The *Picturephone*® System:

Mastergroup Digital Transmission on Modern Coaxial Systems

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We describe in this paper a system currently under development that will adapt the L-4, and later the L-5, coaxial system for digital transmission in mastergroup bands. The terminal equipment will combine two 6.312 Mb/s digital signals and, hence, two Picturephone® *signals in digital form for transmission on the coaxial systems along with analog message channels in other mastergroups. The overall system includes regenerative repeaters at intervals of not more than 300 miles to realize the error rate objective of* 2.6×10^{-7}*, or better, for distances up to 4000 miles.*

I. INTRODUCTION

The introduction of intercity *Picturephone* service will stimulate growth in the amount of digital information requiring transmission over long distances. It is important to provide for this growth and for the increasing capacity required for high-speed data in an evolutionary manner. This has motivated the development of terminal equipment to adapt existing microwave radio[1] and analog coaxial facilities for the transmission of digital signals.

The L-4 coaxial line is an excellent medium for an efficient hybrid transmission system.[2] A high signal-to-noise ratio (S/N), excellent linearity, and well-defined and stable transmission characteristics make it very attractive for multilevel pulse transmission. A mastergroup band provides a convenient subdivision for frequency multiplexing high-speed digital and analog signals. The mastergroup band has a bandwidth of 2.52 MHz and conventionally provides for 600 frequency division multiplexed voice channels. A mastergroup band is also capable of carrying two time-division multiplexed 6.312-Mb/s signals and, thus, can handle two digitalized *Picturephone* signals. It is planned that the digital mastergroup signals will be transmitted over the L-5 coaxial system that is currently under development.

The maximum digital capacity of an L-4 route employing mastergroup digital equipment is equivalent to 108 digital *Picturephone* trunks. (Each of the six mastergroups per coaxial tube could carry two 6.312-Mb/s signals, and there are nine working two-way tube pairs per line, the remaining pair being reserved for protection.) The mastergroup digital capacity of the new L-5 system, employing a new 22-tube coaxial line and transmitting 15 mastergroups per tube, is 300 digital *Picturephone* trunks.

The L-mastergroup digital system, together with the microwave radio system, will provide the Bell System the long-haul, digital capacity it will need in the early 1970s. Digital signals can be routed to any of the metropolitan areas served by L-4 and L-5 coaxial cable routes.

The terminal equipment being developed to adapt L-mastergroup bands for digital transmission is the subject of this paper. The equipment employs the techniques of time division multiplexing, digital processing, vestigial sideband modulation, adaptive equalization, analog-to-digital conversion and digital regeneration.

II. DESIGN OBJECTIVES

Design objectives have been established to ensure performance compatibility with the evolving digital hierarchy and with the L-4 and L-5 Coaxial Systems. The bit rate should be sufficient to accommodate an integral number of 6.312-Mb/s signals. The error rate for a 4000-mile mastergroup digital connection should not exceed 2.6×10^{-7} errors-per-bit more than 5 percent of the time.[3] The timing jitter of 6.312-Mb/s digital signals delivered from receiving mastergroup digital terminals should be no greater than that presented to the corresponding transmitting terminal. In addition, a mastergroup digital signal should not degrade the coaxial system noise performance established by the analog mastergroups. The digital equipment should be compatible with the standard blocking, branching, and frogging rules of the coaxial system and should also be compatible with standard facility switching, restoration, alarm, and maintenance procedures. Thus, the means should be provided for in-service monitoring of the digital facility that allows for quick identification and correction of trouble conditions.

III. SIGNAL FORMAT

The class IV partial-response signaling format[4,5] exhibits a number of characteristics that make it well suited for use in the L-Mastergroup Digital (LMD) System. Foremost is the power distribution as a function of frequency of the baseband signal which has nulls at dc and at a frequency equal to one-half the symbol rate. These nulls permit the transmission of both a carrier pilot and a timing pilot along with the signal, which greatly facilitates coherent demodulation and accurate timing of the received signal. Since the power distribution rolls off gradually near the band edges, the signal is less sensitive to the severe edge-of-band phase distortion introduced by the channel filters located in the LMD terminal.

The partial-response signaling rate can be nearly twice the bandwidth of the channel since satisfactory performance is not dependent upon the provision of a large (50 or 100 percent) excess bandwidth for roll-off (Nyquist) shaping as is often the case for a full-response format. Indeed, satisfactory performance has been obtained in partial-response digital transmission systems with no roll-off band.

The partial-response coding format has the further advantage that violations in the code can be monitored after the received signal has been sampled. The number of violations in the random data signal that occur per unit time provides a measure of the error performance for the system.[6] Coding of the signal in the LMD System is administered in a way that allows the error performance of each regenerative repeater section to be monitored independently. In this way, a trouble condition in any one of the repeater sections can be easily isolated to the appropriate section. The violation detector is also used in a control loop to correct for errors in the sampling time.

IV. INFORMATION RATE

The probability of error per bit for an n-level, class IV partial response signal, transmitted over a channel with optimum raised-cosine shaping and no intersymbol interference is

$$P_{\mathrm{IV}} = \left(\frac{2}{\log_2 N}\right)\left(1 - \frac{1}{N^2}\right)Q\left(\sqrt{\frac{3P_s}{2(N^2 - 1)P_n}}\right)$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{t^2}{2}\right) dt,$$

P_s = channel signal power,
P_n = channel noise power in the Nyquist band,
$\log_2 N$ = number of bits conveyed per pulse, and
$n = 2N - 1$ = number of coded levels transmitted.

The usual assumption has been made that only errors caused by gaussian noise which produce transitions to levels adjacent to the transmitted level need be considered. Thus, with Gray coding, the bit error rate will be $1/\log_2 N$ times the symbol error rate as indicated in the expression for P_{IV}.

The LMD signal must be digitally regenerated in order to prevent noise and other forms of distortion from accumulating over a 4000-mile L-4 or L-5 system and becoming too great to permit efficient use of the mastergroup bandwidth. Because of their size and complexity, the regenerative repeaters must be located only at L-carrier main-stations. In a 4000-mile system, there will be approximately 16 LMD repeaters having a maximum separation of 300 miles (two mainstation sections).

The noise power falling within the Nyquist band at the input to a regenerative repeater, $W_N(L)$ is given by

$$W_N(L) = W - 88 + \log (B_N/B_M) - 10 \log (L_c/L)$$

where

W = expected noise power in 4000 miles of L-4 (40 dBrnc0),
B_N = Nyquist bandwidth (2.215 MHz),
B_M = message channel bandwidth (3 kHz),
L_c = maximum LMD System circuit length (4000 miles), and
L = repeater spacing ($\leqq$300 miles).

By substitution, the worst-case noise power at the repeater is −30 dBm0.

The distribution of voltage for 600-message channels, after modulation into a mastergroup band, is approximately gaussian.[7] The voltage distribution for a mastergroup digital signal is bounded, and randomizing of the digital signal ensures that the peak power level in a master-group band is well controlled. With these considerations in mind, the power level of a mastergroup digital signal has been set equal to the average of a message mastergroup, or $P_s = +11$ dBm0. This is a conservative choice intended to ensure that a mastergroup digital signal contribute no greater intermodulation noise than a message master-group. This establishes the worst-case S/N of the digital signal at the input to a digital repeater at 41 dB.

The 2.6×10^{-7} error rate objective for a 4000-mile connection corresponds to an error rate of approximately 2×10^{-8} per repeater section. The S/N that is required to just achieve 2×10^{-8} error performance can be computed for a 15-level partial response signal from the expression for P_{IV} and is approximately 31 dB. The 10-dB difference between the computed signal-to-noise requirement and the 41-dB ratio expected is the margin that may be allocated to impairments arising from channel imperfections such as amplitude and phase distortion, timing jitter, signal-level variations, quadrature distortion, and imperfect multilevel to binary conversion. Thus, the 15-level class IV partial response signal combines adequate margin for transmission impairments with good bandwidth efficiency. The pulse rate has been set at 4.43 megabauds which results in a bit rate of 13.29 Mb/s. The LMD System can conveniently handle two 6.312-Mb/s signals plus additional capacity for multiplex framing, bit synchronization and miscellaneous control signals.

V. L-MASTERGROUP DIGITAL CHANNEL

The LMD equipment required to adapt the L-4 or L-5 Carrier System for transmission of mastergroup bandwidth digital signals is located only at mainstations. This arrangement not only facilitates maintenance but readily permits the multiplexing of both digital mastergroups and message mastergroups in the same cable. A block diagram of a typical digital channel is given in Fig. 1. The terminal digitally multiplexes two 6.312-Mb/s signals and modulates the combined signal into one of the L-4 mastergroup bands. At intervals up to 300 miles, the repeaters demodulate the line frequency signal to baseband where it is digitally regenerated and modulated back into an appropriate mastergroup band.

Figure 2 is a block diagram of the terminal and associated multiplex equipment. In the figure, the Combiners, the Terminal and the M2L are separated because in the actual equipment they are seperate for maintenance reasons. The M2L time multiplexes (and demultiplexes) two 6.312-Mb/s signals. In the LMD Terminal, the digital processor maps the binary signal into 4-bit partial-response encoded words and presents them to the binary-to-multilevel converter at a rate of 4.43 megabauds. The binary-to-multilevel and multilevel-to-binary converters translate the 4-bit words to and from the 15-level, PAM format. The adaptive equalizer in the receiver provides mop-up equalization on a continuous basis. It corrects for residual amplitude and phase distortion in the terminal networks and also compensates for time varying distortion in the repeatered line, coherent demodulators, and timing recovery circuits. A set of modulators and demodulators (modems) is used to frequency multiplex up to six LMD signals for application to the coaxial transmission system. Thus, message con-

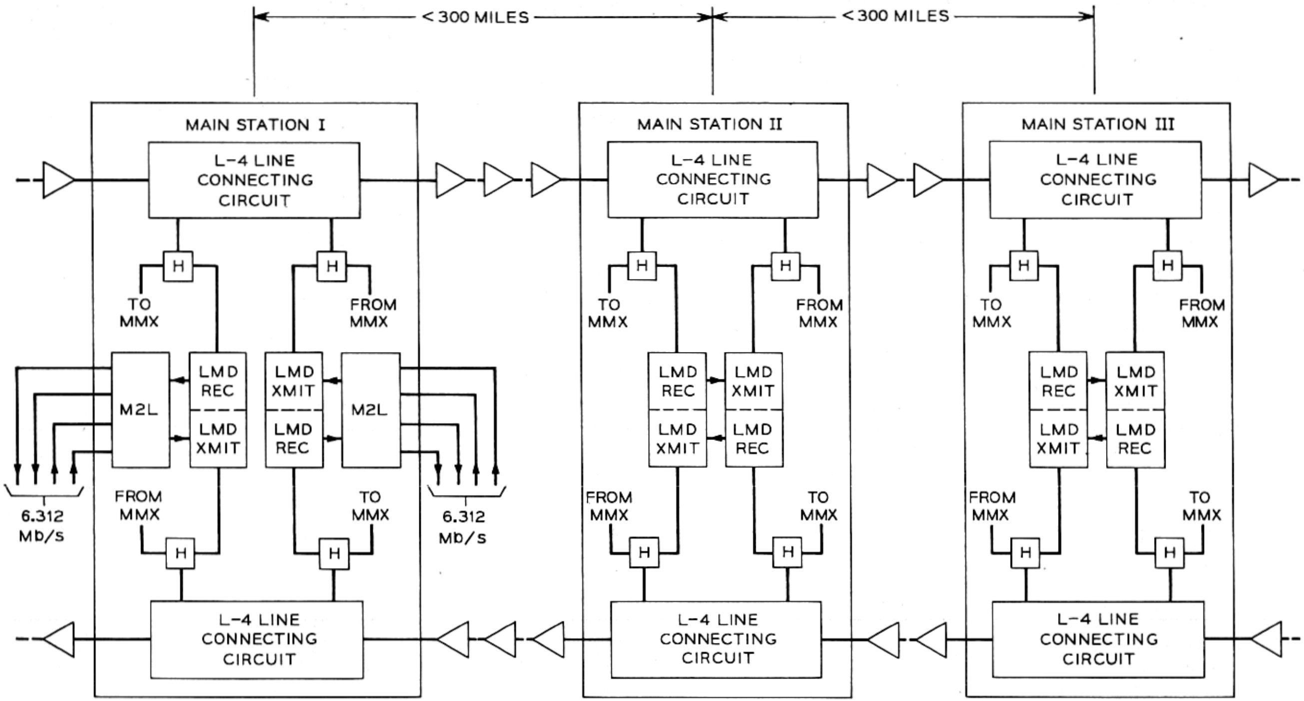

Fig. 1—Message mastergroups from the Mastergroup Multiplex (MMX) or digital signals (6.312 Mb/s) may be added or dropped at main stations. In this example, main stations II and III are regeneration points for an LMD channel, while main station I provides terminals for LMD channels in both directions.

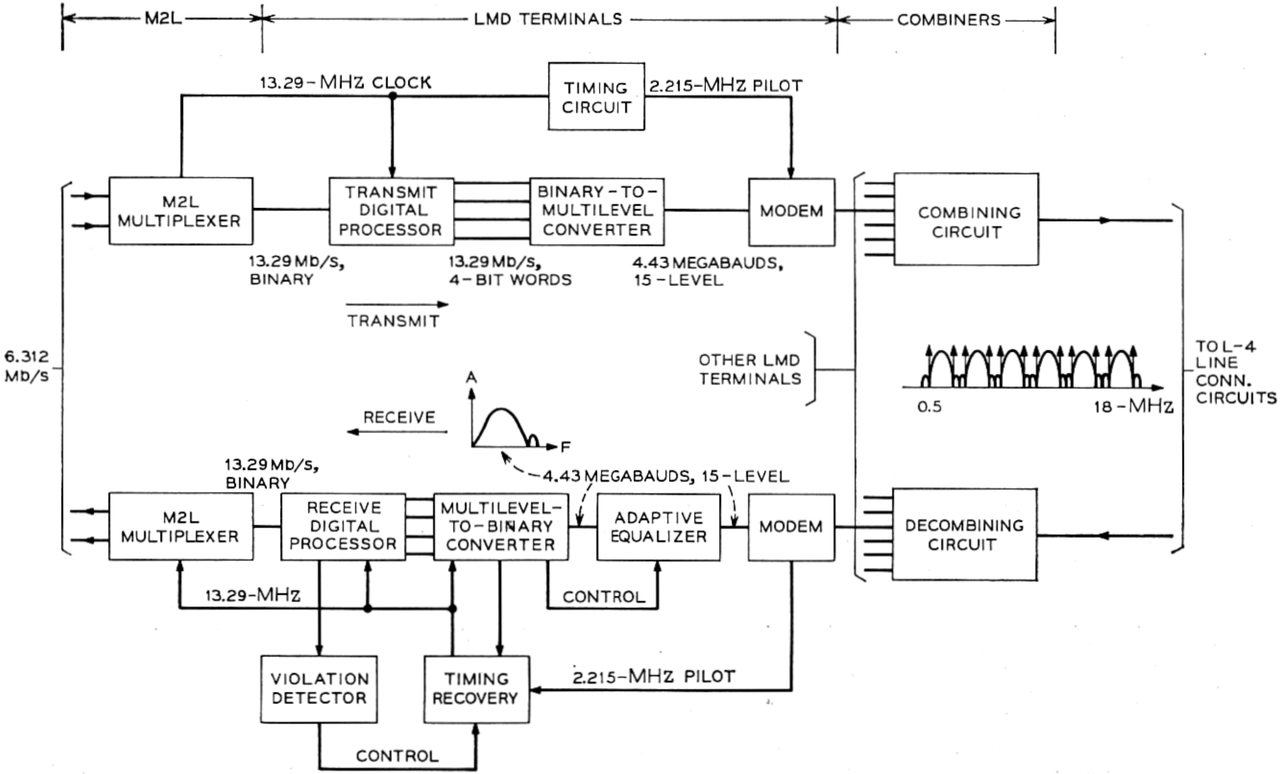

Fig. 2—L-Mastergroup digital signals for a particular coaxial pair are combined, and the composite signal is added to the L-4 line.

veying mastergroups and digital mastergroups can be combined in any convenient assignment.

An LMD regenerative repeater consists of terminals connected at the 13.29-Mb/s interface as indicated in Fig. 3. (The M2L is not required in the repeater.) The repeater demodulates the signal to baseband, converts the 15-level signal to a regenerated 13.29 Mb/s, two-level signal. This basic pulse stream is then converted into a new 15-level signal and modulated into an appropriate mastergroup band. The repeater need not modulate the signal into the same mastergroup band that supplied the input. Thus, a repeater can interconnect any two mastergroups so that frequency frogging can be employed to accommodate the standard L-4 or L-5 blocking, branching, and frogging rules.

The functions and major design features of each of the basic blocks of equipment will be examined in more detail in the following paragraphs.

VI. M2L TIME DIVISION MULTIPLEXER

The time division multiplexer combines two 6.312-Mb/s signals into a single binary stream at 13.29 Mb/s. The multiplexing operation is complicated by the fact that the two 6.312-Mb/s streams are not always exactly at their nominal speed. The technique known as pulse stuffing[8] is used to buffer against rate variations in an adaptive manner. The 13.29-MHz terminal clock supplies more time slots per unit time than required by the input signals (Fig. 4). Pulses that convey no information are inserted into a number of these extra time slots on an optional basis, depending on deviations of the incoming signals from the nominal 6.312 Mb/s. The remaining extra time slots are used to convey control signals to the receiver so that it can delete the extra pulses and separate the two signals in synchronization with the transmitter.

VII. DIGITAL PROCESSOR

The digital processor is designed to perform two basic functions: (*i*) randomize the digital information to prevent discrete frequencies from appearing in the transmitted signal above specified levels, and (*ii*) encode the signal to achieve the desired spectral nulls in such a way as to prevent error propagation at the receiver.

A block diagram of the digital processor is given in Fig. 5. The serial-to-parallel converter groups the randomized 13.29-Mb/s binary

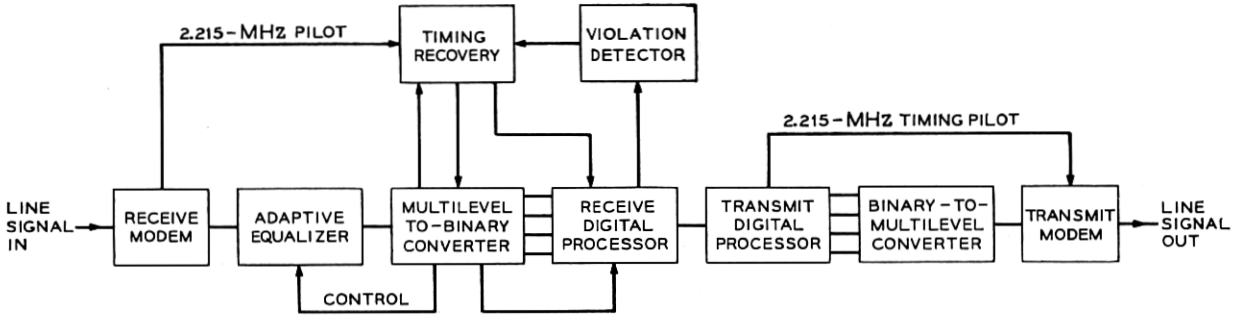

Fig. 3—An LMD repeater comprises two LMD terminals, interconnected at the 13.29-Mb/s interface. Only one direction of transmission is shown.

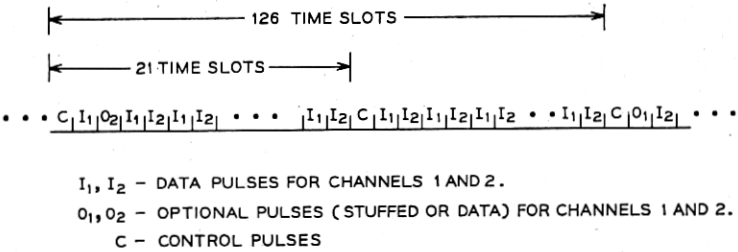

Fig. 4—In the time division line format, pulses are time multiplexed with data pulses into every 21st time slot. After six control pulses have been transmitted, an optional pulse is provided for stuffing in one of the data channels if required. Stuffing may take place in the other data channel following the next 126 time slot sequence.

stream into 3-bit words. Each of the $2^3 = 8$ possible words is uniquely associated with an integer in the range 0 to 7, according to a Gray code. The Gray code ensures that a single level error made at the receiver in estimating the transmitted level will result in only a single bit error. The integer generated in the nth time slot is represented by the symbol D_n.

The encoded sequence, $\{B_n\}$, is obtained from the original sequence, $\{D_n\}$, by applying a pair of operations given by the following equations:

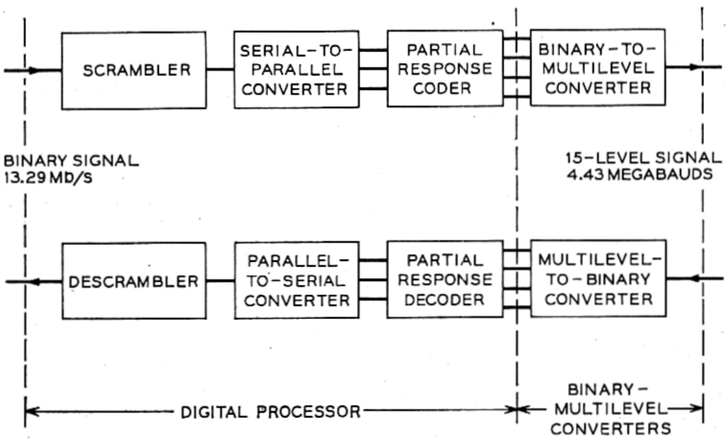

Fig. 5—The digital processing and binary-multilevel conversions indicated perform the digital-analog translations.

$$A_n = (D_n + A_{n-2}) \text{ modulo } 8, \tag{1}$$

$$B_n = A_n - A_{n-2} . \tag{2}$$

By substitution, the overall relation becomes

$$B_n = (D_n + A_{n-2}) \bmod 8 - A_{n-2} . \tag{3}$$

If $(D_n + A_{n-2}) \leqq 7$, then

$$B_n = D_n .$$

If $(D_n + A_{n-2}) > 7$, then

$$B_n = D_n - 8.$$

It follows that the symbols, B_n, can assume any one of the 15 integer values in the range -7 to $+7$. The operation in equation (2) has the transfer function, $1 - \exp(-j4\pi fT)$, which has the desired zeroes at dc and the Nyquist frequency, $(1/2T) = 2.215$ MHz. The operation in equation (1) takes account of the intersymbol dependence established by equation (2) so that the decoding operation of the receiver is independent of previously generated symbols,

$$D_n = (B_n) \text{ modulo } 8. \tag{4}$$

The operation in equation (3) is performed by the digital processor using binary elements. The output of the processor is a sequence of 4-bit binary words which represent the symbols B_n.

The digital processor includes a modulo-scrambler to randomize the digital signal sufficiently to suppress single tones. Discrete frequencies in the LMD signal can be generated by repetitive sequences of input data. *Picturephone* signals, for example, will have concentrations of power at multiples of frame rate, line rate, and sampling rate, plus lines in the spectrum due to periodic components in the original video. Single frequency tones arising from an LMD terminal or repeater and falling out-of-band in adjacent message channels should not exceed -72 dBm0 in order to be inaudible. If complete protection against all pathological digital sequences were attempted, the out-of-band suppression requirements of the transmitting filters would have to be excessive. It is important to minimize these suppression requirements since they strongly influence the in-band phase distortion. Single tones higher than -14 dBm0 can cause intelligible crosstalk if their frequencies fall at or near multiples of 4 kHz. Intermodulation of a message signal with such a tone may appear as undistorted speech in another channel.

VIII. BINARY-TO-MULTILEVEL CONVERTER

The binary-to-multilevel converter generates a voltage pulse that can achieve any one of 15 equally spaced levels for each 4-bit word delivered by the digital processor. As shown in Fig. 6, a weighted current gating circuit is used to perform this function. The multilevel signal is the input to the modem.

IX. MODEM

Since the partial response signal format is generated in the digital processor, the channel networks must be designed to minimize intersymbol interference by satisfying the Nyquist criterion as closely as possible.[9] The amount of bandwidth that is available for the digital signal is somewhat greater than the 2.52 MHz allocated for each analog mastergroup because of the guard space that has been provided between mastergroups. This guard space was originally provided in the message mastergroup multiplex for the skirts of the separation filters.[2] The corresponding skirts of the LMD separation filters can be used to shape the vestigial and roll-off regions of the digital signal. Although, in principle, vestigial and roll-off bands are not required for the partial response signal, they serve several purposes: (*i*) substantially improve

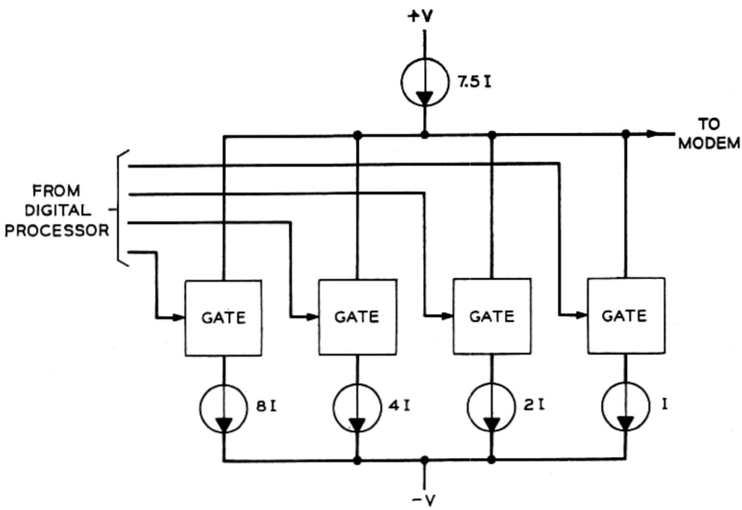

Fig. 6—The binary-to-multilevel converter receives the partial-response encoded signal from the digital processor on four leads and converts it to a 15-level signal for modulation into the appropriate mastergroup band.

network realizability over single sideband, no roll-off networks; (*ii*) permit gentle filter shaping which will minimize in-band amplitude and phase distortion; (*iii*) provide somewhat wider "eyes" which are less subject to timing jitter distortion; and (*iv*) reduce signal overshoot and corresponding LMD circuit linearity requirements, especially important in the M/B converter.

The analog portion of the LMD terminal contains two steps of modulation for all but mastergroup 2 (MG-2) as indicated in Figs. 2 and 7. The 4.43-megabaud, 15-level, partial response signal is first modulated into the MG-2 band. The second step of modulation translates the MG-2 signal into one of the other L-4 mastergroup bands. This modulation system has the advantage that all in-band signal shaping and most of the out-of-band discrimination is provided by the networks associated with the first step of modulation, and hence, this difficult job of network design has to be done only once. New synthesis techniques were developed to optimize the filter designs on the basis of a digital mean-square error criterion.[10] Mastergroup 2 was selected for the first step of modulation because it is surrounded by the narrowest guardbands and, therefore, requires the smallest vestigial and roll-off bandwidths. One further advantage of the two-step modulation technique is that MG-1 can be included in the basic system plan. Two steps of modulation are required for MG 1 to prevent signal leak from impairing performance since the baseband spectrum overlaps the MG-1 frequency band.

The first step of modulation utilizes vestigial sideband modulation with coherent detection. The second step of modulation is a potential source of additional frequency offset that could increase the phase error in the coherent detector. A new carrier recovery circuit has been developed for the LMD terminal, however, which significantly reduces the frequency offset without requiring more stable oscillators. A block diagram of the new circuit is given in Fig. 8, together with the equations that illustrate its operation.

X. ADAPTIVE EQUALIZER

An adaptive equalizer receives the bandlimited signal from the demodulator and filters it to minimize intersymbol interference. This type of equalizer incorporates a tapped delay line and electronically controlled tap attenuators, as indicated in Fig. 9.

The transfer function for the equalizer is given by

$$H_E(f) = \left[\sum_{k=-K}^{K} C_k \exp\left(-j2\pi fkT\right)\right] \exp\left(-j2\pi fKT\right).$$

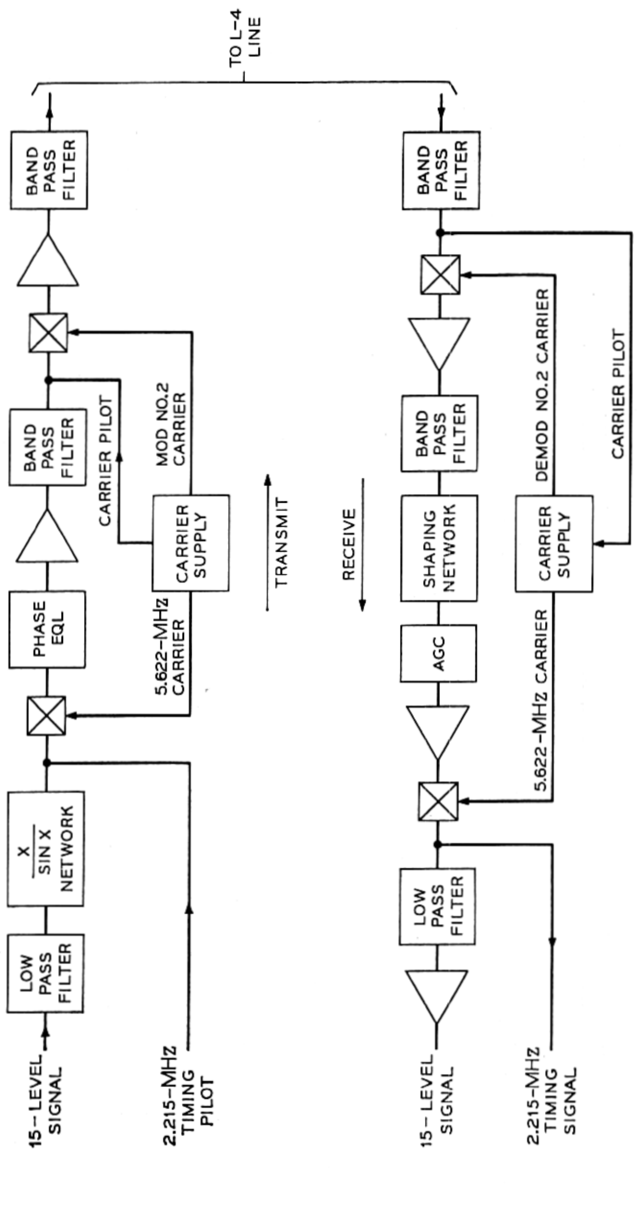

Fig. 7—The LMD modem utilizes two steps of modulation for all but MG-2.

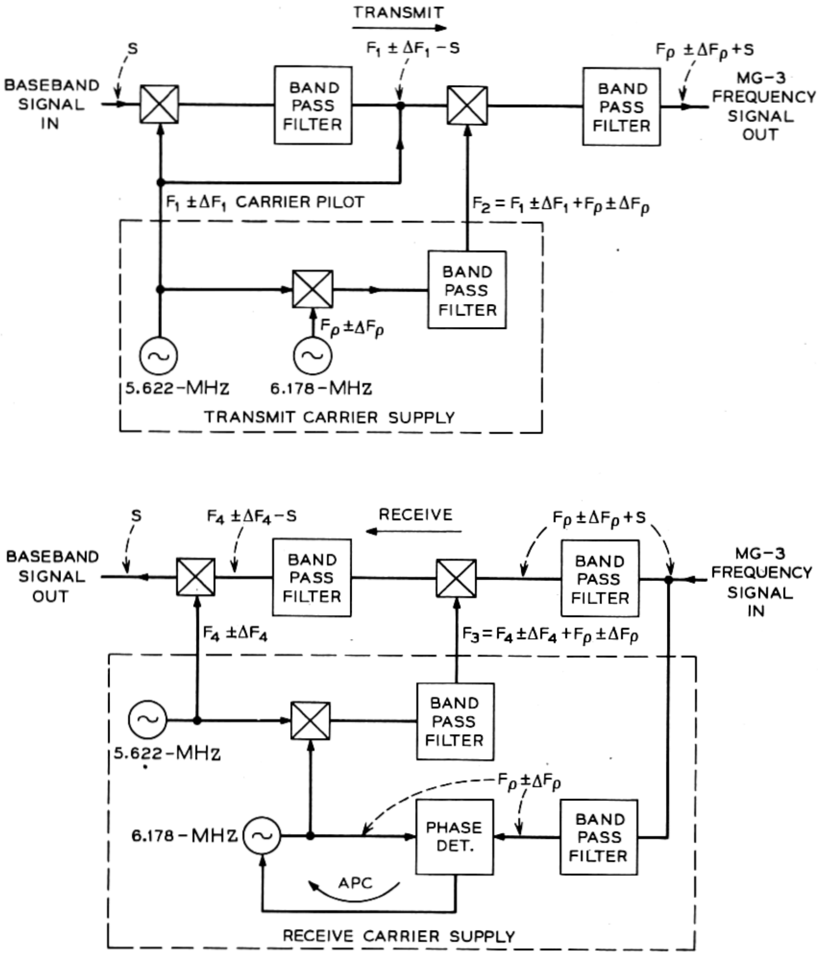

Fig. 8—The carrier recovery circuit as it applies to MG-3 is shown.

The factor in brackets shows the equalizer to be a finite dimension Fourier series synthesizer in the frequency domain. The equalizer is set to approximate the inverse of that portion of the overall channel characteristic that contributes intersymbol interference. The state of the Fourier coefficients, C_k, is continuously updated to compensate for changes in channel characteristics. This adaptive control is based on an algorithm which uses statistical estimates of the sampled pulse response of the equalizer as control information.[11]

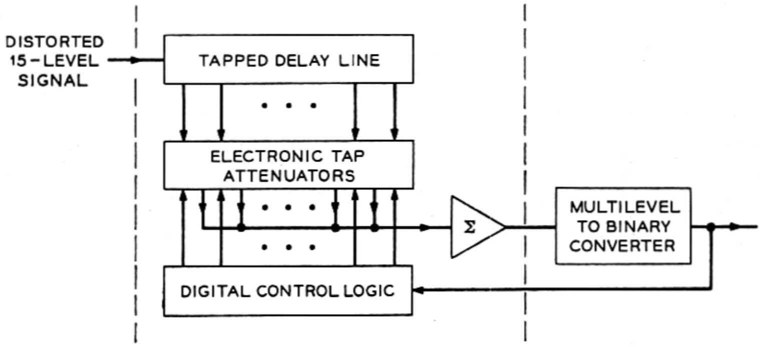

Fig. 9—The adaptive equalizer receives the band-limited signal from the demodulator and filters it to minimize intersymbol interference.

XI. MULTILEVEL-TO-BINARY CONVERTER

The multilevel-to-binary (M/B) converter utilizes the folder-slicer technique[12] to convert the received baseband signal to 6-bit words as indicated in Fig. 10. The signal is first sampled every T seconds and the sample held long enough for the conversion to the binary word to take place. Each folder is essentially a full-wave rectifier. A total of six slicing and five folding operations are used to generate a six-bit word. The first four digits represent the quantized amplitude of the sample

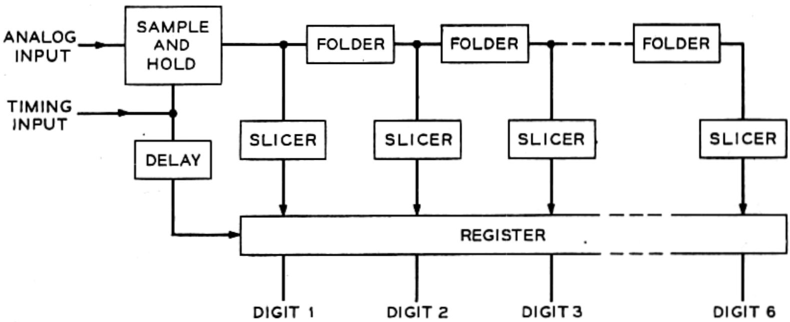

Fig. 10—The multilevel-to-binary converter samples the received 15-level signal at those points in time for which intersymbol interference has been minimized by the adaptive equalizer. Each sample is then represented as a six-bit binary word. The first four bits indicate the quantized amplitude of the sample while the fifth and sixth are used to detect and correct errors in signal level, slicing threshold, and sampling time.

while the fifth is used to detect errors in signal level and slicing threshold. When there are no errors in level or threshold, the output of the fifth slicer will be essentially random. When either one or both parameters are in error, the sense and type of error can be obtained by an appropriate logical combination of the outputs from the first five digits of the M/B converter. The sixth digit provides a measure of distortion at the sampling instants by indicating the percentage of the symbols whose levels deviate from nominal by more than 25 percent. This measure is used as an indication of the quality of transmission and in optimizing adjustments of such parameters as carrier phase and sampling time; it is also used in a control loop to make fine adjustments in the sampling time automatically as described below.

XII. VIOLATION DETECTOR AND TIMING CONTROL CIRCUIT

The following constraint is derived from equation (2) for the sequence, $\{B_m\}$, generated in the transmitter:

$$-A_{m-2} \leqq \sum_{j=0}^{K} B_{m+2j} \leqq 7 - A_{m-2} .$$

When errors occur in transmission, the above constraint is violated, and the violation-detector indicates an error.

Figure 11 illustrates the error detector in block form.[6] The circuit alternately operates on the sequence of odd and even numbered received pulses, B_m. During each pulse interval, the detector supplies an estimate of the received multilevel pulse to the first adder which updates the running sums during alternate pulse intervals. The viola-

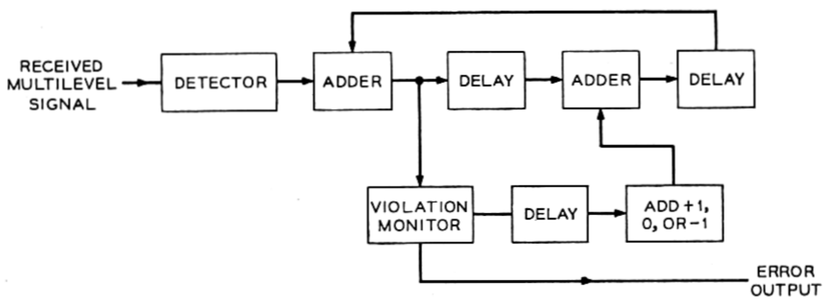

Fig. 11—The violation monitor provides a continuous indication of the error-rate performance of the repeater section.

tion monitor inspects these sums for violations of the correlation constraint. When a violation is noted, an error indication is given, and the running sum is reset. This ensures that a single error does not yield multiple violations.

If the error performance of a repeater section becomes poorer than one error in 10^4 bits, the error detector will trigger a major alarm. Since the error performance of each repeater section can be monitored independently, trouble conditions can be easily isolated to the appropriate section.

This violation detector is also used in a control loop to correct for errors in the sampling time. A block diagram is given in Fig. 12. A 2.215-MHz timing pilot is combined with the baseband digital signal at the transmitting terminal and is used in the receiver to synchronize a 13.29-MHz clock oscillator which generates the various timing signals needed to synchronize the M/B converter, digital processor, etc. The timing recovery automatic phase control (APC) loop does not have to maintain absolute control of the timing phase since an additional timing control circuit, in conjunction with the violation detector, is used to set the phase of the timing signal in the neighborhood of the optimum sampling phase. The timing control circuit operates whenever the error detector indicates the error performance has degraded below a specified threshold. In this way, the sampling time is maintained at approximately the correct value. An additional timing control circuit continually adjusts the timing to the optimum point by use of the sixth bit output on the M/B converter. Since the sixth bit is a measure of distortion, the timing can be automatically adjusted to minimize this parameter.

XIII. SUMMARY

The L-mastergroup digital system will adapt modern coaxial systems for digital transmission on a per-mastergroup basis. Thus, both analog and digital mastergroups will be transmitted on a coaxial system simultaneously. Each LMD channel will carry two 6.312-Mb/s digital signals and, hence, two *Picturephone* signals. These channels are expected to provide a large part of the long-haul transmission capacity required for *Picturephone* service, providing low error rate performance for distances as great as 4000 miles. In the near future, additional equipment will permit the time multiplexing of many slower speed digital signals into high-speed bit streams for transmission over the LMD channels.

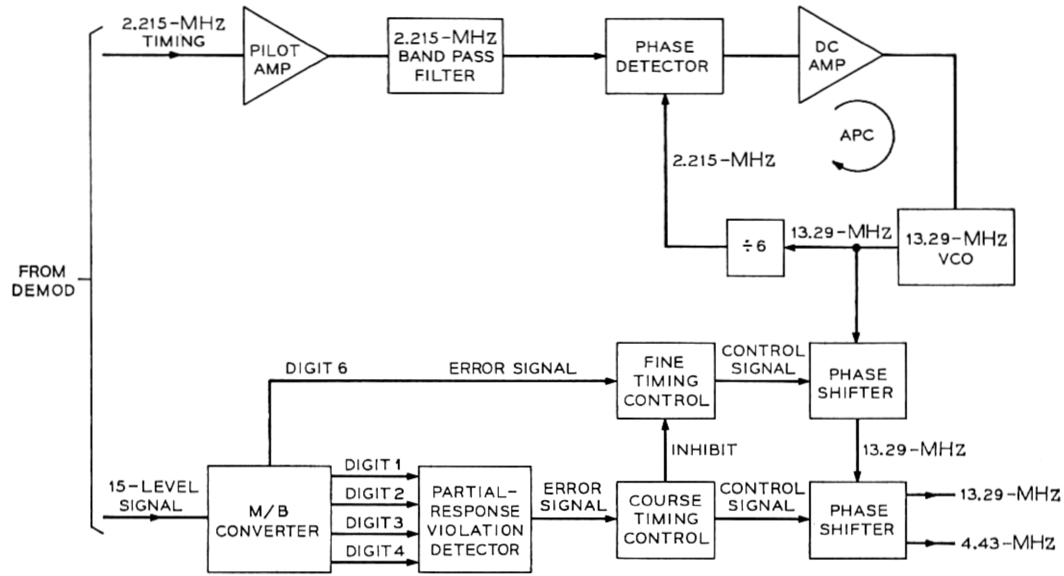

Fig. 12—The timing recovery circuit synchronizes a 13.29-MHz clock oscillator with the 2.215-MHz timing pilot that is transmitted along with the digital signal. The violation detector is used in a control loop to set the phase of the timing signal in the neighborhood of the optimum sampling phase and the sixth bit output of the M/B converter is used in a second control loop to set the timing phase to the optimum position.

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