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Intelligible Crosstalk Performance of Voice-Frequency Customer Loops

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A methodology for evaluating the intelligible crosstalk performance of voice-frequency customer loops is developed in this paper. Using this methodology, intelligible crosstalk probabilities are calculated for a representative sample of loops in the plant. The effect of gain on loop crosstalk performance is then evaluated for a particular example of gain application where length-dependent gain ranging approximately from −1 to 9 dB is added. Two possible locations of gain application are evaluated: the central office and the telephone set. Presently, no crosstalk performance objectives exist for loops. For planning purposes, however, an intelligible crosstalk probability of 0.1 percent has been used in the past as a limit for satisfactory performance. In comparison with this limit, the crosstalk performance of the present loop plant (loops without gain) is satisfactory. For the particular example of gain application considered in this paper, gain applied at the central office has only a small effect on loop crosstalk performance. However, gain applied at the telephone set degrades loop crosstalk performance significantly, increasing the crosstalk probability above the 0.1 percent level on about 15 percent of the sample loops evaluated.

I. INTRODUCTION

A telephone user occasionally receives an extraneous speech signal as a result of interference between communications circuits, which is referred to as crosstalk. Crosstalk not only produces annoyance to the affected customer but also constitutes loss of another customer's privacy when it is intelligible, and is an important concern in transmission systems design and planning. For example, if, with the advancement of loop electronics, gain devices are applied on loops to enhance the speech signal level, the maximum allowable amount of gain and the location of its application may be restricted by the resulting crosstalk performance degradation. In this paper, a methodology is developed for evaluating the intelligible crosstalk performance of voice-frequency customer loops that can be used in loop transmission systems design and planning. In particular, the methodology can be used in (*i*) establishing loop crosstalk performance objectives, (*ii*) allocating the objectives to components of the loop plant, such as cable facilities, central office switches, and customer-premises wiring, and (*iii*) evaluating effects of new technology and new loop design rules on crosstalk performance.

Intelligible crosstalk performance is measured by the crosstalk probability, which is defined as the probability that a customer will hear one or more intelligible crosstalk words during a call. The crosstalk probability on customer loops depends on the probability distributions of such random variables as call holding time, quiet interval between calls, disturbing talker volume, crosstalk path loss, circuit noise, and disturbed-listener hearing acuity. These underlying probability distributions in turn depend on telephone connection configurations and crosstalk coupling loss characteristics of the multipair cables used for loops.

The loop crosstalk evaluation methodology developed in this paper can be divided into three basic parts as shown by the block diagram of Fig. 1: a cable crosstalk coupling model, a telephone connection model, and a crosstalk probability model. The cable crosstalk coupling model provides equations for calculating near-end and far-end crosstalk coupling losses between customer loop wire-pairs in multipair cables. The model contains adjustable parameters, which are estimated by fitting the model to measured crosstalk coupling loss data. The telephone connection model describes typical intraoffice (loop-to-loop) telephone

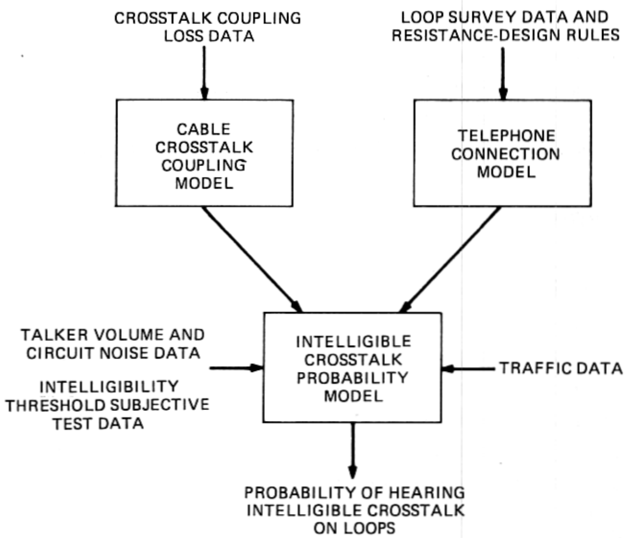

Fig. 1—Modeling of loop crosstalk.

connections as the disturbed connections and identifies potential crosstalk exposures to other intraoffice or toll connections. For the purposes of this study, loop characteristics, such as length, loading, and loss, are described, based on either theoretical loop design rules[1] or the information obtained from the loops sampled in the 1964 Loop Survey.[2] The crosstalk probability model, the last of the three parts shown in Fig. 1, combines the information provided by the preceding two models with data on traffic activity on loops, talker volume, circuit noise, and listener hearing acuity, and determines, by a Monte Carlo simulation, the crosstalk probabilities for loops.

The methodology developed in this paper provides the following features:

(*i*) By virtue of the analytical cable crosstalk coupling model introduced here, the loop crosstalk performance can be evaluated as a function of loop length, rather than only for the fixed length for which measurements are available.

(*ii*) The distribution of crosstalk probability is obtained for all the loops sharing a cable of arbitrary length, or for loops of different lengths sampled from the loop plant.

(*iii*) The telephone connection model developed here is general enough to include a number of different crosstalk exposures, such as near-end and far-end crosstalk occurring in the disturbed customer's loop and near-end and far-end crosstalk occurring in the loop of the customer at the other end of the disturbed connection.

(*iv*) The effect of gain on crosstalk is evaluated for gain applied at the telephone set as well as for gain applied at the central office.

(*v*) For disturbing talkers' speech volumes, the latest speech volume data obtained in 1976[3] is used.

A number of studies on the subject of crosstalk in general were made previously at Bell Laboratories, including those by T. C. Spang, B. E. Davis, M. G. Mugglin, D. H. Morgen,[4] and P. M. Lapsa.[5] Lapsa, in particular, considered a loop crosstalk problem similar to one specific case of the present study—the case of the effect of gain applied at the central office. Focusing primarily on long rural loops with gain applied at the central office and considering near-end crosstalk (NEXT) at the central office as the major crosstalk exposure, he assumed an "electrically long" loop—sufficiently long to render the NEXT coupling loss independent of length—and used measured NEXT coupling loss data. For disturbing talkers' speech volumes, Lapsa used McAdoo's speech volume data obtained in 1960.[6] He concluded that gain of 6 dB or less applied at the central office would be acceptable. In comparison with this, the results of the present paper on the effect of the central office gain are more optimistic because of, among other things, the use of more recent coupling loss and speech volume data in the present study, as discussed in

Section 3.1. In the case of the effect of gain applied at the telephone set, no similar study was made previously that can be compared with the present study.

Section II describes the three basic models constituting the methodology shown in Fig. 1 and determines the probability distributions of the underlying random variables. Section III evaluates the loop crosstalk probability in detail. Section IV is the summary of the loop crosstalk probability evaluation results.

II. METHODOLOGY

2.1 Twisted multipair cable crosstalk coupling model

Crosstalk performance of a customer loop depends on, among other things, the electromagnetic coupling characteristics between the loop and the other loops sharing the same twisted multipair cable. An analytical model was developed to provide equations for the near-end and far-end crosstalk coupling losses between wire-pairs in a cable as a function of frequency, cable length, and terminating impedances. Such a model is necessary because coupling loss measurements are available only for certain frequencies, cable lengths, and terminating conditions. A detailed derivation of the model is described in an unpublished work by the author.[7] In this section, this cable crosstalk coupling model is described in general terms.

A twisted multipair cable consists of a number of twisted wire-pairs stranded together. Each wire-pair is used as a loop, which is permanently assigned to a customer as the transmission path between his telephone set and the serving central office. Although the wire-pairs in a cable are isolated from one another, a certain amount of electromagnetic coupling between simultaneously active pairs is unavoidable.

As illustrated in Fig. 2, crosstalk is referred to as near-end crosstalk (NEXT) when the signal source on the disturbing pair and the point of crosstalk reception on the disturbed pair are at the same end of the cable, and far-end crosstalk (FEXT) when they are at the opposite ends of the cable. The difference in decibels between the disturbing power and the received crosstalk power is referred to as coupling loss. Referring to Fig. 2, NEXT and FEXT coupling losses from pair j into pair i, denoted by NEXT_{ij} and FEXT_{ij}, are defined by the following equations:

$$\text{NEXT}_{ij} = V_{j(\text{disturbing,near-end})} - V_{i(\text{disturbed,near-end})} \qquad (1)$$

$$\text{FEXT}_{ij} = V_{j(\text{disturbing,far-end})} - V_{i(\text{disturbed,far-end})}, \qquad (2)$$

where $V_{j(\text{disturbing,near-end})}$ and $V_{j(\text{disturbing,far-end})}$ are the disturbing signal powers at the source and the far end on the disturbing pair, pair j, expressed in decibels relative to a reference power; and $V_{i(\text{disturbed,near-end})}$ and $V_{i(\text{disturbed,far-end})}$ are the crosstalk signal powers at the near end and

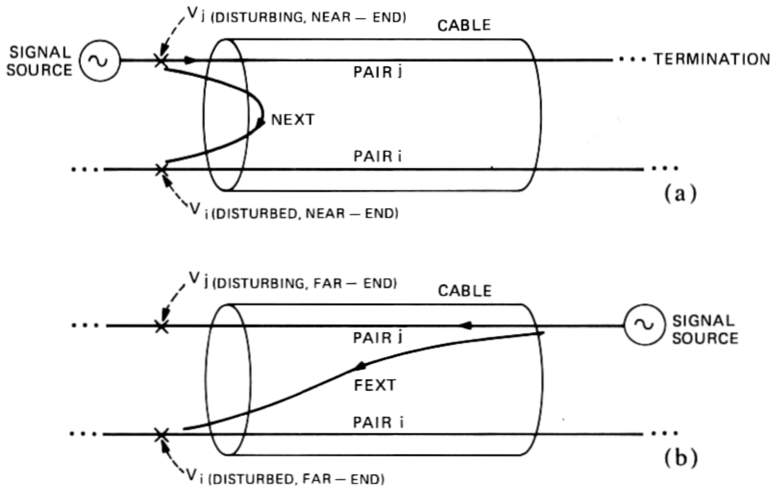

Fig. 2—Definition of NEXT and FEXT: NEXT or FEXT coupling loss from pair j into pair i is the decibel difference between the disturbing volume V_j and the crosstalk volume V_i measured at the points shown by X. (a) Near-end crosstalk (NEXT). (b) Far-end crosstalk (FEXT).

the far end on the disturbed pair, pair i, expressed in decibels relative to a reference power.

Crosstalk performance of a multipair cable can be characterized by determining NEXT and FEXT coupling losses defined by eqs. (1) and (2) for all possible combinations among its wire-pairs. In this paper, the coupling losses are determined analytically by the cable crosstalk coupling model mentioned earlier.[7] The model provides equations for NEXT and FEXT coupling losses as a function of frequency, cable length, and the terminating impedances of the disturbing and disturbed pairs. It contains certain adjustable parameters which are dependent on the proximity between pairs in a cable and which can be determined by fitting the model to measured crosstalk coupling loss data.

The model was fitted to recent crosstalk data measured at Bell Laboratories, Atlanta, on a typical cable used in the loop plant. The data consisted of the NEXT and FEXT coupling losses of 300 pair-to-pair combinations (all possible combinations) in a 25-pair, 26-gauge, nonloaded polyethylene insulated cable (PIC), measured at eight different frequencies (2, 3, 5, 10, 28, 56, 76, and 150 kHz). The length of the measured cable was 3 kft, and all pairs were terminated in pure resistive, 600 ohms at both ends. For each of the 300 pair-to-pair combinations, the model parameters were determined by the least-squares method. Two examples of the results of fitting the model to the data are shown in Fig. 3, where the abscissa is frequency and the ordinate NEXT coupling loss

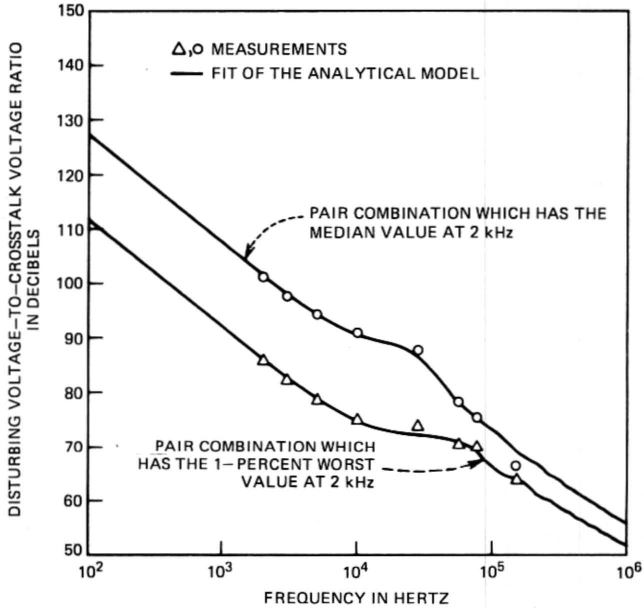

Fig. 3—Two examples of the results of fitting the analytical cable crosstalk coupling model to NEXT coupling loss data measured on a 3-kft, 25-pair, 26-gauge, nonloaded PIC cable with pure resistive 600-Ω terminations.

in decibels. The Δs and Os show the measurements* and the solid curves, the theoretical coupling losses fitted by the model. The rms errors between the measurements and the fitted values for these two particular pair combinations are 0.8 and 1.2 dB, respectively.

Figure 4 presents the cumulative distribution functions (CDFs) of the voice frequency (1 kHz) NEXT and FEXT coupling losses of all the 300 pair-to-pair combinations of the 25-pair cable, calculated by the model for an arbitrarily chosen reference cable length of 1 kft. The far-end and near-end terminating impedances were fixed at (900–j300) ohms and (600 + j200) ohms, respectively, the average terminating impedances of the loops at the central office and at the telephone set, estimated from the 1964 Loop Survey.[2]

Coupling losses vary with cable length. Figures 5 and 6 show length translation factors normalized to 1 kft, as calculated by the model for the voice-frequency NEXT and FEXT coupling losses. Figure 5 shows that, beyond a certain length, in this case about 30 kft, the translation factor for NEXT no longer changes with length. A cable longer than this is referred to as electrically long. From Fig. 5, the NEXT loss at such an electrically long length is about 7 dB smaller than the NEXT loss at 1 kft. Figure 6 shows that FEXT loss keeps decreasing with cable length without saturation.

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* Δs and Os in Fig. 3 identify the pair combinations with the 1-percent worst and the median NEXT coupling loss among the 300 measurements at 2 kHz, respectively.

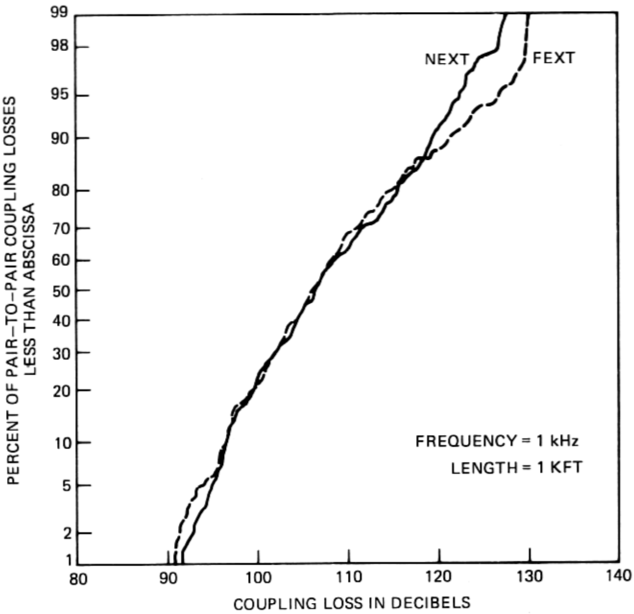

Fig. 4—The cumulative distribution functions (CDFs) of the voice-frequency (1 kHz) NEXT and FEXT coupling losses calculated by the theoretical model with cable length fixed at 1 kft for the 25-pair, 26-gauge, nonloaded PIC cable. The coupling losses at other cable lengths are obtained by using the length translation factors calculated by the model, shown in Figs. 5 and 6.

The NEXT and FEXT coupling losses at lengths other than 1 kft can be obtained by subtracting the corresponding length translation factors determined from Figs. 5 and 6 from the 1-kft coupling losses shown in Fig. 4. For example, the 1-percent worst NEXT coupling loss at 1 kft is, from Fig. 4, about 91 dB and the 1-percent worst NEXT coupling loss at an electrically long length, say 50 kft, is obtained to be 84 dB by subtracting the length translation factor of about 7 dB, determined from Fig. 5, from the 1-kft loss, 91 dB.

The data used to determine the model parameters were measured on an unspliced, laboratory cable. In the plant, several reels of cable may be spliced to form a single long cable. PIC cables are straight spliced; that is, pair identifications on the first reel are maintained over the subsequent reels. This type of splicing has theoretically no effect on the model prediction. For randomly spliced cables, such as pulp cables, the splicing may have some effect because pair locations change over the subsequent reels. At present, there are no appropriate field measurements that can be used to examine the effect of random splicing on crosstalk. However, other things being equal, random splicing should render the crosstalk prediction by the model somewhat conservative (pessimistic) because, with such splicing, the worst crosstalk pair combination of the first reel

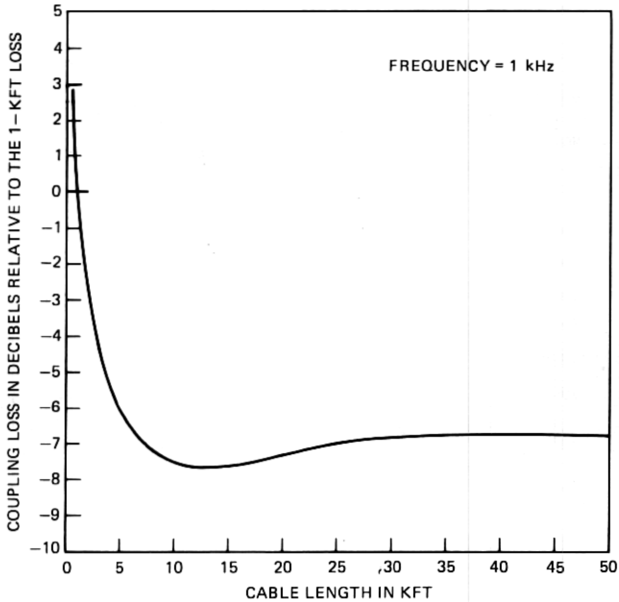

Fig. 5—Length translation factor normalized to 1 kft, calculated by the theoretical model for the voice-frequency NEXT.

would not necessarily be the worst combination in the subsequent reels.

The coupling losses discussed above represent the coupling losses of nonloaded cables, which make up the majority* of the loops in the plant. At the present time, there is no theoretical means of predicting the effect of loading on crosstalk coupling losses. Based on Bell Laboratories coupling loss data measured on loaded cables, it is assumed that, other conditions being equal, loaded cables, which make up a relatively small fraction of the loop plant, have approximately 3 dB smaller NEXT losses than nonloaded cables at 1 kHz. For FEXT, the same FEXT coupling losses are used for both nonloaded and loaded cables.

2.2 Telephone connection model

A model of telephone connections is described in this section to identify potential crosstalk exposures and determine the distributions of received crosstalk volume and other random variables affecting crosstalk performance. On connections involving trunks as well as loops, the crosstalk on trunks is dominant. To evaluate the loop crosstalk taken alone, intraoffice connections, consisting of two loops connected at the central office, are considered the disturbed connections. Intraoffice

* The 1964 Loop Survey (Ref. 2) shows that 84 percent of the loops sampled in the survey are nonloaded loops.

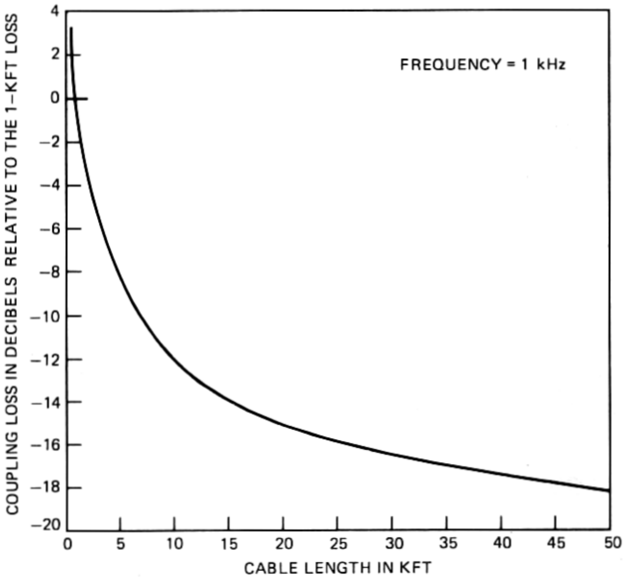

Fig. 6—Length translation factor normalized to 1 kft, calculated by the theoretical model for the voice-frequency FEXT.

connections have relatively low circuit noise, providing low masking on crosstalk intelligibility, and thus are in general most susceptible to intelligible crosstalk. As the disturbing connections, both toll and intraoffice connections are considered.

As shown in Fig. 7, a consumer at one end of an intraoffice connection is subject to the following four potential crosstalk exposures: NEXT and FEXT occurring in his own loop, and NEXT and FEXT occurring in the loop of the customer at the other end of the disturbed connection. Comparing Fig. 2 with Fig. 7, the cable end where the coupling losses are defined corresponds to the telephone set line-terminals for the first two crosstalk exposures and the central office loop terminations for the latter two exposures. For convenience, therefore, the first two exposures will be referred to in this paper as "line terminal NEXT" (LTNEXT) and "line terminal FEXT" (LTFEXT) and the latter two as "central office NEXT" (CONEXT) and "central office FEXT" (COFEXT). Of these four crosstalk exposures, LTNEXT is, in general, most important because, with this exposure, the disturbing talker's volume is attenuated only by the coupling loss between the two loops involved, and there are no additional losses in the crosstalk path. In the other three exposures (LTFEXT, CONEXT, and COFEXT), the disturbing talker's volume is attenuated by loop losses in addition to coupling losses, and thus the crosstalk from such an exposure is less likely to be intelligible than LTNEXT. On the other hand, if gain is applied on loops in the future, the relative importance of the four crosstalk exposures may change depending on the lo-

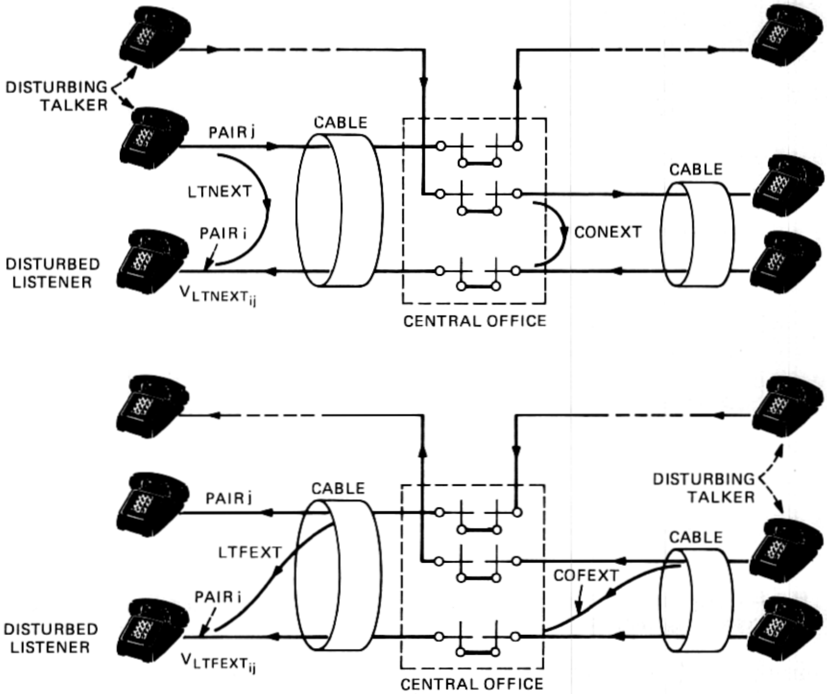

Fig. 7—Four types of potential crosstalk exposures of the intraoffice (loop-to-loop) connection: line-terminal NEXT (LTNEXT), line-terminal FEXT (LTFEXT), central office NEXT (CONEXT), and central office FEXT (COFEXT).

cation of the gain application. The effect of gain on crosstalk will be discussed in Section 2.4.

The crosstalk level in VU (volume units) received at the line-terminals of a disturbed customer's telephone set is the speech level (in VU) at the disturbing talker's telephone set minus the loss (in decibels) of the crosstalk path from the disturbing talker to the disturbed listener. The loss of the crosstalk path includes the loss from the disturbing talker to the point of crosstalk coupling, the coupling loss and the loss from the point of crosstalk coupling to the disturbed customer's telephone set. The crosstalk level on pair i received from pair j for the four crosstalk exposures, denoted by $V_{\mathrm{LTNEXT}_{ij}}$, $V_{\mathrm{LTFEXT}_{ij}}$, $V_{\mathrm{CONEXT}_{ij}}$ and $V_{\mathrm{COFEXT}_{ij}}$, are given by the following equations:

$$V_{\mathrm{LTNEXT}_{ij}} = V_{\mathrm{LT}_j} - \mathrm{LTNEXT}_{ij} \quad (3)$$

$$V_{\mathrm{LTFEXT}_{ij}} = V_{\mathrm{CO}_j} - L_2 - \mathrm{LTFEXT}_{ij} \quad (4)$$

$$V_{\mathrm{CONEXT}_{ij}} = V_{\mathrm{CO}_j} - \mathrm{CONEXT}_{ij} - L_2 \quad (5)$$

$$V_{\mathrm{COFEXT}_{ij}} = V_{\mathrm{LT}_j} - L_1 - \mathrm{COFEXT}_{ij} - L_2, \quad (6)$$

where V_{LT_j} and V_{CO_j} denote the disturbing talker volume at the line terminals and the central office, LTNEXT_{ij}, LTFEXT_{ij}, CONEXT_{ij} and COFEXT_{ij} denote NEXT and FEXT coupling losses at the line terminals and the central office [as defined by eqs. (1) and (2)], and L_1 and L_2 denote the losses of the loops in the two cables involved in the loop-to-loop disturbed connection. Since talker volume may be assumed to have a same distribution on all pairs in a given cable, the subscript j may be dropped from the disturbing talker volume in the above equations.

The electrical talker volume as measured at the serving central office was determined by a recent survey undertaken by Bell Laboratories to be nearly normally distributed with a mean of −22.2 VU (volume unit) and a standard deviation of 4.6 dB for intraoffice calls and a mean of −21.6 VU and a standard deviation of 4.5 dB for toll calls.[3] These latest speech volume data are used in this paper. These data show that there is very little difference in talker volume statistics between intraoffice and toll calls in contrast to the 1960 McAdoo speech volume data,[6] which showed a mean of −24.8 VU with a standard deviation of 7.3 dB for intraoffice calls and a mean of −16.8 VU with a standard deviation of 6.4 dB for toll calls. The standard deviation of the new speech data is considerably smaller than that of the McAdoo data.

The crosstalk volume equations for LTNEXT and COFEXT, eqs. (3) and (6), involve the electrical volume at the telephone set line terminals of the disturbing talker, V_{LT}. Presently, talker volume statistics at the telephone set line terminals are not available. To obtain the line-terminal talker volume statistics, as a function of loop length, from the central office statistics, the following expressions apply:

$$m_{V_{\text{LT}}}(x) = \{m_{V_{\text{CO}}} + m_{E_2}\} - E_1(x) \tag{7}$$

$$s_{V_{\text{LT}}} = (s^2_{V_{\text{CO}}} - s^2_{E_2})^{1/2}, \tag{8}$$

where $m_{V_{\text{LT}}}(x)$ and $s_{V_{\text{LT}}}$ denote the mean and standard deviation of the talker electrical volume at the telephone set line-terminals, $m_{V_{\text{CO}}}$ and $s_{V_{\text{CO}}}$ the mean and standard deviation of the talker volume measured at the central office, $E_1(x)$ the acoustic-to-electric transducer power loss,* as a function of loop length x, between the input acoustic pressure applied at the telephone set transmitter and the output voltage produced at the telephone set line terminals, and m_{E_2} and s_{E_2} the mean and standard deviation of the acoustic-to-electric transducer power loss between the acoustic pressure at the telephone set transmitter and the output voltage at the loop termination at the central office.

In (7), the term in the braces translates the mean electrical talker volume at the central office, $m_{V_{\text{CO}}}$, into the mean acoustic pressure at the transmitter by adding the mean acoustic-to-electric power loss, m_{E_2},

* These transducer power losses are similar to, but different from, the EARS (Electro-Acoustic Rating System) losses discussed in Section 2.4.1: these power losses are frequency-weighted in a different manner than the EARS losses.

averaged over a representative population of loops of various lengths. This translation assumes that the talker acoustic pressure at the transmitter is not correlated with loop length. The subtraction of $E_1(x)$, the acoustic-to-electric power loss at a given loop length x, from the term in the braces translates the mean acoustic pressure into the mean electrical speech volume at the line terminals for that specific loop length x. Figure 8 shows the mean electrical speech volume at the telephone set line terminals as a function of loop length, obtained by eq. (7) from the mean central office talker volume of −22.2 VU of intraoffice calls presented in Ref. 3. From (8), the standard deviation of the line-terminal talker volume is determined to be 3.9 dB.

Circuit noise received at the end of the intraoffice (loop-to-loop) connection is the power sum of three independent noises: (*i*) the far-end talker's carbon transmitter noise (N_1), attenuated by the losses of the two loops of the connection, (*ii*) the noise of the far-end talker's loop including the noise contributed by the central office (N_2), attenuated by the loss of the near-end loop, the disturbed listener's loop, and (*iii*) the noise of the near-end loop (N_3):

$$N = (N_1 - L_1 - L_2) \oplus (N_2 - L_2) \oplus N_3, \tag{9}$$

where L_1 and L_2 denote the losses of the two loops in the connection and

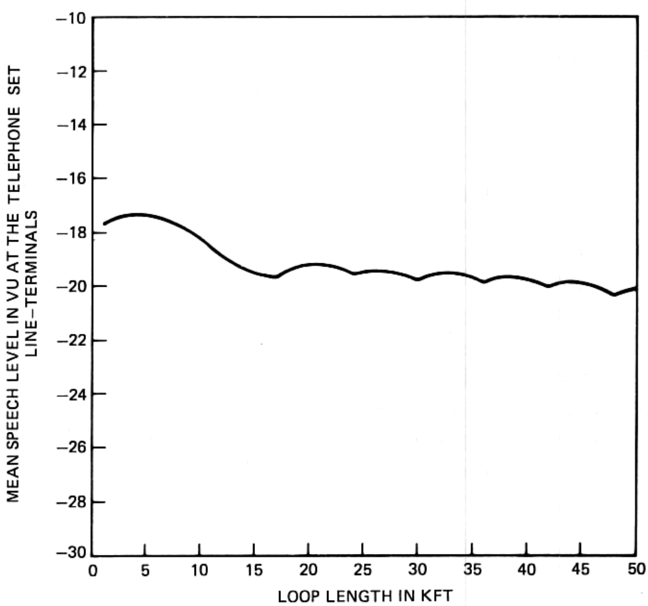

Fig. 8—Mean electrical talker volume at the telephone set line terminals as a function of loop length, obtained from eq. (7) with the central office mean talker volume, −22.2 VU, of intraoffice calls.

$\oplus$ represents the power sum operator.* The far-end talker's carbon transmitter noise is assumed to have a constant value of 10.2 dBrnC.† The 1964 Loop Survey[2] shows that loop noise has little correlation with loop length. Based on the 1964 Loop Survey data, loop noise is assumed to be normally distributed with a mean of −1.1 dBrnC without the central office noise and a mean of 5.6 dBrnC with the central office noise. The standard deviation of loop noise is assumed to be 12.5 dB, both with and without the central office noise. By a Monte Carlo evaluation of eq. (9) with the above component noise statistics, the mean and the standard deviations of the total received noise of the intraoffice connection were determined as a function of the disturbed listener's loop length. For example, for a loop-to-loop connection, with the length of both loops fixed at 7 kft, the mean and standard deviation of the received noise are determined to be 10.5 dBrnC and 8.5 dB, respectively.

2.3 Crosstalk probability model

The discussions hitherto have been concerned with the determination of crosstalk coupling losses, received crosstalk levels for potential crosstalk exposures, and received circuit noise. Whether or not a customer will actually receive intelligible crosstalk, however, is a random event. A mathematical model is developed in this section to evaluate the probability of hearing intelligible crosstalk on loops.

For a customer to receive intelligible crosstalk, the following two conditions must be met simultaneously. First, a potential disturbing circuit must become active during the period when the customer under consideration is engaged in a telephone conversation. Given that the first condition has been met, exposing the customer to crosstalk, the second condition is that the received crosstalk level must exceed the disturbed customer's intelligibility threshold in the presence of circuit noise. The probability that a customer on loop pair i will receive intelligible crosstalk from another loop pair, pair j, in the same cable, denoted by P_{ij}, is expressed by the following equation:

$$P_{ij} = \Pr\{\text{pair } j \text{ active/pair } i \text{ active}\} \times \Pr\{V_{ij} > T(N)\}, \qquad (10)$$

where V_{ij} denotes the crosstalk volume on pair i received from pair j and $T(N)$ denotes intelligibility threshold in the presence of circuit noise N.

The probability of activity coincidence between loops, the first probability in the right-hand side of (10), depends on the distributions of call holding time and quiet interval between calls on loops. This probability was determined in Ref. 5 for average busy-hour loop traffic to be

$$\Pr\{\text{pair } j \text{ active/pair } i \text{ active}\} = 0.17. \qquad (11)$$

* $A \oplus B \equiv 10 \log_{10}(10^{A/10} + 10^{B/10})$.

† L. M. Padula, Bell Laboratories, private communication.

The probability of crosstalk intelligibility, the second probability in the right-hand side of (10), depends on the distributions of crosstalk volume, circuit noise, and listener intelligibility threshold. The received crosstalk volume and circuit noise are determined by (3) through (6) and (9), with the distributions discussed in Section 2.2. Listener intelligibility threshold, which is determined by subjective tests, is defined quantitatively as the speech level at which a subject is just able to understand one or more words of the crosstalk content presented to him in the presence of masking noise.[8]

Intelligibility threshold increases as a function of noise. When noise is relatively high, the increase in intelligibility threshold with noise is linear, that is, decibel for decibel. At low noise levels, the relationship between intelligibility threshold and noise is nonlinear: in this region of noise, as noise is decreased toward an infinitely small value, intelligibility threshold approaches a constant rather than continuously decreasing, indicating a human ear's absolute threshold independent of noise. This functional relationship between intelligibility threshold and noise can be expressed by the following equation in terms of a random variable independent of noise, T_0, and a term varying nonlinearly with noise:

$$T(N) = T_0 + (N \oplus 12.3) \text{ VU}, \tag{12}$$

where $\oplus$ represents the power sum operator defined previously. The above equation is a mathematical expression of the intelligibility threshold data presented by T. K. Sen.[8] Sen's data show that T_0 is normally distributed with a mean of −95 VU and a standard deviation of 2.5 dB for a crosstalk coupling mechanism with a flat frequency spectrum. Sen also observed that the mean of T_0 should be lowered by 2 dB to −97 VU for a crosstalk coupling mechanism with coupling losses that roll off with frequency by 6 dB per octave. Since, as can be seen in Fig. 3, crosstalk coupling losses over the voice band have a 6-dB per octave roll-off, T_0 is assumed to have a mean of −97 VU and a standard deviation of 2.5 dB.

Substituting (12) into (10), we have the following expression for the probability of crosstalk intelligibility:

$$\Pr\{V_{ij} > T(N)\} = \Pr\{V_{ij} - T_0 - (N \oplus 12.3) > 0\}. \tag{13}$$

Because of the power sum, $(N \oplus 12.3)$, analytical evaluation of the above equation is not possible even for normally distributed random variables. A simple but crude way of treating the term $(N \oplus 12.3)$ would be to approximate it with a normal variate. However, such an approximation will result in pessimistic results because the normality assumption allows an infinitely low value for the term when, in fact, the random term $(N \oplus 12.3)$ can never be smaller than 12.3. In this paper, therefore, the above probability is evaluated by a Monte Carlo method.

To apply a Monte Carlo method, the above equation is manipulated in the following manner. For a fixed value of noise, say $N = n_k$, and assuming normal distributions for other random variables, it can be shown that the crosstalk intelligibility probability is given in terms of the standardized normal cumulative distribution function Φ as follows:

$$\begin{aligned} \Pr\{V_{ij} > T(N)/N = n_k\} &= \Pr\{V_{ij} - T_0 - (n_k \oplus 12.3) > 0\} \\ &= \Phi\left[\frac{\{m_{V_{ij}} - m_{T_0} - (n_k \oplus 12.3)\}}{(s_{V_{ij}}^2 + s_{T_0}^2)^{1/2}}\right], \end{aligned} \quad (14)$$

where

$$\Phi(a) \equiv \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{a} e^{-x^2/2}\, dx.$$

The Monte Carlo evaluation procedure of (13) then consists of generating a sequence of random numbers according to the distribution of noise N and evaluating the following average:*

$$\Pr\{V_{ij} > T(N)\} = \frac{1}{M} \sum_{k=1}^{k=M} \Phi\left[\frac{\{m_{V_{ij}} - m_{T_0} - (n_k \oplus 12.3)\}}{(s_{V_{ij}}^2 + s_{T_0}^2)^{1/2}}\right], \quad (15)$$

where M is the number of random samples drawn for noise N, $m_{V_{ij}}$ and $s_{V_{ij}}$ are the mean and standard deviation of the received crosstalk volume determined for a given crosstalk path using (3) through (6), and m_{T_0} and s_{T_0} are the mean and standard deviation of the random variable T_0 of (12).

Using the last equation and the activity coincidence probability of (11) in (10), the probability that a customer on pair i will receive intelligible crosstalk from pair j, P_{ij}, is given by

$$P_{ij} = 0.17 \times \text{eq. (15)}. \quad (16)$$

Finally, the crosstalk probability that the customer on pair i will receive intelligible crosstalk from any of the remaining N-1 pairs in the N-pair cable, denoted by P_i, is given by, assuming small P_{ij}:

$$P_i = \sum_{j=1}^{j=N} P_{ij},\ i = 1,2, \ldots ,N,\ j \neq i. \quad (17)$$

2.4 Effect of gain

The received crosstalk volume and circuit noise equations, (3) through (6) and (9), assume no gain devices on loops, as is the case in the current loop plant. With the advancement of loop electronics, the present loop

* Lapsa (Ref. 5) evaluated a similar probability by numerical evaluation of convolution integrals.

design rules may change in the future and require application of gain on loops. The effect of gain on crosstalk performance is discussed in this section for a particular example of gain application where the required gain is determined as a function of loop length to meet a certain constant loop loss.

2.4.1 Loudness loss of telephone connections

Voice communications over a telephone connection are accomplished by conversion of a talker's acoustic pressure at the transmitter into an electrical signal, transmission of the electrical signal over a transmission medium to the receiving telephone set at the far end and reconversion of the received electrical signal into an acoustic pressure at the listener's receiver. The loudness of the speech perceived by the listener depends on the magnitude of the talker's acoustic pressure and the loss and frequency characteristics of the transmitter, the receiver and the transmission medium. The loudness loss between the input and output acoustic pressure of a connection is quantified by means of the Electro-Acoustic Rating System (EARS), and is referred to as the EARS loss of the connection. For a complete and extensive discussion on the subject of EARS, the reader may refer to Ref. 9.

For interoffice or toll connections, the transmission path consists of one or more trunks in tandem between the two end offices, which are in general derived on carrier facilities, plus a loop at each end. The EARS loss of such a connection is given by the sum of the transmit loop rating (TLR) of the talker's loop (transmit loop) and the receive loop rating (RLR) of the listener's loop (receive loop), plus the electrical loss of the intervening trunks. For intraoffice connections, the transmission path consists of two loops connected together at the central office. The EARS loss of such a loop-to-loop connection is approximately the sum of the TLR and the RLR of the two loops.

The TLR is defined in terms of an acoustic pressure spectrum specified by the EARS methods at the transmitter of a telephone set and the resulting EARS frequency-weighted, electrical voltage (EARS voltage) produced at the transmit loop termination at its central office. The RLR is defined in terms of an EARS voltage applied at the central office termination of a receive loop and the resulting acoustic pressure produced at the telephone set receiver at the other end of the receive loop. The TLR and RLR have a unit analogous to decibels and are loss-like quantities in the sense that an algebraically larger TLR and RLR respectively correspond to a lower output EARS voltage at the central office and a lower output acoustic pressure at the receive telephone set.

Under the present loop design rules, both TLR and RLR vary with loop length, and consequently the EARS loss over the local portion* of a connection varies with the lengths of the two loops. A recent study[10] examined the possibility of providing a constant EARS loss for the local portions of all connections, regardless of loop length. Such a loss plan would permit EARS loss equalization of intraoffice (loop-to-loop) connections for all loop lengths, but would require changing loop design rules to allow for incorporation of gain. Since application of gain would raise the crosstalk level, the maximum amount of allowable gain may be limited by the consequent crosstalk performance degradation.

The amount of gain required for loop EARS loss equalization depends primarily on three factors: (*i*) the constant EARS loss objective for local portions, (*ii*) allocation of the EARS loss objective to the TLR and RLR, and (*iii*) the present values of TLR and RLR, which are determined largely by the length of the loop. In this paper, the required gain is determined as a function of loop length to meet a constant TLR of −21 dB and RLR of 27 dB, regardless of loop length, which amount to a constant EARS loss of 6 dB for intraoffice (loop-to-loop) connections for all loop lengths. This constant EARS loss of 6 dB, allocated as −21 dB to TLR and 27 dB to RLR, was examined as a possible alternative in the recent study mentioned previously[10] to evaluate long-term loss plans for the loop plant.

Presently, loops are designed according to the resistance-design rules[1] that control the electrical losses of loops by limiting loop resistance and requiring load coils when the length exceeds 18 kft. The resistance-design rules are applied with respect to the longest loop among the loops sharing a same cable, and thus the rest of the loops in the same cable would exhibit less loss. The longest loop, or the maximum-loss loop, in a cable assumed to conform to the resistance-design rules will be referred to as a theoretical resistance-design loop.

The TLR and RLR are shown in Figs. 9 and 10 as a function of loop length for a theoretical resistance-design loop.† The constant TLR and RLR are indicated by dashed horizontal lines. The amount of gain required to meet the constant TLR or RLR is then given by the difference between the horizontal line and the length-dependent curve. The required gain is shown in Fig. 11 as a function of loop length. The required transmit and receive loop gains range approximately from −3 to 9 dB and from −1 to 4 dB, respectively. At short loop lengths, the required gain is negative, indicating that a loss, rather than a gain, is required for the loop loss equalization.

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* In this study, the local portion of a connection refers to that part of the connection which comprises the loop plus the telephone set at each end of the connection.

† The TLR and RLR shown in these figures were calculated with a computer program developed by F. B. Stallman, Bell Laboratories.

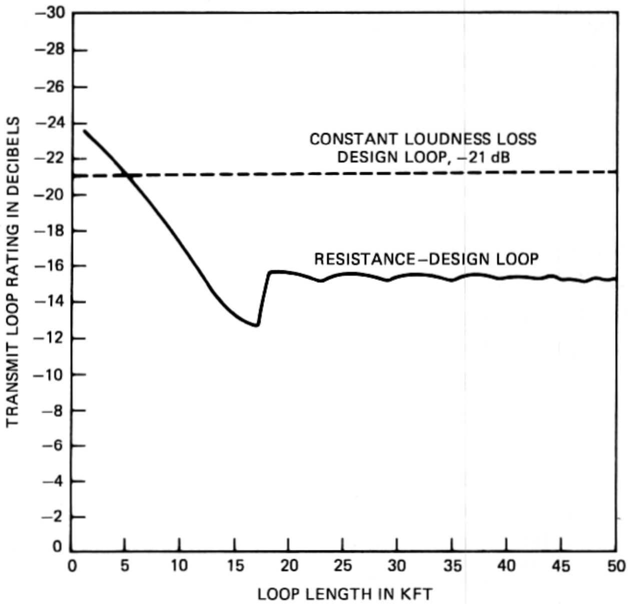

Fig. 9—Transmit loop rating (TLR) of the theoretical resistance-design loop and a constant loudness loss design loop.

2.4.2 Effect of gain on crosstalk volume and noise

For a given amount of gain, the effect on crosstalk performance depends on the location of its application. In this paper, we consider two possible locations: the telephone set and the central office.

Referring to Fig. 12, which is the same as Fig. 7 except for the gain, the crosstalk volume equations, (3) through (6), are modified for gain applied at the telephone set as shown below:

$$V_{\mathrm{LTNEXT}_{ij}} = V_{\mathrm{LT}} + G_{T_2} - \mathrm{LTNEXT}_{ij} + G_{R_2} \tag{18}$$

$$V_{\mathrm{LTFEXT}_{ij}} = V_{\mathrm{CO}} - L_2 - \mathrm{LTFEXT}_{ij} + G_{R_2} \tag{19}$$

$$V_{\mathrm{CONEXT}_{ij}} = V_{\mathrm{CO}} - L_2 - \mathrm{CONEXT}_{ij} + G_{R_2} \tag{20}$$

$$V_{\mathrm{COFEXT}_{ij}} = V_{\mathrm{LT}} + G_{T_1} - L_1 - \mathrm{COFEXT}_{ij} - L_2 + G_{R_2}. \tag{21}$$

The received noise equation, (9), is modified as follows:

$$N = (N_1 + G_{T_1} - L_1 - L_2 + G_{R_2}) \oplus (N_2 - L_2 + G_{R_2}) \oplus (N_3 + G_{R_2}). \tag{22}$$

Referring to Fig. 13, gain applied at the central office will not affect LTNEXT but will affect LTFEXT, CONEXT, and COFEXT. Since the latter three types of crosstalk exposures are in general less significant than the first, the effect of the gain is less pronounced when applied at the central office than at the telephone set. However, depending on loop length, the

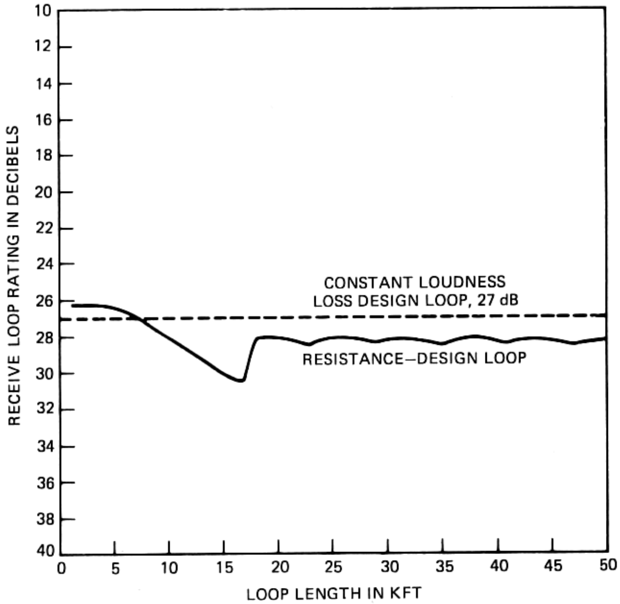

Fig. 10—Receive loop rating (RLR) of the theoretical resistance-design loop and a constant loudness loss design loop.

amount of required gain might be sufficiently large to make these crosstalk exposures significant. The following equations give crosstalk volumes and circuit noise when gain is applied at the central office:

$$V_{\text{LTNEXT}_{ij}} = \text{same as eq. (3)} \tag{23}$$

$$V_{\text{LTFEXT}_{ij}} = V_{\text{CO}} + G_{R_2} - L_2 - \text{LTFEXT}_{ij} \tag{24}$$

$$V_{\text{CONEXT}_{ij}} = V_{\text{CO}} + G_{R_1} - \text{CONEXT}_{ij} + G_{T_1} + G_{R_2} - L_2 \tag{25}$$

$$V_{\text{COFEXT}_{ij}} = V_{\text{LT}} - L_1 - \text{COFEXT}_{ij} + G_{T_1} + G_{R_2} - L_2 \tag{26}$$

$$N = (N_1 - L_1 + G_{T_1} + G_{R_2} - L_2) \oplus (N_2 + G_{T_1} + G_{R_2} - L_2) \oplus N_3. \tag{27}$$

III. RESULTS

The loop crosstalk probabilities were determined first for theoretical resistance-design loops and then for the 1100 loops sampled in the 1964 Loop Survey.[2] In each case, the crosstalk probabilities were determined both without gain and with gain. In the case of loops with gain, two possible locations of gain application were evaluated: the telephone set and the central office. Sections 3.1 and 3.2 present the crosstalk probabilities determined for the theoretical resistance-design loops and the actual loops, respectively.

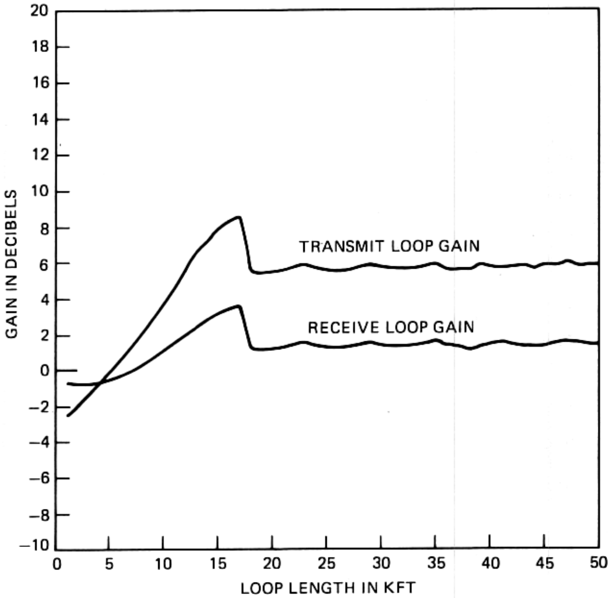

Fig. 11—The required gain on the transmit and receive loop derived from the curves of Figs. 9 and 10.

3.1 Theoretical resistance-design loop

As discussed in Section 2.3, the crosstalk probability for a loop is obtained by summing the crosstalk probabilities between that loop and the rest of the loops in the same cable, considering the four potential crosstalk exposures shown in Fig. 7: LTNEXT, LTFEXT, CONEXT, and COFEXT. The crosstalk probability for loop pair i, P_i, for example, is obtained first by determining the probability P_{ij} for all j, $j \neq i$, by eq. (16) in connection with eq. (3) through (6) for the four crosstalk exposures and then summing P_{ij} over j, as expressed by eq. (17). The crosstalk probability P_i so determined for loop pair i will be referred to as the total crosstalk probability of the pair, and represents the probability of receiving intelligible crosstalk on that loop from any of the remaining loops in the cable through any of the four possible crosstalk exposures.

Table I presents the total crosstalk probabilities calculated for each of the 25 loops of the 25-pair cable used in the cable crosstalk coupling model, with intraoffice type disturbing and disturbed connections. The crosstalk probability with the toll type disturbing connection was almost the same as that with the intraoffice type disturbing connection because, as discussed in Section 2.2, there was very little difference between the intraoffice and toll talker volume statistics.[3] All probabilities discussed hereafter are the probabilities with the intraoffice type disturbing connection.

For the particular results shown in Table I, the two loops of the dis-

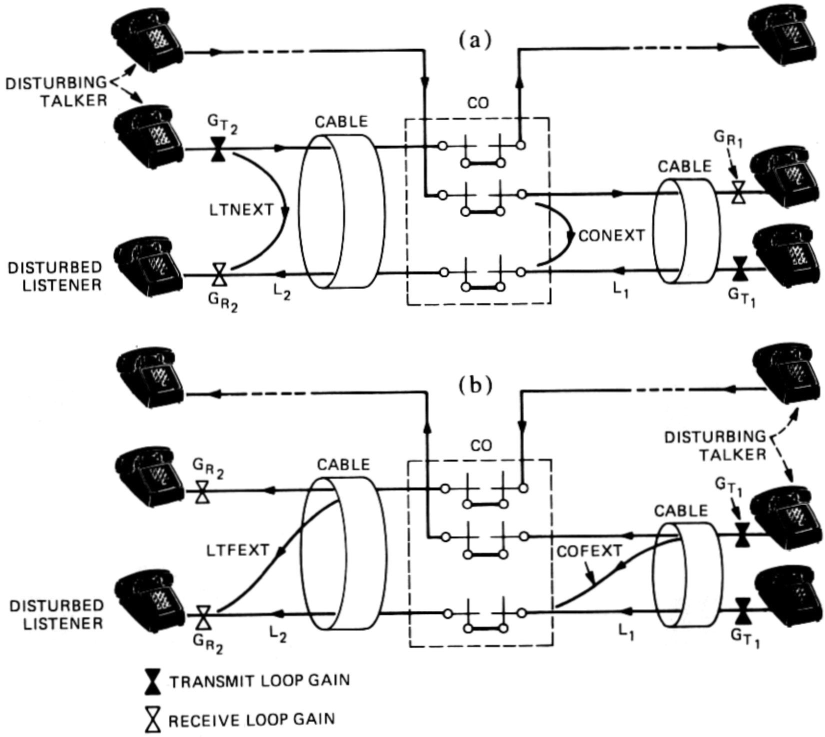

Fig. 12—Application of gain at the telephone set. (a) NEXT. (b) FEXT.

turbed connections were both assumed to be 7 kft, which was estimated to be a typical length of the Bell System loops, based on the 1964 Loop Survey.[2] The loop length dependence of the crosstalk probability is discussed later. As can be seen in this table, there is a wide difference in crosstalk probability between pairs in a cable: the highest crosstalk probability is 3.19×10^{-4} percent (pair 18), the median probability, 1.45×10^{-5} percent (pair 14), and the smallest probability, 1.15×10^{-6} percent (pair 25).

The crosstalk probability of the worst loop, pair 18, was evaluated as a function of the disturbed customer's loop length as presented in Fig. 14. Unlike the disturbed customer's loop, which is permanently assigned to the customer, the other loop of the disturbed connection occurs randomly, depending on the called party. The length of this latter loop was fixed at 7 kft, the representative length mentioned previously. The dashed curves show the crosstalk probabilities for the four exposures, LTNEXT, LTFEXT, CONEXT, and COFEXT, and the solid curve shows the total crosstalk probability, the sum of the four probabilities. As can be seen, the probability of LTNEXT is dominant at all loop lengths except at lengths less than about 2 kft at which the probability of COFEXT is dominant.

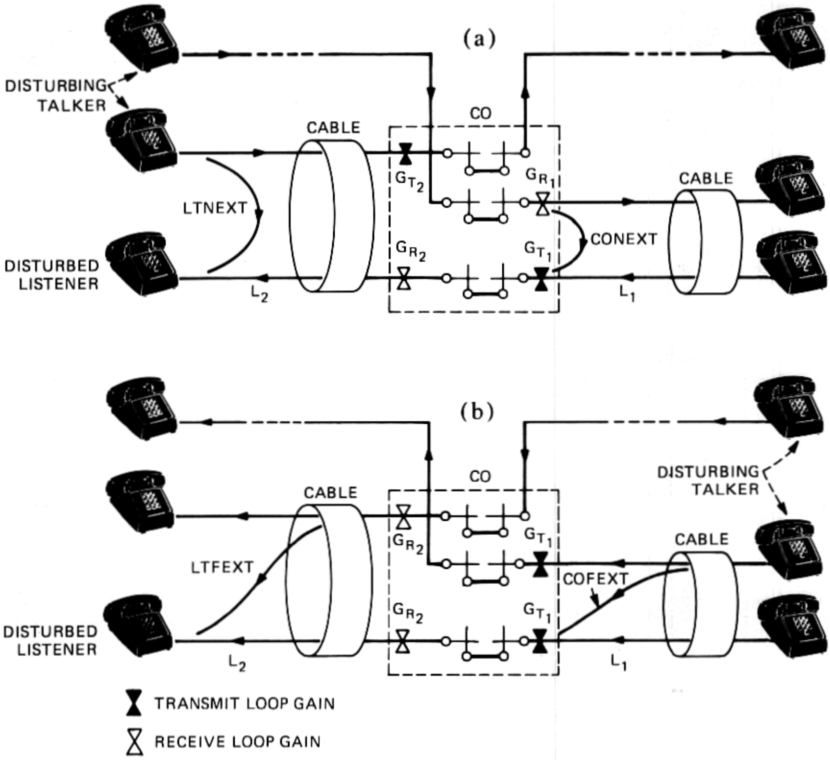

Fig. 13—Application of gain at the central office. (a) NEXT. (b) FEXT.

Since LTNEXT is the dominant crosstalk, the pattern of variation with loop length of the total crosstalk probability in Fig. 14 is determined by the pattern of the LTNEXT probability variation. The behavior of the LTNEXT probability with loop length can be explained by considering the corresponding crosstalk volume equation (3). As can be seen from Figs. 5 and 8, both NEXT coupling loss and line-terminal electrical speech level decrease with increasing loop length. At short loop lengths, since NEXT coupling loss decreases with loop length much faster than disturbing speech volume, the received crosstalk volume of LTNEXT, and consequently the LTNEXT probability, increases with loop length. As loop length is increased further, however, NEXT coupling loss approaches a saturation, that is, the length translation factor given in Fig. 5 does not change, whereas disturbing speech volume still decreases steadily with loop length. Therefore, the received crosstalk volume for LTNEXT, and consequently the LTNEXT probability, decreases as loop length is increased beyond a certain point; in this case, about 9 kft.

According to the resistance-design rules,[1] a cable is loaded when its length exceeds 18 kft. As discussed in Section 2.1, a loaded cable is assumed to have a NEXT coupling loss 3 dB less than a nonloaded cable.

Table I — The total crosstalk probabilities of the 25 loops of the 25-pair, 26-gauge, nonloaded PIC cable, obtained by treating each loop as a 7 kft, theoretical resistance-design loop engaged in an intraoffice (loop-to-loop) connection

Rank	Pair No.	Crosstalk Probability (%)
1	18	3.19×10^{-4}
2	8	2.82×10^{-4}
3	10	2.21×10^{-4}
4	4	1.93×10^{-4}
5	7	1.43×10^{-4}
6	19	1.23×10^{-4}
7	5	1.22×10^{-4}
8	20	1.20×10^{-4}
9	24	6.29×10^{-5}
10	22	4.54×10^{-5}
11	11	4.02×10^{-5}
12	2	3.69×10^{-5}
13	14	1.45×10^{-5}
14	15	1.29×10^{-5}
15	13	1.02×10^{-5}
16	12	1.00×10^{-5}
17	9	4.41×10^{-6}
18	23	3.64×10^{-6}
19	6	3.06×10^{-6}
20	17	2.60×10^{-6}
21	16	2.45×10^{-6}
22	1	2.01×10^{-6}
23	21	1.96×10^{-6}
24	3	1.33×10^{-6}
25	25	1.15×10^{-6}

The sudden increase in the LTNEXT probability at 18 kft is due to the 3-dB drop in NEXT coupling loss with loading. At loop lengths greater than 18 kft, both disturbing talker's electrical signal level and NEXT coupling loss are fairly constant with loop length, and the LTNEXT probability does not change much with loop length.

The effect of gain on the crosstalk probability of the theoretical resistance-design loop is shown in Fig. 15. The solid curve is the total crosstalk probability without gain, the same curve as that shown in Fig. 14, and the two dashed curves are the total crosstalk probability with gain at the telephone set and at the central office, respectively. Without gain, the total crosstalk probability of the theoretical resistance-design loop does not exceed 0.002 percent at all loop lengths. Gain applied at the central office shows very little effect on the crosstalk probability. This is because gain applied at the central office does not affect LTNEXT, the dominant crosstalk, as shown by eq. (23). However, with gain applied at the telephone set line terminals, the total crosstalk probability of the theoretical resistance-design loop can increase up to as much as 0.5 percent, depending on loop length.

Currently, no crosstalk objectives exist for loops. However, for planning purposes, a crosstalk probability of 0.1 percent has generally been used in the past as a limit for satisfactory loop crosstalk performance.

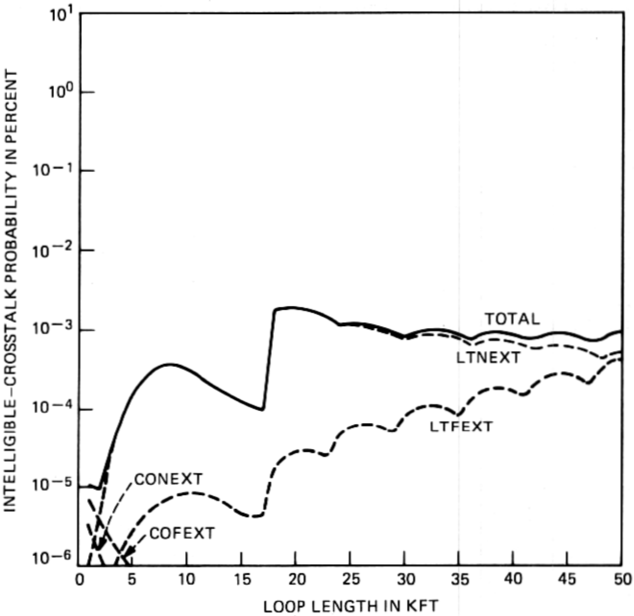

Fig. 14—Crosstalk probabilities of the theoretical resistance-design loop, without gain, evaluated for the worst pair (pair 18) of the 25-pair, 26-gauge PIC cable.

In comparison with this limit, the crosstalk performance of the present resistance-design loops is, from Fig. 15, more than satisfactory.

For the particular example of gain application considered in this paper, gain applied at the telephone set can cause a significant degradation in loop crosstalk performance, depending on loop length. To relate the increase in crosstalk probability to the amount of gain applied, one may compare Figs. 11 and 15. Figure 15 shows that, with gain applied at the telephone set, the crosstalk probability exceeds the 0.1-percent level, the limit mentioned previously, at about 12 kft of loop length. From Fig. 11, one may find that the required gain assumed at this length is 6 dB for the transmit loop and 2 dB for the receive loop, which amounts to a total gain of 8 dB on a crosstalk path. The maximum allowable telephone set gains at other loop lengths and for other values of permitted crosstalk probability can be determined similarly.

With gain applied at the central office, the crosstalk performance of the theoretical resistance-design loop still remains well below the level of 0.1-percent crosstalk probability, for the entire range of gain considered, where the maximum transmit and receive loop gains were about 9 and 4 dB. In a similar evaluation made previously, Lapsa[5] concluded that 9 dB of gain applied at the central office would be excessive. Because of the differences in the methodology as well as in the coupling loss and speech volume data used in the evaluation, a direct comparison between

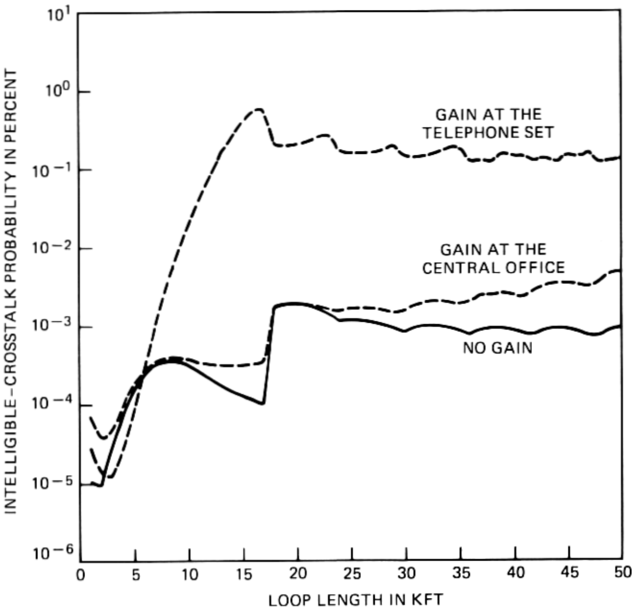

Fig. 15—The effect of gain on the crosstalk probability of the theoretical resistance-design loop, evaluated for the worst pair (pair 18) of the 25-pair, 26-gauge PIC cable.

the previous results and the present results is not possible. Nevertheless, the present results on the effect of the central office gain are, in general, somewhat optimistic in comparison with the previous results because of, among other things, the use of more recent coupling loss and speech volume data in the present study.*

3.2 The 1964 survey loops

The 1964 Loop Survey results[2] provide such information as length and loading conditions on 1100 loops sampled in the plant. Using this information, the crosstalk probabilities were calculated for the 1100 sample loops, first without gain and then with gain assumed either at the telephone set or at the central office. Each loop was treated as though it was the worst pair in a cable, such as pair 18 of Table I. This worst-case evaluation was made because, due to the permanent assignment of a loop to a customer, poor crosstalk performance would focus on a single customer rather than being distributed among many customers.

The total crosstalk probabilities calculated for the 1100 sample loops are shown in Fig. 16 as a scatter plot, where the abscissa is the length and

* The more recent coupling loss data used in the present study show better crosstalk performance than the coupling loss data used in the previous study. As discussed in Section 2.2, the speech volume data used in the present study show a much smaller standard deviation than the McAdoo data used in the previous study, the smaller speech volume variability yielding a smaller crosstalk probability.

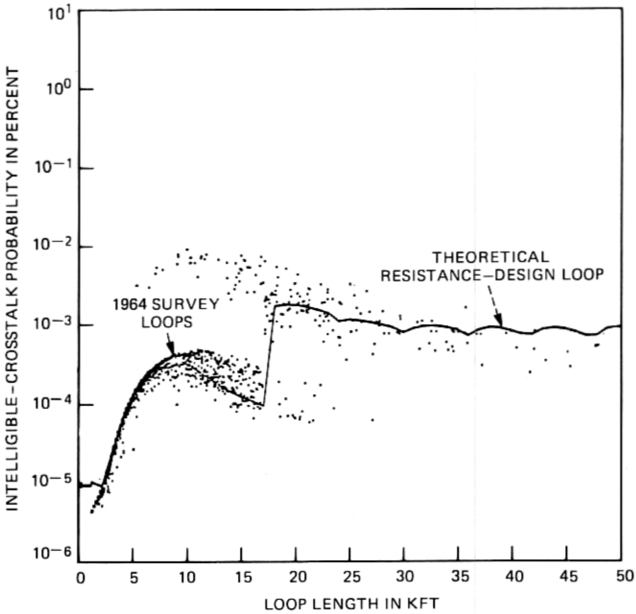

Fig. 16—Scatter plot of the total crosstalk probabilities of the 1964 survey loops, without gain, obtained by assuming that each loop was the worst pair in a cable.

the ordinate the crosstalk probability. For comparison, the total crosstalk probability of the theoretical resistance-design loop is superimposed as a solid curve, which is the same curve as that shown in Fig. 14. The cumulative distribution functions (CDFs) of the crosstalk probabilities of the 1100 sample loops without gain are presented in Fig. 17, where the solid curve shows the CDF of the total crosstalk probability and the dashed curves show the CDFs of the LTNEXT, LTFEXT, CONEXT, and COFEXT probability.

The effect of gain on the crosstalk performance of the sample loops was evaluated with the required gain determined by the difference between the constant TLR of −21 dB and RLR of 27 dB mentioned previously and the actual TLR and RLR, which were calculated from the information provided by the 1964 Loop Survey. The results are compared with the crosstalk probability determined for the present plant (loops without gain) in Fig. 18. The solid curve is the CDF of the crosstalk probability of the sample loops without gain (the same curve as that shown in Fig. 17) and the two dashed curves show the CDFs of the crosstalk probabilities with gain applied at the telephone set and at the central office, respectively.

Without gain, the total crosstalk probability is less than 0.01 percent for all the sample loops; the median is 3×10^{-4} percent. This indicates that the crosstalk performance of the present loop plant is more than

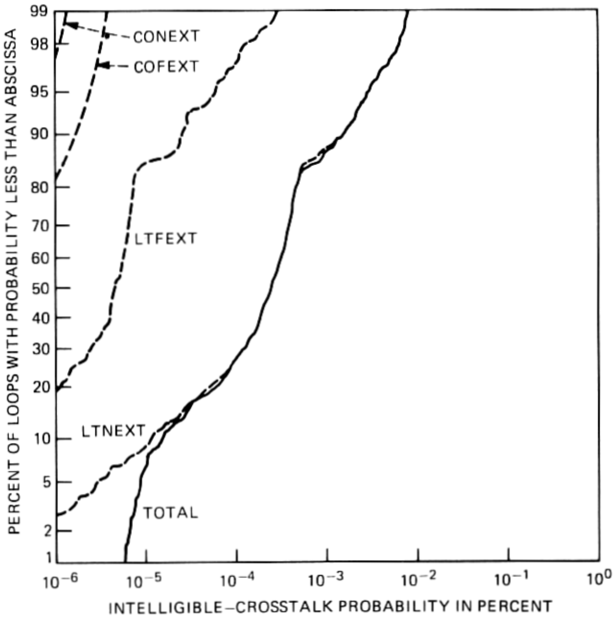

Fig. 17—Cumulative distribution functions of the crosstalk probabilities of the 1964 survey loops, without gain, obtained by assuming that each loop was the worst pair in a cable.

satisfactory in comparison with the 0.1 percent crosstalk probability limit. Gain applied at the central office shows only a small effect on the distribution of the loop crosstalk probabilities in the plant. However, gain applied at the telephone set changes the distribution of the loop crosstalk probabilities significantly, increasing the crosstalk probability above the 0.1-percent level on about 15 percent of the sample loops evaluated.

IV. SUMMARY OF THE RESULTS

The intelligible crosstalk probability is defined as the probability that a customer will hear one or more intelligible crosstalk words during a call. The intelligible crosstalk probability for a loop is obtained by summing the probabilities of intelligible crosstalk between that loop and the rest of the loops in the same cable, considering the four potential crosstalk exposures shown in Fig. 7. Using the methodology developed in Section II, the crosstalk probabilities have been calculated first for theoretical maximum-loss resistance-design loops[1] as a function of loop length and then for the 1100 loops of various lengths sampled from the loop plant in the 1964 Loop Survey.[2]

The crosstalk probabilities were obtained first for loops as they exist in the present plant, that is, loops without gain. The effect of gain devices on the loop crosstalk probabilities was then evaluated for a particular

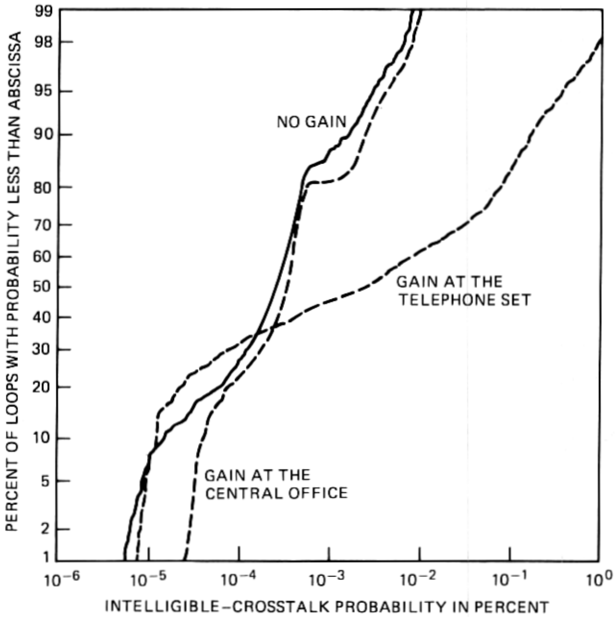

Fig. 18—The effect of gain on the distribution of the total crosstalk probabilities of the 1964 survey loops, obtained by assuming that each loop was the worst pair in a cable.

example of gain application. In this example, the assumed gain was determined as a function of loop length to meet a constant TLR (Transmit Loop Rating) of −21 dB and RLR (Receive Loop Rating) of 27 dB, regardless of loop length, which would equalize the EARS (Electro-Acoustic Rating System)* loss of intraoffice (loop-to-loop) connections at a constant value of 6 dB. For this particular example, gain required for a loop in its transmit direction and receive direction ranged roughly from −3 to 9 dB and from −1 to 4 dB, respectively. Two possible locations of gain application were evaluated: the central office and the telephone set.

Table I shows rank-ordered crosstalk probabilities of the 25 theoretical resistance-design loops without gain in a 25-pair cable, determined with loop length fixed at 7 kft, a representative length of Bell System loops. Figure 15 presents the crosstalk probability of the worst of the 25 loops (pair 18 in Table I) as a function of loop length for the three different cases: loops without gain (the present plant), loops with gain at the central office, and loops with gain at the telephone set. Figure 18 presents the cumulative distribution functions (CDFs) of the crosstalk probabilities of the 1100 sample loops obtained by treating each sample loop as the worst loop in a cable (such as pair 18 of Table I).

Presently, no crosstalk objectives exist for loops. For planning pur-

* See Section 2.4.1 of this paper and Ref. 9 for the discussion of EARS, TLR, and RLR.

poses, however, a crosstalk probability of 0.1 percent has generally been used as a limit for satisfactory loop crosstalk performance. In comparison with this limit, the crosstalk performance of the present loop plant (loops without gain) is more than satisfactory, as can be seen in Fig. 18. With gain at the central office, the crosstalk probability still remains well below the 0.1-percent level for all the sample loops, and thus gain applied at the central office does not appear to have any significant effect on loop crosstalk performance for the entire range of gain considered. However, with gain applied at the telephone set, the crosstalk probability exceeds the 0.1-percent level on about 15 percent of the loops evaluated. These results indicate that, for the particular example of gain application considered in this paper, gain applied at the telephone set may cause a significant crosstalk performance degradation.

V. ACKNOWLEDGMENTS

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