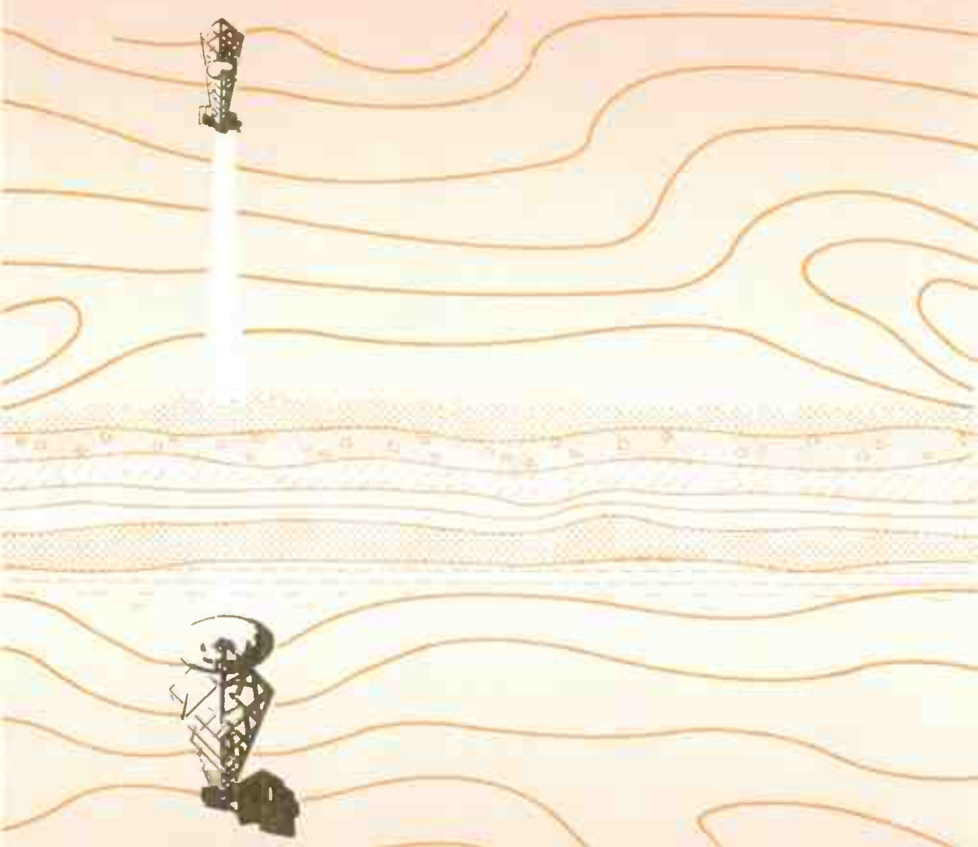
GTE LENKURT

DEMODULATOR

OCTOBER 1974



PCM OVER MICROWAVE PART 2

"In digital communication systems, speech, print, pictures, and computer data are all represented by binary signals. These signals have inevitably to be transmitted over band-limited communication channels, and the bandwidth is usually at a premium. To conserve bandwidth, it is usually necessary to convert the binary signals into other digital signals that require less bandwidth." A. Lender

The September, 1974, issue of the *Demodulator* began a discussion of the transmission of PCM signals over microwave radio. Covered in that issue were some of the functions performed by various components in the digital multiplexer, such as multiplexing, synchronization, desynchronization, and the scrambling of the binary signal to eliminate discrete frequency components during idle conditions. This issue discusses the importance of bandwidth conservation, and the methods by which it is accomplished.

One method of achieving bandwidth conservation is by compressing the incoming digital source information, which is the equivalent of removing redundancy from a message. Human speech, for example, has a redundancy factor of nearly 50%; but, while speech can be compressed, the cost of doing so presently excludes the possibility of commercial utilization. Another technique for the conservation of bandwidth is transformation of the binary source signal into a digital signal requiring less transmission bandwidth.

Duobinary Technique

The transmission of digital data over microwave radio requires that the bandwidth of the data be limited to comply with certain requirements. An approach taken in the past to reduce the bandwidth of the digital bit stream is duobinary encoding, a type of correlative encoding technique invented by Dr. Adam Lender of GTE Lenkurt. (See the February, 1963, issue of the *Demodulator* for a discussion of the duobinary process.) The duobinary power spectral density appears as shown in the example in Figure 1. The energy is contained between zero and 1/2T Hz (where 1/T is the bit rate in bits per second and T is the duration of one bit in seconds) by filtering techniques which eliminate any higher frequencies.

The frequency of the duobinary power spectrum beyond which there is no energy is 1/2T Hz. This cuts off the signal at half its bit rate, meaning, that of the original spectral density of the input binary pulse train, only frequency components of up to 1/2T Hz are being allowed through the system. The straight duobinary spectral density has most of its energy at dc and low frequencies, a situation which poses certain problems when designing voice-frequency order wire for a microwave system.

Order Wire

An important consideration in any microwave transmission system is the inclusion of a voice-frequency order wire in the radio baseband equipment. Order wire is essentially a telephone channel between communications sites, which maintenance personnel can use to resolve problems in the system. The order wire can be implemented in either digital (as part of the bit stream) or analog form. One of the major objectives in implementing order wire in the GTE Lenkurt microwave system is to be able to use

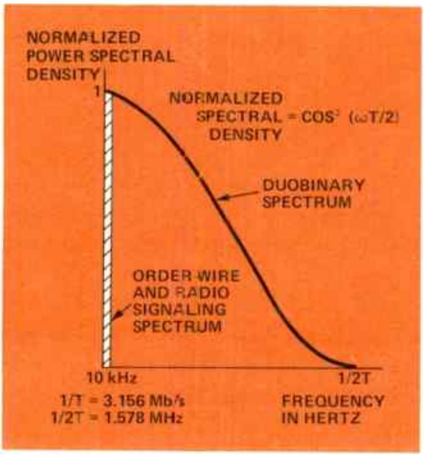


Figure 1. The conflicting spectrums of order wire and duobinary require modification of the duobinary waveform.

conventional, unmodulated analog order wire such as is used in an analog microwave system.

One possible method of providing order wire and radio signaling information is to place these channels at the higher end of the spectrum, above the digital information. This method, however, is inconvenient, since additional circuitry is required to translate the voice frequencies to the upper end of the spectrum, and the noise on the microwave radio system is greater in that part of the spectrum due to the so-called triangular noise voltage distribution. Also, bandwidth restrictions make it necessary to use a coding technique which affords more efficient use of the bandwidth than this method allows. A more practical approach is to place the order wire and service channels at the low end of the energy spectrum; in this way, no additional modulation of the voice signals is required, and bandwidth is conserved.

The basic design of the GTE Lenkurt PCM microwave system requires that both the voice-frequency order wire spectrum and that of the 48 PCM channels be transmitted over the same bandwidth. To accomplish this, however, the distribution of the baseband energy spectrum must be modified in such a way that voice-frequency order wire and signaling channel information do not interfere with the digital information. Clearly, combined transmission of the two spectrums (see Figure 1) would result in mutual interference, since both have significant amounts of power at the low-frequency end.

To accommodate the voice frequencies and signaling at the low-frequency end, the coding scheme should result in a frequency spectrum with a minimum of power concentrated at the low end. Also, to conserve bandwidth, some form of correlative encoding (correlation between digits that are a certain number of time slots apart) is desirable. The method used by GTE Lenkurt to transmit order wire and multiplexed digital information simultaneously within the same frequency spectrum differs somewhat from the straight duobinary technique, and is termed Modified Duobinary Coding.

Modified Duobinary Technique

The modified duobinary approach to digital transmission (also invented by Dr. Lender) has two important advantages: conservation of bandwidth, and allowance for an economical order wire system within the required bandwidth. Modified duobinary encoding compresses the bandwidth of the binary data through a series of filtering processes, which ultimately yield the power spectrum shown in Figure 2.

In the GTE Lenkurt PCM microwave system, the frequency band between 0 and 10 kHz in the modified duobinary spectrum is reserved for order wire and radio signaling information. Like duobinary, modified duobinary still cuts off at 1/2T Hz; unlike duobinary, modified duobinary has a

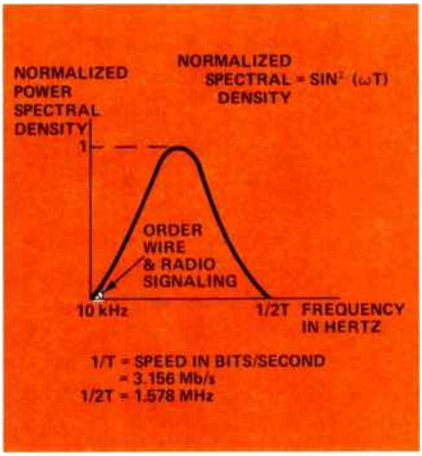


Figure 2. The modified duobinary spectrum contains negligible power at the low-frequency end.

negligible amount of energy at the low-frequency end. The power is contained between zero and 1.578 MHz by filtering techniques which eliminate any higher frequencies. In this case, the 1.578 MHz is exactly half of the incoming bit rate of 3.156 Mb/s, which corresponds to that of a GTE Lenkurt system designed for the transmission of 48 PCM voice channels over microwave radio.

Part of the modified duobinary process takes place in the transmit interface unit (see Figure 3) of the digital multiplexer. As discussed in the previous issue (PCM Over Microwave, Part 1), the scrambler prevents discrete frequency tones from being transmitted by the radio. The modified duobinary encoder encodes the 3.156-Mb/s binary data for the modified duobinary processing. Two additional steps are required for conversion to a modified duobinary waveform. In the first step, a three-level signal is formed from the encoded binary signal by the three-level converter. The second step is an analog function that is divided between the transmitting and receiving filters.

The conversion to a three-level signal constitutes the initial conversion step to a modified duobinary signal. The transmit filter and delay equalizer perform partial conversion of the three-level signal into the modified duobinary format. The remaining conversion is done at the receive filter. The delay equalizer minimizes the differential delay of the transmit and receive filters. If, for example, all the filtering were to be done at the transmitter, during a multipath fade, where increased noise is introduced into the receiver, there would be no further filtering available, and error performance would be degraded. Conversely, it would be undesirable to perform all

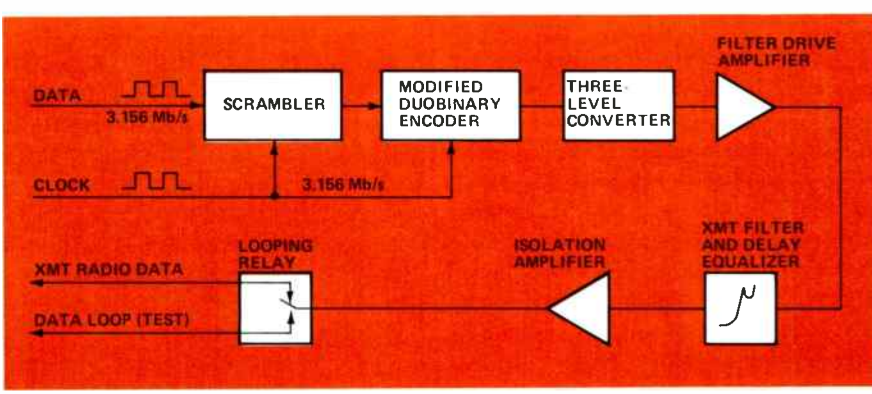


Figure 3. The first part of the conversion to a modified duobinary waveform takes place in the transmit interface unit.

the filtering in the receiver, since this would mean that a wideband signal would have to be transmitted, resulting in excessive use of the frequency spectrum. The solution to this problem is to do partial filtering at the transmitter, and the rest at the receiver. Full conversion to modified duobinary waveform does not actually take place until the output of the receive filter; a complete modified duobinary signal is therefore not transmitted through the medium. And, it is only at the output of the receive filter, in the receive interface unit, that the modified duobinary eye pattern may be observed.

The Eye Pattern

The eye pattern of a random pulse train is formed by dividing the pulse sequence into n-bit segments and superimposing the segments over the n-bit interval. By connecting the pulse stream to an oscilloscope that is synchronized externally with the clock that drives the pulse train, a pattern resembling a human eye is formed. The eye pattern may be produced to monitor overall system performance. By observing the eye, distortion and intersymbol interference can be measured in terms of vertical and horizontal eye openings relative to an undistorted eye. Figure 4 shows a typical eye pattern for a modified duobinary signal.

The eye pattern is sampled by the clock at some optimum point, which will yield either a -1, 0, or $+1$. The performance of the system depends on how well it can extract a signal in the presence of noise. The theoretical rms signal power-to-rms noise power ratio required for a bit error rate of 10^{-6} (one error every million bits) using the duobinary technique is approximately 17 dB. This type of noise performance, however, is theoretical, and would apply only to a perfect system; practically, a typical duobinary system has a noise performance of between 18 dB and 20 dB.

The modified duobinary signal is more susceptible to intersymbol interference than is a straight duobinary waveform. Unlike the duobinary format, which stipulates that a transition from $+1$ directly to -1 cannot take place without a transition to the zero level first, the modified duobinary format allows direct transitions from the positive to the negative level, thus increasing intersymbol interference. In effect, the more intersymbol interference, the more accurate the clock must be. Theoretically, there is a 2-dB penalty in the transition from duobinary to modified duobinary, with the expected signal-to-noise ratio for modified duobinary being around 20 to 22 dB.

Clock Recovery

The receive interface unit is shown in Figure 5 in block diagram form. The receive filter converts the signal into the modified duobinary waveform and limits out-of-band noise generated in the radio receiver. The slicers convert the analog signal into two binary bit streams. Each time the clock pulse rises, it is performing the function of "looking" at the information at a

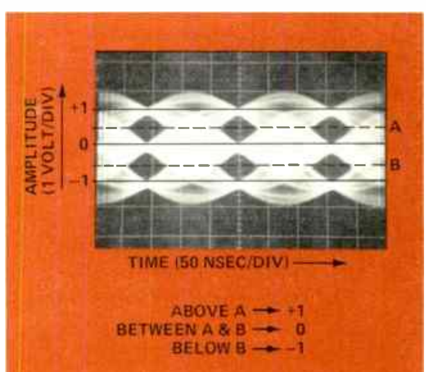


Figure 4. The eye pattern reveals overall system performance.

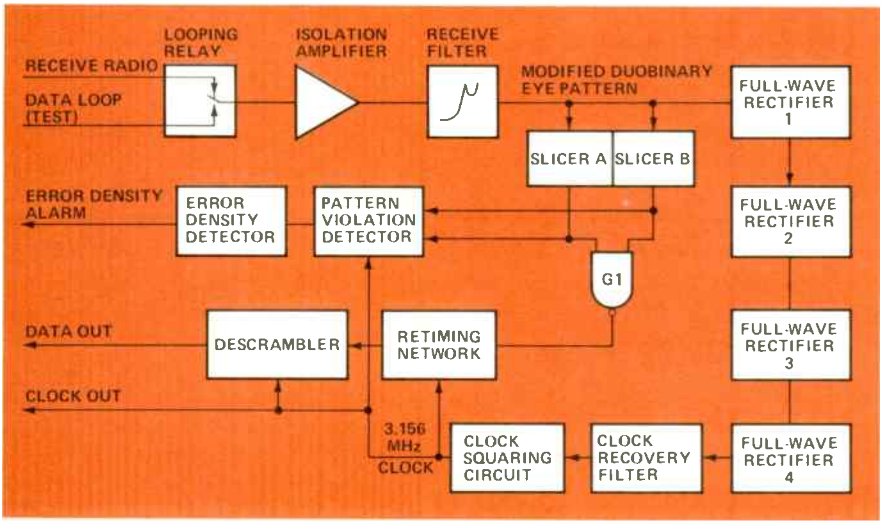


Figure 5. The receive interface unit completes the conversion to modified duobinary, recovers the clock, and descrambles the incoming signal.

particular point in time. The clock must look directly within the area represented by the eye, since that is where the desired information is contained. The rising edge of the clock pulse must therefore sample as close to the center of the eye as possible. Essentially, the clock must decipher whether the information at one particular instant is −1, 0, or +1, at the output of the slicer. Four full-wave rectifier circuits connected in tandem convert the incoming analog signal into a signal with a strong 3.156-MHz component. The clock recovery filter allows only the 3.156-MHz component to pass, thus producing a 3.156-MHz sine wave, which the clock-squaring circuit converts into a 3.156-MHz clock. The descrambler, acting to complement the scrambler in the transmit interface unit, descrambles the data into the original binary data. The pattern violation detector detects modified duobinary pattern violations, which result in errors. The error density detector triggers an alarm when the error rate exceeds 10^{-5} (one error in 100,000 bits).

The overall clock recovery process is especially interesting in this system. Specifically, there are two design objectives which the clock recovery circuit must meet: (1) To produce a clock with a minimum amount of phase jitter, and (2) to minimize clock phase shift caused by temperature variations and variations in the transmit clock frequency. The overall clock recovery process consists of producing a signal derived from the modified duobinary eye pattern with a strong 3.156-MHz component, and filtering the signal to select only that component.

Due to the spectral content of the modified duobinary signal, four successive full-wave rectifications produce a signal with a very strong 3.156-MHz component suitable for filtering. Each of the four full-wave rectifier circuits consists of a constant current source with temperature compensation and a differential amplifier with a gain of 2. The gain of 2 is provided in each rectifier so that the peak-to-peak signal amplitude is not reduced after each rectification.

After four successive full-wave rectifications, the signal frequency spectrum yields a sharp peak at the bit frequency of 3.156 MHz, along with an indefinite number of weaker out-of-band components. This signal is then passed on to the clock recovery filter, to assume the function of the clock.

To meet the first design objective of minimum phase jitter, the clock recovery filter must have a high enough Q so that the out-of-band frequency components are significantly rejected. However, to meet the second design objective of minimum clock phase shift, the Q must not be so high as to produce a phase characteristic which varies greatly with frequency. To meet both objectives satisfactorily, a GTE Lenkurt crystal filter was designed with a Q of approximately 1000 (a low Q for a crystal filter), and with a gradual phase characteristic, thus achieving a combination of minimum jitter and gradual phase shift. A graph of amplitude and phase shift versus frequency is shown in Figure 6. In the band of interest, the gradual phase characteristic of 0.03 degree per Hertz insures a phase-stable clock in spite of small offsets in the transmitting clock. Specifically, system design allows the transmit clock to vary by no more than ±100 hertz, thus preventing the receive clock from varying

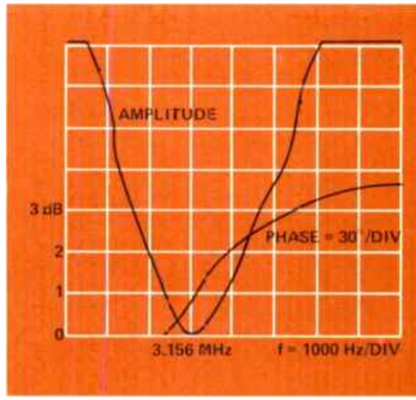


Figure 6. Amplitude and phase shift versus frequency.

more than ±3 degrees. Less than 10 nanoseconds of peak-to-peak jitter appear on the clock, with an increase to 20 nanoseconds at a signal-to-noise ratio of 20 dB. The filter is stable with temperature, having a 0.22 degree/°C phase shift, and a phase shift close to 0.03 degree per Hertz due to frequency offsets in the transmit clock.

This series of articles, up to the present, has dealt with some of the more significant points pertaining to the operation of specific system components involved in the transmission of PCM over microwave radio. The following issue (Part 3) will be a general discussion of the overall operation of the PCM-over-microwave system.

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