Albert Lozano-Nieto. "Telemetry."

Telemetry

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87.1 Introduction

Telemetry is the science of gathering information at some remote location and transmitting the data to a convenient location to be examined and recorded. Telemetry can by done by different methods: optical, mechanical, hydraulic, electric, etc. The mechanical methods, either pneumatic or hydraulic have acceptable results for short distances and are used in environments that have a high level of electromagnetic interference and in those situations where, for security reasons, it is not possible to use electrical signals, for example, in explosive environments. More recently, use of optical fiber systems allows the measurement of broad bandwidth and high immunity to noise and interference. Other proposed telemetry systems are based on ultrasound, capacitive or magnetic coupling, and infrared radiation, although these methods are not routinely used. The discussion in this chapter will be limited to the most-used systems: telemetry based on electric signals. The main advantage of electric over mechanical methods is that electrically based telemetry does not have practical limits regarding the distance between the measurement and the analysis areas, and can be easily adapted and upgraded in already existing infrastructures. Electric telemetry methods are further divided depending on the transmission channel that they use as wire telemetry and wireless (or radio) telemetry. Wire telemetry is technologically the simplest solution. The limitations of wire telemetry are the low bandwidth and low transmission speed that it can support. However, it is used when the transmission wires can use the already existing infrastructure, as, for example, in most electric power lines that are also used as wire telemetry carriers. Wireless telemetry is more complex than wire telemetry, as it requires a final radio frequency (RF) stage. Despite its complexity, it is widely used because it can transmit information over longer distances; thus, it is used in those applications in which the measurement area is not normally accessible. It can also transmit at higher speeds and have enough capacity to transmit several channels of information if necessary.

Figure 87.1 displays a generic telemetry system. It consists of (not all the blocks will be always present) (1) transducers to convert physical variables to be measured into electric signals that can be easily processed; (2) conditioning circuits to amplify the low-level signal from the transducer, limit its bandwidth, and adapt impedance levels; (3) a signal-processing circuit that sometimes can be integrated in the previous circuits; (4) a subcarrier oscillator whose signal will be modulated by the output of the different transducers once processed and adapted; (5) a codifier circuit, which can be a digital encoder, an analog modulator, or a digital modulator, that adapts the signal to the characteristics of the transmission channel, which is a wire or an antenna; (6) a radio transmitter, in wireless telemetry, modulated by

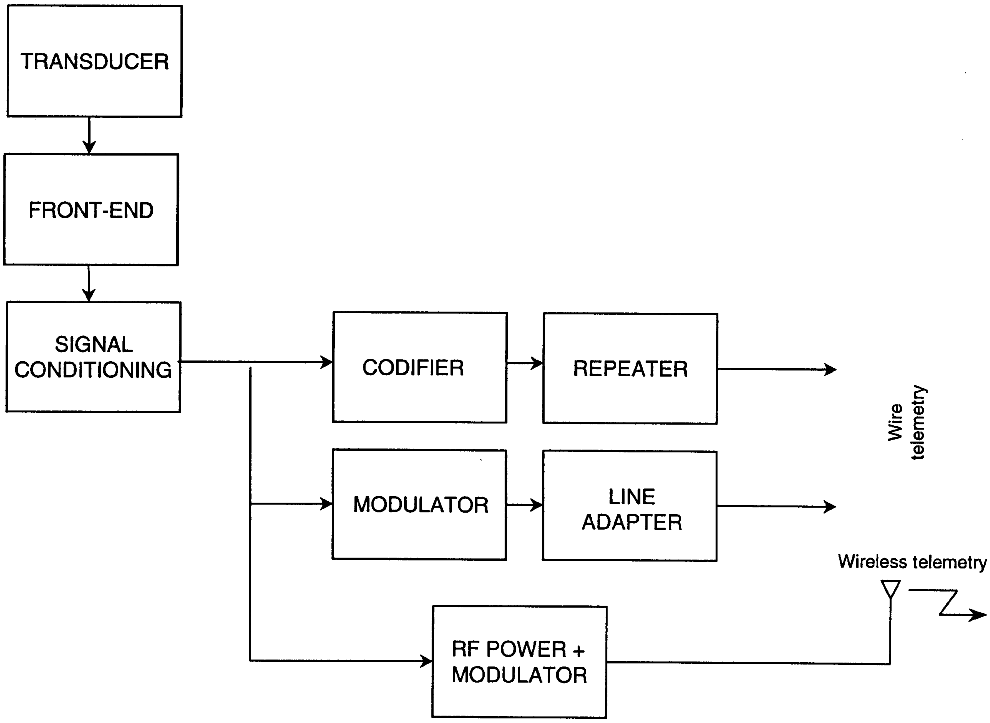

FIGURE 87.1 Block diagram for a telemetry system. Telemetry using wires can be performed in either base-band or by sending a modulated signal, while wireless telemetry uses an RF carrier and an antenna.

the composite signal; (7) an impedance line adapter, in case of wire transmission, to adapt the characteristic impedance of the line to the output impedance of the circuits connected to the adapter; and (8) for wireless communication, a transmitting antenna. The receiver end consists of similar modules. For wireless telemetry, these modules are (1) a receiving antenna designed for maximum efficiency in the RF band used; (2) a radio receiver with a demodulation scheme compatible with the modulation scheme; and (3) demodulation circuits for each of the transmitted channels. For wire telemetry, the antenna and the radio receiver are replaced by a generic front end to amplify the signal and adapt the line impedance to the input impedance of the circuits that follow. The transmission in telemetry systems, in particular wireless ones, is done by sending a signal whose analog variations in amplitude or frequency are a known function of the variations of the signals from the transducers. More recently, digital telemetry systems send data digitally as a finite set of symbols, each one representing one of the possible finite values of the composite signals at the time that it was sampled. The effective communication distance in a wireless system is limited by the power radiated by the transmitting antenna, the sensitivity fo the receiver and the bandwidth of the RF signal. As the bandwidth increases, the contribution of noise to the total signal also increases, and consequently more transmitted power is needed to maintain the same signal-to-noise ratio (SNR). This is one of the principal limitations of wireless telemetry systems. In some applications, the transmission to the receiver is done on base band, after the conditioning circuits. The advantage of base-band telemetry systems is their simplicity, although because of the base-band transmission, they are normally limited to only one channel at low speeds.

Not uncommonly, measurement system needs to acquire either different types of signals or the same type of data at different locations in the process that is being monitored. These different information signals can be transmitted using the same common carrier by multiplexing the data signals. Multiplexing allows different signals to share the same channel. Multiplexing techniques are usually considered either frequency division multiplexing (FDM) or time division multiplexing (TDM). In FDM, different subcarrier

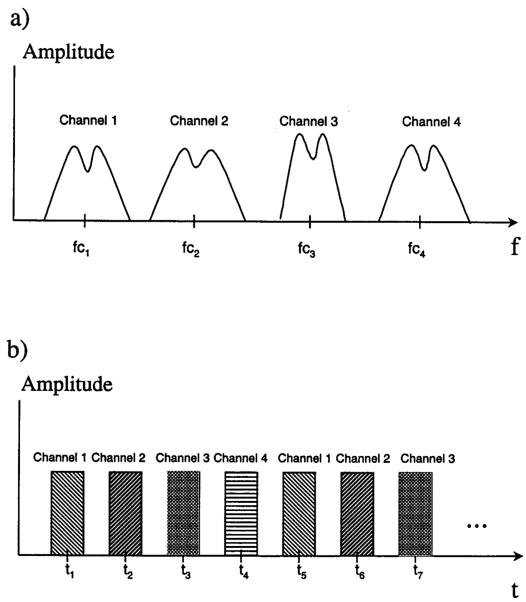

FIGURE 87.2 Basic characteristics of (a) FDM and (b) TDM signals. In FDM different channels are allocated at different subcarrier frequencies (f_{c1}, f_{c2},…) while in TDM only one channel is transmitted at a given time. The remaining channels are transmitted sequentially.

frequencies are modulated by the different measurement channel signals, which causes the information spectrum to shift from base band to the subcarrier frequency. Then, the subcarrier frequencies modulate the RF carrier signal, which allows the transmission of all desired measurement channels simultaneously. In TDM, the whole channel is assigned entirely to each measurement channel, although only during a fraction of the time. TDM techniques use digital modulation to sample the different measurement channels at different times. Then, these samples are applied sequentially to modulate the RF carrier. Figure 87.2 illustrates these concepts by showing frequency and time graphs for FDM and TDM, respectively.

Almost all instrumentation and measurement situations are candidates for use of a telemetry link. Telemetry is widely used in space applications for either telemeasurement of a distant variable or telecommandment of actuators. In most of these types of applications, for example, in space telemetry, it is very important to design the telemetry systems to minimize the consumption of power [1]. Some land-mobile vehicles, such as trains, also use telemetry systems, either wireless or by using some of the existing power wires to transmit data to the central station and receive its commands [2]. In clinical practice, the telemetry of patients increases their quality of life and their mobility, as patients do not need to be connected to a measurement system to be monitored. Several medical applications are based on implanting a sensor in a patient and transmitting the data to be further analyzed and processed either by radio [3] or by adapted telephone lines [4] from the receiving station. Optical sensors and fiber-optic communications are used in industry to measure in environments where it is not desirable to have electric signals such as explosive atmospheres [5]. The designer of a telemetry system needs also to keep in mind the conditions in which the system will have to operate. In most of the applications, the telemetry systems must operate repeatedly without adjustment and calibration in a wide range of temperatures. Finally, as different telemetry systems are developed, the need to permit tests to be made interchangeable at all ranges increases, which require compatibility of transmitting, receiving, and signal-processing equipment at all ranges. For this reason, the Department of Defense Research and Development Squad created the Guided Missiles Committee, which formed the Working Group on Telemetry. This later became the Inter-Range Instrumentation Group (IRIG) that developed Telemetry Standards. Today, the IRIG Standard 106-96 is the primary Telemetry Standard used worldwide by both government and industry.

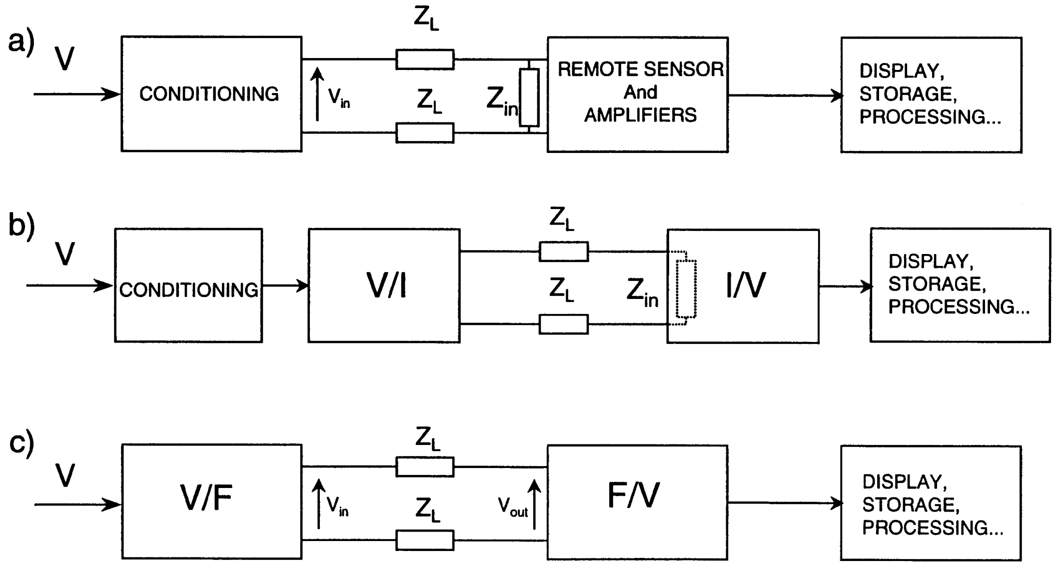

FIGURE 87.3 Different configurations for base-band telemetry. In voltage-based-base band telemetry (a) the information is transmitted as variations of a voltage signal. Current-based-base band telemetry (b) is based on sending a current signal instead of a voltage signal to neutralize the signal degradation due to the voltage divider made up by the input impedance of the receiver (Z_{in}) and the impedance of the lines (Z_L). In frequency-based base-band telemetry (c), the information is transmitted as variations of frequency which makes this system immune to noise and interference that affect the amplitude of the transmitted signal.

87.2 Base-Band Telemetry

Base-band telemetry uses a wire line to communicate the signal from the transducer after being processed and conditioned with the receiver. We will briefly describe telemetry systems based either on amplitude or frequency. More in-depth study of these base-band telemetry systems can be found in Reference 6.

Base-Band Telemetry Based on Amplitude

Voltage-Based Base-Band Telemetry

Figure 87.3a shows a simple voltage-based telemetry system. The signal from the transducer is amplified, normally to a voltage level between 1 and 15 V, and sent through a line consisting of two wires to the receiver. By making the low end of the scale 1 V, this system can detect short circuits [6]. The main problem of this configuration is the limitation on the transmission distance, which depends on the resistance of the line and the input resistance for the receiver. Also, the connecting wires form a loop that is very susceptible to interference from parasitic signals.

Current-Based Base-Band Telemetry

The limitation on transmission distance of the voltage-based system due to the impedance of the line are solved by using a current signal instead of a voltage, as is shown in Figure 87.3b. This requires an additional conversion module after the signal-processing circuits from voltage to current. At the receiver end, the signal is detected by measuring the voltage across a resistor. The most-used system in industry is the 4 to 20 mA loop. This means that 0 V is transmitted as 4 mA, while the highest voltage value is transmitted as a 20-mA current. The advantage of transmitting 4 mA for 0 V is the easy detection of an open circuit in the loop (0 mA). Other standard current values are 0 to 5, 0 to 20, 10 to 50, 1 to 5, and 2 to 10 mA. Also, voltage drops due to resistance of the wires do not affect the transmitted signal, which allows the use of thinner wires. Because this is a current mode, the parasitic voltages induced in the line

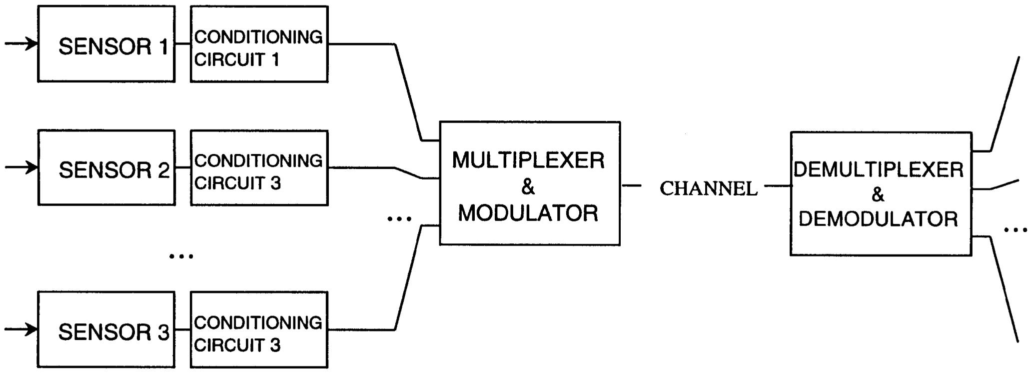

FIGURE 87.4 In multiple-channel telemetry a common transmission channel is used to transmit the measured signals from different channels using different sharing schemes.

do not affect the signal either. Current-based telemetry allows the use of grounded or floating transmitters with few modifications [6].

Base-Band Telemetry Based on Frequency

Frequency-based transmission is known to have higher immunity to noise than amplitude-based transmission. Frequency-based telemetry, shown in Figure 87.3c, is used in the presence of inductive or capacitive interference due to its immunity to noise. It also offers the possibility of isolating the receiver from the transmitter. The signal at the output of the conditioning circuit modifies the frequency of the telemetry signal, normally using a voltage-to-frequency converter. In the receiver, a frequency-to-voltage converter performs the opposite function. A special case of frequency-based telemetry is pulse telemetry, in which the modulating signal changes some characteristics of a train of pulses. Because of its importance and widespread use, pulse telemetry will be analyzed in-depth in the following sections.

87.3 Multiple-Channel Telemetry

Most of the industrial processes in which telemetry is used require the measurement of different physical variables to control the process, the measurement of only one physical variable at different locations, or normally a combination of both. In these multiple-channel measurements, base-band telemetry is not an option, as it would require building a different system for each channel. Multiple channel telemetry is achieved by sharing a common resource (transmission channel), as is shown in Figure 87.4. The sharing of the transmission channel by all the measurement channels is designated by *multiplexing*. There are two basic multiplexing techniques: FDM and TDM. In FDM, different channels are assigned to different spectral bands and the composite signal is transmitted through the communication channel. In TDM, the information for different channels is transmitted sequentially through the communication channel.

Frequency Division Multiplexing

In FDM, shown in Figure 87.5a, each measurement channel modulates a sinusoidal signal of different frequency. These sinusoidal signals are called subcarriers. Each of the modulated signals is then low-pass-filtered to ensure that the bandwidth limits are observed. After the filtering stage, all the modulated signals are fed into a summing block, producing what is known as a base-band signal. A base-band signal indicates here that the final carrier has not yet been modulated. The spectrum of the base-band signal is shown in Figure 87.5b, where it is possible to see how each measurement channel spectrum signal is allocated its own frequency. This composite signal finally modulates a carrier signal whose frequency depends on the transmission medium that is used. The signal is then fed into a transmission wire (similar

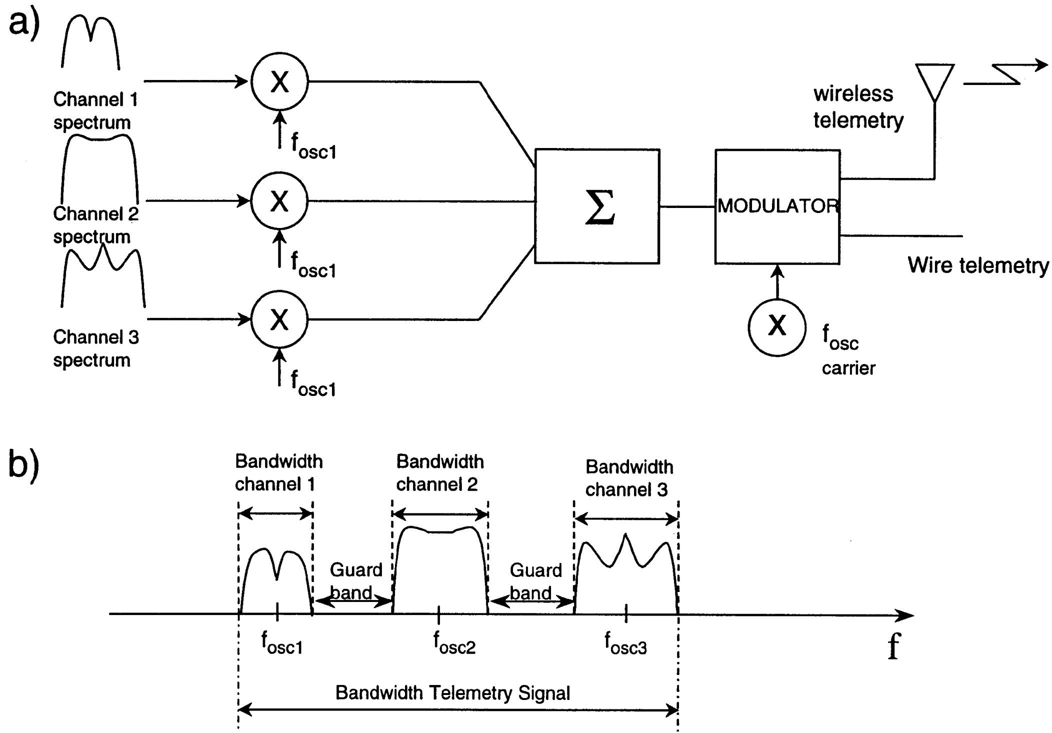

FIGURE 87.5 The different channels in an FDM system (a) are allocated at different subcarrier frequencies producing a composite signal shown in (b) that is later modulated by an RF frequency according to the transmission channel used. The guard bands limit the closeness of contiguous channels to avoid intermodulation and cross talk.

TABLE 87.1 Frequency Bands Allocated for Telemetry

Frequency band, MHz	Uses	Notes
72–76	Biotelemetry	Low power devices; restricted by Part 15 of FCC rules
88–108	Educational	Four frequencies in this band; part 90 of FCC rules
154	Industry	Band in TV channels 7–13
174–216	Biotelemetry	Low-power operations restricted to hospitals
216–222	Multiple	BW < 200 kHz
450–470	General	Telemetry as secondary basis; limited to 2 W of RF
467	Industry	Business band; limited to 2 W of RF
458–468	Biotelemetry	Band in TV channels 21–29
512–566	Biotelemetry	Low-power operations restricted to hospitals
1427–1435	Fixed	Uses in land mobile services (telemetering and telecommand)
1435–1535	Aeronautical	
2200–2290	Mobile	

to TV-broadcasting systems by cable) or, more commonly, into an antenna in the case of wireless telemetry systems. In wireless telemetry, the frequency of the carrier cannot be chosen arbitrarily, but is chosen in accordance with international agreements on the use of the electromagnetic spectrum. In the U.S., the Federal Communications Commission (FCC) is the body that regulates the allocation of frequencies for different communication services. Table 87.1 shows the most common telemetry frequency bands and their intended use. Table 87.1 is for informational purposes only, and it is not a comprehensive guide to telemetry frequencies. To find the allowed telemetry frequencies for a specific application, the maximum power allowed, and other limitations, the reader should consult the applicable FCC documents [7,8].

The allocation of bands is a process subject to change. For example, in October 1997 the FCC assigned some of the TV channel bands for patient telemetry inside hospitals, with restricted power. The FCC publishes all changes that affect frequency bands or other technical characteristics for telemetry.

At the receiver end, the carrier demodulator detects and recovers the composite base-band signal. The next step is to separate each of the subcarriers, by feeding the signal into a bank of parallel passband filters. Each channel is further demodulated, recovering the information from the transducer. The main practical problem of FDM systems is the cross talk between channels. Cross talk appears due to the nonlinearities of the electronic devices, which originates when the signal for one channel partially modulates another subcarrier in addition to the one assigned to that channel. Cross talk also originates when the spectra for two adjacent channels overlap. To avoid this effect, the subcarriers have to be chosen so that there is a separation (guard band) between the spectra of two contiguous channels. By increasing the guard band, the possibility of cross talk decreases, but the effective bandwidth also increases. The effective bandwidth equals the sum of the bandwidth of all channels, plus the sum of all the guard bands.

There are three alternative methods for each of the two modulation processes: the modulation of the measurement channel signals and the modulation of the composite signal. These methods are amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). The usual combinations are FM/FM, FM/PM, or AM/FM [6]. Here, we will analyze only on the subcarrier modulation schemes, while the modulation for the RF signal is analyzed in Chapter 81.

Subcarrier Modulation Schemes for Frequency Division Multiplexing

Subcarrier Modulation of Amplitude.

In an AM subcarrier modulation scheme, the amplitude of a particular subcarrier signal is changed according to the value of the measured channel assigned to that frequency. The resulting AM signal is given by

$$v(t) = A_c\left[1 + m(t)\right]\cos\left(\omega_c t\right)$$

where A_c is the amplitude of the carrier, $m(t)$ the modulating signal, and ω_c the frequency of the carrier.

The advantage of this type of modulation is the simplicity of the circuits that perform the modulation and the circuits required for the demodulation, in order to recover the modulating signal that carries the desired information. The percentage of modulation denotes the extent to which a carrier has been amplitude modulated. Assuming for simplicity that the modulating signal is sinusoidal of frequency ω_m, such as

$$m(t) = m \times \cos\left(\omega_m t\right)$$

the percentage of modulation (P) can be found as

$$P = m \times 100\ (\%)$$

In a more general way, the percentage of modulation (P) is expressed as

$$\frac{P}{100\%} = \frac{A_{c(\max)} - A_{c(\min)}}{2A_c}$$

where $A_{c(\max)}$ and $A_{c(\min)}$ are the maximum and minimum values that the carrier signal achieves.

Figure 87.6 shows the spectrum of an amplitude-modulated signal, assuming that the modulating signal is a band-limited, nonperiodic signal of finite energy. Figure 87.6 shows that it consists of two

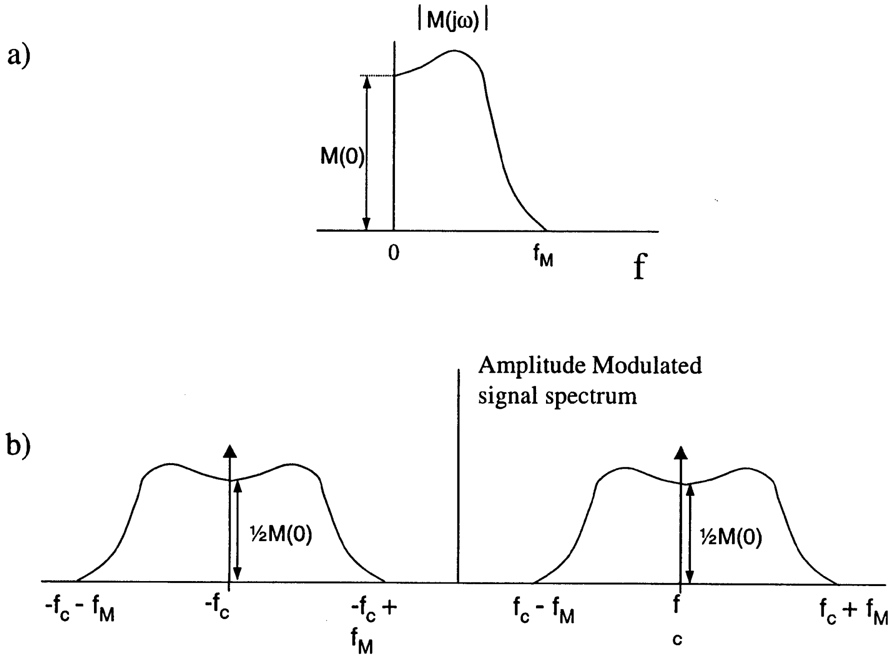

FIGURE 87.6 Resulting spectrum after amplitude modulation of a signal shown in (a). The resulting spectrum has doubled the required bandwidth, while only 0.25 of the total power is used in transmitting the desired information.

sidebands that are symmetrical in reference to the subcarrier. Figure 87.6 shows the main disadvantages of AM schemes. First, the bandwidth of the modulated channel is two times the bandwidth of the modulating signal, due to the two similar sidebands that appear. This results in an inefficient use of the spectrum. Second, the analysis of power for each of the components in Figure 87.6 shows that at least 50% of the transmitted power is used in transmitting the subcarrier, which is independent of the measured signal, as it does not contain any information. The remaining power is split between the two sidebands, which results in a maximum efficiency that it is theoretically possible to achieve of below 25%. The third main problem of AM is the possibility of overmodulation, which occurs when $m > 1$. Once a signal is overmodulated, it is not possible to recover the modulating signal with the simple circuits that are widely used for AM telemetry transmission.

The limitations of AM subcarrier modulation can be overcome using more efficient modulation techniques, such as double sideband (DSB), single sideband (SSB), and compatible single sideband (CSBB), which are also considered AM techniques. However, the complexity of these modulation systems and the cost associated with systems capable of recovering subcarrier signals modulated this way cause these not to be used in most commercial telemetry systems. Most of the available systems that use AM subcarrier techniques, use the traditional AM that has been described here, because its simplicity overcomes the possible problems of its use.

Subcarrier Modulation of Frequency.

FM (or PM) is by far the most-used subcarrier modulation scheme in FDM telemetry systems. These angle modulations are inherently nonlinear, in contrast to AM. Angle modulation can be expressed as

$$v(t) = A\cos\left[\omega_c t + \phi(t)\right]$$

where $\phi(t)$ is the modulating signal, that is, the signal from the transducers after conditioning.

It is then possible to calculate the value of the instantaneous frequency as

$$f = \frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}t}\left[\omega_c t + \phi(t)\right] = \frac{\omega_c}{2\pi} + \frac{\mathrm{d}}{\mathrm{d}t}\phi(t)$$

This equation shows how the signal $v(t)$ is modulated in frequency. We can analyze two parameters that can be derived from the previous equations: frequency deviation and modulation index. Frequency deviation (f_m) is the maximum departure of the instantaneous frequency from the carrier frequency. The modulation index (β) is the maximum phase deviation. The following equations show how these parameters are related. The value of the instantaneous frequency (f) is [9]

$$f = \frac{\omega_c}{2\pi} + \frac{\beta\,\omega_m}{2\pi}\cos\left(\omega_m t\right) = f_c + \beta\, f_m \cos\left(\omega_m t\right)$$

The maximum frequency deviation is Δf and is given by

$$\Delta f = \beta f_m$$

Therefore, we can write the equation for the frequency modulated signal as

$$v(t) = A\cos\left[\omega_c t + \frac{\Delta f}{f_m}\sin\left(\omega_m t\right)\right]$$

The previous equation shows that the instantaneous frequency, f, lies in the range $f_c \pm \Delta f$. However, it does not mean that all the spectral components lie in this range. The spectrum of an angle-modulated waveform cannot be written as a simple equation. In the most simple case, when the modulating signal is a sinusoidal signal, a practical rule states that the bandwidth of an FM signal is twice the sum of the maximum frequency deviation and the modulating frequency. For modulating signals commonly found in measuring systems, the bandwidth is dependent upon the modulation index; that is, as the bandwidth allocated for each channel is limited, the modulation index will also be limited.

Frequency Division Multiplexing Telemetry Standards

IRIG Standard 106-96 is the most used for military and commercial telemetry, data acquisition, and recording systems by government and industry worldwide [10]. It recognizes two types of formats for FM in FDM systems: proportional-bandwidth modulation (PBW) and constant-bandwidth modulation (CBW). It also allows the combination of PBW and CBW channels. In PBW, the bandwidth for a channel is proportional to the subcarrier frequency. The standard recognizes three classes of subcarrier deviations: 7.5, 15, and 30%. There are 25 PBW channels with a deviation frequency of 7.5%, numbered 1 to 25. The lowest channel has a central frequency of 400 Hz, which means that the lower deviation frequency is 370 Hz and the upper deviation frequency is 430 Hz. The highest channel (channel 25) has a center frequency of 560,000 Hz (deviation from 518,000 to 602,000 Hz). The center frequencies have been chosen so that the ratio between the upper deviation limit for a given channel and the lower deviation limit for the next channel is around 1.2. There are 12 PBW channels with a deviation frequency of 15%, identified as A, B, … L. The center frequency for the lowest channel is 22,000 Hz (deviation from 18,700 Hz to 25,300 Hz), while the center frequency for the highest channel is 560,000 Hz (476,000 to 644,000 Hz), with a ratio for the center frequencies of adjacent channels being about 1.3. There are also 12 PBW channels for a deviation frequency of 30%, labeled from AA, BB, … to LL. The center frequency for these channels is the same as that for the 15% channels.

TABLE 87.2 Characteristics of Constant Bandwidth (CBW) Channels for FDM

Channel Denomination	Frequency Deviation, kHz	Lowest Channel Center Frequency, kHz	Highest Channel Center Frequency, kHz	No. of Channels	Separation between Channels, kHz
A	±2	8	176	22	8
B	±4	16	352	22	16
C	±8	32	704	22	32
D	±16	64	1408	22	64
E	±32	128	2816	22	128
F	±64	256	3840	15	256
G	±128	512	3584	7	512
H	±256	1024	3072	4	1024

CBW channels keep the bandwidth constant and independent of its carrier frequency. There are eight possible maximum subcarrier frequency deviations labeled A (for 2 kHz deviation) to H (for 256 kHz deviation). The deviation frequency doubles from one group to the next. There are 22 A-channels, whose center frequency range from 8 to 176 kHz. The separation between adjacent channels is a constant of 8 kHz. Table 87.2 shows a summary of the characteristics of CBW channels.

IRIG Standard 106-96 gives in its appendix criteria for the use of the FDM Standards. It focuses on the limits, most of the time dependent on the hardware used, and performance trade-offs such as data accuracy for data bandwidth that may be required in the implementation of the system. The subcarrier deviation ratio determines the SNR for a channel. As a rule of thumb, the SNR varies as the three-halves power of the subcarrier deviation ratio. On the other hand, the number of subcarrier channels that can be used simultaneously to modulate an RF carrier is limited by the channel bandwidth of the RF carrier as well as considerations of SNR. Given a limited RF bandwidth, as more channels are added to the FDM system, it is necessary to reduce the deviation ratio for each channel, which reduces the SNR for each channel. It is then very important to evaluate the acceptable trade-off between the number of subcarrier channels and the acceptable SNR values. A general equation that might be used to estimate the thermal noise performance of an FM/FM channel is the following [11]:

$$\left(\frac{S}{N}\right)_{\mathrm{d}} = \left(\frac{S}{N}\right)_{\mathrm{c}} \left(\frac{3}{4}\right)^{1/2} \left(\frac{B_{\mathrm{c}}}{F_{\mathrm{ud}}}\right) \left(\frac{f_{\mathrm{dc}}}{f_{\mathrm{s}}}\right) \left(\frac{f_{\mathrm{ds}}}{F_{\mathrm{ud}}}\right)$$

where $(S/N)_{\mathrm{d}}$ represents the SNR at the discriminator output, $(S/N)_{\mathrm{c}}$ represents the SNR of the receiver, B_{c} is the intermediate-frequency bandwidth of the receiver, F_{ud} is the subcarrier discriminator output filter (at –3 dB), f_{s} is the subcarrier center frequency, f_{dc} is the carrier peak deviation for the subcarrier considered, and f_{ds} is the subcarrier peak deviation.

According to the Standard, the FM/FM composite FDM signal that is used to modulate an RF carrier can be of PBW format, CBW format, or a combination of both, with the only limitation that the guard bands between the channels used in the mixed format are equal or greater than the guard bands for the same channels in an unmixed format.

Time Division Multiplexing

TDM is a transmission technique that divides the time into different slots, and assigns one slot to each measurement channel. In TDM, all the transmission bandwidth is assigned entirely to each measurement channel during a fraction of the time. After the signals from the measurement channels have been low-pass filtered, they are sequentially sampled by a digital switch that samples all the measurement channels in a period of time (T) that complies with the Nyquist criteria. Figure 87.7a shows a basic block diagram for an FDM system. The output of the sampler is a train of AM pulses that contains the individual samples for the channels framed periodically, as is shown in Figure 87.7b. Finally, the composite signal modulates an RF carrier. The set of samples from each one of the input channels is called a frame. For

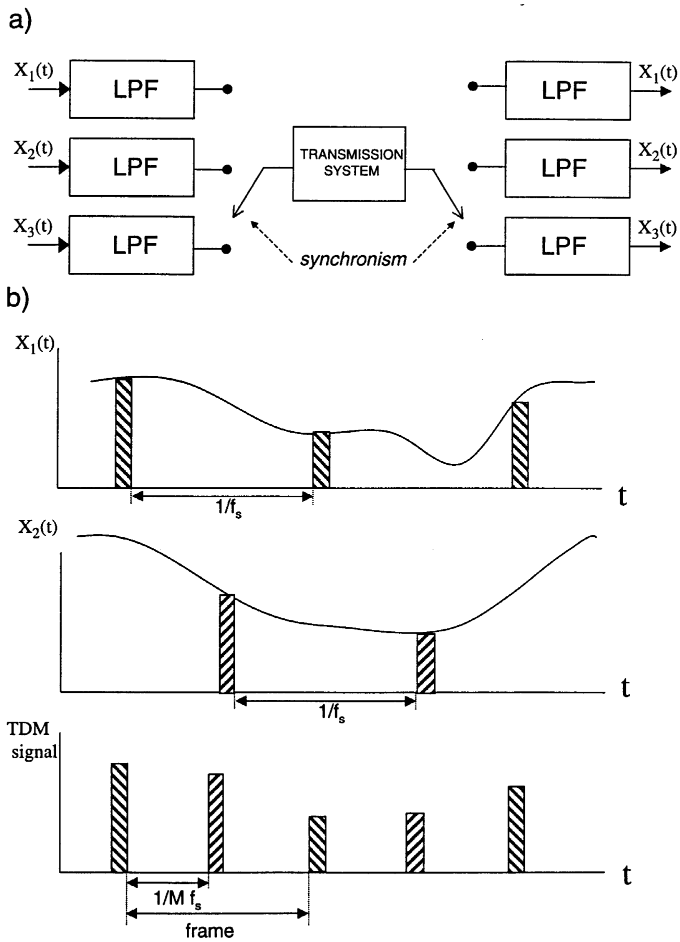

FIGURE 87.7 TDM systems (a) are based on sequentially sampling *M* different channels at a sampling frequency f_s, and sending the information for each channel sequentially (b). In TDM, the synchronism between transmitter and receiver is critical to recovery of the sampled signal. In this figure, the TDM signal is made of only two channels to increase readability. The blocks labeled LPF represent low-pass filters.

M measurement channels, the period between two consecutive pulses is $T_s/M = 1/Mf_s$, where T_s is the sampling period. The period between samples from the same channel is T_s. At the receiver end, by separating the digital signals into different channels by a synchronized demultipler and by low-pass filtering, it is possible to recover the original signal for each measurement channel.

TDM systems have advantages over FDM systems. First, FDM requires subcarrier modulators and demodulators for each channel, whereas in TDM only one multiplexer and demultiplexer are required. Second, TDM signals are resistant to the error sources that originate cross talk in FDM: nonideal filtering and cross modulation due to nonlinearities. In TDM, the separation between channels depends on the sampling system. However, because it is impossible in practice to produce perfectly square pulses, their rise and fall times are different from zero. It is then necessary to provide guard time between pulses, similar to the band guards in FDM systems. Cross talk in TDM can be easily estimated assuming that the pulse decay is exponential with a time constant (τ) approximately equal to

$$\tau = \frac{1}{2\pi B}$$

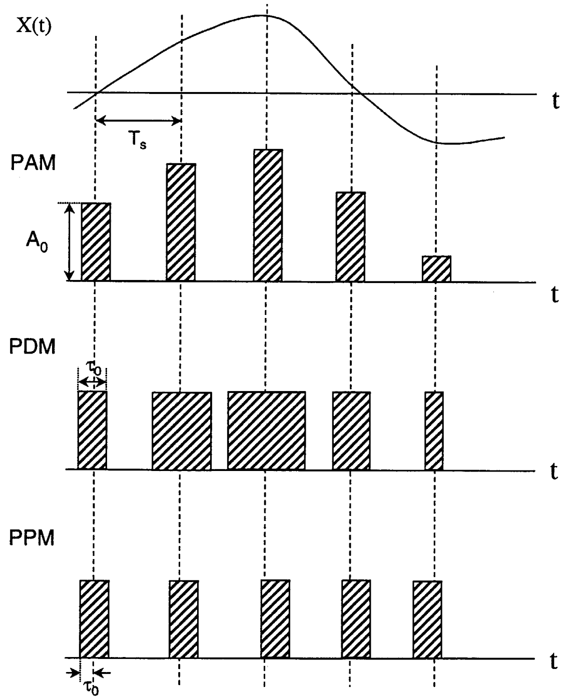

FIGURE 87.8 Different analog modulation schemes used in TDM. The variations in amplitude of the signal $x(t)$ are transmitted as amplitude variations of pulses (PAM), duration changes of pulses (PDM), or changes in the relative position of the pulses (PPM). In all the cases, the level 0 is transmitted by a pulse whose amplitude (A_0), duration (τ_0), or relative position (τ_0) is different from 0.

where B is the –3 dB channel bandwidth. The cross talk (k) between channels can be approximated as

$$k = -54.5 T_g \,(\text{dB})$$

where T_g is the minimum time separation between channels, called guard time.

A common situation in measurement systems occurs when the M signals that need to be measured have very different speeds. The channel sampling rate is determined by the fastest signal, thus needing an M-input multiplexer capable of handling signals at that sampling frequency. A convenient solution is to feed several slow signals into one multiplexer, then combine its output with the fast signal in a second multiplexer [6].

Analog Subcarrier Modulation Schemes for Time Division Multiplexing

In analog modulation for subcarriers the signal that results after the multiplexing and sampling process modulates a train of pulses. The most common methods for analog subcarrier modulation are pulse amplitude modulation (PAM), pulse duration modulation (PDM), and pulse position modulation (PPM). Figure 87.8 illustrates these three modulation schemes, where the pulses are shown square for simplicity. In analog modulation, the parameter that is modulated (amplitude, duration, or relative position) changes proportionally to the amplitude of the sampled signal. However, in PAM and PDM the values have an offset, so that when the value of the sample is zero, the pulse amplitude or the pulse width is different from zero. The reason for these offsets is to maintain the rate of the train of pulses constant, which is very important for synchronization purposes. The common characteristics of the different analog modulation schemes for pulses in TDM are (1) a modulated signal spectrum with a large low-frequency content, especially close to the sampling frequency; (2) the need to avoid overlaying

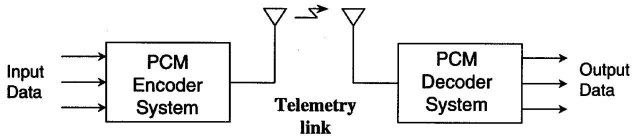

FIGURE 87.9 Block diagram showing a basic PCM link for telemetry.

between consecutive pulses in order to conserve the modulation parameters; and (3) the possibility of reconstructing the original samples from the modulated signal through low-pass filtering after demultiplexing. The reduction of noise depends on the bandwidth of the modulated signal, with this being the principal design criterion.

Pulse Amplitude Modulation.
PAM waveforms are made of unipolar, nonrectangular pulses whose amplitudes are proportional to the values of the samples. It is possible to define the modulation index using similar criteria as in analog AM. Similarly, in PAM the modulation index is limited to values less than 1.

Pulse Duration Modulation.
PDM is made of unipolar, rectangular pulses whose durations or widths depend on the values of the samples. The period between the center of two consecutive pulses is constant. The analysis of the resulting spectrum shows that it is possible to reconstruct the samples by low-pass filtering [9].

Pulse Position Modulation.
PPM is closely related to PDM, as PPM can be generated through PDM. In PPM the information resides on the time location of the pulses rather than in the pulses by themselves. It is then possible to transmit very narrow pulses to reduce the energy needed; this energy reduction is the most important advantage of PPM.

Pulse Code Modulation for Time Division Multiplexing.
All the previously analyzed subcarrier modulation schemes in telemetry systems are based on an analog signal that modulates either an analog carrier or a train of pulses. Pulse code modulation (PCM) is different: it is a digital modulation in which the measured signal is represented by a group of codified digital pulses. Two variations of PCM that are also often used are delta modulation (DM) and differential pulse code modulation (DPCM). In analog modulation schemes, the modulating signal from the transducer can take any value between the limits. If noise alters the modulating signal, it is impossible to decide its real value. Instead, if not all the values in the modulating signal are allowed, and the separation between the allowed levels is higher than the expected noise values, it is then possible to decide which were the values sent by the transmitter. This immunity against noise makes PCM systems one of the preferred alternatives for telemetry. Figure 87.9 shows the basic elements of a PCM telemetry system. A PCM encoder (or PCM commutator) converts the input data into a serial data format suitable for transmission through lines by wireless techniques. At the receiving end, a PCM decoder (or PCM decommutator) converts the serial data back into individual output data signals. PCM systems transmit data as a serial stream of digital words. The PCM encoder samples the input data and inserts the data words into a PCM frame. Words are assigned specific locations in the PCM frame, so the decoder can recover the data samples corresponding to each input signal. The simplest PCM frame consists of a frame synchronization word followed by a string of data words. The frame repeats continually to provide new data samples as the input data change. Frame synchronization enables the PCM decoder to locate the start of each frame easily.

Pulse Code Modulation Telemetry Standards.
IRIG Standard 106-96 also defines the characteristics of PCM transmission for telemetry purposes, in particular, the pulse train structure and system design characteristics. The PCM formats are divided into two classes for Standards purposes: class I and class II. The simpler types are class I, whereas the more

TABLE 87.3 Summary of the Most Relevant PCM Specifications According to IRIG 106-96

Specification	Class I	Class II
Class format support	Class I (simple formats) supported on all ranges	Class II (complex formats) requires concurrence of range involved
Primary bit representation (PCM codes)	NRZ-L, NRZ-M, NRZ-S, RNRZ-L, BiØ-L, BiØ-M, BiØ-S	Same as class II
Bit rate	10 bps to 5 Mbps	10 bps to > 5 Mbps
Bit rate accuracy and stability	0.1%	Same as class I
Bit jitter	0.1 bit	Same as class I
Bit numbering	MSB = bit number 1	Same as class I
Word length	4 to 16 bits	4 to 64 bits
Fragmented words	Not allowed	Up to 8 segments each; all segments in the same minor frame
Minor frame length	<8192 bits or <1024 words (includes synchro)	<16,384 bits (includes synchro
Major frame length	<256 minor frames	Same as class I
Minor frame numbering	First minor frame in each major frames in number 1	Same as class I
Format change	Not allowed	Frame structure is specified by frame format identification (FFI) word in every minor frame

complex types are class II. Some of the characteristics of class II systems are bit rates greater than 5 Mbit/s, word lengths in excess of 16 bits, fragmented words, unevenly spaced subcommutation, format changes, tagged data formats, asynchronous data transmission, and merger of multiple format types, among others. Table 87.3 provides a brief summary of relevant PCM specifications. Readers interested in the detailed specifications and descriptions should refer to Chapter 4 of the IRIG 106-96 Standard [10].

The following PCM codes, shown in Figure 87.10, are recognized by the IRG Standards: NRZ-L (nonreturn to zero — level), NRZ-M (nonreturn to zero — mark), NRZ-S (nonreturn to zero — space), BiØ-L (Biphase — level), BiØ-M (Bi-Phase — mark) and BiØ-S (Biphase — space). The Standard also recommends that the transmitted bit stream be continuous and contain sufficient transitions to ensure bit acquisition and continued bit synchronization. Bit rates should be at least 10 bits/s. If the bit rate is above 5 Mbit/s, the PCM system is classified as class II. In reference to the word formats, the Standard defines a fixed format as one that does not change during transmissions with regard to the frame structure, word length or location, commutation sequence, sample interval, or measurement list. Individual words may vary in length from 4 bits to not more than 16 bits in class I and not more than 64 bits in class II. Fragmented words, defined as a word divided into not more than eight segments and placed in various locations within a minor frame, are only allowed in class II. All word segments used to form a data word are constrained to the boundaries of a single minor frame. The Frame Structure allowed by the Standards for PCM telemetry specifies that data are formatted into fixed frame lengths, that contain a fixed number of equal-duration bit intervals. A minor frame is defined as the data structure in time sequence from the beginning of a minor frame synchronization pattern to the beginning of the next minor frame synchronization pattern. The minor frame length is the number of bit intervals from the beginning of the frame synchronization pattern to the beginning of the next synchronization pattern. The maximum length of a minor frame will not exceed 8192 bits nor 1024 words in class I and will not exceed 16,384 bits in class II. Minor frames consist of the synchronization pattern, data words, and subframe synchronization words if they are used. The Standard allows the use of words of different length if they are multiplexed in a single minor frame. Figure 87.11 shows a graphical representation of a PCM frame structure. Major frames contain the number of minor frames required to include one sample of every parameter in the format. Their length is defined as minor frame length multiplied by the number of minor frames contained in the major frame. The maximum number of minor frames per major frame is limited to 256.

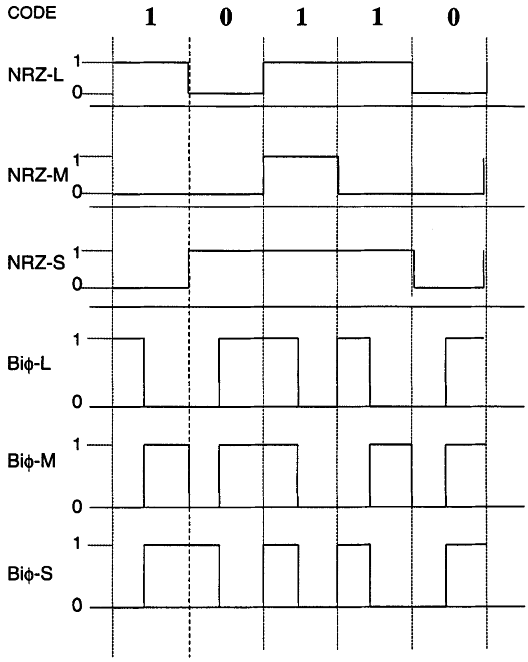

FIGURE 87.10 Different PCM codes. All lower levels in NRZ use a value different from zero. In biphase codes the information resides in the transitions rather than in the levels. In NRZ-L, a 1 is represented by the highest level, while a 0 is represented by a lower level. In NRZ-M, a 1 is represented by a change in level, while a 0 is represented by no change in level. In NRZ-S, a 1is represented by no change of level, while a 0 is represented by a change of level. In Biϕ-L, a 1 is represented by a transition to the lower level, while a 0 is represented by a transition to the higher level. In Biϕ-M, the 1 is represented by no change of level at the beginning of the bit period, while the 0 is represented by a change of level at the beginning of the bit period. In Biϕ-S, a 1 is represented by changing the level at the beginning of the bit period, while the 0 is represented by no change of level at the beginning of the bit period.

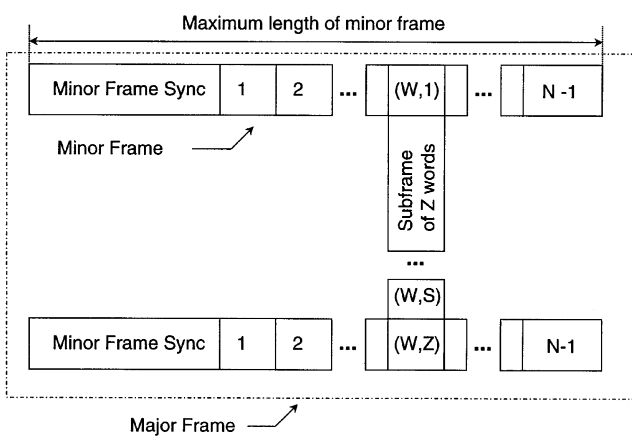

FIGURE 87.11 Structure of a PCM Frame. The maximum length of a minor frame is 8192 bits or 512 for class I and 16,284 bits for class II. A major frame contains $N \times Z$ words, where Z is the number of words in the maximum subframe, and N is the number of words in the minor frame. Regardless of its length, the minor frame synchronism is considered as one word. W is the word position in the minor frame, while S is the word position in the subframe.

Appendix C in the 106-96 IRIG Standard gives recommendations for maximal transmission efficiency in PCM telemetry. The intermediate-frequency (IF) bandwidth for PCM telemetry data receivers should be selected so that 90 to 99% of the transmitted power spectrum is within the receiver 3-dB bandwidth. The IF also has effects on the bit error probability (BEP) according to the following equation for NRZ-L PCM/FM [10]:

$$\text{BEP} = 0.5\text{e}^{(k\,\text{SNR})}$$

where $k \approx -0.7$ for IF bandwidth equal to bit rate

$k \approx -0.65$ for IF bandwidth equal to 1.2 times bit rate

$k \approx -0.55$ for IF bandwidth equal to 1.5 times bit rate

Other data codes and modulation techniques have different BEP vs. SNR performance characteristics, but in any case they will have similar trends.

The Standard also specifies the recommended frame synchronization patterns for general use in PCM telemetry. There are different lengths for synchronization patterns, but in all of them the 111 is the first bit sequence transmitted. The patterns for lengths 16 to 30 were selected in order to minimize the probability of false synchronization over the entire pattern overlap portion of the ground station frame synchronization [12]. The spectral density (S) for the NRZ and BiØ codes are

$$\text{NRZ Codes} \qquad S = \frac{\sin^2(\pi f T)}{(\pi f T)^2}$$

$$\text{Biphase Codes} \qquad S = \frac{\sin^4(\pi f T/2)}{(\pi f T/2)^4}$$

The calculation of spectral densities allows the determination of the BEP for the previous type of codes assuming perfect bit synchronization. These calculations show that for the same SNR, the lowest BEP is achieved for NRZ-L and Bi codes, followed by NRZ and BiØ mark and space codes and finally for random NRZ-L codes (RNRZ-L).

Telemetry data are usually recorded onto magnetic tape for later analysis. When recording PCM data, it is important to ensure that the tape recorder provides sufficient frequency response to capture and reproduce the PCM signal. Useful rules to calculate the maximum bit rate for various PCM codes specify that for NRZ and RNRZ codes the maximum bit rate is 1.4 times the tape recorder frequency response while for all biphase codes, the maximum rate is 0.7 times the tape recorder response. To limit the transmission bandwidth that PCM creates because it is a digital signal with sharp transitions, the PCM signal is usually passed through a premodulation filter before it is fed into the transmitter input. The filter cutoff frequency can be calculated as 0.7 times the PCM bit rate for NRZ and RNRZ codes and 1.4 times the PCM bit rate for all biphase codes.

Defining Terms

Bandwidth: The range of frequencies occupied by a signal.

Carrier: A frequency that is modulated by a signal containing information.

Channel: A subcarrier that carries information.

Constant bandwidth (CBW) channel: A channel whose bandwidth is independent of its carrier frequency.

Deviation ratio: The ratio of the maximum carrier frequency deviation to the maximum data frequency deviation.

Frequency deviation: The difference between the center frequency of a carrier and its upper or lower deviation limit.

Frequency division multiplexing (FDM): A composite signal consisting of a group of subcarriers arranged so that their frequencies do not overlap or interfere with each other.

Frequency response: The highest data frequency that can be carried by the channel.

IRIG: Inter-Range Instrumentation Group of the Range Commanders Council (RCC).

Proportional bandwidth (PBW) channel: A channel whose bandwidth is proportional to its carrier frequency.

Remote switching: Telemetry consisting only of yes/no or on/off orders.

Signaling: Telemetry consisting of binary information.

Subcarrier: A carrier combined with other carriers to create a composite signal.

Subcarrier bandwidth: The difference between the upper and lower frequencies of a modulated carrier.

References

1. B.P. Dagarin, R.K. Taenaka, and E.J. Stofel, Galileo probe battery system, *IEEE Aerospace Electron. Syst. Mag.*, 11 (6): 6–13, 1996.
2. M.W. Pollack, Communications-based signaling: advanced capability for mainline railroads, *IEEE Aerospace Electron. Syst. Mag.*, 11 (11): 13–18, 1996.
3. M.C. Shults, R.K. Rhodes, S.J. Updike, B.J. Gilligan, and W.N. Reining, A telemetry-instrumentation system for monitoring multiple subcutaneously implanted glucose sensors, *IEEE Trans. Biomed. Eng.* 41: 937–942, 1994.
4. M. Rezazadeh and N.E. Evans, Multichannel physiological monitor plus simultaneous full-duplex speech channel using a dial-up telephone line, *IEEE Trans. Biomed. Eng.*, 37: 428–432, 1990.
5. Y.S. Trisno, P. Hsieh, and D. Wobschall, Optical pulses powered signal telemetry system for sensor network application, *IEEE Trans. Instrum. Meas.*, 39: 225–229, 1990.
6. R. Pallás-Areny and J.G. Webster, *Sensors and Signal Conditioning*, New York: John Wiley & Sons, 1991, 352–379.
7. Part 90: Private land mobile radio services. Subpart J: Non voice and other specialized operations (Sec. 90.238: Telemetry), *Code of Federal Regulations*, Title 47, Telecommunication. Chapter I: Federal Communications Commission.
8. Part 15: Radio frequency devices, *Code of Federal Regulations*, Title 47, Telecommunication. Chapter I: Federal Communications Commission.
9. H. Taub and D. L. Schilling, *Principles of Communication Systems*, 2nd ed., New York: McGraw-Hill, 1986.
10. IRIG, *Telemetry Standard IRIG 106-96*, Range Commander Council, U.S. Army White Sands Missile Range, 1996.
11. K. M. Uglow, Noise and bandwidth in FM/FM radio telemetry, *IRE Trans. Telemetry Remote Control*, 19–22, 1957.
12. J.L. Maury and J. Styles, Development of optimum frame synchronization codes for Goddard space flight center PCM telemetry standards, *Proc. Natl. Telemetering Conf.*, 1964.

Further Information

E. H. Higman, Pneumatic instrumentation, in B.E. Noltingk, Ed., *Instrument Technology: Instrumentation Systems*, Vol. 4, London: Butterworths, 1987.

C.H. Hoeppner, Telemetry, in R. C. Dorf, Ed., *The Electrical Engineering Handbook*, Boca Raton, FL: CRC Press, 1993.

R.S. Mackay, *Bio-Medical Telemetry*, 2nd ed., Piscataway, NJ: IEEE Press, 1993.

Telemetry Group, *Test Methods for Telemetry Systems and Subsystems. Document 118-97*, Range Commanders Council, U.S. Army White Sands Missile Range, 1997.

Telemetry Group, *Telemetry Applications Handbook Document 119-88*, Range Commanders Council, U.S. Army White Sands Missile Range, 1988.