

Bruce R. Elbert



INTRODUCTION TO
SATELLITE
COMMUNICATION

THIRD EDITION

Introduction to Satellite Communication

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two classes of techniques: private key encryption, of which the Digital Encryption Standard (DES) is the most common example, and public key encryption, which is embodied in the RSA standard (named after its inventors, Ronald L. Rivest, Adi Shamir, and Leonard Adelman). For most satellite communication applications, private key encryption is most popular. The DES standard can be utilized in the United States, where it was developed under government sponsorship.

The adequacy of DES was challenged when it became the foundation of Wired Equivalent Privacy (WEP), the encryption technique most common in IEEE 802.11 (WiFi) networks. Simple 64 bit and even 128 bit encryption keys have proven ineffective against attacks from hackers using commercial computers. Techniques that frequently change the key thwart hackers because they are unable to derive the key before the next change is effected.

For all intents and purposes in commercial satellite communications, public and private key encryption are highly adequate to protect user data from intrusion and unauthorized interception. Even without encryption, it has been argued that the requirement to use a specialized receiver provides a low level of security. That argument does not hold up in attractive consumer services with low-cost receivers, such as DTH TV and S-DARS, so encryption becomes the norm. The techniques and the equipment do their jobs very well, but the problem comes from the need to adequately protect the keys. Because of the repeating nature of the encryption techniques and the tendency of pirates to be able to find out what they want, keys are changed routinely and often. They usually are distributed over the same satellite link that is to be protected. If pirates have been able to overcome the key once, they are in the position to acquire the new keys when those keys subsequently are broadcast over the satellite.

Auxiliary systems like smart cards and special chips add another level of security on top of encryption. An authorized user needs three things: the decryption device, the key, and the smart card. If the system is compromised, the operator distributes new cards (which is cheaper than distributing new encryption devices). Another defense is to require users to hook their equipment to the Internet so the operator can transfer information such as the new key or an encryption technique upgrade. As is evident, security is a process of implementing a technique that is adequate until broken, then strengthening the system in response to the increasing capability of the hacker or pirate. It is, after all, a game of cat and mouse, in which the mouse has all the motivation to break through and obtain the information (TV programs, computer programs, and the like) without paying the originator. Of course, the pirate must pay to play the game, so there is a cost nevertheless.

5.2 Digital Modulation

Digital modulation involves transferring the bit stream to an RF carrier, for which techniques like QPSK and 16QAM are popular. This discussion is an introduction to the theory and the practice of digital modulation design, with emphasis on the typical satellite link. The steps in the process include generating a bit in the form of a pulse that meets certain criteria for bandwidth and shaping; transferring those shaped pulses onto a carrier, typically using some form of PSK; allowing for

impairments, noise, and interference along the link; and providing a suitable demodulator capable of recovering the pulses from the carrier and cleaning them up to reproduce a digital bit stream with minimum errors due to the previous elements. Readers wishing a more detailed discussion suitable for making specific design decisions should review [4]. Nontechnical readers not needing an understanding of modulation theory can skip this section entirely.

Nearly all digital modulation relies on the basic characteristic of a pulse, shown in the time and frequency plots in Figure 5.7. The pulse has a fixed duration of T seconds, which means a continuous stream of such pulses would have a rate $1/T$ bits per second. If $T = 0.001$ second (1 ms), then $1/T = 1,000$ bps (1 kbps). The frequency spectrum of the pulse, shown in the figure, is a maximum at zero frequency and passes through the X-axis at a frequency equal to the bit rate ($1/T$, or 1,000 Hz for the previous example). Successive sidebands have zero values at multiples of $1/T$. The bandwidth of the main lobe is proportional to $1/T$, the bit rate. The formula for the spectral shape of pulse amplitude is simply the ratio

$$\sin(\pi FT)/(\pi FT)$$

That formula is plotted more precisely between -4 and $+4$ in Figure 5.8 and converted in relative power in decibels in Figure 5.9. The shorthand way of referring to the formula is $\sin(x)/x$. The value at zero frequency, which is actually referenced to the carrier center frequency, is not zero even though $\sin(0) = 0$. In fact, the value of $\sin(0)/0$ is 1, because for small angles $\sin(x) = x$. The important relationship here is that a fixed pulse length produces maximum energy at zero (e.g., carrier center frequency) and an extended frequency spectrum.

Because of bandwidth taken by sidebands, the spectrum of the pulse should be filtered to minimize the occupied bandwidth. That is illustrated in Figure 5.10, where the attenuation characteristic of a low-pass filter is shown superimposed on the spectrum of a rectangular pulse. After filtering (the heavy line), the output spectrum is confined within the bandwidth of the pulse spectrum's main lobe. Due to the same mathematical relationship that causes a rectangular pulse to have an

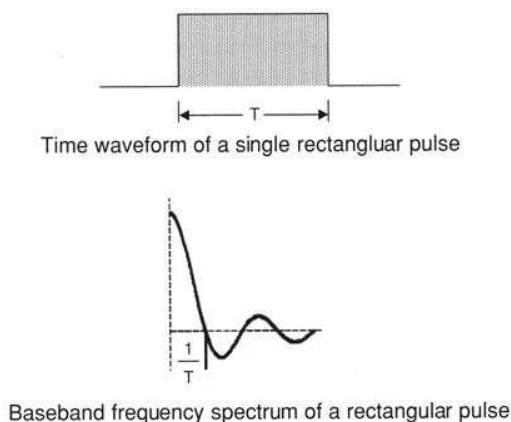


Figure 5.7 Characteristics of a rectangular pulse in the time and frequency domain.

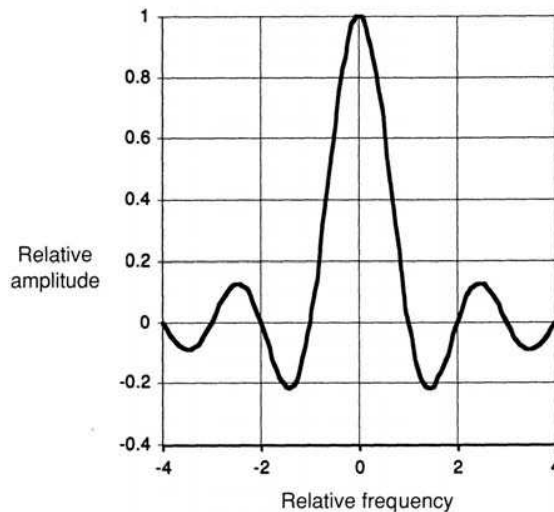


Figure 5.8 Amplitude versus frequency spectrum of a PSK carrier with rectangular pulse modulation.

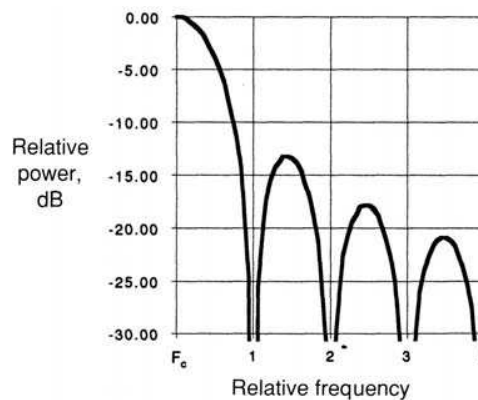


Figure 5.9 Power spectrum of rectangular pulse modulation shown on a decibel scale.

infinite spectrum, a limited spectrum alters the pulse so that it has infinite duration in time. Instead of a rectangular shape, a filtered pulse has a time waveform with an oscillating tail. A stream of filtered pulses contains residual tails, which increase the chance for errors. That is comparable to increasing the link noise level or adding interference; hence, the presence of tails is called intersymbol interference (ISI). If too little of the pulse spectrum is passed by the link, the ISI can so degrade reception that satisfactory operation is impossible. That, of course, is why adequate modulation bandwidth must be allowed.

The error-causing effect of ISI can be reduced by aligning the pulse tails so their zero crossings occur at times when the pulse main lobes are at their peaks. That can be done by proper filter design and demodulator timing. Figure 5.11 shows an ideal rectangular spectrum and a spectrum shaped like a cosine curve (called the raised cosine spectrum). Both occupy approximately the same band-

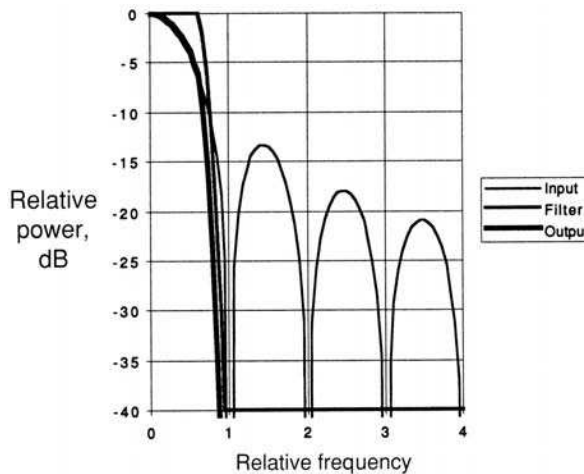


Figure 5.10 Baseband frequency spectra of a rectangular pulse before and after filtering to reduce the transmission bandwidth.

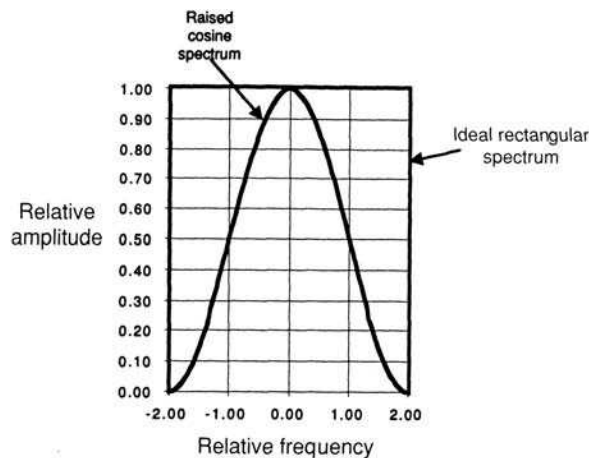


Figure 5.11 Frequency spectra of bandwidth-limited pulses using rectangular and raised cosine shaping.

width. The corresponding pulse waveforms in time are plotted in Figure 5.12, clearly showing the reduction in the oscillating tail produced by spectral filtering. Both pulse waveforms have zero crossings at the times corresponding to main lobe peaks $(-3, -1, -1, 1, 2, 3, \dots)$, thus precluding ISI. In addition, the raised cosine spectrum pulse has a much weaker tail, making it less sensitive to timing errors in the demodulator. This type of shaping is one technique used to efficiently reduce the modulated bandwidth of a digital carrier. Typically, the necessary RF bandwidth of a properly filtered pulse is $(1 + \alpha)$ times the bit rate (expressed in Hertz), where α is the roll-off factor. Typical values of α are in the range of 0.2 to 0.4.

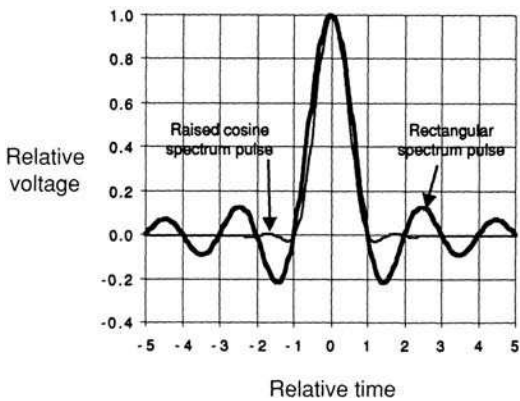


Figure 5.12 Comparison of pulse waveforms with limited bandwidths for rectangular spectrum and raised cosine spectrum shaping.

5.2.1 Frequency Shift Keying

An early form of digital modulation used in radio communications was FSK. Illustrated in Figure 5.13, FSK is obtained by switching between two discrete frequencies: F_1 and F_2 , which correspond to the “1” and “0” states, respectively (or vice versa). That aspect causes FSK to consume twice the bandwidth of PSK. The principal advantage of FSK historically was that simple hardware could be used in the modulator and the demodulator. That lack of sophistication also means that FSK requires more signal power for the same performance in terms of error rate, which would have to be reflected in the link budget analysis. FSK was used in the first telephone modems, which were capable of between 600 and 1,200 bps. There may still be a role for more efficient FSK waveforms that overlap the spectrum pairs.

5.2.2 Phase Shift Keying

The technique of PSK, discussed in Chapter 4, is the most common system for transmitting and receiving high-speed digital information over satellites. PSK

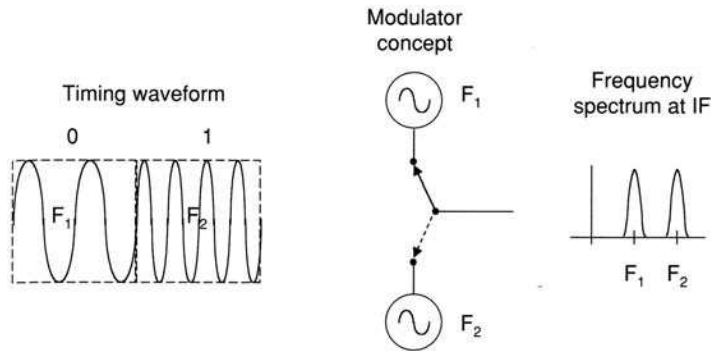


Figure 5.13 FSK as shown in time and frequency can be generated from two oscillators of different frequencies.

modems operate at rates between 64 kbps and 1,000 Mbps. BPSK uses two phase states: 0 and 180 degrees; QPSK uses four states split into pairs: 0 degrees and 180 degrees (the in-phase, or “I,” component) and 90 degrees and 270 degrees (the quadrature, or “Q,” component). Four possible phase states are illustrated in Figure 5.14 using vector diagrams, each representing a two-bit combination. A property called orthogonality is used in QPSK, wherein the I and Q components are separated by 90 degrees from each other, shown in Figure 5.15 by orthogonal vector pairs. That is similar in effect to the use of cross-polarization isolation to achieve frequency reuse (see Chapter 4). QPSK transmits 2 bits per symbol, meaning that the vector position in Figure 5.14 represents 2 bits of digital information. As a result, QPSK is efficient in the way bandwidth and power are used. Adding another bit per symbol forms eight-phase PSK, a technique that increases capacity but subjects the signal to greater degradation from noise and interference and the repeater impairments.

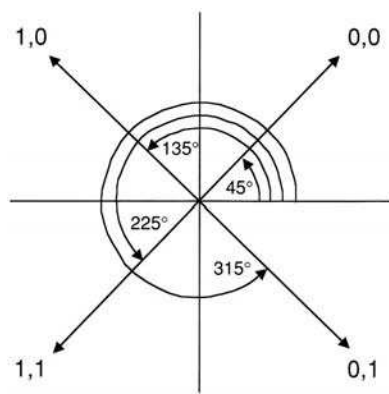


Figure 5.14 QPSK modulation vector diagram, indicating the four vector (phase) states and the corresponding encoded bit patterns.

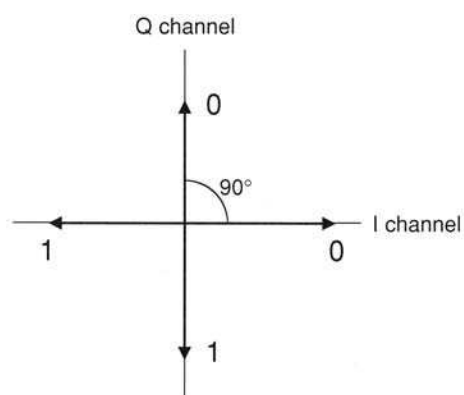


Figure 5.15 Orthogonal properties of the I and Q channels in QPSK.

5.2.3 Amplitude and Phase Shift Keying

QPSK is an efficient modulation method principally in terms of power; however, there are circumstances where its occupied bandwidth exceeds what is available or affordable. A solution may be found through a more complex waveform that comes under the general class called bandwidth efficient modulation (BEM). A point to keep in mind is that while BEM may be efficient in terms of bandwidth, it is not in terms of power. It will be necessary to compensate for this trade-off by using more satellite EIRP or a larger Earth station antenna (i.e., higher G/T on receive).

The most common form of BEM is amplitude and phase shift keying (APSK), in which both the phase and the amplitude are varied to carry the information bits. Figure 5.16 presents the phasor diagram, also referred to as the signal constellation, for the version of 16APSK adopted by the DVB-S2 standard. In it we see two concentric circles, the first identical to a QPSK waveform and the inner circle being divided into 12 sectors (i.e., 12-phase PSK). In total, there are 16 possible signal states to correspond to 4 bits of data. This is indicated in the figure where there are 16 different combinations of four bits, with only one bit difference between adjacent locations in the signal space.

This waveform uses a shift between two amplitude states and up to 12 different phase states. It was devised to improve performance in a repeater channel of the type found on bent-pipe repeater satellites, as discussed at the end of this chapter. A 32APSK waveform that adds an outer ring with 16 additional phase states produces five bits per signal state.

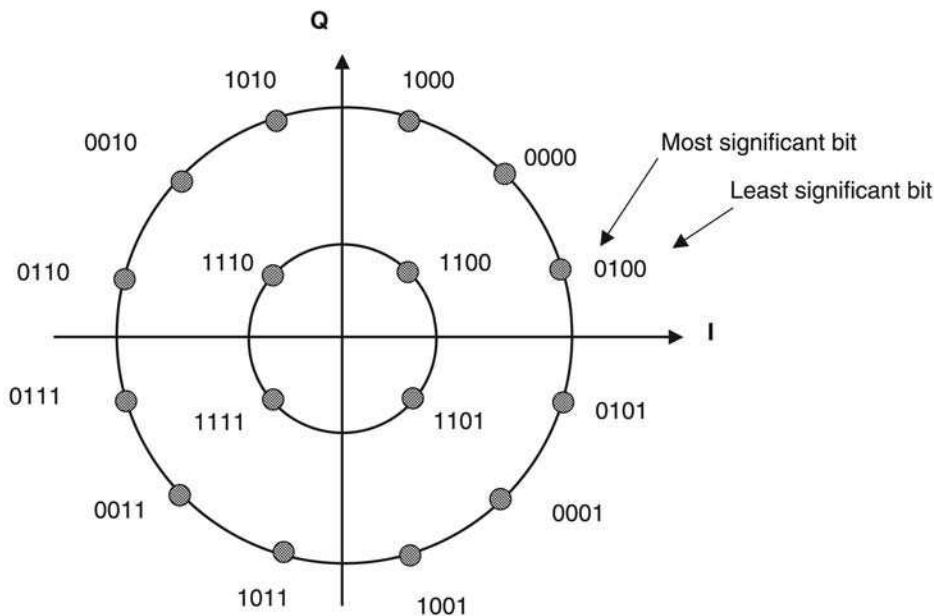


Figure 5.16 Vector constellation diagram for 16APSK, based on the DVB-S2 standard.

With the BEM constellations, there are always smaller data state regions in the phase-amplitude constellation than with BPSK or QPSK. Noise, however, corrupts both phase and amplitude, so can more easily cause wrong data state decisions at the receiver. Thus, with a higher data rate per unit of bandwidth, the C/N on the channel must be significantly higher than would be acceptable for PSK or FSK.

The ultimate payoff from BEM is in a dynamic arrangement called adaptive coding and modulation (ACM) wherein the modulation format and coding rate are automatically altered on the link to increase throughput under ideal conditions or fall back to a more resilient combination at a lower data rate under conditions of high channel error rate (e.g., fading).

Because of the higher data rate per unit of bandwidth, the C/N on the channel must be significantly higher than would be acceptable for PSK or FSK. Ideally, the RF channel should be linear to allow the complex modulation format to pass unimpaired. Continued improvements in satellite channel performance make hybrid modulation more practical. An example would be in a digital processing payload, in which the spacecraft receives a hybrid modulated carrier, recovers the bits, and retransmits the signal in a linear fashion.

5.3 Multiple Access Methods

The basic concept of multiple access is to permit Earth stations to transmit to the same satellite without interfering with one another. RF carriers can be maintained separate in frequency, time, or code, as indicated in Figure 5.17 by three perpendicular axes. Hence, the use of FDMA, TDMA, and CDMA, which are discussed in the following sections.

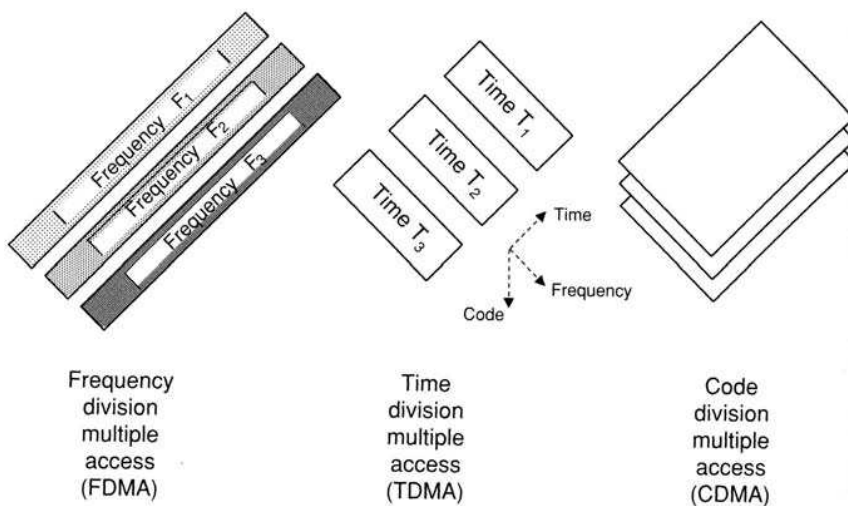


Figure 5.17 Generic multiple access methods using the three dimensions of frequency, time, and code.