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ANALOG FM/FM VS. DIGITAL COLOR TV TRANSMISSION ABOARD SPACE STATION

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Summary

Langley Research Center is developing an integrated fault tolerant network to support data, voice, and video communications aboard Space Station. The question of transmitting the video data via dedicated analog channels or converting it to the digital domain for consistency with the rest of the data is addressed. The recommendations in this paper are based on a comparison in the signal-to-noise ratio (SNR), the type of video processing required aboard Space Station, the applicability to Space Station, and how they integrate into the network.

Introduction

For Space Station rendezvous and proximity operations, a video image system will provide man with enhanced and augmented capability for man-in-the-loop manipulation and observations. As the Space Station matures, some of these operations will become nearly autonomous with man monitoring and a video system could be a supportive element for this autonomy trend. In addition, the Orbital Maneuvering Vehicle (OMV) has a remotely piloted vehicle (RPV) requirement implying potentially extensive video for viewing. Obviously, full motion and high fidelity video images are required to perform the above task.

Langley Research Center took on the task of developing a fault-tolerant integrated network for Space Station. The transmission of video data to and from points in the Space Station will be supported by the network. Typically, the output of video cameras is an analog signal. Hence, the transmission of these data can be accomplished via dedicated analog channels or by first converting the data to the digital domain before transmitting it over the network. That leads to a question to be resolved: Which method will be most beneficial? Although most data transmissions are accomplished in the digital domain, further analysis and trade off must be considered before the choice is made. This paper compares the FM and the PCM in terms of signal-to-noise ratio (SNR), their applicability to Space Station, which is most suited for the type of video processing needed aboard Space Station, and how they integrate to the rest of the network. Based on the above criteria, a recommendation is presented.

Bandwidth and Signal-to-Noise Ratio

First, the signal-to-noise ratio will be derived by using an ideal unrealizable communication system implied by the Shannon-Hartley law to establish a figure of merit. Then a comparison between the practical PCM and FM systems will be presented, particularly in the exchange of bandwidth (BW) for signal-to-noise ratio (SNR). Suppose we have a communication system (fig. 1) transmitting signal $X(t)$ bandlimited to f_x Hz. Further, suppose that the system is ideal, the channel bandwidth is B_T, and the noise power spectral density is $\eta/2$. Also, let us assume that the average signal power at the receiver is S_r and that the desired value of the output SNR is $(S/N)_d$. The channel capacity of such a system is given by Shannon-Hartley law as

$$C = B_T \log_2[1 + (S/N)_r] \tag{1}$$

where $(S/N)_r$ is the SNR at the receiver input. At the receiver output, the information rate can be no greater than R_{max}, where

$$R_{max} \geq f_x \log_2[1 + (S/N)_d] \tag{2}$$

An optimum or ideal system is defined as one that is operating at its capacity, with maximum output rate that is

$$R_{max} = C$$

or $B_T \log_2[1 + (S/N)_r] = f_x \log_2[1 + (S/N)_d]$

solving for $(S/N)_d$ we have

$$(S/N)_d = [1 + (S/N)_r]^{B_T/f_x} - 1$$

$$\approx [1 + (S/N)_r)]^{B_T/f_x} \qquad (3)$$

when the SNR is large. In eq. (3) the input SNR $(S/N)_r$ is given by

$$(S/N)_r = \frac{Sr}{\eta B_T} \qquad (4)$$

The ratio of B_{T/f_x} is called the bandwidth expansion ratio (or BW compression ratio if the ratio is less than one).

Let $H = B_{T/f_x}$

and $\alpha = \dfrac{Sr}{\eta f_x}$

then eq. (3) can be rewritten as

$$(S/N)_d = [1 + \frac{\alpha}{H}]^H - 1 \approx \left(\frac{\alpha}{B}\right)^H \tag{5}$$

if the SNR is large.

Eq. (5) shows that, in an ideal system, the SNR at the output and the bandwidth are exponentially related. This means that doubling the transmission BW of an ideal system squares the output SNR. Alternately, since $\alpha = Sr/\eta f_x$ is proportional to the transmitted power S_T, the transmitted power can be reduced to the square root of its original value without reducing $(S/N)_d$ by increasing the bandwidth by a factor of 2.

The primary goal of the ideal system is to achieve reliable information transfer in the context of an information theoretic approach. In analog systems it is very difficult to assess the information rate. The primary concern in such applications might be SNR, threshold power, and BW requirement rather than channel capacity and its utilization. In fig. (1), if we assume that the system is operating with large SNR, the FM and PCM schemes are above threshold, and the message signal is normalized to $E[X^2(t)] = E[X^2(t)] = 1/2$; then

$$(S/N)_d = 3\left(\frac{f_\Delta}{f_x}\right)^2 S_x\left(\frac{S_r}{\eta f_x}\right) \tag{6}$$

where (f_Δ/f_x) is the deviation ratio

and S_x is the power of $X(t)$

The PCM SNR at the receiver output is given by

$$(S/N)_d = \frac{2^{2N}}{1+4Pe2^{2N}} \tag{7}$$

where N is the word length

and P_e is the probability of a bit error.

Equation 7 is valid for all values of input signal-to-noise ratio. However, notice when P_e gets very small, i.e., the detection threshold is reached, the value $1+4\ P_e\ 2^{2N}$ tends to 1 and

$$(S/N)_d = 2^{2N} \tag{8}$$

One can conclude from eq. 8 that increase in the input power above threshold level yields no improvement in the value of $(S/N)_d$.

The performance of the PCM operating above threshold is limited by quantizing noise, and the SNR is given by

$$(S/N)_d = Q^2 \tag{9}$$

where Q is the number of quantizer levels.

Now if we assume a binary PCM, and if the sampling rate is $f_s = 2f_x$, then the transmission bandwidth B_T is given by

$$B_T = f_x \log_2 Q \tag{10}$$

Solving for Q we obtain

$$Q = 2^{(B_T/F_x)} = 2^H \tag{11}$$

For a PCM that is operating above threshold, the value of Q in eq. 9 can be substituted by the value of Q in eq. 11 and we have

$$(S/N)_d = 2^{2H} \tag{12}$$

Eq. (6) shows that the FM does not have an exponential power dependence, while the PCM does have an exponential power-bandwidth relationship.

In order to compare $(S/N)_d$ to $(S/N)_r = \alpha$ and compare α to H, we must derive an expression for α for the PCM. In order to derive the α for the PCM, the following assumptions are made: the noise has a Gaussian distribution; the $(S/N)_d$ needed to be produced = 50 dB; and a binary PCM is used. Hence, we need to derive the minimum $(S/N)_r = \alpha$ needed to produce $(S/N)_d = 50$ dB. To calculate the $(S/N)_r$ a threshold point must be defined. The point at which symbol error due to channel noise occurs with probability $P_e < 10^{-4}$ is chosen as the threshold.

For PCM, P_e is obtained by

$$P_e = G\left(\sqrt{\frac{3Sr}{\eta 3r_s}}\right) *$$

with $r_s = 2f_x \log_2 Q$

$$P_e = G\left(\frac{\sqrt{\alpha}}{\log_2 Q}\right)$$

then for $P_e < 10^{-4}$

or $$G\left(\sqrt{\frac{\alpha}{\log_2 Q}}\right) < 10^{-4}$$

*$G(Z_o)$ is the area under a normal Pdf.

if Z_o satisfies $G(Z_o) = 10^{-4}$ then we have

$$\alpha \geq (\log_2 q)\, Z_o^2$$

since $(S/N)_d = Q^2$

then for $(S/N)_d = 10^5$

we need $Q = 316$.

Knowing the value of Q we can compute H. Fig. (2) indicates that increasing the transmitted power for the PCM beyond threshold yields no further improvement in $(S/N)_d$ since the limiting value of $(S/N)_d$ is determined by quantization. Fig. (3) indicates that the power-bandwidth exchanges in PCM is considerably better than the FM. The PCM system requires about 6 dB more power than the ideal system. In summary, we can say that FM and PCM offer wideband noise reduction and PCM is better than FM at low input SNR. In addition, the exchange of bandwidth for power is easier to accomplish in PCM as has been shown. Since PCM can be easily time scaled, time can also be exchanged for signal power. Thus, the communications system designer has added flexibility to meet a given performance criteria.

Suitability for Image Processing

The following candidate image processing functions may be required of the video system aboard the Space Station: Smoothing, enhancement, restoration and filtering, data compression, feature extrapolation detection and identification, interpolation/extrapolation, spectral estimation, spectral factorization, and synthesis.

These capabilities are much easier done in the digital domain than in the analog domain in terms of computation, speed, and hardware complexity. The reasons for the above is the availability of integrated circuits that are more reliable and stable than the analog circuits. In addition, in the analog domain a circuit that does a particular function does not lend itself to doing another function unless the computations are quite similar to each other, while in the digital domain the flexibility is a lot greater than the analog. In other words, in order to do the previously mentioned processing in the analog domain, we might end up with a dedicated circuit for each function. In addition, it is easy to store and time scale PCM signals. Digital memories can accomplish storage and retrieving a lot more efficiently than analog. PCM signals can be time-dimension multiplexed a lot easier than analog. With PCM systems, source coding and channel coding can be used to reduce the redundancy in messages and to reduce the effects of noise and interference.

Applicability to Space Station

One of the design considerations in the network is to use intelligent nodes, where the nodes make the routing decision in cooperation with other nodes. The connection among these nodes will be fiber optic buses. Hence, there will be constant conversion from electric to optic and vice versa at each node. That will result in a considerable amount of loss and the need to regenerate the signal. PCM signals can be completely regenerated at each repeater station if the repeater spacing is such that the magnitude of the noise is less than 1/2 the separation between levels (with a high probability). With the exception of occasional errors, a noise and distortion free signal is transmitted at each repeater. Furthermore, the effect of noise does not accumulate and in designing repeaters one needs to be concerned only about the effects of channel noise and signal loss between repeater stations. Repeaters for analog modulation schemes consist of amplifiers that raise the signal level at each transmitting station. While raising the signal level, the amplifier also raises the level of the noise. However, the above issue might not be of great importance, since utilizing FM means a dedicated video channel where the loss and noise might not be of considerable magnitude. Some might argue that FM is more applicable to Space Station since the complexity of a PCM system is greater than that required for the FM. However, the complexity varies little as the number of channels is increased. Hence, PCM can compare quite favorable when the number of channels is large, which might be the case in Space Station.

Integrability to the Network

Since all other components on the network require a digital communication channel, the use of FM will require separate analog channels. In that case, if the video data are to be used in any other purpose other than display, the data must be converted into the digital domain. Using the PCM does not mean that it eliminates the choice of having separate video channels. It will add the flexibility of either using dedicated channels or integrating the video channels with the rest of the network.

Concluding Remarks

It has been shown that the PCM has a better flexibility in power bandwidth trade-off, is better in image processing and is integrable to the network. Therefore, it is obvious that the PCM will be a more beneficial scheme to use in transmitting the video data. The only exception where the FM will be a better choice is in case the video data will not require any processing and only be used in display.

References

1) Shanmugan, K. S.: "Digital and Analog Communication Systems," Published by John Wiley and Sons, 1979.

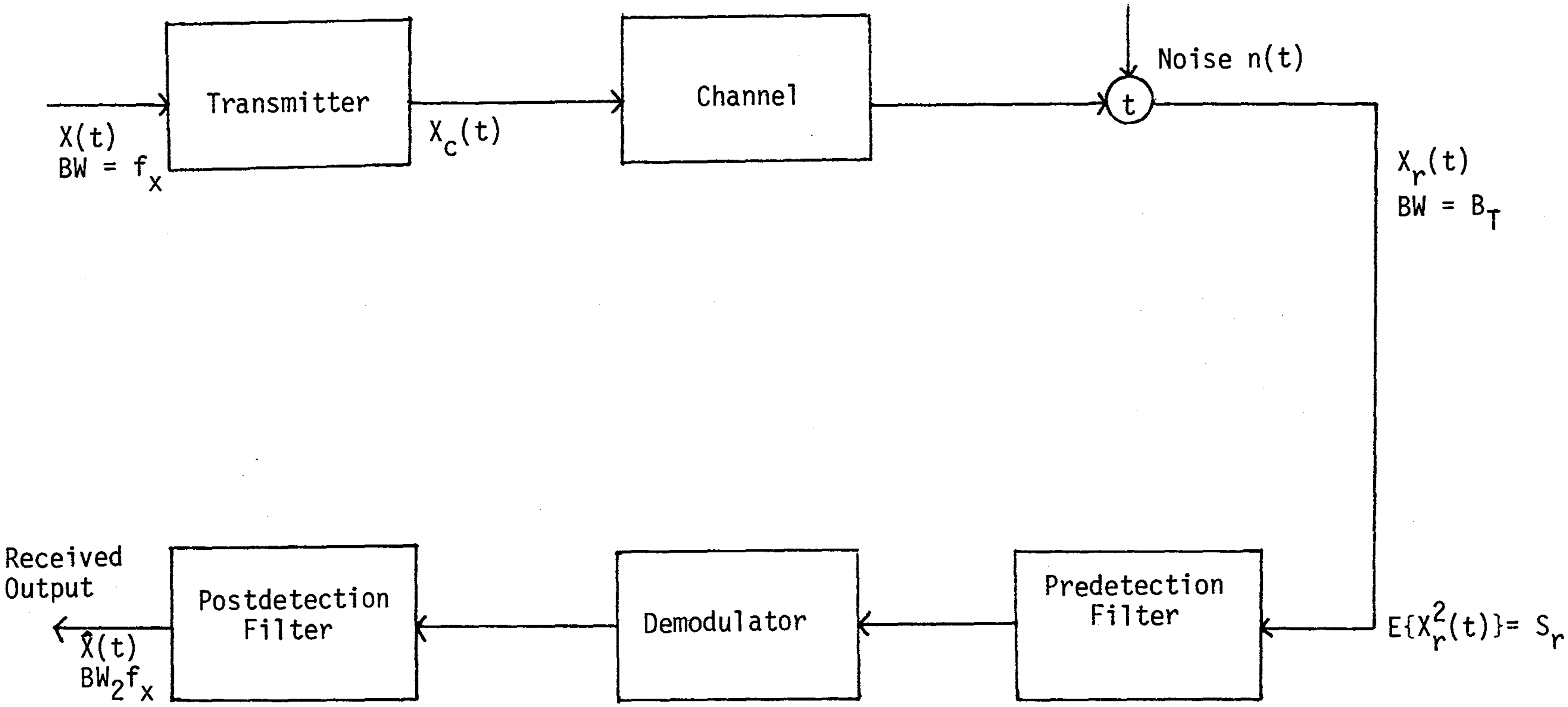

Fig. 1- Block diagram of a communication system.

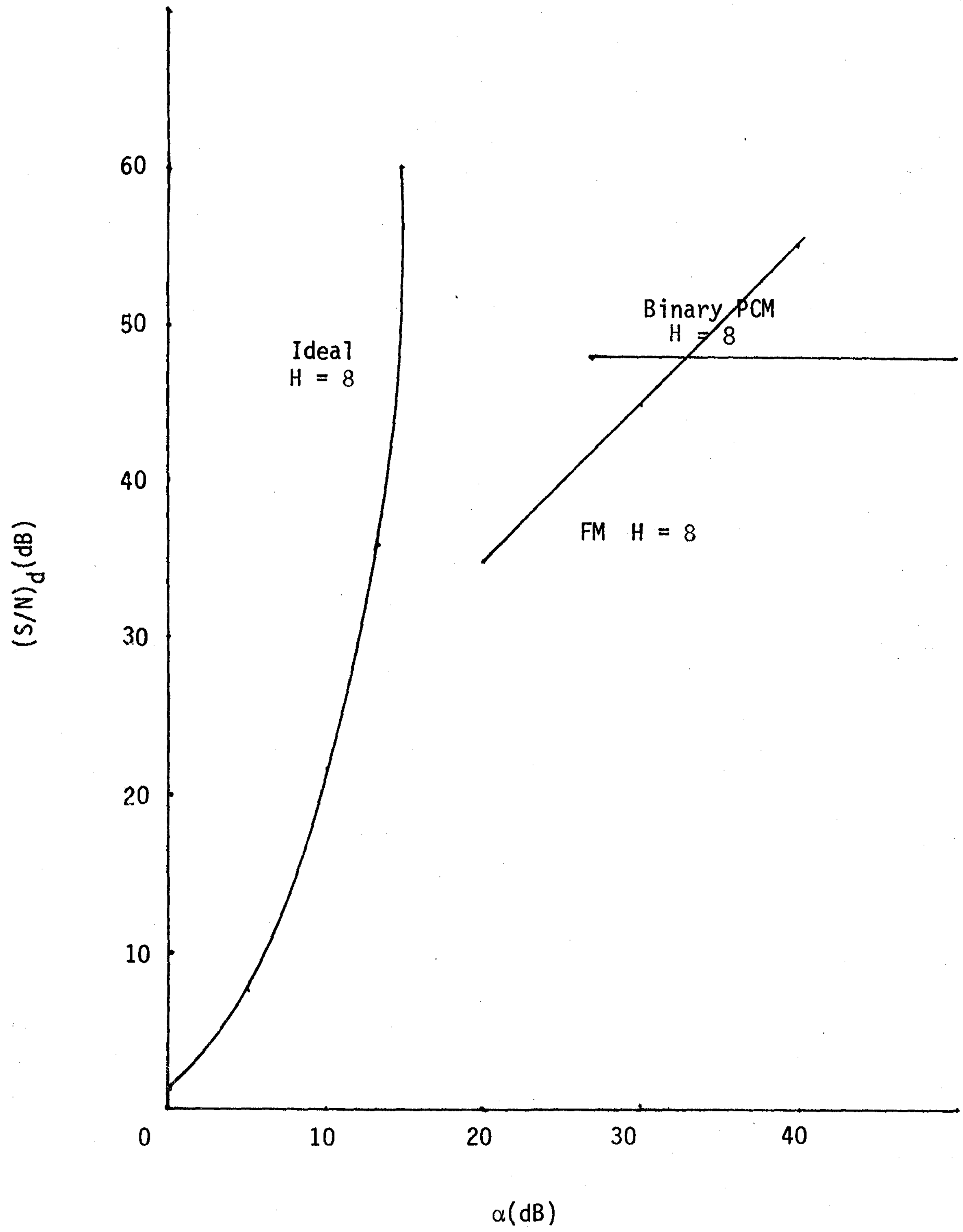

Fig. 2- SNR in Communication System vs $\alpha = (S/N)_r$ and H = 8.

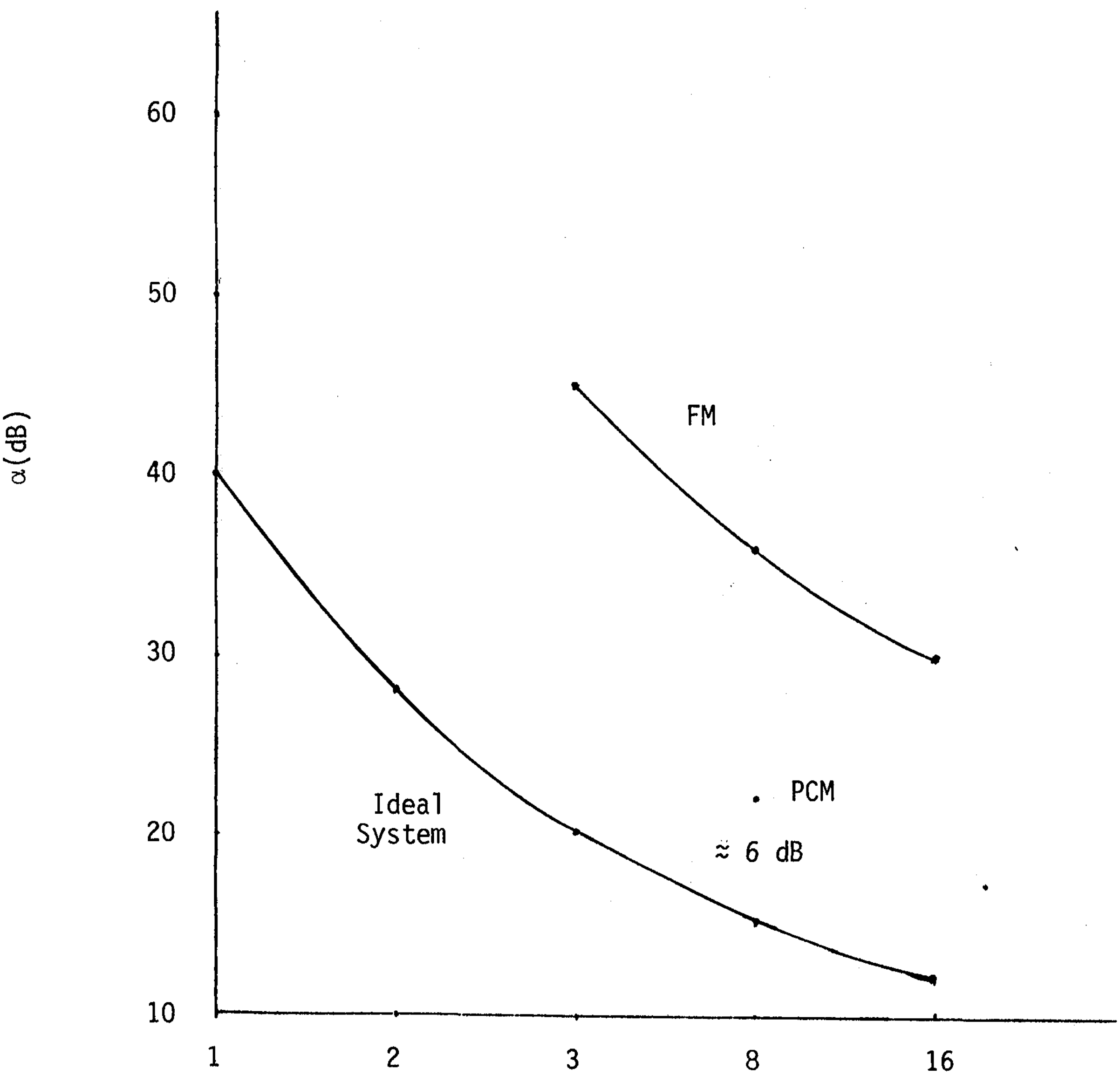

Fig. 3- α vs H With $(S/N)_d$ = 50(dB)

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