Then the probability density function (PDF) of n can be written as

$$p(n) = \frac{1}{\sqrt{\pi N_o}} \exp\{-\frac{n^2}{N_o}\} \tag{1.9}$$

This result will be frequently used in this book.

Strictly speaking, the AWGN channel does not exist since no channel can have an infinite bandwidth. However, when the signal bandwidth is smaller than the channel bandwidth, many practical channels are approximately an AWGN channel. For example, the line-of-sight (LOS) radio channels, including fixed terrestrial microwave links and fixed satellite links, are approximately AWGN channels when the weather is good. Wideband coaxial cables are also approximately AWGN channels since there is no other interference except the Gaussian noise.

In this book, all modulation schemes are studied for the AWGN channel. The reason of doing this is two-fold. First, some channels are approximately an AWGN channel, the results can be used directly. Second, additive Gaussian noise is ever present regardless of whether other channel impairments such as limited bandwidth, fading, multipath, and other interferences exist or not. Thus the AWGN channel is the best channel that one can get. The performance of a modulation scheme evaluated in this channel is an upper bound on the performance. When other channel impairments exist, the system performance will degrade. The extent of degradation may vary for different modulation schemes. The performance in AWGN can serve as a standard in evaluating the degradation and also in evaluating effectiveness of impairment-combatting techniques.

1.2.2 Bandlimited Channel

When the channel bandwidth is smaller than the signal bandwidth, the channel is bandlimited. Severe bandwidth limitation causes intersymbol interference (ISI) (i.e., digital pulses will extend beyond their transmission duration (symbol period T_s)) and interfere with the next symbol or even more symbols. The ISI causes an increase in the bit error probability (P_b) or bit error rate (BER), as it is commonly called. When increasing the channel bandwidth is impossible or not cost-efficient, channel equalization techniques are used for combatting ISI. Throughout the years, numerous equalization techniques have been invented and used. New equalization techniques are appearing continuously. We will not cover them in this book. For introductory treatment of equalization techniques, the reader is referred to [1, Chapter 6] or any other communication systems books.

1.2.3 Fading Channel

Fading is a phenomena occurring when the amplitude and phase of a radio signal change rapidly over a short period of time or travel distance. Fading is caused by interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times. These waves, called multipath waves, combine at the receiver antenna to give a resultant signal which can vary widely in amplitude and phase. If the delays of the multipath signals are longer than a symbol period, these multipath signals must be considered as different signals. In this case, we have individual multipath signals.

In mobile communication channels, such as terrestrial mobile channel and satellite mobile channel, fading and multipath interference are caused by reflections from surrounding buildings and terrains. In addition, the relative motion between the transmitter and receiver results in random frequency modulation in the signal due to different Doppler shifts on each of the multipath components. The motion of surrounding objects, such as vehicles, also induces a time-varying Doppler shift on multipath component. However, if the surrounding objects move at a speed less than the mobile unit, their effect can be ignored [2].

Fading and multipath interference also exist in fixed LOS microwave links [3]. On clear, calm summer evenings, normal atmospheric turbulence is minimal. The troposphere stratifies with inhomogeneous temperature and moisture distributions. Layering of the lower atmosphere creates sharp refractive index gradients which in turn create multiple signal paths with different relative amplitudes and delays.

Fading causes amplitude fluctuations and phase variations in received signals. Multipath causes intersymbol interference. Doppler shift causes carrier frequency drift and signal bandwidth spread. All these lead to performances degradation of modulations. Analysis of modulation performances in fading channels is given in Chapter 10 where characteristics of fading channels will be discussed in more detail.

1.3 BASIC MODULATION METHODS

Digital modulation is a process that impresses a digital symbol onto a signal suitable for transmission. For short distance transmissions, baseband modulation is usually used. Baseband modulation is often called line coding. A sequence of digital symbols are used to create a square pulse waveform with certain features which represent each type of symbol without ambiguity so that they can be recovered upon reception. These features are variations of pulse amplitude, pulse width, and pulse position. Figure 1.3 shows several baseband modulation waveforms. The first one is the non-return to zero-level (NRZ-L) modulation which represents a symbol 1 by a positive

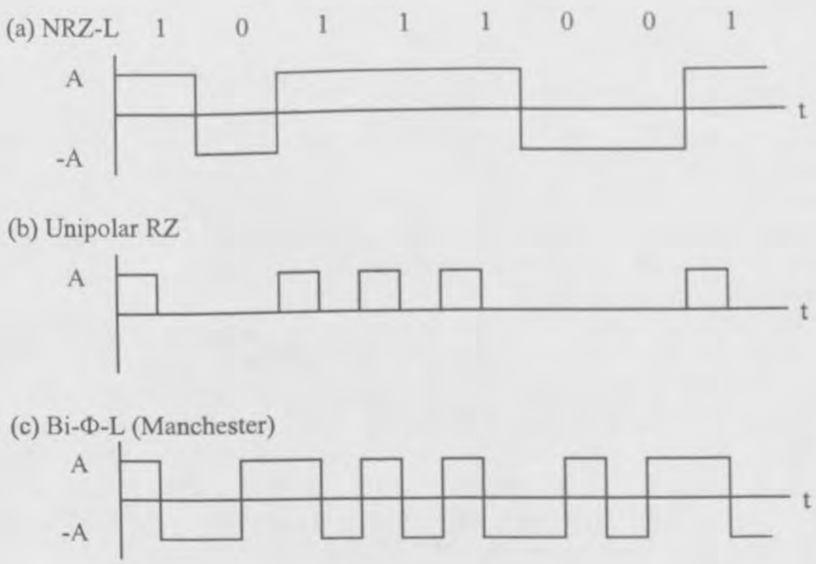

Figure 1.3 Baseband digital modulation examples.

square pulse with length T and a symbol 0 by a negative square pulse with length T. The second one is the unipolar return to zero modulation with a positive pulse of T/2 for symbol 1 and nothing for 0. The third is the biphase level or Manchester, after its inventor, modulation which uses a waveform consisting of a positive first-half T pulse and a negative second-half T pulse for 1 and a reversed waveform for 0. These and other baseband schemes will be discussed in detail in Chapter 2.

For long distance and wireless transmissions, bandpass modulation is usually used. Bandpass modulation is also called carrier modulation. A sequence of digital symbols are used to alter the parameters of a high-frequency sinusoidal signal called carrier. It is well known that a sinusoidal signal has three parameters: amplitude, frequency, and phase. Thus amplitude modulation, frequency modulation, and phase modulation are the three basic modulation methods in passband modulation. Figure 1.4 shows three basic binary carrier modulations. They are amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). In ASK, the modulator puts out a burst of carrier for every symbol 1, and no signal for every symbol 0. This scheme is also called on-off keying (OOK). In a general ASK scheme, the amplitude for symbol 0 is not necessarily 0. In FSK, for symbol 1 a higher frequency burst is transmitted and for symbol 0 a lower frequency burst

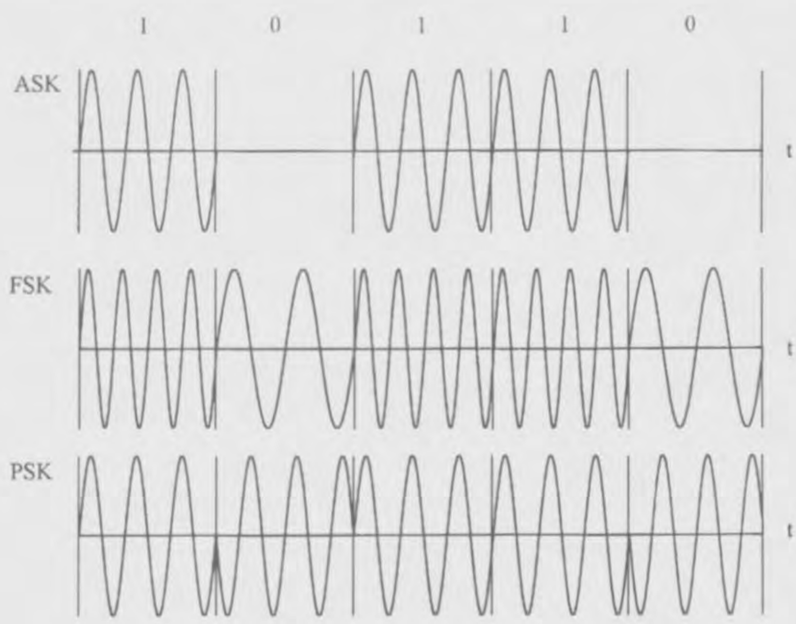

Figure 1.4 Three basic bandpass modulation schemes.

is transmitted, or vice versa. In PSK, a symbol 1 is transmitted as a burst of carrier with 0 initial phase while a symbol 0 is transmitted as a burst of carrier with 180° initial phase.

Based on these three basic schemes, a variety of modulation schemes can be derived from their combinations. For example, by combining two binary PSK (BPSK) signals with orthogonal carriers a new scheme called quadrature phase shift keying (QPSK) can be generated. By modulating both amplitude and phase of the carrier, we can obtain a scheme called quadrature amplitude modulation (QAM), etc.

1.4 CRITERIA OF CHOOSING MODULATION SCHEMES

The essence of digital modem design is to efficiently transmit digital bits and recover them from corruptions from the noise and other channel impairments. There are three primary criteria of choosing modulation schemes: power efficiency, bandwidth efficiency, and system complexity.

1.4.1 Power Efficiency

The bit error rate, or bit error probability of a modulation scheme is inversely related to E_b/N_o, the bit energy to noise spectral density ratio. For example, P_b of ASK in the AWGN channel is given by

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \tag{1.10}$$

where E_b is the average bit energy, N_o is the noise power spectral density (PSD), and $Q(x)$ is the Gaussian integral, sometimes referred to as the Q-function. It is defined as

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-u^2} du \tag{1.11}$$

which is a monotonically decreasing function of x. Therefore the power efficiency of a modulation scheme is defined straightforwardly as the required E_b/N_o for a certain bit error probability (P_b) over an AWGN channel. $P_b = 10^{-5}$ is usually used as the reference bit error probability.

1.4.2 Bandwidth Efficiency

The determination of bandwidth efficiency is a bit more complex. The bandwidth efficiency is defined as the number of bits per second that can be transmitted in one Hertz of system bandwidth. Obviously it depends on the requirement of system bandwidth for a certain modulated signal. For example, the one-sided power spectral density of an ASK signal modulated by an equiprobable independent random binary sequence is given by

$$\Psi_s(f) = \frac{A^2T}{4}\text{sinc}^2\left[T(f - f_c)\right] + \frac{A^2}{4}\delta(f - f_c)$$

and is shown in Figure 1.5, where T is the bit duration, A is the carrier amplitude, and f_c is the carrier frequency. From the figure we can see that the signal spectrum stretches from $-\infty$ to ∞. Thus to perfectly transmit the signal an infinite system bandwidth is required, which is impractical. The practical system bandwidth requirement is finite, which varies depending on different criteria. For example, in Figure 1.5, most of the signal energy concentrates in the band between two nulls, thus a null-to-null bandwidth requirement seems adequate. Three bandwidth efficiencies

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