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FINAL REPORT

A DETERMINATION OF TECHNICAL CRITERIA FOR THE COORDINATION OF DIGITAL AND ANALOGUE MICROWAVE SYSTEMS

VOLUME II INTERFERENCE INTO DIGITAL SYSTEMS

FOR: THE DEPARTMENT OF COMMUNICATIONS
JOURNAL TOWER NORTH
300 SLATER STREET
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Prepared by
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ABSTRACT

This report is Volume II of a two part study related to the coordination of digital and analog microwave systems. This volume presents the effects of digital and analog interference on a 91 Mb/s 8GHz QPRS digital radio system. The performance criteria used for digital systems in an interference environment are discussed and methods of theoretically determining performance degradation in the presence of thermal noise, intersymbol interference (ISI), co-channel interference (CCI) and adjacent channel interference (ACI) are outlined. Finally, the results of a theoretical and experimental study on the performance of the digital radio system under various interference conditions are presented in a set of curves.

1. INTRODUCTION

This report provides information on the effects of analog and digital interference on the performance of a 91 Mb/s 8 GHz Digital Radio System employing Quadrature Partial Response Signalling (QPRS). Interference guidelines for route co-ordination and system design are provided. Methods of analytically calculating the degradation of digital system performance due to thermal noise, intersymbol interference (ISI), co-channel interference (CCI) and adjacent channel interference (ACI) are discussed. The results of an experimental and theoretical interference study on the Northern Telecom RD-3 are presented in graphical form. The set of curves presents the following relationships:

a) Single frequency interference susceptibility.
b) The effect on Bit Error Rate (BER) of adjacent channel interference.
c) The effect on BER of co-channel interference.
d) The effect on BER of both adjacent and co-channel interference combined.
e) Frequency coordination interference objectives for digital into digital and analog into digital.

2. PERFORMANCE CRITERIA

Because of the nature of an analog radio system (non-regenerative repeaters) the interference noise from each hop accumulates throughout the entire route. Therefore the C/I objectives are dependent on the amount of noise added due to interference over a 4000 mile hypothetical reference circuit (HRC) under non-faded conditions. The C/I objectives are based on the following:

i) Calculations (based on the radiated power spectrum) of the increase in noise due to an exposure at various levels.

ii) Assumptions as to the number of exposures and their levels over the 4000 mile HRC.

iii) The allocation of noise to the various sources in any radio system.

Therefore interference noise objectives are established on a per hop basis so that the overall system objective can be met.

In a Digital Radio System the parameter that best characterizes the Digital System Performance is the Bit Error Rate (BER). A receiver error occurs when the decision circuitry is caused to make a wrong decision due to distortion in the baseband signal. Normally an erroneous decision is made because of a peak in the Gaussian noise (inherent receiver thermal noise), which causes a closure of the eye pattern at the decision time. Under nominal conditions of no fading or interference, the error rate will be rather small (eg., 10^{-19}) and depends solely on the intrinsic receiver design. The introduction of interference into the digital system does not, as a rule cause decision errors directly, except for very small C/I values. This is due to the fact that the interference is peak-limited and normally of insufficient amplitude to cause a complete closure of the eye pattern. The interference does however degrade the eye opening thus increasing the susceptibility to eye closure due to peaks in Gaussian noise. The effect of interference on a digital system is to reduce the fade margin, indirectly causing an increase in residual BER (BER at nominal receive signal levels). The degradation in fade margin and increase of the residual BER are therefore the relationships that best characterize the performance of a digital radio when subjected to various types of interference. These relationships are presented in Section 5 for the RD-3 radio system, under a variety of RF interference (CCI and ACI) conditions.

Since most digital radio systems make use of regenerative repeaters there is no noise build up from one hop to the next. There is however an accumulation of decision errors throughout the route, analogous to noise build up in analog radio systems. Therefore the overall digital system objective is to maintain the BER below some acceptable level for a large percentage of the time.

3. SOURCES OF INTERFERENCE

There are three main sources of interference which can affect the performance of a digital radio system, Intersymbol Interference (ISI), Co-Channel Interference (CCI) and Adjacent Channel Interference (ACI). To determine the effects of analog into digital interference arising from various channelization plans, the continuous range of frequencies between co-channel and adjacent channel are included.

3.1 Intersymbol Interference

In order to transmit a bit stream made up of ideal rectangular pulses a system would have to have an infinite bandwidth. In digital transmission the information is not characterized by the pulse shape but by the pulse amplitude at the decision time. As long as the signal amplitude is within the correct threshold levels at the appropriate decision time, then the extracted information is independent of the actual signal shape. Therefore a certain amount of signal distortion can be tolerated without causing an increase in the BER of the system. When the bandwidth of a system is limited, distortion is introduced into the pulses causing them to spread with an oscillatory tail at both the beginning and end of the pulse (Gibb's phenomenon). This spreading causes a pulse to interfere with the preceding and following pulses. If this bandlimited pulse has a non-zero amplitude at any of the adjacent pulse decision times, intersymbol interference results. Under extreme conditions (excessive bandlimiting) the ISI may be large enough to directly cause decision errors.

In the RD-3 digital radio a quadrature partial response signalling (QPRS) modulation scheme is utilized. This modulation technique introduces a controlled amount of ISI in order to achieve relatively high spectral efficiency. The QPRS signal can be generated using baseband coding techniques to attain the desired spectral shape. The signal, after being coded and QAM modulated is a multiple level signal which is very vulnerable to the AM compression and AM to PM conversion of the microwave power amplifiers, making the baseband coding technique undesirable. To avoid this the partial response can also be generated using frequency domain techniques via the transmit and receive filters. Since the spectral shaping is done after the power amplification stages the above problems are alleviated. For this reason the frequency domain approach has been implemented on the RD-3 for the generation of the QPRS signal. The transmit and receive filters are designed to achieve the desired spectral shaping as well as to limit the adjacent channel interference and thermal noise. The criteria used in the filter design is discussed further in section 3.3.

At the receiver the original signal must be detected in the presence of the controlled intersymbol interference. This is accomplished by using a 5 tap decision feedback equalizer which subtracts the ISI effects (oscillatory components) at the decision times, since the ISI characteristics are known. The filter design constraints are relaxed by making the decision feedback equalizer taps adjustable.

3.2 Co-Channel Interference

Co-Channel Interference (CCI) is RF inter-channel interference from another radio channel having a frequency that falls into the receiver bandwidth. CCI becomes a problem when the coupling between channels at the same or similar frequency is excessive. Figure 1 illustrates some of these CCI sources for a typical frequency arrangement. CCI source 1 is an example of over-reach interference which is at the same frequency but opposite polarization as the desired receive signal F1 (H). It's effects can be reduced by the careful choice of repeater site locations and by choosing antennas with good discrimination characteristics (directivity and cross polarization). Source 2 is CCI which is at the same frequency and polarization as the desired receive signal. It's magnitude is dependent on the front to back discrimination of the antennas. Source 3 represents interference from other radio systems (analog or digital) that transmit within the receive bandwidth of the channel in question. Again the choice of repeater site location and antenna discrimination characteraretics are fundamental in reducing these inter-channel interference effects.

3.3 Adjacent Channel Interference

Adjacent channel interference (ACI) is caused by RF interference from channels adjacent to the wanted channel. The magnitude of the ACI is directly dependent on the receive filter characteristics. The suppression of ACI is just one of the factors considered when designing the receive filters in a QPRS system. As mentioned earlier, both the transmit and receive filters are designed as part of the frequency domain approach to using the QPRS modulation scheme. Since the DRS-8 will, in some cases, operate in the same band as analog radio systems, the transmit filter must provide appropriate suppression of spurious emissions outside the 40 MHz band. Also the QPRS spectrum must be limited (via the transmit filter) so that adjacent channel interference within the DRS-8 system is minimized. The transmit filter was designed to maintain the spectral emissions within the mask recommended by the FCC in FCC Rules Vol. VII, Part 21.106.

Once the transmit filter configuration was established, an optimization routine (BNR computer program) was used to optimize the receive filter design to minimize the effects of adjacent channel interference and thermal noise as well as control the intersymbol interference.

4.0 METHODS FOR EVALUATING INTERFERENCE INTO DIGITAL SYSTEMS

Basically there are three methods of analytically determining the effects of various types of interference on a digital receiver, exact method, direct simulation and bounded approximation.

4.1 Exact Solution

The exact solution method as it implies gives the exact solution for the probability of error P(e) for a digital radio in an interference and noise environment. The basis of this technique is to convolve the probability density functions (PDF) of the interferers with the PDF of the thermal (Gaussian) noise of the receiver. The expression for the P(e) is then derived from the convolved PDF. The main drawback of this method is that the PDF for the interferers is needed to make use of this technique. Except for trivial situations (Gaussian noise) the PDF for various interferers (digital, analog etc.) are not known explicitly. Also for computational efficiency, approximations must be made in the model and the results are no longer exact. Shimbo and Celebiler (8) have developed exact expressions for the P(e) in a thermal noise and intersymbol interference environment which can be used to obtain the results to any degree of accuracy.

4.2 Direct Simulation

This method uses computer techniques to simulate a typical bit error rate (BER) interference test set up. Interferers (co-channel, adjacent channel and intersymbol) are applied to the receiver input along with the thermal (Gaussian) noise. The decision errors are detected after the decision block and the P(e) is determined using the accumulated error statistics. In order to obtain effective results many simulation runs must be made with different pseudo random sequences. When small P(e) are to be estimated (i.e. below 10^{-5}) one finds that the method becomes impractical because of the long and costly simulation runs needed to obtain a reliable P(e). Therefore the cost factor is the main drawback of this technique. This method was applied by Castellani and Sant' Agostino (1).

4.3 Bounded Approximation

The basis of this technique is to develop an upper (and/or lower) bound expression for the probability of an error P(e) due to various interferers, without having to know their probability density functions explicitly. Dodo and Kurematsu (2) have approximated the interference by Gaussian noise which directly adds to the receiver thermal

(Gaussian) noise. By using this Gaussian approximation the P(e) expression can be developed easily. This method gives a good estimate when the interfering power is of the same order of magnitude as the thermal noise. For larger interference power the results tend to be pessimistic.

Benedetto, Biglieri and Castellani (3), have developed upper and lower bound expressions for P(e), in M-Ary coherent phase shift keyed (CPSK) systems in the presence of any number of Co-channel and Adjacent Channel Interferers, Intersymbol Interference and Gaussian Noise. Although this method gives a tight upper and lower bound for P(e) it is very inefficient from the standpoint of computation time.

Rosenbaum and Glave (4, 5, 6) have developed a computationally efficient expression for P(e) which is dependent only on the RMS and peak values of the interfering envelope. The method characterizes the interfering statistics of the maximum PDF that satisfy the constraints (RMS and peak values) so that the resultant P(e) expression is an upper bound expression. Rosenbaum and Glave have extended their method from handling the Intersymbol Interference and Gaussian Noise case only (4) to the case where multiple Co-channel and Adjacent Channel Interferers are included along with the Intersymbol Interference and Gaussian Noise (6). This technique gives a tight upper bound for the P(e) and is easy to implement on the computer making it very attractive as an analytical tool.

The theoretical curves presented in this study were calculated using the Glaves Bound Technique because of it's above mentioned desirable characteristics. Since the curves will be an upper bound for the P(e) the designer can be sure that the actual P(e) will not exceed these limits (assuming the RMS and peak values have been chosen correctly).

5. EXPERIMENTAL AND THEORETICAL INTERFERENCE RESULTS

The curves presented in this section are the results of an interference study done on the RD-3 8 GHz digital radio. The RD-3 makes use of a QPRS modulation scheme to achieve a 2.25 bits/s per Hz spectral efficiency.

5.1 Single Frequency Receiver Susceptibility

As discussed earlier one of the parameters that best characterizes the effects of interference on a digital radio is the degradation in fade margin. For the RD-3 the FM interference objective was established such that there would be no more than 1 dB degradation in fade margin due to the interference. Figure 2 shows the measured RD-3 receiver susceptibility to continuous wave interference. The ordinate S/I is the RMS signal to single frequency interference ratio, which causes a 1 dB degradation in fade margin, versus frequency, relative to the center frequency F0. First the nominal threshold level (Receive signal level for a BER of 10^{-4}) was established without interference. Then the CW interference level that caused a 1 dB degradation in fade margin for the range of frequency separations shown was determined. For frequency separations beyond about 100 MHz the required interference power (to cause a 1 dB degradation in fade margin) was not attainable with the test equipment used. The response at -280 MHz is due to the image response of the mixer. The outer boundary (limit) represents the recommended limits for FM into the RD-3.

5.2 Adjacent and Co-Channel Interference Effects

There are three interference mechanisms associated with the RD-3: direct exposure, AGC takeover and receiver overload. Direct exposure occurs when interference falls within about ± 25 MHz of the wanted carrier frequency. The interfering signal superimposes on the wanted digital signal causing a partial eye closure, degrading the fade margin (refer to section 2.0). AGC takeover occurs when the interfering signal starts to control the AGC detector in the IF main amplifier causing the desired signal level to drop below the range of the baseband AGC circuit (approx. 6 dB). When the baseband signal level decreases the decision feedback equalizer, because of it's static operation (fixed feedback gains), can no longer remove the controlled intersymbol interference introduced at the transmitter. This will in turn cause a degradation in both the fade margin and residual BER. This takeover effect is limited by the IF bandpass filters to a maximum of about 100 MHz frequency separation. Therefore, this phenomenon occurs for frequencies from 25 MHz to 100 MHz, away from the wanted carrier. Performance degradation due to receiver overload is caused by non-linear effects which cause higher order products of the wanted and interfering signal to fall in the pass band of the wanted signal. This type of system degradation only occurs for relatively high levels of interference.

Digital radio systems offer the possibility of doubling the channel capacity through cross polarized operation (frequency reuse). The RD-3 has been characterized under various conditions of adjacent and co-channel interference. The results of theoretical and experimental studies are presented in Figures 4 through 7. The offset frequency plan of Figure 3 was adopted during the measurement program. Channel 4 is taken to be the wanted channel with adjacent copolarized channels 3 and 5. Channels 9 and 10 are cross polarized co-channel interferers.

Figure 4 shows the relationship between BER and receive signal level (dBm) for various levels of two adjacent channel interferers (ch.3 and ch.5) near the thermal noise threshold of the receiver. It can be seen that the fade margin degradation is less than 1 dB when the two adjacent channel interferers are 6 dB higher than the wanted channel. Figure 5 shows the effect of adjacent channel upfades on the BER of the RD-3. The first five data points were measured experimentally while the curve was completed using an extrapolation technique (Chan's method (9)) to complete the curve for small BER. Chan has developed a graphical technique that makes use of a few measured points to extrapolate the curve for small BER. The technique improves the BER estimates for low error rates over that of most test setups. The accuracy is within about one order of magnitude. This curve shows the effect on BER when the adjacent channel's interfering power exceeds that of the wanted channel (under nominal receive levels). Figure 6 shows the degradation in BER for two co-channel interferers (equal power) and two adjacent channel interferers under nominal receive signal levels. For this frequency plan these curves give the designer the required co-channel XPD needed to maintain a given BER. Figure 7 shows the relationship between the BER and receive signal level for three combinations of co-channel and adjacent channel interference.

5.3 Frequency Co-Ordination and Route Design

Figure 8 presents a set of theoretical curves and corresponding experimental points that relate the C/I (faded) versus degradation of fade margin for both analog into digital and digital into digital co-channel interference. For the analog curves the FDM-FM signal was modeled as a single tone at the carrier frequency, since for low modulation indices most of the power is in the carrier component. This was done to reduce the cost and complexity of the theoretical and experimental analysis. For the co-channel situation the error should be nil but for frequency separations that cause the interferer to be sitting on the receive filter skirts the results will tend to be optimistic. This will be discussed further for figure 10.

The two theoretical curves were calculated using Glaves bound as outlined by Rosenbaum and Glaves (6). The peak factors (PF) and peak values of the interfering envelopes were the inputs to the algorithm. The peak factor for the carrier tone (analog case) is simply $\sqrt{2}$ while the peak factor and peak value for the digital interferers were determined using computer simulation techniques. By maintaining a constant BER (10^{-4}) one can determine (via Glaves Bound Technique) the degradation of fade margin for various C/I's. The experimental curves were measured by establishing the desired C/I and then fading the C/I until a BER of 10^{-4} was detected. This procedure gives the degradation in Fade margin for various C/I's at full fade. Since both the wanted and interfering signals are faded simultaneously the degradation in threshold can not be obtained directly from these curves. The curves in Figure 9 were calculated to relate the degradation in fade margin (C-Co) to the Co/I where:

Co is the threshold level (i.e. -70 dBm for BER of 10^{-4} without interference).

C is the receiver threshold level with interference ($C \leq Co$)

The transformation from Figure 8 to Figure 9 was achieved by solving the following analytical expression for C.

$$\mathrm{Log}\ (C-C_o)=a\,(C/I)+b$$

a=-.119, b=3.054 for digital into digital

a=-.0986, b=7.414 for analog into digital

Since C appears on both sides of the equation an iterative procedure was used to solve for C. Now figure 9 can be used to detemine the degradation in fade margin for various co-channel interference levels.

Figure 10 shows the reduction in C/I (as per figure 9) for an analog interferer at various frequency separations. Because the analog interferer was modeled as a single sinusoid figure 10 is the receive filter response of the RD-3 radio. Therefore for frequency separations of 20 MHz or more the curve will tend to be optimistic. One would expect the curve to broaden slightly for these larger frequency separations, as the single tone analog model breaks down.

6. SUMMARY

In this report the effects of analog and digital interference on the RD-3 8 GHz digital radio (QPRS 90 Mbit system) has been discussed. Interference guidelines for route co-ordination and system design have been presented.

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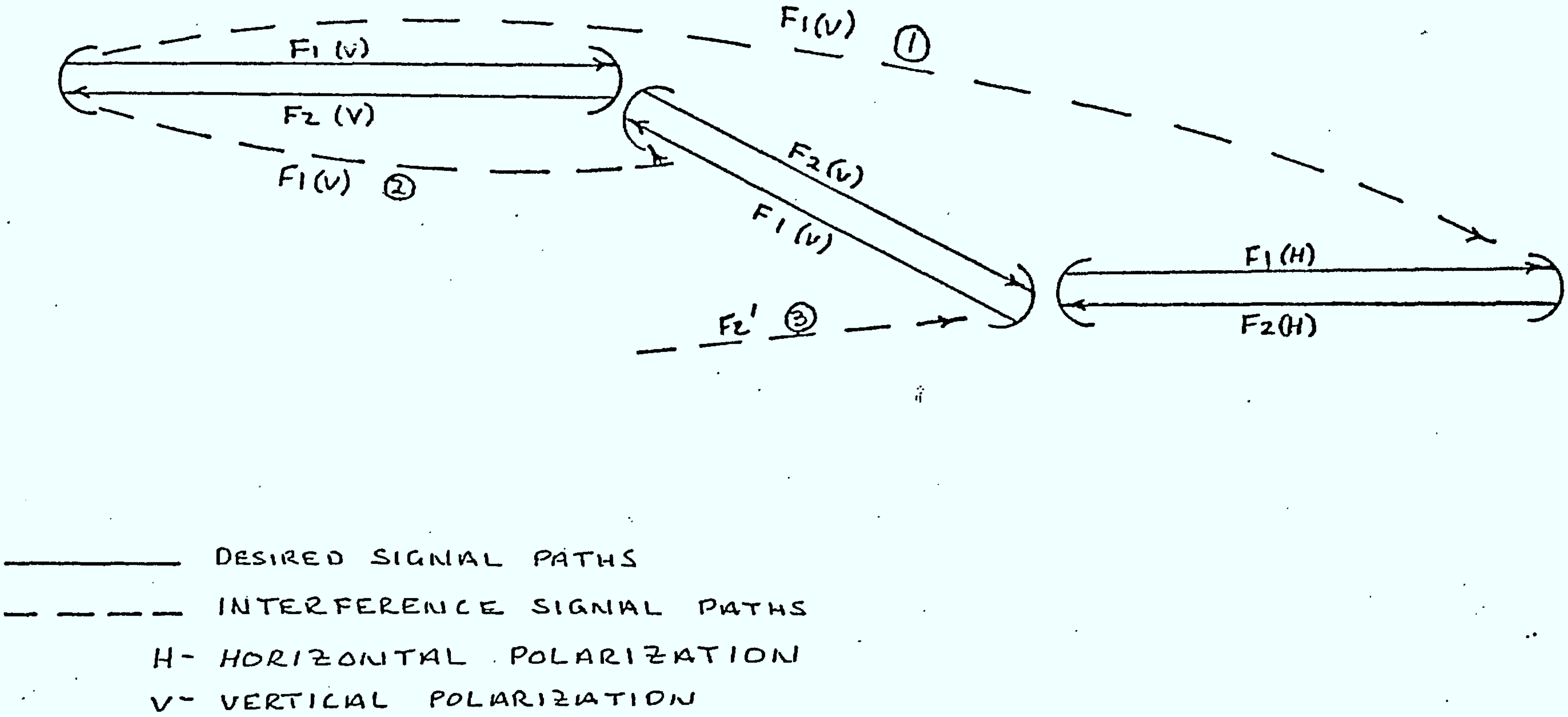


FIG 1: SOURCES OF CO-CHANNEL INTERFERENCE

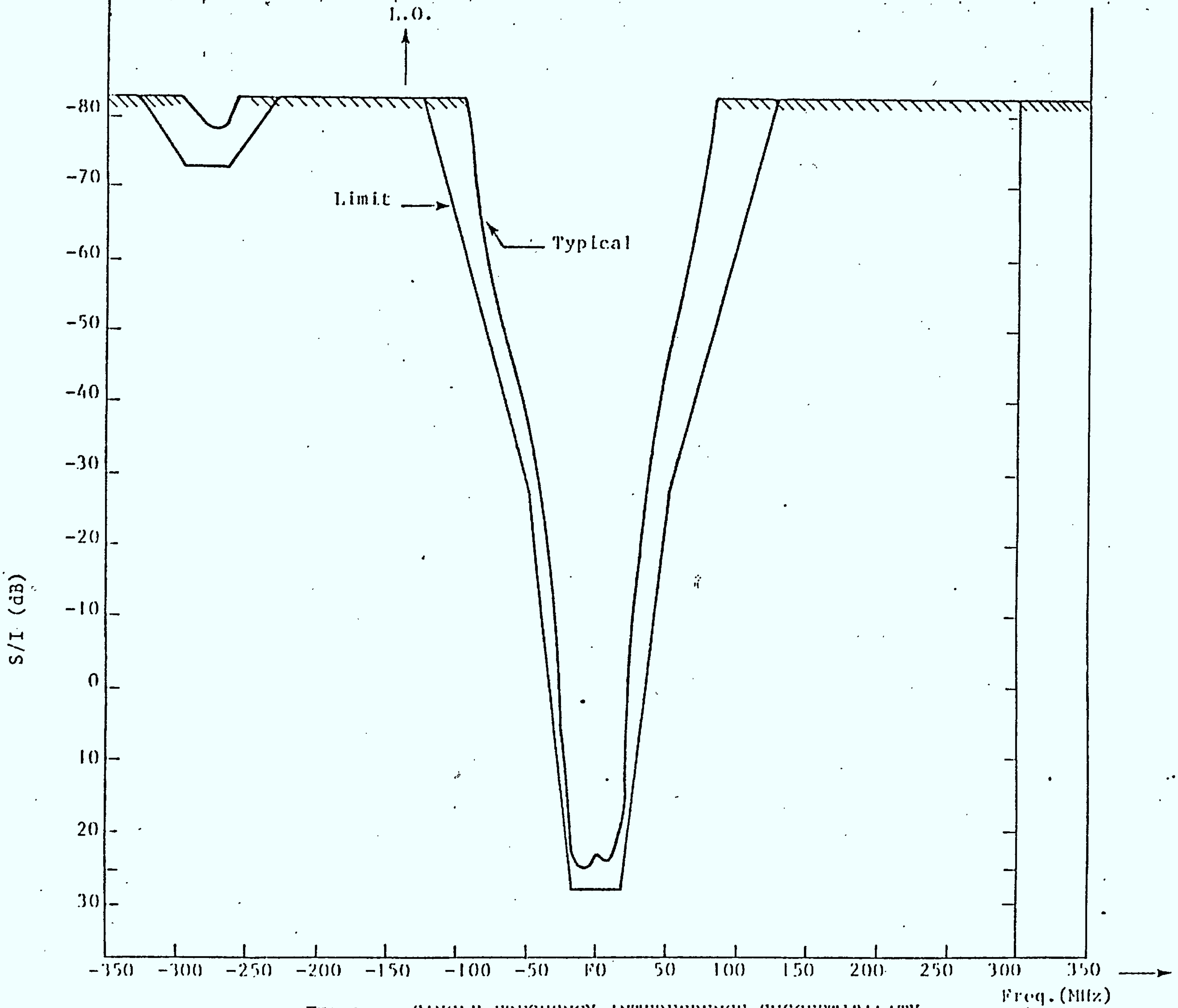
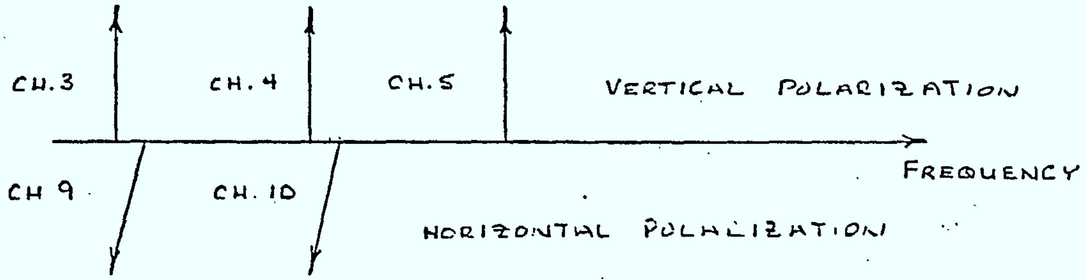


FIG 2: SINGLE FREQUENCY INTERFERENCE SUSCEPTIBILITY



Working Channel

Channel #4 RF=7867.59 MHz

Co-Channel

Channel #9 RF=7832.11 MHz

Channel #10 RF=7873.15 MHz

Adjacent Channel

Channel #3 RF=7826.85 MHz

Channel #5 RF=7908.33 MHz

Figure 3 - Experimental Frequency Plan

BER 10^{-7} or higher for ≥ 300 msec.

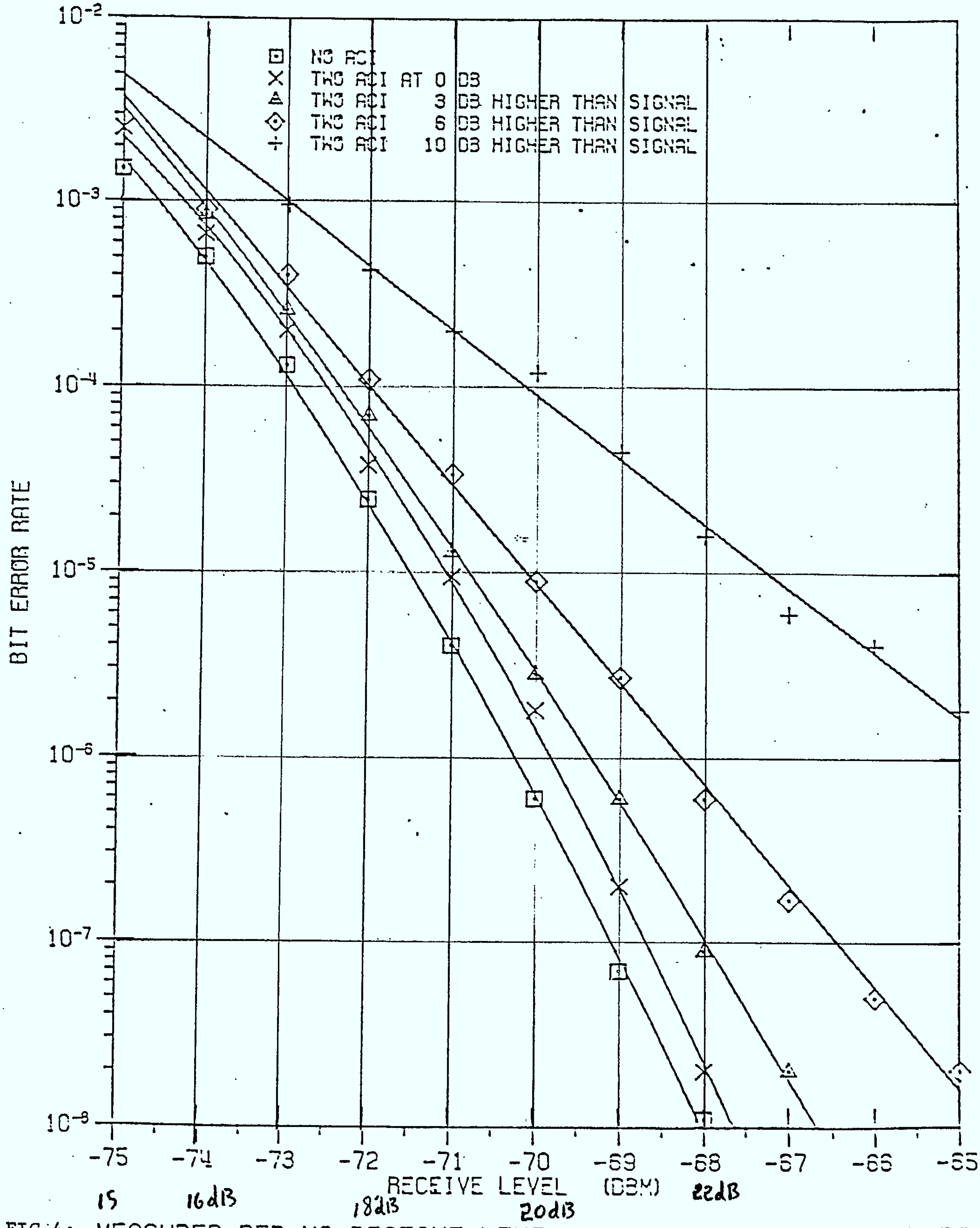


FIG 4: MEASURED BER VS RECEIVE LEVEL WITH VARIOUS INTERFERERS

co-polarized

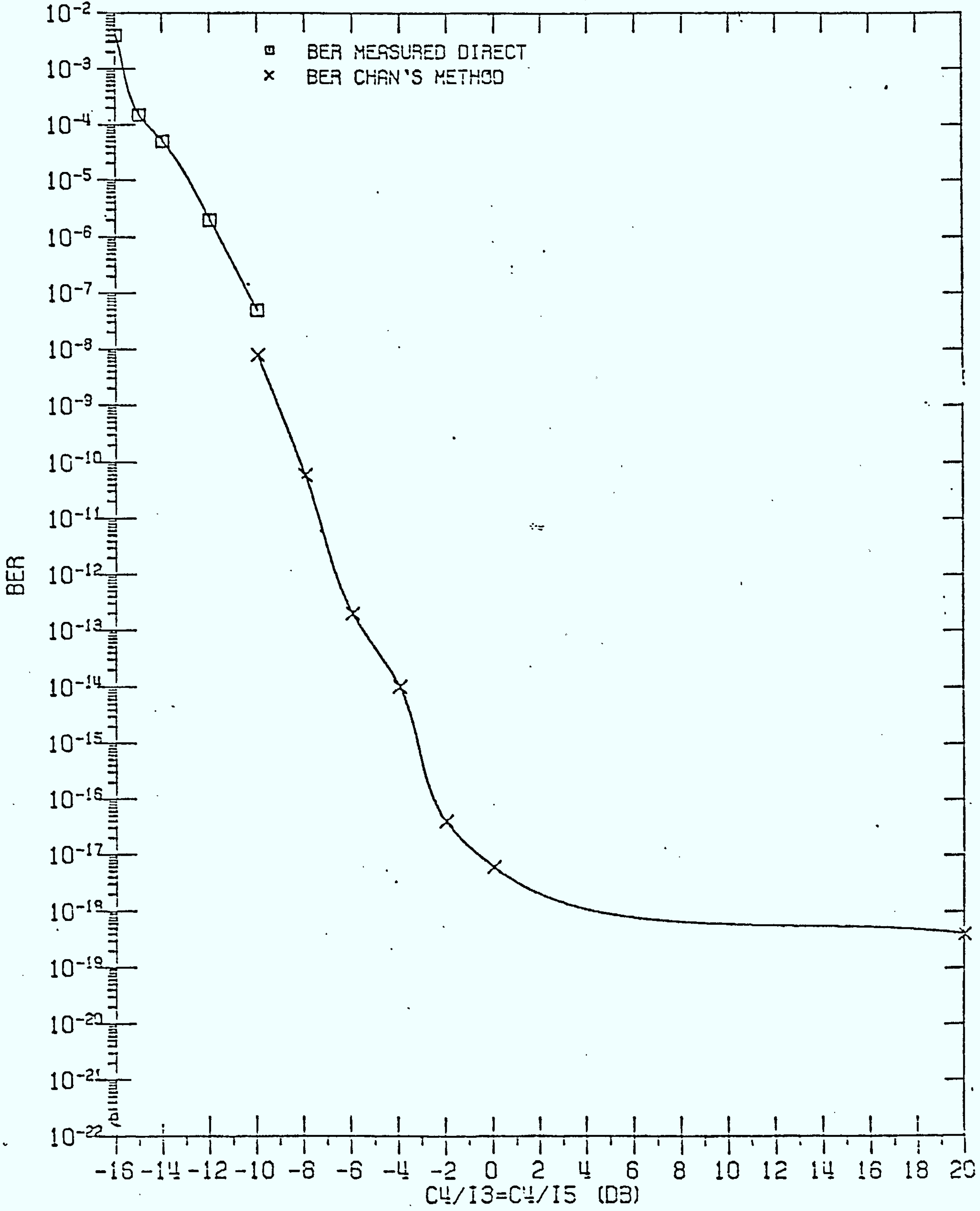


FIG 5: EFFECT OF ADJACENT CHANNEL UPFADE ON BER

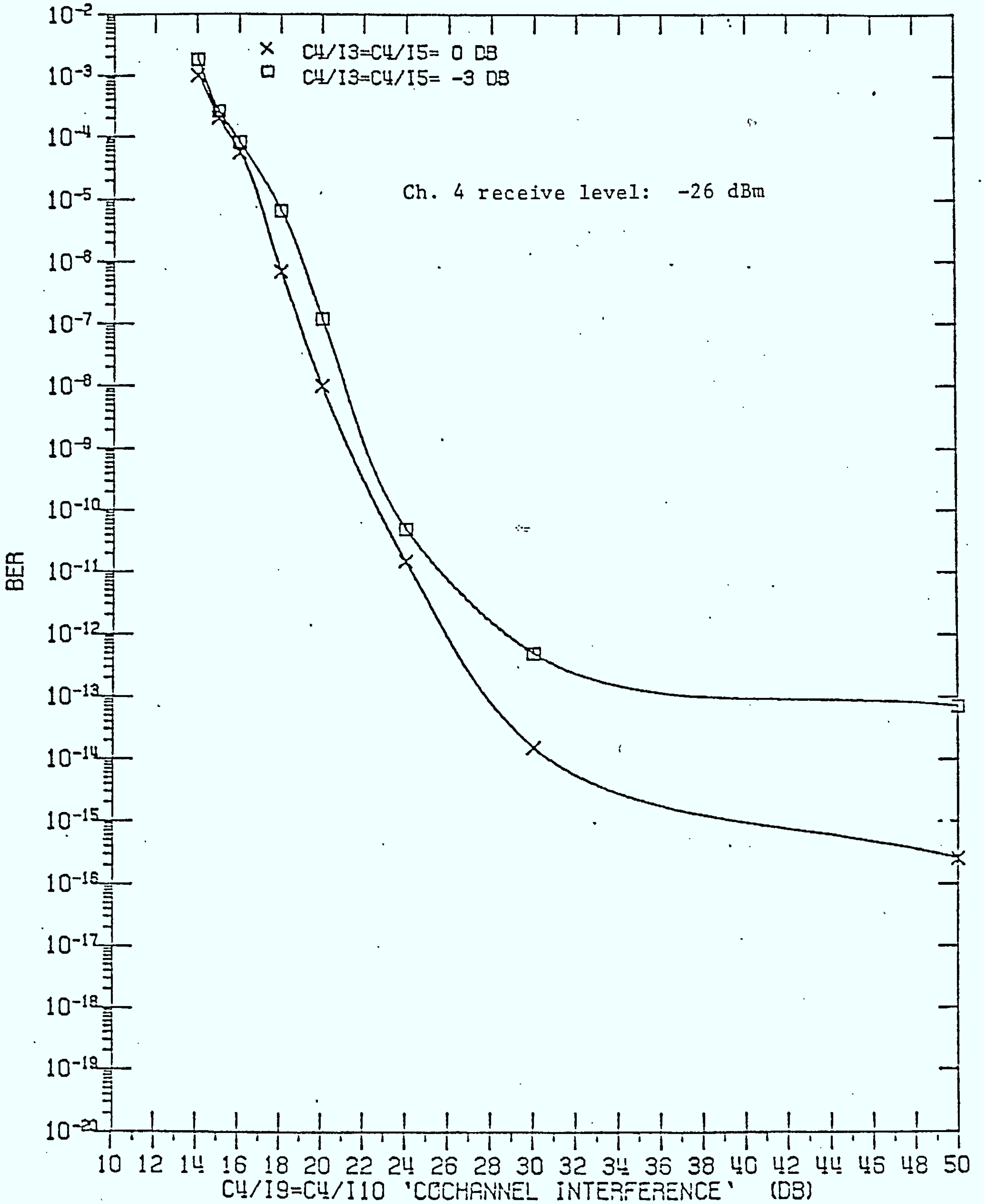


FIG 6: RESIDUAL BER VS ADJACENT CHANNEL AND COCHANNEL INTERFERENCE

$\left.\begin{array}{l}\text{CH 9}\\\text{CH 10}\end{array}\right\} \rightarrow \text{XPD}$

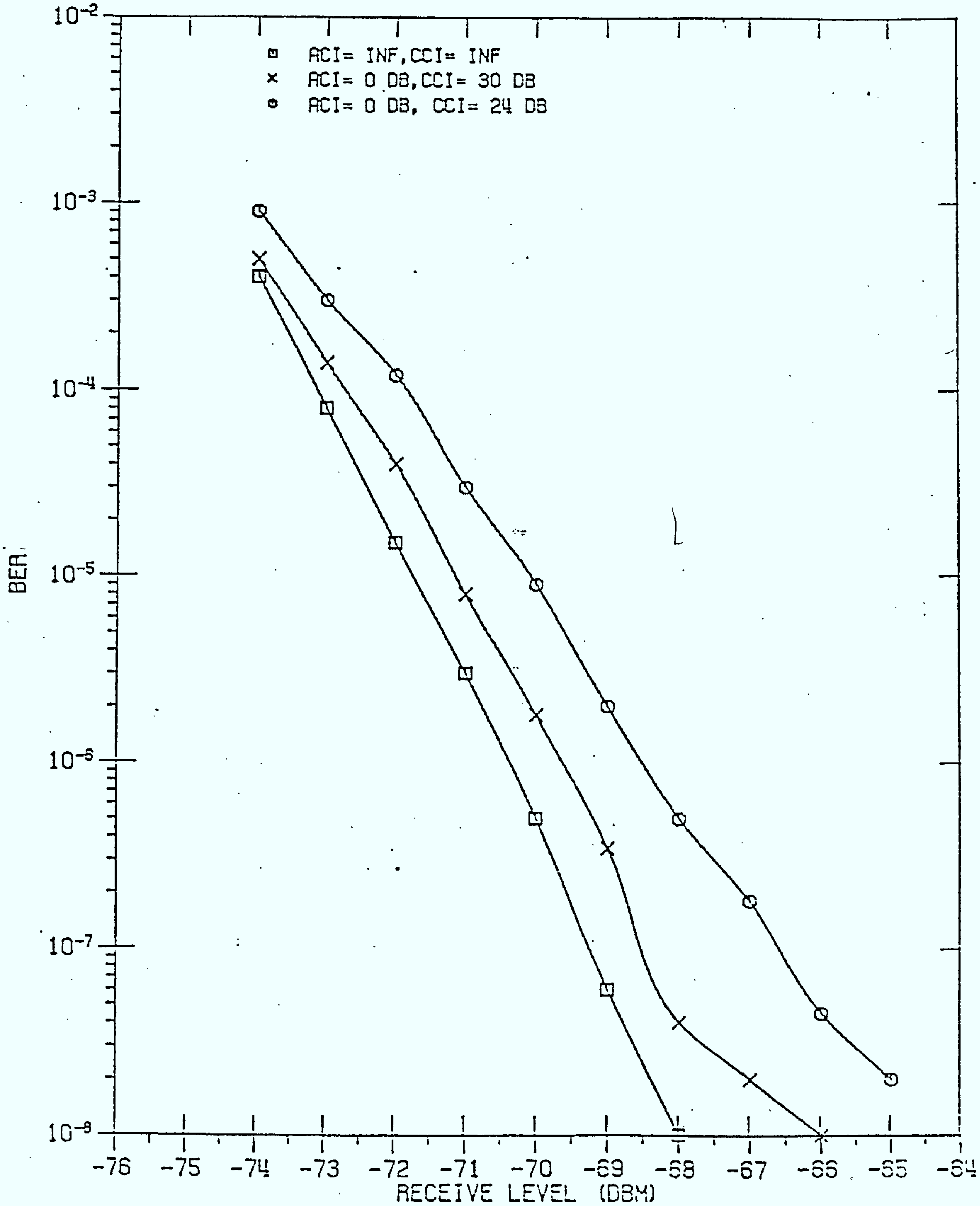


FIG 7: EFFECT OF CCI (CH9 & CH10) AND ACI (CH3 & CH5) ON FADEMARGIN OF

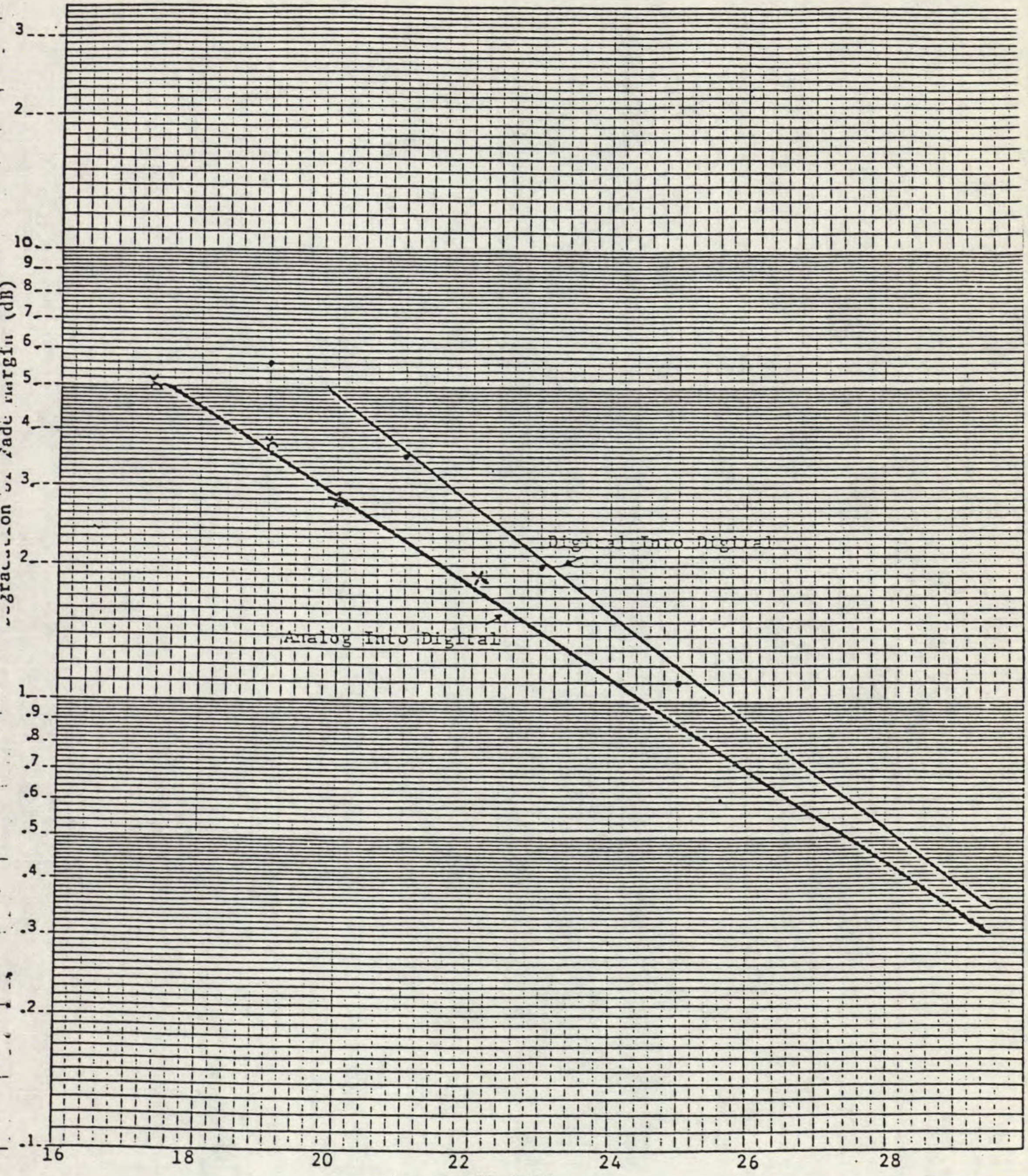
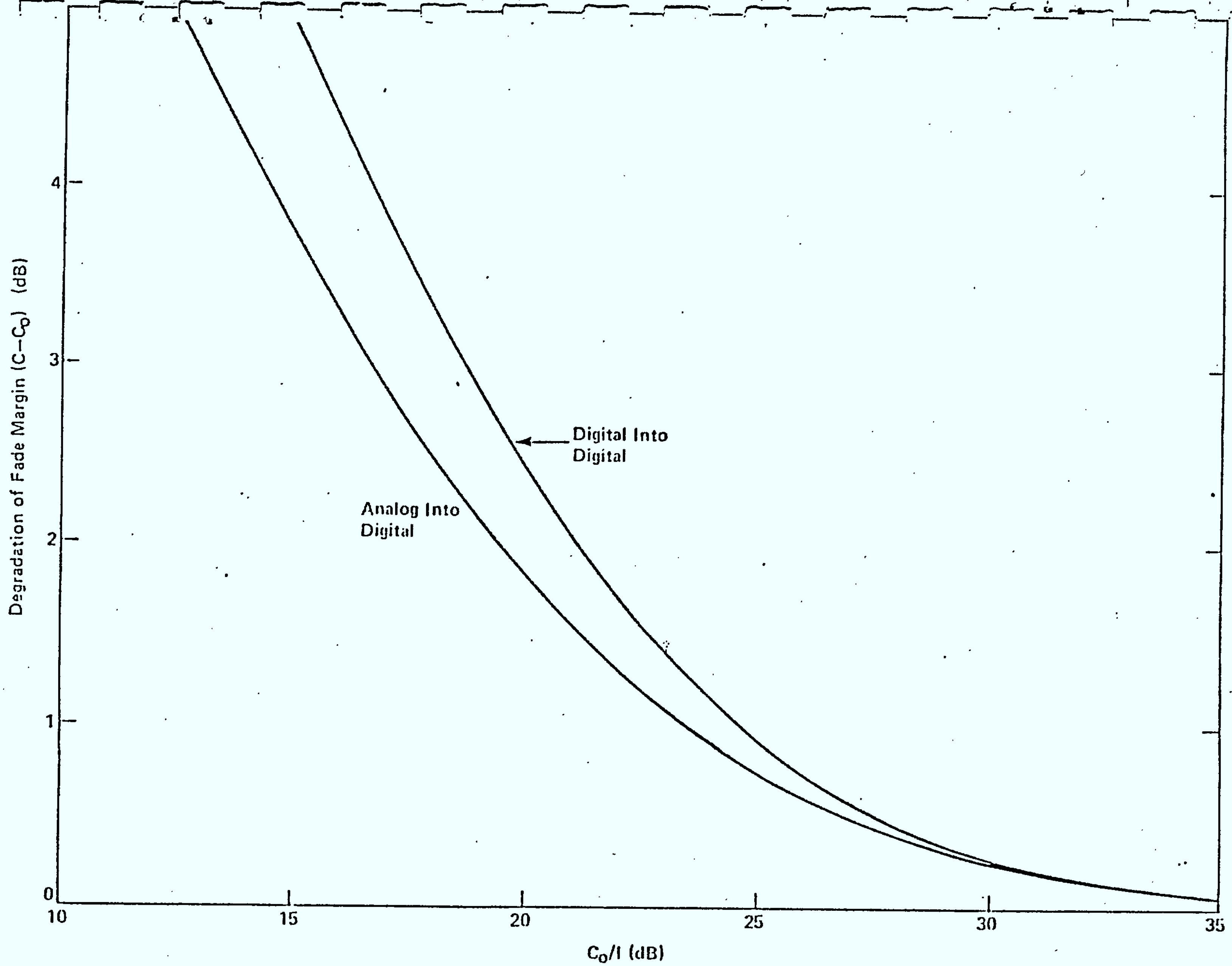


FIG 8: Degradation of fade margin vs. Carrier to Interference ratio at full fade.



C

C_o

FIG 9: Degradation of Fade Margin vs C_o/I

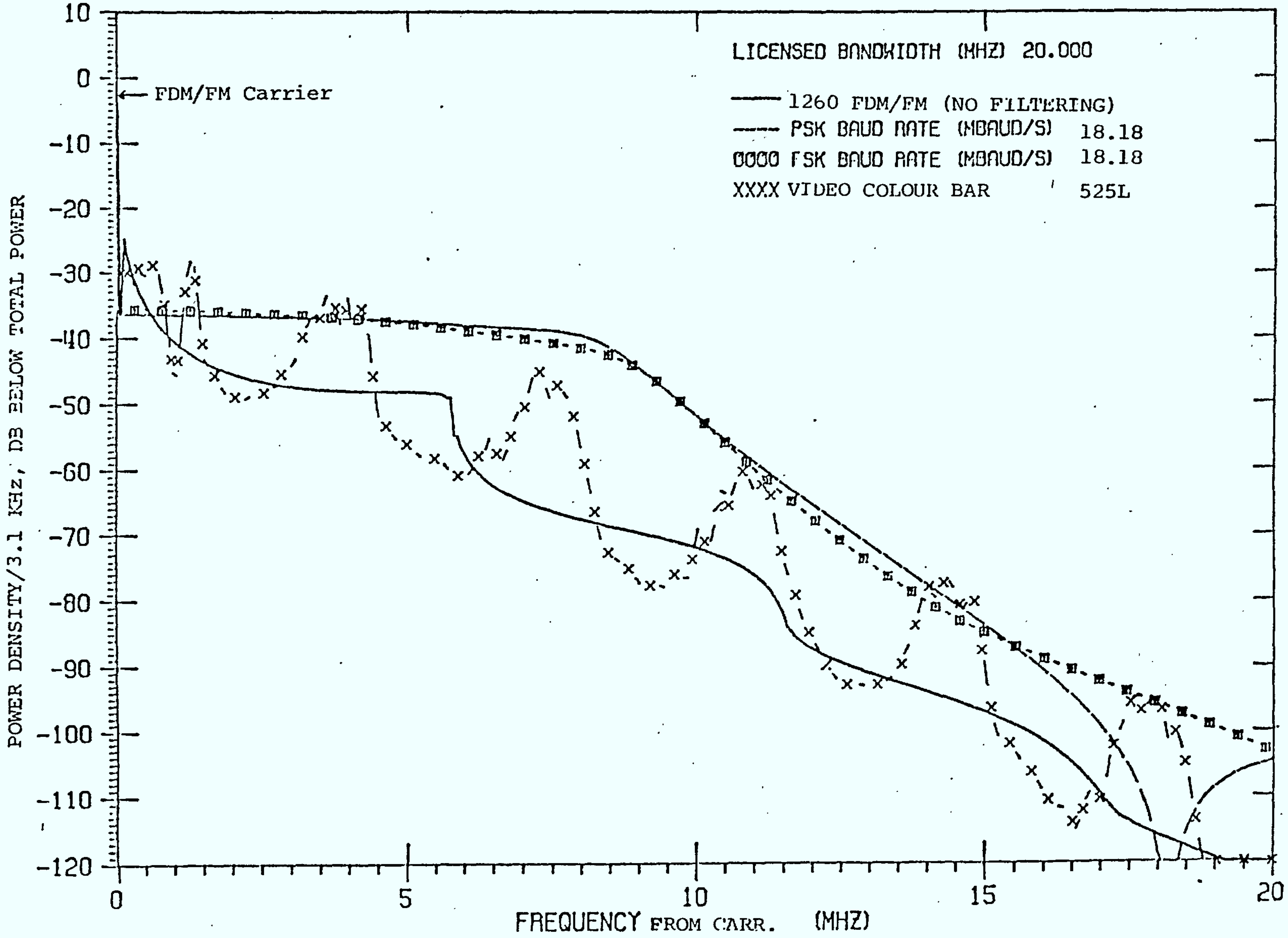


FIGURE
L-1

FM POWER SPECTRA

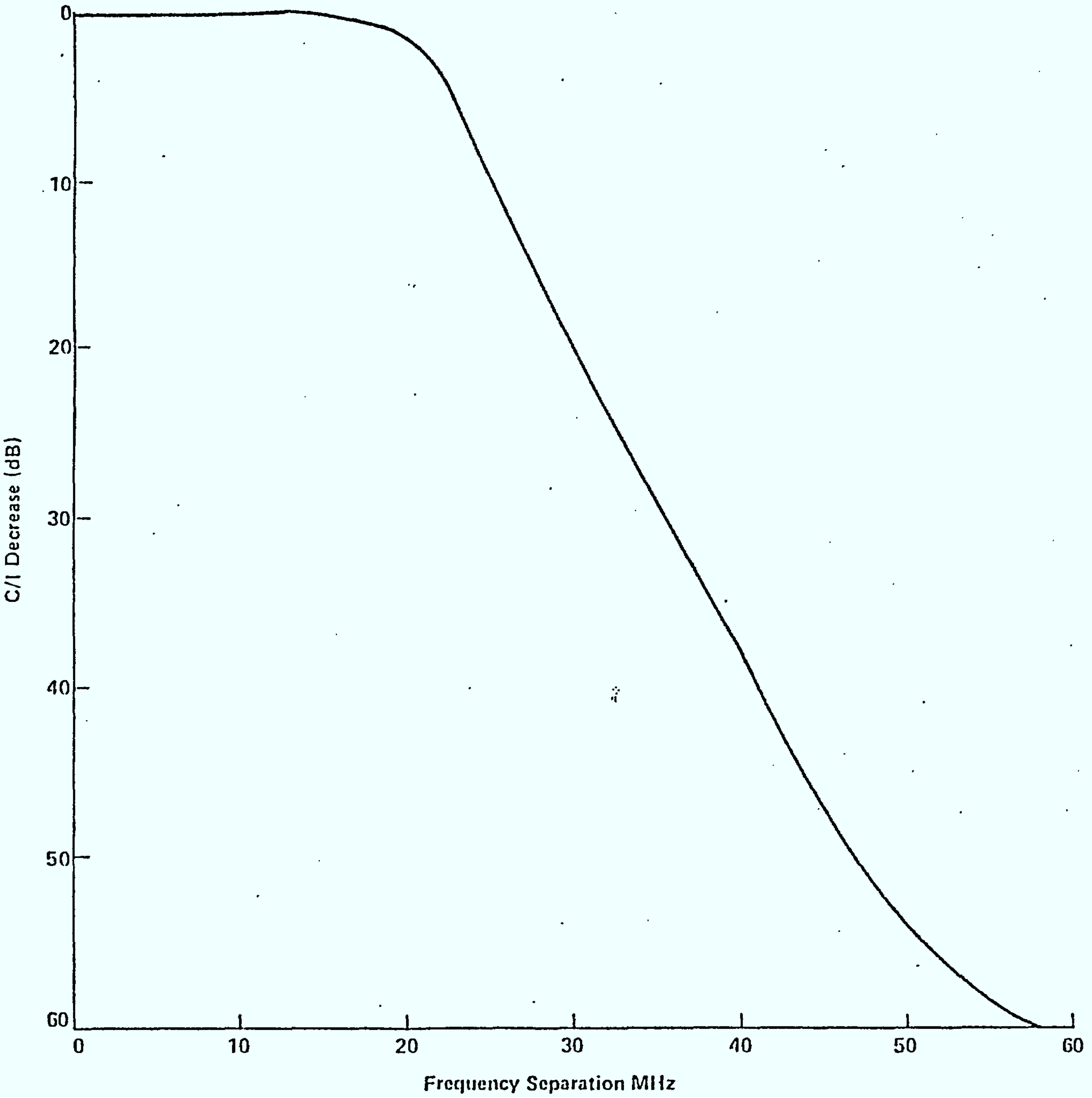


FIG 10: Reduction in C/I Requirement for Analog Into Digital Interference