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Spurious Signal Criteria for Voiceband Telephone Equipment

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A set of requirements is derived for spurious metallic and longitudinal signals generated by voiceband terminals which will assure that those signals will not interfere with other systems and services using the same multipair cable. These requirements are necessary because of the crosstalk coupling which exists between the pairs of a cable. The requirements were derived from cable crosstalk measurements and the susceptibilities to interference of voice services, program services, single channel carrier systems, and multichannel carrier systems.

I. INTRODUCTION

A customer's telephone terminal equipment is usually connected to the serving central office by a pair of wires. This pair of wires, referred to as a loop, is normally a part of a multipair cable containing 6 to 2700 pairs. Most of these pairs will be used for voice frequency service for other customers. However, pairs within this cable can be used for services such as data and broadcast program channels or systems such as subscriber loop carrier used to serve multiple customers. These other services and systems are not restricted to voiceband frequencies but can cover a frequency range from dc to several megahertz.

Pairs within a common cable sheath are in very close proximity to each other and, as a result, a small portion of the electromagnetic field, set up by the customer's communication signal, can couple into other pairs. Cable design and manufacturing techniques are used to minimize this coupling but cannot eliminate it. This coupled signal can interfere with other signals in the cable if its level is not controlled. To control this interference, requirements are placed on the maximum allowed signal levels and administrative rules, referred to as spectrum management,[1] are used. Because of the large number of voiceband terminals, specialized administrative processes are not used for them. Such use would lead to inefficient use of cable facilities and would be economically burdensome. The interference caused by voiceband systems is controlled by requirements on the maximum allowed signal levels. These requirements provide reasonable assurance that the interference to other users will be kept to a satisfactory level without unduly affecting the customer's performance.

The output signal of a voiceband terminal can be categorized as follows:

(*i*) The desired metallic signal in the nominal 100 to 4000 Hz voiceband.

(*ii*) A sparious metallic signal above 4000 Hz.

(*iii*) A spurious longitudinal signal above 100 Hz.

This paper derives signal power limits on the two kinds of spurious signals. The maximum signal power limitations on the desired metallic signal are controlled by a different constraint, multichannel carrier overload, rather than multipair cable crosstalk. Spurious signals can cause unwanted signals into systems and services in the same cable via the crosstalk coupling between pairs. These unwanted signals generally appear as unintelligible noise-like signals. The requirements for controlling these signals are derived by considerations of (*i*) the coupling characteristics of cables and (*ii*) vulnerability to interference of systems and services which may share the same cable. The paper examines each of these considerations and concludes with a discussion of the derivation of the actual requirements for each type of spurious signal.

Limits on the output signal power of voiceband terminals that may be connected to the switched telephone network are specified in the FCC registration rules.[2] The limits on spurious signals derived in this paper are somewhat different from the existing FCC rules. On May 10, 1977 AT&T petitioned the FCC to amend its requirements on spurious signals to conform to the limits derived in this paper.[3]

II. CABLE CROSSTALK COUPLING CHARACTERISTICS

The amount of spurious signals coupled from one pair into other pairs in a multipair cable depends on the cable characteristics and the characteristics of the terminations.[4–8] The cable characteristics of importance are the design parameters such as pair twist lengths, stranding and cabling lays, and pair unbalance, and the relative positions of the pairs in the cable. In addition, the coupling is influenced by the frequency, mode of excitation, and terminating impedances of the disturbing and the disturbed pairs.

Cable design and manufacturing techniques reduce but do not eliminate the coupling. The most significant couplings are those to the nearby or adjacent pairs. In general, pairs that are more separated have substantially reduced coupling because they are shielded from one another and because electromagnetic fields due to a signal on a wire pair decrease rapidly as the distance from that pair increases. Because of these facts, the development of signal level limitations is primarily concerned with the coupling into nearby or adjacent pairs. It is assumed that, if spurious signals from any one adjacent pair are controlled, the amount of coupling from all other pairs will be small.

The amount of coupling to nearby or adjacent pairs must be determined by measurement. Identification of that pair which will have the lowest coupling loss to a particular disturbed pair is difficult to make. Measurements of all two-pair combinations are made. Generally, the worst couplings of this distribution are those from each pair to each adjacent pair. Thus the average adjacent pair coupling can be determined from this larger distribution. Traditionally, the 1-percent worst coupling is taken as being the average adjacent pair coupling.

The mode of excitation of the applied signal greatly influences the amount of this coupling. There are two principal modes of excitation on cables; metallic and longitudinal. In cables, the two insulated conductors of the disturbing pair are twisted and close together. For metallic excitation, the currents in the two conductors are in opposite directions so that coupling to other pairs in the cable due to minor asymmetries that occur in cable manufacture is small. Crosstalk losses are large in this case. However, when a longitudinal signal is applied, the currents in the two conductors of the disturbing pair are in the same direction, with the return current in the sheath. The effect of manufacturing asymmetries on coupling is greatly increased because of the larger spacing and lack of twisting between the pairs and sheath that are carrying currents in the opposite direction. Thus, a much larger amount of interference is induced into an adjacent pair with a longitudinal signal than for an equal value of metallic signal. Coupling losses from a longitudinal signal are commonly 25 dB less than from a metallic signal. Some control is needed for crosstalk due to longitudinally induced noise signals. Usually they are at significantly lower levels than metallic signals.

As indicated, couplings between pairs in a cable must be determined by measurement. For convenience, the coupling is stated in terms of the amount of attenuation (loss) which a signal on a disturbing pair would experience in coupling to the disturbed pair. This crosstalk loss is defined as being near-end (NEXT) or far-end (FEXT). Each of these types of crosstalk is illustrated in Fig. 1. Figures 2 and 3 show smoothed

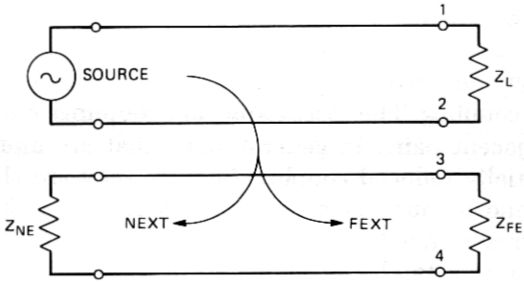

Fig. 1—Basic crosstalk circuit.

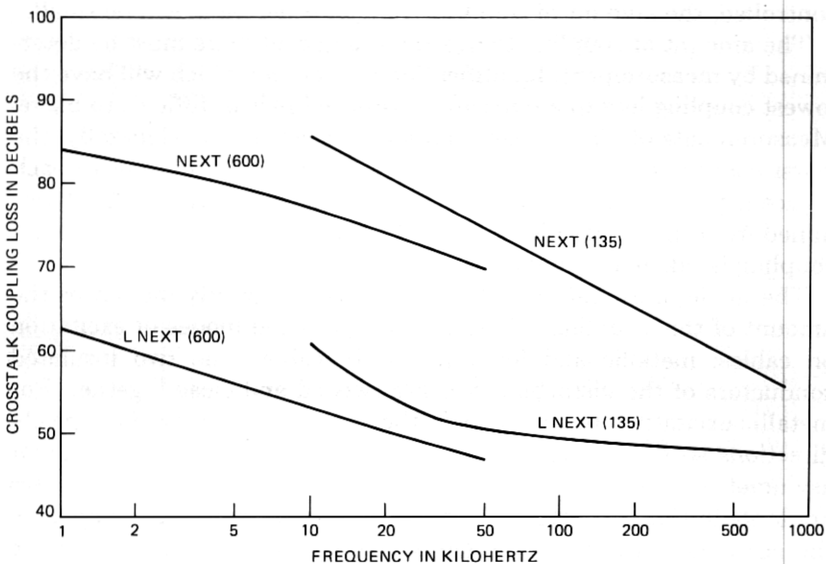

Fig. 2—One-percent metallic and longitudinal near-end crosstalk loss used in deriving the revised signal power criteria.

composite 1-percent metallic and longitudinal near-end and far-end coupling losses measured on a number of cables. Their values were used in this study. The loss is indicated in terms of the impedance of the systems which could occupy the disturbed pair. Low-frequency systems are typically designed to an impedance of 600 ohms, while at higher frequencies, systems are designed to an impedance of 135 ohms.

III. VULNERABILITY OF SYSTEMS AND SERVICES

A customer's voiceband terminal is usually assigned a cable pair at random. Thus, the customer's pair may be adjacent to a pair containing any of a large number of services and systems. The adjacent pair could contain any of the following services:

(*i*) Voiceband services.

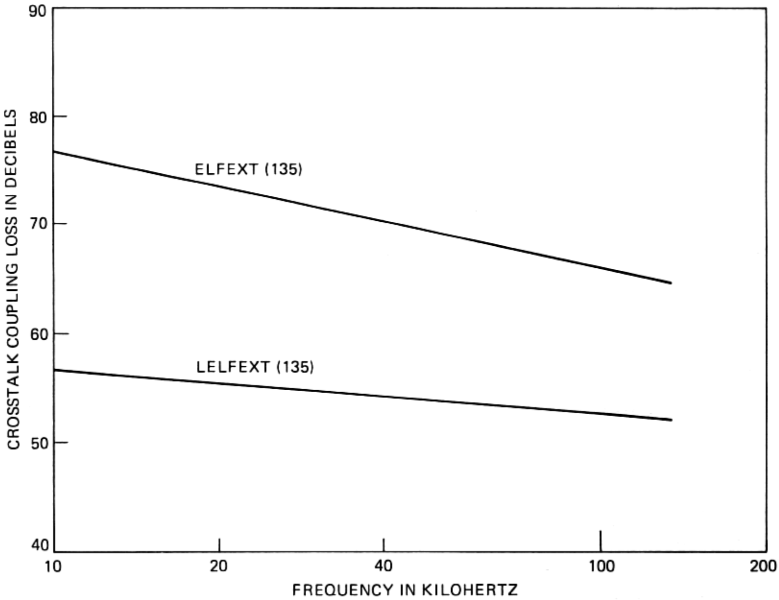

Fig. 3—One-percent metallic and longitudinal equal-level far-end crosstalk for 3 kft of cable used in deriving the revised signal power criteria.

(*ii*) Program audio transmission services.
(*iii*) Private-line, baseband data services.
(*iv*) Slow-scan, video-type services.

Carrier systems are also being increasingly used to provide more than one voice channel over a cable pair. The types of carrier systems that could be used on an adjacent pair are:

(*i*) Analog single channel loop carrier systems.
(*ii*) Analog multichannel loop and trunk carrier systems.
(*iii*) Digital multichannel loop and trunk carrier systems.

The signal power of the customer's terminal must be controlled so that performance of any of the above systems and services is not degraded. Performance of a service or system is considered degraded when the interference caused by a customer's terminal is greater than its allocated share of the service or system's noise objective. The maximum allowed value of signal power at the output of a customer's terminal is that value which causes interference in the disturbed system or service to just equal the noise allotted to interference from other systems.

The allocation is a function of the particular type of system or service. This section derives the maximum disturbing spurious signal levels for each type, considering the desired performance of the service or system, the equipment design, and crosstalk coupling. These maximum levels for spurious signals are combined into a single requirement in Section IV by considering the system or service most vulnerable to interference at each frequency. Our current analysis indicates that carrier system considerations control the maximum allowable level above 4 kHz, while program audio and voiceband services are controlling below 4 kHz.

3.1 Voice services

Voiceband services are susceptible to interference in the frequency range from 100 Hz to 4 kHz from other voiceband terminals in the same cable. When terminals meet the metallic voiceband signal limitations as set in the FCC registration rules, the resulting noise interference into other voiceband services will not be excessive. However, signal level limitations on spurious longitudinal energy are necessary to assure protection of voiceband services in the frequency range 100 Hz to 4 kHz.

These longitudinal signal limitations depend upon the following:

(*i*) Noise requirement for voiceband service.

(*ii*) The crosstalk coupling between pairs.

The noise requirement is stated in terms of a weighted noise power across the voiceband. The maximum total noise objective for voiceband service is 20 dBrnC.[9] Half this noise is allocated to crosstalk interference; therefore, $N = 17$ dBrnC. The maximum longitudinal signal voltage that may be introduced by a voiceband terminal at any given frequency, (f), is:

$$V_S(f) = N - 92.2 - W(f) + \text{NEXT}\,(f),$$

where

$V_S(f)$	is maximum allowed single frequency longitudinal voltage on the disturbing pair in dBV.
N	is the maximum permissible noise interference on the disturbed pair due to crosstalk in dBrnC. To convert this to dBV across 600 ohms, 92.2 must be subtracted.
$W(f)$	is the C-message noise weighting (see Fig. 6).
$\text{NEXT}(f)$	is the near-end longitudinal crosstalk coupling loss in decibels (see Fig. 2).

For a signal not having all its voiceband longitudinal energy in a relatively narrow band, the single frequency maximum longitudinal voltage at any one frequency must be reduced to account for energy at other frequencies. To set proper limits on longitudinal signals that contain tones at more than one frequency in the voiceband and/or "broadband" energy, the following mathematical relationship must be satisfied:

$$N - 92.2 \leq 20 \log \int_{100}^{4000} 10^{\{[W(f) - \text{NEXT}(f) + V(f)]/20\}}\, df,$$

where $V(f)$ is the frequency spectrum of the longitudinal voltage on the disturbing pair expressed in dBV per hertz. If $V(f)$ is just a single frequency tone at some frequency f_0 and has no energy at any other frequencies, it may be treated as a delta function, the right-hand side of the above equation will reduce to $W(f_0) - \text{NEXT}(f_0) + V(f_0)$, and one obtains the constraint given previously for the single frequency tone.

The maximum single frequency allowable voltage level can be computed from the values shown in Table I. The output voltage that a signal source applies is a function of the input impedance of the cable pair it is connected to. If the maximum allowable longitudinal voltage levels are specified across an impedance that is different from the actual input impedance of the cable pair, a correction must be made. For longitudinal signals, a high impedance source was assumed and the compliance testing value was assigned a constant value of 500 ohms. Since the input impedance of a cable varies widely with frequency, an adjustment was necessary and the correction formula is:

$$\text{Impedance Correction (Longitudinal)} = 20 \log \left| \frac{Z_{in}}{500} \right|,$$

where Z_{in} is the longitudinal input impedance* of a cable as shown in Fig. 4. The impedance corrections were used in computing Table I.

3.2 *Program audio transmission services*

Program services are furnished over private-line, baseband circuits having a frequency range from about 30 Hz up to either 5, 8, or 15 kHz. Figure 5 illustrates the method used in implementing a typical program service, and the possible coupling of interference from a voiceband terminal. A program circuit is usually implemented using nonloaded cable with amplifiers and equalizers to compensate for the loss and frequency response characteristics of the cable.

The output of a voiceband terminal will contain its primary voiceband output signal in the frequency range from 300 Hz to 4 kHz and possibly some additional energy in the 4 to 15-kHz band. Some of the energy in both bands is coupled into the program channel and will appear as noise in that channel. Signal limitations on voiceband terminals must be specified to control this noise. A metallic voiceband signal must meet the voiceband limitations set forth in the FCC registration rules. The noise interference resulting from such a signal would be at least 10 dB below that permitted for a signal in the 4- to 15-kHz band. It would, therefore, have little influence on the total

* The longitudinal input impedance of a cable pair is the input impedance of a transmission line where one conductor is the sheath of the cable and the other is that obtained by simplexing the two conductors of that pair together.

Table I—Maximum allowable single frequency voltage levels into voice and program circuits

System	Frequency (kHz)	Noise Objective With Weighting (dBV-600Ω)	Gain of Amplifier Equalizer Combination $G(f)$ (dB)	Metallic NEXT(f) (dB)	Metallic Maximum Allowable Noise $V(f)$ Across Z_{in} (dBV)	Metallic Maximum Allowable Noise $V(f)$ Across 300Ω (dBV)	Longitudinal NEXT(f) (dB)	Longitudinal Maximum Allowable Noise $V(f)$ Across Z_{in} (dBV)	Longitudinal Maximum Allowable Noise $V(f)$ Across 500Ω (dBV)
FM Broadcast	0.1	−62.2	2.5	93.0	29.2	22.3	71.5	7.8	4.3
	0.5	−62.2	5.7	87.0	20.1	14.1	65.5	−1.4	−3.9
	1.0	−62.2	8.9	84.0	12.9	8.5	62.5	−8.6	−12.1
	2.0	−62.2	12.5	82.0	7.3	5.0	59.5	−15.1	−15.5
	4.0	−62.2	17.5	80.0	0.3	0.0	57.0	−22.7	−19.6
	6.0	−62.2	20.8	78.8	−4.2	−3.3	55.7	−27.7	−22.5
	8.0	−62.2	23.5	78.0	−7.7	−5.4	54.0	−31.6	−25.1
	10.0	−62.2	25.8	77.0	−11.0	−8.5	53.3	−34.8	−26.8
	12.5	−61.5	28.1	76.0	−13.6	−10.0	52.3	−37.3	−28.6
	15.0	−58.7	30.0	75.0	−13.7	−10.0	51.5	−37.2	−27.8
AM 8 kHz	0.1	−33.2	3.0	93.0	56.2	49.2	71.5	34.7	31.2
	0.5	−53.2	7.0	87.0	26.2	20.2	65.5	4.7	1.2
	1.0	−59.2	11.1	84.0	13.7	9.3	62.5	−7.8	−11.3
	2.0	−63.0	15.9	82.0	3.1	0.4	59.5	−19.3	−19.7
	4.0	−65.3	22.3	80.0	−7.6	−7.9	57.0	−30.6	−27.5
	6.0	−64.8	26.5	78.8	−12.5	−11.6	55.7	−36.0	−31.0
	8.0	−60.6	30.0	78.0	−12.6	−10.5	54.0	−36.5	−30.0
AM 5 kHz	0.1	−33.2	3.5	93.0	56.3	49.3	71.5	34.8	31.3
	0.5	−53.2	7.5	87.0	26.3	20.3	65.5	4.8	1.3
	1.0	−59.2	12.0	84.0	12.8	8.4	62.5	−8.7	−12.2
	2.0	−63.0	17.1	82.0	1.9	−0.4	59.5	−10.5	−20.9
	4.0	−65.3	24.0	80.0	−9.3	−9.6	57.0	−32.3	−29.2
	5.0	−65.2	26.2	79.3	−12.1	−11.8	56.0	−35.3	−31.1
Voice	0.1	−32.7	—				71.5	38.8	35.3
	0.5	−67.7	—				65.5	−2.2	−5.7
	1.0	−75.2	—		Not Applicable		62.5	−12.7	−16.2
	2.0	−73.9	—				59.5	−14.4	−14.8
	3.0	−72.7	—				58.0	−14.7	−13.2
	4.0	−60.7	—				57.0	3.8	6.8

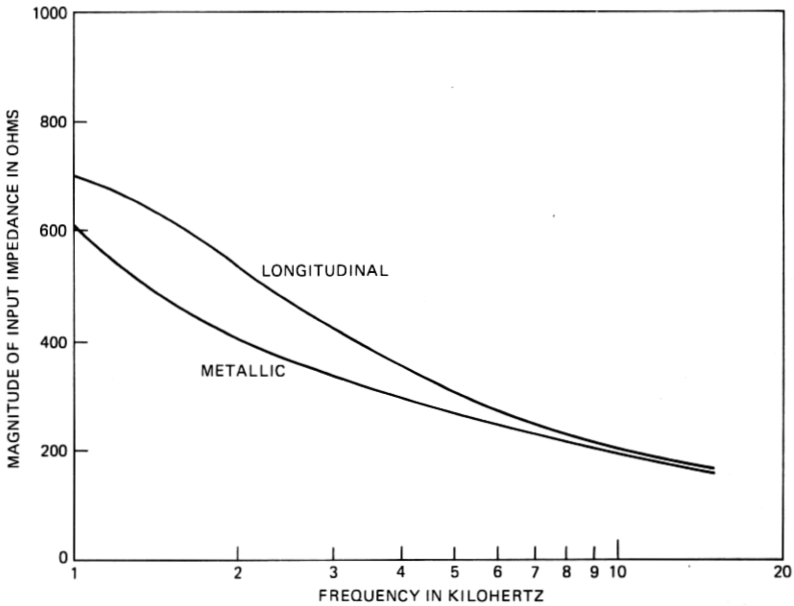

Fig. 4—Metallic input impedance of 5.5 miles of 22-gauge cable terminated in 600 ohms and longitudinal input impedance of 6 miles of 26 gauge cable terminated in 100 ohms.

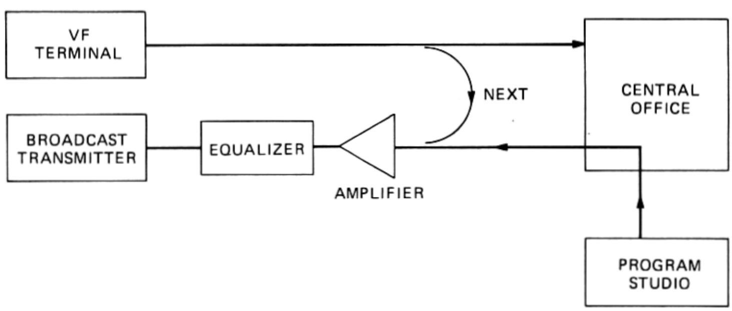

Fig. 5—Noise interference model for program circuit.

noise power in the program channel. Thus, the metallic signal limitation need be examined only in the 4- to 15-kHz band. However, signal level limitations on spurious longitudinal energy must be considered both for the voiceband as well as the 4- to 15-kHz band.

The following factors must be examined in developing the signal limitation:

(*i*) Noise requirement for program service.
(*ii*) The crosstalk coupling between cable pairs.

(*iii*) Gain of the amplifier.

(*iv*) Frequency shaping of the equalizer.

The maximum total noise levels permitted for AM, FM, and TV audio are set forth in Part 73 of the FCC Rules and Regulations[10] applicable to the broadcast industry. Noise induced on common carrier services carrying broadcast material must be below these levels. The allocation of noise requirements is shown in Table II. The terms "program" and "15 kHz flat" refer to the weighting filter used in measuring the noise with a Western Electric Type 3 noise measuring set. The weighting filter frequency characteristics are shown in Fig. 6.

Program circuits are implemented with amplifiers and equalizers which are spaced at the lesser distance corresponding to 30-dB loss at the highest channel frequency, or 12-dB loss at 1000 Hz. Application of this requirement results in the spacing of the amplifier-equalizer combinations shown in Table III.

Throughout their bandwidth, program circuits are designed to have an end-to-end loss or attenuation distortion of not greater than ±1 dB. To achieve this, the combination of the amplifier and equalizer has a gain characteristic shown in Fig. 7.

The maximum out-of-band metallic or longitudinal signal voltage is obtained in the same manner as the maximum allowable voiceband longitudinal signal. In this case, the single frequency maximum voltage is given by the equation:

$$V_S(f) = N - W(f) - G(f) + \text{NEXT}(f),$$

where

$V_S(f)$ is the maximum allowed single frequency metallic or longitudinal voltage on the disturbing pair in dBV.

Table II—Noise requirements allocation

	Total Circuit Requirement		Allocation for Crosstalk	
	dBrn	dBm	dBm	dBV (600 ohm)*
AM (5 kHz or 8 kHz) program	36	−54	−57	−59.2
FM 15 kHz flat	33	−57	−60	−62.2
TV audio 15 kHz flat	38	−52	−55	−57.2

* dBV is dB relative to 1 volt and is related to dBm by the formula dBV = dBm − 2.2 across 600 ohms.

Table III—Amplifier-equalizer combinations

	Cable Gauge	
Type of Circuit	22	24
AM 5 kHz	6.6 mi	4.9 mi
AM 8 kHz	6.9 mi	5.1 mi
FM and TV 15 kHz	5.5 mi	4.0 mi

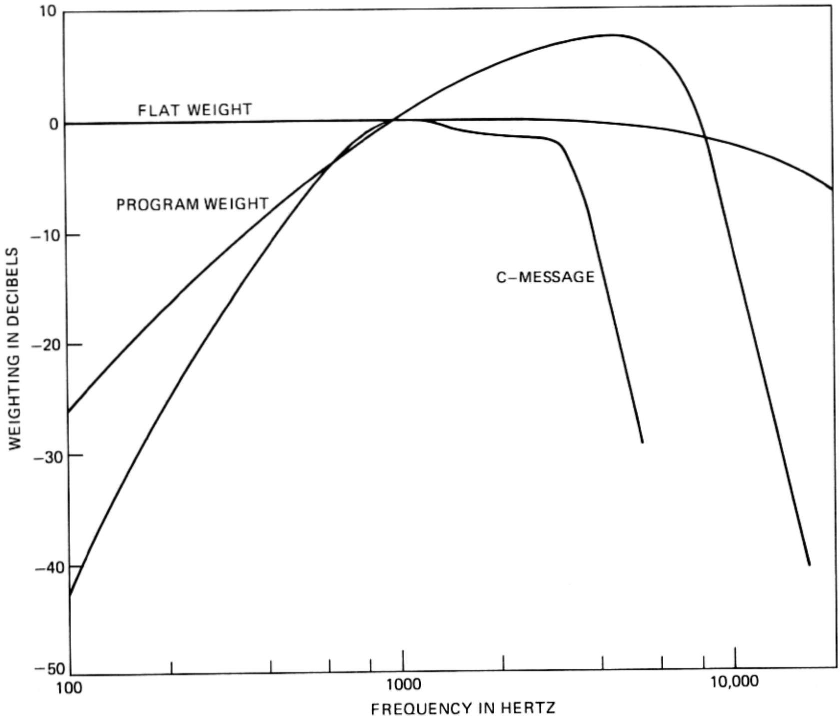

Fig. 6—3A noise measuring set program, C-message, and flat weighting curves.

N	is the maximum permissible noise interference on the disturbed pair due to crosstalk in dBV.
$W(f)$	is noise weighting in dB.
$G(f)$	is gain of the amplifier and equalizer in dB.
$\text{NEXT}(f)$	is the near-end metallic or longitudinal crosstalk coupling loss in decibels.

At the maximum repeater spacing, the maximum allowed voltage is independent of the cable gauge used in implementing the circuit since $G(f)$ and $\text{NEXT}(f)$ are not functions of gauge. Table I shows the results of this computation by frequency for metallic and longitudinal signals.

These maximum allowable voltage levels are computed at the input to a cable pair. They may be specified across the input impedance of the cable which varies widely with frequency or, to simplify the overall requirement, a constant value of 300 ohms may be used for metallic voltages and a correction made in the maximum allowable voltages to account for impedance variation. Assuming the voice terminal has a source impedance for metallic signals of 600 ohms, the difference in dBV between the voltage measured across a 300-ohm load and the

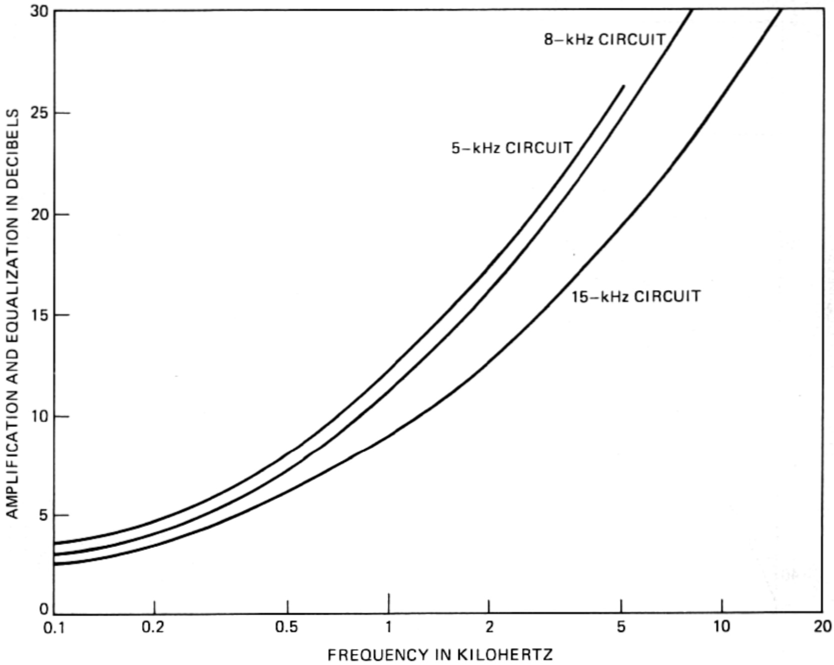

Fig. 7—Gain of amplifier-equalizer combination for 5-, 8-, and 15-kHz program circuits.

input impedance of the cable is:

$$\text{Impedance Correction (Metallic)} = 20 \log \left| \frac{Z_{\text{in}}(f) + 600}{3Z_{\text{in}}(f)} \right|.$$

$Z_{\text{in}}(f)$ for 22 gauge cable is shown in Fig. 4. For longitudinal signals, the same approach was used as for voice service. These impedance corrections were used in computing the results shown in Table I.

3.3 Private-line baseband data services and digital multichannel carrier systems

The number of baseband and high-speed data services and digital carrier systems present in the same cables with voiceband services is constantly increasing. These systems, however, are not as prone to noise interference as analog services and carrier systems. For digital carrier systems, information is represented in terms of 0 or 1 bits, which are sent as pulse or no pulse signals. To interfere with a digital system, the noise must be sufficiently high to hamper the pulse/no pulse decision process. This must be a relatively higher level of noise than that required to interfere with analog services and carrier systems if the noise is spread over a reasonable time period. However, it is possible if the interference is concentrated in a relatively short time period, as a noise spike, to cause interference into a data service or digital carrier system but meet the average noise requirement for analog systems. To avoid this problem, the final requirement was formulated in terms of the rms voltage rather than an average voltage.

3.4 Analog single and multichannel carrier systems

Increasingly greater use is being made of analog carrier systems to provide more than one voiceband telecommunication channel over a cable pair. These systems, known as subscriber loop carrier systems, are of two classes: single channel systems and multichannel systems.* These systems are susceptible to interference from about 4 kHz up to 1 MHz. Voiceband terminal equipment may emit energy in this frequency range along with its primary voiceband energy. A portion of this spurious high frequency energy will be introduced into adjacent pairs in the same cable through crosstalk coupling. Hence, both a desired signal and an interfering signal appear at the input to the receiving carrier terminal. This composite signal is demodulated in the receiving carrier terminal (by a process analogous to that occurring in an AM radio receiver) and appears at the output of the carrier terminal as a voice signal plus noise. Thus, the customer whose service is provided over the carrier system will experience degradation of service by this noise signal which originally was in the 4-kHz to 1-MHz frequency band. In *N*3 carrier systems, in addition to increased channel noise, excessive signal or tones at or near any of its 24 nominal carrier frequencies may "beat" with the carrier. This will cause a slow variation in the amplitude of the derived channel and will be perceived by the customer as variations in volume of the conversation.

Single and multichannel carrier systems that conform to REA[11] (Rural Electrical Administration) specifications use the frequency band between 4 and 60 kHz for communication from the subscriber terminal to the central office and frequencies above 60 kHz for transmission from the central office to the subscriber.† Spurious energy in the frequency range from 4 to 60 kHz will interfere with the signal transmitted toward the central office, while energy above 60 kHz will interfere with the signal transmitted toward the subscriber.

For convenience, interference into a carrier system will be classified into three types. Figures 8 and 9 depict the two types of interference which may occur at the central office. In Type 1 interference (Fig. 8), energy in the 4- to 60-kHz band is coupled via far-end crosstalk into the carrier receiver. In Type 2 interference (Fig. 9), energy from a far-

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* Multichannel subscriber systems typically provide services to 6 to 8 customers. In addition, *N*3 and *T*1 carrier systems may be used in subscriber loop plant to provide larger numbers of channels.

† In some multichannel carrier systems, the lower frequency band may be extended to 76 kHz.

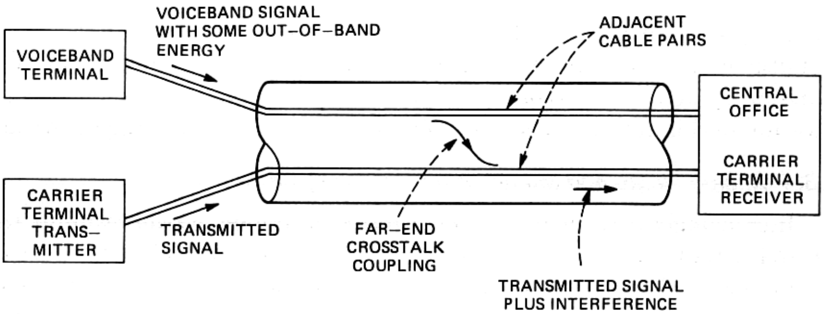

Fig. 8—Type 1 interference-voiceband terminal interfering with carrier system at central office terminal.

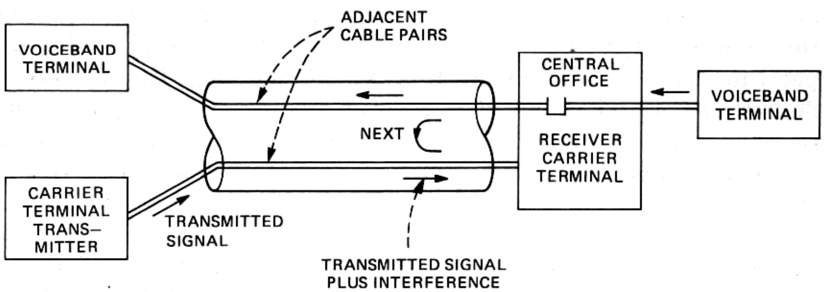

Fig. 9—Type 2 interference—voiceband terminal interfering with carrier system at central office terminal via near-end crosstalk.

end voiceband terminal is coupled via near-end crosstalk at the central office to a carrier terminal. The interference to the carrier system in this case is particularly insidious because the spurious noise source could be any loop connected to the central office. In Type 3 interference (Fig. 10), spurious energy above 60 kHz can interfere with the remote carrier terminal. In this case, the energy is coupled into the carrier system due to near-end crosstalk.

Depending upon the type of carrier system and the frequency spectrum of the out-of-band interference, one of these three types of interference will determine the maximum disturbing signal level that may be applied by a voiceband terminal. The approach taken in developing the appropriate limitations was to quantitatively determine for each type of carrier system the value of the disturbing signal which causes the noise in the disturbed channel to equal its system noise objective. The systems considered were typical of each of the classes of carrier systems. The classes considered were noncompandored and compandored single channel carrier systems, multichannel carrier systems, and the *N*3 carrier system.

The amount of induced noise will depend on the following factors:

(*i*) The frequency spectrum of the voiceband terminal output.

(*ii*) The physical layout of the cable.

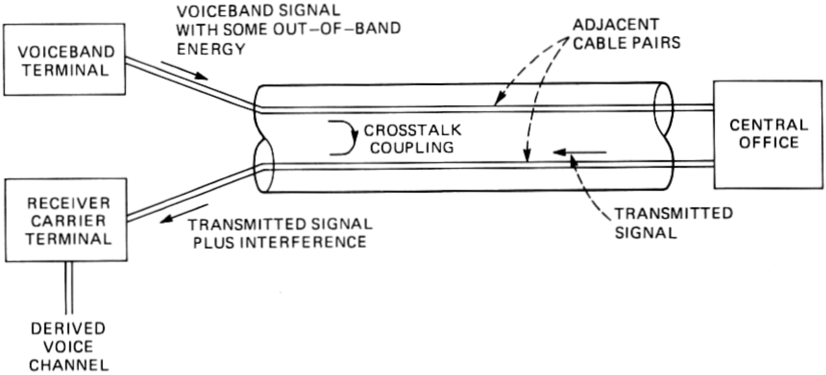

Fig. 10—Type 3 interference-voiceband terminal interfering with carrier system at remote terminal.

(*iii*) The design of the carrier system.

(*iv*) The interference path loss.

The following sections present the noise objectives and discuss each of the above factors. The values used for these factors in deriving maximum allowable levels are summarized in Tables IV, V, and VI.

3.4.1 Frequency spectrum of voiceband terminal output

The receivers for all analog carrier systems are designed to receive only the energy present on the line in a narrow band about the carrier for that channel. The amount of energy present in that channel will depend on the frequency spectrum of the interfering signal from the voiceband terminal. For instance, a terminal whose frequency spectrum decreases more rapidly at higher frequencies may interject less noise than a terminal having a relatively flat spectrum. For single channel and multichannel carrier systems, which are double-sideband, amplitude-modulated systems, the narrow band for receiving noise is that 8-kHz band occupied by each channel. *N*3 carrier, on the other hand, being a single sideband amplitude modulation system, has a band that is 4 kHz wide.

In addition to its susceptibility to random noise in these 4-kHz bands, the *N*3 carrier system is susceptible to "beats" at each of its 24 carrier frequencies. Beat interference may occur when the interfering tones are within a few hertz of the carrier frequencies. To meet the overall *N*3 system beat objective, a carrier-to-intersystem interference ratio of at least 51 dB is required.* Since energy is also present from the voiceband signal being carried on the *N*3 channel, spurious signals at or near the carrier frequency must be at least 53 dB below the power of the carrier signal at the input to the carrier system's gain regulator.

* The beat objective for *N*3 carrier is the same as that for *N*2 carrier derived in Ref. 12.

Table IV—Maximum allowable random noise signal into single channel and multichannel carrier systems

System	Controlling Interference Types	Frequency Band (kHz)	Received Carrier Level (dBm)	Noise Objective (dBrnC)	Susceptibility to Noise dBV-(135Ω)	Metallic: Interference Path Loss (dB)	Metallic: Maximum Allowable Noise dBV-(135Ω)	Longitudinal: Interference Path Loss (dB)	Longitudinal: Maximum Allowable Noise dBV-(90Ω)
NSCC	1	24–32	−18	20	−97	75	−22	55	−42
	3	72–80	−39	20	−118	72	−46	50	−68
CSCC	2	24–32	−40	20	−121	86	−35	59	−56
	3	72–80	−47	20	−96	72	−24	50	−46
MCC1	1	12–20	−40	15	−97	77	−20	56	−41
		20–28	−40	15	−97	76	−21	55	−42
		28–36	−40	15	−97	75	−22	54	−43
		36–44	−40	15	−97	74	−23	54	−43
		44–52	−40	15	−97	73	−24	54	−43
		52–60	−40	15	−97	73	−24	54	−43
	3	72–80	−42	15	−99	72	−27	50	−49
		80–88	−41	15	−98	71	−27	49	−49
		88–96	−41	15	−98	70	−28	49	−49
		96–104	−41	15	−98	69	−29	49	−49
		104–112	−41	15	−98	69	−29	49	−49
		112–120	−40	15	−97	68	−30	49	−48
MCC2	1	8–16	−40	15	−96	78	−18	57	−39
		16–24	−40	15	−96	77	−19	56	−40
		24–32	−40	15	−96	76	−20	55	−41
		32–40	−40	15	−96	75	−21	55	−41
		40–48	−40	15	−96	74	−22	54	−42
		48–56	−40	15	−96	73	−23	54	−42
		56–64	−40	15	−96	73	−23	53	−43
		64–72	−40	15	−96	72	−24	53	−43
	3	92–100	−40	15	−93	70	−23	49	−44
		100–108	−40	15	−93	69	−24	49	−44
		108–116	−40	15	−93	69	−24	49	−44
		116–124	−40	15	−93	68	−25	49	−44
		124–132	−40	15	−93	68	−25	49	−44
		132–140	−40	15	−93	67	−26	49	−44
		140–148	−40	15	−93	67	−26	49	−44
		148–156	−40	15	−93	67	−26	48	−45
MCC3	1	4–12	−40	15	−96	[illegible]	[illegible]	[illegible]	[illegible]

Table V—Maximum allowable random noise signal into N3

					Metallic		Longitudinal	
System	Frequency Band (kHz)	Minimum Received Carrier Level (dBm)	Noise Objective (dBrnC)	Suscepti-bility to Random Noise (dBv-135Ω)	Inter-ference Path Loss (dB)	Maximum Allowable Signal (dBv-135Ω)	Inter-ference Path Loss (dB)	Maximum Allowable Signal (dBv-90Ω)
N3	40 ± 4	−41	20	−84	81	−3	56	−28
	48 ± 4	−41	20	−84	81	−3	56	−28
	56 ± 4	−42	20	−85	80	−5	56	−29
	64 ± 4	−43	20	−86	79	−7	56	−30
	72 ± 4	−44	20	−87	78	−9	56	−31
	80 ± 4	−45	20	−88	78	−10	56	−32
	88 ± 4	−46	20	−89	78	−11	56	−33
	96 ± 4	−47	20	−90	77	−13	56	−34
	104 ± 4	−48	20	−91	76	−15	56	−35
	112 ± 4	−49	20	−92	76	−16	56	−36
	120 ± 4	−50	20	−93	75	−18	56	−37
	128 ± 4	−51	20	−94	75	−19	56	−38
	176 ± 4	−52	20	−95	73	−22	56	−39
	184 ± 4	−53	20	−96	73	−23	56	−40
	192 ± 4	−53	20	−96	73	−23	56	−40
	200 ± 4	−54	20	−97	73	−24	56	−41
	208 ± 4	−54	20	−97	72	−25	56	−41
	216 ± 4	−55	20	−98	72	−26	56	−42
	224 ± 4	−55	20	−98	72	−26	56	−42
	232 ± 4	−56	20	−99	72	−27	57	−42
	240 ± 4	−56	20	−99	72	−27	57	−42
	248 ± 4	−57	20	−100	72	−28	57	−43
	256 ± 4	−57	20	−100	72	−28	57	−43
	264 ± 4	−58	20	−101	72	−28	57	−44

Table VI—Maximum allowable single frequency levels that will not cause excessive beat interference with N3 carrier systems

					Metallic		Longitudinal	
System	Frequency Band (kHz)	Minimum Received Carrier Level (dBm)	Interference-to-Carrier Ratio to Meet Beat Objective (dB)	Susceptibility to Tones (dBv-135Ω)	Interference Path Loss (dB)	Maximum Allowable Tone (dBv-135Ω)	Interference Path Loss (dB)	Maximum Allowable Tone (dBv-90Ω)
N3	40 ± .1	−41	−53	−103	81	−22	56	−47
	48 ± .1	−41	−53	−103	81	−22	56	−47
	56 ± .1	−42	−53	−104	80	−24	56	−48
	64 ± .1	−43	−53	−105	79	−26	56	−49
	72 ± .1	−44	−53	−106	78	−28	56	−50
	80 ± .1	−45	−53	−107	78	−29	56	−51
	88 ± .1	−46	−53	−108	78	−30	56	−52
	96 ± .1	−47	−53	−109	77	−32	56	−53
	104 ± .1	−48	−53	−110	76	−34	56	−54
	112 ± .1	−49	−53	−111	76	−35	56	−55
	120 ± .1	−50	−53	−112	75	−37	56	−56
	128 ± .1	−51	−53	−113	75	−38	56	−57
	176 ± .1	−52	−53	−114	73	−41	56	−58
	184 ± .1	−53	−53	−115	73	−42	56	−59
	192 ± .1	−53	−53	−115	73	−42	56	−59
	200 ± .1	−54	−53	−116	73	−43	56	−60
	208 ± .1	−54	−53	−116	72	−44	56	−60
	216 ± .1	−55	−53	−117	72	−45	56	−61
	224 ± .1	−55	−53	−117	72	−45	56	−61
	232 ± .1	−56	−53	−118	72	−46	57	−61
	240 ± .1	−56	−53	−118	72	−46	57	−61
	248 ± .1	−57	−53	−119	72	−47	57	−62
	256 ± .1	−57	−53	−119	72	−47	57	−62
	264 ± .1	−58	−53	−120	72	−48	57	−63

3.4.2 Physical layout of cable

The transmitted carrier signal will be attenuated by the cable. The amount of attenuation to the receiver will depend upon the cable gauge and length between the carrier transmitter and receiver. The receiver increases its gain in proportion to the attenuation, thus increasing its sensitivity to noise. Hence, for interference Types 2 and 3 (see Figs. 9 and 10), the carrier terminal will be more sensitive to a disturbing signal when used on longer length cable. To assure that these types of interference do not exceed the noise objective for all applications of the carrier system, the carrier system must be evaluated where the system is operating at its longest design length.

For Type 1 interference, the carrier signal and the interference simultaneously decrease for longer length cable. To assure that this type of interference remains below the noise objective, the carrier system needs to be evaluated for those applications where the ratio of the interference signal-to-carrier signal is a maximum. This ratio was calculated under the following conditions:

(*i*) The voiceband terminal is located 3.5 kft from the central office, and

(*ii*) for single channel carrier systems, the carrier terminal is located in close proximity to the voiceband terminal, or

(*iii*) for multichannel carrier systems, the carrier terminal is located at least 3.5 kft from the central office.

3.4.3 Design of the carrier system

The characteristics of the receiving carrier terminal control the conversion of the incoming high-frequency signal into a voice frequency output. The characteristics that need to be considered are: the lowest expected received carrier level, the type of modulation used (single or double sideband), the demodulation efficiency, and compandor efficiency, if used.* Based on these characteristics, the maximum allowable interfering signal level can be calculated on the disturbed pair which will cause the voice frequency channel to equal its noise objective. This signal level is called the "susceptibility" of the system and is expressed in dBm.

The susceptibility is a function of the receiver characteristics. The response of a carrier receiver to noise is of the form:

$$P_0 = P_I - P_c + K,$$

where P_0, P_I, and P_c are the power levels in dBm of the receiver

* A compandor is used to reduce the effect of noise induced in the cable. This device compresses the range of the speech signal at the transmitting terminal and expands it back at the receiver.

output, the interfering noise in the sideband(s), and the carrier, respectively. The constant K depends on the particular receiver and compandor characteristics.* Once the value of K has been established for a particular system, the susceptibility of any particular system may be determined by solving for P_I with the output power P_0 of the receiver equal to the noise objective, and the carrier power P_c equal to the received carrier level.†

The noise objective for a carrier system depends on its application. The overall loop noise objective is 20 dBrnC. With a single channel system, the remote carrier terminal is normally located on the customer's premises. The channel noise objective for a single channel system, therefore, equals the loop noise objective. For a multichannel carrier system (MCC), the remote carrier terminal is usually located some distance from the customer's premises. Therefore, 15 dBrnC is allocated to that portion of the loop between the central office and the MCC remote terminal. This allocation allows for the additional noise occurring on the remaining portion of the loop from the MCC terminal to the customer's premises. The random noise objective for $N3$ carrier is the trunk noise objective of 28 dBrnC.[13] The allocation for intersystem interference is 20 dBrnC.

3.4.4 *Interference path loss*

The amount of noise introduced into a particular carrier system depends on the interference path loss between the disturbing and disturbed pairs. The interference path loss (IPL) in decibels is defined as:

$$\text{IPL} = 20 \log \frac{V_2}{V_1},$$

where

V_1 is the voltage appearing on the disturbed pair,
V_2 is the voltage of the signal applied by the disturbing voice terminal.

This loss is primarily due to the crosstalk coupling loss. However, pairs in close proximity to one another within the cable do not always

* The susceptibility in dBm is converted to dBV by subtracting 9 dB, since the nominal impedance of a carrier terminal is approximately 135 ohms and

$$\text{dBV} = \text{dBm} - 10 \log \frac{1000}{R} = \text{dBm} - 9$$

at 135 ohms.

† $N3$ carrier, all multichannel loop carriers, and some single channel loop carrier systems are compandored. Typically, a compandor will give a system an additional 30-dB noise advantage.

terminate at the same physical location. Thus, path loss can consist of the following two components:

(*i*) Crosstalk coupling loss.

(*ii*) Cable attenuation to the point of crosstalk exposure.

For Type 1 interference, the interference path loss is equal to the far-end coupling loss. As the length of the cable increases from the central office, far-end coupling loss will first decrease due to the increased amount of exposure between pairs and then begin to increase due to cable attenuation of the coupled signal. The coupling loss will be a minimum at about 3.5 kft. For Type 2 interference, the path loss is equal to the near-end crosstalk coupling loss plus the loss through the office and the cable to the voiceband terminal. To assure that the noise objective for the carrier system would not be exceeded, the cable attenuation for a short loop (2 kft, 26 gauge) was used.

For Type 3 interference, the path loss is equal to the near-end coupling loss plus the added loss between the point of crosstalk exposure and the voiceband terminal. Usually this added loss will be zero. In most instances, the voiceband terminal and the carrier terminal will be in relatively close proximity. This is because binder groups of 50 to 100 pairs would normally be assigned to serve neighboring homes, or adjacent businesses. On the other hand, for the *N*3 carrier systems, the carrier terminal is usually not located in close proximity to the voiceband terminal. Thus, it was assumed that at least 2 kft of cable exists between the disturbing terminal and the *N*3 carrier terminal.

3.4.5 Calculation of the maximum allowable voltages

The maximum allowable disturbing metallic and longitudinal voltages were calculated for each of the three types of interference for the single channel, multichannel, and *N*3 systems. The formula used was:

$$\text{Maximum voltage} = \text{Susceptibility} + \text{Interference Path Loss}.$$

At a given frequency, one of the types of interference was found to be controlling. Tables IV, V, and VI present the values for the controlling type of interference for each of the systems.

IV. DEVELOPMENT OF THE METALLIC AND LONGITUDINAL REQUIREMENTS

Section III developed the maximum allowable metallic and longitudinal disturbing signals for each of the systems considered. These calculated values above 4 kHz are graphically depicted as a function of frequency in Figs. 11 and 12. Figure 13 depicts the calculated longitudinal values between 100 Hz and 4 kHz. In each of these curves, the line segments represent the frequency band over which the voltage is applicable. For instance, in Fig. 11 the maximum allowable metallic

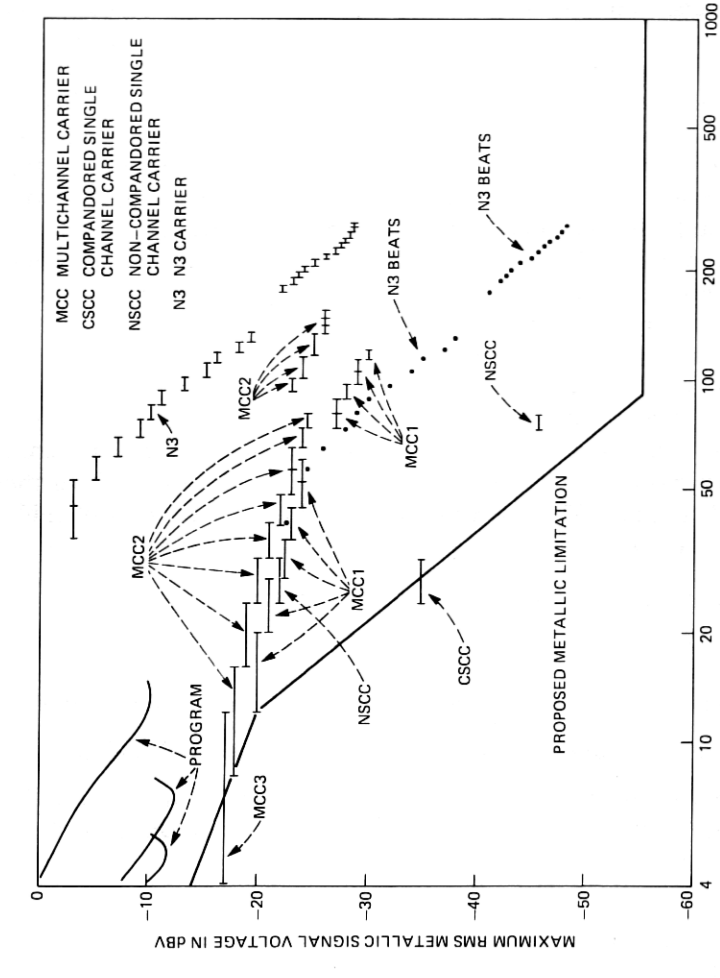

Fig. 11—Maximum permissible metallic voltage from 4 kHz to 1 MHz.

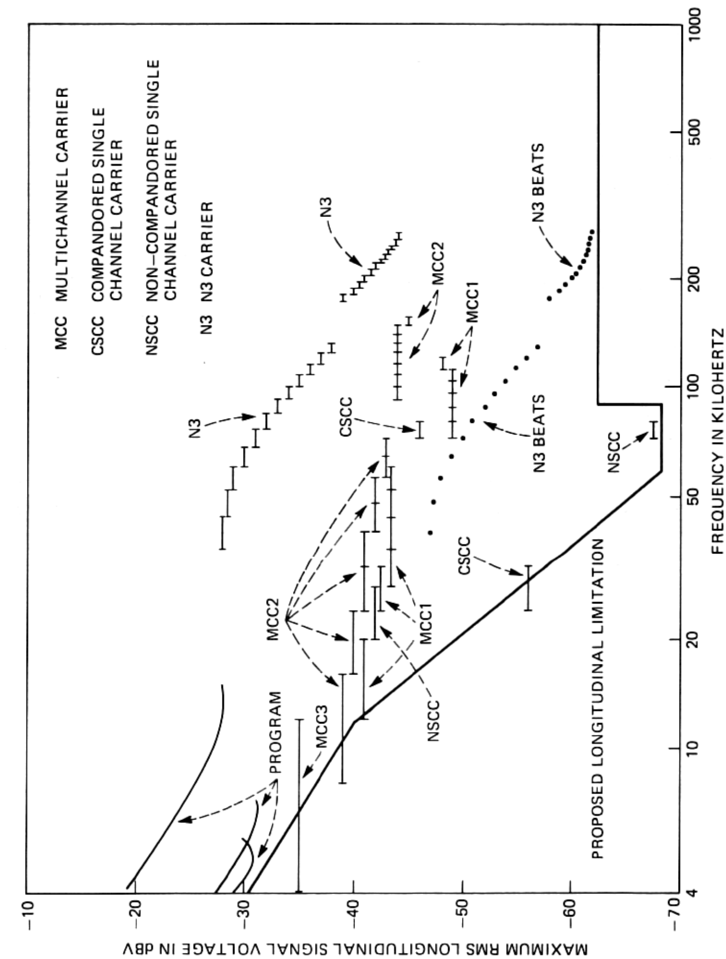

Fig. 12—Maximum permissible longitudinal voltage from 4 kHz to 1 MHz.

disturbing signal for a typical compandored single channel carrier system (CSCC) is −35 dBV between 24 kHz and 32 kHz.

The systems depicted on the figures are only examples of systems which could use this band. Other systems can and will be developed which have similar sensitivities but use different frequencies. Thus, requirements applicable over the entire band are needed. A requirement is needed to protect voice in the 100-Hz to 4-kHz band and to protect program circuits in the 100-Hz to 15-kHz band. Above 4 kHz, a requirement is needed which limits the total power into carrier systems.

As indicated in Figs. 11 and 12, the maximum allowable metallic and longitudinal voltage required to protect multichannel subscriber carrier systems (MCC1, MCC2 and MCC3) between 4 kHz and 15 kHz is sufficient to protect program circuits. Thus, the requirements from 100 Hz to 4 kHz are based on the susceptibility of voice and program services and from 4 kHz to 1 MHz, on the susceptibility of carrier systems.

The longitudinal requirement in the band from 100 Hz to 4 kHz was developed based on the maximum allowable voltages indicated in Fig. 13. This figure depicts the loci of the maximum allowable signal levels as a function of frequency for narrowband noise signals such as single frequency tones for program services and voice service. The voltage limitation which would satisfy all of these requirements is indicated on this figure. This voltage limitation curve permits a signal having frequency components near 100 Hz to be applied at a higher level than

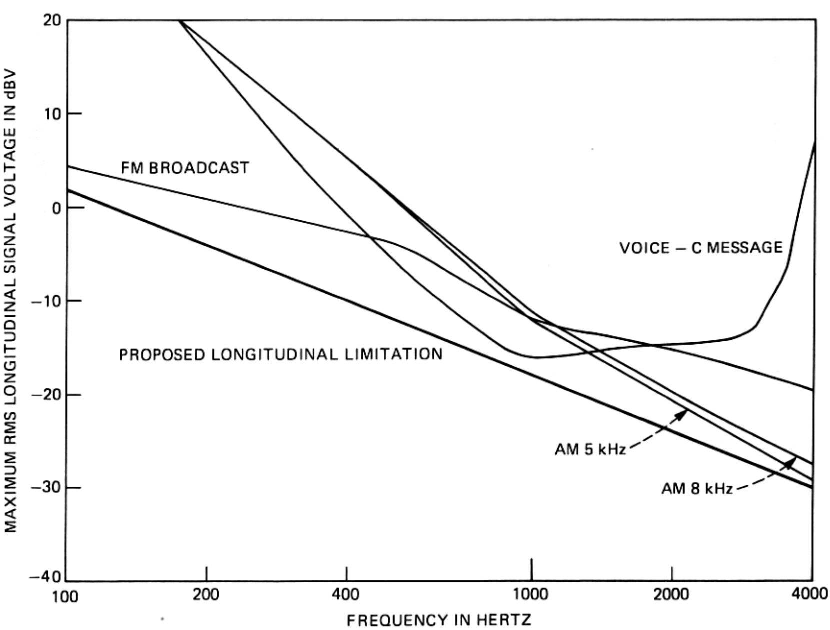

Fig. 13—Maximum permissible longitudinal voltage from 100 Hz to 4 kHz.

one having components near 4 kHz. To allow maximum flexibility for signals having relatively narrow bandwidths and yet control the total noise power in the program channel for signals having energy over the entire band, a weighting filter approach was developed. This approach achieves the relationship given by the integral in Section 3.1. With this approach, a signal in the 100-Hz to 4-kHz band is applied to a filter. The rms voltage at the output of the filter is measured to determine compliance with the criteria. The desired filter frequency transfer characteristics is the inverse of this voltage limitation.

In the 4-kHz to 1-MHz band, requirements are needed to limit the total power into carrier systems. Carrier systems are sensitive to noise in 8-kHz bands centered about their carrier frequencies. Since the frequencies of the carriers can be assigned anywhere within the 4-kHz to 1-MHz frequency range, the requirement must be stated over all possible 8-kHz bands. The magnitude of the maximum allowable voltage decreases with increasing frequency. The proposed metallic and longitudinal limitations in this band must be chosen to be at least equal to the maximum allowable voltages required by each of the systems.

At frequencies above 50 kHz, metallic voltage levels must be limited to values slightly lower than those determined solely by the foregoing carrier system metallic signal level susceptibility considerations. At these frequencies, the longitudinal balance of a series or parallel connected device is difficult to control. The longitudinal balance for many devices will decrease to close to 6 dB above 50 kHz. Spurious high-frequency metallic voltage applied by a voiceband terminal which is connected to a cable pair having at least one other terminal device on it will be converted into a longitudinal signal due to such imbalance. If the applied metallic voltage level was equal to a requirement based only on metallic carrier system susceptibility, the resulting longitudinal signal would exceed the maximum allowable longitudinal signal level specified in Fig. 12. The metallic signal voltage requirement must be no greater than 7 dB above the longitudinal voltage requirement at frequencies above 50 kHz.

In order not to cause interference into data services, the signal levels given in Figs. 11, 12, and 13 were expressed as requirements in terms of root-mean-square (rms) voltages averaged over 100 ms. The voltage requirement has been chosen (as opposed to power) as the more appropriate measure because cable crosstalk is, by definition, a voltage phenomenon. The 100-ms averaging interval corresponds approximately to the ability of the human ear to respond to noise.

V. CONCLUSION

The metallic and longitudinal signal level requirements developed in this paper are shown graphically in Figs. 11, 12, and 13. These requirements are given in the appendix as they were proposed on May 10, 1977 by AT&T in a petition for rulemaking to Part 68 of the FCC Rules and Regulations. These signal level requirements reflect more accurately than the current requirements the present vulnerability of carrier systems and services in the loop cable plant today.

VI. ACKNOWLEDGMENTS

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APPENDIX

May 10, 1977 AT&T Proposed Changes in Longitudinal and Metallic Signal Power Rules of Part 68 of the FCC Rules and Regulations

A1. Longitudinal voltage in the 100-Hz to 4-kHz frequency range

The weighted root-mean-squared voltage* averaged over 100 ms that is the result of all the component longitudinal voltages in this band after weighting according to the curve in Fig. 14 shall not exceed the maximum indicated under the conditions stated in Section A3. The weighting curve in Fig. 14 has an absolute gain of unity at 4 kHz.

Frequency Range	Max rms Voltage	Longitudinal Terminating Impedance
100 Hz to 4 kHz	−30 dBV	500 ohms

A2. Voltage in 4-kHz to 1-MHz frequency range

The root-mean-squared voltage as averaged over 100 milliseconds at the telephone connections of registered terminal equipment and registered protective circuitry, in all of the possible 8-kHz bands within the indicated frequency range and under the conditions specified in Section A3 shall not exceed the maximum indicated below.

(*i*) Metallic Voltage

Frequency of 8-kHz Band	Maximum Voltage in All 8-kHz Bands	Metallic Terminating Impedance
4 kHz to 12 kHz	$-(6.4 + 12.6 \log f)$ dBV	300 ohms
12 kHz to 90 kHz	$(23-40 \log f)$ dBV	135 ohms
90 kHz to 1 MHz	−55 dBV	135 ohms

where

f = center frequency in kilohertz of each of the possible 8-kHz bands beginning at 8 kHz

dBV = $20 \log_{10}$ voltage in volts

* Average magnitudes may be used for signals that have peak to rms ratios of 20 dB and less. Root-mean-square limitations must be used instead of average values if the peak-to-rms ratio of the interfering signal exceeds this value.

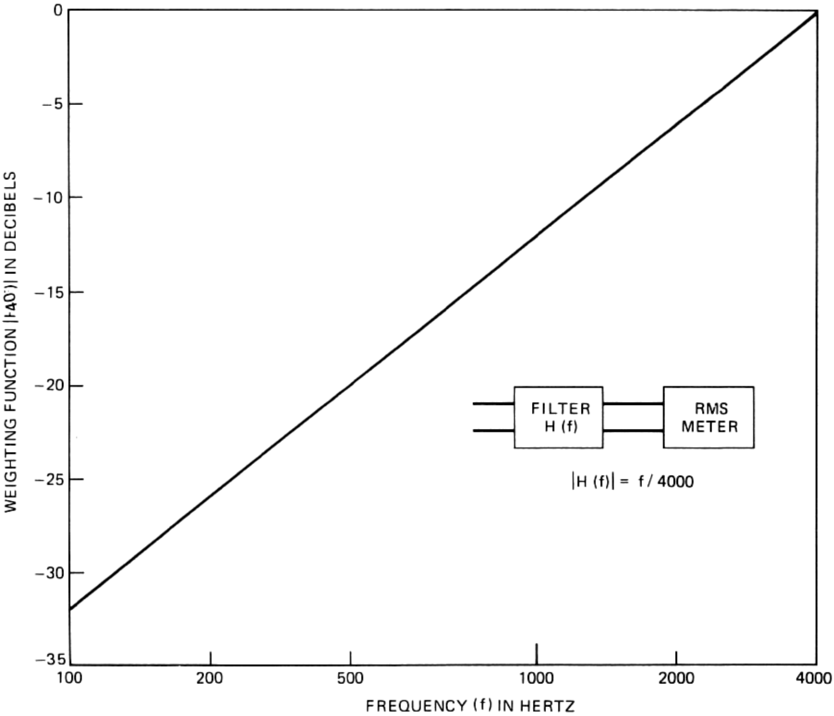

Fig. 14—Weighting function.

(*ii*) Longitudinal Voltage

Frequency of 8-kHz Band	Maximum Voltage in All 8-kHz Bands	Longitudinal Terminating Impedance
4 kHz to 12 kHz	$-(18.4 + 20 \log f)$ dBV	500 ohms
12 kHz to 60 kHz	$(3\text{–}40 \log f)$ dBV	90 ohms
60 kHz to 90 kHz	−68 dBV	90 ohms
90 kHz to 1 MHz	−62 dBV	90 ohms

A3. Requirements in Sections A1 and A2 apply under the following conditions:

(*i*) All registered terminal equipment and all registered protective circuitry must comply with the limitations when connected to a termination equivalent to the circuit depicted in Fig. 15 and when placed in all operating states of the equipment except during network control signaling.

(*ii*) All registered terminal equipment and all registered protective circuitry must comply with the limitations in off-hook states over the range of loop currents that would flow with the equipment connected to a loop simulator circuit.

(*iii*) Registered terminal equipment and registered protective circuitry with provision for through transmission from other

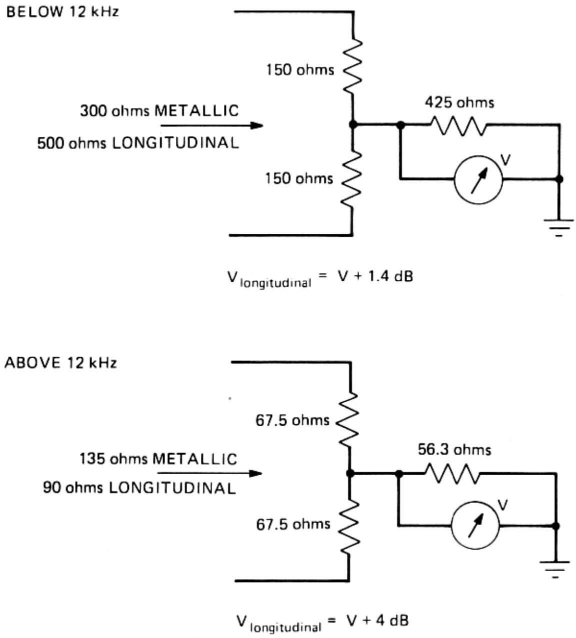

Fig. 15—Measurement terminations.

equipments shall comply with the limitations, with a 1000-Hz tone applied from a 600-ohm source (or, if appropriate, a source which reflects a 600-ohm impedance across tip and ring) at the maximum level that would be applied during normal operation. Registered protective circuitry for data shall also comply with the tone level 10 dB higher than that expected during normal operation.

(*iv*) Voice terminal equipment containing electroacoustic transducers for live voice input, including recording services, shall comply with the limitations with a 1000-Hz acoustic signal applied to the electro-acoustic transducers that results in a power delivered into the 600-ohm load impedance of −13 dB with respect to one milliwatt.

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