ANALOG AND DIGITAL TRANSMISSION OF DATA

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Contents

1. Model of a Communication System
2. Analog Transmission
2.1 Amplitude Modulation
2.2 Angle Modulation
3. Pulse Modulation
3.1. Sampling Theorem
3.2. Pulse-Code Modulation
4. Data Transmission
4.1. Baseband Data Transmission
4.2. Passband DataTransmission
5. Spread-Spectrum Modulation
6. Multiplexing and Multiple Accessing
7. Conclusion
Glossary
Bibliography
Biographical Sketch

Summary

In this chapter, the author describes some important concepts dealing with analog and digital transmission techniques. Description of the analog techniques begins with what amplitude modulation is, and then moves on to describe variants of it, namely, double sideband-suppressed carrier modulation, single sideband modulation, and vestigial sideband modulation. Then, moving on to digital techniques, the chapter describes pulse-code modulation, followed by descriptions of amplitude-shift keying, phase-shift keying, and frequency-shift keying, and spread-spectrum modulation. A brief discussion of multiplexing and multiple-access techniques concludes the chapter.

1. Model of a Communication System

Figure 1 shows the block diagram of a communication system. The system consists of three major parts: (1) transmitter, (2) communication channel, and (3) receiver. The purpose of the transmitter is to change the message signal (supplied by an information source) into a form suitable for transmission over the channel. This modification is achieved by means of modulation. The channel may be a transmission line (as in telephony), optical filter (as in optical communications), or merely free space (as in wireless communications). In propagating through the channel, the transmitted signal is distorted because of possible nonlinearities or imperfections in the frequency response of the channel. Other sources of degradation are noise and interference picked up by the signal during the course of transmission through the channel. Noise and distortion constitute two basic problems in the design of transmission systems. Usually, the transmitter and receiver are carefully designed to minimize the effects of channel noise and distortion on the quality of reception. The purpose of the receiver is to reconstruct the original message signal from the received signal. This reconstruction is accomplished by a process known as *demodulation*, which is the reverse of the modulation process in the transmitter. However, owing to the unavoidable presence of noise and distortion in the received signal, the receiver cannot recreate the original message signal exactly. We therefore speak of the reconstruction as one of estimation, in the sense that the receiver produces an "estimate" of the message signal, optimized in some statistical sense.

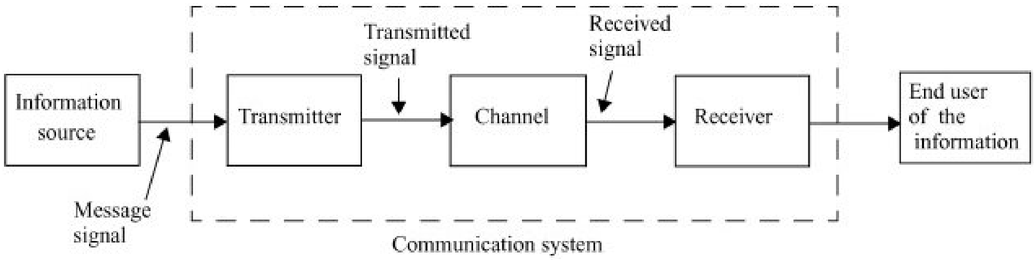

Figure 1. Model of an electrical communication system

In a communication system, typically there are two primary resources: *transmitted power*, and *channel bandwidth*. The design objective is therefore to use these two resources as efficiently as possible. With one resource considered to be more important than the other, we may classify communication channels as power-limited or band-limited. For example, a telephone channel is an example of *band-limited channel*, whereas a satellite channel is an example of *power-limited channel*.

2. Analog Transmission

Modulation, basic to the transmission of a message signal over a channel, is defined as the process by which some characteristic of a carrier is varied in accordance with a modulating wave. In analog modulation, the modulating wave consists of an analog message signal (e.g., voice signal, video signal), and the carrier consists of a sine wave. Basically, there are two types of analog modulation: amplitude modulation and angle modulation. In amplitude modulation, the amplitude of the sinusoidal carrier is varied in accordance with the message signal. In angle modulation, on the other hand, the angle of the sinusoidal carrier is varied in accordance with the message signal.

2.1 Amplitude Modulation

To describe amplitude modulation in analytic terms, define the sinusoidal carrier as

$$c(t) = A_c \cos(2\pi f_c t) \tag{1}$$

where A_c is the carrier amplitude and f_c is the carrier frequency. Let $m(t)$ denote the message signal. An *amplitude-modulated* (AM) *wave* is described by

$$s(t) = A_c[1 + k_a m(t)]\cos(2\pi f_c \ ) \tag{2}$$

where k_a defines amplitude sensitivity of the modulator. The envelope of the AM wave $s(t)$ is

$$a(t) = A_c[1 + k_a m(t)] \tag{3}$$

where | . | denotes the absolute value of the encoded quantity. The envelope of $s(t)$ has the same shape as the message signal $m(t)$, provided we satisfy two requirements:

1. $|k_a \ m(t)| < 1$ for all t

2. The carrier frequency f_c is large compared to the highest frequency component of $m(t)$.

Providing these two requirements are satisfied, we may use a simple device known as the *envelope detector* for recovery of the original message signal from an AM wave. The series type of envelope detector consists of 3 elements: diode, capacitor, and resistor. The resistor plays the role of a load, and the capacitor in parallel with it is included to suppress high-frequency components.

The spectrum of the AM wave $s(t)$ (i.e., the Fourier transform of $s(t)$) consists of a carrier, upper sideband, and lower sideband. Let W denote the highest frequency component of the message signal $m(t)$. For positive frequencies, the carrier is located at f_c, the upper sideband extends from f_c to $f_c + W$, and the lower sideband extends from $f_c - W$ to f_c. The transmission bandwidth of the AM wave is therefore $2W$.

Double-Sideband Suppressed-Carrier Modulation

The carrier $c(t)$ is usually independent of the message signal $m(t)$. This means that transmission of the carrier represents waste of power, which is a serious shortcoming of amplitude modulation, in that only a fraction of the total transmitted power is affected by $m(t)$. To overcome this shortcoming, $c(t)$ is suppressed from $s(t)$, resulting in *double-sideband suppressed-carrier (DSB-SC) modulation*, which is defined by

$$s(t) \ = \ c(t)m(t) \ = \ A_c \cos(2\pi f_c)m(t) \tag{4}$$

Note that unlike amplitude modulation, the envelope of a DSB-SC modulated wave is different from the message signal. To recover $m(t)$ from $s(t)$, we require the use of coherent detection. Specifically, to perform coherent detection, the receiver has to provide a local carrier that is synchronous to the carrier in the transmitter in both phase and frequency. Then multiplying the modulated signal $s(t)$ of Eq. (4) by the local carrier, denoted by $A'_c \cos(2\pi ft)$, and applying the resulting product signal to a low-pass filter with a cutoff frequency equal to the message bandwidth *W*, the receiver (in the absence of channel noise) produces an exact replica of the message signal except for a scaling factor, which is trivial.

Single-Sideband Modulation

Amplitude modulation and DSB-SC modulation share a common limitation: they both waste channel bandwidth. In either case, one-half of the transmission bandwidth is occupied by the upper sideband of the modulated wave, and the other half is occupied by the lower sideband. However, the upper and lower sidebands are uniquely related to each other by virtue of their symmetry about the carrier frequency; that is, given the amplitude and phase spectra of either sideband, we can uniquely determine the other. This means that insofar as information transmission is concerned, only one sideband is necessary. When the carrier and one sideband are suppressed at the transmitter, the scheme is referred to as *single-sideband (SSB) modulation*. Basically, the essential function of SSB modulation is to translate the spectrum of the modulating wave, either with or without inversion, to a new location in the frequency domain; the transmission bandwidth required is therefore one-half that of amplitude or DSB-SC modulation, that is, the transmission bandwidth is *W*. The benefit of using SSB modulation is therefore derived principally from the reduced bandwidth requirement and elimination of the high-power carrier wave. However, a disadvantage of SSB modulation is increased cost and complexity.

Vestigial Sideband Modulation

Single-sideband modulation is rather well suited for the transmission of voice because of the energy gap in the spectrum of voice signals between zero and a few hundred hertz. When the message signal contains significant components at extremely low frequencies (as in the case of television and computer data), however, the upper and lower side-bands meet at the carrier frequency. This means that the use of SSB modulation is inappropriate for the transmission of such information-bearing signals because of the practical difficulty of isolating one sideband. To overcome this difficulty, we may use another scheme known as *vestigial sideband* (VSB) modulation, which is a compromise between SSB and DSB-SC modulation. In this modulation scheme, one side-band is passed almost completely, whereas just a trace (vestige) of the other wideband is retained. The transmission bandwidth required by VSB modulation is therefore

$$B_T = W + f_V \qquad (5)$$

where W is the message bandwidth and f_{V} is the width of the vestigial sideband.

Vestigial sideband modulation has the virtue of conserving bandwidth almost as efficiently as SSB modulation, while retaining the excellent low-frequency characteristics of double-sideband modulation. Thus, VSB modulation has become standard for the analog transmission of television and similar signals where good phase characteristics and transmission of low-frequency components are important, but the bandwidth required for double-sideband transmission is unavailable or uneconomical.

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Biographical Sketch

Simon Haykin received his B.Sc. (First-class Honors), Ph.D., and D.Sc., all in Electrical Engineering from the University of Birmingham, England. He is the author of numerous books, including the most widely used books: Communication Systems (4th edition, Wiley), Adaptive Filter Theory (4th edition, Prentice-Hall), Neural Networks: A Comprehensive Foundation (2nd edition, Prentice-Hall) and the about to be published new book on Adaptive Radar: Signal Processing (Wiley), as well as numerous refereed journal papers. He is a Fellow of the Royal Society of Canada, recipient of the Honorary Degree of Doctor of Technical Sciences from ETH, Zurich, Switzerland, and the Henry Booker Gold Medal from URSI, as well as other prizes and awards. Currently, he holds the title "Distinguished University Professor" in the ECE Department at McMaster University, Canada.