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Digital Data System:

Local Distribution System

By E. C. BENDER, J. G. KNEUER, and W. J. LAWLESS

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The local distribution portion of the Digital Data System is discussed in this paper. Baseband, bipolar transmission over telephone cable pairs is used to extend the digital channel from the serving central office to the customer's location. The performance and requirements of these local channels are presented. The design and performance of the local distribution hardware are examined. Design features include (i) automatic equalization by means of an automatic line-build-out network and (ii) control mode indication by means of bipolar format violations.

I. INTRODUCTION

An important design consideration in planning the Digital Data System was the method of providing local distribution, the interconnection of the customer's terminal equipment to the serving DDS office. Since this interconnection is supplied to each customer, factors such as economy, ease of installation, and reliability were considered.

To minimize the investment required for installation of new telephone plant, a decision was made to use the existing type of subscriber loop plant for DDS local distribution. Thus, the copper pairs from the subscriber's location to the serving central office may be used for DDS as well as for telephone and other services. Since not all local subscriber offices are DDS offices, interoffice trunk cable will also be used as part of the DDS loop.

The local transmission system consists of station equipment, either a data service unit (DSU) or a channel service unit (CSU), to couple the data signals to the cable pairs; two cable pairs, one for each direction of transmission; and central office equipment, an office channel unit (OCU) to convert the digital signals present on the local loop into regenerated bits formed into 8-bit bytes for interconnection to the digital multiplexers.[1]

In addition to transmitting the basic digital signals, means must be provided for transmitting control mode information over the local loop. This mode information may be used by the customer's terminal equipment for control procedures and, as is shown later, is used for internal DDS maintenance and testing originating within the DDS network.

This paper discusses the type of pulse transmission and the automatic equalization used in both the station and office equipment. Performance of the local distribution system is examined in the presence of several degradations. Facility considerations such as cable selection and gauge/length limitations are listed. Maintenance aspects of the local distribution system are discussed. Finally, the equipment is described on a block-diagram level.

II. BASEBAND, BIPOLAR TRANSMISSION

2.1 Bipolar format

The data channel between the station and central office is provided by baseband transmission over the cable pairs. To provide protection against large longitudinal voltages impressed on cable pairs owing to inductive interference from power lines and other sources, it is necessary to isolate electronic circuits from the cable pairs. A reliable and inexpensive means for doing this, which is the method used in DDS, is to isolate the line by means of transformers. The resulting channel has a low-frequency cutoff and therefore requires a signal without dc content. Since unrestricted data patterns can contain a significant dc content, some means must be provided to ensure that the transmitted signal is dc-free. The method used here is to convert the binary data pulse into a bipolar format that removes any dc energy. This method of baseband transmission is used on T1 lines[2] and has proven to be a reliable and inexpensive pulse transmission scheme. Another characteristic of bipolar transmission is the additional information that can be conveyed by means of violations of the bipolar coding rule. As will be shown, this violation procedure is used to transmit the control mode information mentioned earlier.

Encoding binary data into the bipolar format is implemented as follows. A binary 1 is transmitted as a positive or negative pulse with successive pulses alternating in polarity and is called a "bipolar pulse." A binary 0 is transmitted as 0 volts. The "alternating polarity" bipolar rule results in a signal with no net dc component. Figure 1 is a typical bipolar pulse sequence.

2.2 Line driver

A line driver is used in both the station and central office equipment to couple the bipolar signals to the cable pairs. The line driver contains an amplifier, a low-pass filter, and lightning protection circuitry.

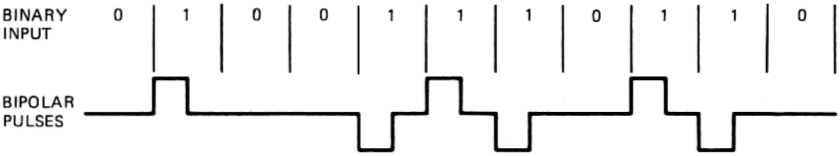


Fig. 1—Bipolar pulse sequence.

2.3 Line receiver

On ordinary paired telephone cable, insertion loss is an increasing function of both frequency and distance. Thus, transmission of high-frequency signals over long distances becomes difficult unless compensatory measures are taken. This is most often done in the form of equalization which counteracts the distributed loss of cable with lumped gain at the receiver.

It is desirable to design a receiver that will compensate the more popular gauges of cable (19, 22, 24, and 26 gauge) over an extensive range of distances. This has been accomplished by using an automatic line-build-out (ALBO) network coupled with fixed equalization within the line receiver. The necessary adjustments are automatic and adaptive. Therefore, installation procedures are simple and the equalization precise, being for the most part independent of the gauge, length, and temperature of the cable pairs.

A simplified block diagram of the line receiver is shown in Fig. 2. The incoming signal passes through the line circuit that contains the line transformer and lightning protection circuits. Noise filtering is provided by a low-pass filter. The ALBO circuit then adds loss to short cable pairs, making all cable pairs appear equivalent in length to match the equalizer. The equalizer adds sufficient gain and frequency compensation to equalize the maximum-length loop. Thus, the combination of cable, ALBO, and equalizer results in a channel with flat loss up to frequencies sufficient to transmit the required bit rate. The output of the equalizer then passes through a three-level slicing circuit

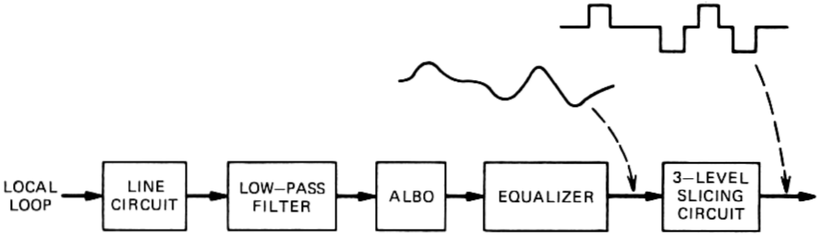


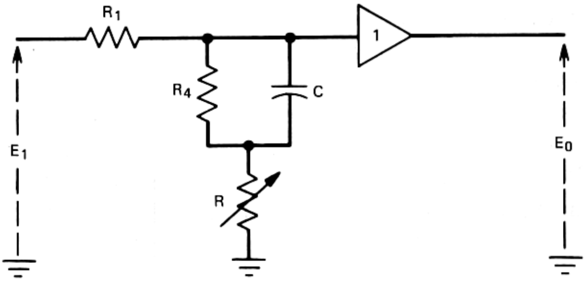
Fig. 2—Line receiver block diagram.

which regenerates the signal in amplitude as shown on Fig. 2. The signal is not sampled by this circuit, so it is not "time-regenerated."

2.4 Operation of ALBO and equalizer

As stated above, the ALBO adds loss to short cable pairs in such a manner as to make every pair appear as a maximum length pair for the corresponding bit rate. Typical loss characteristics of cable pairs can be approximated by a single-pole, low-pass filter in which the flat loss is directly proportional to cable length and the frequency of the pole is inversely proportional to length. The ALBO, shown in simplified form in Fig. 3, consists of an adjustable zero, adjustable flat loss, and a fixed pole. The adjustable zero effectively cancels the equivalent pole of the cable pair. The flat loss combines with the loss of the cable pair such that, with the fixed pole, the combination approximates the loss characteristics of a maximum length loop.

The flat loss and zero location are functions of the variable resistor R, which is realized physically by an FET varistor. Resistor R is inversely controlled by peak detecting circuitry at the output of the equalizer. The peak of the equalized signal has been found to closely track the cable loss at one-half the signaling frequency. Thus, as the associated cable pair becomes longer, the peak signal becomes less, resistor R increases, ALBO loss decreases, and the zero location tends toward the fixed pole. Therefore, on a maximum-length cable pair, the ALBO is essentially transparent, adding neither gain nor loss at any frequency.



FOR $R \ll R_1$

$$\frac{E_0}{E_1} = \frac{R}{R_1} \cdot \frac{S + 1/R_V C}{S + 1/R_F C},$$

WHERE

$$R_V = \frac{RR_4}{R+R_4}$$

$$R_F = \frac{R_1 R_4}{R_1+R_4}$$

Fig. 3—ALBO simplified diagram.

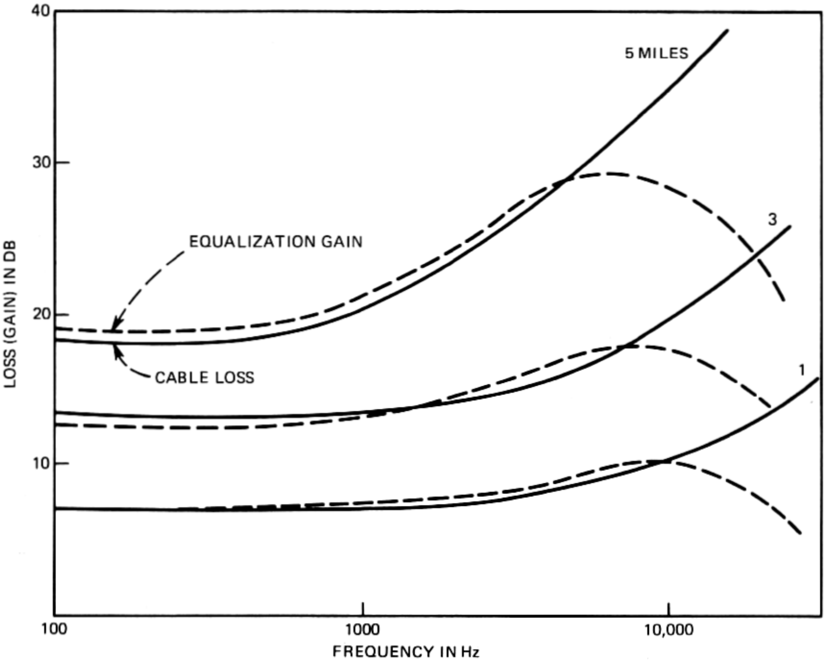


Fig. 4—26-gauge cable loss and equalization for 9.6-kb/s service.

The equalizer is designed to compensate for maximum-length loops. As such, it has fixed gain and a single zero which cancels the effective pole of the ALBO plus cable combination.

Although not explicitly shown in Fig. 2, the line receiver incorporates additional filtering for the suppression of out-of-band noise and crosstalk. To judge how well the ALBO and equalizer match cable characteristics, see Fig. 4 which depicts the insertion loss of various lengths of 26-gauge cable. The inverse of the equalization characteristic for 9.6-kb/s service is also shown, which closely tracks the cable loss over the necessary frequency ranges.

The ultimate measure of performance is eye closure or intersymbol interference. The peak value of intersymbol interference is shown as a function of cable length in Fig. 5 for 9.6-kb/s service on 26-gauge cable. The interference is calculated at the peak of the signal, which is the nominal sampling point, with a value of 100 percent representing a closed eye. The interference is seen to represent only a small fraction of the completely closed eye over a large range in distance.

At long distances, not only does intersymbol interference increase but the possibility exists of unstable operation. For this reason, it has been decided to limit the length of a loop to 31 dB of insertion loss at

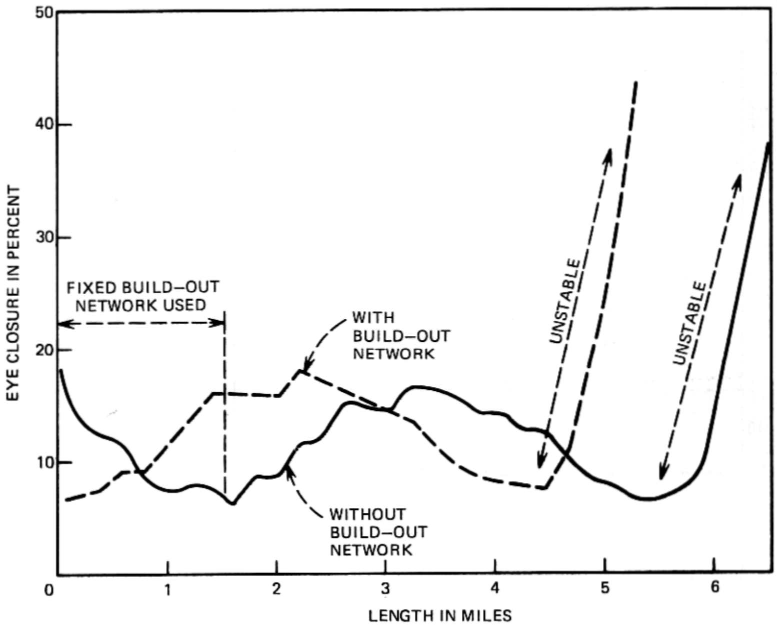


Fig. 5—Eye closure vs length for 9.6-kb/s service on 26-gauge cable.

one-half the signaling frequency. For 9.6-kb/s service on 26-gauge cable, this limit occurs at 4.7 miles, which is well beyond the normal supervision range of most central offices. The additional margin available according to Fig. 5 is used to absorb discontinuities resulting from bridged taps or mixed gauges and temperature effects.

The ALBO is unable to fully compensate for very short distances of cable. As a result, amplifier saturation causes an unacceptable amount of signal distortion. To prevent this situation from occurring, a fixed build-out network internal to the receiver is used for short cable pairs. The additional signal attenuation achieved by this pad allows the ALBO to compensate without saturation and results in the performance indicated in Fig. 5. The build-out network is used whenever the insertion loss of the loop at one-half the signaling frequency is less than 10 dB. On Fig. 5, this loss corresponds to a length of approximately 1.5 miles.

Although it is not shown, performance at other bit rates on 19-, 22-, 24-, or 26-gauge pairs is similar to that of Fig. 5. In all cases, the maximum allowable length of the loop is 31 dB of insertion loss at half the signaling frequency and the fixed build-out is inserted whenever the loop has less than 10 dB of loss.

2.5 Performance and requirements

The previous section considered performance in terms of intersymbol interference. This section considers the effect of outside interference, particularly background and impulse noise, upon the performance of the loop transmission system.

The long-term background noise objective on Bell System loops is 20 dBrn.[3] The noise, which is assumed to be white gaussian noise, is measured across 600 ohms and through a C-message weighting filter which has an equivalent bandwidth of approximately 2 kHz. When this is referenced to the 135-ohm line receiver, an equivalent objective can be found using the following factors:

90 dB	for conversion from dBrn to dBm
$\frac{2}{1}$	for change in bandwidth from 2 to 1 kHz
$\frac{600}{135}$	for change in termination from 600 to 135 ohms.

Thus, the objective at the line receiver becomes

$$20 - 90 - 10 \cdot \log_{10}\left(\frac{2}{1}\right) + 10 \cdot \log_{10}\left(\frac{600}{135}\right) = -66.5 \text{ dBm per kHz.}$$

The equalization shape used to match the cable loss yields a noise gain 3 dB greater than the peak signal gain. This gain is equivalent to the gain at one-half the signaling frequency, which is a maximum of 31 dB. Therefore, an equivalent noise objective at the receiver decision point is $-66.5 + 31 + 3 = -32.5$ dBm per kHz.

Among the four different services, the 56-kb/s service will have the least tolerance to noise because of its large bandwidth. For this service, the effective bandwidth of the receiver, assuming a maximum-length loop, is 48 kHz. Therefore, for cable pairs meeting the background noise objective, the total noise at the decision point is less than -15.8 dBm. With a decision level of 6 dBm, this yields almost a 22-dB signal-to-noise ratio. The associated probability of error, P, is given by

$$P_e = \frac{3}{4} \cdot \left\{1 - \operatorname{erf}\left(\frac{d}{\sigma\sqrt{2}}\right)\right\},$$

where

$$20 \cdot \log_{10}\left(\frac{d}{\sigma}\right) = 22.$$

The factor of $\frac{3}{4}$ arises from the bipolar nature of transmission. That is, a ±1 is sent from the transmitter one-half the time on the average. In each occurrence, there is a probability of $\frac{1}{2}$ that a noise peak will enhance rather than degrade the signal. Thus, for one-quarter of the time, no error can occur. Evaluating the expression yields a 4-dB margin with respect to an error rate of 10^{-10}. This margin is ample to ensure that errors caused by background noise will be negligible on cable pairs meeting the 20-dBrnC loop objective. Lower speed services of 2.4, 4.8, and 9.6 kb/s require less bandwidth than 56-kb/s service and will have even greater tolerance to background noise.

Although background noise is expected to be negligible, this cannot be assumed for impulse noise. The performance objective for a 56-kb/s DDS local loop is that 99.95 percent of all 1-second intervals should be error-free.[4] Using a conservative assumption that each "second in error" contains only a single error, an equivalent objective on error rate is 0.9 error per half hour. As shown in the appendix, each noise pulse that exceeds the decision level of the receiver causes an average of $\frac{3}{16}$ error. Thus, to meet the error rate objective, noise pulses above the decision level are required to occur less often than 4.8 per half hour.

As was the case for background noise, the decision level is equivalent to $6 - 34 = -28$ dBm at the receiver input. The equivalent bandwidth of the receiver for impulse noise is, however, greater than that found for background noise. This results from the impulse noise bandwidth being a function of the voltage spectrum, whereas background noise is a function of the power spectrum. For the worst-case 56-kb/s receiver, the impulse bandwidth is 64 kHz. Thus, the requirement on impulse noise is less than 4.8 impulses per half hour exceeding a threshold of -28 dBm in a 64-kHz bandwidth.

Measuring equipment commonly used to measure impulse noise, such as the Western Electric 6F noise measuring set, has an effective bandwidth of 34 kHz. Impulse counts in different bandwidths tend to be related as the square of the ratio of bandwidths. Thus, when measured through a 6F set, the objective becomes 1.4 counts per half hour above 62 dBrn (0 dBm = 90 dBrn). This objective is approximately 10 dB more severe than present objectives for cable pairs assigned to 50-kb/s wideband data service.[5]

Lower rate services require less bandwidth than 56-kb/s service, and the objectives are adjusted accordingly. Since an objective of 1.4 counts per 30 minutes is difficult to measure, 10 times as many counts may be allowed for each 10-dB decrease in threshold.

Crosstalk is another factor that must be considered when evaluating loop performance. Again, since crosstalk loss between cable pairs decreases with frequency, 56-kb/s service is the most critical.

At 56 kHz, there is only a 1-percent chance of within-unit near-end crosstalk loss between cable pairs being less than 72 dB. Also, an upper bound on signal power expected from other services is 6 dBm.

Thus, there would only be a small chance of interference exceeding $6 - 72 = -66$ dBm. The decision level referenced to the cable pair is $6 - 34 = -28$ dBm, yielding a 38-dB signal-to-noise ratio. A 38-dB signal-to-noise ratio is ample to ensure that crosstalk from other services will be a negligible source of impairment.

It is also necessary to consider crosstalk from other synchronous DDS services. In this case, the possibility exists of several DDS services, transmitting a periodic pattern synchronously, all at the same bit rate. The worst case would be for 56-kb/s services transmitting an alternating ±1 signal (steady mark from the customer) on the line. The peak value of this signal would be 12 dBm with almost all the power occurring at 28 kHz. At 28 kHz, near-end crosstalk loss between pairs exhibits a mean of 97 dB with a standard deviation of 8.6 dB for the assumed normal distribution. The 1-percent worst-crosstalk loss would be 77 dB, resulting in a disturbing voltage of −65 dBm. Assuming a decision level-to-crosstalk ratio of 18 dB, which yields a 10^{-10} error rate for gaussian noise, the overall margin available is $-28 - 18 + 65 = 19$ dB.

Using Monte Carlo techniques for summing log-normally distributed powers,[6] it can be shown that this margin is sufficient to absorb 50 multiple disturbers. Since cable pair units typically contain less than 100 pairs, 50 disturbers is the maximum number to be expected in this four-wire service. Thus, adequate protection exists from intrasystem crosstalk.

The conclusions reached above were verified in a field experiment at Freehold, New Jersey. For eight loops (two of each gauge) examined, the C-message weighted background noise was measured to be less than 0 dBrn. With respect to impulse noise, the worst-case loop was a 24-gauge loop with long-term noise as shown in Fig. 6. Data errors and "seconds-in-error" were also measured concurrent with impulse noise. The error rate was found to be approximately 7×10^{-9}, with 99.97 percent of the 1-second intervals being error-free. Thus, background noise, impulse noise, and the resulting error performance were all within objectives.

2.6 Facility considerations

To ensure successful loop transmission, consideration must be given to the characteristics of presently available loop plant. The maximum allowable loop distance is a function of the particular cable gauge and service rate being considered, as shown in Table I. Mixed gauge loops are permitted with maximum distances determined by linear interpolation within Table I. Temperature considerations yield less than a

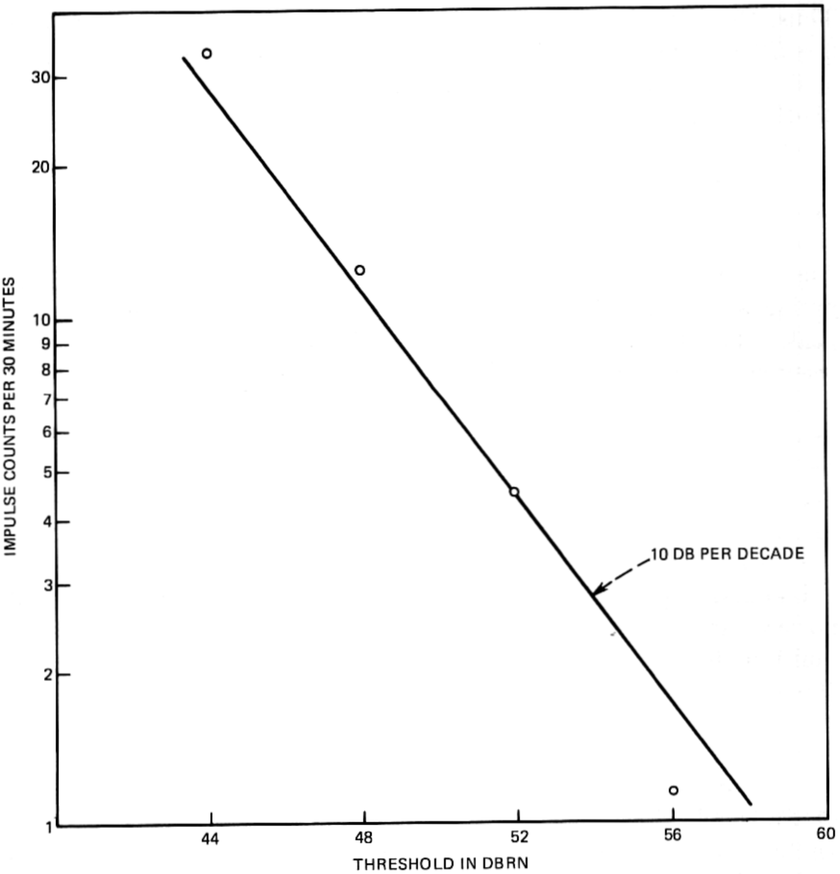


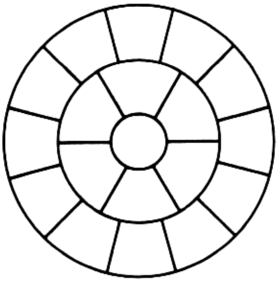
Fig. 6—Impulse noise on worst-case loop.

2-percent reduction in length for every 10°F change in maximum temperature above the nominal 70°F.

Data transmission can be seriously impaired by perturbations in the nominal transmission characteristics of cable pairs caused by loading coils, build-out capacitors, and excessive bridged tap. Therefore, such additions will not be permitted on the loop pairs.

Table I — Maximum distance in miles

	2.4 kb/s	4.8 kb/s	9.6 kb/s	56 kb/s
19 gauge	21.6	16.4	12.7	7.7
22 gauge	13.9	10.7	8.1	4.6
24 gauge	10.6	8.0	6.1	3.3
26 gauge	7.9	6.1	4.7	2.4



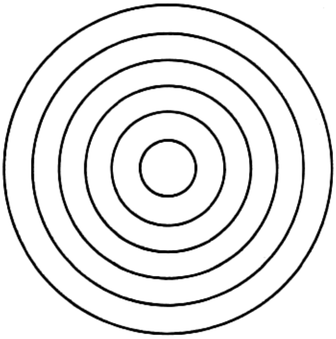


Fig. 7—Cable cross section.

A consideration in providing DDS service is the coordination between DDS and other services that use pairs within the same cable. Certain amounts of segregation are necessary so that undue crosstalk from DDS, particularly at 56 kb/s, is not accumulated in other services. Segregation is achieved by placing susceptible services in adjacent or alternate cable units (splicing groups in the case of layer cable), as in Fig. 7.

2.7 Digital loopbacks

As pointed out in Ref. 7, emphasis has been placed on the maintenance features and testing capabilities of the Digital Data System. Full-time, in-service performance monitoring and protection switching for long-haul and short-haul facilities and multiplex terminals are provided. For the local distribution portion of DDS, alternative strategies present a more attractive cost picture. To maintain the high degree of availability[4] required for the DDS, emphasis has been placed on providing means for very rapid trouble isolation in the event of transmission failure. To accomplish this, digital loopbacks have been incorporated in the local distribution equipment as shown in Fig. 8.

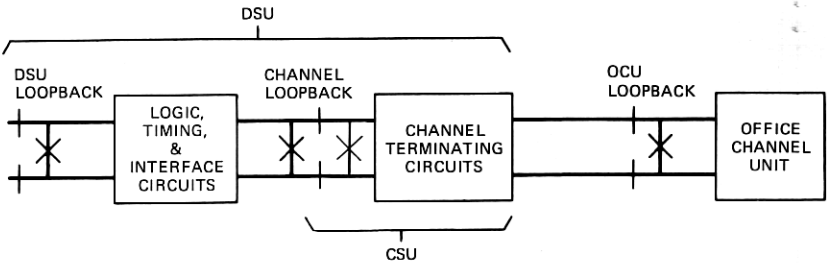


Fig. 8—Digital loopbacks.

In the event of a local distribution trouble, these loopbacks enable rapid isolation of the faulty component so that the proper repair force can be dispatched to quickly restore service. For a channel terminated with a data service unit, three distinct loopbacks are provided. For channels terminated with a channel service unit, two digital loopbacks are provided. Each of these loopbacks can be remotely activated by a distant serving test center (STC). Once activated, digital signals can be transmitted from the STC and looped back to determine the quality of the channel up to the loopback point.

2.8 Network control signals

The private line point-to-point service initially provided in the DDS permits serial binary transmission from end to end without restrictions on the bit patterns. However, for system maintenance within the network and to provide the customer with unmistakable means of indicating and interpreting channel status, additional transmission capacity has been uniquely dedicated to network control information. To protect the control features from accidental or deliberate misuse, the transmission formats have been kept distinct from those of normal data, and customer access to the reserved capacity is strictly limited by the OCU. Thus, the control indication scheme described below applies, in general, only for transmission toward the station.

As described in Ref. 1, the cross-connect format between OCUs and multiplexing equipment (and at tandem multiplexing points) is based on 8-bit bytes as follows:

$$F1 \quad D2 \quad D3 \quad D4 \quad D5 \quad D6 \quad D7 \quad C8.$$

Bit F1 is used either for the subrate multiplexer framing code or for data in the case of 56-kb/s service (in which case, the notation D1 will apply in what follows). Bits D2 through D7 are used for data in all services. Bit C8 is dedicated as the network control mode identifier. When bit C8 is a 1, bits D1 (or D2) through D7 are identified as customer data. When bit C8 is a 0, bits D2 through D7 are interpreted

Table II — Network control codes

F1*	D2–D4	D5–D7	C8	Interpretation
1	1 1 1	1 1 1	0	Idle code
0	0 1 0	1 1 0	0	DSU loopback
0	0 1 0	1 0 1	0	OCU loopback
0	0 1 0	1 0 0	0	CHANNEL loopback
0	0 0 1	1 1 0	0	Test code
0	0 0 1	1 0 1	0	MUX out of sync
0	0 0 1	1 0 0	0	Unassigned MUX channel

* Bit column F1 assignments are shown for 56-kb/s operation. For substrate channels (2.4, 4.8, and 9.6 kb/s), this position is dedicated to the subrate multiplexer framing code independent of the content of the remainder of the byte.

as network control information. The various network control codes are listed in Table II. The entries in Table II are grouped according to the content of bits D2 through D4. The first, idle code, stands alone. It indicates no transmission in the customer data stream and is accessible to the user for such purposes as acknowledgment or alerting. The customer is blocked from sending the remaining codes into the network, but they can pass from the network into the local channel for control and information purposes. The group of three loopback codes controls system-initiated remote testing on the local channel. The final group of three indicates trouble or maintenance activities at higher transmission levels of the network, which make the receiving channel unavailable to the customer. By treating the members of these groups as equivalent for local cable transmission, it becomes possible to use bits D5 through D7 to encode the network control information in a form that is distinct from user data. This is accomplished through bipolar format violations without increasing the pulse rate above the service data rate.

In the OCU, bits D1 (or D2 for subrate channels) through D7 are taken from the intraoffice byte and retimed to the service data rate. When bit C8 is a 1, the normal bipolar rule applies, and the resultant line signal carries no indication of the network byte structure. When bit C8 is a 0, a bipolar violation encoding rule is applied. This format violation scheme for network control indication may be explained in terms of the following notation, following Croissier[8]:

0 any 0 level pulse
B any ±1 level pulse transmitted according to the normal polarity alternation rule (the normalized unity level is written here for simplicity)
X a system-determined pulse that may be either a 0 or a B
V a ±1 level pulse transmitted in violation of the normal alternation rule.

When bit C8 is a 0, bits D1 (or D2) through D4 are still encoded by the normal rule, but bits D5 through D7 are replaced with a bipolar violation sequence, X–0–V. The violation pulse, V, uniquely establishes the network control mode and also identifies the byte alignment for interpretation of the network control bits, D2 through D4. The system-determined pulse, X, is set to force the number of B pulses between violations to be odd. This causes successive violations to alternate in sign, thus limiting dc build-up in the transmitted signal. The 0 pulse serves to block occurrences of the sequence, B–V, which can increase intersymbol interference effects.

The encoding rule is probably best seen from an example. Consider two successive idle bytes generated at the far-end OCU in a 56-kb/s system.

$$\Big|\,1\quad \underline{1\quad 1\quad 1}\quad \underline{1\quad 1\quad 1}\quad 0\,\Big|\,1\quad \underline{1\quad 1\quad 1}\quad \underline{1\quad 1\quad 1}\quad 0\,\Big|\,.$$

The underlining emphasizes the grouping of D2 through D4 and D5 through D7 in the control code treatment. The digits are retimed at the near-end OCU in groups of 7 at the 56-kb/s service rate, the four 1s of D1 through D4 transmitted as Bs, and D5 through D7 overwritten with X–0–V.

$$\Big|\,B\quad \underline{B\quad B\quad B}\quad \underline{X\quad 0\quad V}\,\Big|\,B\quad \underline{B\quad B\quad B}\quad \underline{X\quad 0\quad V}\,\Big|\,.$$

The signed values of the resulting line signal might then be

$$\Big|\,+\quad \underline{-\quad +\quad \overset{(X\,=\,B)}{-}}\quad \underline{+\quad 0\quad +}\,\Big|\,-\quad \underline{+\quad -\quad \overset{(X\,=\,B)}{+}}\quad \underline{-\quad 0\quad -}\,\Big|\,.$$

Note that either the sign of the initial B or the use of the X in the first byte might have been different, since the prior state of the system was not given. However, with the first byte established, the second byte is strictly determined with a negative B following the positive V, and $X = B$ to provide an odd number of Bs between Vs. With the violation detected, the specific network control state is identified by bits D2 through D4, which for the example are recognized as the three 1s of the idle code.

The example given for 56 kb/s applies equally to subrate services, except that for the lower rates the F1 bit does not appear on the local loop. Thus, continuous control codes will repeat on a six-bit instead of a seven-bit basis.

As mentioned above, the OCU does not permit the user to freely indicate all network control states back into the 64-kb/s stream. However, an idle code from the station is translated to the corresponding 64-kb/s byte.

One additional violation code occurs with bit C8 in the 1, or data, state. To prevent drift of the receiver timing recovery and ALBO circuits, it is necessary to suppress long strings of 0 pulses on the local loop. For this reason, whenever data bits D2 through D7 are all 0s, the zero suppression network control code is transmitted on line in the form

$$\underline{0\ \ 0\ \ 0}\ \ \underline{X\ \ 0\ \ V}.$$

At the station, this is recognized and interpreted as a sequence of six data 0s. The same rule applies from the station toward the OCU, except that any string of six 0s is suppressed without reference to byte alignment.

III. OFFICE CHANNEL UNIT

3.1 Format conversion

The principal function of the OCU is to perform a format and rate conversion between the local loop signal at the digital service rate and the 64-kb/s intraoffice signal. The former has been described in detail in earlier sections of this paper. The latter has been described in Ref. 1, but is briefly summarized as follows.

For 56-kb/s service, seven local-loop line bits plus the network control identifier, C8, are retimed to produce a 64-kb/s signal directly. For subrate speeds, six local-loop line bits are grouped between the F1 and C8 bits to produce one 64-kb/s byte. But the local-loop transmission time for six subrate line bits exceeds the 125-μs byte interval at 64 kb/s, so each byte is repeated an appropriate number of times to fill out the additional 64-kb/s byte intervals. For 9.6, 4.8, and 2.4 kb/s, the number of repetitions are 5, 10, and 20, respectively.

The intraoffice signal is transmitted over limited-length balanced pairs through coupling transformers. The signal format is bipolar but without violations. Line driving and terminating circuits are much simpler than those required for the local loops, without closely controlled levels and impedances, shaping filters, or equalizers.

3.2 Block diagram description

Figure 9 is an OCU block diagram. As with all other DDS equipment, operation is synchronous with an office clock source.[9] Clocks are dis-

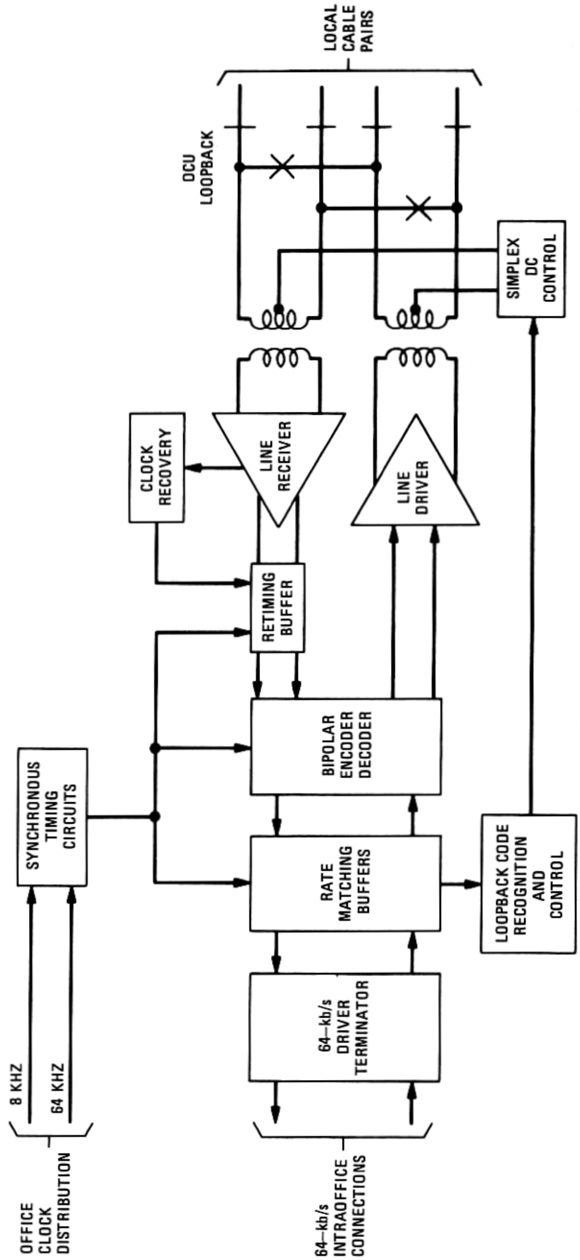


Fig. 9—OCU block diagram.

tributed at 8 and 64 kHz, defining byte and bit timing for the intraoffice 64-kb/s signals. The timing signals for all OCUs are derived by counting down from 1.344 MHz, the least-common multiple of 64 kHz and the four data service rates. A voltage-controlled oscillator driving the countdown chain is adjusted to maintain phase lock with the office clock distribution at the 64-kHz counting level. Byte reference is established to the 8-kHz office clock, and a family of synchronous clock pulses is derived at the 64-kHz and data service rates. Additional pulses are produced once per byte to control data transfer in the rate matching buffers and to establish the bipolar encoder violation sequence. The various paths are abbreviated as single lines in the block diagram.

The rate-matching buffers provide storage to assemble one byte in either direction. On the receiving side, an additional byte of recirculating storage provides the 64-kb/s repetition required for subrate speeds. The bipolar encoder and decoder operate at the service data rate according to the rules given in Section IX.

The line driver and line receiver characteristics have already been described in detail. Essentially identical circuits are used in the OCU, the DSU, and the CSU. The line coupling and protection circuits include the line isolation transformers, lightning protection networks, and the fixed line-build-out pad. Both transformers are center-tapped on the line side, and a small direct current (<20 ma) is simplexed through the local-loop pairs to prevent resistance build-up in unsoldered splices.

Because total delay around the local channel cables is variable, a clock recovery circuit is necessary to establish the data sampling time at the line receiver. A one-bit retiming buffer is used to realign the sampled data with the office-controlled clock of the synchronous timing circuits.

Loopback control codes from the intraoffice connection are detected and distinguished in the recognition circuits as 8-bit bytes. The appropriate loopback state is indicated on the basis of three successive loopback codes received and terminated on the basis of five successive byte intervals without the loopback code indication. This rule applies both at the OCU and the DSU.

In the case of OCU loopback, a relay in the line coupling and protection circuits disconnects the local loop pairs and connects the line driver to the line receiver through both coupling transformers and the fixed build-out pad.

The CHANNEL loopback code is also recognized at the OCU, and a second relay reverses the polarity of the simplexed direct current for detection at the station. During the CHANNEL loopback, violations are suppressed at the bipolar encoder.

In the case of DSU loopback, no special action is taken at the OCU, but the network control code is transmitted with violations for detection at the DSU.

3.3 Multiple OCU arrangement

The block diagram of Fig. 9 indicates the functions of an individual OCU without reference to shared common circuitry. For economy and flexibility, timing circuits and interconnection cabling are organized on the basis of a bay-mounted, two-shelf equipment assembly that can accommodate 20 individual OCUs as plug-in circuit packs. The OCUs for all rates are mechanically interchangeable, with components mounted on two printed circuit boards joined by a common faceplate. The complete circuit pack measures approximately 1.4 × 8 × 10 inches.

The synchronous timing circuits are not included in the OCUs, but are provided in common for each shelf. The 1.344-MHz source oscillator and the basic phase lock circuitry are provided on a single circuit pack at the center of the shelf. A specific rate clock generator on a separate circuit pack is necessary to provide the remaining countdown circuits to generate all clocks necessary for each rate. The specific rate clock generator is inserted to serve five OCU positions on one side of each shelf, which are then dedicated only for OCUs of that service rate.

For 56-kb/s services, the 64-kb/s intra-office driver-terminators for one half-shelf of five OCUs are mounted on a common circuit pack. For subrate services, two arrangements are possible. In hub offices where individual channel cross-connection is required, the driver-terminator circuit pack is used for each group of five OCUs. In an end office where individual channel cross-connection is not provided and efficient multiplexing is not essential, a five-channel integral subrate multiplexer circuit pack may be used in place of the driver-terminators. This circuit pack which is physically interchangeable with the driver-terminator circuit pack enables subrate multiplexing within the OCU shelf.

Power supply arrangements for the OCUs are also multiple. A single dc-to-dc power conversion unit, connected to the office battery supply, provides power for two shelves containing up to 20 OCUs. An OCU power shelf contains two such active power units, plus a working spare, to provide power for four shelves of OCUs. Each power unit contains protective voltage monitoring circuits that control automatic spare transfer and alarm circuits in the power shelf to maintain full service in the event of a single power unit failure.

IV. DATA SERVICE UNIT

The DSU is the more complex of the two customer location units provided in the DDS. It includes clock recovery and logic circuitry to convert between the local loop format and a synchronous binary interface with timing signals provided to the customer terminal. A separate set of control leads in the interface selects the transmission modes (data or idle code) and indicates receiver network control modes. The interface characteristics of the DSU are described in detail in Ref. 4.

A block diagram of the DSU is given in Fig. 10. The line-driver, line-receiver, and clock-recovery circuits are as in the OCU except for the loopback paths. The clock recovery is the overall timing source, since the station is slaved to the network timing. All circuit operation is at the service data rate.

The bipolar encoder and decoder implement the rules given in Section IX. The decoder indicates X–0–V sequences to the network control detection circuitry which identifies the control codes on the basis of the preceding three bits. The DSU idle and out-of-service conditions are indicated after three successive codes are received and cleared after two successive codes are received without the control state indication.

The DSU loopback code is recognized at the DSU according to the frequency rule described under the OCU. The DSU loopback relay breaks the data leads at the customer terminal and provides a loopback path through all DSU line, logic, and interface circuitry.

Polarity reversal of the simplexed direct current from the OCU indicates the CHANNEL loopback command. The reversed current operates a relay through a diode bridge, and a second-stage relay provides the loopback path through the line receiver and line driver without retiming. The OCU suppresses bipolar violations in this mode, as mentioned above, because the untimed regeneration exhibits excessive pulse width distortion in the presence of violations. The use of the line receiver and line driver in the loopback path is necessary, since local channel constraints to ensure desired performance are based on one-way loss characteristics of the local cable. Thus, a round-trip loopback over just the cable pairs could exceed the range limitation. In the DSU, the CHANNEL loopback path is closed directly between the line receiver and line driver to minimize the DSU circuitry involved, so that this test may serve to distinguish between faults in the loop cable and faults in the extensive DSU circuitry bypassed during the test.

The DSU housing[10] measures approximately 12 × 4 × 11 inches. Status lights indicate the presence of required 115-V, 60-Hz power, each of the two loopback conditions, and loss-of-line signal from the OCU. A slide switch permits manual selection of either loopback.

V. CHANNEL SERVICE UNIT

The CSU is the simpler of the two customer location units provided in the DDS. It includes the circuitry necessary to implement the

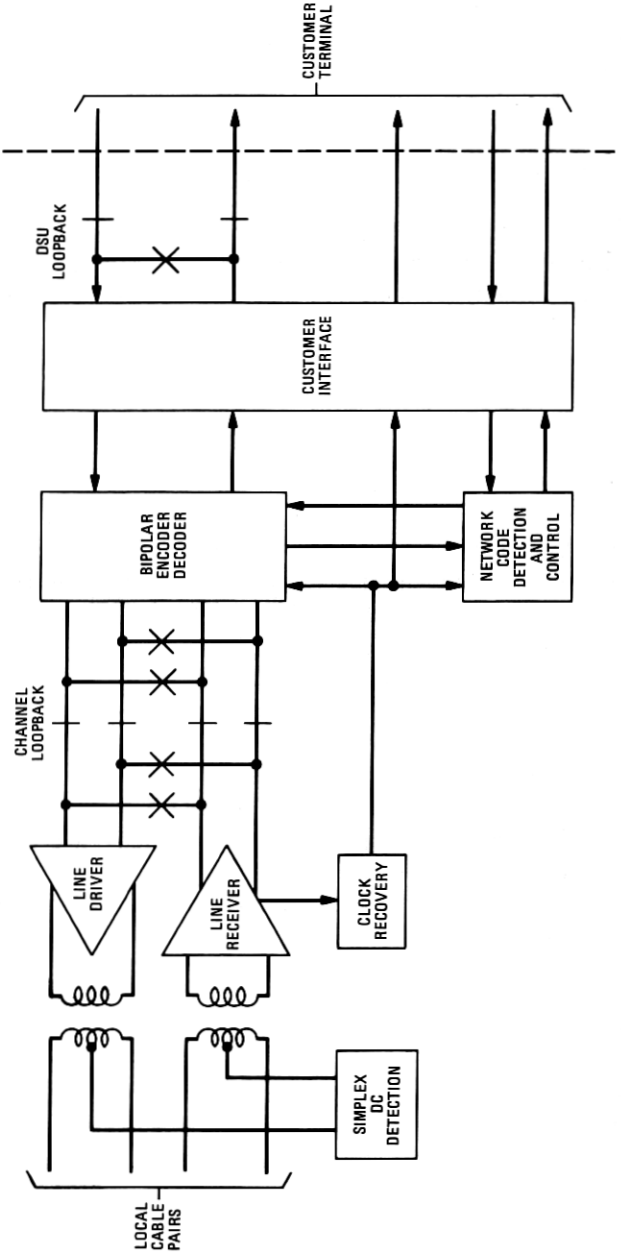


Fig. 10—DSU block diagram.

CHANNEL loopback function required in remote maintenance testing. As noted above, this must encompass the line receiver and line driver. No timing recovery or code conversion circuits are included, and its three-level dc-free interface signals correspond directly to the local channel line signals. Lower cost and simplicity of physical interconnection offer an alternative for the user able to perform his own clock recovery and code conversion functions. The interface characteristics of the CSU are described in detail in Ref. 4.

A block diagram of the CSU is given in Fig. 11. The line driver and line receiver are as in the DSU, including the diode bridge and sensing relay required for CHANNEL loopback.

The digital output of the line receiver is derived from two voltage comparators acting continuously on the filtered and equalized signal. Threshold references for the comparators are set at $\pm\frac{1}{2}$ the nominal peak signal amplitude maintained by the ALBO. The outputs of the comparators directly control a three-level interface driver to provide a replica of the line signal. The slicing action of the comparators yields an amplitude-regenerated signal characterized by distinct transitions between fixed levels. Coupling to the interface is through a balanced isolation transformer. The two outer signal levels are ±1.4 V, with a pulse duty cycle typically 65 percent of the bit interval but varying with line characteristics and received pulse sequences.

The interface terminator in the transmitting direction also includes a balanced isolation transformer. The customer is required to provide 50-percent duty-cycle pulses to maintain correct pulse shaping in the line driver circuit.

Only the CHANNEL loopback function is implemented in the CSU. Unlike the CHANNEL loopback arrangement in the DSU, the loopback path is closed at the customer interface. Thus, CHANNEL loopback in the CSU serves as a test of both the local cable and all the CSU circuitry.

The CSU housing[10] measures approximately 8 × 5 × 3 inches. Status lights indicate the presence of required 115-V, 60-Hz power and the loopback condition.

VI. SUMMARY

In DDS local distribution between serving central offices and customer locations, the transmission medium is subscriber-loop cable pairs. This paper has described the baseband, bipolar transmission method used to provide the synchronous digital service and its associated control indications over these pairs.

Engineering requirements on the local cable pairs are described in relation to the performance objectives. These requirements include removal of inductive loading, limitations on bridged taps, and a range

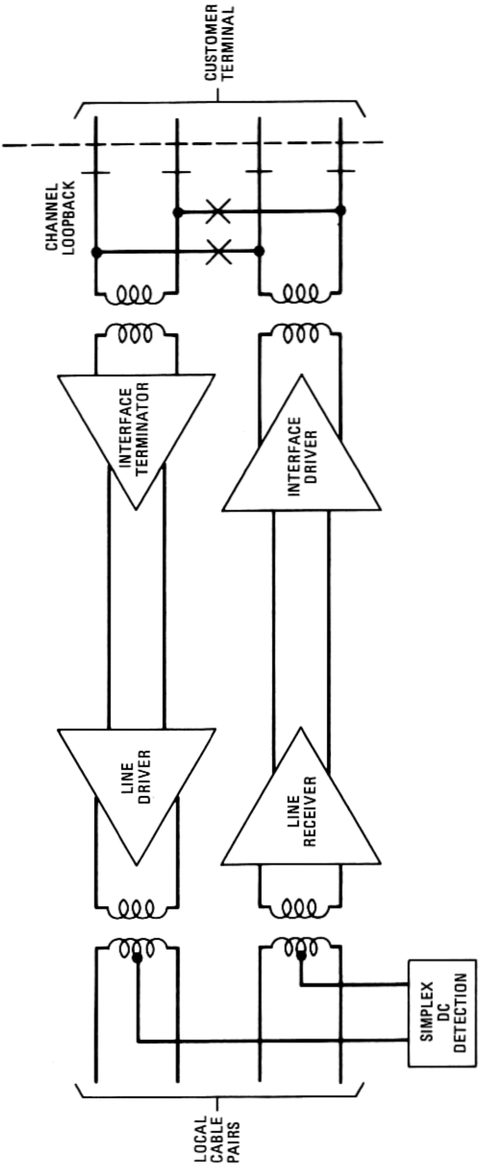


Fig. 11—CSU block diagram.

limitation which depends on the data rate and the cable gauge. Reliable attainment of the objectives depends on installation noise tests of the individual loops. Certain sensitive services may experience interference from 56-kb/s DDS loop signals if appropriate separations are not maintained.

Line driving and terminating circuits at the station and the office are similar. All terminators include ALBO networks to compensate for cable length. Station units may include synchronization and logic circuits to provide a standard data interface (data service unit) or may provide only a controlled level bipolar interface (channel service unit). The office channel unit provides rate conversion logic to transform the customer signal to the standard 64-kb/s office format of the DDS. Digitally controlled remote loopback paths are provided at both station and office to permit unaided fault isolation from the serving test center.

VII. ACKNOWLEDGMENTS

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APPENDIX

Impulse Noise

Several different methods exist that can be used to relate data errors to impulse noise. The one under consideration notes that the receiver appears as a bandpass filter with peak response at the signaling frequency. Thus, impulse noise will tend to appear at the output of the receiver as bursts of a sine wave of frequency equal to the signaling frequency.

Each half-cycle of the sine wave burst has the potential to cause an error and so may be considered a separate noise pulse. From previous experience, it is expected that the long-term number of noise peaks that exceed a given amplitude threshold will increase by a factor of 10 for each 10-dB decrease in threshold. In other words,

$$n(v) = n(v_0) \cdot \left(\frac{v}{v_0} \right)^{-2}, \tag{1}$$

where $n(v)$ is the number of events per unit time greater than v_0 volts. For each half-cycle noise pulse of amplitude v, the probability of an error is proportional to the duration of the pulse above the decision threshold. Note that the maximum duration is one-half the bit interval and assume v_0 represents the threshold,

$$p(e|v) = \frac{\pi/2 - \sin^{-1}(v_0/v)}{\pi}, \tag{2}$$

for

$$v \geqq v_0.$$

Thus, the expected number of errors per noise pulse of peak greater than v_0, $E^*\{N(e)\}$, is given by

$$E^*\{N(e)\} = \int_{v_0}^{\infty} p(e|v)p(v)dv. \tag{3}$$

But $p(v)$ is simply

$$\frac{d}{dv}\left[1 - \frac{n(v)}{n(v_0)}\right].$$

Therefore, evaluating the integral,

$$E^*\{N(e)\} = \tfrac{1}{4}. \tag{4}$$

Note that only $\frac{3}{4}$ of the noise pulses above the decision threshold during the receiver sampling time will cause errors. Thus, the true expected number of errors per pulse is

$$E\{N(e)\} = \tfrac{3}{4}\cdot E^*\{N(e)\} = \tfrac{3}{16}. \tag{5}$$

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