Quadrature Modulation Hybrid Voice and Data Modem

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Summary.- The Quadrature Modulation Hybrid Modem is a new system designed to provide voice only, data only, or combined voice and data communication. It provides good voice intelligibility at low values of C/N_0 by making use of a quadrature modulation technique which permits essentially nonthresholding demodulation of the voice signal. Power sharing between voice and data signals can be easily changed to accommodate different requirements. Intelligibility tests have been performed and indicate an intelligibility of 90% in the voice-only modem at a value of C/N_0 of 43 dB-Hz, and an intelligibility of 80% in the combined voice and data mode at a value of C/N_0 of 43 dB-Hz with an error rate for data of 10^{-5}.

Introduction.- The Quadrature Modulation Hybrid Modem is a new system which provides voice, data, or combined voice and data communications. It is designed to provide good voice intelligibility at low values of C/N_0 (carrier power/noise spectral density). The system makes use of a quadrature modulation technique for the transmission of voice signals or, in combination with DPSK modulation, for the transmission of voice and data signals on a common carrier. The modulation is such that a narrowband phase lock loop can be used at the demodulator to provide a coherent reference for demodulation of the voice or voice-plus-data signal. Because the loop is narrowband, loop thresholding does not occur until the value of C/N_0 is well below that at which voice intelligibility is lost. This is in contrast to FM demodulators where thresholding occurs at values of C/N_0 where the voice signal is still intelligible.

The modulation technique permits power sharing between voice and data to be easily changed so as to accommodate various requirements for voice performance or data rates. Further, in the voice and data mode, when the voice signal is low or absent, power not actually used for the voice signal is used for data. Thus, the error rate performance is superior to that theoretically attainable in a system in which power is continuously shared between voice and data.

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Laboratory tests conducted with the cooperation of the Transportation Systems Center of the U.S. Department of Transportation and CBS Laboratories Intelligibility Testing Services indicate that, in the voice-only mode, an intelligibility of 90% is provided at a value of C/N_0 of 43 dB-Hz, and an intelligibility of 80% is provided at a value of C/N_0 of 40 dB-Hz.

In the voice and data mode, 1200 bits per second data is provided at an error rate of 10^{-5}, and intelligibility of 90% is achieved at a value of C/N_0 of 46 dB-Hz. Eighty percent intelligibility is achieved at a value of C/N_o of 43 dB-Hz. These results have also been verified in tests conducted over a link from the ATS-6 satellite to an aircraft.

Quadrature Voice Modulation Without Data.- The block diagram in Figure 1 illustrates the operation of the quadrature voice modulator. The preprocessed voice signal, V(t), is fed to a balanced modulator together with a carrier signal, $\sin \omega_0 t$. The preprocessing consists of high frequency pre-emphasis, amplitude compression and filtering. The output of the modulator is the product of V(t) and $\sin \omega_0 t$, which is a suppressed carrier amplitude modulated signal. The signal $\sin \omega_0 t$ is also phase shifted by 90° to yield $\cos \omega_0 t$, which is added to $V(t) \sin \omega_0 t$. The output of the adder is $V(t) \sin \omega_0 t+\cos \omega_0 t$. The vector diagram in Figure 2 shows the various signals which occur in the modulator. Up to this point, the circuitry is similar to an Armstrong FM modulator, except the preprocessing is different and the amplitude ratio of $V(t) \sin \omega_0 t$ to $\cos \omega_0 t$ is large compared with an Armstrong FM modulator. In an Armstrong modulator, the amplitude ratio of $V(t) \sin \omega_0 t$ to $\cos \omega_0 t$ is kept small so that the sum signal $V(t) \sin \omega_0 t + \cos \omega_0 t$ is essentially a constant envelope signal; the sum signal is fed to a high ratio frequency multiplier to yield a high deviation FM or PM signal. In the quadrature modulator, the sum signal $V(t) \sin \omega_0 t + \cos \omega_0 t$ is not a constant envelope signal because $V(t) \sin \omega_0 t$ can be larger than $\cos \omega_0 t$. To yield a constant amplitude signal, the sum signal is passed through a hard limiter as shown in Figure 1. The quadrature modulator generates a constant envelope carrier of frequency $\omega_0/2\pi$ and phase angle ρ(t), where $\rho(t)= \tan^{-1} V(t)$. This constant envelope carrier can now be readily transmitted using efficient Class-C amplifiers.

The angle of voice modulation, ρ(t), determines the ratio of power in the carrier, $\cos \omega_0 t$, to the power in the voice component, $V(t) \sin \omega_0 t$. If the maximum angle of modulation is held to $\rho max(t)= 72°$, then at peak voice modulation, one-tenth of the total transmitter power is in the carrier and nine-tenths of the power is in the voice signal. At the demodulator, for a total received signal-to-noise spectral density (C/N_0) of 46 dB-Hz, for example, the minimum carrier C/N_0 would be 36 dB-Hz ana the voice C/N_0 would be 45.6 dB-Hz at periods of peak modulation.

A phase-locked loop is used for demodulation of the quadrature modulated voice signal. The phase-locked loop is a narrowband carrier tracking loop and is used to provide coherent frequency reference for demodulation of the received signal. Basically, the demodulator tracks the carrier and demodulates the signal component which is in quadrature with the carrier. Referring to Figure 2, this is the signal V'(t). As is evident from the figure, V'(t)= sin ρ(t) or, in terms of V(t), V'(t) is given by

$$V'(t) = \sin \tan^{-1} V(t).$$

The inverse trigonometric operation $\tan \sin^{-1} V'(t)$ can be performed to recover the voice signal, V(t), in its orginal form. Tests have been performed in the laboratory to determine the effect of this nonlinearity on voice intelligibility. There was found to be no difference in voice quality of intelligibility between compensation and noncompensation for nonlinearity.

The quadrature modulation technique provides for nonthresholding of the voice signal. The carrier tracking loop is narrowband (noise bandwidth = 100 Hz) and provides a coherent frequency reference at low received carrier-to-noise spectral densities (C/N_0) that are well below the point where the voice signal is no longer intelligible. This type of demodulator does not experience the breakup in voice signal common to all FM systems at low C/N_0 ratios.

Quadrature Voice Modulation With Data. - The block diagram in Figure 3 illustrates the operation of the quadrature voice modulator in combination with the transmission of differentially coherent phase-shift-keyed (DCPSK) data. The preprocessed voice signal is balanced modulated onto the $\sin \omega_0 t$ in-phase carrier component. The $\cos \omega_0 t$ quadrature component is now fed to a phase-shift-key (PSK) modulator where the $\cos \omega_0 t$ carrier is modulated with differentially encoded data. The voice and data signals are added together and then passed through a hard limiter. The vector diagram in Figure 4 shows the various signals as they appear in the modulator. Referring to Figure 4, the voice signal maintains the correct polarity, as either a binary “0” ($\cos \omega_0 t$) or a binary “1” ($\cos(\omega_0 t + 180°)$) is transmitted. The amplitude of the voice vector $V'(t) \sin \omega_0 t$ is dependent only on the angle of modulation, ρ(t). The data carrier, $\cos(\omega_0 t + \theta(nT))$ maintains the correct phase of 0° or 180° regardless of the voice signal level. The amplitude of the data vector is amplitude modulated by the voice signal. During periods of voice transmission, power is diverted from the data carrier and placed in the voice carrier. The angle of modulation, ρ(t), determines the ratio of data power to voice power. Selection of ρmax(t) will depend on system requirements, such as required voice intelligibility, data bit rate and received data bit error rate.

A Costas loop is used for demodulation of the quadrature modulated voice and data signal. A Costas loop is implemented because a no-carrier tracking loop must be used to generate a coherent reference frequency for demodulation of the data and voice signals.

The Costas loop is designed to demodulate the simultaneous transmission of voice and data or to demodulate data only. During the simultaneous transmission of voice and data, the Costas loop tracks the data signal and generates a coherent reference frequency for phase demodulation of voice and data signals. The Costas loop is designed as a narrowband tracking loop (noise bandwidth = 100 Hz) to provide a coherent frequency reference at low received carrier-to-noise spectral densities that are well below the point where the voice signal is no longer intelligible.

The quadrature modulator technique not only offers an improved method of narrowband voice transmission, but provides for the simultaneous transmission of data and voice signals at little increase in total power transmitted. In the test results that follow, it is shown that it costs only 1.5 dB increase in total power to send voice in addition to 1200 bps data. Not only is there a savings in transmitted power, but there is a reduction in bandwidth from two individual subcarriers to a common carrier.

Quadrature Voice Modem Performance Test Results. - Two quadrature voice modems were delivered to the Department of Transportation under Contract DOT-TSC-631. The quadrature voice modems were designed for operation with the ATS-6 satellite during aeronautical communication tests. The performance of the quadrature voice modulation technique is illustrated in Figure 5, where the voice intelligibility of Hybrid Modem S/N 2 is shown in the voice-only and voice-plus-data mode. The hybrid modem intelligibility scores are based on the test tapes recorded during acceptance testing of the DOT-TSC Hybrid Modem S/N 2. These test tapes were evaluated by CBS Laboratories for the Department of Transportation. Each data point in Figure 5 is based on scoring 500 monosyllabic words generated from the Harvard PB-50 word lists.

The data bit error rate (BER) test results for Hybrid Modem S/N 2 is shown in Figure 6 for the data-only and voice-plus-data mode. From Figures 5 and 6, it is seen that a single quadrature voice modem operating at 43 dB-Hz in the voice-plus-data mode provides 80% voice intelligibility and better than 10^{-5} BER performance. By conventional communication methods, two modems are required to offer the same performance. These two modems require twice the bandwidth and twice the power of the hybrid modem.

The superior error rate performance of the quadrature voice modem in the voice-plus-data mode is due to the fact that the carrier power is split between the voice and data signal only during periods of conversation. When no one is talking, all signal power is devoted to the data signal. If the signal power was continuously split between the voice and data signals, as is done in a conventional voice/digital data system, then the theoretical curve for data error rate would move over 3 dB as shown in Figure 6. Since in the hybrid modem, the power not actually used for voice transmission is available for data, and since even in continuous conversation, the voice signal is low level or absent, the error rate performance in the voice and data mode is only 1.5 dB poorer than the theoretical error rate performance for data alone. This performance is 1.5 dB better than the theoretical error rate performance of a system which continually splits carrier power between voice and data signals.

A detailed analysis of error rate performance in the combined voice and data mode is given in the following section.

Analysis of Error Rate Performance in Voice and Data Mode. - In this section, a detailed analysis is presented of the error rate performance in the combined voice and data mode. Measured speech statistics are presented and are used to predict error rate as a function of C/N_0.

In the combined speech and data mode of operation, the instantaneous probability of error for the data channel is related to the instantaneous power in the data channel. From Figure 7, it can be seen by simple geometric analysis that the probability of error conditioned on a particular value of the speech signal is given by

$$P_r[\varepsilon|v] = 2\,Q\left[(\cos\ \tan^{-1}\ v)\sqrt{\frac{2\,E_b}{N_0}}\right],$$

where E_b/N_0 is the energy per bit divided by the noise spectral density
v is the ratio of the applied instantaneous speech voltage to the signal voltage (equivalently, the ratio of applied instantaneous speech voltage to data voltage before clipping)
Q is defined as

$$Q(\alpha) = \int_{\alpha}^{\infty} \frac{1}{\sqrt{2\pi}}\, e^{-\beta^2/2}\, d\beta\ .$$

In the absence of a speech signal, the probability of error is

$$P_r[\varepsilon] = 2\,Q\left[\sqrt{\frac{2\,E_b}{N_0}}\right] \quad \text{(no speech signal).}$$

In the combined speech and data mode, the probability of error is given by averaging $P_r[\epsilon|v]$ over all values of v, that is,

$$P_r[\varepsilon] = \int_{\substack{\text{over} \\ \text{all } v}} P_r[\varepsilon|v]\, p(v)\, dv\ ,$$

where p(v) is the probability density for the ratio of the speech signal to the data signal.

The function ρ(v) is a function of the relative magnitude of the speech signal to the data signal, the particular speech pattern (for example, whether the speech is intermittent or continuous), and the processing that has been performed on the speech prior to modulation (for example, the speech compression used to enhance intelligibility increases the probability of large values of v). Measurements have been made of the probability density of the speech signal as processed in the hybrid modem for two different speech patterns. One of these is shown in Table 1 and is for a PB-50 word list. A second set of data was taken for a continuous ATC message.

Using these probability densities, the probability of error has been computed for a maximum modulation angle, ρ, of 58° (the design value for Hybrid Modem #1). The results for the PB-50 word list are given in Table 2. Figure 8 shows plots of the the probability of error for the two speech patterns as a function of C/N_0 for a 1200 bps data rate. For comparison, the measured values taken during acceptance testing for the Hybrid Modem S/N 1 are also shown. As can be seen, the agreement between measured and predicted results is very good.

Table 1. Probability Density for Speech After Compression in Hybrid Modem (PB-50 Word List)

Quantum Step Magnitude	Probability	Quantum Step Magnitude	Probability
16	0.00076	8	0.01360
15	0.00131	7	0.01772
14	0.00197	6	0.02175
13	0.00262	5	0.02449
12	0.00331	4	0.02884
11	0.00425	3	0.04638
10	0.00650	2	0.26035
9	0.00951	1	0.55665

Table 2. Probability of Error in Voice and Data Mode (PB-50 Word List)

E_b/N_0 (dB)	$P_r[\varepsilon]$ Data Only	$P_r[\varepsilon]$ Voice and Data
0.0	0.157E-00	0.168E-00
1.0	0.113E-00	0.122E-00
2.0	0.750E-01	0.833E-01
3.0	0.458E-01	0.525E-01
4.0	0.250E-01	0.300E-01
5.0	0.119E-01	0.154E-01
6.0	0.478E-02	0.690E-02
7.0	0.155E-02	0.270E-02
8.0	0.382E-03	0.929E-03
9.0	0.673E-04	0.291E-03
10.0	0.774E-05	0.868E-04
11.0	0.523E-06	0.243E-04
12.0	0.180E-07	0.595E-05
13.0	0.267E-09	0.117E-05
14.0	0.136E-11	0.1-9E-06

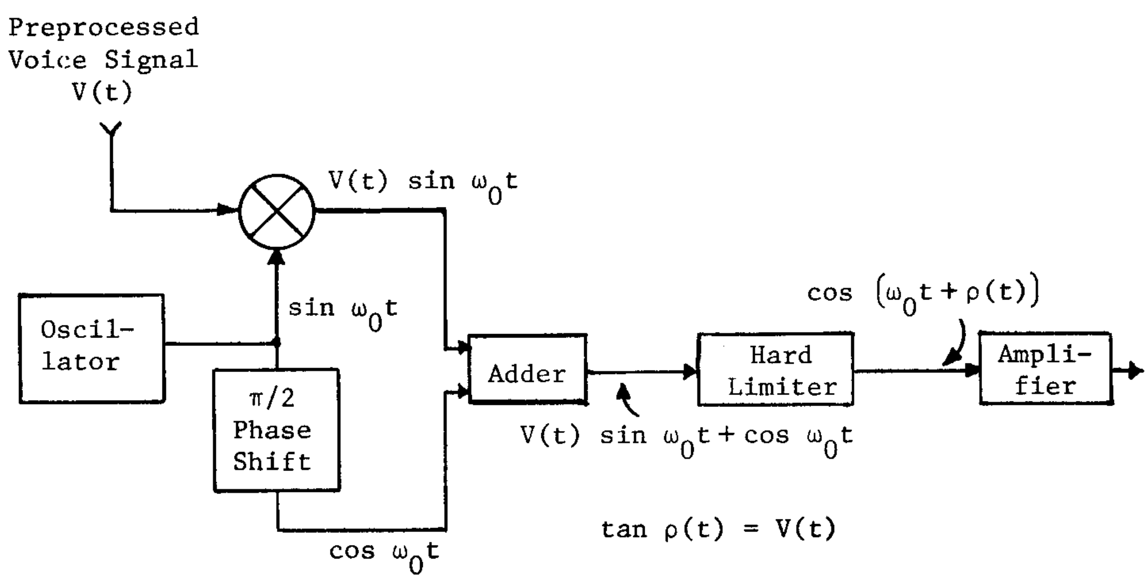

Figure 1. Quadrature Voice Modulator

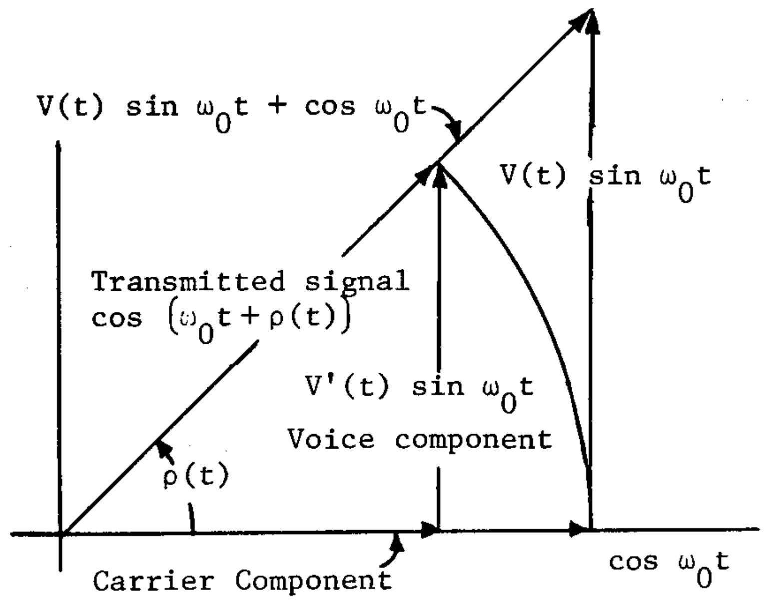

Figure 2. Quadrature Modulator Vector Diagram

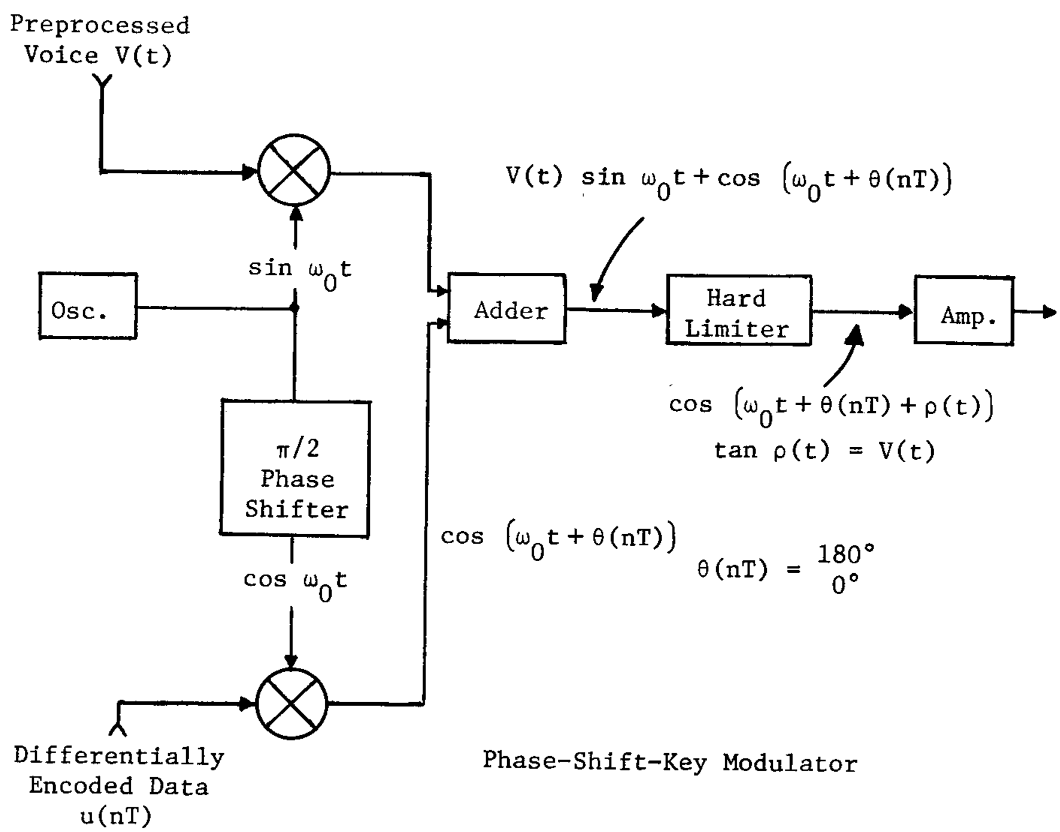

Figure 3. Voice and Data Quadrature Modulator

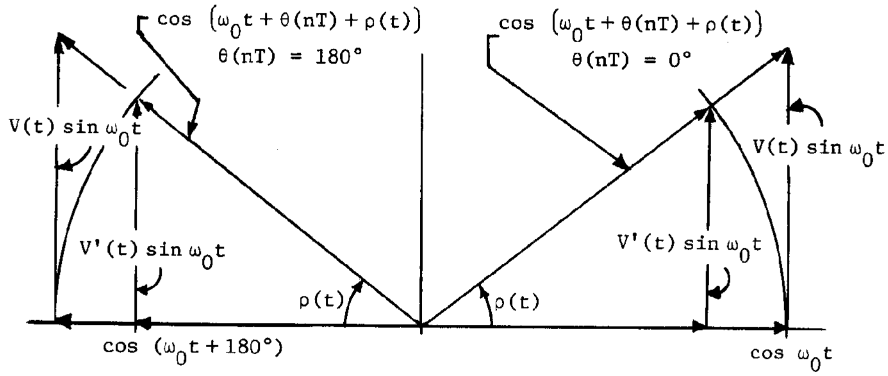

Figure 4. Voice and Data Quadrature Modulator Vector Diagram

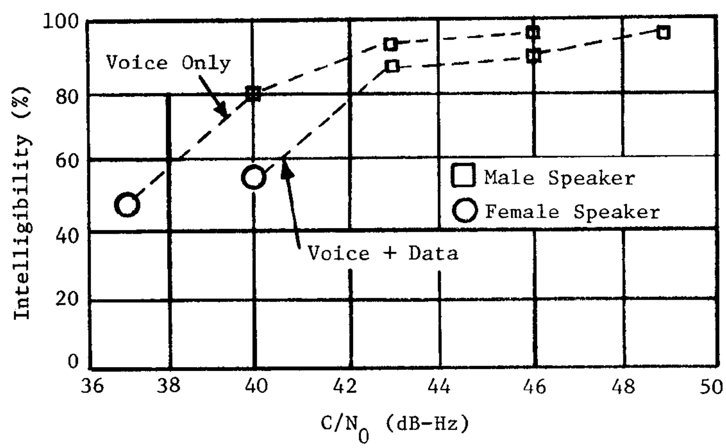

Figure 5. Hybrid Modem Voice Intelligibility Test Results

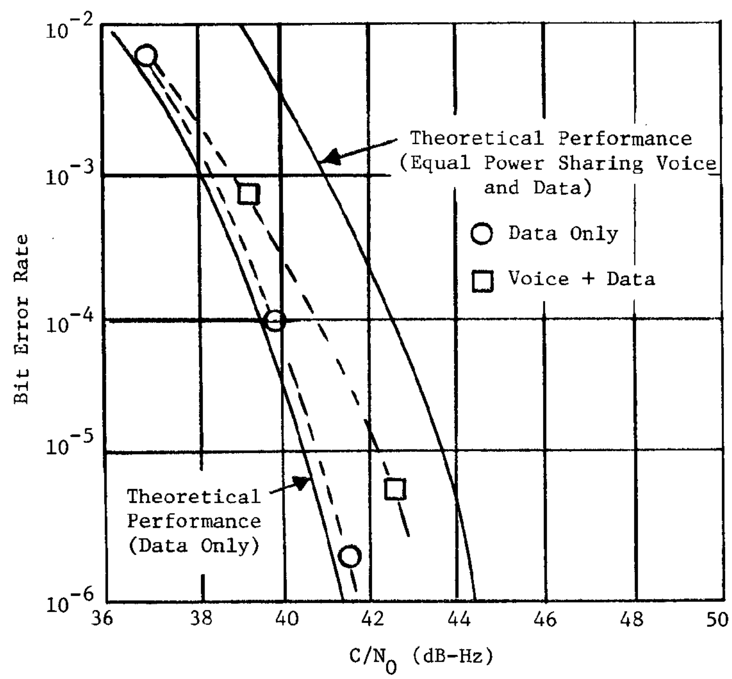

Figure 6. Hybrid Modem 1200 bps Data Error Rate Performance

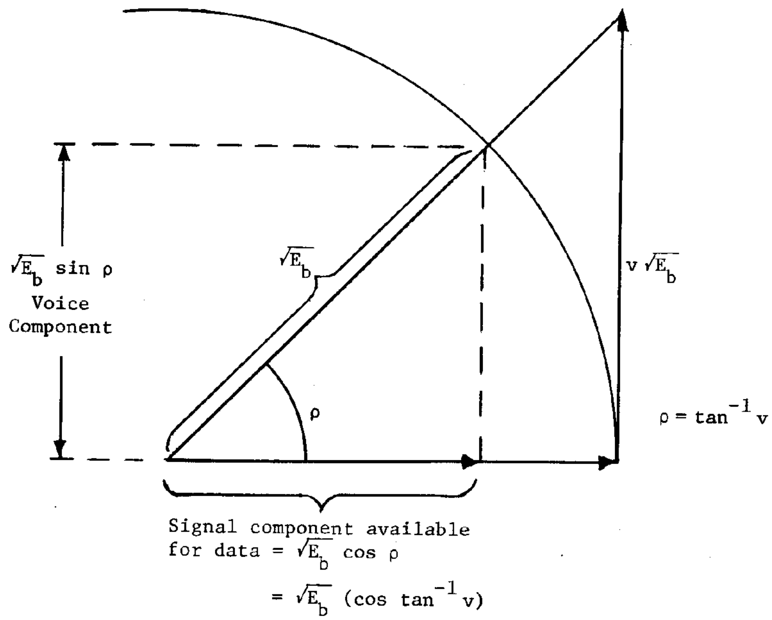

Figure 7. Power Sharing Between Voice and Data

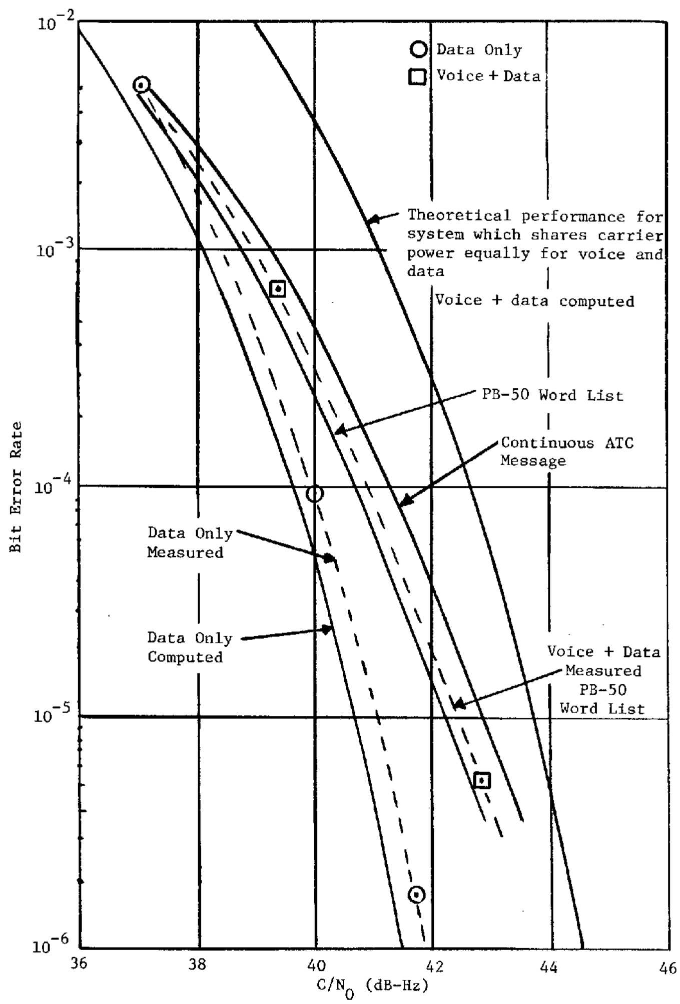

Figure 8. Hybrid Modem 1200 bps Data Error Rate Performance