2	21.4	21.4	18.0	18.0
% TB2, m = 4	49.0	49.0	49.0	49.0	49.0
	99.995	99.997	99.997	99.999	99.999

Table 2. Equipment Parameters and Configurations

Radio Equipment:		
Transmitter power (kW)	10	
Modulation	FM	FM
IF bandwidth (MHz)	1.5	10.0
Noise figure (dB)	2.5	2.5
Deviation ratio	3.8; 8.5	1.4; 4.4
Multiplex Equipment:		
Modulation	SSB/FDM	SSB/FDM
Equiv. voice channel	24	120
Baseband (kHz)	60 - 156	60 - 552
Preemphasis (μsec)	1.56	0.86
Channel loading (dBm0)	-5	-5
Data Modem:		
Modulation	4DPSK	4DPSK
Data rate (kbps)	2.4/v.ch	40.8/12v.ch
Diversity:		
Combiner	max. ratio	max. ratio
Order	1,2,4	1,2,4

Table 3. Calculation of Worst Differential Time Delay

Path			A	B	C
Path distance	d	(miles)	381.5	168.4	86.7
Real earth radius	R_o	(miles)	3963	3963	3963
Effective earth radius	R	(miles)	5280	5280	5280
Half scattering angle	θ'	(radians)	$0.030(1.7^o)$	$0.016(0.9^o)$	$0.008(0.45^o)$
Frequency	f	(MHz)	882	882	882
Wavelength	λ	(feet)	1.11	1.11	1.11
Antenna dia.	D	(feet)	60	28	28
Half ant. beamwidth	α'	(radians)	$0.011(0.65^o)$	$0.025(1.4^o)$	$0.025(1.4^o)$
Velocity propagation	C	(miles/second)	186,000	186,000	186,000
Diff. time delay	Δ_o	(seconds)	0.5×10^{-6}	0.3×10^{-6}	0.1×10^{-6}
Antenna gain, each end	G	(dB)	41.8	35.2	35.2
Half coupling loss*	$1/2G_L$	(dB)	3.8	1.0	0.6
Path ant. gain each end	$1/2G_p$	(dB)	38.4	34.2	34.6
Half path ant. beam†	α''	(radians)	$0.017(1.00^o)$	$0.027(1.55^o)$	$0.026(1.50^o)$
Beam broadening factor	α''/α'	(ratio)	1.56	1.11	1.07
Adjusted time delay	Δ_a	(seconds)	0.78×10^{-6}	0.33×10^{-6}	0.11×10^{-6}

*Coupling loss (see Table 1) is assumed to be shared by both antennas.
†Path antenna beamwidth is derived from path antenna gain, each end.

Table 4. Channel Loading and Frequency Deviation

No. equivalent voice channels, n	24		120	
Top baseband frequency, kHz, f_m	156		552	
<u>One Equivalent Voice Channel (for 2.4 kbps data)</u>				
Loading per channel, dBm0	-5.0(1/3.16)‡		-5.0(1/3.16)‡	
10 log n, dB	+13.8(24.0)		+20.8(120.0)	
RMS multiplex loading, dBm0	+8.8(7.6)		+15.8(38.0)	
Peak-rms multiple*, dB	+12.0(16.0)		+12.0(16.0)	
Peak multiplex loading, dBm0	+20.8(120.0)		+27.8(600.0)	
0 dBm0 test tone peak deviation, kHz	75*	169†	42†	137†
0 dBm0 test tone rms deviation, kHz	53	120	30	97
-5 dBm0 test channel rms deviation, kHz, F_{ch}	30	68	17	55
RMS multiplex deviation, kHz; ΔF_r	146	330	186	600
Peak multiplex deviation, kHz, ΔF_p	584	1320	744	2400
Deviation ratio, $m_p = \Delta F_p / f_m$	3.8	8.5†	1.4†	4.4†
<u>12 Equivalent Voice Channels (for 40.8 kbps data)§</u>				
5.8 dBm0 test channel rms deviation, kHz, F_{ch}	105	238	60	193

*Measured
†7 dB higher than 75 kHz
‡Numbers inside brackets are ratios
§The frequency deviation of 12 equivalent voice channels is $\sqrt{12}$ or 3.5 times that of one equivalent voice channel.

Table 5. Thermal Noise Performance Above Threshold (No Diversity)
Top Voice Channel with Preemphasis - Median Time Block 2

Path	A	B				C			
Trans. power, dBw	40.0 (10 kW)	40.0 (10 kW)				40.0 (10 kW)			
Basic transmission loss L_{bsr}, dB	-231.9	-206.5				-196.5			
Path antenna gain G_p, dB	75.9	68.5				69.3			
Line losses, etc.	- 2.0	- 2.0				- 2.0			
Rec. carrier power C, dBw	-118.0	-100.0				- 89.2			
Rec. noise figure F, dB	2.5	2.5				2.5			
10 $\log_{10}$ KT, dBw	-204.0	-204.0				-204.0			
IF band, B_{if}, dB	61.8 (1.5 MHz)	61.8 (1.5 MHz)		70.0 (10 MHz)		61.8 (1.5 MHz)		70.0 (10 MHz)	
Therm. noise N_t, dBw	-139.7	-139.7		-131.5		-139.7		-131.5	
Carrier-to-thermal noise C/N_t, dB	21.7	39.7		31.5		50.5		42.3	
No. voice chan. n	24	24		120		24		120	
Voice channel band-width kHz	4	4		4		4		4	
Top baseband frequency f_m, kHz	156	156		552		156		552	
Deviation ratio, m_p	3.8	3.8	8.5	1.4	4.4	3.8	8.5	1.4	4.4
RMS voice channel deviation F_{ch}, kHz	30	30	68	17	55	30	68	17	55
Carrier-to-thermal noise C/N_t, dB	21.7	39.7	39.7	31.5	31.5	50.5	50.5	42.3	42.3
20 log (F_{ch}/f_m), dB	- 14.3	-14.3	- 7.3	-30.0	-20.0	-14.3	- 7.3	-30.0	-30.0
10 log (B_{if}/b), dB	25.7	25.7	25.7	34.0	34.0	25.7	25.7	34.0	34.0
Preemphasis P, dB	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Chan. signal-to-therm. noise S/N_t, dB	37.1	55.1	62.1	39.5	49.5	65.9	72.9	50.3	60.3

NOTE

The signal-to-thermal noise S/N_t for twelve equivalent channels is the same as that for one equivalent voice channel calculated here.

Table 6. Thermal Noise Performance Below FM Threshold (No Diversity) Top Voice Channel with Preemphasis

Path	A	B				C			
Carrier-to-thermal noise C/N_t, dB	6	6				6			
No. voice channels n	24	24		120		24		120	
IF band, B_{if}, dB	61.8 (1.5 MHz)	61.8 (1.5 MHz)		70.0 (10 MHz)		61.8 (1.5 MHz)		70.0 (10 MHz)	
Voice channel bandwidth b, kHz	4	4		4		4		4	
Top baseband frequency f_m, kHz	156	156		552		156		552	
Deviation ratio m_p	3.8	3.8	8.5	1.4	4.4	3.8	8.5	1.4	4.4
RMS voice channel deviation F_{ch}, kHz	30	30	68	17	55	30	68	17	55
$2\,(C/N_t)$, dB	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
$20 \log F_{ch}$, dB	89.6	89.6	96.6	84.6	94.8	89.6	96.6	84.6	94.8
$-10 \log B_{if}$	- 61.8	-61.8	-61.8	-70.0	-70.0	-61.8	-61.8	-70.0	-70.0
$-10 \log b$	- 36.0	-36.0	-36.0	-36.0	-36.0	-36.0	-36.0	-36.0	-36.0
Constant, dB	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Preemphasis P, dB	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Chan. signal/noise ratio S/N_t, dB	13.2	13.2	20.2	0.0	10.0	13.2	20.2	0.0	10.0

NOTE

The signal-to-thermal noise S/N_t for twelve equivalent channels is the same as that for one equivalent voice channel calculated here.

Table 7. Path Intermodulation Noise Performance (No Diversity) Top Voice Channel with Preemphasis - Median Time Block 2

Path	A			B				C	
Path distance d St. miles	.381.5			168.4				86.7	
Adjusted path delay Δ_a, 10^{-6} seconds	0.78			0.33				0.11	
No. voice channels, n	24		24		120		24		120
Carrier-to-thermal noise ratio, dB	21.7		39.7		31.5		50.5		42.3
Voice channel band-width kHz	4		4		4		4		4
Top baseband frequency f_m, kHz	156		156		552		156		552
Deviation ratio, m_p	3.8	3.8	8.5	1.4	4.4	3.8	8.5	1.4	4.4
RMS multiplex deviation ΔF_r, kHz	146	146	330	186	600	146	330	186	600
$f_m/\Delta F_r$ in ratios	1.07	1.07	1.07	2.97	0.92	1.07	0.47	2.97	0.92
$\Delta_a \Delta F_r$ in ratios (10^{-1})	1.13	0.48	1.09	0.61	1.98	0.16	0.36	.20	.66
$(\Delta_a \Delta F_r)^2$ in ratios	1.28×10^{-2}	0.23×10^{-2}	1.18×10^{-2}	0.37×10^{-2}	3.94×10^{-2}	0.026×10^{-2}	0.11×10^{-2}	$.041 \times 10^{-2}$	$.46 \times 10^{-2}$
$H(8\Delta_a^2 \Delta F_r^2)$ in ratios	124×10^{-4}	4×10^{-4}	100×10^{-4}	8.8×10^{-4}	1000×10^{-4}	0.055×10^{-4}	1.4×10^{-4}	$.10 \times 10^{-4}$	11.1×10^{-4}
$0.192 [f_m/\Delta F_r]^2$ $H(8\Delta_a^2 \Delta F_r^2)$	26×10^{-4}	8.5×10^{-5}	4.2×10^{-4}	1.6×10^{-3}	1.6×10^{-2}	1.2×10^{-6}	5.8×10^{-6}	1.8×10^{-5}	1.8×10^{-4}
Path intermod./signal N_{ip}/S in dB	- 25.8	-40.7	-33.7	-28.0	-18.0	-59.3	-52.3	-48.0	-38.0
Signal/intermod. S/N_{ip} in dB	25.8	40.7	33.7	28.0	18.0	59.3	52.3	47.5	37.5

NOTE

Signal-to-intermodulation noise S/N_{ip} for twelve equivalent channels the same as that for one equivalent voice channel calculated here.

Table 8. Signal-to-Total Noise Ratio and Probability of Bit Error (No Diversity) - Top Voice Channel

Path	A	B				C			
Path dist. d, miles	381.5	168.4				86.7			
Voice channels n	24	24		120		24		120	
Voice ch. bw b, kbps	4	4		4		4		4	
Dev. ratio m_p	3.8	3.8	8.5	1.4	4.4	3.8	8.5	1.4	4.4
Car./th. noise C/N_t, dB	0	0				0			
Th. noise/sig. N_t/S, dB	- 1.0	- 1.0	- 8.0	+12.0	+ 2.0	- 1.0	- 8.0	+12.0	+ 2.0
Path IM./sig. N_{ip}/S, dB	- 3.2	- 5.8	+ 1.2	+ 0.8	+10.8	-17.0	-10.0	-11.2	- 1.2
Tot. noise/sig. N/S, dB	0.9	+ 0.2	+ 1.7	+12.0	+ 2.5	- 1.0	- 6.0	+12.0	+ 3.7
Error in 10^{-1}; m=1	12.3	10.5	14.8	158	17.8	7.9	2.5	158	23.4
Car./th. noise C/N_t, dB	6	6				6			
Th. noise/sig. N_t/S, dB	- 13.2	-13.2	-20.2	- 0.0	-10.0	-13.2	-20.2	- 0.0	-10.0
Path IM/sig. N_{ip}/S, dB	- 12.0	-14.2	- 7.2	- 7.6	+ 2.4	-25.4	-18.4	-19.6	- 9.6
Tot. noise/sig. N/S, dB	- 9.7	-11.0	- 7.0	+ 0.7	+ 3.1	-13.0	-16.3	0.0	- 7.0
Error in 10^{-2}; m = 1	10.8	7.9	20.0	118	204	5.0	2.3	100	20
Car./th. noise C/N_t, dB	12	12				12			
Th. noise/sig. N_t/S, dB	- 25.0	-25.0	-32.0	-15.0	-25.0	-25.0	-32.0	-15.0	-25.0
Path IM./sig. N_{ip}/S, dB	- 19.1	-21.2	-14.2	-14.6	- 4.6	-32.4	-25.4	-26.6	-16.6
Tot. noise/sig. N/S, dB	- 18.2	-19.0	-14.2	-11.9	- 4.6	-24.3	-24.6	-14.8	-16.1
Error in 10^{-3}; m = 1	15.0	12.6	38	65	350	3.7	3.4	33	24
Car./th. noise C/N_t, dB	22	22				22			
Th. noise/sig. N_t/S, dB	- 37.0	-37.0	-44.0	-30.0	-40.0	-37.0	-44.0	-30.0	-40.0
Path IM./sig. N_{ip}/S, dB	- 26.1	-28.2	-21.2	-21.6	-11.6	-39.4	-32.4	-33.6	-23.6
Tot. noise/sig. N/S, dB	- 25.2	-27.7	-21.2	-21.0	-11.6	-35.0	-32.2	-28.5	-23.6
Error in 10^{-3}; m = 1	3.0	1.7	7.6	7.9	69	.32	.60	1.4	4.4
Car./th. noise C/N_t, dB	32	32				32			
Th. noise/sig. N_t/S, dB	- 47.0	-47.7	-54.0	-40.0	-50.0	-47.0	-54.0	-40.0	-50.0
Path IM./sig. N_{ip}/S, dB	- 33.0	-35.2	-28.2	-28.6	-18.6	-46.4	-39.4	-40.6	-30.6
Tot. noise/sig. N/S, dB	- 32.9	-35.0	-28.2	-28.3	-18.6	-43.7	-39.4	-37.3	-30.6
Error in 10^{-4}; m = 1	5.1	3.2	15	15	140	.42	1.1	1.8	8.7

NOTE

1. Signal-to-total noise S/N for twelve equivalent channels the same as that for one equivalent voice channel calculated here.
2. For 2.4 kbps data channel (one equivalent voice channel) multiple probability of error by 0.6.
3. For 40.8 kbps data channel (12 equivalent voice channels), multiple probability of error by 0.85.

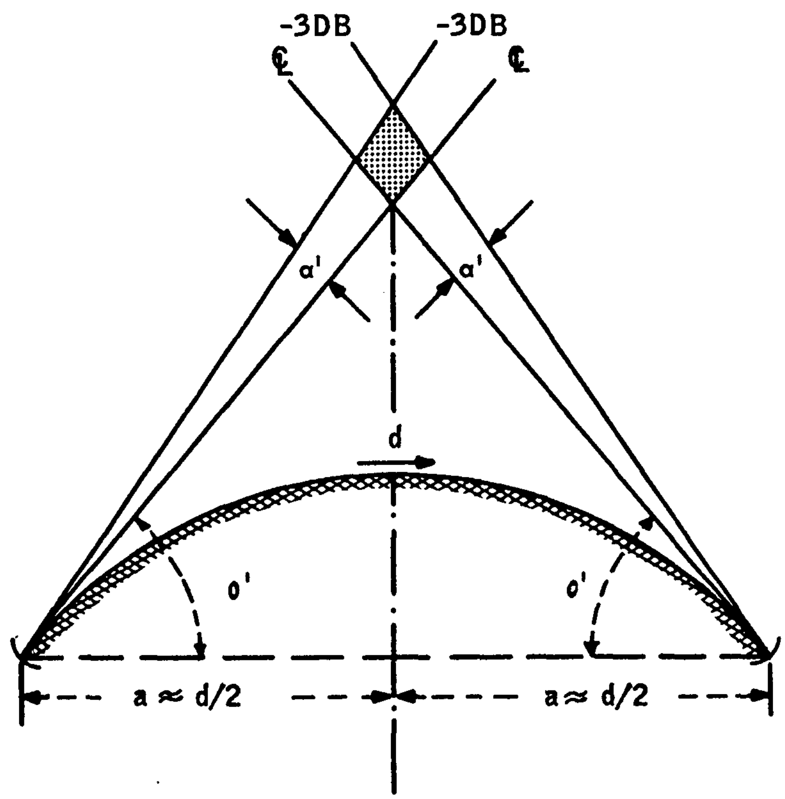

Figure 1-1. Symmetrical Tropospheric Scatter Path

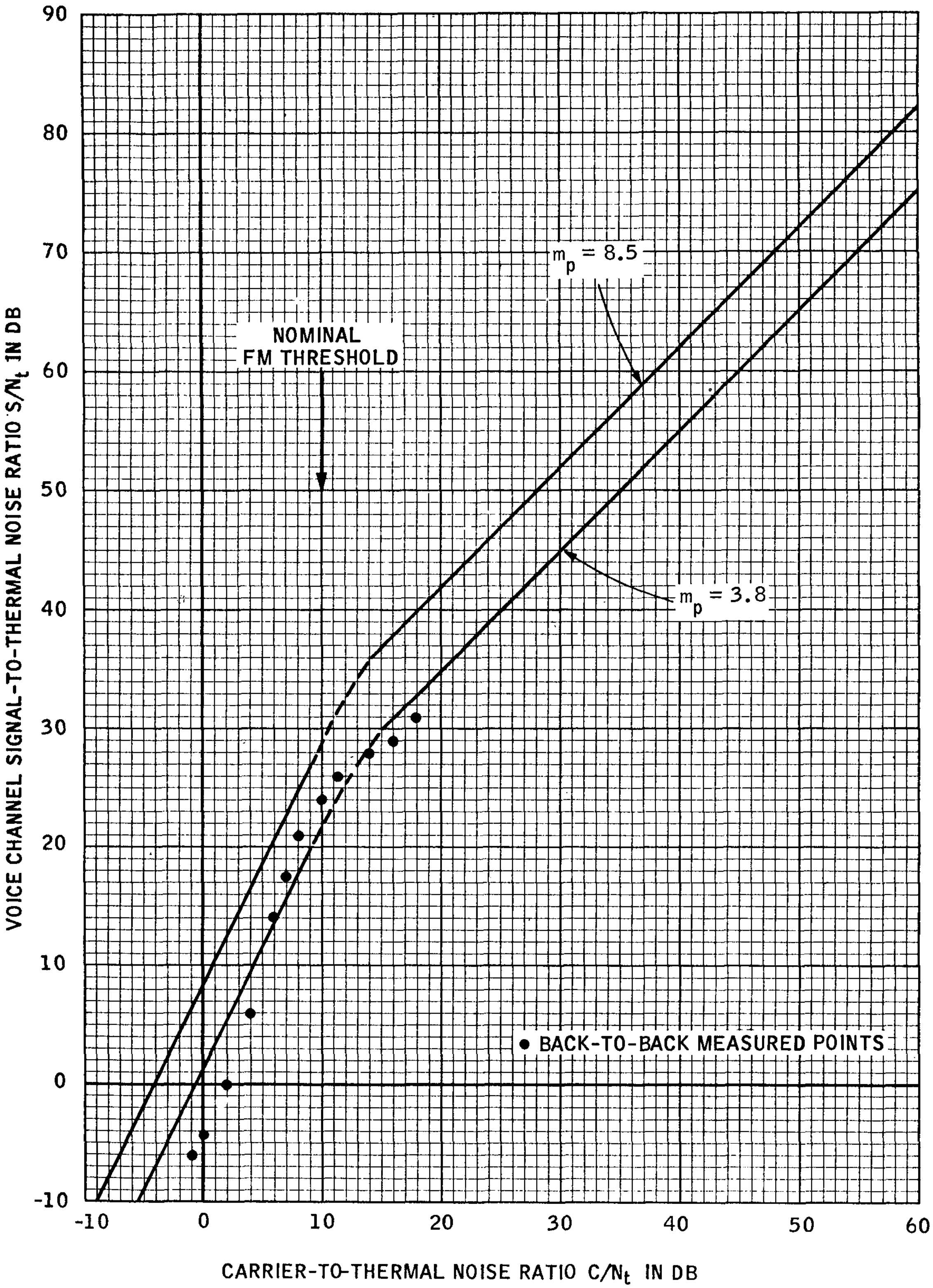

Figure 2. Top Voice Channel Thermal Noise Performance (No Diversity) (24 voice channel system)

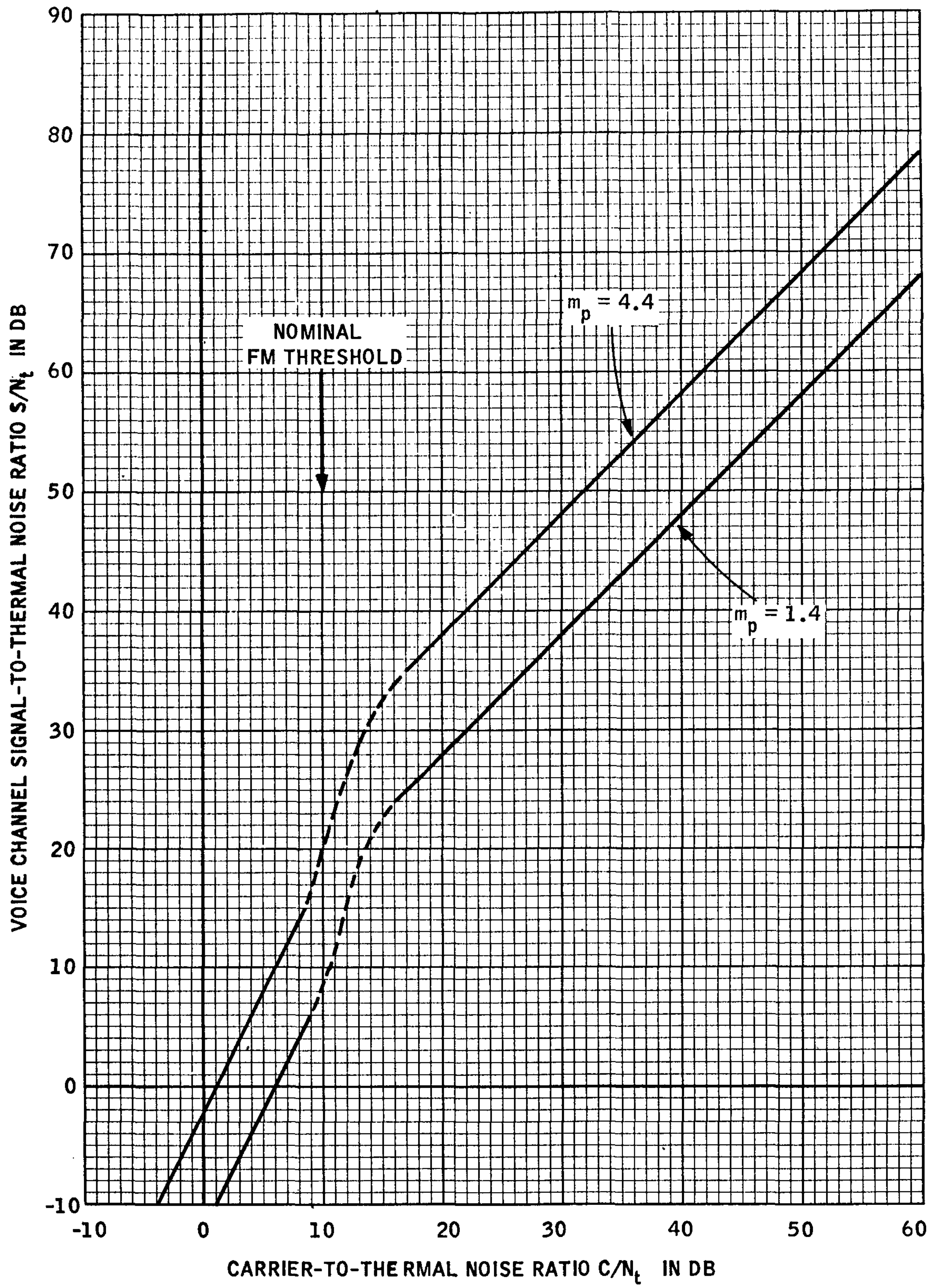

Figure 3. Top Voice Channel Thermal Noise Performance (No Diversity) (120 voice channel system)

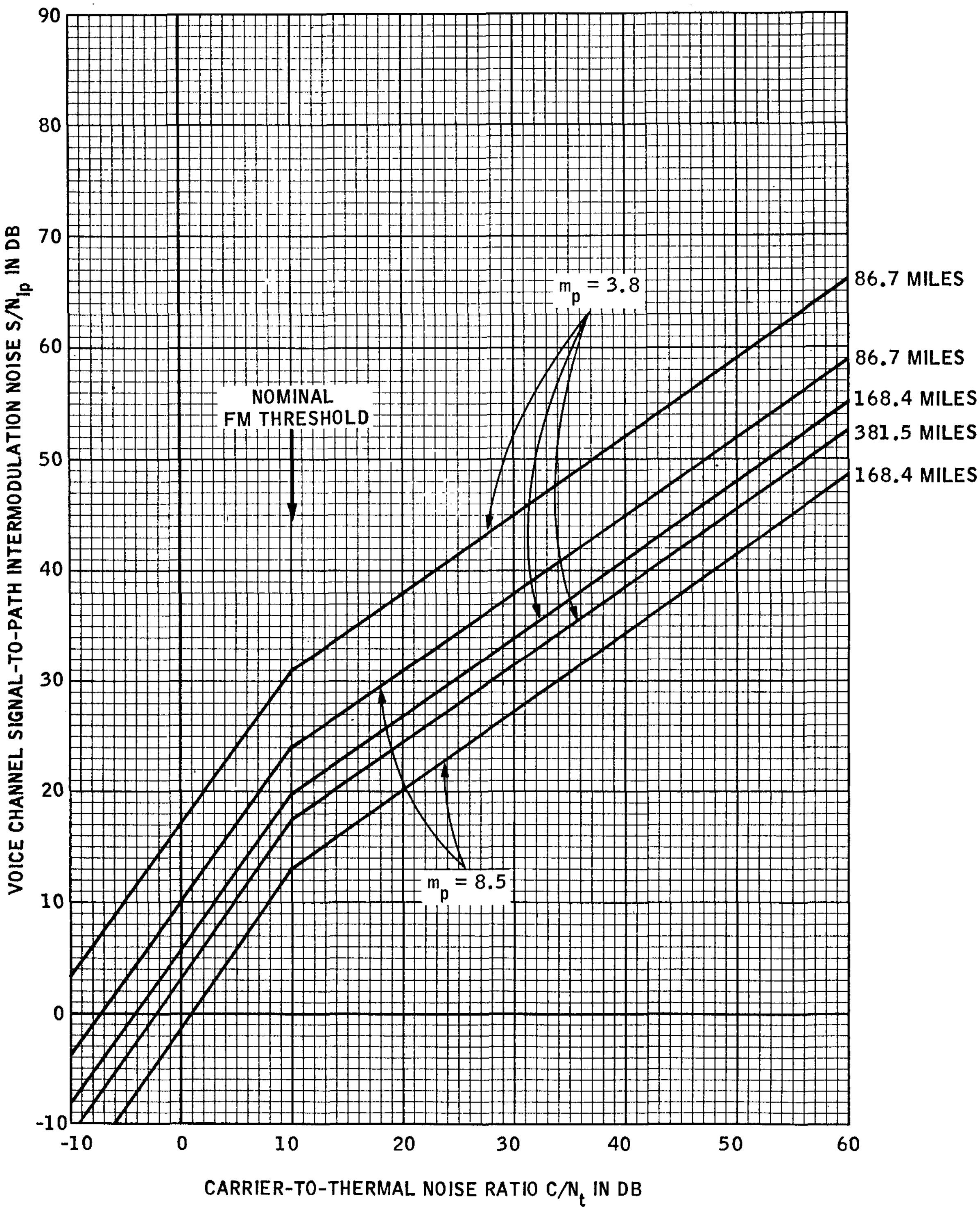

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Figure 4. Top Voice Channel Intermodulation Noise Performance (No Diversity) (24 voice channels)

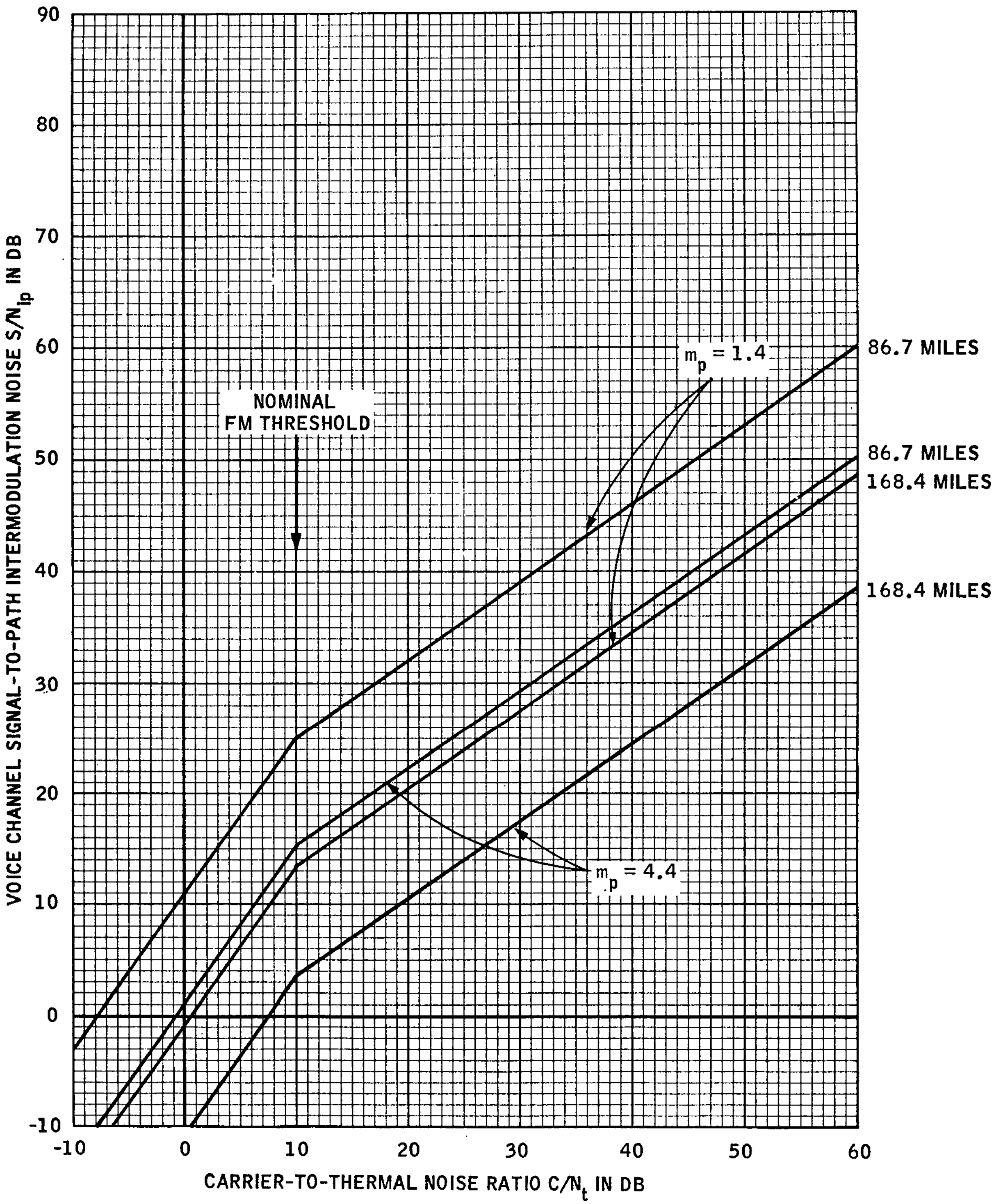

Figure 5. Top Voice Channel Intermodulation Noise Performance (No Diversity) (120 voice channels)

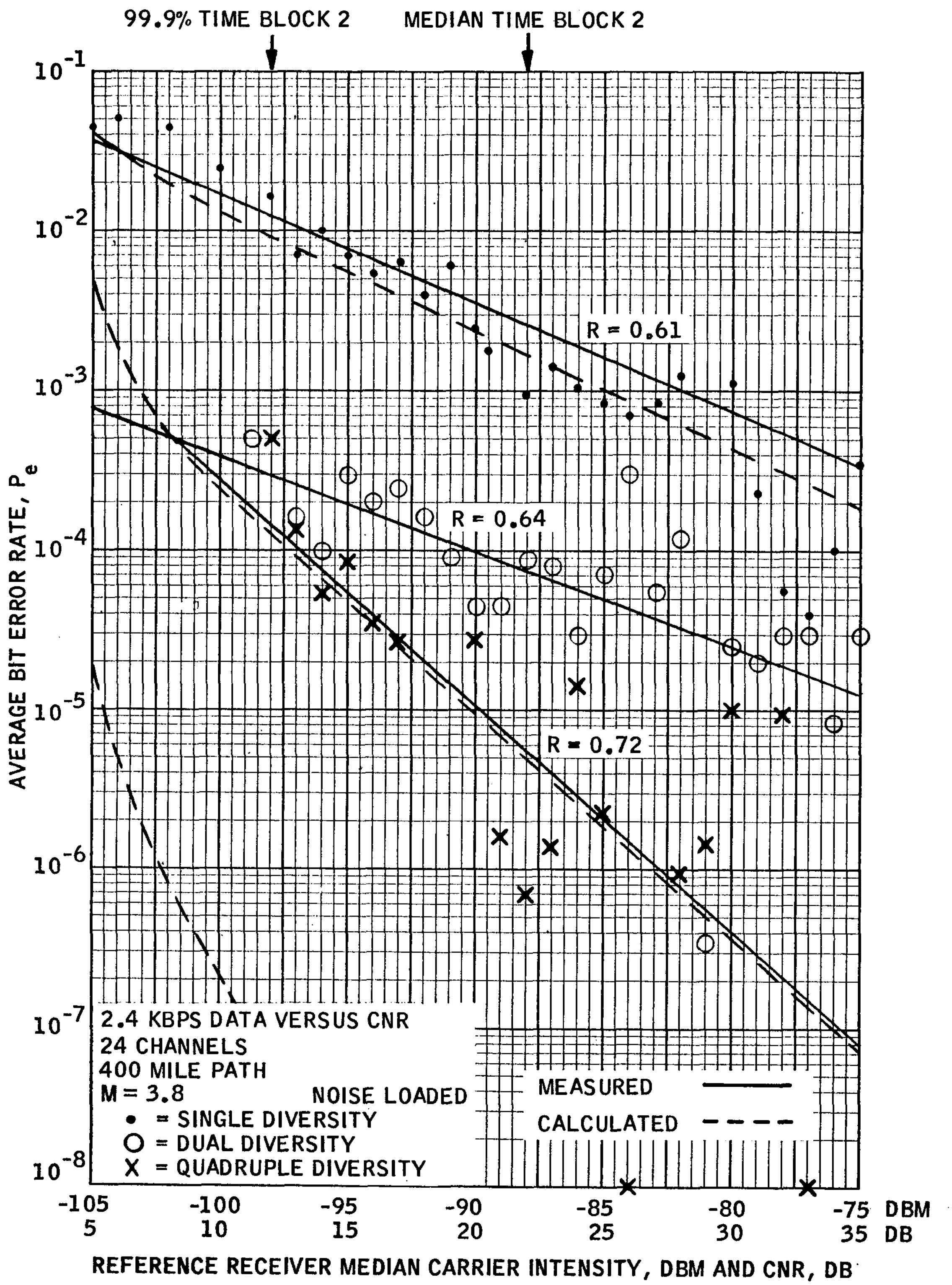

Figure 6. 400 Mile Path 24 Channels, M = 3.8, 2.4 kbps data Versus Signal Level

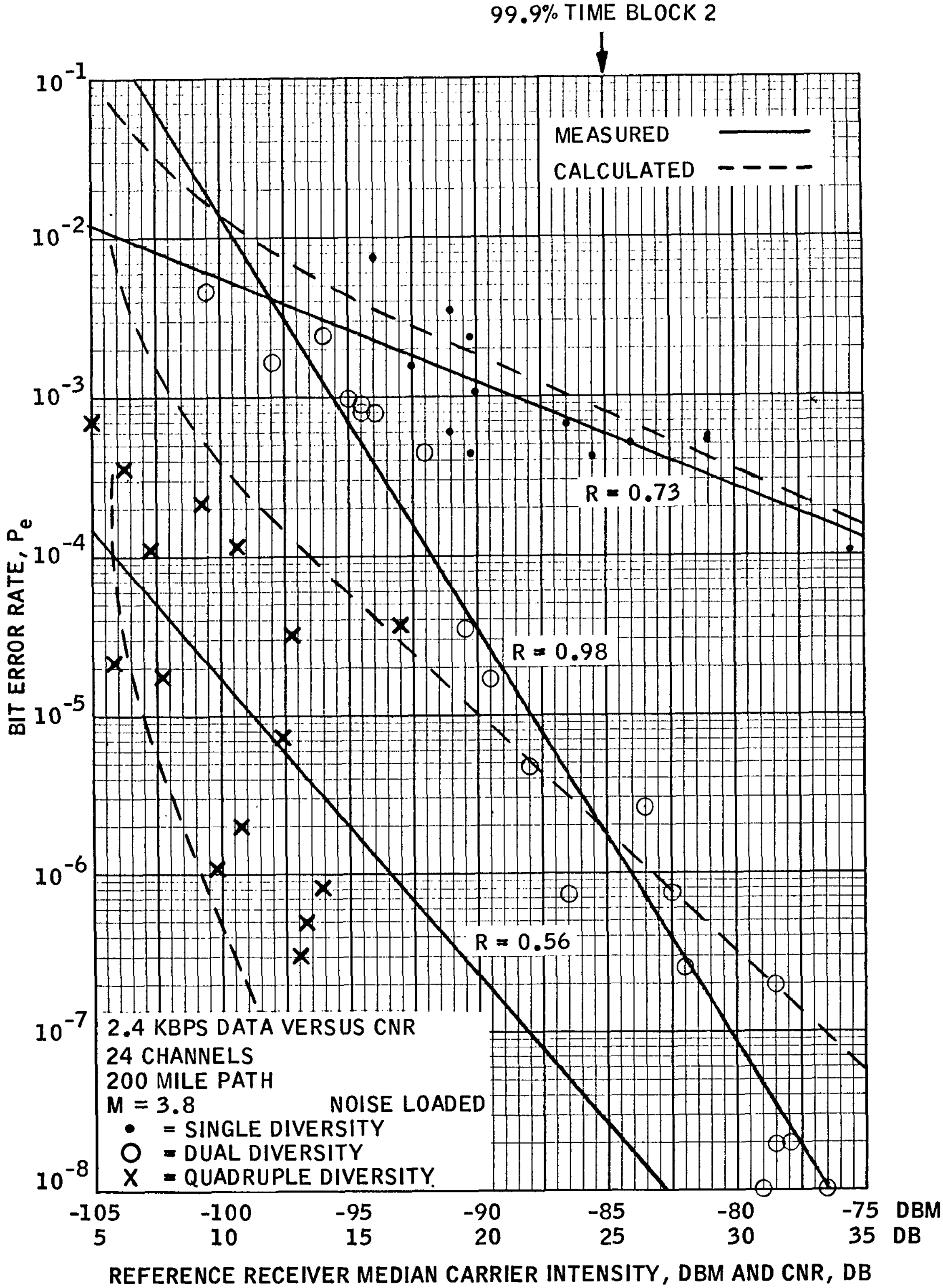

Figure 7. 200 Mile Path 24 Channels, M = 3.8, 40.8 kbps data Versus Signal Level

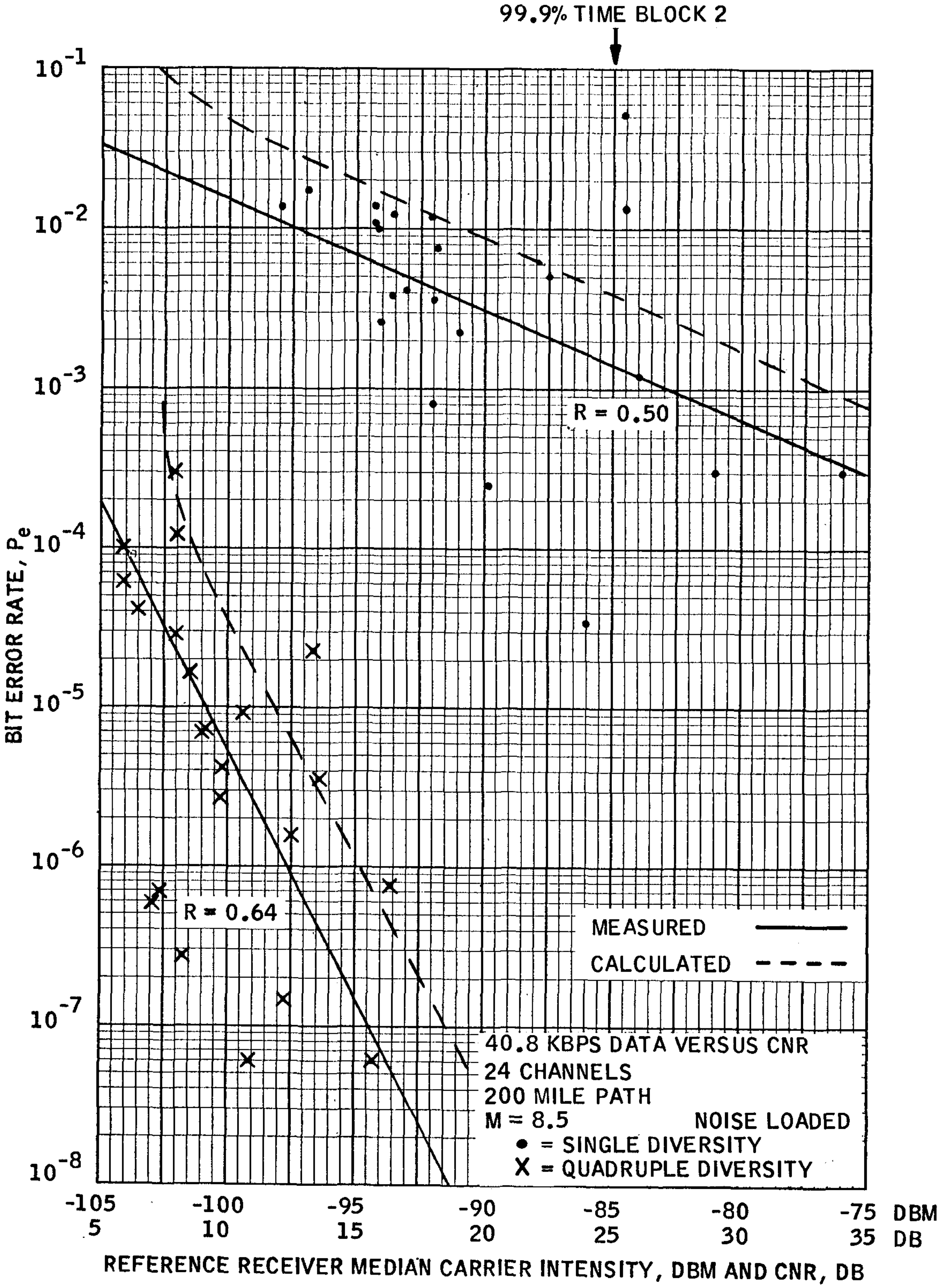

Figure 8. 200 Mile Path 24 Channels, M = 8.5, 40.8 kbps data P_e Versus Signal Level

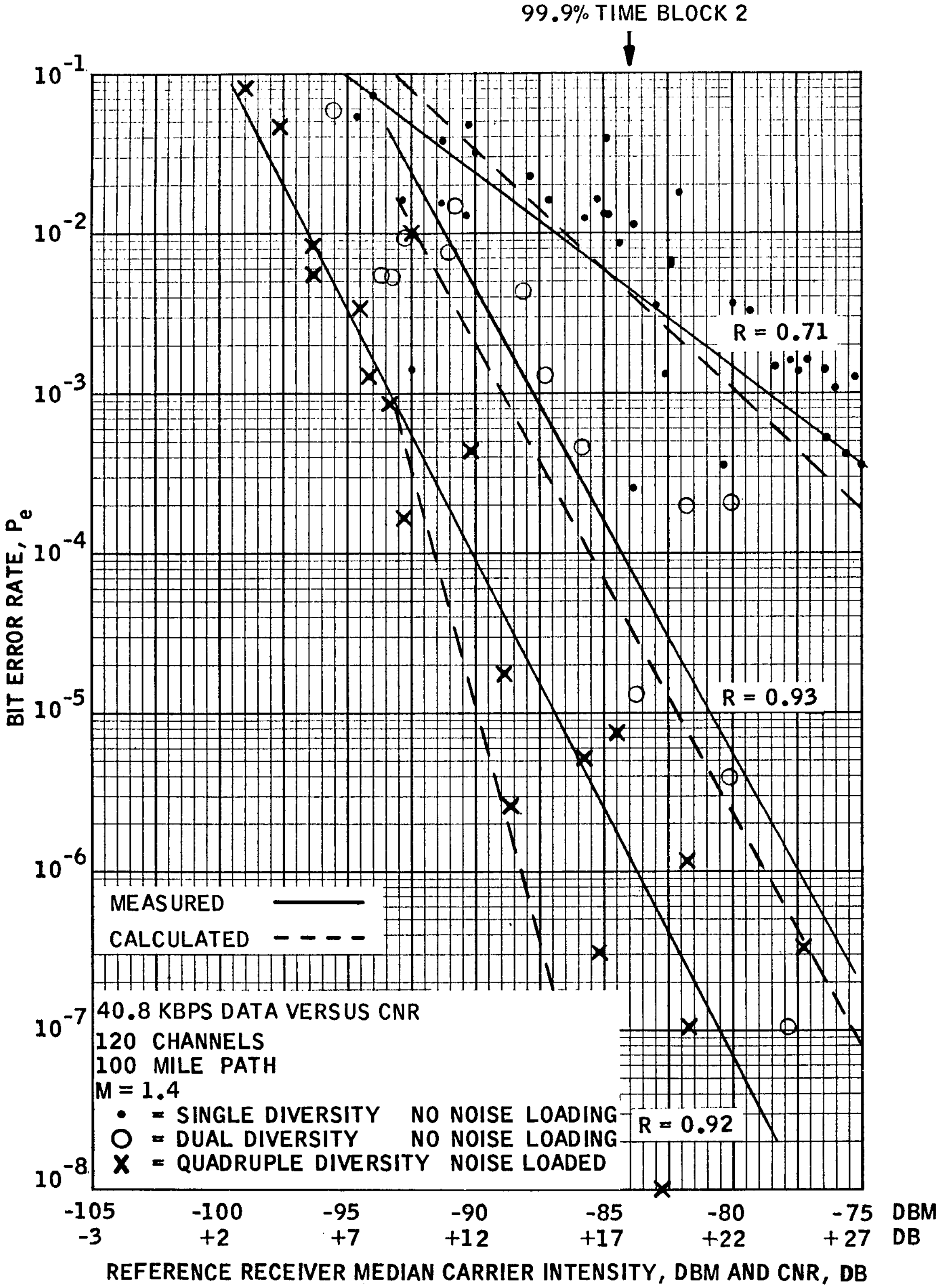

Figure 9. 100 Mile Path 120 Channels, M = 1.4, 40.8 kbps data Versus Signal Level

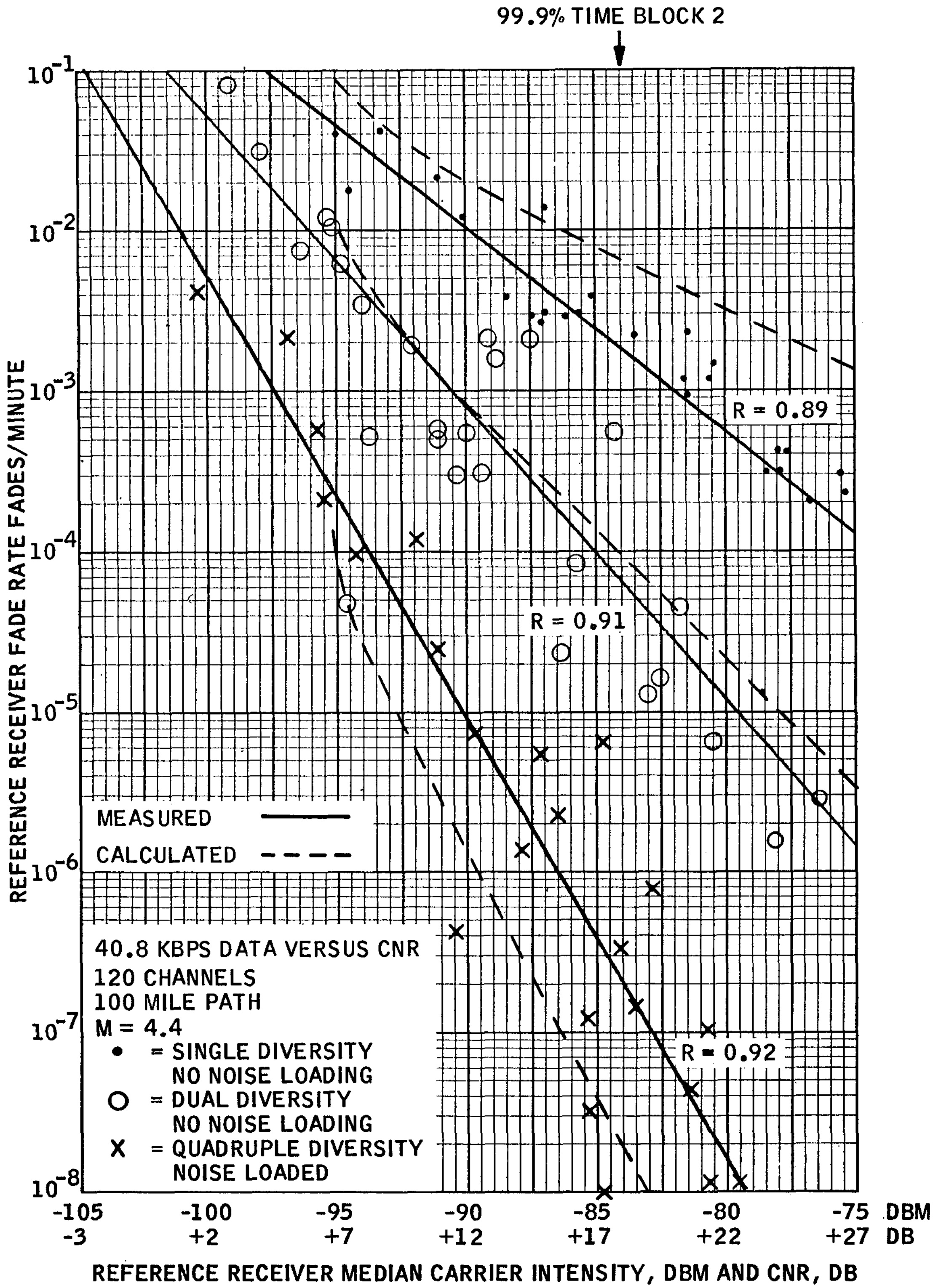

Figure 10. 100 Mile Path 120 Channels, M = 4.4, 40.8 kbps data Versus Signal Level