CHAPTER 3

LOS SYSTEM NOISE CONSIDERATIONS

The performance of a multichannel microwave communication system should be evaluated by how well it meets the requirements of the user. Fundamentally, the purpose of a communications system is to transfer some form of intelligence, or "signal," from one point to another. An ideal system would deliver at the receiving end a signal identical in every detail to the signal applied at the transmitting end, with nothing altered and nothing added.

In a real communications system, this ideal performance is never completely achieved. In such a system every characteristic of the signal is altered to some degree, and there is always something added along the way. Thus, the received signal is always a somewhat less than faithful reproduction of the signal applied at the transmitting end, plus some other elements which are mostly unrelated to the original signal and which may be present even when the signal is completely absent.

Communications system performance is measured by how closely the received signal resembles the transmitted signal and how free it is of these other elements. The definition and measurement of the performance thus falls into two natural categories. In the first category would be considered technical characteristics which define accuracy or fidelity of the reproduced signal: amplitude-frequency response, level stability, phase response, delay distortion, etc. These characteristics are, more or less, under the control of the equipment designer and may be held to almost any desired value.

In the second category would be considered all the extraneous elements appearing at the channel output, not a part of the input signal. These elements are usually lumped together in a single category called "noise." The following material treats noise in terms of its appearance in the derived voice channels. Noise in a voice channel has been selected as a criterion even though most systems carry telegraph and data as well as voice.

The basic voice channel is familiar to all, is reasonably well standardized, and there is a large body of experience to draw on. Furthermore, the majority of equipments used for modern telegraph and data service are designed to operate over such a carrier-derived voice channel, or some fraction or multiple of it. It is not difficult to evaluate the effect on a data system of a particular level of noise in the 4 kHz band.

3.1 UNITS AND OBJECTIVES

Measurement of noise is an effort to characterize a complex signal. To specify the amplitudes of noise, it is convenient to define it at some reference point in the system.

Amplitudes at any other physical location can be related to this reference point if the loss or gain between them is known. Up to now, channel noise has been considered in terms of signal-to-noise (S/N) ratio, expressed in dB, with the "signal" understood to be a 1 kHz test tone with 0 dBm power at a 0 transmission level point, with noise being the unweighted noise in a 3 kHz bandwidth. The "signal" in S/N ratio really means "standard signal" taken as the test tone level.

Conceptually, S/N ratio is the significant end result and it is considerably more convenient for purposes of calculation to have the channel noise expressed in an absolute form. One such way is in terms of a unit identified as dBa, F1A-weighted. This reference level, or 0 dBa, is equivalent to a 1 kHz tone with a power of -85 dBm or of a 3 Hz white noise band with a power of -82 dBm.

A second way of expressing noise, developed by CCITT and CCIR, is in terms of picowatts psophometrically weighted (pwp). The reference level, 1 pwp, is the equivalent of an 800 Hz tone with a power of -90 dBm, a 1 kHz tone with a power of -91 dBm, or a 3 kHz band of white noise with a power of about -88 dBm. The shapes of the F1A weighting curve and the psophometric curve are essentially identical (see figure 3-1).

Using the following equation, dBa can be converted to picowatts, or vice versa:

$$\text{dBa} = -6 + 10 \log_{10} \text{pwp} \tag{3-1}$$

Since dBa and picowatt are both absolute units, it is necessary to relate them to some specific transmission level before they have real significance. One common way to do this is to add a zero to the unit to indicate that it is referred to as a zero transmission level point. The resulting units, written as dBa0 and pwp0, can be converted to S/N ratios identified by the formulas:

$$\text{S/N} = 82 - \text{dBa0} \tag{3-2}$$

$$\text{S/N} = 88 - 10 \log_{10} \text{pwp0} \tag{3-3}$$

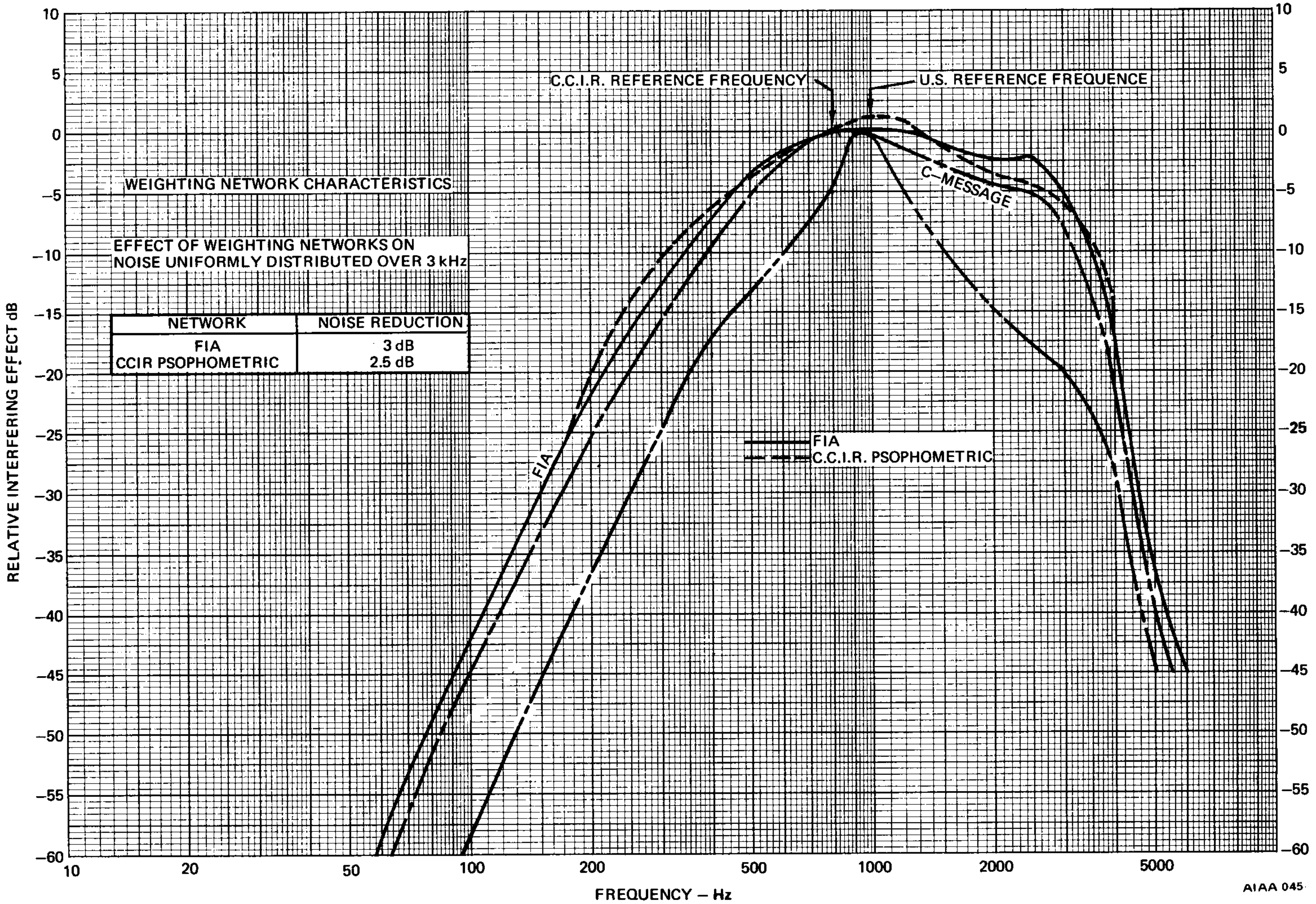
These relations are correct only if the noise is essentially white noise. Noise produced in multichannel microwave systems is almost entirely of this type, so the correlations are valid for microwave noise. Table 3-1 correlates S/N ratio, dBa, and picowatts for noise which is essentially random (i.e., "white" noise, since only in this case is a summation on a power addition basis valid). Figures A-11 and A-12 in Appendix A gives dBa versus picowatts in graphical form.

The dBa and the psophometric picowatt are equally valid absolute noise units but differ somewhat in application, because one is logarithmic and the other linear. The linear unit, picowatt, has the advantage that addition of noise powers becomes a matter of simple arithmetical addition of the picowatts. Addition of powers expressed in logarithmic units, such as the dBa, is not quite so simple but can be done relatively easily by the use of figures A-11 and A-12 in Appendix A.

Table 3-1. Comparison of Noise Performance Units

S/N	dBa0	pw$_p$0	S/N	dBa0	pw$_p$0	S/N	dBa0	pw$_p$0
28	54	1,000,000	48	34	10,000	68	14	100.0
29	53	794,000	49	33	7,940	69	13	79.4
30	52	631,000	50	32	6,310	70	12	63.1
31	51	502,000	51	31	5,020	71	11	50.2
32	50	398,000	52	30	3,980	72	10	39.8
33	49	316,000	53	29	3,160	73	9	31.6
34	48	252,000	54	28	2,520	74	8	25.2
35	47	200,000	55	27	2,000	75	7	20.0
36	46	159,000	56	26	1,590	76	6	15.9
37	45	126,000	57	25	1,260	77	5	12.6
38	44	100,000	58	24	1,000	78	4	10.0
39	43	79,400	59	23	794	79	3	7.9
40	42	63,100	60	22	631	80	2	6.3
41	41	50,200	61	21	502	81	1	5.0
42	40	39,800	62	20	398	82	0	4.0
43	39	31,600	63	19	316	83	-1	3.0
44	38	25,200	64	18	252	84	-2	2.5
45	37	20,000	65	17	200	85	-3	2.0
46	36	15,900	66	16	159	86	-4	1.6
47	35	12,600	67	15	126	87	-5	1.3
48	34	10,000	68	14	100	88	-6	1.0

NOTE: Flat S/N ratio in a 3-kHz band; dBa0, F1A weighted; and psophometrically weighted picowatts.



NETWORK	NOISE REDUCTION
FIA	3 dB
CCIR PSOPHOMETRIC	2.5 dB

Figure 3-1. Weighting Network Characteristics

When only system-generated noise is considered with its measurement at the radio baseband output point, there is little difference whether weighting is used. For this noise, the effect of weighting is to reduce the noise by a fixed, known amount (3 dB for F1A weighting and about 2 dB for psophometric weighting). Using weighting changes the numerical value of a noise reading by that fixed amount. It is equivalent to changing the noise unit itself. A noise level giving a flat S/N ratio of 50 dB will give an F1A weighted ratio of 53 dB, but the noise quantity is the same.

When noise in the complete system and its measurement at the voice channel output is considered with all the multiplex equipment and drop equipment connected and functioning, weighting is far more significant. In this case there may be substantial amounts of noise which are not random. Much of this noise may be at very low or very high frequencies where the affect on measurements of noise power is far out of proportion to the affect on actual transmission quality. For this reason, telephone practice is to use weighted noise units.

To evaluate the affect of audio frequency noise on typical equipments when noise measurements are being made, weighting networks are used. In the case of FM, the weighting network is a 75-microsecond de-emphasize network. This is a simple rc network which starts to attenuate at about 400 Hz and has an attenuation of 17 dB at 15 kHz. For purposes of this discussion, the F1A weighting network and the CCITT weighting network apply. These networks are intended to simulate telephone set response. The networks are used only for noise measurements and are removed from the circuit when connections are made to the telephone network. The response of these networks are shown in figure 3-1. The weighting curve includes telephone frequency characteristics as well as the hearing of an average person. The remainder of the communication system is assumed to provide transmission which is essentially flat across the band of a voice channel. Significance of the weighting curves of figure 3-1 is that, for example, a 200 Hz tone of a given power is 20 dB less disturbing than a 1 kHz tone of the same power, Note how noise at the band edges affects unweighted measurements out of proportion to its actual interfering affect.

Even though weighting is based strictly on voice transmission, it is quite possible that for data transmission systems designed to operate over a voice channel, a weighted measurement may be as good a criterion as an unweighted one or perhaps even better. Because of phase effects near the band edges, such data circuits are usually located in the interior part of the band. This is an area where the weighting characteristic introduces the least change.

3.2 NOISE SOURCES

Noise which appears in a microwave system voice channel comes from a number of different sources, some of which vary in a rather complex manner. It is useful to consider three general types of noise classified in accordance with how they vary.

3.2.1 Thermal Noise

This is noise generated by the receiver "input termination" plus noise generated in the receiver "front end." In a microwave receiver, "input termination" is an antenna coupled to the atmosphere and "front end" noise is essentially that noise internal to the first active devices of the receiver. In an FM system, thermal noise varies in an inverse relation to the RF level at the receiver input and, therefore, is affected by fading. It is not affected by system loading; however, it sets the minimum level to which signals can be allowed to fall.

3.2.2 Intrinsic or Idle Noise

This noise, also thermal in nature, is generated by random current variations in the radio equipment and is present whether or not a modulating signal is being applied. Typical intrinsic noise sources would be thermal noise generated within low level amplifiers and mixer rectifiers, shot noise in tubes, noises in semiconductor multipliers, traveling wave tube (TWT) noise, and FM residual noise.

Figure 3-2 illustrates an oscillograph recording connected to a wideband intrinsic (thermal) noise source. Three general observations can be made about such a waveform.

a. Waveform Repetition. The waveform never repeats itself exactly during any period, therefore, it is nonperiodic.

b. Waveform Time Interval. Measuring the time interval between the various zero crossings and converting this data into frequency indicates that frequency components in the wave occur equally or are of equal magnitude across the noise source bandwidth. This result is in accordance with kinetic theory of heat predictions (the thermal noise source power spectrum is flat with frequency).

c. Waveform Amplitude. Peaks of various heights occur and if measurements are taken over a long enough period, all magnitudes can be recorded. This indicates that the thermal noise signal has no unique peak. If distribution of the various signal magnitudes were computed, results would indicate a normal or gaussian distribution is approached. This conclusion is not unreasonable when considering the physical mechanism of the noise generation process. The noise signal appearing across conductor terminals is due to a sum of a large number of current pulses caused by random flights of electrons between collisions with the conductor molecules. The statistical central limit theorum states that the distribution approached by the sum of a large number of individual independent random components is a normal or gaussian distribution. Hence, magnitudes occurring in the noise signal have such a distribution. Because of this, thermal noise is also referred to as gaussian noise. The probability density function of a normal distribution is shown in figure 3-3 and its equation is:

$$\text{prob}\,(e_n) = \frac{1}{\sigma_n \sqrt{2\pi}} \exp\left(\frac{-e_n^2}{2\sigma_n^2}\right) \qquad (3\text{-}4)$$

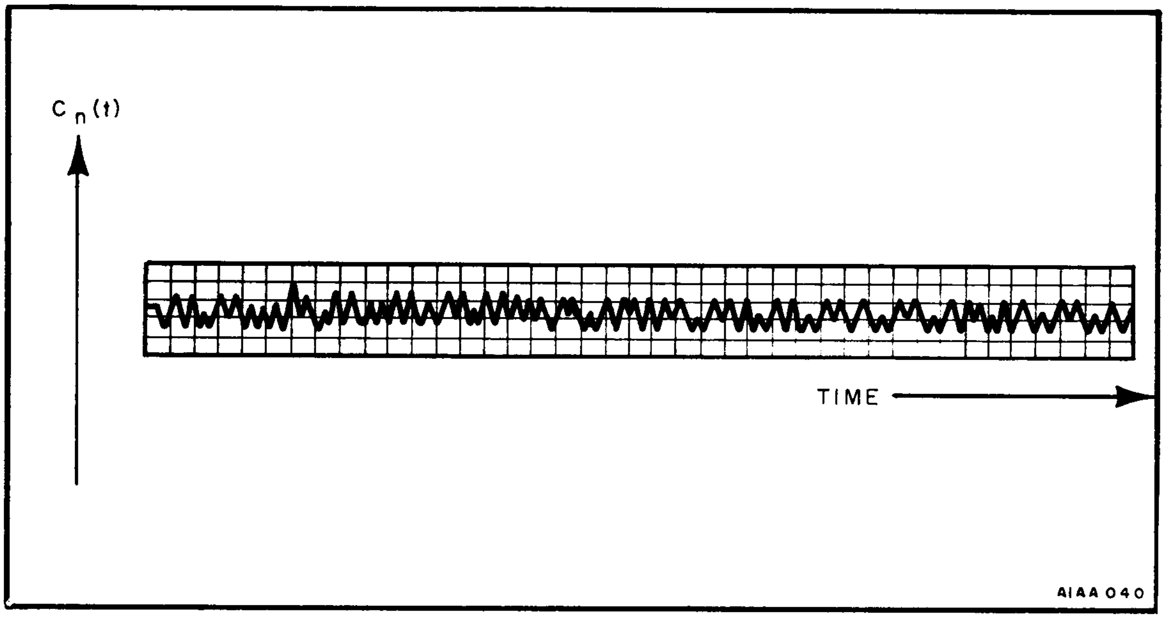


Figure 3-2. Oscillograph Recording of Wideband Thermal Noise

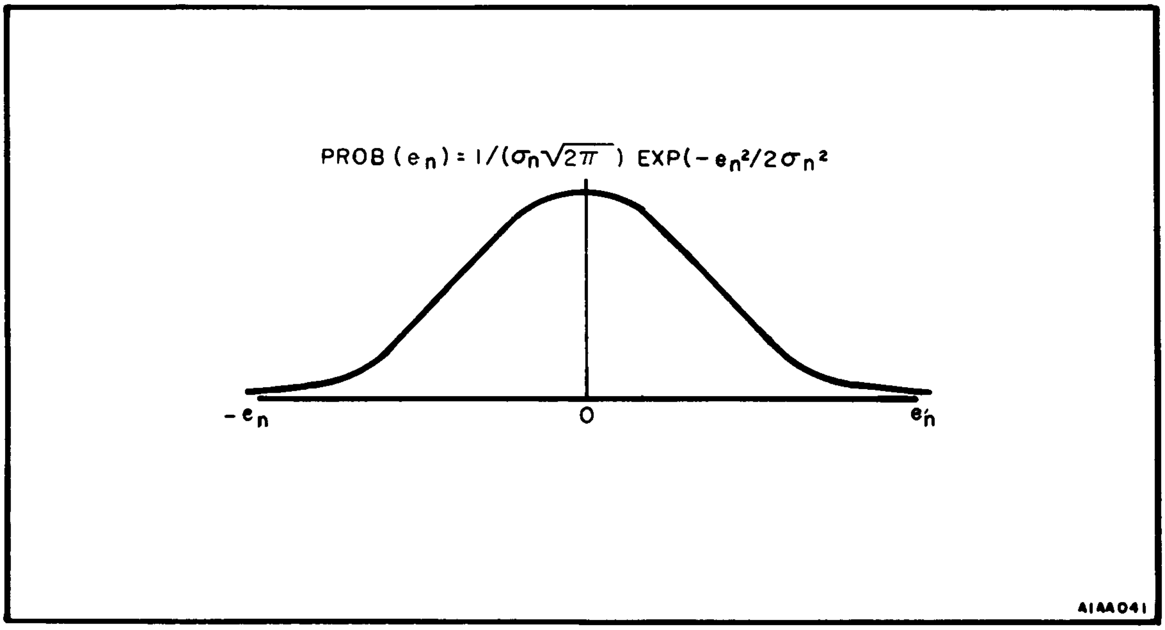


Figure 3-3. Gaussian Probability Density Function Distribution

The term σ_n is not only the standard deviation of the probability distribution described, but also the RMS magnitude of thermal noise signal having that distribution of signal magnitudes.

The amount of intrinsic noise generated is a characteristic of radio equipment that can be measured between terminals under conditions of no modulating signal and adequate received signal strength. It is not affected by the RF input level or system loading.

3.2.3 Intermodulation Noise

This noise is actually spurious signals created by intermodulation between the various frequency components of the total composite signal. Noise due to intermodulation products are generated by any nonlinearity in the receiver, transmitter terminal equipment, or transmission media. This nonlinearity will generate spurious frequencies in the receiver passband. The RF input stage, modulator, and detector in wideband FM systems always have some nonlinearity and tend to produce intermodulation products. If two or more RF carriers are put through a nonlinear element, typical resultant intermodulation products are shown in figure 3-4. Intermodulation product levels are determined by RF carrier levels and the degree of unit nonlinearity processing the signal. Since a multichannel system baseband spectrum is extraordinarily complex, the number of intermodulation products produced in such a system approaches infinity. Statistically this noise becomes very similar to intrinsic and thermal noise. Intermodulation noise increases as system loading increases, but it is not directly affected by the RF input level. Figure 3-5 illustrates the balancing of idle and intermodulation noise.

3.3 DCS REFERENCE CIRCUIT NOISE PARAMETERS

DCS Standards define performance requirements for the total communications system by transfer function parameters for the overall reference circuit. These overall parameters are distributed between two major subdivisions of the total system, i.e., transmission medium, and multiplex equipment. Consequently, when the transmission medium and multiplex equipment portions of the system are designed separately to measure up to performance characterisitcs defined by the respective parameters, the DCS Standards for the total system will be met.

The DCS Standards categorize noise sources in accordance with the two major subdivisions of the total system, identified in Table 3-2, and includes noise from all sources. However, noise from different sources is treated differently depending on its nature and magnitude. Transmitter and receiver noise is controlled by providing adequate signal levels. Radio and electrical interference must be discriminated against by equipment design which includes selective filtering, shielding, and directivity (in the case of antennas). Noise from the propagation path-atmospheric noise and path intermodulation noise (due to multipath signals) is relatively insignificant in line-of-sight radio propagation.

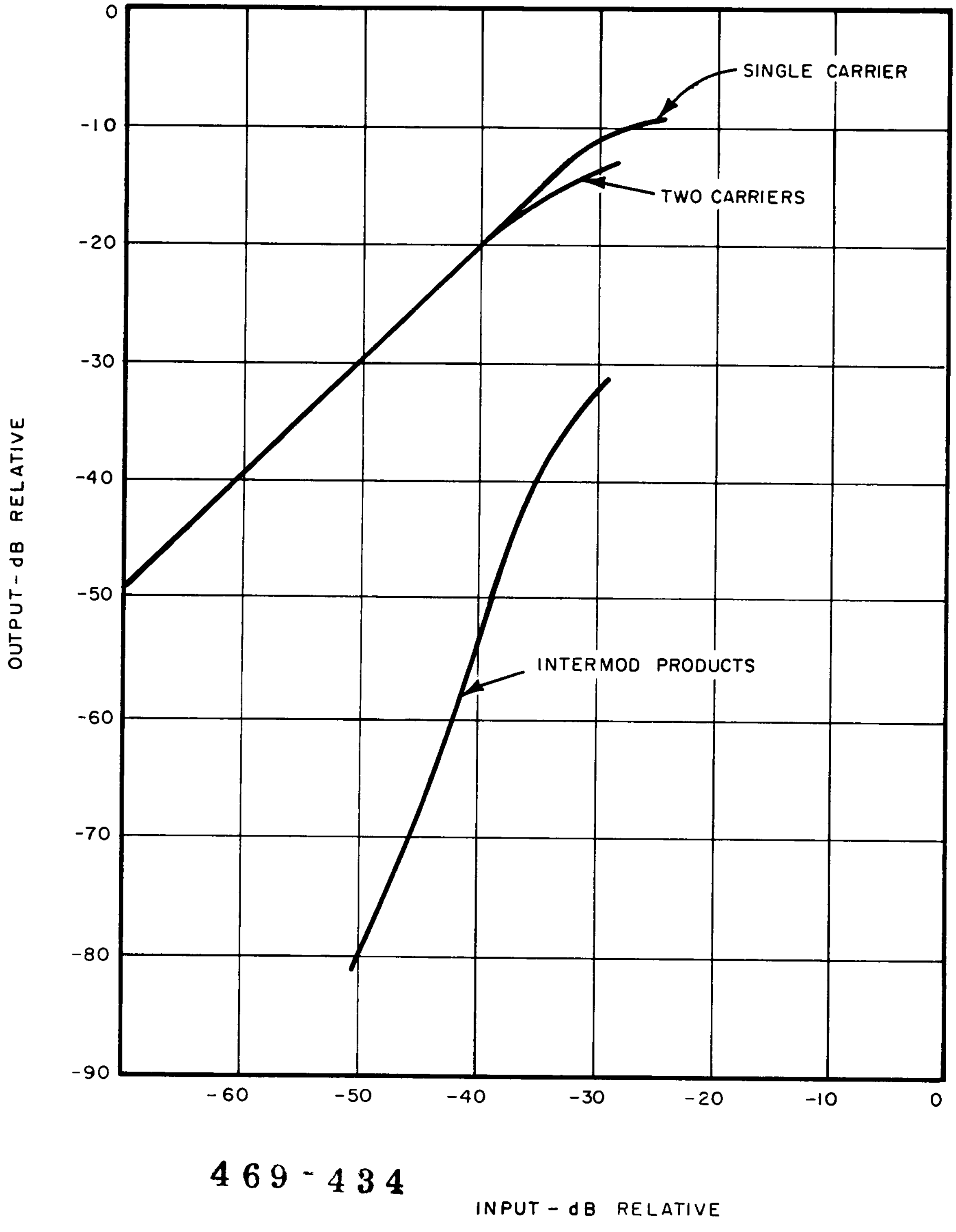


Figure 3-4. Typical Intermodulation Distortion Products - Third Order

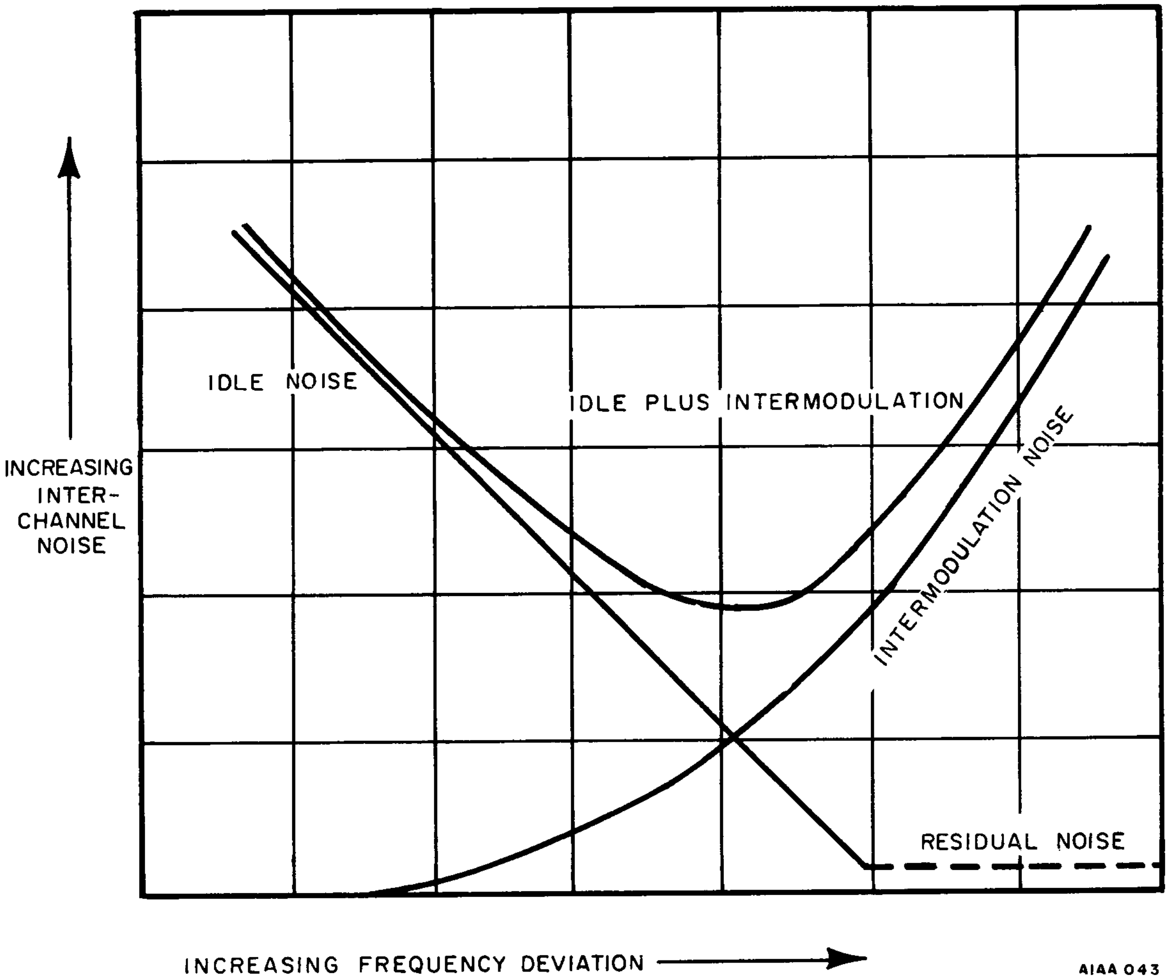


Figure 3-5. Per Channel Noise Versus Frequency Deviation

Table 3-2. Division of Noise Sources Used in Standards

CATEGORY	SOURCES
Transmission medium	Transmitters, receivers, propagation path, radio and electrical interference, feeder echo
Multiplex	Multiplex equipment

Basic noise allocation dictated by the DCS Standards is identified in Table 3-3. In addition to the basic allocations, the DCS Standards provide for prorating noise allowances on the basis of:

- o Transmission medium distance
- o Multiplexing stages for the multiplex equipment.

Table 3-3. Noise Allocations for DCS Reference Circuit

NOISE CATEGORY	MEDIAN NOISE ALLOCATION PER VOICE CHANNEL
Transmission medium	20,000 pwp* per 6,000 nautical miles
Multiplex equipment	5,000 pwp* distributed among all multiplex equipment
Total Noise	25,000 pwp*

*Picowatts psophometrically weighted (pwp) measured at, or referred to, a zero transmission level point.

3.3.1 Transmission Medium Noise

Transmission medium noise is allocated on the basis of circuit length. Thus, 20,000 pwp of noise power is allowed for the transmission medium of the overall reference circuit length of 6,000 nautical miles. Allowance for circuits of lesser length is obtained from the relationship:

$$\text{Noise (pwp)} = \frac{L\ (\text{NM})}{6,000} \times 20,000 = 3\ 1/3 \times L(\text{NM}) \qquad (3\text{-}5)$$

where L is the circuit length in nautical miles.

Converting to kilometers, the relationship becomes:

$$\text{Noise (pwp)} = 1.8 \times L' \quad \text{(km)} \tag{3-6}$$

where L' is the circuit length in kilometers.

The DCS Standards suggest a subdivision of transmission medium noise allowance into two equal parts for thermal and equipment intermodulation components, with provision that such subdivision be applied unless other tradeoffs are indicated. The intent is to attain the least total noise. Therefore, any proportionality between thermal and equipment intermodulation components which produces a smaller total noise than a balance of the two should be considered a suitable tradeoff.

3.3.2 Multiplex Equipment Noise

Multiplex equipment noise specifications in the DCS Standards are treated as follows:

- Total transfer function noise allocation for the 6,000 MM DCS Microwave (LOS) Reference Circuit.

- Total noise allocation for one Link of the Reference Circuit (Reference Link).

- Maximum noise allowance, at a specified loading per multiplexed channel, for each stage of Frequency Division Multiplex (FDM) equipment.

In the design of a LOS system, the transfer function noise specification is the fundamental criterion as it gives the total noise allowance for the Reference Circuit. Based on the overall circuit allowance, the noise allocation per Reference Link and per mile is determined. The DCS Standards noise performance per FDM multiplexed stage is for a channel loading level that exceeds the operating channel loading capabilities of real systems. Consequently, in most cases, the DCS Standards FDM equipment noise levels are not directly applicable to FDM system design. Additional information on the foregoing major subdivision of the total system is presented in the system design considerations.

3.4 NOISE PERFORMANCE

Each of the three kinds of noise identified earlier affects system operation in a different way, as shown in figure 3-6. This graph shows noise performance for one hop of a high quality microwave system. Note: This is a plot of typical worst per-channel noise as a function of receiver input level and system loading. Noise is shown at the left as unweighted S/N ratio in a 3 kHz voice channel, and at the right in dBa, F1A weighted, at a 0 transmission level point. The curve is typical for the top channel (in which noise is usually the greatest) of a 300 channel system. The effect of the receiver front-end noise on the channel S/N ratio is shown by the long line starting at the lower left-hand corner and running to the upper right-hand corner. It is evident that this noise is the controlling factor when the RF input is lower than about -40 dBm. Threshold noise is almost entirely of this type.

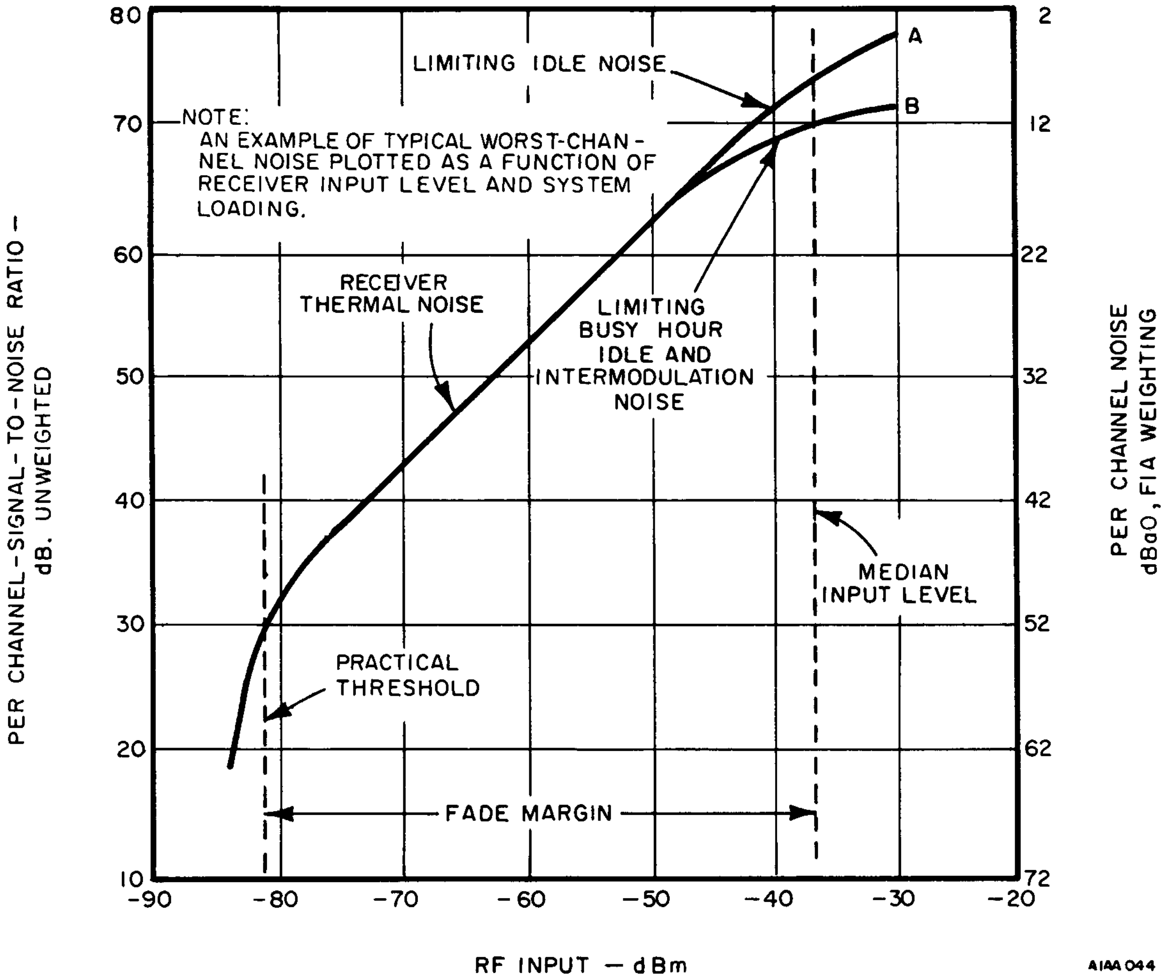


Figure 3-6. Noise Performance of One Hop of a High-Quality Microwave System

At high receiver input levels, idle noise becomes the controlling factor and limits the available S/N ratio as shown by the bend in the upper line at the upper right-hand corner. This noise sets an upper limit to the channel S/N ratio when the system is in an idle or unloaded condition.

The effect of intermodulation noise is shown by the lower branch line. This noise sets the limit to the channel S/N ratio when the system is loaded to simulate busy hour conditions.

A noise characteristic curve such as figure 3-6 assists understanding of microwave noise performance, since it includes, essentially, all of the noise effects shown for all operating conditions. Three significant bits of information derived from the curve are: noise level at the practical threshold point, noise level at the normal RF receiver input level point under busy hour loading conditions, and fade margin.

A microwave system meeting the requirements identified in figure 3-6 is usually engineered to have a median RF input level somewhere between -30 and -40 dBm. This level permits having a very high S/N ratio during periods of no fading or very little fading, a condition which exists for all but a very small percentage of the time. It also has a fade margin which permits the RF input level to drop by at least 40 dBm (about one ten-thousandth of normal) before the S/N ratio becomes objectionable.

With a typical median input level of about -37 dBm, as shown in figure 3-6, system S/N during non-fading periods will be very high. It approaches Curve A during periods of light loading and drops a few dB towards Curve B during heavy loading periods of the busy hour. Only after the input signal has faded several dB does the S/N ratio begin to drop significantly as receiver thermal noise begins to exceed the other noises. Over the straight line portion of the curve, the S/N ratio varies with the receiver input level. It is determined only by the receiver noise figure and the deviation ratio used for the particular channel. Over this curve portion, the unweighted S/N ratio in dB in the derived 3 kHz voice channel can be calculated from equation 3-7.

$$S/N\ (\mathrm{dB}) = C + 136 - NF + 20 \log D \qquad (3\text{-}7)$$

where:

C = receiver input level in dBm,

NF = receiver noise figure in dB,

D = deviation ratio, or peak deviation for the channel divided by the carrier frequency of the channel.

Signal-to-thermal noise ratio can be improved in three ways: increasing input level with higher transmitting power or bigger antennas, lowering receiver noise figure, or increasing the deviation ratio. In practice, system and equipment designers raise effective power and lower receiver noise as far as economically practicable. The effect of increasing the deviation ratio is not so simple. It improves the S/N ratio for thermal and idle noise, but degrades for intermodulation noise. For this reason, the equipment designer must choose a deviation ratio which provides an optimum balance between the different types of noise.

When the receiver input signal becomes very high, a point is reached where the signal-to-thermal-noise ratio is no longer directly dependent on the receiver input level. This effect is indicated by the bend in the upper right branch of the curve. Here, thermal noise produced in transmitter circuits and those portions of the receiver circuits not affected by automatic gain control (AGC) provides an upper S/N limit for non-loaded conditions. This portion of the curve, though of some interest, is not really operationally significant since the S/N ratio makes little difference if the system is not being used.

In this area of high receiver input level, the lower branch is the significant operational curve. This gives the signal-to-total-noise ratio since it includes thermal noise, idle noise, and intermodulation noise under loaded conditions.

3.5 MULTIPLEX NOISE

The noise performance curve of figure 3-6 applies only to one hop of a microwave system, and does not include the noise contribution of the associated multiplex equipment. The multiplex noise must be added to the microwave noise (or transmission medium noise) to get the system S/N ratio. Multiplex noise under loaded conditions is approximately 20 to 23 dBa0 for a pair of carrier terminals (refer to Table 1-1). This noise is considerably higher than the noise shown for the single microwave hop. For a one or two hop system, overall noise is mainly that of multiplex. For a long microwave system in which the multiplex noise appears only once and the per-hop microwave noise many times, the latter becomes the controlling factor.

Refer to DCS Reference Link, 1,000 NM (figure 1-5) for the following assumed multiplex noise assessment.

Multiplex equipment for translating from a given frequency to a higher one and back is assumed to have total noise as follows (one terminal):

- Channel translation, 345 pwp or 19.4 dBa0
- Group modem equipment, 70 pwp or 12.5 dBa0
- Supergroup modem equipment, 60 pwp or 11.8 dBa0
- Through group filter and AGC equipment, 50 pwp or 11.0 dBa0.

Total noise for one link (excluding group filter and AGC equipment) is 475 pwp (one terminal). Thus, a set of equipment for translating from audio to baseband and back to audio at each terminal of a link will have the following noise allowance (two terminals):

- Channel translation, 345 pwp
- Group modem equipment (2 at 70 pwp), 140 pwp
- Supergroup modem equipment (3 at 60 pwp), 180 pwp
- Through group filter and AGC equipment (3 at 50 pwp), 150 pwp.

Total noise for one link = 815 pwp (two terminals). Total for six links = 4890 pwp or 30.9 dBa0. This compares with the standard allocation of 5000 pwp for multiplex noise over the reference circuit.

The above summations on a power-addition basis result from multiplex noise being essentially intermodulation products composed primarily of even order harmonics which are fully incoherent even on tandem hops. This incoherency is furthered by random interconnection of telephone channels, groups, and supergroups at the junctions between the homogeneous reference circuit sections.

Multiplex or terminal equipment noise is primarily due to intermodulation products resulting from a number of causes, such as:

- Improper level setting for individual channels.
- Nonlinearity of terminal modulator/demodulator.
- Improper alignment or failure of baseband amplifiers.
- Any AFC malfunction which results in operation off the IF baseband center.
- Amplifier amplitude and phase nonlinearities.

In summary, multiplex noise results from either a nonlinearity or a malfunction having a nonlinear effect. The concept of amplifier nonlinearity (figure 3-7) by contrasting the transfer characteristics of an ideal and an actual amplifier. These nonlinearities tend to produce undesirable frequency components (intermodulation products). These spurious products include the sums and differences of each frequency and its harmonics present in the modulating signal, and all of the other frequencies and their harmonics. In a multichannel radio system, intermodulation products are so varied that they resemble white noise. Intermodulation products from individual channels increase the noise levels in all channels.

The remainder of multiplex noise can be attributed to intrinsic or idle noise. These noise sources are listed in table 3-4. However, with the exception of thermal noise, the contribution of these sources is negligible.

3.6 INTERFERENCE

Interference is divided into two major categories: intentional interference and unintentional interference, with the following definitions:

- Intentional interference is deliberate in nature and utilized to curtail reception of desired signals.
- Unintentional interference is generally created by lack of sufficient frequency spectrum between RF equipments, RF energy emission at other than assigned frequencies, reception of energy at other than the assigned frequency at the receiver.

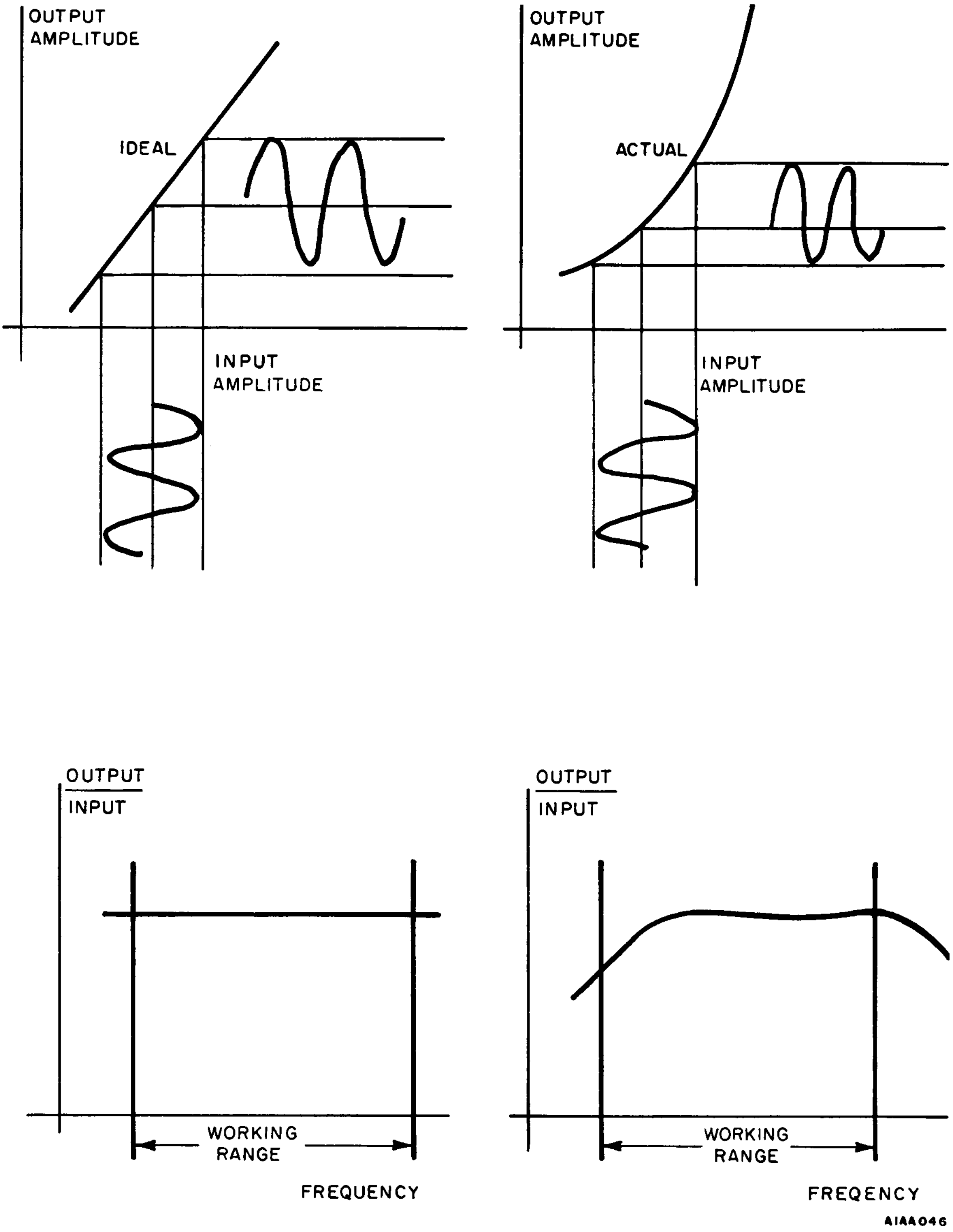


Figure 3-7. Nonlinearity in Amplifiers

Table 3-4. Multiplex-Intrinsic Noise Sources

TYPE	ORIGIN	CHARACTERISTICS	FOUND IN
Thermal	Random Thermal motion of carriers within conducting medium	White Gaussian amplitude distribution	All components
Shot	Random passage of carriers across discontinuity, such as semiconductor junction	White Gaussian amplitude distribution	Transistors, diodes, electron tubes
Excess	Produced by passage of current through semiconductor material	$1/f$ (i.e., noise power inversely proportional to frequency) Gaussian amplitude distribution	All semiconductor devices
Avalanche	Thought to be result of cascade (multiplying) of carriers in high voltage gradient which arrive at junction as bundles	White Gaussian amplitude distribution	Diodes, transistors, capacitors
Multistate	Mechanism unknown, is probably a surface phenomenon	No fixed relationship Non-Gaussian	Some diodes and transistors

Mutual interference between systems is the greatest source of radio frequency interference. In almost every case, this is identified as narrow band interference as compared to the broadband characteristics of non-system sources. This means that the interference is at a single frequency or only a very narrow portion of the spectrum. The number of system interference sources are relatively small, but the manner in which they combine provide a large number of mutual interference types.

Various types and sources of unintentional interference which may occur in a multichannel system are:

- Same channel (cochannel) interference.
- Image channel interference.

- Adjacent channel interference.
- Direct adjacent channel interference.
- Limiter transfer action.

3.6.1 Same Channel (Cochannel) Interference

The problem of same channel interference illustrated in figure 3-8 shows, in block form, four consecutive repeaters and five typical interference paths. Separate receiving and transmitting antennas are shown although some systems use only a single antenna. The two most serious potential interference paths are labeled "1" and "2". Here, transmitting antenna high-level signals interfere with receiving antenna low-level signals. When determining permissible interference levels, it is important to note that the receiving antenna signal level should be the signal level expected when the desired channel is experiencing the deepest allowable fade. The high-level signal is reduced by back-to-back ratios of path 2 antennas, but only the side-to-side loss between path 1 antennas attenuates the signal.

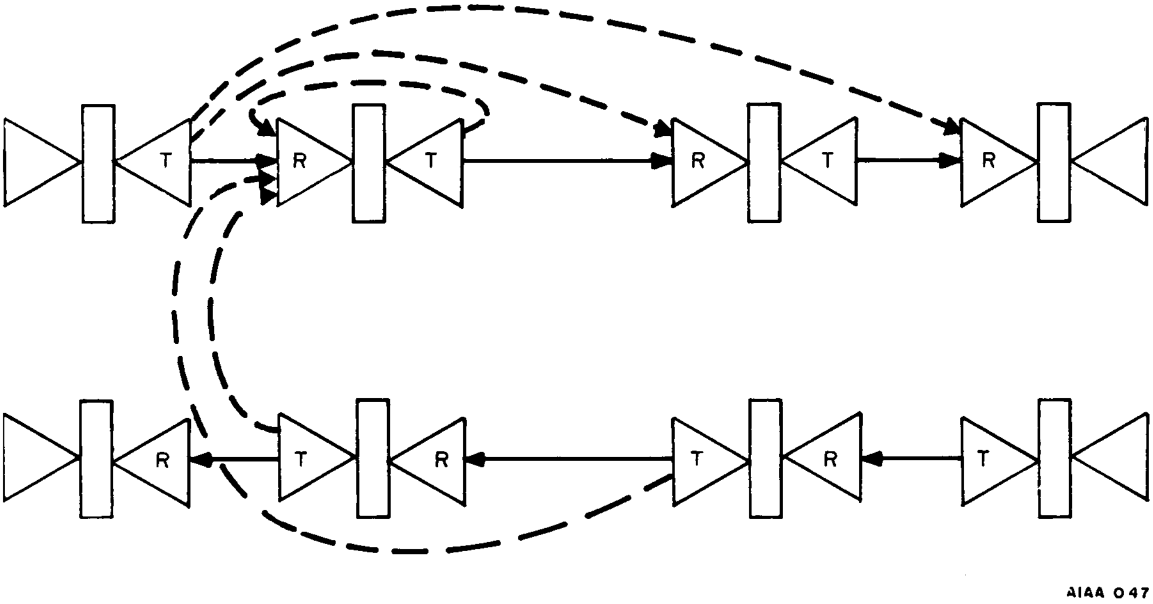


Figure 3-8. Same Channel Interference

In practice, the amount of loss is not adequate. Additional loss might be introduced if the desired signal is cross polarized with respect to the interfering signal, but this method is unreliable. This is due to the complex and unknown nature of the coupling path, particularly with respect to its influence on polarization direction. The problem of excessive coupling can be avoided by using different transmitting and receiving frequencies at a given repeater.

Another source of same channel interference is path 3 in figure 3-8. For this path, using a two-frequency allocation, two signals are received on the same frequency. Normally, the signal is about the same level at the receiving station. In this case, interference will be reduced by the front-to-back ratio of a single antenna which may be about 70 dB for a delay lens or horn reflector antenna but only about 40 to 50 dB for a parabolic antenna. Further advantage might be obtained by using orthogonal polarizations. As noted previously, this method is also unreliable.

Two other sources of same channel interference are identified by the paths 4 and 5 in figure 3-8. Path 4 type of interference presents no problem since frequency frogging is used in adjacent hops. Overreach interference, represented by path 5, is potentially troublesome but can be reduced to tolerable proportions by locating the transmission path in every thrid hop slightly out of line.

3.6.2 Image Channel Interference

Image channel interference is illustrated in figure 3-9. Two signals with carrier frequencies of 11,000 MHz are shown. These signals are separated with filters and applied to modulators for translation to 70 MHz intermediate frequency (IF). Assume a beat oscillator frequency of 11,070 MHz is used for the 11,000 MHz signal. If the filters are ideal, there will not be any problem. However, suppose rejection of the 11,140 MHz signal by filter 1 is inadequate, then, this signal would beat with the 11,070 MHz beat oscillator tone to give an unwanted 70 MHz IF interference. This is known as image channel interference, and is defined as the channel which differs in frequency from the beat frequency by the same amount as the desired channel, but is on the other side of the beat frequency.

One impractical way to avoid image channel interference is to leave the image channel empty. Alternatively, adequate filtering must be provided to prevent excessive interference even if a deep fade occurs on the desired channel. Cross polarization in adjacent channels is helpful here.

3.6.3 Adjacent Channel Interference

Adjacent channel interference occurs when two FM channels are placed close together in frequency so that the sidebands from one extend into the other. Figure 3-10 shows how this can happen by making use of the power spectral density of a carrier which has been phase-modulated by a baseband signal consisting of random noise. Interference can be prevented by removing the higher order sidebands with filters before the two signals are combined. However, this cannot be done without causing some signal distortion.

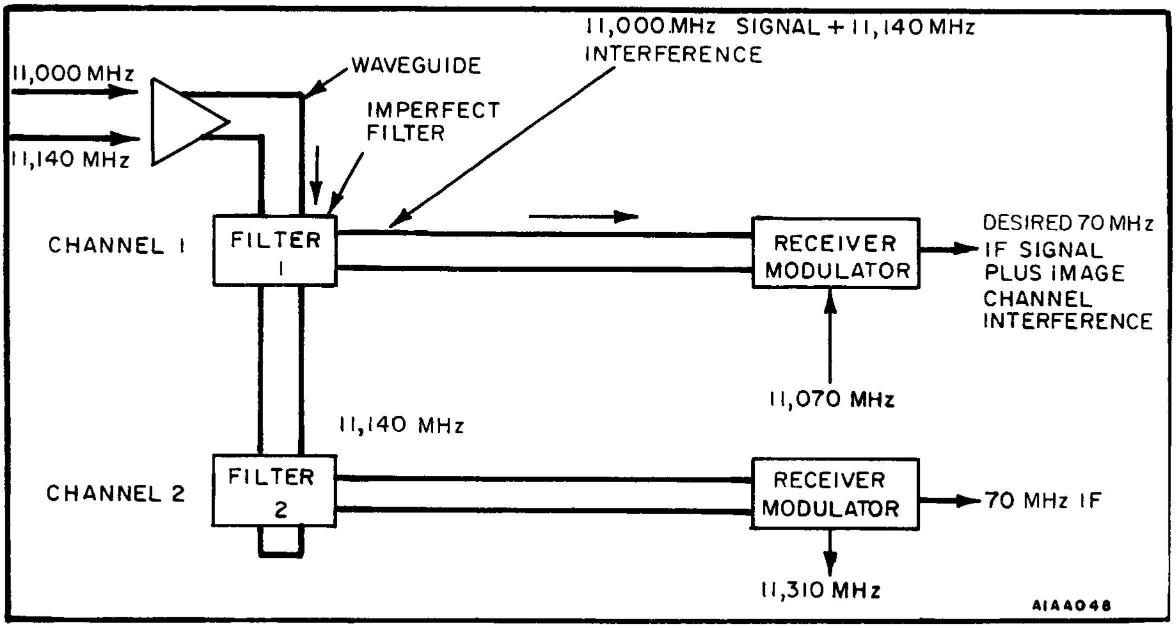


Figure 3-9. Image Channel Interference

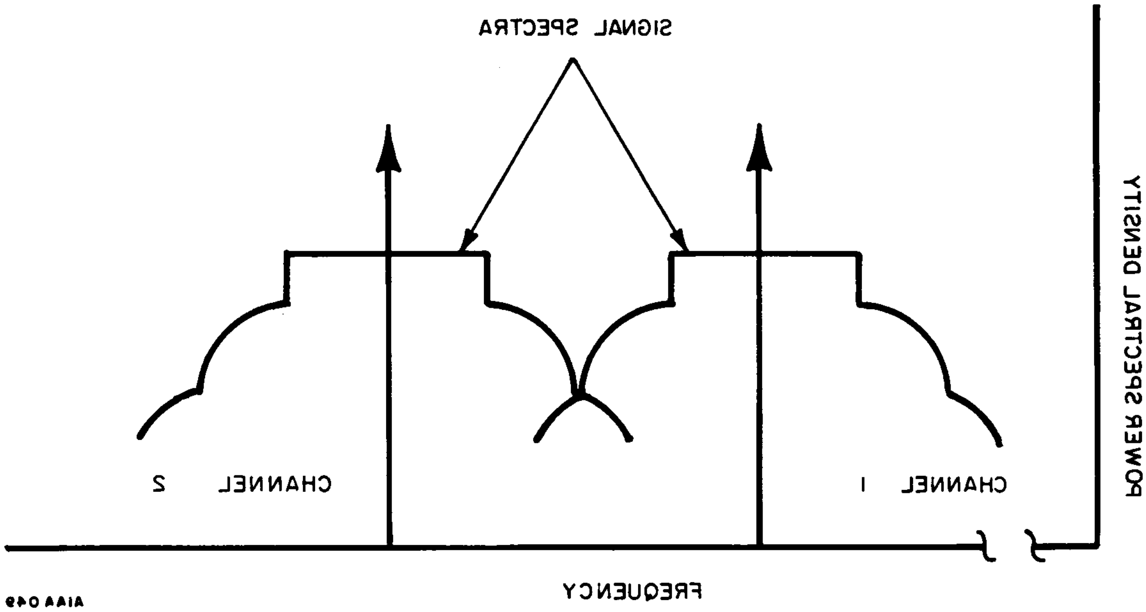


Figure 3-10. Adjacent Channel Interference

It is evident that channel spacing has an important influence on the problem of filtering overlapping sidebands. This fact has given rise to a rule which is sometimes used in the design of long-haul, heavy-route systems. The rule states that channel spacing should be at least three times the top baseband frequency. This ensures that second order sidebands from an interfering channel will not overlap first order sidebands in an adjacent channel. Applying this rule, generally leads to practically realizable channel filters.

3.6.4 Direct Adjacent Channel Interference

Interference due to overlapping sidebands will generally be garbled or unintelligible since the disturbing sidebands are inverted with respect to the disturbed carrier. In systems with very closely spaced channels, however, a more complicated form of adjacent channel interference has been noted in which the interference is intelligible. This type of interference, where the signal on the adjacent channel appears as an identical signal in the disturbed channel, is termed direct adjacent channel interference (DACI). The mechanism producing this type of interference, although not fully understood, is believed to involve phase to amplitude conversion of the interfering carrier and its sidebands in the selectivity "skirts" of the disturbed channel. This results in amplitude to phase conversion in the disturbed channel limiters or other nonlinear devices.

3.6.5 Limiter Transfer Action

Using limiters in the radio repeater may result in interference between channels and is often referred to as limiter transfer action. The basic mechanism of this interference is illustrated in figure 3-11. Three adjacent radio channels with carriers spaced 20 MHz are shown. Channel 2 is assumed to be cross-polarized with respect to channels 1 and 3. Assume that channel 1 is carrying a 7 MHz baseband tone with a sufficiently low index of modulation such that only first order sidebands need to be considered. At station A, channel 1 output will consist of a carrier and single frequency sidebands 7 MHz on each side of the carrier. At station B, channel 1 signal upper sideband appears as an interfering tone 13 MHz off center frequency in the channel 2 receiver. Amplitude of the tone reaching the channel 2 limiter depends on the cross-polarization discrimination between channels 1 and 2 on the station A to station B path, and the channel 2 receiver gain 13 MHz off center frequency. The channel 2 carrier and interfering tone represent a composite AM-PM signal at the limiter input. The AM component is removed by the limiter and the PM component remains. However, the limiter output has the carrier and sidebands, 13 MHz on each side of the carrier. This signal is transmitted by channel 2 at station B. At station C, channel 2 signal upper sideband appears as an interfering tone, 7 MHz off center frequency in the channel 3 receiver. Amplitude of this tone depends on cross-polarization discrimination between channels 2 and 3 on the station B to station C path, and the loss of the channel 2 radio transmitter 13 MHz off center frequency. Thus, a baseband signal in one channel may appear as interference at the same baseband frequency in another channel. In addition, the channel 2 lower sideband can couple back to the channel 1 receiver at station C. In either case, an analysis

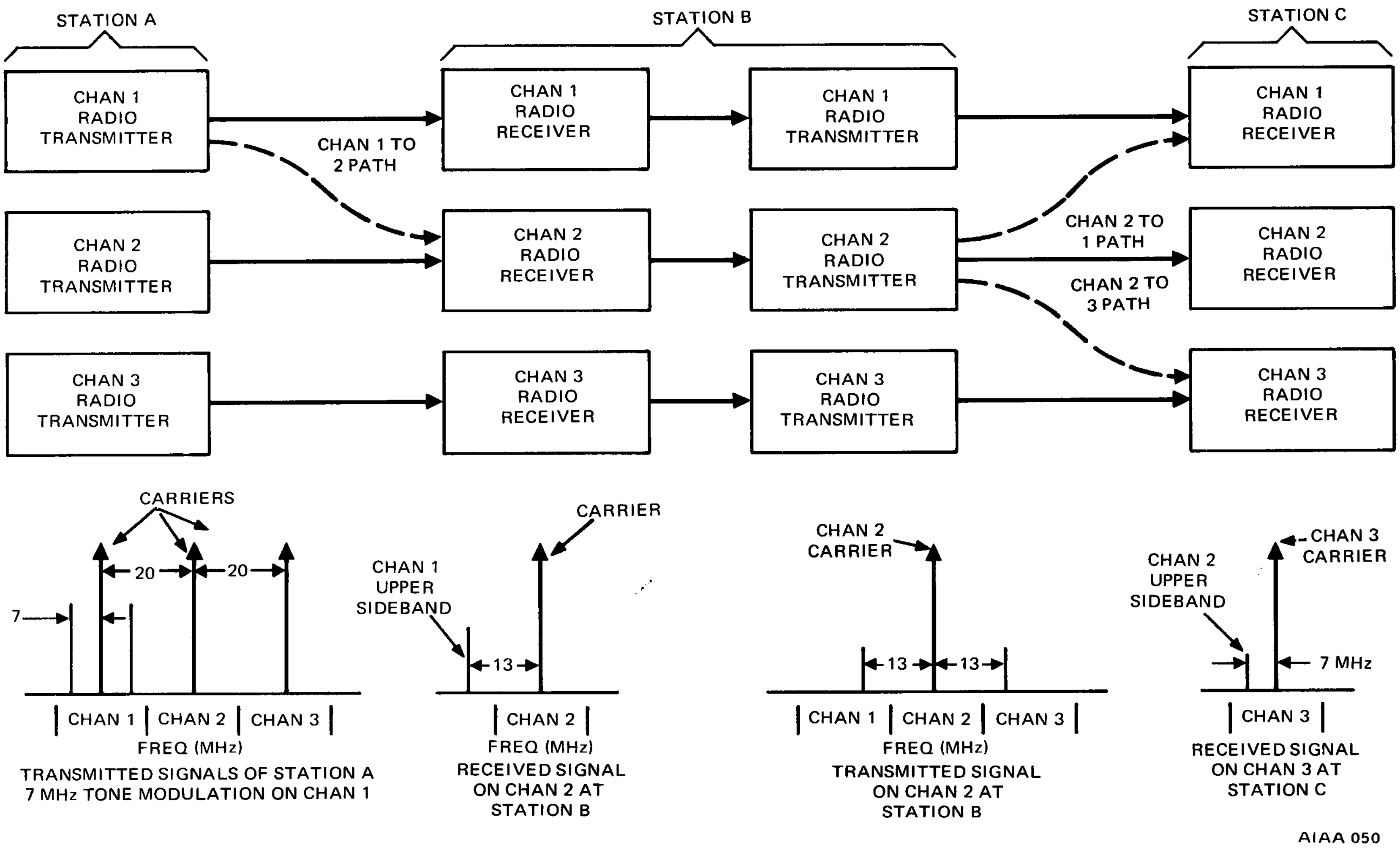


Figure 3-11. Limiter Transfer Action

should include a study of frequency tolerances of the various beat frequency oscillators used in the paths to determine actual frequency range about the nominal within which the interfering tone may appear at the third station.

Tests have shown that limiter transfer action is in exact accordance with elementary FM theory. The mechanism may become an important consideration when a high-level tone is present on a channel, or a carrier is located near the edge of a broadband radio channel.

3.6.6 Tone Interference

Tone interference, though possibly caused in several different ways, is essentially single frequency in nature. Important sources of this type of interference are the previously discussed same and image channel interferences, and beat oscillators in or near the equipments involved.

Unless the frequency allocation is carefully planned, a beat oscillator frequency for one channel may fall within the band of another RF channel. An extremely large amount of filtering will be required to keep the high-level beat oscillator output from leaking out of the converter where it is used and getting into the other channel at the same frequency. There are higher order products, possibly 4th or 5th order, which may be produced in a converter if the extraneous tones from other RF channels or other beat oscillators are present. Those products which fall in the frequency band of the desired output constitute tone interferences.

3.7 CROSSTALK

Crosstalk is unwanted coupling from one signal path onto another. Crosstalk may be due to direct inductive or capacitive coupling between conductors. It may also be caused by coupling between radio antennas, or by cross-modulation between channels and single frequency signals (carriers or pilots) in multichannel carrier systems. Such cross-modulation may occur in any nonlinear element, such as repeater electron tubes or terminal modulators. In many instances, the resulting interference in carrier systems is unintelligible due to the interfering signal being inverted, displaced in frequency, or otherwise distorted. In these cases, crosstalk is generally grouped with other noise type interferences.

When coupling paths give rise to intelligible (or nearly intelligible) interference, it is necessary to design the cable, open-wire line, antenna, repeater, or modulator so that the probability of hearing a "foreign" conversation will be less than a prescribed value. In normal practice, a one percent chance is considered tolerable and is based on an arbitrary judgment.

Three major crosstalk paths between physical four-wire systems are shown in figure 3-12. These are: the near-end path between the opposite directions of transmission, the interaction crosstalk paths from the output of one repeater into a paralleling cable pair (a voice circuit perhaps) and then into the input of the same or another repeater, and the far-end path from the output of one repeater to the input of another.

Two cables are used alternately to provide the pairs for each direction of transmission. By using physical isolation, the near-end crosstalk paths between the opposite directions of transmission are automatically eliminated. The interaction crosstalk path is effectively broken up by alternating ("frogging") the two directions of transmission between the two cables in successive repeater sections. In this way, the interaction path is made to terminate at the high-level point at a repeater output and is, therefore, less serious by the gain of a repeater. These measures do not, of course, affect the far-end crosstalk between carrier systems in the same cables. This last path is improved by rather elaborate carrier frequency balancing of the cable pairs.

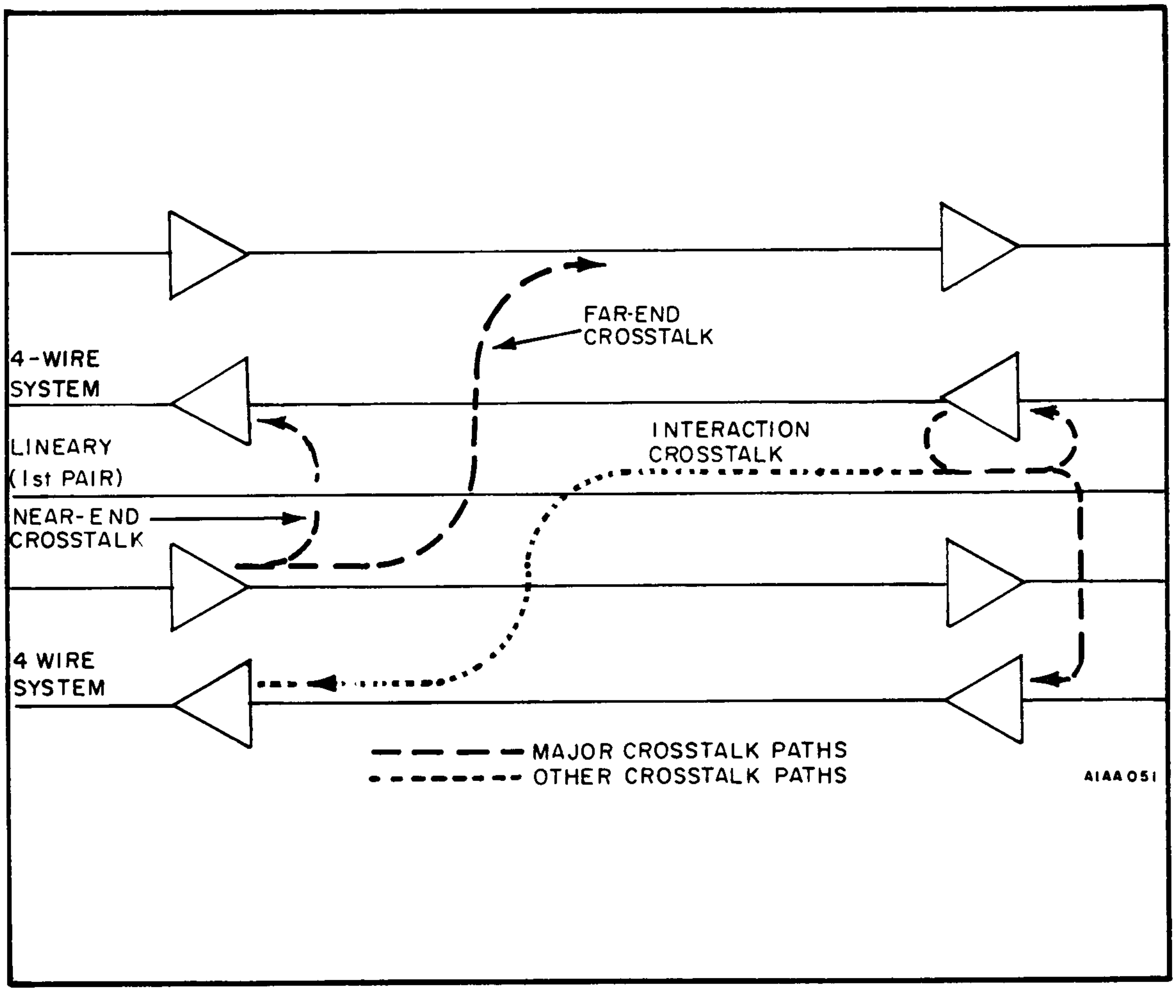


Figure 3-12. Physical Four-Wire Operation and Some Important Crosstalk Paths

3.8 DISTORTION

Distortion appears in a multichannel microwave system as intermodulation noise and attributed to two factors, delay and echoes. Any signal that carries intelligence is a composite signal; i.e., it contains a number of frequencies, often harmonically related, in some given phase relationship. If such a signal is passed through a system or component which has different delays at different frequencies, the output signal will not be identical in shape to the input signal. DCAC 330-175-1 requires that differential delay distortion (1000-2600 Hz) not exceed 1000 μsec over the 6000 NM reference circuit.

Echoes are generated by reflection from discontinuities in the transmission path. Because of this, the signal becomes modified in phase by the reflected energy. When the FM signal is translated to baseband, the signal will have a distortion component proportional to the frequency of the product (second or third order).

Various types of distortion which may occur in a microwave system are:

- Feeder distortion
- Path distortion
- Group delay
- AM to PM conversion
- Telegraphic distortion

3.8.1 Feeder Distortion

Often a source of considerable noise in microwave high capacity systems is the transmission line (waveguide system). Microwave transmission lines are similar to cable pairs and coaxial tubes with regard to impedance match. Mismatches cause multiple reflections which add a delayed, attenuated replica (echo) of the desired signal. In an FM system, the effect of an echo is to introduce distortion into the message channels. The distortion level is a function of the round trip echo delay time, echo amplitude, number of message channels (baseband width), frequency band of the particular message channel being observed, RMS deviation of the radio, and the radio channel frequency. A typical relationship between time delay and distortion is shown in figure 3-13. Distortion is always directly proportional to the echo amplitude, which must be about 60 dB below the incidental signal to reduce distortion to an inconsequential value. Short time delay echoes are not as degrading as long time delay echoes, and a point is reached where increased echo delay no longer increases distortion. Note that the waveguide length is related to the interfering effect of an echo and, for that reason, should be held to a minimum.

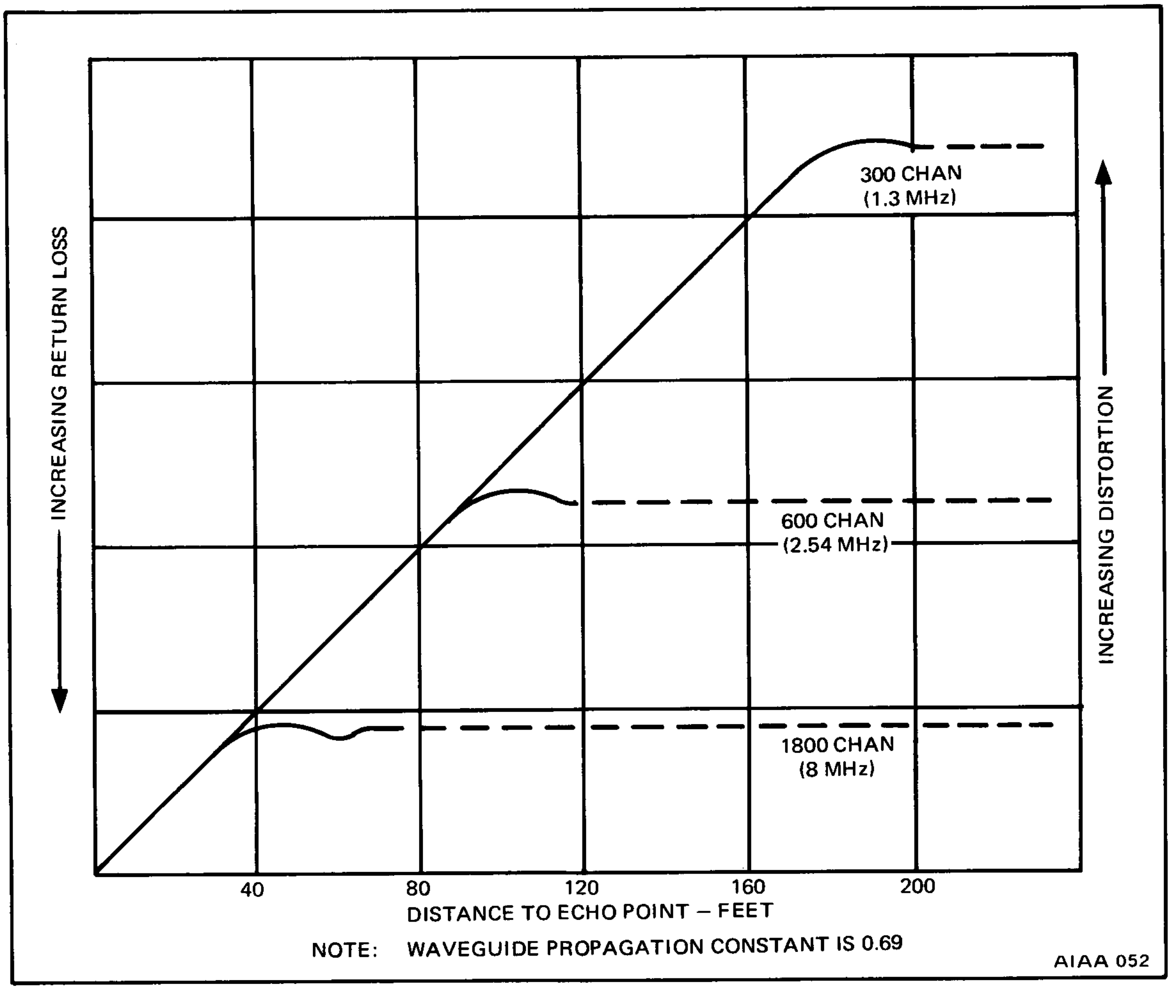


Figure 3-13. Typical Relationship of Echo Magnitude and Delay Versus Distortion

The difference in level between the incidental signal and the reflected signal is known as "return loss." Poor return loss results in signal cancellation due to the phase relation of the two signals, intermodulation distortion and other degradation to the microwave signal. Return loss (expressed in dB) is a measure of discontinuities in the transmission equipment, waveguide, antenna, and connecting flanges. It is defined by:

$$R_L = \text{return loss} = 20 \log_{10} \frac{1}{\text{reflection coefficient}} \tag{3-8}$$

where:

$$\text{reflection coefficient} = \frac{\text{reflected signal}}{\text{incident signal}} \text{ (expressed as voltage or current)}$$

Reflection and re-reflection may occur at any point in the transmission path. The actual echo added to the desired signal is composed of many components with various amplitudes and phases. Since echo phasing is a function of distance and frequency, some radio frequency channels may experience more severe distortion than other channels. For this reason, it is necessary to specify component performance over the complete transmission band, and to adequately evaluate the antenna feed system after installation.

This discussion gives an idea of the physical mechanism associated with feeder distortion. A mathematical analysis of the phenomenon would show that the 2nd order distortion is proportional to the square of the line length, the 3rd order distortion to the cube of the line length, etc. For this reason, feeder noise increases so rapidly with line length. Poor feeder return loss performance is indicated by a high frequency ripple in the group delay pattern.

3.8.2 Path Distortion

The distortion producing phenomenon present in feeders occurs in a similar way in the propagation medium along the transmission path. The basic difference between feeder echoes and transmission path echoes is: the former comprise relatively weak echoes with delays ranging upward from approximately 0.1 μsec, and the latter comprise powerful echoes approaching the main signal level with very short time delays (usually less than 0.01 μsec) and is caused by atmospheric multipath transmission and ground reflections.

Selective fading is caused by destructive interference between a microwave signal and one or more lagging echoes. In addition, nonselective type of fading causes receiver FM noise to contribute to the total distortion. An efficient means of coping with multipath fading is diversity transmission.

Another cause of distortion involving the propagation medium, is the presence of RF interference generated within the microwave system or externally to the microwave link, but affecting its performance.

3.8.3 Group Delay Distortion

Nonlinearity of the IF and RF circuits phase characteristics produces nonlinear distortion in FM systems. If some of the frequencies which make up a given signal do not travel at the same speed in traversing a medium (tuned circuit, propagation path, transmission line, etc.), but are attenuated more than others, the signal arrives at its destination distorted. Ideally, the phase shift (θ) versus frequency (f) characteristic should be linear. If the phase shift through a device is a linear function of frequency, the group delay, $t_d = -d\,\theta/d\omega_1$ (figure 3-14) will remain constant. Therefore, a signal can be transmitted without distortion. In general t_d is not constant but a function of ω, which expressed in a power series can be written:

$$t_d(\omega) = t_{d1} + t_{d2}\left(\frac{\omega-\omega o}{B/2}\right) + t_{d3}\left(\frac{\omega-\omega o}{B/2}\right)^2 + - - - \qquad (3\text{-}9)$$

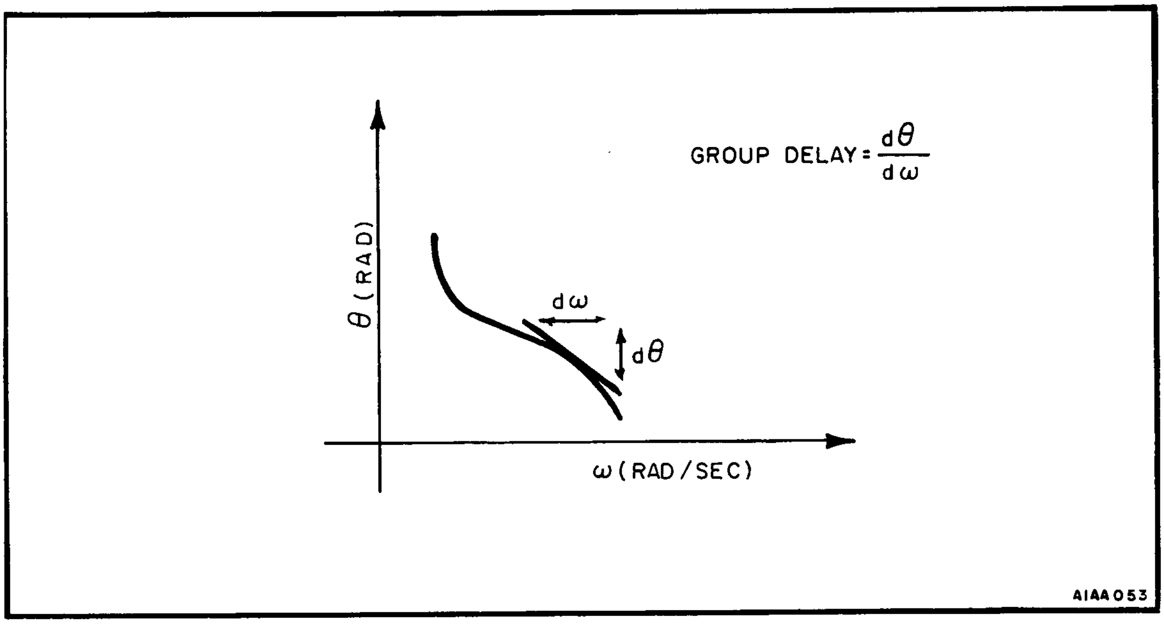


Figure 3-14. Phase Versus Frequency Through a Transmission Device

The meaning of the coefficients is shown on figure 3-15.

A network designed to make the group delay essentially constant over the desired frequency range is called a delay equalizer. Such an equalizer introduces compensating delays at certain frequencies and has minimal effect on the circuit amplitude response. Adequate uniformity of IF and RF circuits amplitude/frequency response is also necessary (measured at signal levels below limiting) so that the amplitude relationship of all significant sidebands are preserved.

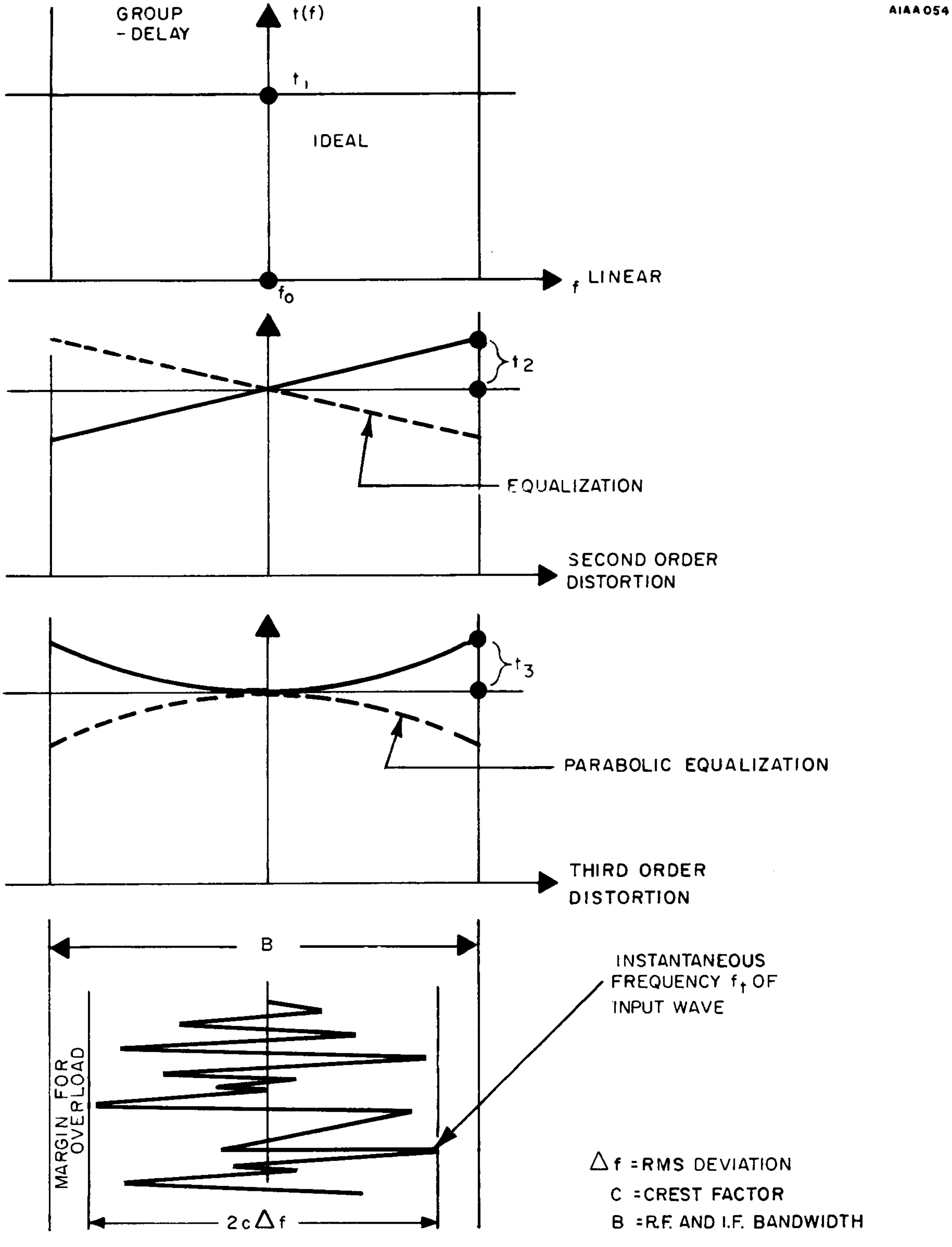


Figure 3-15. Group Delay Frequency Characteristics of Repeaters

3.8.4 AM to PM Conversion Distortion

Most active amplifying circuits exhibit a characteristic that will change the phase of a signal passing through as a function of the AM modulation on that signal. What is more important, it will also change the phase of any other signal passing through the amplifier at the same rate as the AM signal and in proportion to the percent of AM modulation. This amplifier characteristic is the AM to PM conversion coefficient (K_Θ), and is expressed in degrees per dB.

In any FM system there is some AM modulation generated on the carrier as the carrier is deviated in frequency because of the gain slope in the amplifier. This gain slope (K_G) is expressed in dB/Hz.

These two factors combine in an FM system to produce crosstalk between carriers that can be intelligible in the case of telephone traffic. The amount of phase modulation produced on a carrier from another FM carrier passing through a common amplifier is given by:

$$\Theta_1 = \Delta F_1 \, K_\Theta \, K_G \tag{3-10}$$

where, ΔF_1 is the peak frequency deviation of one carrier. The peak frequency deviation induced on the other carrier is given by:

$$\Delta f_2 = \Theta_1 \; F_b \tag{3-11}$$

where, F_b is the modulation frequency of the first carrier. The level of crosstalk between the two carriers is given by:

$$\frac{\Delta F_2}{\Delta f_2} = x = \frac{\Delta F_2}{K_\Theta \, K_G \, F_b \, \Delta F_1 \left[1 + \left(\frac{a_2}{a_1} \right)^2 \right]} \tag{3-12}$$

where, a_1 and a_2 are the carrier amplitudes.

The crosstalk ratio for a given system is a function of the baseband frequency. Therefore, it is only a factor for high channel capacities and at the higher groups of channels.

3.8.5 Telegraph Distortion

The term "telegraph distortion" originated long before data transmission became common, but it is equally applicable to digital telegraph (or data) signals, since this type is normal in the DCS.

In binary transmission, the signal is always in one of two states, marking or spacing. At various points in a transmission system, the signals may appear as DC signals, audio frequency signals, or RF signals. As DC, the two binary states can be either ON or OFF, or positive and negative. As AM audio or RF signals, the two binary states will be ON and OFF. As frequency-shift-keyed (FSK) or phase-shift-keyed (PSK) audio or RF signals, the two binary states will be two frequencies or two phase positions, respectively.

Any change in the duration of mark and/or space intervals as compared to their ideal durations is termed "telegraph distortion." Distortion may be introduced by the sending end instrument, the transmission medium, or any equipment between the sending and receiving end instruments. Telegraph distortion can occur to varying degrees in different parts of a system, so it is essential to minimize it in each part. The DCS Standards specify the amount which may be introduced by sending end instruments, and the amount which should be tolerated by receiving end instruments. Between these two extremes, it is controlled by specifying frequency response and envelope delay of various subsystems and components.

Most telegraphic distortion can be attributed to sending and/or receiving electromechanical teletype equipment. There are several different types of telegraphic distortion and are mainly caused by the end equipment. The remaining distortion is caused by combinations of the foregoing principal types of distortion and are identified for information purposes only.

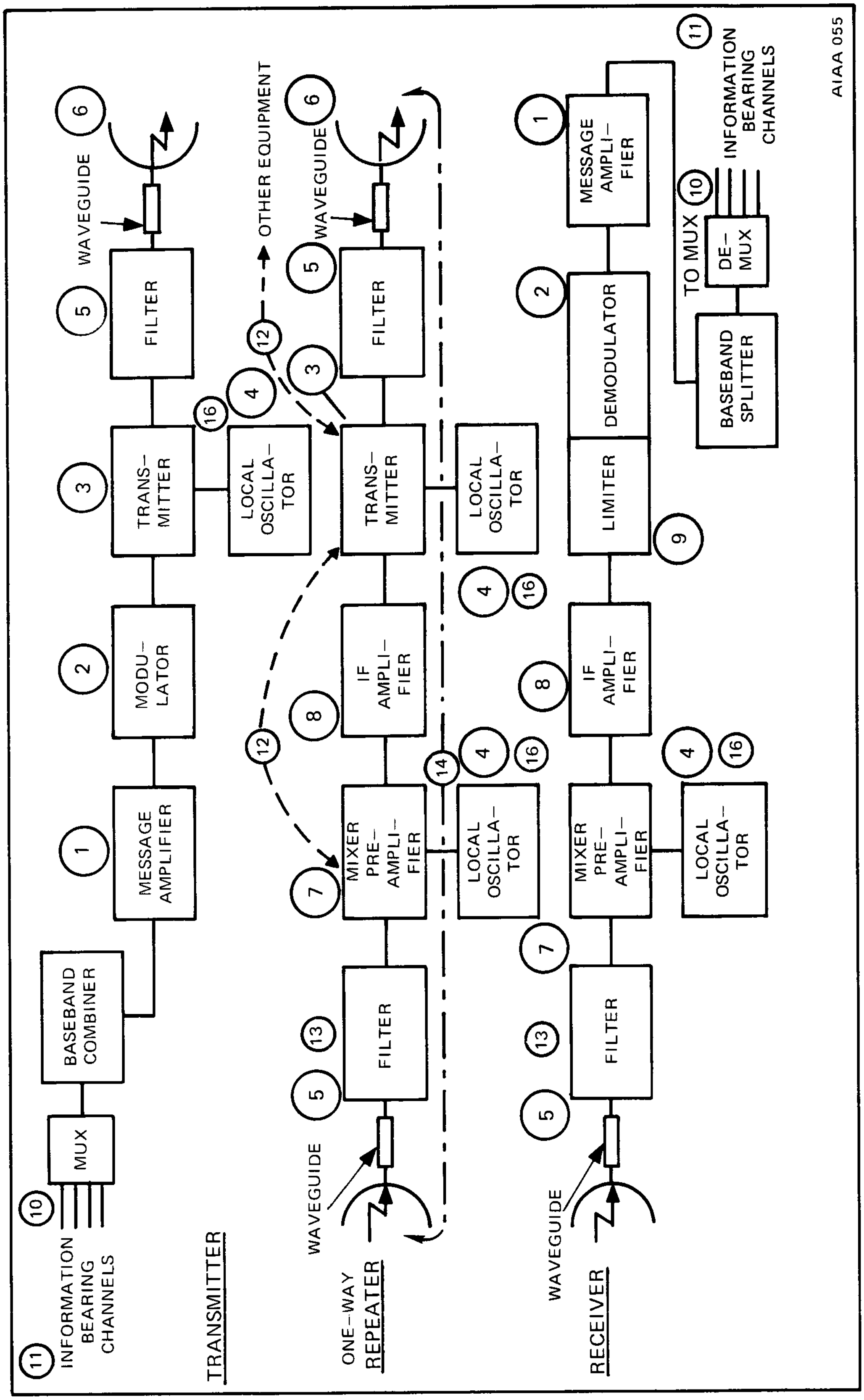
- Bias distortion
- End distortion
- Characteristic distortion
- Fortuitous distortion
- Cyclic distortion
- Speed distortion

3.9 SUMMARY

To catalog the various noise sources that comprise a multichannel microwave system noise budget, refer to Table 3-5 and figure 3-16. The various noise sources identified and discussed in this chapter are tabulated and keyed to a simplified block diagram of a multichannel communications system consisting of two terminals and one intermediate heterodyne repeater. The signal can be traced from the information bearing input channels at the transmitter terminal to the corresponding receiver terminal output channels.

Table 3-5. Sources of Noise

NUMERICAL KEY	NOISE TYPE	REFERENCE PARAGRAPH
1, 2	Intrinsic, Intermodulation	3.2.2, 3.2.3
3	AM to PM Conversion, Thermal	3.2.1, 3.8.4
4	Thermal	3.2.1
	Intrinsic	3.2.2
5	Feeder Distortion	3.8.1
6	Path Distortion	3.8.2
7	Thermal	3.2.1
8	Group Delay	3.8.3
9	Limiter Transfer Action	3.6.5
10	Multiplex Noise	3.5
11	Telegraph Distortion	3.8.5
12	Crosstalk	3.7
13	Image Channel Interference	3.6.2
14	Same Channel Interference	3.6.1
15	Adjacent Channel Interference, Direct Adjacent Channel Interference	3.6.3, 3.6.4


TRANSMITTER
11
INFORMATION BEARING CHANNELS
10
MUX
BASEBAND COMBINER
1
MESSAGE AMPLIFIER
2
MODU- LATOR
3
TRANS- MITTER
16
4
LOCAL OSCILLA- TOR
5
FILTER
WAVEGUIDE
6
ONE-WAY
REPEATER
WAVEGUIDE
5
13
FILTER
7
MIXER PRE- AMPLI- FIER
LOCAL OSCILLA- TOR
14
4
16
12
8
IF AMPLI- FIER
TRANS- MITTER
LOCAL OSCILLA- TOR
4
16
3
12
OTHER EQUIPMENT
5
FILTER
WAVEGUIDE
6
RECEIVER
WAVEGUIDE
5
13
FILTER
7
MIXER PRE- AMPLI- FIER
4
16
LOCAL OSCILLA- TOR
8
IF AMPLI- FIER
LIMITER
9
2
DEMODULATOR
1
MESSAGE AMPLI- FIER
TO MUX
BASEBAND SPLITTER
DE- MUX
10
INFORMATION BEARING CHANNELS
11
AIAA 055