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Transmission Facilities for General Purpose Wideband Services on Analog Carrier Systems

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Abstract—Three new general purpose wideband data facilities provide for the transmission of synchronous and nonsynchronous, 2-level data at bit rates ranging from 19.2 to 250 kb/s. These facilities make use of half-group, group, and supergroup bandwidth telephone facilities. The major components involved are the type 303 wideband data station, the exchange area transmission systems (local loop, N-Carrier, T1 Carrier), and the long-haul transmission systems [L-type multiplex (LMX) terminals, and coaxial cable and microwave radio circuits]. The group band system is representative and is discussed in some detail.

The analog carrier systems were designed principally to handle voice frequency transmission and they present special problems when they are adapted to accommodate wideband signals. For example, up to eight LMX group connector filters may be encountered in a 4000 mile circuit and each connector introduces over 150 μs of delay distortion in the transmission band. Special delay equalizers are added to each connector which reduce the distortion to ± 3 μs in the band 64 to 104 kHz.

The modulation schemes utilized in the various wideband modems were carefully tailored to the respective carrier systems. The LMX modem, used as an example in this paper, utilizes vestigial sideband, suppressed carrier, amplitude modulation. A carrier frequency pilot is added to the transmitted signal to facilitate carrier recovery in the receiver. The pilot is separated from the wideband signal in the receiver by a crystal bandpass filter. The filtered pilot is used for two functions; it is used to control an AGC circuit and hence the level of the received signal, and it is used in a multiple loop APC circuit to coherently demodulate the wideband signal. The APC circuit is new and promises improved performance over the conventional phase-locked oscillator when used in a coherent detector. It is capable of maintaining smaller phase errors in the presence of phase perturbations and, furthermore, the recovered carrier is always at exactly the correct frequency and hence the circuit is incapable of *breaking lock*.

Introduction

THE ANALOG carrier systems that play a prominent role in the transmission of wideband (data) signals in the Bell System are the N-Carrier for short-haul transmission and the L-Multiplex for coast-to-coast transmission. Local loops, which interconnect the data set on the customer's premises and the central office equipment, make use of ordinary pairs in the telephone cables. In addition, there is a new digital time-multiplexed transmission system, the T1 Carrier, that is used for exchange area service. The analog facilities were designed principally to handle voice transmission, and they present special problems when they are adopted to accommodate wideband signals.

Three distinct general purpose wideband services are available: supergroup, having a maximum channel capacity of 250 kb/s, full-group, which can handle up to 50 kb/s, and half-group, capable of 19.2 kb/s operation. These systems are designated *general purpose* in that they can handle synchronous or nonsynchronous, 2-level data at any bit speed up to their respective design maxima. Furthermore, the transmission facilities described in this paper are analog and can accept any signal that falls within their signal spectrum and power handling capabilities [1].

Transmission Facilities

Figure 1 shows a possible coast-to-coast wideband connection, although all carrier systems do not necessarily appear in one circuit [2]. The type 303 data set transmitter attenuates the low-frequency components in the 2-level data signal by means of a simple high-pass filter. The low-frequency components are reinserted at the data set receiver by a regenerative feedback circuit [3]. The consequent reduction in low-frequency content in the transmitted signal alleviates low-frequency transmission requirements. A baseband repeater system (local loop) is available which permits transmission of the restored polar line signal over ordinary pairs in telephone cable. The local loop is currently used for wideband transmission up to 20 miles, although most circuits are less than 10 miles in length.

The N-Carrier transmission system (Fig. 1) is used on short-haul routes up to 200 miles. The N-Carrier wideband terminals, as well as those for L-Carrier and T1 Carrier, incorporate modulation schemes that are carefully tailored to the facilities. The bandwidth of the N-Carrier line is sufficient for half-group or full-group wideband service, but is insufficient for supergroup service. The latter is restricted to the use of a baseband local loop or T1 Carrier for exchange area transmission.

The T1 Carrier system utilized pulse code modulation and time-multiplexing techniques to provide short-haul transmission of 24 voice frequency signals. The system has a synchronous bit speed of 1.544 mb/s. New wideband

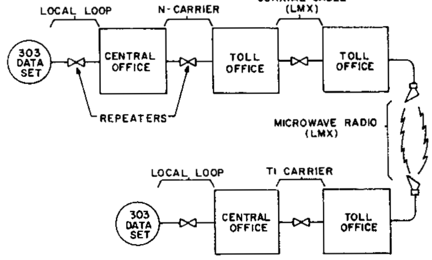

Fig. 1. Wideband transmission circuit.

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terminals permit it to handle either eight 50-kb/s or two 250-db/s data channels in place of the voice channels [4]. The half-group data service is in a format that is not readily handled by the T1 Carrier [3].

The long-haul transmission plant is made up of LMX terminals together with repeatered coaxial cables and point-to-point microwave radio channels. The terminals include several steps of single sideband, suppressed carrier, amplitude modulation. Twelve voice channels which are normally multiplexed in a group band extending from 60 to 108 kHz can be replaced with either two half-group wideband channels or one full-group channel. Five group channels are modulated into the supergroup band and ten supergroups are combined in a mastergroup band. The 250 kb/s service replaces five group channels and operates directly into the 312 to 552 kHz supergroup band. The various radio systems carry one to three mastergroups; the L3 Carrier multiplexes three mastergroups into a 7.97 MHz band; and, shortly, L4 Carrier will introduce a 16.98 MHz broadband channel composed of six mastergroups. The type 303 data service involves only the group and supergroup bands, but the signals can be multiplexed into any position in the L3, L4, or radio spectra.

The restored polar line signal is recovered at the output of each of the transmission facilities depicted in Fig. 1. Thus, the type 303 data set can operate directly into any one of them, and, furthermore, the order of interconnection of the various systems is unimportant.

The modulation techniques utilized in the various wideband modems were carefully selected for optimum performance considering the particular data service and carrier facility involved. Each combination generates unique problems and constraints. The LMX group-band terminal is representative, however, and therefore the remainder of the paper will be devoted to a discussion of this system.

LMX Group Band System

Wideband Equipment

The new equipment that has to be added to a LMX circuit to adapt it for data transmission is shown in Fig. 2. The upper diagram depicts a standard voice circuit consisting of a telephone set, local cable pairs, LMX terminals, and coaxial cable and microwave facilities. In the lower figure, the system has been adapted for 50 kb wideband service. The 303 data set requires an additional cable pair to provide 4-wire transmission.[1] Special amplifiers and loss equalizers are spliced into the local cable to adapt it for wideband signals. At the telephone office, a data transmitter and receiver (wideband modem) are added to modulate the restored polar line signal into the group band. Finally, special delay and loss equalizers are added at connector points to correct the delay and attenuation distortion introduced by the LMX bandpass filters.

The delay distortion introduced by the LMX terminal equipment is depicted in Fig. 3. The upper characteristic represents the relative envelope delay of the terminal receiver and transmitter alone and the lower delay characteristic is of the group connector filter. The total relative envelope delay distortion (consisting of the sum of the two characteristics in Fig. 3) is indicated by the dotted curve in Fig. 4. The delay equalizer that is added to each connector reduces the distortion to approximately ± 3 μs as represented by the solid curve. A new connector and equalizer have recently been designed that will further improve the equalization to ± 1.5 μs per link so that the residual delay distortion will be ± 12 μs for a typical 4000 mile circuit.

50 kb Wideband Modem Channel Characteristics

The 50 kb modem baseband channel characteristic is shown in Fig. 5. It is designed to have a 50 Hz to 37 kHz, nearly square band and all in-band shaping is done in the type 303 data set [3]. The square band characteristic

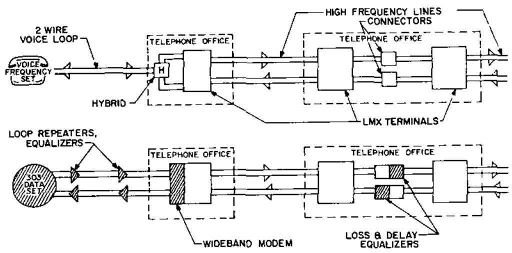


Fig. 2. LMX terminal and local loop modifications for wideband service.

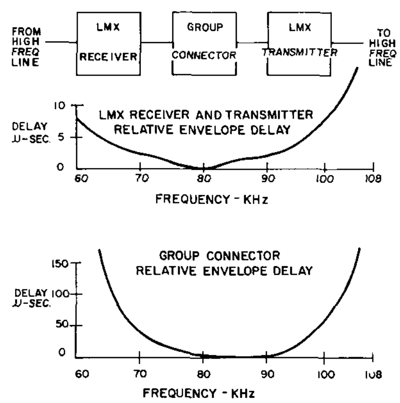


Fig. 3. Delay at junctions between LMX systems.

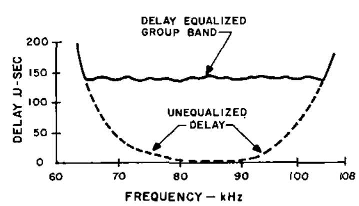


Fig. 4. Residual delay distortion of the group band for one link of LMX.

[1] A voice frequency coordination channel accompanies every standard wideband channel and requires two additional cable pairs not shown in the figure.

permits several modems to be connected in tandem if desired. The high-pass filter located in the type 303 data set transmitter shapes the spectrum at low frequencies and a rolloff network in the data set receiver shapes the high-frequency band.

The group band data channel after modulation is shown in Fig. 6. The wideband modem for the LMX system incorporates vestigial sideband, suppressed carrier, amplitude modulation with coherent demodulation [5]. Vestigial sideband operation permits optimum utilization of the available bandwidth. Suppressing the carrier results in maximum signal-to-noise performance since the LMX system is both total-power and single-tone limited [2]. The basic group extends from 60 to 108 kHz. The available bandwidth is somewhat restricted by a 104.08 kHz pilot tone which is used for automatic gain regulation of the LMX broadband terminals. The frequency band between the pilot and the 108 kHz band edge is available, however, for the voice frequency coordination channel. The wideband modem carrier frequency is 100 kHz, which divides the band into a 4 kHz vestigial upper sideband and a 37 kHz lower sideband, resulting in an equivalent baseband of 37 kHz.

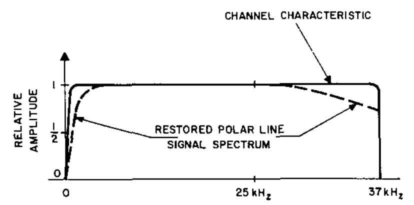


Fig. 5. Baseband 50 kb/s channel.

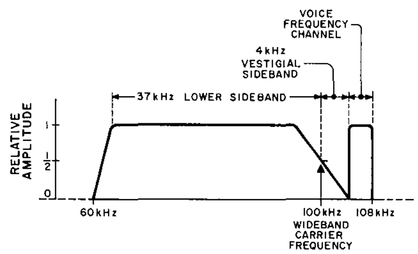


Fig. 6. Group frequency 50 kb/s channel.

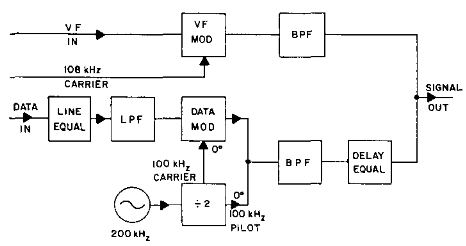


Fig. 7. Fifty kb/s wideband transmitter.

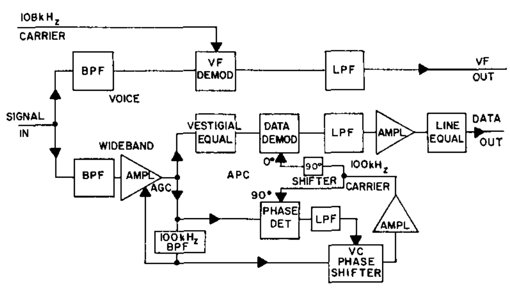


Fig. 8. Fifty kb/s wideband receiver.

Wideband Transmitter

A block diagram of the transmitter is shown in Fig. 7. The baseband signal first passes through a line equalizer and low-pass filter. The line equalizer can be adjusted to compensate for variations in the loss and delay slope of the intra-office wiring. The low-pass filter limits the noise bandwidth and suppresses high-frequency signal components which would cause frequency foldover upon modulation. A crystal-controlled oscillator generates a 200 kHz sine wave which is then divided to 100 kHz by a single stage counter. In this way a square wave carrier is generated with a precise 50 percent duty cycle for modulating the wideband signal. The carrier drives a balanced, two transistor, product modulator. The signal at the output of the modulator is double sideband, amplitude modulated. Power in the vicinity of the carrier frequency is small because of the high-pass filtering carried out in the data set. A carrier frequency pilot tone which is in-phase with the modulating carrier is added to the modulated signal at a power 9 dB below the average power in one sideband. The bandpass filter following the modulator passes the lower sideband and a 4 kHz vestige of the upper sideband. The filter suppresses all modulation products that fall outside the data channel to prevent interference with adjacent group channels that are multiplexed on either side of the wideband channel. The signal is then delay and loss equalized and combined with the voice frequency coordination channel for transmission over the LMX facilities. The equalizer corrects the delay and amplitude distortion introduced by all transmission networks in the transmitter and receiver and also for the residual delay distortion in one link of LMX.

Wideband Receiver

A block diagram of the wideband receiver is shown in Fig. 8. The voice frequency and wideband signal are first separated by bandpass filters for demodulation. The receiving bandpass filters also limit the noise bandwidth and prevent adjacent channels from interfering with the received signals.

The 100 kHz carrier pilot is separated from the data signal by a narrow band crystal filter. The pilot is used to control the gain of the receiving amplifier and hence the power level of the received signal. The AGC circuit is fast-acting to supplement the slow-acting regulators of the LMX terminals. Impairments due to signal level variations arise in two ways: 1) if the signal level is allowed to drop at the input of a link, the S/N ratio in that link will be reduced, and 2) a signal level variation at the input of a slicer is equivalent to a variation in the slice level and hence a decrease in noise immunity.

The filtered 100 kHz pilot is also used as a carrier to coherently demodulate the wideband signals. Phase errors introduced by the crystal pick-off filter and associated circuits are corrected by a voltage-controlled phase shifter. The error voltage that controls the phase shifter is generated by a detector in which the phase of the recovered carrier and the phase of the received carrier pilot are compared. This form of APC circuit has been called a phase-locked filter.

The demodulated data signal is passed through a low-pass filter to suppress unwanted modulation products and then amplified to the required interface power level. A small attenuation and slope equalizer is used to compensate for intraoffice wiring similar to that in the transmitter.

Coherent Demodulator

The design of an APC circuit for use in a coherent demodulator poses some interesting problems. For example, since the average power of the group band data signal is 9 dB above the level of the carrier pilot, it is a potential source of interference in the carrier recovery circuit. The interference of data signals is minimized by transmitting the carrier pilot at the same phase as that used for modulation. For proper operation, the phase detector carrier must be in quadrature with the pilot and, therefore, the data components near the carrier are suppressed in the phase detector by phase cancellation. This condition is enhanced by maintaining flat transmission through the vestigial region in the transmitter and placing the vestigial shaping network at the input of the data demodulator in the receiver. The signal energy that falls outside the double sideband region is suppressed by a low-pass filter located at the output of the phase detector.

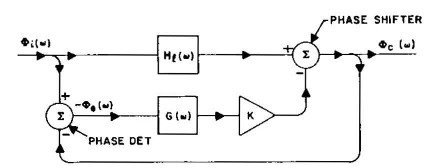
The commonly used circuit for carrier recovery is the phase-locked oscillator, consisting of a voltage-controlled oscillator in a feedback loop. It suffers from an inherent narrow bandwidth. This attribute can often be used to advantage when phase averaging or smoothing is required, but can contribute excessive signal impairment when used in a wideband modem. The carrier-recovery circuit should be capable of tracking faithfully the short-term as well as the long-term phase perturbations introduced by the broadband facilities [2].

The phase-locked filter exhibits no inherent band limiting characteristic and in principle can be made to track phase perturbations of any desired frequency and amplitude faithfully. (In practice the bandwidth of the control loop must be limited to restrict the noise bandwidth.) The equivalent linear circuit for the phase-locked filter is given in Fig. 9. This equivalent circuit is valid for phase errors less than about 30 degrees[2] but this in no way restricts the amplitude or frequency of the input phase perturbations that can be considered.

[2] This restriction results from the use of a phase detector with a sinusoidal transfer characteristic rather than one with a linear characteristic as assumed in Fig. 9.

The closed loop transfer function, $\Phi_c(\omega)/\Phi_i(\omega)$, and the transfer characteristic of phase error relative to input phase jitter, $\Phi_e(\omega)/\Phi_i(\omega)$, are also given in Fig. 9. These expressions emphasize the principle characteristics of the phase-locked filter. The circuit response is not significantly influenced by the bandwidth of the crystal filter, providing the filter bandwidth is small compared to the loop bandwidth. The gain constant K can generally be selected on the basis of constant phase error requirements (due to frequency offset) permitting an independent optimization of the transient response in terms of $G(\omega)$, the low-pass filter characteristic.

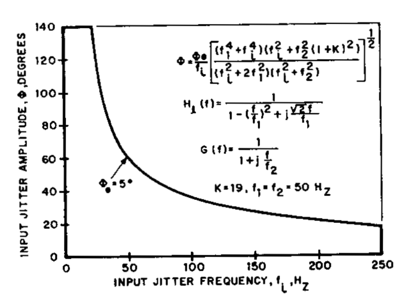
It is desirable to maintain the peak phase error of the recovered carrier resulting from phase jitter below approximately 5 degrees so that the transmission impairment from this source be insignificant [3]. Some idea of the amount of transmission phase jitter that can be tolerated may be obtained by calculating the phase error resulting from sinusoidal input phase jitter at various frequencies and amplitudes. The magnitude of the sinusoidal input jitter is plotted in Fig. 10 (for a representative circuit) as a function of the frequency of the input jitter that results in a peak phase error of 5 degrees. This characteristic is for a phase-locked filter with a loop bandwidth, $(1 + K) f_2$, of 1000 Hz. Note that the permitted frequency of the input jitter must generally be much less than the loop bandwidth if the phase error is to be maintained below the 5-degree boundary.



$$\frac{\Phi_c(\omega)}{\Phi_i(\omega)} = \frac{\frac{H_\ell(\omega)}{H_\ell(0)} + KG(\omega)}{1 + KG(\omega)}$$

$$\frac{\Phi_e(\omega)}{\Phi_i(\omega)} = \frac{\frac{H_\ell(\omega)}{H_\ell(0)} - 1}{1 + KG(\omega)}$$

Fig. 9. Equivalent circuit of phase-locked filter.



$$\Phi = \frac{\Phi_e}{f_i}\left[\frac{(f_1^4+f_i^4)(f_i^2+f_2^2(1+K)^2)}{(f_i^2+2f_1^2)(f_i^2+f_2^2)}\right]^{\frac{1}{2}}$$

$$H_1(f) = \frac{1}{1-\left(\frac{f}{f_1}\right)^2 + j\frac{\sqrt{2}f}{f_1}}$$

$$G(f) = \frac{1}{1+j\frac{f}{f_2}}$$

Fig. 10. Magnitude of sinusoidal input jitter, Φ producing a peak phase error of 5°, as a function of jitter frequency f_i.

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Conclusion

The telephone carrier systems were originally designed for voice frequency transmission but have proven adaptable to high-quality wideband service. This has been accomplished by the careful selection of a general data format (restored polar) and of modulation schemes tailored for each of the facilities. This paper describes the wideband terminal equipment designed for the LMX group band. Other signal processing schemes are required for the wideband terminals designed for the N-carrier and Tl Carrier facilities.

The phase-locked filter promises improved performance over the phase-locked oscillator when used in a coherent demodulator. It is not only capable of maintaining smaller phase errors in the presence of phase perturbations but the recovered carrier is always at exactly the correct frequency and hence the circuit is incapable of *breaking lock*. Loss of pilot automatically shuts off the receiver, preventing the generation of unintelligible signals due to noncoherent demodulation.

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Concise Papers

The Covariance of the Frequency of a Narrowband Gaussian Random Process

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***Abstract*—The mean and covariance of the instantaneous frequency of a narrowband, zero-mean, stationary, Gaussian random process are found when the quadrature components of the process are identically distributed. When the quadrature components are stationary and statistically independent, the mean and covariance expressions are identical to well-known expressions.**

The mean and covariance of the instantaneous frequency of a narrowband, zero-mean, stationary Gaussian random process have been found by Lawson and Uhlenbeck [1], and Rice [2], under the constraint that the quadrature components of the process are statistically independent and identically distributed. Another method of finding the mean and covariance of the instantaneous frequency of a zero-mean, narrowband, Gaussian random process is presented here. The process need not be stationary, and the quadrature components need not be statistically independent; however, the quadrature components must be identically distributed. When the process is not stationary, or the quadrature components are not statistically independent, the covariance of the frequency contains a term that is not present in Lawson and Uhlenbeck's [1] or Rice's [2] expressions.

The mean and covariance of the instantaneous frequency are of interest in the analysis of FM systems that use a fading channel. When the multiplicative disturbances of the channel are modeled as a random, time-variant linear filter, with a time-variant transfer function that is a realization of a zero-mean, Gaussian random field [3], the channel output is a realization of a zero-mean, nonstationary, Gaussian random process. The results given here are directly applicable to a FM system using such a channel.

The complex representation [4]–[6] is used for all narrowband Gaussian random processes throughout this note, thus all narrowband Gaussian random processes are zero-mean and jointly circularly complex, i.e.,

$$E[x(t)] = 0 \text{ and } E[x(t)y(u)] = 0. \tag{1}$$

The statistics of two such processes are thus completely determined by the cross-covariance function

$$c_{xy}(t,u) = E[x(t)y^*(u)] \tag{2}$$

and the two auto-covariance functions

$$c_x(t,u) = E[x(t)x^*(u)] \text{ and } c_y(t,u) = E[y(t)y^*(u)]. \tag{3}$$

[The well-known expectation operator is $E[\cdot]$ and y^* is the complex conjugate (and transpose, if appropriate) of y.] Other well-known properties of the complex representation are that the magnitude of the complex representation $|x(t)|$ is the envelope of the narrowband process, and that the phase of the complex representation $\phi[x(t)]$ is the phase of the narrowband process.

This note is also concerned with $s(t)$, the instantaneous complex frequency of a process, which is defined as the derivative, with respect to time, of the natural logarithm of the process

$$s(t) \triangleq \frac{d}{dt} \ln[x(t)] = \dot{\ln}[x(t)] = \dot{x}(t)/x(t). \tag{4}$$

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