THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 57, No. 7, September 1978
Printed in U.S.A.

Speech Signal Power in the Switched Message Network

By W. C. AHERN, F. P. DUFFY, and J. A. MAHER

(Manuscript received December 15, 1977)

Speech signal power at the main distributing frame in class 5 switching offices is characterized in terms of equivalent peak level (EPL) and average conversational signal power measures. The results indicate that there is little dependence of speech signal power on call destination or originating class of service. Small differences between various subpopulations are explained for the most part by loop characteristics. The switched telecommunications network is essentially transparent to customers in the sense that talker signal power has not been found to be sensitive to factors which affect the transmission path between class 5 central offices.

Present-day speech volumes for toll calls, which average −21.6 VU (volume units), are substantially lower than those found in a survey conducted in 1960,[1] which averaged −16.3 VU, and the ranges of volumes within all call destination categories are substantially smaller than the 1960 ranges. Several substantial changes have been introduced into the telephone plant since 1960 which tend to increase the uniformity of service in the network from the viewpoint of speech volumes. These include a decrease in the proportion of toll grade battery, loss plan improvements, replacement of the 300-type telephone set with the 500-type set, and an increase in direct trunking between class 5 offices.

I. INTRODUCTION

The characterization of speech signal power on Bell System message circuits is an essential step in the determination of signal power loading and crosstalk objectives. Knowledge of speech signal characteristics is also important to designers of a wide variety of telecommunications equipment.

Speech levels at the class 5 office were last characterized in the 1960 Speech Volume Survey[1] in terms of volume units (VU). In the years since the last survey, there have been substantial changes in the Bell System network. For example, the proportion of toll grade battery has been substantially reduced, the 300-type telephone set has been almost completely phased out, direct distance dialing is now virtually universal, and new loop and trunk design methods have been introduced. Also, in the intervening years, research in speech signal measurement has led to a new measure of speech level known as the equivalent peak level (EPL).[2] This, together with advanced digital data acquisition technology, has facilitated the measurement of speech signal power with greater precision than was possible in 1960.

This paper presents the results of a speech signal power survey made in 1975–1976. The measurements were made at 36 class-5-office main distributing frames (MDFs), which constitute a statistical sample of acceptable precision from all the MDFs within the Bell System. The class 5 (local or end) office MDF was selected as the measurement interface because it has access to all customer loops and all classes of local and toll traffic; dialed address information is readily available; only the customer's loop and station equipment is interposed between the customer and the point of measurement; and the customer's loop current may be measured. A three-stage statistical sampling scheme was employed, which resulted in measurements of near-end and far-end talker power on more than 10,000 calls originating from approximately 2500 loops. Average conversational signal power (averaged over the entire observation interval) and EPL were the measures used for talker signal characterization. Loop dc current, class of service, switch type, and call destination were also recorded.

Survey results are presented in Section II, the methodology is presented in Section III, and comparisons of the present survey results with prior survey results are given in Section IV.

II. SURVEY RESULTS

Table I summarizes the findings of this survey. The results indicate that there is little dependence of speech signal power on call destination or originating class of service. In the sections that follow, it is shown that the small differences between various subpopulations are explained for

Table I—Summary of speech signal powers

Subclass	Near-End Mean Equivalent Peak Level (dBm)
Residence	−11.0
Business	−10.4
Local	−10.8
Toll	−10.1
Combined	−10.7

the most part by loop characteristics, and there is little if any variation in speech signal power that may be attributable to psychological factors such as call distance, perception of received volume, etc. The indication from the data is that the switched telecommunications network is essentially transparent to customers in the sense that talker signal power has not been found to be sensitive to call distance, local or toll call classification, or other factors that affect the transmission path from class 5 to class 5 central office.

2.1 General

In this survey, speech signal power measurements were made on customer loops at class 5 switching office main distributing frames (MDFs) during actual telephone conversations. The parties originating calls on sampled loops are referred to as the "near-end" speakers in the following discussion; the called parties are referred to as the "far-end" speakers. The far-end speakers were more distant than the near-end speakers from the MDFs at which the measurements were made, except for some intrabuilding calls.

The survey results characterize near- and far-end speech signal powers in terms of the equivalent peak level (EPL) and average conversational signal power measures, which are discussed in Section 3.3.3. The differences are also characterized between near- and far-end signal powers and between the EPL and average power measures. In addition, the influences of loop current, originating class of subscriber service, call destination, call distance, originating switch, and demographic features upon speech signal powers are investigated.

2.2 Speech signal powers at main distributing frames

The distributions of speech signal power at main distributing frames can be approximated by normal distributions. Histograms and cumulative distribution functions (CDFs) are given for the EPL and average power measures of speech signal power for the near- and far-end speakers in Figs. 1 through 4. The "bell" shapes of the histograms and the straight line shapes of the CDFs, which are plotted on normal probability grids, attest to the normality of these distributions. Because of this, the distributions are completely defined by the means and standard deviations listed in the first four lines of Table II.

While the near- and far-end signals encounter similar populations of station set and subscriber loop losses, the far-end signals also encounter end-office-to-end-office transmission losses. As a result of these additional losses, which will be referred to as the "apparent network loss" during the remainder of this paper, the average far-end signal power is generally lower than the average near-end signal power. The apparent network loss is a function of call destination, i.e., the greater the call

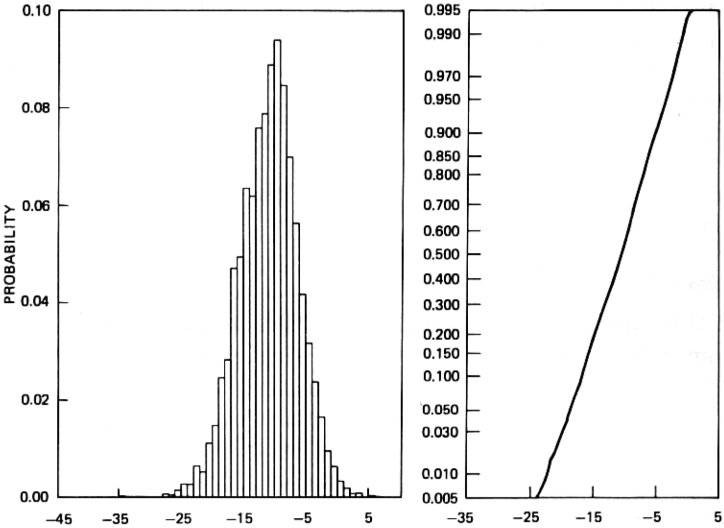

Fig. 1—Near-end equivalent peak level (dBm) distribution.

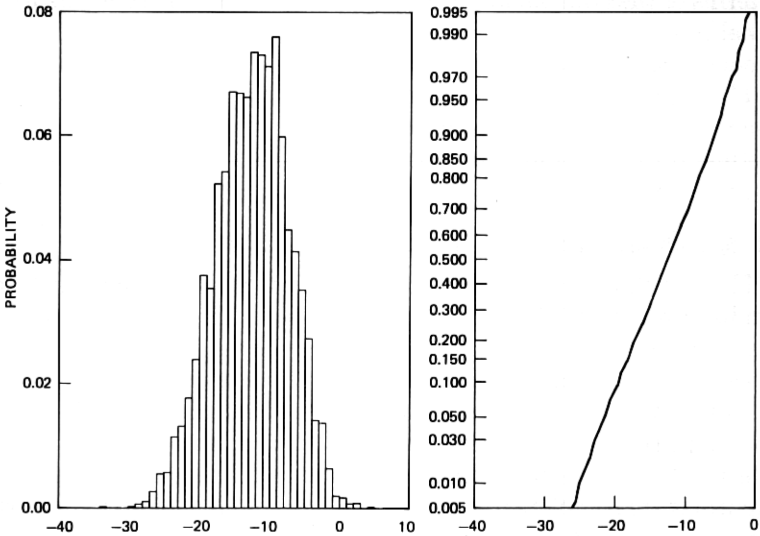

Fig. 2—Far-end equivalent peak level (dBm) distribution.

distance between end offices the more the signals are attenuated. This source of variation explains the greater variability among the far-end signal powers. These near-end, far-end differences exist for both EPL and average power; however, a comparison of the near- and far-end EPL results gives a difference of 2.1 dB, while a similar comparison for the average power measures gives a difference of 2.9 dB. In the following

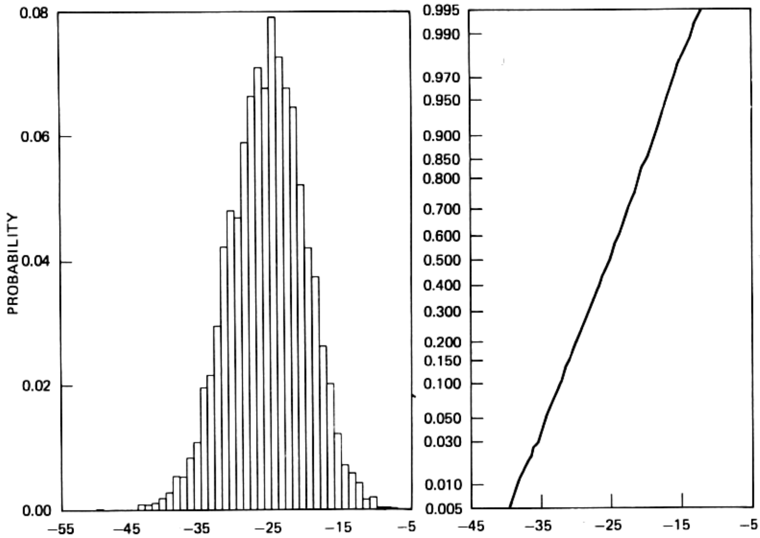

Fig. 3—Near-end average signal power (dBm) distribution.

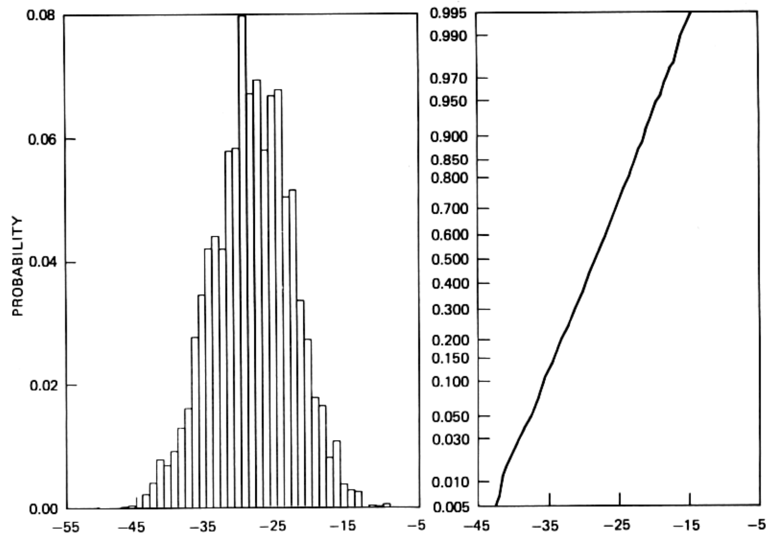

Fig. 4—Far-end average signal power (dBm) distribution.

paragraph, this apparent anomaly is shown to be caused by a difference in the speech activity of near- and far-end speakers.

The EPL, which is derived from the speech samples exceeding a threshold, is a measure of the speaker's peak signal power, and therefore is unaffected by silent periods in the conversation. The average signal power for conversational speech, however, includes intervals of speech and silence alike. Therefore, the average power measure is lower than the corresponding EPL. This is illustrated by the results in Table II, which show that the average difference between EPL and average power is 14.6 dB for the near-end measures and 15.6 dB for the far-end measures. Such differences represent activity factors in the sense that they are logarithmically related to the amount of silence during a conversation.[3] They indicate that calling parties (near-end) tend to speak more than called parties (far-end) during telephone conversations. Due to these different speech activity characteristics, the apparent network loss result based upon average power is overestimated by about 1 dB. This finding explains the apparent anomaly noted above, and suggests that EPL is more appropriate than average power for estimating apparent network loss.

Comparisons of near-end EPL and average power with the far-end measurements are provided in the scatter diagrams in Figs. 5 and 6. The correlation coefficients are 0.31 and 0.57 for the EPL and average power comparisons, respectively. While the relationships are statistically significant, the modest positive correlations indicate that the signal power of one speaker is not strongly influenced by the signal power of the other.

Average signal power is strongly related to EPL. The results of the linear regressions of the near- and far-end EPLs on the corresponding average powers are given in Figs. 7 and 8, respectively. The near-end regression shows that average power = −14.27 + 1.04 EPL, and the far-end regression shows that average power = −15.40 + EPL. The values of R^2, the square of the correlation, on the figures indicate that approximately 85 percent of the variation in average signal power is accounted for by the regression fits.

Signal power at the MDF is dependent upon loop loss and the telephone set electroacoustic efficiency. While these parameters were not measured, the near-end loop current, which was measured, has been found to relate to the overall loop and telephone set loss.[4] The histogram

Table II—Systemwide speech signal power results

Transmission Characteristic	Mean	90% C.I.	Std. Dev.	Sample
Near-end EPL (dBm)	−10.7	±0.5	4.6	10251
Far-end EPL (dBm)	−12.7	±0.4	5.2	8976
Near-end average power (dBm)	−25.3	±0.5	5.3	10251
Far-end average power (dBm)	−28.3	±0.4	5.6	8976
Near minus far-end EPL (dB)	2.1	±0.4	5.9	8478
Near minus far-end average power (dB)	2.9	±0.4	6.7	8478
Near-end EPL minus average power (dB)	14.6	±0.1	2.1	10251
Far-end EPL minus average power (dB)	15.6	±0.1	2.1	8976
Near-end loop current (mA)	42.2	±1.9	12.8	10749

90% C.I. = 90-percent confidence interval for the mean estimate.
Std. Dev. = Standard deviation of the signal power or loop current population.
Sample = Total sample size in calls used to calculate estimates.

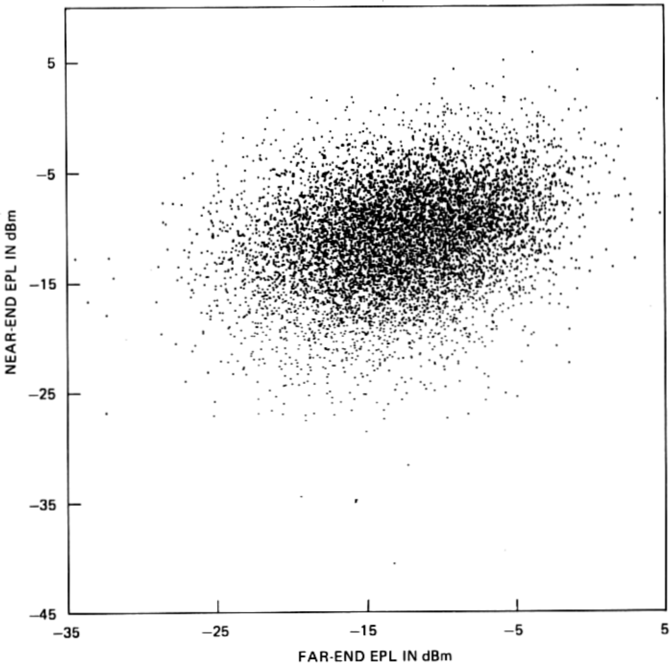

Fig. 5—Comparison of near- and far-end equivalent peak level.

and CDF for loop current are given in Fig. 9. The distribution is positively skewed, which means that it deviates from normality due to some large values of loop current associated with short loops. The distribution also deviates from normality at the lower tail because of a truncation of loop currents below 20 mA due to engineering limitations for signaling and transmission systems. Table II shows that the average loop current is 42.2 mA and the standard deviation is 12.8 mA.

Near-end EPL and average power are plotted as a function of loop current in Figs. 10 and 11, respectively. The scatter diagrams indicate that EPL and average signal power increase as loop current increases. Loop and telephone set characteristics suggest that a nonlinear relationship exists between loop current and the total loop and telephone set loss.[4] Nonlinear regression confirms this; however, the improvement in fit over the linear model, while statistically significant, is not of practical interest. The linear regressions of EPL and average power on loop current indicate that signal power increases about 0.13 dB per 1.0 mA increase in loop current. However, signal power varies substantially about the regression lines, indicating that loop current alone is not a good predictor of signal power. Visually, the variance appears to depend upon loop current; however, an analysis within loop current categories indicates that the variance is constant.

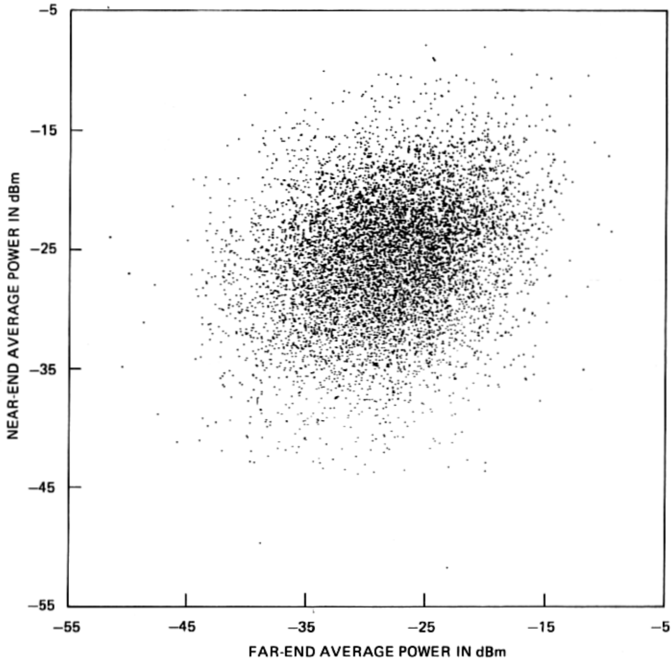

Fig. 6—Comparison of near- and far-end average power.

A more vivid illustration of the relationship between signal power and loop current is given in Fig. 12 by plotting the average EPL for each of the 36 MDFs in the sample as a function of the average loop current per MDF. The scatter shows a positive correlation, and the correlation coefficient is 0.82. A linear regression indicates that average EPL = −19.06 + 0.20 average loop current, and that the regression fit accounts for 67 percent of the variability in average EPL among MDFs.

2.3 Signal power and class of service

Class of service identifies the subscriber as a business or residential customer and identifies the station terminals as Bell or customer-provided equipment (CPE). The analyses discussed in this section deal with these service perspectives on the basis of originating class of service. The terminating customer class of service was not determined for the calls in this survey.

2.3.1 Business versus residential

The survey results for business- and residential-originated calls are summarized in Table III. Comparisons of the near-end EPL and average power results indicate that business-associated signal powers tend to be slightly higher than residential-associated signal powers, and that

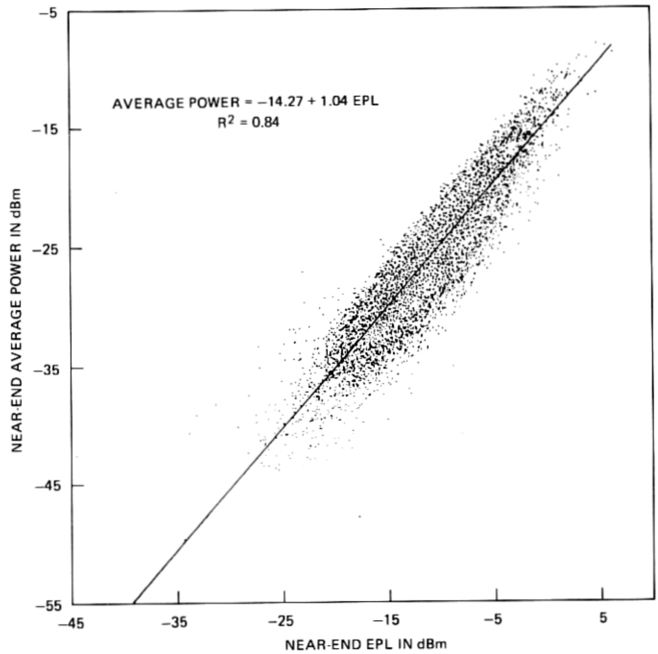

Fig. 7—Linear regression of near-end average power on equivalent peak level.

the variability among signal powers is about the same in both service categories. The 90-percent confidence intervals for the business and residential averages overlap, indicating that the differences are not statistically significant. Business loop currents are significantly higher and more variable than residential loop currents. The 5.3-mA difference in average loop current combined with the finding in Section 2.2, which indicates that EPL increases 0.13 dB per 1.0 mA increase in loop current, suggests that the business average EPL should be about 0.7 dB higher than the residential average. This difference agrees with the residence-business difference found for the near-end talker.

The far-end signal power results derived from the analysis by originating class of service are almost identical in the business and residential classifications. Since the originating parties in either category place calls to business and residential stations alike, the far-end speakers in each originating class of service category represent a mixture of business and residential customers. The far-end class of service mixture within each originating class of service category is sufficiently close to the overall traffic composition that the far-end results in each category are essentially the same as the far-end results for all telephone traffic listed in Table II. It is interesting to note that, although the average calling dis-

Table III—Originating class of service speech signal power results

Transmission Characteristic	Business				Residential			
	Mean	90% C.I.	Std. Dev.	Sample	Mean	90% C.I.	Std. Dev.	Sample
Near-end EPL (dBm)	−10.4	±0.7	4.6	6072	−11.0	±0.4	4.7	4179
Far-end EPL (dBm)	−12.8	±0.5	5.2	5228	−12.7	±0.4	5.2	3748
Near-end average power (dBm)	−25.0	±0.8	5.2	6072	−25.7	±0.4	5.4	4179
Far-end average power (dBm)	−28.4	±0.5	5.5	5228	−28.2	±0.4	5.6	3748
Near minus far-end EPL (dB)	2.5	±0.7	6.0	4916	1.7	±0.3	5.8	3562
Near minus far-end average power (dB)	3.4	±0.7	6.7	4916	2.5	±0.3	6.6	3562
Near-end EPL minus average power (dB)	14.6	±0.2	2.1	6072	14.7	±0.1	2.1	4179
Far-end EPL minus average power (dB)	15.7	±0.1	2.1	5228	15.5	±0.1	2.1	3748
Near-end loop current (mA)	45.0	±2.9	13.9	6384	39.7	±1.2	11.1	4365

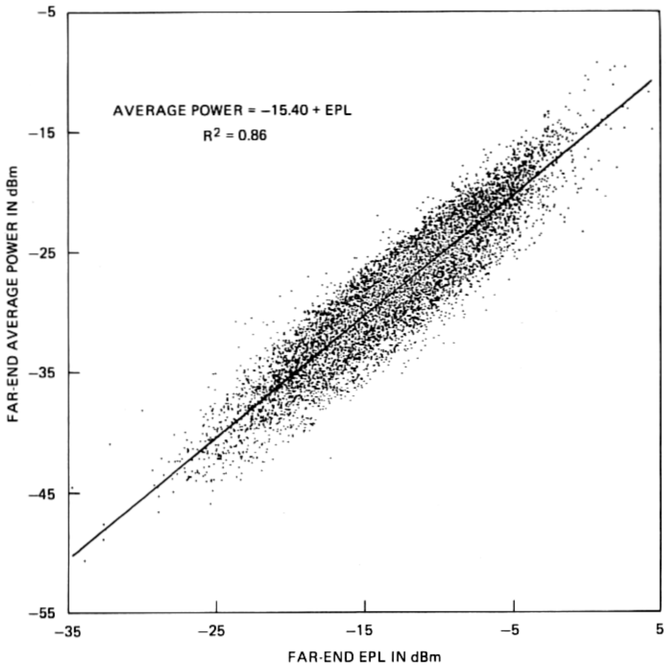

Fig. 8—Linear regression of far-end average power on equivalent peak level.

tance for the business-originated calls (50 ± 12 miles) is over 3.5 times the average for the residential calls (14 ± 4 miles), there is no noticeable call distance impact upon far-end talker received signal power. This does not imply that call distance has no influence upon network loss; it does imply that most of the data represent local calls or very short toll calls, and thus any potential call distance influence is not apparent.

Speaker speech activity during a telephone conversation is not affected by originating class of service. The EPL-average power differences have similar distributions for business- and residential-originated conversations.

The signal power distributions are all close to normal for business and residential calls. Therefore, the EPL and average power results listed in Table III completely define the signal power distributions for all practical applications. The business and residential loop current distributions differ significantly and are presented in Figs. 13 and 14, respectively. The business loop current distribution is comparable to the 1964 General Loop Survey[5] computed loop current distribution. The residential distribution has a greater proportion of lower current loops than the 1964 Survey result.

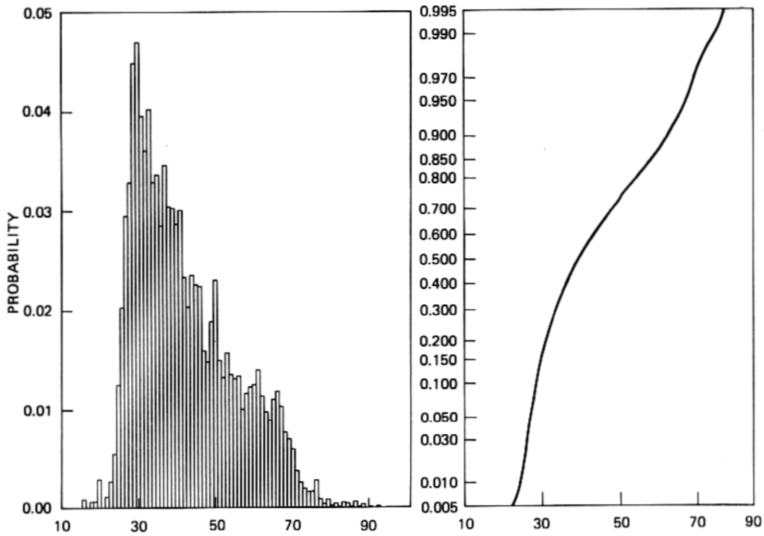

Fig. 9—Near-end loop current (mA) distribution.

2.3.2 Bell versus customer-provided equipment

Business calls are further classified on the basis of terminal equipment ownership in this section. One category contains those business calls which originated from subscriber lines with terminal equipment leased from the Bell System, and the second category contains those calls which originated from subscriber lines with customer-provided equipment (CPE). The results of this analysis are tabulated in Table IV. The near-end estimates show that the Bell signal powers on the average are more than 2 dB higher than the CPE signal powers, and that they are also somewhat less variable. The reason for this difference is suggested by examining the relationship between loop current and EPL for Bell and CPE loops, respectively. The correlation coefficients are 0.39 and 0.16, respectively, indicating that speech signal power on CPE loops is less strongly influenced by loop current than in the case of Bell loops. The reason for this is that the CPE station equipment battery is provided by a local power supply and not over the metallic loop facility. Thus, the electroacoustic efficiency of CPE station equipment is unrelated to the loop current observed in the central office, and the lower mean and higher variance in signal power may be attributable to the various local battery supplies and electroacoustic efficiencies of CPE terminals.

Comparisons of the far-end signal power estimates indicate that those far-end signals associated with CPE-originated calls have slightly lower signal powers than those associated with Bell-originated calls. The absence of detailed information about the far-end customers prevents further analyses to determine the cause of this difference.

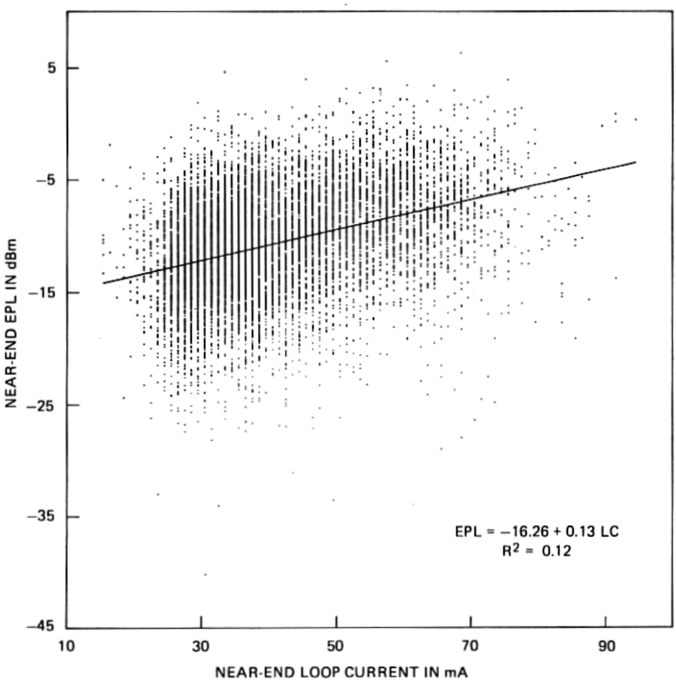

Fig. 10—Linear regression of equivalent peak level on loop current.

The signal power distributions again are all close to normal for both Bell- and CPE-originated business calls. The loop current distributions for both categories are comparable to the distributions given in the previous section for business calls in general.

2.4 Signal power and call destination

Four categories of call destination are considered in the following discussion; (*i*) intrabuilding local calls, (*ii*) interbuilding local calls, (*iii*) Home Numbering Plan Area (HNPA) toll calls, and (*iv*) Foreign Numbering Plan Area (FNPA) toll calls. The first two of these categories characterize local calls, and the last two characterize toll calls.

The trend lines in Fig. 15 summarize the relationships between signal power and call destination and between loop current and call destination. The near-end EPL and average power appear to increase slightly as the call destination becomes more remote from the originating office, with the exception of a slight drop in signal power for interbuilding local calls. The 90-percent confidence intervals for the four EPL estimates and for the four average power estimates overlap, which indicates that the differences among categories are not statistically significant. About half of the increase or decrease in signal power can be attributed to the call destination trend for loop current, which is plotted at the bottom of

Table IV—Bell and customer-provided equipment speech signal power results

Transmission Characteristic	Bell Business				CPE Business			
	Mean	90% C.I.	Std. Dev.	Sample	Mean	90% C.I.	Std. Dev.	Sample
Near-end EPL (dBm)	−10.4	±0.7	4.6	2857	−12.5	±1.2	5.1	2552
Far-end EPL (dBm)	−12.8	±0.5	5.2	2404	−14.0	±0.5	5.1	2228
Near-end average power (dBm)	−24.9	±0.7	5.2	2857	−27.5	±1.3	5.4	2552
Far-end average power (dBm)	−28.4	±0.5	5.5	2404	−29.3	±0.4	5.1	2228
Near minus far-end EPL (dB)	2.5	±0.7	6.0	2304	1.8	±1.3	6.2	2065
Near minus far-end average power (dB)	3.4	±0.7	6.7	2304	1.6	±1.6	6.6	2065
Near-end EPL minus average power (dB)	14.6	±0.2	2.1	2857	15.1	±0.1	2.4	2552
Far-end EPL minus average power (dB)	15.7	±0.1	2.1	2404	15.3	±0.2	2.0	2228
Near-end loop current (mA)	45.1	±2.9	14.0	2957	37.8	±3.2	11.3	2715

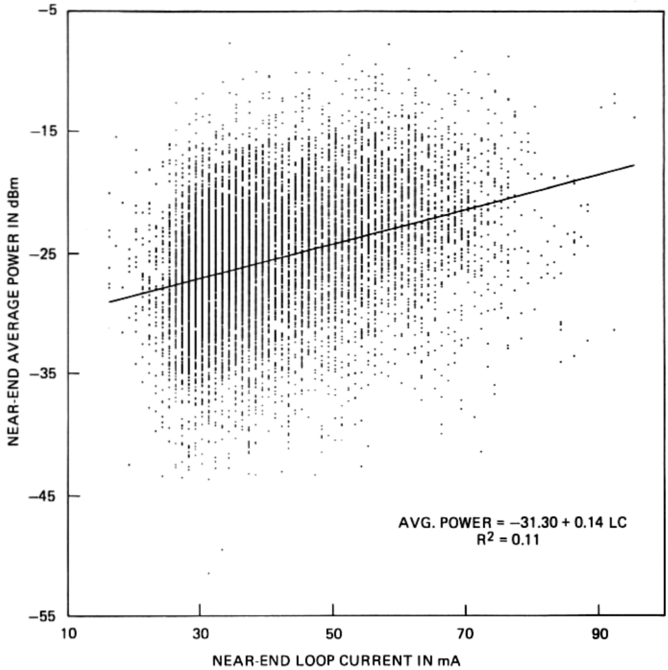

Fig. 11—Linear regression of average power on loop current.

Fig. 15. The correlation coefficients for near-end EPL and loop current are between 0.30 and 0.40 for all four destination categories. As the loop current decreases or increases, the EPL and average power trend lines follow. Since loop currents tend to be higher for business-originated calls (Section 2.3.1) and since the HNPA and FNPA categories of calls have increasingly more business-originated traffic (intrabuilding: 34 percent, interbuilding: 50 percent, HNPA: 59 percent, and FNPA: 69 percent), loop current tends to increase as the call destination becomes more remote. Interbuilding local calls, however, present an exception to this behavior which is not understood. It may be a real deviation from the overall trend, or it may be a random statistical phenomenon. Since the trends are so slight, further investigation of the interbuilding results is not warranted.

Examination of the near-end EPL and average power distributions within the individual call destination categories shows that they are close to normal in all categories except the FNPA category. In the FNPA category, both distributions modestly deviate from normality in the upper 10-percent tail due to a truncation of EPL around 0 dBm and a truncation of average power around −15 dBm. The reason for this truncation is not known; however, it represents a threshold above which speakers rarely drift. In the other call destination categories, 0 and −15 dBm signal

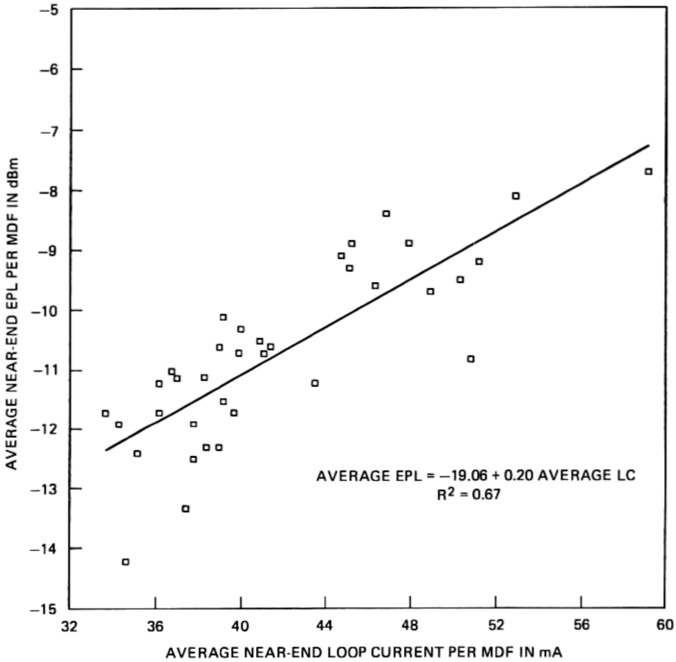

Fig. 12—Linear regression of equivalent peak level on loop current using MDF averages.

powers fall in the highest 1 percent of the EPL and average powers, respectively. The distributions for far-end EPL and average power are essentially normal in all categories.

The far-end signal powers tend to decrease as the call destination becomes more remote from the originating office due to increases in end-office-to-end-office network transmission loss. In the case of intrabuilding local calls where both parties are served by the same local switching office, the only additional network loss encountered by far-end signals is the switching office loss itself. As a result, the near- and far-end signal powers differ only slightly for intrabuilding local calls. These differences increase for interbuilding local calls and HNPA calls, which have similar far-end signal powers, due to an increase in the number of switching offices and trunks involved in the transmission path and the via net loss design[6] adopted for these arrangements of facilities. Likewise, an even greater difference between near- and far-end signal power is observed in the FNPA category. The detailed statistics associated with the trends illustrated in Fig. 15 are listed in Table V.

The correlation between near- and far-end signal powers also appears to depend upon call destination. A comparison of near- and far-end EPL provides correlation coefficients of 0.36, 0.27, 0.23, and 0.14 for intrabuilding, interbuilding, HNPA, and FNPA calls, respectively. The cor-

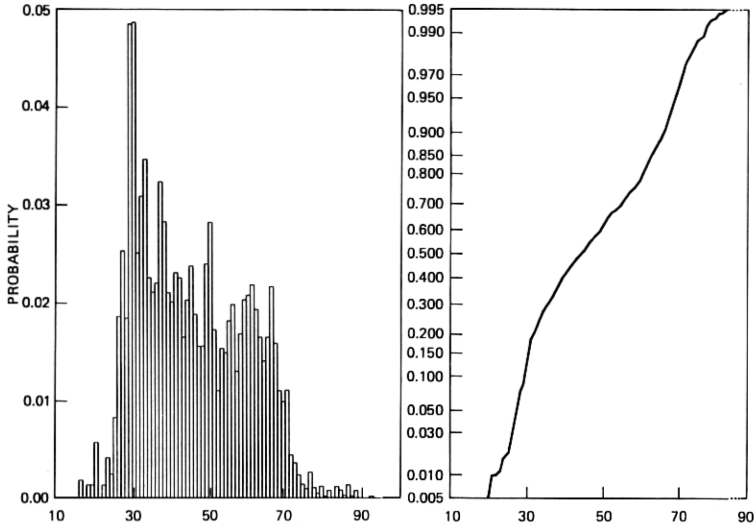

Fig. 13—Near-end loop current (mA) distribution for business.

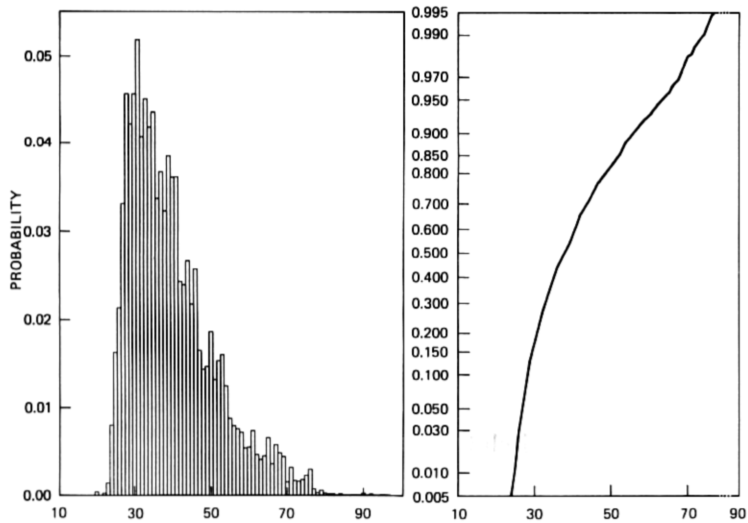

Fig. 14—Near-end loop current (mA) distribution for residential.

relation becomes poorer as the call destination becomes more remote because of the overall increasing and opposite impacts of network transmission loss and loop current on far-end and near-end signal powers, respectively.

The intrabuilding and interbuilding local call data were pooled to obtain overall local results, and the HNPA and FNPA data were pooled

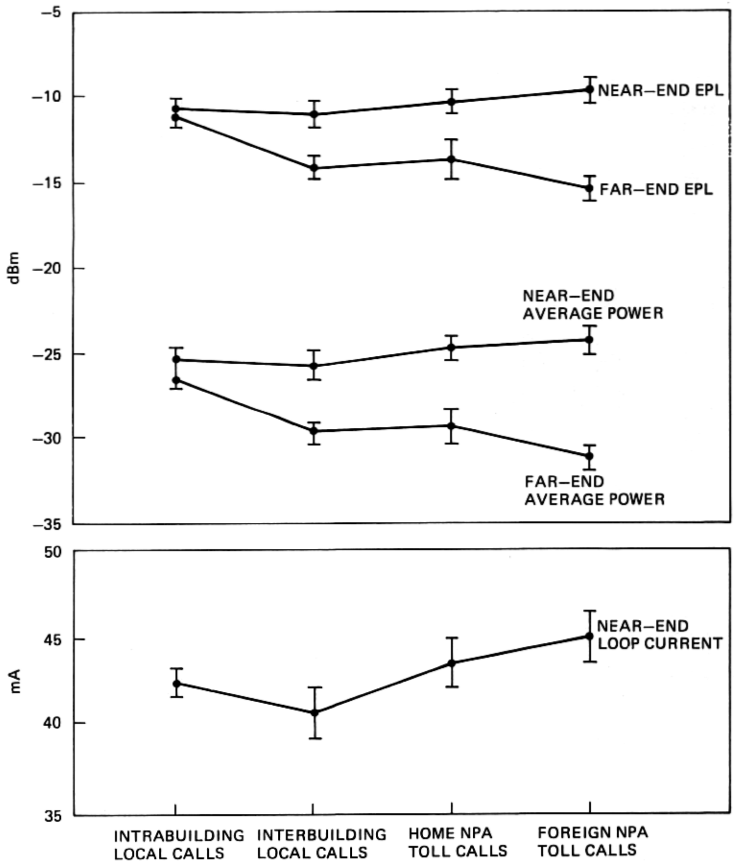

Fig. 15—Relationship of call destination to signal power and loop current.

to obtain overall toll results. Briefly, near-end toll signal powers are slightly, but not significantly, higher than near-end signal powers for local calls, and far-end toll signal powers are significantly lower than far-end powers for local calls. The reasons for these characteristics are discussed above. The only additional observation at this point is that the local loop current distribution resembles the residential distribution in Fig. 14 and the toll loop current distribution resembles the business distribution in Fig. 13. The dominance of residential and business traffic for local and toll calls, respectively, is responsible for these similarities.

2.5 Additional speech signal power analyses

The signal power data were also analyzed to determine the impact of call distance, local switch type, and several demographic factors upon

Table V—Call destination speech signal power results

Transmission Characteristic	Intrabuilding Local Calls				Interbuilding Local Calls				Home NPA Toll Calls				Foreign NPA Toll Calls			
	Mean	90% C.I.	Std. Dev.	Sample	Mean	90% C.I.	Std. Dev.	Sample	Mean	90% C.I.	Std. Dev.	Sample	Mean	90% C.I.	Std. Dev.	Sample
Near-end EPL (dBm)	−10.7	±0.5	4.6	3697	−11.0	±0.7	4.7	3704	−10.3	±0.6	4.5	995	−9.8	±0.7	4.3	763
Far-end EPL (dBm)	−11.0	±0.5	4.8	3348	−14.1	±0.4	4.8	3140	−13.6	±1.1	5.5	862	−15.4	±0.6	4.7	645
Near-end average power (dBm)	−25.3	±0.5	5.3	3697	−25.7	±0.8	5.5	3704	−24.7	±0.7	5.2	995	−24.2	±0.8	4.8	763
Far-end average power (dBm)	−26.5	±0.5	5.4	3348	−29.7	±0.5	5.2	3140	−29.3	±1.0	5.7	862	−31.1	±0.6	4.9	645
Near minus far-end EPL (dB)	0.2	±0.3	5.3	3170	3.2	±0.6	5.8	2980	3.6	±0.9	5.8	828	5.8	±1.0	6.1	617
Near minus far-end average power (dB)	1.0	±0.3	6.2	3170	3.9	±0.6	6.6	2980	4.9	±0.7	6.5	828	7.0	±1.1	6.7	617
Near-end EPL minus average power (dB)	14.6	±0.1	2.1	3697	14.7	±0.1	2.1	3704	14.4	±0.2	1.9	995	14.4	±0.3	1.9	763
Far-end EPL minus average power (dB)	15.6	±0.1	2.1	3348	15.6	±0.1	2.1	3140	15.7	±0.3	2.0	862	15.7	±0.3	2.1	645
Near-end loop current (mA)	42.4	±1.7	12.4	3875	40.7	±3.0	12.4	3864	43.6	±2.9	13.6	1029	45.1	±3.0	13.8	791

speech signal power. Call distance is defined as the airline distance between the originating and terminating local switching machines. Near-end signal power and loop current do not appear to be correlated with call distance. Far-end signal power is weakly correlated with call distance in a negative sense, due to the increase in network transmission loss which accompanies longer call distances as a result of the via net loss design.[6]

In the second of these analyses, the data were classified by originating local switching machine type. No significant relationship was found between machine type and near-end signal power.

Three demographic factors were considered in the third analysis. The first factor, geographical location, does not play an important role in determining speech signal power. While the average near-end signal power is highest in the northeast section of the country and lowest in the southwest, the range of the differences is only 2.7 dB, and the correlation between loop current and signal power accounts for about 40 percent of the difference between geographic areas. The second factor, city or town population, tends to mask rather than uncover relationships between signal power and population. A more appropriate measure is the population density of the exchange served by the local telephone office. The third demographic factor, locality type, was defined to capture the impact of population density upon speech signal power. Five locality types were considered: downtown areas of large and midsize cities, downtown areas of small towns, outer-urban areas, and suburban areas. Large cities were defined as cities with populations of 100,000 or more people; mid-size cities were defined as cities with populations ranging from 20,000 to 100,000 people; and small towns were defined as cities or towns with populations of 20,000 or less people. The outer-urban classification denotes areas with a mixture of residential dwellings and business establishments on the outlying fringes of large cities, and the suburban classification denotes areas which primarily contain residential dwellings. The average near-end EPL and loop current both exhibit the same trends with locality types. Both are highest for downtown MDFs in large cities and lowest for outer-urban areas. These results correlate with the fact that in the first case the population of customers is rather concentrated, and they tend to have relatively short loops, while in the second case the population of customers is rather widespread, and they tend to have relatively long loops. Between these extremes, the average EPL and loop current for small towns are higher than for mid-size cities, and both have higher averages than suburban areas. As illustrated in Figs. 16 and 17, the differences among the categories are not large; however, they do suggest a dependence of loop current and, as a result, EPL upon varying densities of populations.

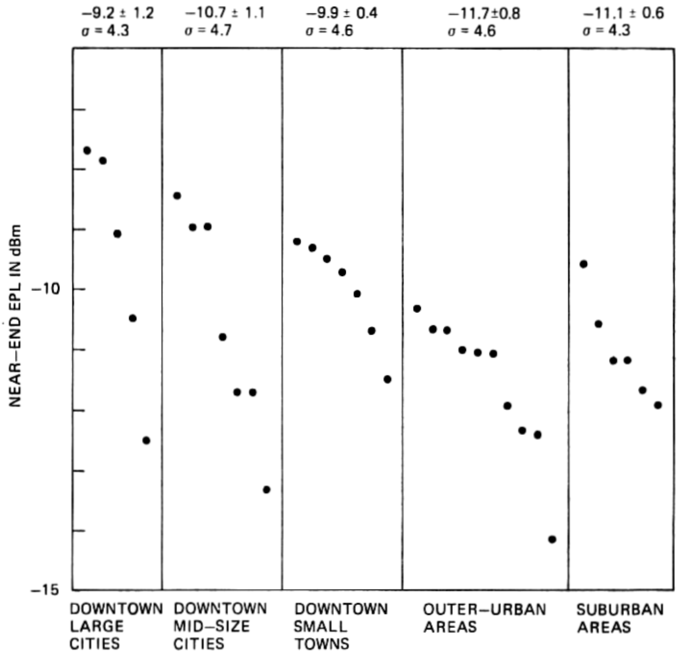

Fig. 16—Average signal power per MDF by locality type.

III. METHODOLOGY

3.1 Statistical survey sample plan

The Loop Signal Power Survey sampling plan consists of three major components—a precise definition of the target population and parameters, a scheme for the selection and measurement of a sample of calls, and the choice of the estimation formulas. Section 3.1.1 defines the target population and parameters, Section 3.1.2 describes the scheme used to select and measure a statistical sample of calls, and Section 3.1.3 describes the statistical estimation and confidence interval formulas used to estimate the target parameters.

3.1.1 Target population and measured parameter definitions

The target population consists of voice calls originating over the public switched network where the subscriber's loop is classified as business, single party residence, coin semipublic, Private Branch Exchange (PBX), or Centralized Exchange (centrex) service. The aggregate of subscriber loops in the target population are naturally partitioned according to the local MDF in which they terminate. In addition, the subscriber loops terminating in an MDF are naturally dichotomized into a customer-provided equipment (CPE) substratum and a Bell equipment substratum. A loop was identified as belonging to the CPE substratum when

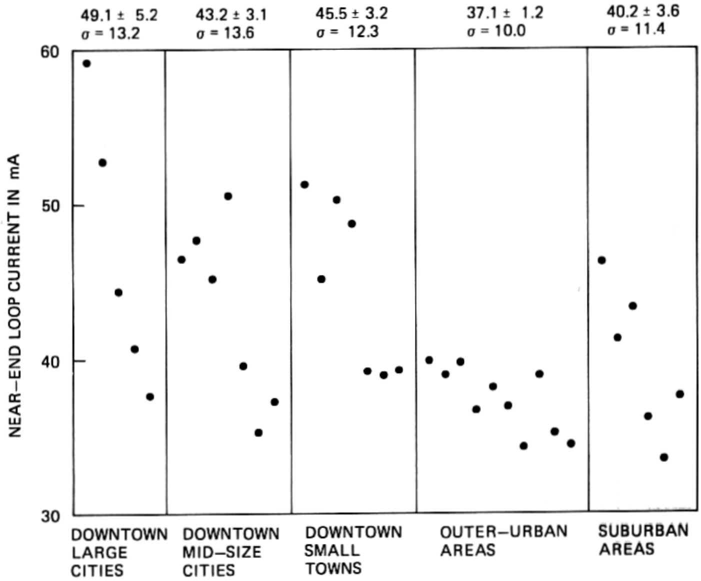

Fig. 17—Average loop current per MDF by locality type.

the local operating company billing records and a follow-up station verification identified the connection to the subscriber's loop of a protective connecting arrangement (PCA) listed in Table VI. A PCA is designed to interconnect non-Bell terminal equipment with the Bell System public switched network.

For potential statistical advantage, the MDFs were partitioned into 12 strata according to the average 1970 population census of the communities within the plant district where an MDF was located. The 12 strata were constructed so that they are approximately the same size with respect to the total number of business, residence, PBX, centrex, coin semipublic, and switched data telephone lines terminating on MDFs within the stratum. This form of stratification was suggested by the results of the 1960 Speech Volume Survey, which indicated a correlation of speech volume with city population. Stratification by city size offered the potential for reduction of the variability in speech signal power within

Table VI—Protective connecting arrangements (PCA)

PCA USOC*	Associated Non-Bell Terminal Equipment
STP	Key telephone system
STC	Single line set
C2ACP	Single line or key telephone system
CD8, CDH	PBX or centrex CU
CDA, CD1, CD7, CD9	Cord switchboard or console

* USOC—Bell System Universal Service Order Code.

each of the strata and, as a result, an increase in the precision of estimates of the mean signal power.

In general, the choice of the criterion for stratification is arbitrary and does not affect the validity of the final survey conclusions; however, a judicious choice of a stratification scheme can lead to an estimate of the mean with a smaller confidence interval than would be obtained otherwise.

Each loop associated with the target population is indexed by its stratum number, MDF number within a stratum, substratum number (e.g., 1 Bell, 2 CPE) and loop number within an MDF substratum.

The target population parameters estimated in the Loop Signal Power Survey are defined by the ratio

$$R = Y/X,$$

where

$$Y = \sum_{h=1}^{L} \sum_{i=1}^{N_h} \sum_{a=1}^{D_{hi}} \sum_{j=1}^{M_{hia}} \sum_{k=1}^{Q_{hiaj}} Y_{hiajk},$$

X is defined similarly to Y with Y_{hiajk} replaced by X_{hiajk},

N_h is the number of MDFs located in class 5 offices in stratum h, for $h = 1, 2, \ldots, L$,

D_{hi} is the number of substrata into which the subscriber loops that terminate in the ith MDF of stratum h are partitioned ($D_{hi} = 2$),

M_{hia} is the number of subscriber loops that are in substratum a and terminate on the ith MDF in stratum h,

and

Y_{hiajk} and X_{hiajk}, $k = 1, 2, \ldots, Q_{hiaj}$, represent measurements associated with the Q_{hiaj} completed calls which originate from loop ($hiaj$). Loop ($hiaj$) is identified as the jth loop terminating in substratum a of the ith MDF in stratum h.

Some examples of applications of the ratio parameter R are given below.

Application One: Fraction of Calls Where the Mean Transmitted Signal Power Exceeds Some Threshold

Suppose Y_{hiajk} is defined as 1 if the kth completed call on loop ($hiaj$) is in the target population and the mean signal power exceeds some threshold T, and 0 otherwise. Second, suppose X_{hiajk} is defined as 1 if this call is in the target population, and 0 otherwise. R is then equal to the fraction of completed calls in the target population for which the transmitted mean signal power exceeds T. This form of the ratio parameter is applicable to target populations such as completed calls (toll and/or local) originating from the Bell and/or CPE subclasses of loops.

Application Two: The Mean Originating Signal Power Per Call

Suppose X_{hiajk} is defined as in Application One, and Y_{hiajk} is defined as a measure of signal power of the kth completed call originating on loop $(hiaj)$, then R is equal to the mean originating signal power per call.

3.1.2 Survey sampling scheme

The calls which were measured in the Loop Signal Power Survey were statistically selected in such a way as to permit precise estimates of the population parameters described in Section 3.1.1 and at the same time limit the costs of obtaining the measurements. The actual statistical sample selection scheme used was a classical three-stage sampling scheme with stratification and substratification. From each of the 12 strata described in Section 3.1.1, three MDFs were selected with probabilities of selection proportional to estimates of the total number of business, residence, PBX, centrex, and coin semipublic lines terminating on each MDF. The locations of the 36 sampled MDFs are illustrated in Fig. 18. A stratified random sample of CPE and Bell loops, which terminated on the 36 MDFs, was selected, specially designed measurement equipment was connected to these sampled loops, and signal power measurements were made on a sample of calls originating over the loops. The selection of the CPE loops was made from a billing records inventory of subscriber telephone numbers that were being billed for a PCA with one of the Universal Service Order Codes (USOC) listed in Table VI. A random sample of Bell loops was obtained by generating a list of random four-digit numbers and prefixing a local three-digit NNX code for each NNX associated with the MDF. These lists were forwarded to the local repair service bureau for determination of the class of service of each

Fig. 18—Locations of sampled MDFs.

telephone number and the location of the loop on the MDF. A stratified random sample of CPE and Bell loops, identified as members of the target population, was ordered according to the location on the vertical side of the MDF. Approximately 1 week prior to the scheduled arrival of the Bell Laboratories survey team, a verification was made by local operating company craft people to assure that each selected line was working, that the telephone number-cable-pair and horizontal frame assignments were correct, and that no bridged lines were present. From this verified list, a stratified sample of up to 30 CPE loops and at least 69 Bell loops (for a total of 99) were selected for connection to the survey equipment. The equipment included a device which, when activated, scanned the 99 loops for an originating off-hook signal. Following seizure of the loop and the establishment of a connection, the measurement process was started manually if a conversation ensued. Conversation was detected by utilizing an equipment operator's monitor channel which provided unintelligible speech during periods of conversation through the use of a low speech sampling rate. Because toll calls were relatively scarce, provision was made for the equipment operator to abort the measurement of local calls to obtain additional toll calls. The measurement period in a local office was 3 days.

The survey equipment provided peg count data from which the number of originated completed calls was estimated for each loop. These data formed the basis for traffic weights used to estimate the target population parameters.

3.1.3 Estimation formulas and confidence intervals

This section is devoted to a discussion of the statistical estimation formulas that are used to estimate the ratio parameter R. These formulas are tailored to the survey sample design discussed in Section 3.1.2. The form of the estimation formulas require the following information relative to the sampling plan:

n_h—the number of sampled MDFs in primary stratum h for $h = 1, 2, \ldots, L$. ($n_h = 3$ for $h = 1, 2, \ldots 12$).

z_{hi}—the probability of selection into the first stage sample of the ith sampled MDF in stratum h for $i = 1, 2, \ldots, n_h$ and $h = 1, 2, \ldots, L$.

m_{hia}—the number of measured subscriber loops that belong to the ath substratum of the ith sampled MDF in stratum h for $i = 1, 2, \ldots n_h$; $a = 1, 2, \ldots D_{hi}$, and $h = 1, 2, \ldots, L$.

q_{hiaj}—the number of calls associated with loop $(hiaj)$ on which signal power measurements were made.

L, M_{hia}, D_{hi} and Q_{hiaj} are defined as in Section 3.1.1, and

(x_{hiajk}, y_{hiajk}), $k = 1, 2, \ldots, q_{hiaj}$ represents a sample of q_{hiaj} values of (X_{hiajk}, Y_{hiajk}), $k = 1, 2, \ldots Q_{hiaj}$, where

X_{hiajk} and Y_{hiajk} are defined as in the definition of R.

A three-stage estimator of the ratio $R = Y/X$ where Y and X are defined as in Section 3.1.1 is

$$r = y/x,$$

where

$$y = \sum_{h=1}^{L} \sum_{i=1}^{n_h} \sum_{j=1}^{m_{hia}} \sum_{k=1}^{q_{hiaj}} w_{hiaj} y_{hiajk},$$

$$w_{hiaj} = \frac{1}{n_h} \frac{1}{z_{hi}} \frac{M_{hia}}{m_{hia}} \frac{Q_{hiaj}}{q_{hiaj}},$$

and x is defined similarly to y with y_{hiajk} replaced by x_{hiajk}.

The mean squared error of r is defined as

$$\text{VAR}(r) = E(r - R)^2,$$

where $E(\cdot)$ denotes expected value.

A consistent estimator of $\text{VAR}(r)$ is

$$v(r) = \frac{1}{x^2} \sum_{h=1}^{L} \frac{1}{n_h(n_{h-1})} \sum_{i=1}^{n_h} \left[\frac{y_{hi} - rx_{hi}}{z_{hi}} - \frac{1}{n_h} \sum_{i=1}^{n_h} \frac{y_{hi} - rx_{hi}}{z_{hi}} \right]^2,$$

where

$$y_{hi} = \sum_{a=1}^{D_{hi}} \sum_{j=1}^{m_{hia}} \sum_{k=1}^{q_{hiaj}} \frac{M_{hia}}{m_{hia}} \frac{Q_{hiaj}}{q_{hiaj}} y_{hiajk}$$

and x_{hi} is defined similarly to y_{hi} with y_{hiajk} replaced by x_{hiajk}.

An application of the Central Limit Theorem yields an approximate 90-percent confidence interval for R as the interval

$$(r - 1.645\sqrt{v(r)}, r + 1.645\sqrt{v(r)}).$$

3.2 Data acquisition plan

In this section, requirements pertaining to acquisition equipment capacity, compatibility, transparency, privacy, etc., are summarized, and a block diagram of the Loop Signal Power Survey acquisition equipment is discussed.

3.2.1 Requirements

As indicated in Section 3.1, the sample plan called for access to 99 customer loops in each of 36 class 5 offices and measurements of near- and far-end signal power on live calls. Determination of call destination required the detection of call originations on loop start and ground start lines, and the detection of dial pulse and *TOUCH-TONE®* address information. Because of the loop-to-loop and call-to-call variability in impedance at the MDF interface, the measurement of real power was required rather than bridged voltage. In the course of accessing and measuring calls, no detectable impairment (loss or switching clicks) was to be added to the connection. Monitoring of intelligible speech was prohibited by privacy considerations. Speech signals are predominantly half-duplex in nature; however, both parties sometimes talked at the same time. Because the point of measurement was a two-wire point, it was necessary to devise a method to sort the speech signal data into two categories, near-end and far-end.

3.2.2 Data acquisition equipment

Figure 19 is a block diagram of the equipment used to acquire speech signal power data. The 99 customer loops were accessed at the protector socket of the MDF. Access cables connected the customers' loops to the acquisition console protector panel. This panel provided series access to 99 loops, circuit protection, and an electrical interface with the instrumentation switch. This interface contained current sensing resistors for the detection of metallic speech current and loop dc current. Modified service observing equipment was bridged across the tip-ring interface at this point to allow the detection of outgoing call seizures and the de-

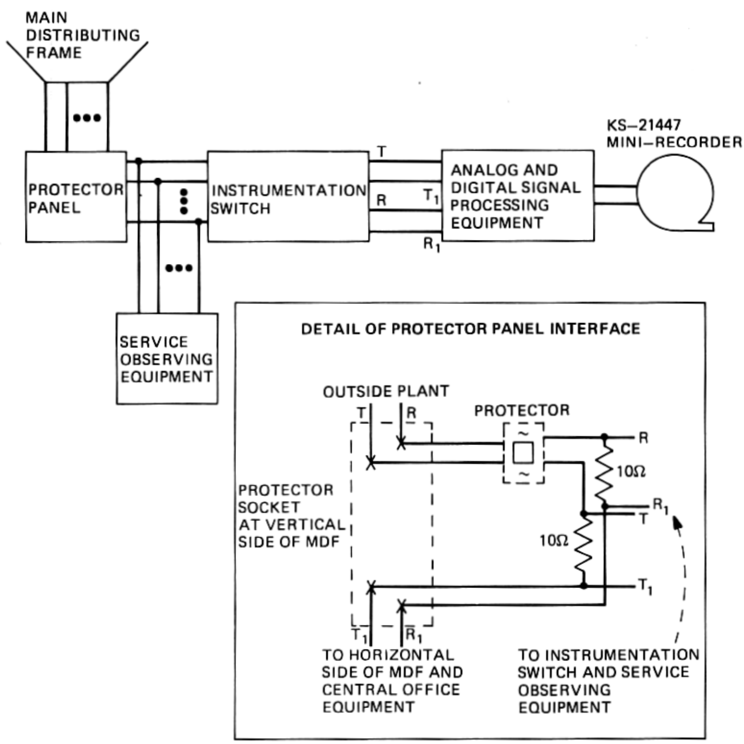

Fig. 19—Loop signal power survey data acquisition console.

tection of dial pulse/*TOUCH-TONE* address digits. The instrumentation switch connected the four leads associated with the current sensing resistors of one of the 99 loops to the analog signal processing equipment for the detection, amplification, and filtering of the metallic speech voltage and current.

The resulting voltage and current signals were simultaneously sampled at the rate of 200 samples per second using dual 12-bit A-D converters. The sampled data were stored in a buffer memory, combined with label information, and written in 16-kb blocks on a minirecorder magnetic tape unit. A paper-tape printer recorded off-hook event times for each of the 99 loops so that traffic weights referred to in Section 3.1 could be determined. In addition, the dialed area and office code were recorded on the tape. The digitally recorded speech signal data were subsequently analyzed in a manner described in the next section.

The loss due to the current sensing resistors and bridged equipment was negligible. This, combined with click supression circuitry, made the measurement equipment transparent from the customer's point of view. The low rate of sampling made the recorded speech signal unintelligible but allowed the recovery of pertinent signal power information. A low speech sampling rate was also used to make the equipment operator's monitor channel unintelligible, yet permit the identification of call progress signals. The acquisition of simultaneous speech voltage and current samples permitted the discrimination of the near-end from the far-end talker in a manner discussed in the next section.

3.3 Analysis of data

This section explains how voltage and current samples were processed to obtain measures of speech signal power for each talker in the two-way conversations.

3.3.1 Raw speech signal power data processing

The raw data upon which speech signal equivalent peak level (EPL) and average power estimates are based consisted of metallic speech voltage and current samples. The metallic speech voltage and current on the loop were amplified and filtered to exclude signals higher than 4 KHz and remove the effect of 60 Hz, its first two odd harmonics, and low frequency noise below 100 Hz. The resultant voltage and current analog signals were then simultaneously sampled at the rate of 200 samples per second using two 12-bit linear A-D converters. The digital sampled data were then recorded on tape cartridges, which were later reformatted onto standard computer tape.

The first step in computer processing of the digitally recorded signals consisted of removal of dc bias produced in the analog signal processing filters and computation of the instantaneous power (watts) associated with each voltage-current sample pair. The equipment was designed so that the power values were positive (voltage and current in phase) when the signal source was the near-end talker and and negative (voltage and current out of phase) when the signal source was the far-end talker.

3.3.2 Discrimination of near-end and far-end talkers

Conversational speech is predominantly half-duplex, but brief periods occur when both talkers are active at the same time. The stream of instantaneous power samples is therefore positive or negative for half-duplex talk-spurts. However, during double talking, the sign of the power samples may change rapidly and the magnitudes of the power samples become useless for estimation of near-end or far-end talker power. To properly sort the power sample stream into two distinct "bins" corresponding to the near-end and far-end talkers, empirical algorithms were developed in laboratory simulations, and one algorithm (SGN algorithm) was chosen for use during the speech signal processing phase of the survey.

The SGN algorithm uses the sign and magnitude of the power in short subsequences of the stream of speech power samples to generate two sequences of speech power samples corresponding to near-end and far-end talkers.

Let $\{p\}$ be the sequence of instantaneous speech signal power values computed from the relationship: $p = v \cdot i$, where $\{v\}$ and $\{i\}$ are sequences of instantaneous, simultaneous samples of speech signal metallic voltage and current, respectively.

Let the sequence $\{p\}$ be divided into consecutive subsequences of length l. Associated with the ith subsequence is the average power:

$$\overline{p}_i = \frac{1}{l} \sum_{k=il-l+1}^{il} p_k.$$

$$\text{Let SGN}(\overline{p}_i) = \begin{cases} -1 \text{ if } \overline{p}_i > 0 \\ 0 \text{ if } \overline{p}_i = 0 \\ +1 \text{ if } \overline{p}_i < 0. \end{cases}$$

The SGN algorithm depends on two conditions for every subsequence:

Condition 1: $\text{SGN}(\overline{p}_i) = \text{SGN}(\overline{p}_{i-1})$

Condition 2: $|\overline{p}_i| \geq \alpha|\overline{p}_{i-1}|$.

If either condition is true, then SGN $(\overline{p}_i)$ determines the sources of the speech signal for the ith subsequence. As stated earlier, the sign convention is such that a positive value indicates that the near-end talker is the source (far-end samples set to 0), and a negative value indicates that the far-end talker is the source (near-end samples set to 0). After the source is determined, the nonzero power samples are set positive and placed in the appropriate (near- or far-end) sequence.

If neither of the above conditions is true, then the direction is indeterminant and all power samples in the ith subsequence are set to 0. Laboratory investigations established that the values $l = 2$ and $\alpha = 10$ give good performance with the sample rate used in the survey (200 samples per second). The output from the SGN algorithm consists of two sequences of positive instantaneous signal power samples representing the near-end and far-end talkers.

3.3.3 Measures of speech signal power

Two measures of speech signal power are developed from each of the near-end and far-end sequences described above. The first measure is the average speech signal power defined over the observation interval (generally about a minute) as follows:

$$\text{Near-end average power} = 30 + 10 \log \frac{1}{n} \sum_{k=1}^{n} p_k \text{ near-end (dBm)}$$

$$\text{Far-end average power} = 30 + 10 \log \frac{1}{n} \sum_{k=1}^{n} p_k \text{ far-end (dBm)},$$

where p_k-end represents the elements in the sequence of instantaneous power samples for the direction of interest, and n is the total length of the power sample sequence.

The second measure used to characterize speech signal power is an estimate of the peak power in the distribution of samples of talker signal power. The estimator is the empirical equivalent peak level (EPL), developed by Brady. A complete discussion of the EPL and its properties is given by Brady in Ref. 2. The EPL is developed from the power sample sequence for the direction of interest as follows.

Let the instantaneous power of the kth sample be defined as:

$$p_k = v_k i_k \text{ watts.}$$

In logarithmic units,

$$p_k = 10 \log p_k \text{ (dBw).}$$

Define a threshold ϕ and multiplier δ_k so that:

$$\delta_k = \begin{cases} 1 & \text{if } p_k > \phi \\ 0 & \text{otherwise} \end{cases}.$$

The average power over threshold is defined:

$$\overline{p}_\phi = 10 \log \left(\frac{\sum_{k=1}^{n} p_k \delta_k}{\sum_{k=1}^{n} \delta_k} \right).$$

Now define $D = \overline{p}_{\phi} - \phi$ dB. From D compute Δ using the following empirical rule:

$$D \leq 6.75, \text{ then } \Delta = (D - 2.75)/0.4$$

$$6.75 < D \leq 13.5, \text{ then } \Delta = D/0.675$$

$$13.5 < D, \text{ then } \Delta = (D + 2.88)/0.819.$$

From Δ compute EPL as:

$$\text{EPL} = \Delta + \phi.$$

Some important properties of the EPL are that it is independent of the talker's activity since it is not affected by the silent periods in the conversation, and its estimate varies little over a wide range of threshold values. Some laboratory investigations indicate that a threshold of 10 to 20 dB below EPL gives good performance in the presence of noise; a threshold of 20 dB below EPL was selected as giving the best noise rejection without discarding an excessive number of samples. The EPL computation was iterated until the threshold was 20 ± 3 dB below the EPL value.

IV. COMPARISON WITH PREVIOUS DATA

In 1960, measurements of talker volume were made on live traffic using VU meters.[1] These measurements of talker volume are compared with the current survey results, which have been translated from EPL to VU using an empirical correction factor. These results are listed in Table VII together with the 1960 survey results.

The 1960 survey results differ substantially from the current results in that the toll volumes were substantially higher in 1960 and the ranges of volumes within the various call destination categories were substantially greater. There have been some substantial changes in the telephone plant since 1960 that may help to explain these differences. The proportion of toll grade battery has decreased substantially, resulting in a decrease in toll call speech volume. Loss plan improvements, the phasing out of the 300-type telephone set, and the growth of direct trunking have all tended to increase the uniformity of service in the network and make it more transparent to customers. The apparent result is a network with remarkable uniformity of speech signal power.

Table VII—Comparison with 1960 speech volume survey

	1960		1975–1976	
Call Destination	Average VU	Std. Dev.	Average VU	Std. Dev.
Intra-building	−24.8	7.3	−22.2	4.6
Inter-building	−23.1	7.3	−22.5	4.7
Toll	−16.8	6.4	−21.6	4.5

V. ACKNOWLEDGMENTS

Many individuals contributed to the Loop Signal Power Survey. P. W. Freeman, J. M. MacMaster, and E. J. Vlacich designed and assembled the test equipment, T. W. Thatcher, Jr. handled all phases of logistic support, and F. Grizmala, S. Vitale, and P. R. Wild developed software packages and processed the data with the help of C. Keinath. In addition, many individuals from Bell Laboratories and the Bell System operating companies participated in the data collection phase of the survey. We extend our thanks to all who have helped in this project.

REFERENCES

1. K. L. McAdoo, "Speech Volumes on Bell System Message Circuits—1960 Survey," B.S.T.J., *42*, No. 5 (September 1963).
2. P. T. Brady, "Equivalent Peak Level: A Threshold-Independent Speech-Level Measure," J. Acoust. Soc. Am., *44*, No. 3 (September 1968).
3. Bell System Center for Technical Education, *Telecommunications Transmission Engineering*, Vol. 1, Chapter 12, 1974.
4. D. H. Merchant, unpublished works.
5. P. A. Gresh, "Physical and Transmission Characteristics of Customer Loop Plant," B.S.T.J., *48*, No. 10 (December 1969).
6. *Notes on Distance Dialing*, Section 6, New York: American Telephone and Telegraph Company, 1975.