13-2 PULSE MODULATION

13-2.1 Introduction—Types

Pulse modulation may be used to transmit *analog* information, such as continuous speech or data. It is a system in which continuous waveforms are *sampled* at regular intervals. Information regarding the signal is transmitted only at the sampling times, together with any synchronizing pulses that may be required. At the receiving end, the original waveforms may be reconstituted from the information regarding the samples, if these are taken frequently enough. Despite the fact that information about the signal is not supplied continuously, as in AM and FM, the resulting receiver output can have negligible distortion.

Pulse modulation may be subdivided broadly into two categories, *analog* and *digital*. In the former, the indication of sample amplitude may be infinitely variable, while in the latter a code which indicates the sample amplitude to the nearest predetermined level is sent. *Pulse-amplitude* and *pulse-time* modulation are both analog, while the *pulse-code* and *delta* modulation systems are both digital. All the modulation systems to be discussed have sampling in common, but they differ from each other in the manner of indicating the sample amplitude.

The two types of analog pulse modulation, pulse-amplitude and pulse-time modulation, correspond roughly to amplitude and frequency modulation. The digital systems are quite unlike anything that we have so far studied. The reasons why pulse modulation is increasingly used instead of the more familiar continuous modulation systems will become apparent as the chapter progresses.

Pulse-amplitude modulation (PAM) Pulse-amplitude modulation, the simplest form of pulse modulation, is illustrated in Figure 13-4. It forms an excellent introduction to pulse modulation in general. PAM is a pulse modulation system in which the signal is

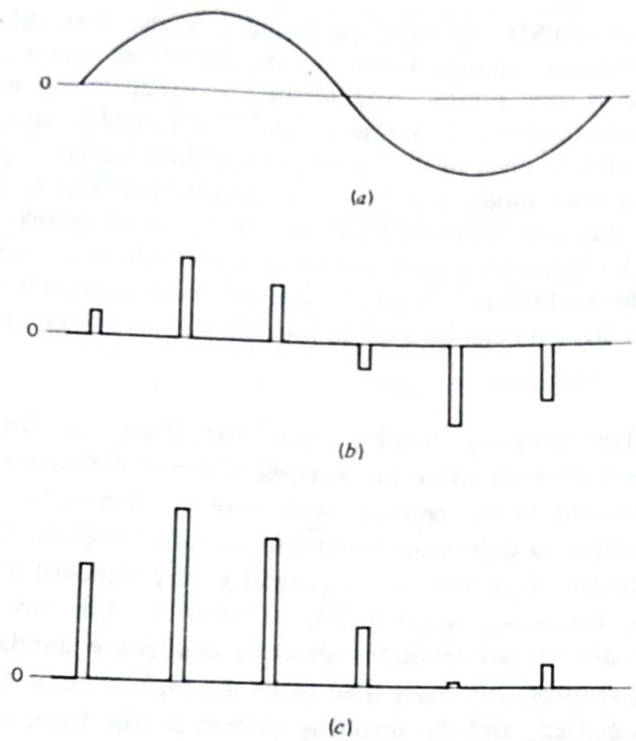

FIGURE 13-4 Pulse-amplitude modulation. (*a*) Signal; (*b*) double-polarity PAM; (*c*) single-polarity PAM.

sampled at regular intervals, and each sample is made proportional to the amplitude of the signal at the instant of sampling. The pulses are then sent by either wire or cable, or else are used to modulate a carrier. As shown in Figure 13-4, the two types are double-polarity PAM, which is self-explanatory, and single-polarity PAM, in which a fixed dc level is added to the signal, to ensure that the pulses are always positive. The ability to use constant-amplitude pulses is a major advantage of pulse modulation, and since PAM does not utilize constant-amplitude pulses, it is infrequently used. When it is used, the pulses *frequency-modulate* the carrier.

It is very easy to generate and demodulate PAM. In a generator, the signal to be converted to PAM is fed to one input of an AND gate. Pulses at the sampling frequency are applied to the other input of the AND gate to open it during the wanted time intervals. The output of the gate then consists of pulses at the sampling rate, equal in amplitude to the signal voltage at each instant. The pulses are then passed through a pulse-shaping network, which gives them flat tops. As mentioned above, frequency modulation is then employed, so that the system becomes PAM-FM. In the receiver, the pulses are first recovered with a standard FM demodulator. They are then fed to an ordinary diode detector, which is followed by a low-pass filter. If the cutoff frequency of this filter is high enough to pass the highest signal frequency, but low enough to remove the sampling frequency ripple, an undistorted replica of the original signal is reproduced.

Pulse-time modulation (PTM) In PTM the signal is sampled as before, but the pulses indicating instantaneous sample amplitudes themselves all have a constant amplitude. However, one of their timing characteristics is varied, being made proportional to the sampled signal amplitude at that instant. The variable characteristic may be the width, position of frequency of the pulses, so that three different types of PTM are possible. Pulse-frequency modulation has no significant practical applications and will be omitted. The other two forms of PTM will be discussed below. It should be noted that all forms of PTM have the same advantage over PAM as frequency modulation has over amplitude modulation. In all of them the pulse amplitude remains constant, so that amplitude limiters can be used to provide a good degree of noise immunity.

Sampling theorem The sampling theorem states that, *if the sampling rate in any pulse modulation system exceeds twice the maximum signal frequency, the original signal can be reconstructed in the receiver with minimal distortion*. The sampling theorem is used in practice to determine minimum sampling speeds. Consider pulse modulation used for speech. Transmission is generally over standard telephone channels, so that the audio frequency range is 300 to 3400 Hz. For this application, a sampling rate of 8000 samples per second is almost a worldwide standard. This pulse rate is, as can be seen, comfortably more than twice the highest audio frequency. The sampling theorem is satisfied, and the resulting system is free from sampling error.

13-2.2 Pulse-Width Modulation

Introduction The pulse-width modulation of PTM is also often called PDM (pulse-duration modulation) and, less often, PLM (pulse-length modulation). In this system, as shown in Figure 13-5, we have a fixed amplitude and starting time of each pulse, but the width of each pulse is made proportional to the amplitude of the signal at that instant. In Figure 13-5, there may be a sequence of signal sample amplitudes of 0.9, 0.5, 0 and −0.4 V. These can be represented by pulse widths of 1.9, 1.5, 1.0 and 0.6 μs, respectively. The width corresponding to zero amplitude was chosen in this system to be 1.0 μs, and it has been assumed that signal amplitude at this point will

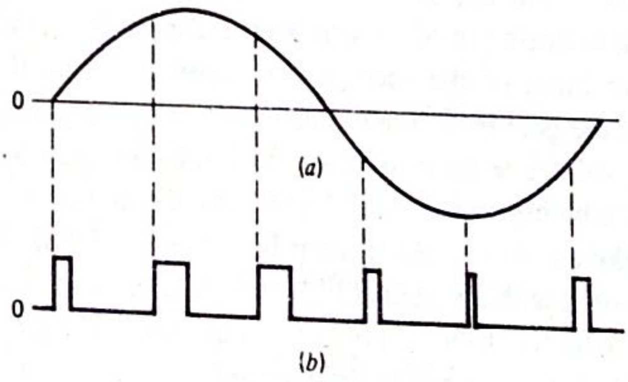

FIGURE 13-5 Pulse-width modulation. (*a*) Signal; (*b*) PWM (width variations exaggerated).

vary between the limits of +1 V (width = 2 μs) and −1 V (width = 0 μs). Zero amplitude is thus the average signal level, and the average pulse width of 1 μs has been made to correspond to it. In this context, a negative pulse width is not possible. It would make the pulse end before it began, as it were, and thus throw out the timing in the receiver. If the pulses in a practical system have a recurrence rate of 8000 pulses per second, the time between the commencement of adjoining pulses is $10^6/8000 =$ 125 μs. This is adequate not only to accommodate the varying widths but also to permit *time-division multiplexing*, as explained in Chapter 15.

Pulse-width modulation has the disadvantage, when compared with *pulse-position modulation* (PPM), which will be discussed next, that its pulses are of varying width and therefore of varying power content. This means that the transmitter must be powerful enough to handle the maximum-width pulses, although the average power transmitted is perhaps only half of the peak power. PWM still works if synchronization between transmitter and receiver fails, whereas pulse-position modulation does not.

Generation and demodulation of PWM Pulse-width modulation may be generated by applying trigger pulses (at the sampling rate) to control the starting time of pulses from a monostable multivibrator, and feeding in the signal to be sampled to control the duration of these pulses. The circuit diagram for such an arrangement is shown in Figure 13-6.

The emitter-coupled monostable multivibrator of Figure 13-6 makes an excellent voltage-to-time converter, since its gate width is dependent on the voltage to which the capacitor C is charged. If this voltage is varied in accordance with a signal voltage, a series of rectangular pulses will be obtained, with widths varying as required. Note that the circuit does the twin jobs of sampling and converting the samples into PWM.

It will be recalled that the stable state for this type of multivibrator is with T_1 OFF and T_2 ON. The applied trigger pulse switches T_1 ON, whereupon the voltage at C_1 falls as T_1 now begins to draw collector current, the voltage at B_2 follows suit and T_2 is switched OFF by regenerative action. As soon as this happens, however, C begins to charge up to the collector supply potential through R. After a time determined by the supply voltage and the RC time constant of the charging network, B_2 becomes sufficiently positive to switch T_2 ON. T_1 is simultaneously switched OFF by regenerative

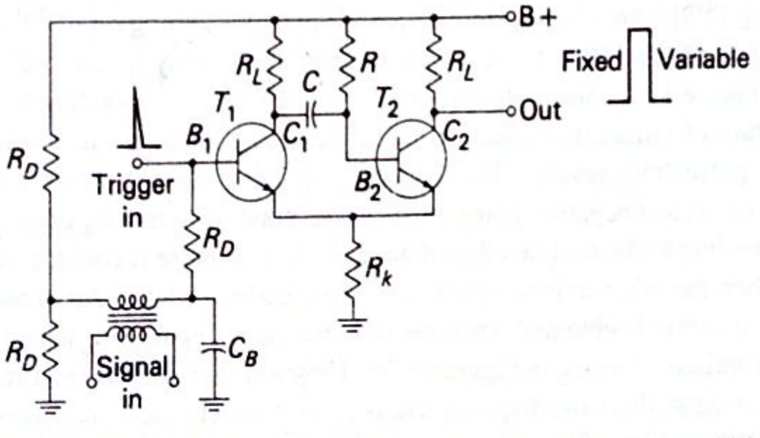

FIGURE 13-6 Monostable multivibrator generating pulse-width modulation.

action and stays OFF until the arrival of the next trigger pulse. The voltage that the base of T_2 must reach to allow T_2 to turn on is slightly more positive than the voltage across the common emitter resistor R_k. This voltage depends on the current flowing through the circuit, which at the time is the collector current of T_1 (which is then ON). The collector current depends on the base bias, which is governed by the instantaneous changes in the applied signal voltage. The applied modulation voltage controls the voltage to which B_2 must rise to switch T_2 ON. Since this voltage rise is linear, the modulation voltage is seen to control the period of time during which T_2 is OFF, that is, the pulse duration. It should be noted that this pulse duration is very short compared to even the highest signal frequencies, so that no real distortion arises through changes in signal amplitude while T_2 is OFF.

The demodulation of pulse-width modulation is quite a simple process. PWM is merely fed to an integrating circuit from which a signal emerges whose amplitude at any time is proportional to the pulse width at that time. This principle is also employed in the very efficient so-called *class D* amplifiers. The integrating circuit most often used there is the loudspeaker itself.

13-2.3 Pulse-Position Modulation (PPM)

The amplitude and width of the pulses is kept constant in this system, while the position of each pulse, in relation to the position of a recurrent reference pulse is varied by each instantaneous sampled value of the modulating wave. This means that the transmitter must send synchronizing pulses to operate timing circuits in the receiver. As mentioned in connection with PWM, pulse-position modulation has the advantage of requiring constant transmitter power output, but the disadvantage of depending on transmitter-receiver synchronization.

Generation and demodulation of PPM Pulse-position modulation may be obtained very simply from PWM, as shown in Figure 13-7. Considering PWM and its generation again, it is seen that each such pulse has a leading edge and trailing edge (like any other pulse, of course). However, in PWM the locations of the leading edges are fixed, whereas those of the trailing edges are not. Their position depends on pulse width, which is determined by the signal amplitude at that instant. Thus, it may be said that *the trailing edges of PWM pulses are, in fact, position-modulated.* The method of obtaining PPM from PWM is thus accomplished by "getting rid of" the leading edges and bodies of the PWM pulses. This is surprisingly easy to achieve.

Figure 13-7*a* and *b* shows, once again, PWM corresponding to a given signal. If the train of pulses thus obtained is differentiated, then, as shown in Figure 13-7*c*, another pulse train results. This has positive-going narrow pulses corresponding to leading edges and negative-going pulses corresponding to trailing edges. If the position corresponding to the trailing edge of an unmodulated pulse is counted as zero displacement, then the other trailing edges will arrive earlier or later. An unmodulated PWM pulse is one that is obtained when the instantaneous signal value is zero. These pulses are appropriately labeled in Figure 13-7*b*. They will therefore have a time displacement other than zero; this time displacement is proportional to the instantaneous value of the signal voltage. The differentiated pulses corresponding to the leading edges are re-

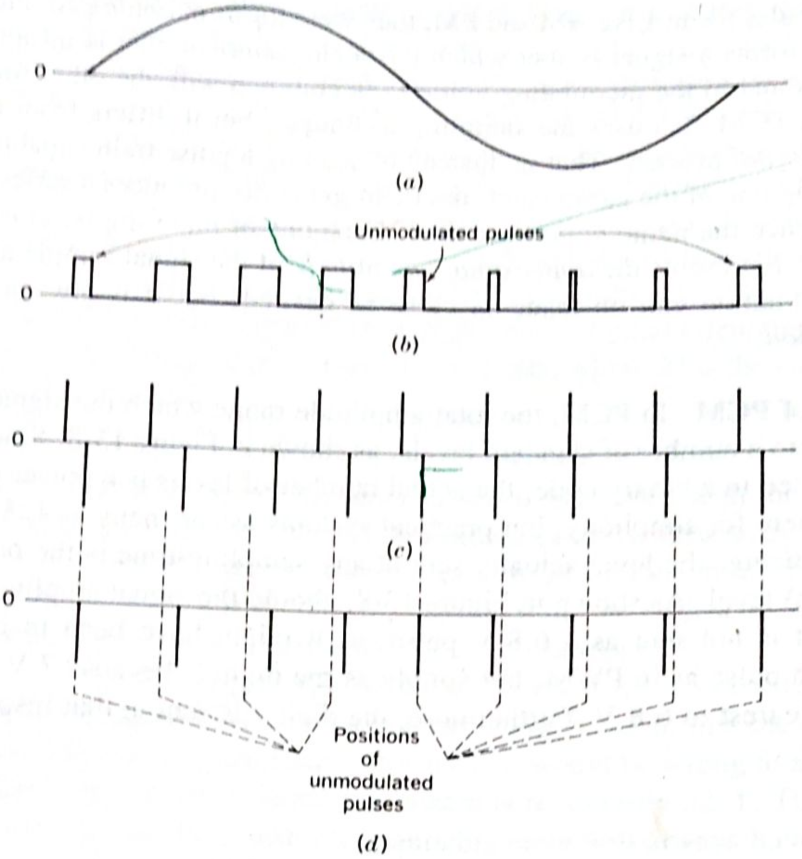

FIGURE 13-7 Generation of pulse-position modulation. (*a*) Signal; (*b*) PWM; (*c*) differentiated; (*d*) clipped (PPM).

moved with a diode clipper or rectifier, and the remaining pulses, as shown in Figure 13-7*d*, are position-modulated.

When PPM is demodulated in the receiver, it is again first converted into PWM. This is done with a flip-flop, or bistable multivibrator. One input of the multivibrator receives trigger pulses from a local generator which is synchronized by trigger pulses received from the transmitter, and these triggers are used to switch OFF one of the stages of the flip-flop. The PPM pulses are fed to the other base of the flip-flop and switch that stage ON (actually by switching the other one OFF). The period of time during which this particular stage is OFF depends on the time difference between the two triggers, so that the resulting pulse has a width that depends on the time displacement of each individual PPM pulse. The resulting PWM pulse train is then demodulated.

13-2.4 Pulse-Code Modulation (PCM)

Pulse-code modulation is just as different from the forms of pulse modulation so far studied as they were from AM or FM. PAM and PTM differed from AM and FM because, unlike in those two continuous forms of modulation, the signal was sampled