THE RF TRANSMISSION SYSTEMS HANDBOOK

Edited by

Jerry C. Whitaker

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THE RF TRANSMISSION SYSTEMS

HANDBOOK

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Preface

Radio frequency (RF) transmission is one of the oldest forms of electronics. From the days of Hertz and Marconi, RF transmission has pioneered the art and science of electronics engineering. It has also served as the basis for a myriad of related applications, not the least of which includes audio amplification and processing, video pickup and reproduction, and radar. RF technology has reshaped our national defense efforts, radically changed the way we communicate, provided new products and services, and brought nations together to celebrate good times and mourn bad times.

RF is an invisible technology. It is a discipline that often takes a back seat to other subjects taught in colleges and universities. Yet RF transmission equipment has reshaped the way we live.

This book is intended to serve the information needs of persons who specify, install, and maintain RF equipment. The wide variety of hardware currently in use requires that personnel involved in RF work be familiar with a multitude of concepts and applications. This book examines a wide range of technologies and power devices, focusing on devices and systems that produce in excess of 1 kilowatt (kW).

Extensive theoretical dissertations and mathematical explanations have been included to the extent that they are essential for an understanding of the basic concepts. Excellent reference books are available from this publisher that examine individual RF devices and the underlying design criteria. This book puts the individual elements together and shows how they interrelate.

The areas covered by *The RF Transmission Systems Handbook* range from broadcasting to electronic counter-measures. The basic concepts and circuit types of all major RF applications are covered. The generous use of illustrations makes difficult or complex concepts easier to comprehend. Practical examples are provided wherever possible. Special emphasis is given to radio and television hardware because these applications provide examples that can readily be translated to other uses.

The RF Transmission Systems Handbook is divided into the following major subject areas:

- **Applying RF Technology**. Common uses of radio frequency energy are examined and examples given. This treatment includes an overview of RF bands, modulation methods, and amplifier operating classes.
- **Solid-State Power Devices**. The operating parameters of semiconductor-based power devices are discussed, and examples of typical circuits are given. Included is an outline of the basic principles of bipolar and FET semiconductors, including potential failure modes.
- **Power Vacuum Tube Devices**. The basic principles and applications of gridded vacuum tubes are outlined, and example circuits provided.
- **Microwave Power Tubes**. The operating principles of classic microwave devices and new high-efficiency tubes are given. This treatment reviews the basic concepts of klystrons, traveling-wave tubes, and other microwave power devices.

- **RF Components and Transmission Line**. The operation of hardware used to combine and conduct RF power are explained, including coaxial transmission line, waveguide, hot-switches, and circulators.
- **Antenna Systems**. An overview of antenna theory and common designs is given and basic operating parameters are described. Examples are provided of antennas used in radio and TV broadcasting, satellite service, and radar.

RF power technology is a complicated but exciting science. It is a science that advances each year. The frontiers of higher power and higher frequency continue to fall as new applications drive new developments by manufacturers. Radio frequency technology is not an aging science. It is a discipline that is, in fact, just reaching its stride.

Jerry C. Whitaker
Editor

Editor

Jerry Whitaker is technical director of the Advanced Television Systems Committee, Washington D.C. He previously operated the consulting firm Technical Press. Whitaker has been involved in various aspects of the communications industry for more than 25 years. He is a fellow of the Society of Broadcast Engineers (SBE) and an SBE-certified Professional Broadcast Engineer. He is also a member and fellow of the Society of Motion Picture and Television Engineers, and a member of the Institute of Electrical and Electronics Engineers. Whitaker has written and lectured extensively on the topic of electronic systems installation and maintenance.

Whitaker is the former editorial director and associate publisher of *Broadcast Engineering* and *Video Systems* magazines. He is also a former radio station chief engineer and TV news producer.

Whitaker is the author of several books, including:

- *The Resource Handbook of Electronics*, CRC Press, 2000
- *The Communications Facility Design Handbook*, CRC Press, 2000
- *Power Vacuum Tubes Handbook*, 2nd edition, CRC Press, 1999
- *AC Power Systems*, 2nd edition, CRC Press, 1998
- *DTV Handbook*, 3rd edition, McGraw-Hill, 2000
- Editor-in-Chief, *NAB Engineering Handbook*, 9th edition, National Association of Broadcasters, 1999
- Editor-in-Chief, *The Electronics Handbook*, CRC Press, 1996
- Co-author, *Communications Receivers: Principles and Design*, 3rd edition, McGraw-Hill, 2000
- *Electronic Display Engineering*, McGraw-Hill, 2000
- Co-editor, *Standard Handbook of Video and Television Engineering*, 3rd edition, McGraw-Hill, 2000
- Co-editor, *Information Age Dictionary*, Intertec/Bellcore, 1992
- *Radio Frequency Transmission Systems: Design and Operation*, McGraw-Hill, 1990

Whitaker has twice received a Jesse H. Neal Award Certificate of Merit from the Association of Business Publishers for editorial excellence. He also has been recognized as Educator of the Year by the Society of Broadcast Engineers. He resides in Morgan Hill, California.

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Contents

1

Applications of RF Technology

Jerry C. Whitaker
Editor

1.1 Introduction

Radio frequency (RF) power amplifiers are used in countless applications at tens of thousands of facilities around the world. The wide variety of applications, however, stem from a few basic concepts of conveying energy and information by means of a radio frequency signal. Furthermore, the devices used to produce RF energy have many similarities, regardless of the final application. Although radio and television broadcasting represent the most obvious use of high-power RF generators, numerous other common applications exist, including:

- Induction heating and process control systems
- Radio communications (two-way mobile radio base stations and cellular base stations)
- Amateur radio
- Radar (ground, air, and shipboard)
- Satellite communications
- Atomic science research
- Medical research, diagnosis, and treatment

Figure 1.1 illustrates the electromagnetic spectrum and major applications.

Modulation Systems

The primary purpose of most communications systems is to transfer information from one location to another. The message signals used in communication and control systems usually must be limited in frequency to provide for efficiency transfer. This frequency may range from a few hertz for control systems to a few megahertz for video signals. To facilitate efficient and controlled distribution of these signals,

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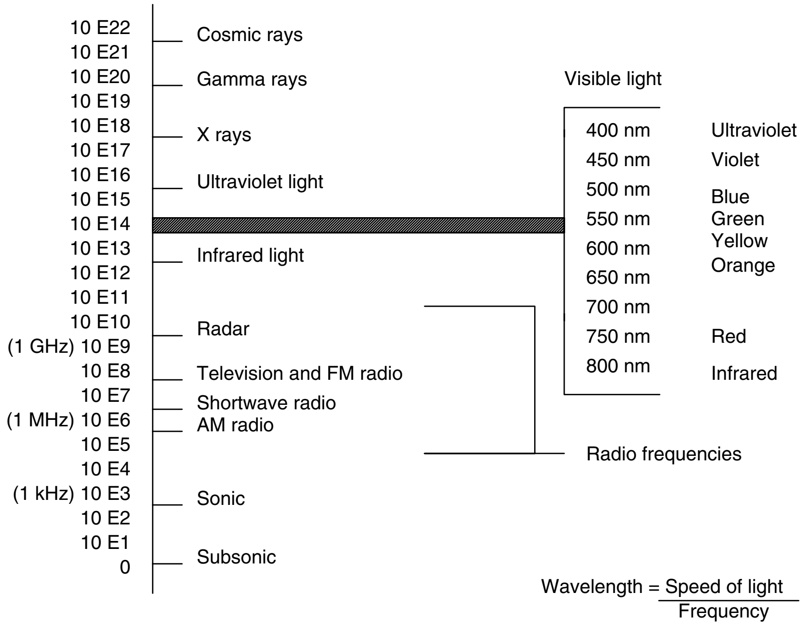

FIGURE 1.1 The electromagnetic spectrum.

an *encoder* is generally required between the source and the transmission channel. The encoder acts to *modulate* the signal, producing at its output the *modulated waveform*. Modulation is a process whereby the characteristics of a wave (the *carrier*) are varied in accordance with a message signal, the modulating waveform. Frequency translation is usually a by-product of this process. Modulation can be continuous, where the modulated wave is always present, or pulsed, where no signal is present between pulses.

There are a number of reasons for producing modulated waves, including:

- *Frequency translation*. The modulation process provides a vehicle to perform the necessary frequency translation required for distribution of information. An input signal can be translated to its assigned frequency band for transmission or radiation.
- *Signal processing*. It is often easier to amplify or process a signal in one frequency range as opposed to another.
- *Antenna efficiency*. Generally speaking, for an antenna to be efficient, it must be large compared with the signal wavelength. Frequency translation provided by modulation allows antenna gain and beamwidth to become part of the system design considerations. Use of higher frequencies permits antenna structures of reasonable size and cost.
- *Bandwidth modification*. The modulation process permits the bandwidth of the input signal to be increased or decreased as required by the application. Bandwidth reduction can permit more efficient use of the spectrum, at the cost of signal fidelity. Increased bandwidth, on the other hand, permits increased immunity to transmission channel disturbances.
- *Signal multiplexing*. In a given transmission system, it may be necessary or desirable to combine several different signals into one baseband waveform for distribution. Modulation provides the vehicle for such *multiplexing*. Various modulation schemes allow separate signals to be combined at the transmission end, and separated (*demultiplexed*) at the receiving end. Multiplexing can be accomplished using *frequency-domain multiplexing* (FDM) or *time-domain multiplexing* (TDM).
- *Modulation of a signal does not come without undesirable characteristics*. Bandwidth restriction or the addition of noise or other disturbances are the two primary problems faced by the transmission system designer.

Spread-Spectrum Systems

The specialized requirements of the military led to the development of *spread-spectrum* communications systems. As the name implies, such systems require a frequency range substantially greater than the basic information-bearing signal. Spread-spectrum systems have some or all of the following properties:

- Low interference to other communications systems
- Ability to reject high levels of external interference
- Immunity to jamming by hostile forces
- Provides for secure communications paths
- Operates over multiple RF paths

Spread-spectrum systems operate with an entirely different set of requirements than the transmission systems discussed previously. Conventional modulation methods are designed to provide for the easiest possible reception and demodulation of the transmitted intelligence. The goals of spread-spectrum systems, on the other hand, are secure and reliable communications that cannot be intercepted by unauthorized persons. The most common modulation and encoding techniques in spread-spectrum communications include:

- *Frequency hopping,* where a random or *pseudorandom number* (PN) sequence is used to change the carrier frequency of the transmitter. This approach has two basic variations: *slow frequency hopping*, where the hopping rate is smaller than the data rate; and *fast frequency hopping*, where the hopping rate is larger than the data rate. In a fast frequency hopping system, the transmission of a single piece of data occupies more than one frequency. Frequency hopping systems permit multiple-access capability to a given band of frequencies because each transmitted signal occupies only a fraction of the total transmitted bandwidth.
- *Time hopping,* where a PN sequence is used to switch the position of a message-carrying pulse within a series of frames.
- *Message corruption,* where a PN sequence is added to the message before modulation.
- *Chirp spread spectrum,* where linear frequency modulation of the main carrier is used to spread the transmitted spectrum. This technique is commonly used in radar and has also been applied to communications systems.

In a spread-spectrum system, the signal power is divided over a large bandwidth. The signal, therefore, has a small average power in any single narrowband slot. This means that a spread-spectrum system can share a given frequency band with one or more narrowband systems.

RF Power Amplifiers

The process of generating high-power RF signals has been refined over the years to an exact science. Advancements in devices and circuit design continue to be made each year, pushing ahead the barriers of efficiency and maximum operating frequency. Although different applications place unique demands on the RF design engineer, the fundamental concepts of RF amplification are applicable to virtually any system.

Frequency Sources

Every RF amplifier requires a stable frequency reference. At the heart of most systems is a quartz crystal. Quartz acts as a stable high *Q* mechanical resonator. Crystal resonators are available for operation at frequencies ranging from 1 kHz to 300 MHz and beyond.

The operating characteristics of a crystal are determined by the *cut* of the device from a bulk “mother” crystal. The behavior of the device strongly depends on the size and shape of the crystal and the angle of the cut. To provide for operation at a wide range of frequencies, different cuts, vibrating in one or more selected modes, are used.

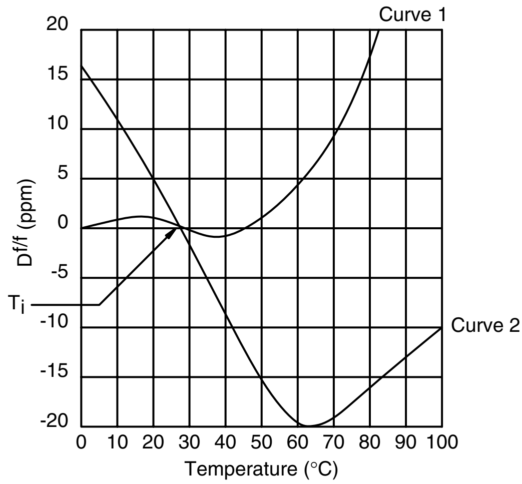

FIGURE 1.2 The effects of temperature on two types of AT-cut crystals.

Crystals are temperature sensitive, as shown in Fig. 1.2. The extent to which a device is affected by changes in temperature is determined by its cut and packaging. Crystals also exhibit changes in frequency with time. Such *aging* is caused by one or both of the following:

- Mass transfer to or from the resonator surface
- Stress relief within the device itself

Crystal aging is most pronounced when the device is new. As stress within the internal structure is relieved, the aging process slows.

The stability of a quartz crystal is inadequate for most commercial and industrial applications. Two common methods are used to provide the required long-term frequency stability:

- *Oven-controlled crystal oscillator:* a technique in which the crystal is installed in a temperature-controlled box. Because the temperature is constant in the box, controlled by a thermostat, the crystal remains on-frequency. The temperature of the enclosure is usually set to the *turnover temperature* of the crystal. (The turnover point is illustrated in Fig. 1.2.)
- *Temperature-compensated crystal oscillator* (TCXO): a technique where the frequency-vs.-temperature changes of the crystal are compensated by varying a load capacitor. A thermistor network is typically used to generate a correction voltage that feeds a varactor to re-tune the crystal to the desired on-frequency value.

Operating Class

Power amplifier (PA) stage operating efficiency is a key element in the design and application of an RF system. As the power level of an RF generator increases, the overall efficiency of the system becomes more important. Increased efficiency translates into lower operating costs and usually improved reliability of the system. The operating mode of the final stage, or stages, is the primary determining element in the maximum possible efficiency of the system.

All electron amplifying devices are classified by their individual *class of operation*. Four primary class divisions apply to RF generators:

- *Class A:* a mode wherein the power amplifying device is operated over its linear transfer characteristic. This mode provides the lowest waveform distortion, but also the lowest efficiency. The basic operating efficiency of a class A stage is 50%. Class A amplifiers exhibit low intermodulation distortion, making them well suited for linear RF amplifier applications.

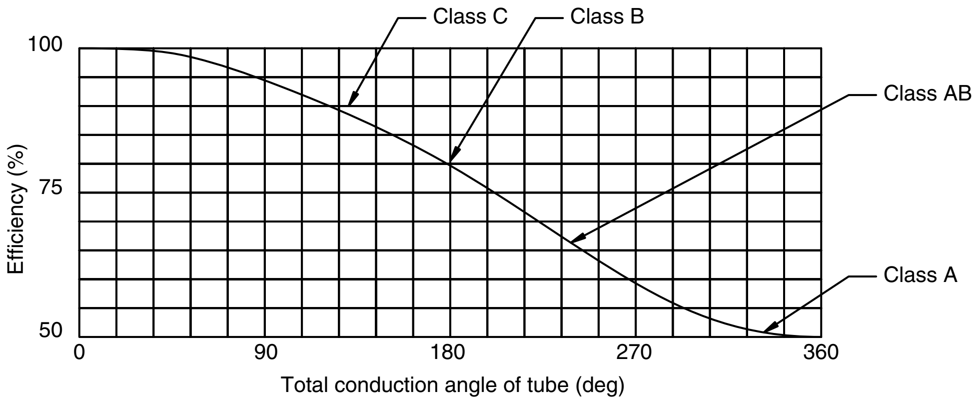

FIGURE 1.3 Plate efficiency as a function of conduction angle for an amplifier with a tuned load.

- *Class B:* a mode wherein the power amplifying device is operated just outside its linear transfer characteristic. This mode provides improved efficiency at the expense of some waveform distortion. Class AB is a variation on class B operation. The transfer characteristic for an amplifying device operating in this mode is, predictably, between class A and class B.
- *Class C:* a mode wherein the power amplifying device is operated significantly outside its linear transfer characteristic, resulting is a pulsed output waveform. High efficiency (up to 90%) can be realized with class C operation; however, significant distortion of the waveform will occur. Class C is used extensively as an efficient RF power generator.
- *Class D:* a mode that essentially results in a switched device state. The power amplifying device is either *on* or *off*. This is the most efficient mode of operation. It is also the mode that produces the greatest waveform distortion.

The angle of current flow determines the class of operation for a power amplifying device. Typically, the conduction angle for class A is 360°; class AB is between 180° and 360°; class B is 180°; and class C is less than 180°. Subscripts can also be used to denote grid current flow in the case of a power vacuum tube device. The subscript "1" means that no grid current flows in the stage; the subscript "2" denotes grid current flow. Figure 1.3 charts operating efficiency as a function of the conduction angle of an RF amplifier.

The class of operation is not directly related to the type of amplifying circuit. Vacuum tube stages may be grid- or cathode-driven without regard to the operating class. Similarly, solid-state amplifiers may be configured for grounded emitter, grounded base, or grounded collector operation without regard to the class of operation.

Operating Efficiency

The design goal of all RF amplifiers is to convert input power into an RF signal at the greatest possible efficiency. DC input power that is not converted to a useful output signal is, for the most part, converted to heat. This heat represents wasted energy, which must be removed from the amplifying device. Removal of heat is a problem common to all high-power RF amplifiers. Cooling methods include:

- Natural convection
- Radiation
- Forced convection
- Liquid
- Conduction
- Evaporation

The type of cooling method chosen is dictated in large part by the type of active device used and the power level involved. For example, liquid cooling is used almost exclusively for high-power (100 kW) vacuum tubes; conduction is used most often for low-power (20 W) transistors.

Broadband Amplifier Design

RF design engineers face a continuing challenge to provide adequate bandwidth for the signals to be transmitted, while preserving as much efficiency as possible from the overall system. These two parameters, while not mutually exclusive, often involve trade-offs for both designers and operators.

An ideal RF amplifier will operate over a wide band of frequencies with minimum variations in output power, phase, distortion, and efficiency. The bandwidth of the amplifier depends to a great extent on the type of active device used, the frequency range required, and the operating power. As a general rule, bandwidth of 20% or greater at frequencies above 100 MHz can be considered *broadband*. Below 100 MHz, broadband amplifiers typically have a bandwidth of one octave or more.

Most development in new broadband designs focuses on semiconductor technology. Transistor and MOSFET (metal oxide semiconductor field effect transistor) devices have ushered in the era of *distributed amplification*, where multiple devices are used to achieve the required RF output power. Semiconductor-based designs offer benefits beyond active device redundancy. Bandwidth at frequencies above 100 MHz can often be improved because of the smaller physical size of semiconductor devices, which translates into reduced lead and component inductance and capacitance.

Amplifier Compensation

A variety of methods can be used to extend the operating bandwidth of a transistorized amplifier stage. Two of the most common methods are series- and shunt-compensation circuits, shown in Fig. 1.4. These two basic techniques can be combined, as shown. Other circuit configurations can be used for specific requirements, such as phase compensation.

Stagger Tuning

Several stages with narrowband response (relative to the desired system bandwidth) can be cascaded and, through the use of *stagger tuning*, made broadband. While there is an efficiency penalty for this approach, it has been used for years in all types of equipment. The concept is simple: offset the center operating frequencies (and, therefore, peak amplitude response) of the cascaded amplifiers so the resulting passband is flat and broad.

For example, the first stage in a three-stage amplifier is adjusted for peak response at the center operating frequency of the system. The second stage is adjusted above the center frequency, and the third stage is adjusted below center. The resulting composite response curve yields a broadband trace. The efficiency penalty for this scheme varies, depending on the power level of each stage, the amount of stagger tuning required to achieve the desired bandwidth, and the number of individual stages.

Matching Circuits

The individual stages of an RF generator must be coupled together. Rarely do the output impedance and power level of one stage precisely match the input impedance and signal-handing level of the next stage. There is a requirement, therefore, for broadband matching circuits. Matching at RF frequencies can be accomplished with several different techniques, including:

- *Quarter-wave transformer:* a matching technique using simply a length of transmission line 1/4-wave long, with a characteristic impedance of:

$$Z_{line} = \sqrt{Z_{in} \times Z_{out}} \tag{1.1}$$

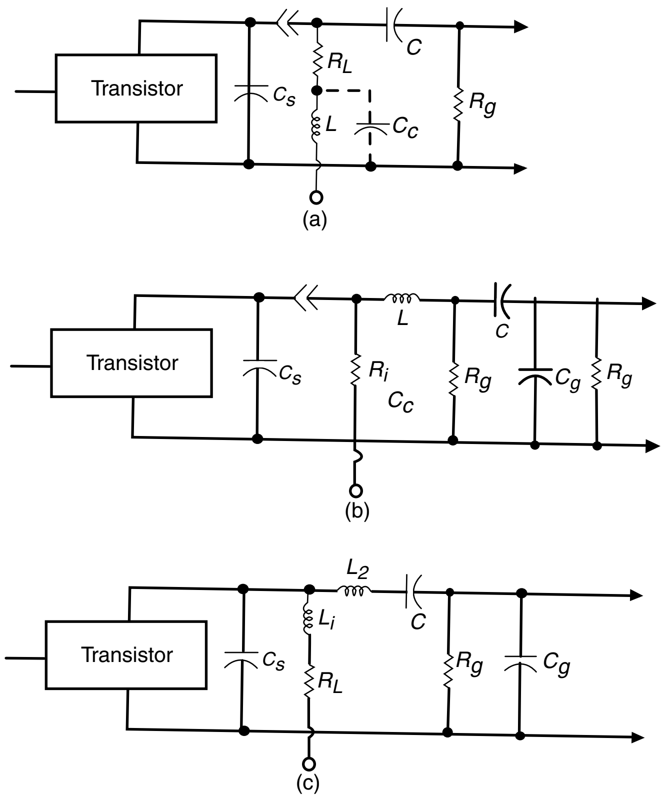

FIGURE 1.4 High-frequency compensation techniques: (a) shunt, (b) series, (c) combination of shunt and series. (After Fink, D. and Christiansen, D., Eds., *Electronics Engineer's Handbook*, 3rd ed., McGraw-Hill, New York, 1989.)

where Z_{in} and Z_{out} are the terminating impedances. Quarter-wave transformers can be cascaded to achieve more favorable matching characteristics. Cascaded transformers permit small matching ratios for each individual section.

- *Balun transformer:* a transmission-line transformer in which the turns are physically arranged to include the interwinding capacitance as a component of the characteristic impedance of the transmission line. This technique permits wide bandwidths to be achieved without unwanted resonances. Balun transformers are usually made of twisted wire pairs or twisted coaxial lines. Ferrite toroids can be used as the core material.
- Other types of lumped reactances.
- Short sections of transmission line.

Power Combining

The two most common methods of extending the operating power of semiconductor devices are *direct paralleling* of components and *hybrid splitting/combining*. Direct paralleling has been used for both tube and semiconductor designs; however, application of this simple approach is limited by variations in device operating parameters. Two identical devices in parallel do not necessarily draw the same amount of current (supply the same amount of power to the load). Paralleling at UHF frequencies and above can be difficult because of the restrictions of operating wavelength.

The preferred approach involves the use of identical stages driven in parallel from a *hybrid coupler*. The coupler provides a constant-source impedance and directs any reflected energy from the driven stages to a *reject port* for dissipation. A hybrid coupler offers a voltage standing wave ratio or VSWR-canceling effect that improves system performance. Hybrids also provide a high degree of isolation between active devices in a system.

Output Devices

Significant changes have occurred within the past 10 years or so with regard to power amplifying devices. Vacuum tubes were the mainstay of RF transmission equipment until advanced semiconductor components became available at competitive prices. Many high-power applications that demanded vacuum tubes can now be met with solid-state devices arranged in a distributed amplification system. Metal oxide silicon field effect transistor (MOSFET) and bipolar components have been used successfully in radio and television broadcast transmitters, shortwave transmitters, sonar transmitters, induction heaters, and countless other applications.

Most solid-state designs used today are not simply silicon versions of classic vacuum tube circuits. They are designed to maximize efficiency through class D switching and maximize reliability through distributed amplification and redundancy.

The principal drawback to a solid-state system over a vacuum tube design of comparable power is the circuit complexity that goes with most semiconductor-based hardware. Preventive maintenance is reduced significantly, and — in theory — repair is simpler as well in a solid-state system. The parts count in almost all semiconductor-based hardware, however, is significantly greater than in a comparable tube system. Increased parts translate (usually) into a higher initial purchase price for the equipment and increased vulnerability to device failure of some sort.

Efficiency comparisons between vacuum tube and solid-state systems do not always yield the dramatic contrasts expected. While most semiconductor amplifiers incorporate switching technology that is far superior to class B or C operation (not to mention class A), power losses are experienced in the signal splitting and combining networks necessary to make distributed amplification work.

It is evident, then, that vacuum tubes and semiconductors each have their benefits and drawbacks. Both technologies will remain viable for many years to come. Vacuum tubes will not go away, but are moving to higher power levels and higher operating frequencies.

1.2 Broadcast Applications of RF Technology

Broadcasting has been around for a long time. Amplitude modulation (AM) was the first modulation system that permitted voice communications to take place. This simple modulation system was predominant throughout the 1920s and 1930s. Frequency modulation (FM) came into regular broadcast service during the 1940s. Television broadcasting, which uses amplitude modulation for the visual portion of the signal and frequency modulation for the aural portion of the signal, became available to the public in the mid-1940s. More recently, digital television (DTV) service has been launched in the United States and elsewhere using the conventional television frequency bands and 6-MHz bandwidth of the analog system, but with digital modulation.

AM Radio Broadcasting

AM radio stations operate on 10-kHz channels spaced evenly from 540 to 1600 kHz. Various classes of stations have been established by the Federal Communications Commission (FCC) and agencies in other countries to allocate the available spectrum to given regions and communities. In the United States, the basic classes are *clear*, *regional*, and *local*. Current practice uses the CCIR (international) designations as class A, B, and C, respectively. Operating power levels range from 50 kW for a clear channel station to as little as 250 W for a local station.

High-Level AM Modulation

High-level anode modulation is the oldest and simplest way of generating a high power AM signal. In this system, the modulating signal is amplified and combined with the dc supply source to the anode of

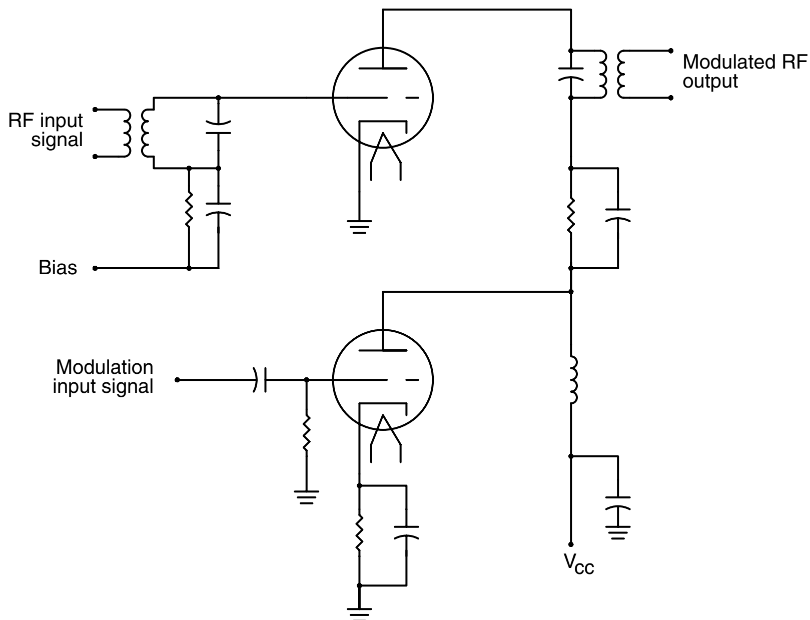

FIGURE 1.5 Simplified diagram of a high-level, amplitude-modulated amplifier.

the final RF amplifier stage. The RF amplifier is normally operated class C. The final stage of the modulator usually consists of a pair of tubes operating class B in a push–pull configuration. A basic high-level modulator is shown in Fig. 1.5.

The RF signal is normally generated in a low-level transistorized oscillator. It is then amplified by one or more solid-state or vacuum tube stages to provide final RF drive at the appropriate frequency to the grid of the final class C amplifier. The audio input is applied to an intermediate power amplifier (usually solid state) and used to drive two class B (or class AB) push–pull output devices. The final amplifiers provide the necessary modulating power to drive the final RF stage. For 100% modulation, this modulating power is equal to 50% of the actual carrier power.

The modulation transformer shown in Fig. 1.5 does not usually carry the dc supply current for the final RF amplifier. The modulation reactor and capacitor shown provide a means to combine the audio signal voltage from the modulator with the dc supply to the final RF amplifier. This arrangement eliminates the necessity of having dc current flow through the secondary of the modulation transformer, which would result in magnetic losses and saturation effects. In some newer transmitter designs, the modulation reactor has been eliminated from the system, thanks to improvements in transformer technology.

The RF amplifier normally operates class C with grid current drawn during positive peaks of the cycle. Typical stage efficiency is 75 to 83%. An RF tank following the amplifier resonates the output signal at the operating frequency and, with the assistance of a low-pass filter, eliminates harmonics of the amplifier caused by class C operation.

This type of system was popular in AM broadcasting for many years, primarily because of its simplicity. The primary drawback is low overall system efficiency. The class B modulator tubes cannot operate with greater than 50% efficiency. Still, with inexpensive electricity, this was not considered to be a significant problem. As energy costs increased, however, more efficient methods of generating high-power AM signals were developed. Increased efficiency normally came at the expense of added technical complexity.

Pulse-Width Modulation

Pulse-width modulation (PWM), also known as pulse-duration modulation (PDM), is one of the most popular systems developed for modern vacuum tube AM transmitters. Figure 1.6 shows the basic PDM scheme. The PDM system works by utilizing a square-wave switching system, illustrated in Fig. 1.7.

The PDM process begins with a signal generator (see Fig. 1.8). A 75-kHz sine wave is produced by an oscillator and used to drive a square-wave generator, resulting in a simple 75-kHz square wave. The square wave is then integrated, resulting in a triangular waveform that is mixed with the input audio in a summing circuit. The resulting signal is a triangular waveform that rides on the incoming audio. This

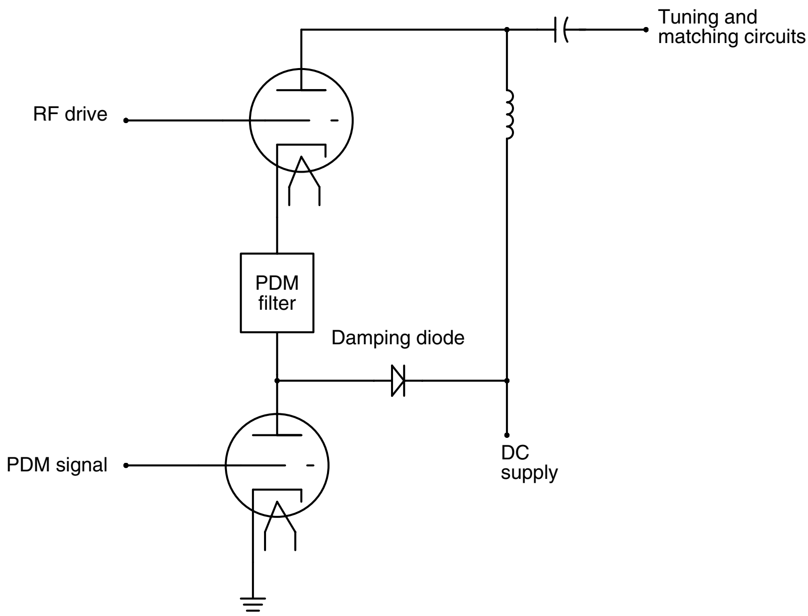

FIGURE 1.6 The pulse-duration modulation (PDM) method of pulse-width modulation.

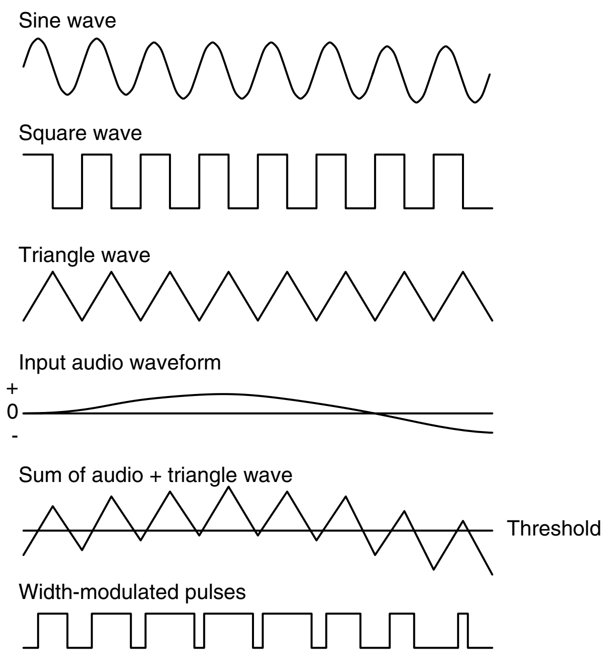

FIGURE 1.7 The principles waveforms of the PDM system.

composite signal is then applied to a threshold amplifier, which functions as a switch that is turned on whenever the value of the input signal exceeds a certain limit. The result is a string of pulses in which the width of the pulse is proportional to the period of time the triangular waveform exceeds the threshold. The pulse output is applied to an amplifier to obtain the necessary power to drive subsequent stages. A filter eliminates whatever transients may exist after the switching process is complete.

The PDM scheme is, in effect, a digital modulation system with the audio information being sampled at a 75-kHz rate. The width of the pulses contains all the audio information. The pulse-width-modulated signal is applied to a *switch* or *modulator tube*. The tube is simply turned *on*, to a fully saturated state, or *off* in accordance with the instantaneous value of the pulse. When the pulse goes positive, the modulator tube is turned on and the voltage across the tube drops to a minimum. When the pulse returns to its minimum value, the modulator tube turns off.

This PDM signal becomes the power supply to the final RF amplifier tube. When the modulator is switched on, the final amplifier will experience current flow and RF will be generated. When the switch or modulator tube goes off, the final amplifier current will cease. This system causes the final amplifier to operate in a highly efficient class D switching mode. A dc offset voltage to the summing amplifier is used to set the carrier (no modulation) level of the transmitter.

A high degree of third-harmonic energy will exist at the output of the final amplifier because of the switching-mode operation. This energy is eliminated by a third-harmonic trap. The result is a stable amplifier that normally operates in excess of 90% efficiency. The power consumed by the modulator and its driver is usually a fraction of a full class B amplifier stage.

The damping diode shown in the previous figure is included to prevent potentially damaging transient overvoltages during the switching process. When the switching tube turns off the supply current during a period when the final amplifier is conducting, the high current through the inductors contained in the PDM filters could cause a large transient voltage to be generated. The energy in the PDM filter is returned to the power supply by the damping diode. If no alternative route is established, the energy will return by arcing through the modulator tube itself.

The PWM system makes it possible to completely eliminate audio frequency transformers in the transmitter. The result is wide frequency response and low distortion. It should be noted that variations on this amplifier and modulation scheme have been used by other manufacturers for both standard broadcast and shortwave service.

Digital Modulation

Current transmitter design work for AM broadcsting has focused almost exclusively on solid-state technology. High-power MOSFET devices and digital modulation techniques have made possible a new generation of energy-efficient systems, with audio performance that easily surpasses vacuum tube designs.

Most solid-state AM systems operate in a highly efficient class D switching mode. Multiple MOSFET driver boards are combined through one of several methods to achieve the required carrier power.

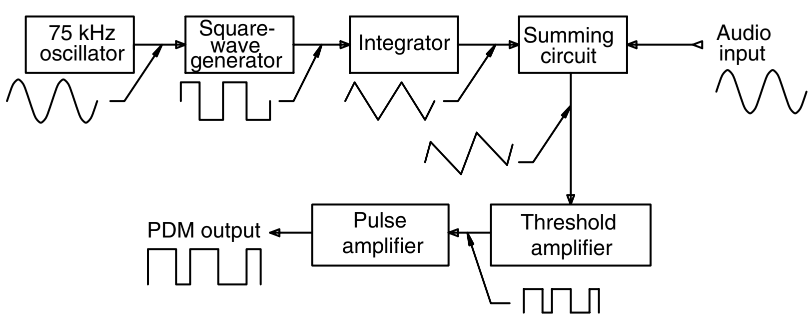

FIGURE 1.8 Block diagram of a PDM waveform generator.

Shortwave Broadcasting

The technologies used in commercial and government-sponsored shortwave broadcasting are closely allied with those used in AM radio. However, shortwave stations usually operate at significantly higher powers than AM stations.

International broadcast stations use frequencies ranging from 5.95 to 26.1 MHz. The transmissions are intended for reception by the general public in foreign countries. Table 1.1 shows the frequencies assigned by the Federal Communications Commission (FCC) for international broadcast shortwave service in the United States. The minimum output power is 50 kW. Assignments are made for specific hours of operation at specific frequencies.

TABLE 1.1 Operating Frequency Bands for Shortwave Broadcasting

Band	Frequency (kHz)	Meter Band (m)
A	5,950–6,200	49
B	9,500–9,775	32
C	11,700–11,975	25
D	15,100–15,450	19
E	17,700–17,900	16
F	21,450–21,750	14
G	25,600–26,100	11

Very high-power shortwave transmitters have been installed to serve large geographical areas and to overcome jamming efforts by foreign governments. Systems rated for power outputs of 500 kW and more are not uncommon. RF circuits designed specifically for high power operation are utilized.

Most shortwave transmitters have the unique requirement for automatic tuning to one of several preset operating frequencies. A variety of schemes exist to accomplish this task, including multiple exciters (each set to the desired operating frequency) and motor-controlled variable inductors and capacitors. Tune-up at each frequency is performed by the transmitter manufacturer. The settings of all tuning controls are stored in memory. Automatic retuning of a high-power shortwave transmitter can be accomplished in less than 30 seconds in most cases.

Power Amplifier Types

Shortwave technology has advanced significantly within the last 5 years, thanks to improved semiconductor devices. High-power MOSFETs and other components have made solid-state shortwave transmitters operating at 500 kW and more practical. The majority of shortwave systems now in use, however, use vacuum tubes as the power-generating element. The efficiency of a power amplifier/modulator for shortwave applications is of critical importance. Because of the power levels involved, low efficiency translates into higher operating costs.

Older, traditional tube-type shortwave transmitters typically utilize one of the following modulation systems:

- Doherty amplifier
- Chireix outphasing modulated amplifier
- Dome modulated amplifier
- Terman-Woodyard modulated amplifier

FM Radio Broadcasting

FM radio stations operate on 200-kHz channels spaced evenly from 88.1 to 107.9 MHz. In the United States, channels below 92.1 MHz are reserved for noncommercial, educational stations. The FCC has established three classifications for FM stations operating east of the Mississippi River and four classifications for stations west of the Mississippi. Power levels range from a high of 100 kW *effective radiated power* (ERP) to 3 kW or less for lower classifications. The ERP of a station is a function of transmitter power output (TPO) and antenna gain. ERP is determined by multiplying these two quantities together and allowing for line loss.

A transmitting antenna is said to have "gain" if, by design, it concentrates useful energy at low radiation angles, rather than allowing a substantial amount of energy to be radiated above the horizon (and be lost in space). FM and TV transmitting antennas are designed to provide gain by stacking individual radiating elements vertically.

At first examination, it might seem reasonable and economical to achieve licensed ERP using the lowest transmitter power output possible and highest antenna gain. Other factors, however, come into play that make the most obvious solution not always the best solution. Factors that limit the use of high-gain antennas include:

- Effects of high-gain designs on coverage area and signal penetration
- Limitations on antenna size because of tower restrictions, such as available vertical space, weight, and windloading
- Cost of the antenna

Stereo broadcasting is used almost universally in FM radio today. Introduced in the mid-1960s, stereo has contributed in large part to the success of FM radio. The left and right sum (monophonic) information is transmitted as a standard frequency-modulated signal. Filters restrict this *main channel* signal to a maximum of about 17 kHz. A pilot signal is transmitted at low amplitude at 19 kHz to enable decoding at the receiver. The left and right difference signal is transmitted as an amplitude-modulated subcarrier that frequency-modulates the main FM carrier. The center frequency of the subcarrier is 38 kHz. Decoder circuits in the FM receiver matrix the sum and difference signals to reproduce the left and right audio channels. Figure 1.9 illustrates the baseband signal of a stereo FM station.

Modulation Circuits

Early FM transmitters used *reactance modulators* that operated at low frequency. The output of the modulator was then multiplied to reach the desired output frequency. This approach was acceptable for monaural FM transmission but not for modern stereo systems or other applications that utilize subcarriers on the FM broadcast signal. Modern FM systems all utilize what is referred to as *direct modulation*. That is, the frequency modulation occurs in a modulated oscillator that operates on a center frequency equal to the desired transmitter output frequency. In stereo broadcast systems, a composite FM signal is applied to the FM modulator.

Various techniques have been developed to generate the direct-FM signal. One of the most popular uses a variable-capacity diode as the reactive element in the oscillator. The modulating signal is applied to the diode, which causes the capacitance of the device to vary as a function of the magnitude of the modulating signal. Variations in the capacitance cause the frequency of the oscillator to vary. Again, the magnitude of the frequency shift is proportional to the amplitude of the modulating signal, and the rate of frequency shift is equal to the frequency of the modulating signal.

The direct-FM modulator is one element of an FM transmitter exciter, which generates the composite FM waveform. A block diagram of a complete FM exciter is shown in Fig. 1.10. Audio inputs of various types (stereo left and right signals, plus subcarrier programming, if used) are buffered, filtered, and preemphasized before being summed to feed the modulated oscillator. It should be noted that the oscillator is not normally coupled directly to a crystal, but a free-running oscillator adjusted as closely as possible to the carrier frequency of the transmitter. The final operating frequency is carefully maintained by an automatic frequency control system employing a *phase-locked loop* (PLL) tied to a reference crystal oscillator or frequency synthesizer.

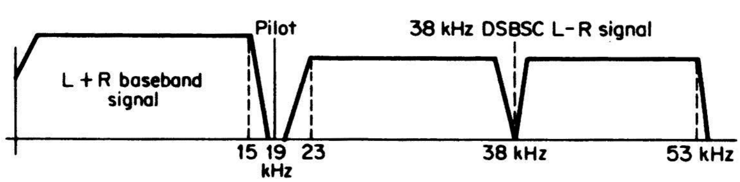

FIGURE 1.9 Composite baseband stereo FM signal.

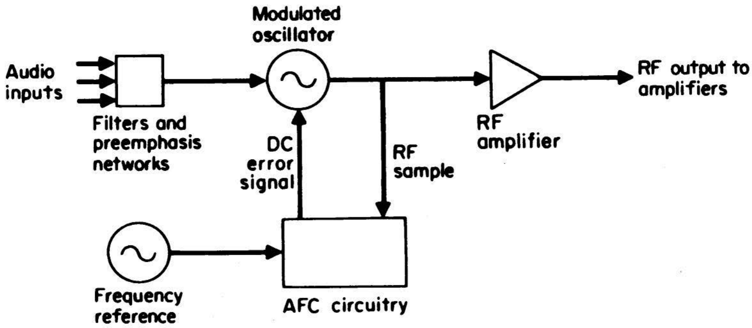

FIGURE 1.10 Block diagram of an FM exciter.

A solid-state class C amplifier follows the modulated oscillator and raises the operating power of the FM signal to 20 to 30 W. One or more subsequent amplifiers in the transmitter raise the signal power to several hundred watts for application to the final power amplifier stage. Nearly all current high-power FM transmitters utilize solid-state amplifiers up to the final RF stage, which is generally a vacuum tube for operating powers of 5 kW and above. All stages operate in the class C mode. In contrast to AM systems, each stage in an FM power amplifier can operate class C because no information is lost from the frequency-modulated signal due to amplitude changes. As mentioned previously, FM is a constant-power system.

Auxiliary Services

Modern FM broadcast stations are capable of not only broadcasting stereo programming, but one or more subsidiary channels as well. These signals, referred to by the FCC as *Subsidiary Communications Authorization* (SCA) services, are used for the transmission of stock market data, background music, control signals, and other information not normally part of the station's main programming. These services do not provide the same range of coverage or audio fidelity as the main stereo program; however, they perform a public service and can represent a valuable source of income for the broadcaster.

SCA systems provide efficient use of the available spectrum. The most common subcarrier frequency is 67 kHz, although higher subcarrier frequencies may be utilized. Stations that operate subcarrier systems are permitted by the FCC to exceed (by a small amount) the maximum 75-kHz deviation limit under certain conditions. The subcarriers utilize low modulation levels, and the energy produced is maintained essentially within the 200-kHz bandwidth limitation of FM channel radiation.

FM Power Amplifiers

Most high-power FM transmitters manufactured today employ cavity designs. The 1/4-wavelength cavity is the most common. The design is simple and straightforward. A number of variations can be found in different transmitters but the underlying theory of operation is the same. The goal of any cavity amplifier is to simulate a resonant tank circuit at the operating frequency and provide a means to couple the energy in the cavity to the transmission line. Because of the operating frequencies involved (88 to 108 MHz), the elements of the "tank" take on unfamiliar forms.

A typical 1/4-wave cavity is shown in Fig. 1.11. The plate of the tube connects directly to the inner section (tube) of the plate-blocking capacitor. The blocking capacitor can be formed in one of several ways. In at least one design, it is made by wrapping the outside surface of the inner tube conductor with multiple layers of insulating film. The exhaust chimney/inner conductor forms the other element of the blocking capacitor. The cavity walls form the outer conductor of the 1/4-wave transmission line circuit. The dc plate voltage is applied to the PA (power amplifier) tube by a cable routed inside the exhaust chimney and inner tube conductor. In this design, the screen-contact fingerstock ring mounts on a metal plate that is insulated from the grounded-cavity deck by a blocking capacitor. This hardware makes up

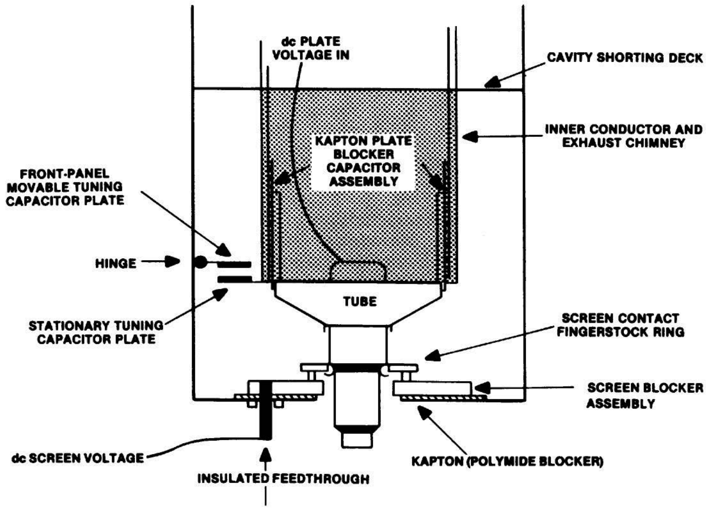

FIGURE 1.11 Physical layout of a common type of 1/4-wave PA cavity for FM broadcast service.

the screen-blocker assembly. The dc screen voltage feeds to the fingerstock ring from underneath the cavity deck through an insulated feedthrough.

Some transmitters that employ the 1/4-wave cavity design use a grounded-screen configuration in which the screen contact fingerstock ring is connected directly to the grounded cavity deck. The PA cathode then operates at below ground potential (i.e., at a negative voltage), establishing the required screen voltage for the tube.

Coarse tuning of the cavity is accomplished by adjusting the cavity length. The top of the cavity (the cavity shorting deck) is fastened by screws or clamps and can be raised or lowered to set the length of the assembly for the particular operating frequency. Fine-tuning is accomplished by a variable-capacity plate-tuning control built into the cavity. In the example, one plate of this capacitor, the stationary plate, is fastened to the inner conductor just above the plate-blocking capacitor. The movable tuning plate is fastened to the cavity box, the outer conductor, and is mechanically linked to the front-panel tuning control. This capacity shunts the inner conductor to the outer conductor and varies the electrical length and resonant frequency of the cavity.

Television Broadcasting

Television transmitters in the United States operate in three frequency bands:

- Low-band VHF: channels 2 through 6 (54–72 MHz and 76–88 MHz)
- High-band VHF: channels 7 through 13 (174–216 MHz)
- UHF: channels 14 through 69 (470–806 MHz). UHF channels 70 through 83 (806–890 MHz) have been assigned to land mobile radio services. Certain TV translators may continue to operate on these frequencies on a secondary basis.

Because of the wide variety of operating parameters for television stations outside the United States, this section focuses primarily on TV transmission as it relates to the United States (Table 1.2 shows the frequencies used by TV broadcasting). Maximum power output limits are specified by the FCC for each type of service. The maximum effective radiated power for low-band VHF is 100 kW; for high-band VHF, it is 316 kW; and for UHF, it is 5 MW.

The second major factor that affects the coverage area of a TV station is antenna height, known in the broadcast industry as *height above average terrain* (HAAT). HAAT takes into consideration the effects of the geography in the vicinity of the transmitting tower. The maximum HAAT permitted by the FCC for

TABLE 1.2 Channel Designations for VHF and UHF Television Stations in the U.S.

Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)
2	54–60	30	566–572	57	728–734
3	60–66	31	572–578	58	734–740
4	66–72	32	578–584	59	740–746
5	76–82	33	584–590	60	746–752
6	82–88	34	590–596	61	752–758
7	174–180	35	596–602	62	758–764
8	180–186	36	602–608	63	764–770
9	186–192	37	608–614	64	770–776
10	192–198	38	614–620	65	776–782
11	198–204	39	620–626	66	782–788
12	204–210	40	626–632	67	788–794
13	210–216	41	632–638	68	794–800
14	470–476	42	638–644	69	800–806
15	476–482	43	644–650	70	806–812
16	482–488	44	650–656	71	812–818
17	488–494	45	656–662	72	818–824
18	494–500	46	662–668	73	824–830
19	500–506	47	668–674	74	830–836
20	506–512	48	674–680	75	836–842
21	512–518	49	680–686	76	842–848
22	518–524	50	686–692	77	848–854
23	524–530	51	692–698	78	854–860
24	530–536	52	698–704	79	860–866
25	536–542	53	704–710	80	866–872
26	542–548	54	710–716	81	872–878
27	548–554	55	716–722	82	878–884
28	554–560	56	722–728	83	884–890
29	560–566				

a low- or high-band VHF station is 1000 ft (305 m) east of the Mississippi River, and 2000 ft (610 m) west of the Mississippi. UHF stations are permitted to operate with a maximum HAAT of 2000 ft (610 m) anywhere in the United States (including Alaska and Hawaii).

The ratio of visual output power to aural power can vary from one installation to another; however, the aural is typically operated at between 10 and 20% of the visual power. This difference is the result of the reception characteristics of the two signals. Much greater signal strength is required at the consumer's receiver to recover the visual portion of the transmission than the aural portion. The aural power output is intended to be sufficient for good reception at the fringe of the station's coverage area, but not beyond. It is of no use for a consumer to be able to receive a TV station's audio signal, but not the video.

In addition to the full-power stations discussed previously, two classifications of low-power TV stations have been established by the FCC to meet certain community needs. They are:

- *Translators:* low-power systems that rebroadcast the signal of another station on a different channel. Translators are designed to provide "fill-in" coverage for a station that cannot reach a particular community because of the local terrain. Translators operating in the VHF band are limited to 100 W power output (ERP), and UHF translators are limited to 1 kW.
- *Low-power television* (LPTV): a service established by the FCC to meet the special needs of particular communities. LPTV stations operating on VHF frequencies are limited to 100 W ERP and UHF stations are limited to 1 kW. LPTV stations originate their own programming and can be assigned by the FCC to any channel, as long as full protection against interference to a full-power station is afforded.

Television Transmission Standards

Analog television signals transmitted throughout the world have the following similarities.

- All systems use two fields interlaced to create a complete frame.
- All contain luminance, chrominance, syncronization, and sound components.
- All use amplitude modulation to put picture information onto the visual carrier.
- Modulation polarity, in most cases, is negative (greatest power output from the transmitter occurs during the sync interval; least power output occurs during peak white).
- The sound is transmitted on an aural carrier that is offset on a higher frequency than the visual carrier, using frequency modulation in most cases.
- All systems use a vestigial lower sideband approach.
- All systems derive a luminance and two-color difference signals from red, green, and blue components.

There the similarities stop and the differences begin. There are three primary color transmission standards in use.

- NTSC (National Television Systems Committee): used in the United States, Canada, Central America, most of South America, and Japan. In addition, NTSC has been accepted for use in various countries or possessions heavily influenced by the United States. The major components of the NTSC signal are shown in Fig. 1.12.
- PAL (Phase Alternation each Line): used in England, most countries and possessions influenced by the British Commonwealth, many western European countries, and China. Variation exists in PAL systems.
- SECAM (SEquential Color with [Avec] Memory): used in France, countries and possessions influenced by France, the U.S.S.R. (generally the Soviet Bloc nations, including East Germany), and other areas influenced by Russia.

The three standards are incompatible for the following reasons.

- Channel assignments are made in different frequency spectra in many parts of the world. Some countries have VHF only; some have UHF only; others have both. Assignments with VHF and UHF do not necessarily coincide between countries.
- Channel bandwidths are different. NTSC uses a 6-MHz channel width. Versions of PAL exist with 6-MHz, 7-MHz, and 8-MHz bandwidths. SECAM channels are 8-MHz wide.
- Vision bands are different. NTSC uses 4.2 MHz. PAL uses 4.2 MHz, 5 MHz, and 5.5 MHz, while SECAM has 6-MHz video bandwidth.
- The line structure of the signals varies. NTSC uses 525 lines per frame, 30 frames (60 fields) per second. PAL and SECAM use 625 lines per frame, 25 frames (50 fields) per second. As a result, the scanning frequencies also vary.
- The color subcarrier signals are incompatible. NTSC uses 3.579545 MHz, PAL uses 4.43361875 MHz, while SECAM utilizes two subcarriers, 4.40625 MHz and 4.250 MHz. The color subcarrier values are derived from the horizontal frequencies in order to interleave color information into the luminance signal without causing undue interference.
- The color encoding system of all three standards differ.
- The offset between visual and aural carriers varies. In NTSC, is it 4.5 MHz; in PAL, the separation is 5.5 or 6 MHz, depending on the PAL type; and SECAM uses 6.5-MHz separation.
- One form of SECAM uses positive polarity visual modulation (peak white produces greatest power output of transmitter) with amplitude modulation for sound.
- Channels transmitted on UHF frequencies may differ from those on VHF in some forms of PAL and SECAM. Differences include channel bandwidth and video bandwidth.

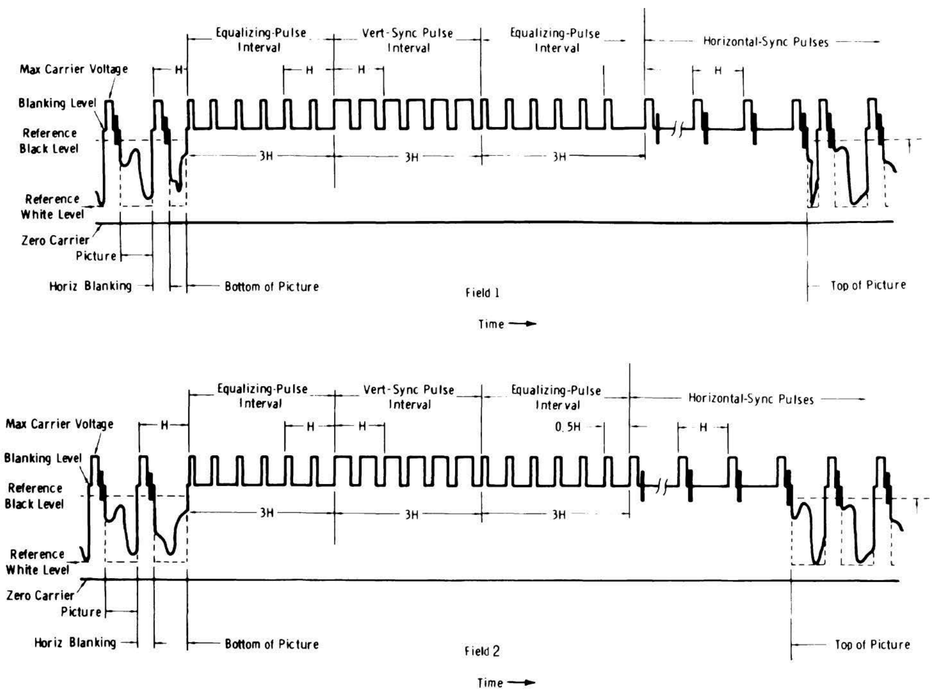

FIGURE 1.12 The major components of the NTSC television signal. H = time from start of line to the start of the next line. V = time from the start of one field to the start of the next field.

It is possible to convert from one television standard to another electronically. The most difficult part of the conversion process results from the differing number of scan lines. In general, the signal must be disassembled in the input section of the standards converter, and then placed in a large dynamic memory. Complex computer algorithms compare information on pairs of lines to determine how to create the new lines required (for conversion to PAL or SECAM) or how to remove lines (for conversion to NTSC). Non-moving objects in the picture present no great difficulties, but motion in the picture can produce objectionable artifacts as the result of the sampling system.

Transmitter Design Considerations

An analog television transmitter is divided into two basic subsystems: (1) the *visual* section, which accepts the video input, amplitude-modulates an RF carrier, and amplifies the signal to feed the antenna system; and (2) the *aural* section, which accepts the audio input, frequency-modulates a separate RF carrier, and amplifies the signal to feed the antenna system. The visual and aural signals are usually combined to feed a single radiating antenna. Different transmitter manufacturers have different philosophies with regard to the design and construction of a transmitter. Some generalizations can, however, be made with respect to basic system design. Transmitters can be divided into categories based on the following criteria:

- Output power
- Final stage design
- Modulation system

Output Power

When the power output of a TV transmitter is discussed, the visual section is the primary consideration. Output power refers to the peak power of the visual stage of the transmitter (*peak of sync*). The

FCC-licensed ERP is equal to the transmitter power output times feedline efficiency times the power gain of the antenna.

A low-band VHF station can achieve its maximum 100-kW power output through a wide range of transmitter and antenna combinations. A 35-kW transmitter coupled with a gain-of-4 antenna would do the trick, as would a 10-kW transmitter feeding an antenna with a gain of 12. Reasonable parings for a high-band VHF station would range from a transmitter with a power output of 50 kW feeding an antenna with a gain of 8, to a 30-kW transmitter connected to a gain-of-12 antenna. These combinations assume reasonable feedline losses. To reach the exact power level, minor adjustments are made to the power output of the transmitter, usually by a front panel power control.

UHF stations that want to achieve their maximum licensed power output are faced with installing a very high power (and very expensive) transmitter. Typical pairings include a transmitter rated for 220 kW and an antenna with a gain of 25, or a 110-kW transmitter and a gain-of-50 antenna. In the latter case, the antenna could pose a significant problem. UHF antennas with gains in the region of 50 are possible but not advisable for most installations because of the coverage problems that can result. High-gain antennas have a narrow vertical radiation pattern that can reduce a station's coverage in areas near the transmitter site. Whatever way is chosen, getting 5-MW ERP is an expensive proposition. Most UHF stations therefore operate considerably below the maximum permitted ERP.

Final Stage Design

The amount of output power required of a transmitter will have a fundamental effect on system design. Power levels usually dictate whether the unit will be of solid-state or vacuum tube design; whether air, water, or vapor cooling must be used; the type of power supply required; the sophistication of the high-voltage control and supervisory circuitry; and whether *common amplification* of the visual and aural signals (rather than separate visual and aural amplifiers) is practical.

Tetrodes are generally used for VHF transmitters above 5 kW and for low-power UHF transmitters (below 5 kW). As solid-state technology advances, the power levels possible in a reasonable transmitter design steadily increase. As of this writing, all-solid-state VHF transmitters of 60 kW have been produced.

In the realm of UHF transmitters, the klystron and related devices reign supreme. Klystrons use an electron bunching technique to generate high power (55 kW from a single tube is not uncommon) at UHF frequencies. They are currently the first choice for high-power service. Klystrons, however, are not particularly efficient. A stock klystron with no special circuitry might be only 40% efficient. Various schemes have been devised to improve klystron efficiency, one of the oldest being *beam pulsing*. Two types of pulsing are in common use:

- *Mod-anode pulsing*, a technique designed to reduce power consumption of the device during the color burst and video portion of the signal (and thereby improve overall system efficiency).
- *Annular control electrode* (ACE) *pulsing*, which accomplishes basically the same thing by incorporating the pulsing signal into a low-voltage stage of the transmitter, rather than a high-voltage stage (as with mod-anode pulsing).

Variations of the basic klystron intended to improve UHF transmitter efficiency include the following:

- The *inductive output tube* (IOT): a device that essentially combines the cathode/grid structure of the tetrode with the drift tube/collector structure of the klystron.
- The *multi-stage depressed collector* (MSDC) *klystron:* a device that achieves greater efficiency through a redesign of the collector assembly. A multi-stage collector is used to recover energy from the electron stream inside the klystron and return it to the beam power supply.
- *Modulation system:* a number of approaches may be taken to amplitude modulation of the visual carrier. Most systems utilize low-level, intermediate frequency (IF) modulation. This approach allows superior distortion correction, more accurate vestigial sideband shaping, and significant economic advantages to the transmitter manufacturer.

Elements of the Transmitter

An analog television transmitter can be divided into four major subsystems:

- The exciter
- Intermediate power amplifier (IPA)
- Power amplifier
- High-voltage power supply

Figure 1.13 shows the audio, video, and RF paths for a typical design. The exciter includes of the following circuits:

- Video input buffer
- Exciter-modulator
- RF processor

Depending on the design of the transmitter, these sections may be separate units or simply incorporated into the exciter itself. A power supply section supplies operating voltages to the various subassemblies of the transmitter.

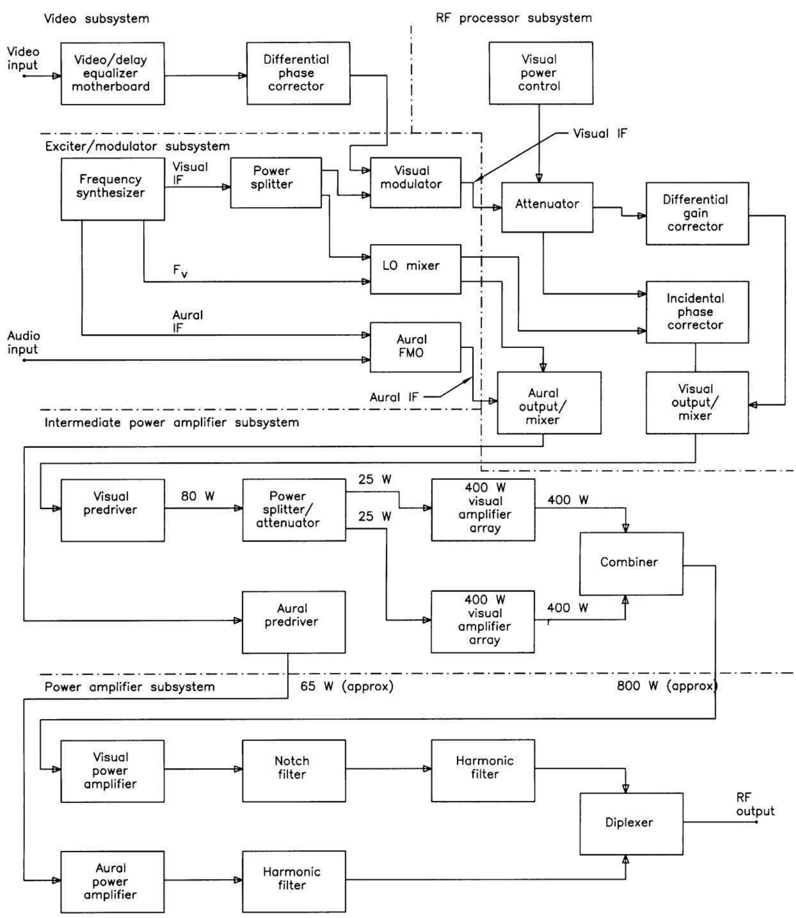

FIGURE 1.13 Simplified block diagram of a television transmitter.

Intermediate Power Amplifier

The function of the IPA is to develop the power output necessary to drive the power amplifier stages for the aural and visual systems. A low-band, 16- to 20-kW transmitter typically requires about 800 W RF drive, and a high-band, 35- to 50-kW transmitter needs about 1600 W. A UHF transmitter utilizing a high-gain klystron final tube requires about 20 W drive, while a UHF transmitter utilizing a klystrode tube needs about 80 W. Because the aural portion of a television transmitter operates at only 10 to 20% of the visual power output, the RF drive requirements are proportionately lower.

Virtually all transmitters manufactured today utilize solid-state devices in the IPA. Transistors are preferred because of their inherent stability, reliability, and ability to cover a broad band of frequencies without retuning. Present solid-state technology, however, cannot provide the power levels needed by most transmitters in a single device. To achieve the needed RF energy, devices are combined using a variety of schemes.

A typical "building block" for a solid-state IPA provides a maximum power output of approximately 200 W. To meet the requirements of a 20-kW low-band VHF transmitter, a minimum of four such units would have to be combined. In actual practice, some amount of *headroom* is always designed into the system to compensate for component aging, imperfect tuning in the PA stage, and device failure.

Most solid-state IPA circuits are configured so that in the event of a failure in one module, the remaining modules will continue to operate. If sufficient headroom has been provided in the design, the transmitter will continue to operate without change. The defective subassembly can then be repaired and returned to service at a convenient time.

Because the output of the RF up-converter is about 10 W, an intermediate amplifier is generally used to produce the required drive for the parallel amplifiers. The individual power blocks are fed by a splitter that feeds equal RF drive to each unit. The output of each RF power block is fed to a hybrid combiner that provides isolation between the individual units. The combiner feeds a bandpass filter that allows only the modulated carrier and its sidebands to pass.

The inherent design of a solid-state RF amplifier permits operation over a wide range of frequencies. Most drivers are broadband and require no tuning. Certain frequency-determined components are added at the factory (depending on the design); however, from the end-user standpoint, solid-state drivers require virtually no attention. IPA systems are available that cover the entire low- or high-band VHF channels without tuning.

Advances continue to be made in solid-state RF devices. New developments promise to substantially extend the reach of semiconductors into medium-power RF operation. Coupled with better devices are better circuit designs, including parallel devices and new push–pull configurations. Another significant factor in achieving high power from a solid-state device is efficient removal of heat from the component itself.

Power Amplifier

The power amplifier (PA) raises the output energy of the transmitter to the required RF operating level. As noted previously, solid-state devices are increasingly being used through parallel configurations in high-power transmitters. Still, however, the majority of television transmitters in use today utilize vacuum tubes. The workhorse of VHF television is the tetrode, which provides high output power, good efficiency, and good reliability. In UHF service, the klystron is the standard output device for transmitters above 20 kW.

Tetrodes in television service are operated in the class B mode to obtain reasonable efficiency while maintaining a linear transfer characteristic. Class B amplifiers, when operated in tuned circuits, provide linear performance because of the *fly-wheel effect* of the resonance circuit. This allows a single tube to be used instead of two in push–pull fashion. The bias point of the linear amplifier must be chosen so that the transfer characteristic at low modulation levels matches that at higher modulation levels. Even so, some nonlinearity is generated in the final stage, requiring differential gain correction. The plate (anode) circuit of a tetrode PA is usually built around a coaxial resonant cavity, which provides a stable and reliable tank.

UHF transmitters using a klystron in the final output stage must operate class A, the most linear but also most inefficient operating mode for a vacuum tube. The basic efficiency of a non-pulsed klystron is approximately 40%. Pulsing, which provides full available beam current only when it is needed (during peak of sync), can improve device efficiency by as much as 25%, depending on the type of pulsing used.

Two types of klystrons are presently in service: integral cavity and external cavity devices. The basic theory of operation is identical for each tube; however, the mechanical approach is radically different. In the integral cavity klystron, the cavities are built into the klystron to form a single unit. In the external cavity klystron, the cavities are outside the vacuum envelope and bolted around the tube when the klystron is installed in the transmitter.

A number of factors come into play in a discussion of the relative merits of integral-vs.-external cavity designs. Primary considerations include operating efficiency, purchase price, and life expectancy.

The PA stage includes a number of sensors that provide input to supervisory and control circuits. Because of the power levels present in the PA stage, sophisticated fault-detection circuits are required to prevent damage to components in the event of a problem either external to or inside the transmitter. An RF sample, obtained from a directional coupler installed at the output of the transmitter, is used to provide automatic power-level control.

The transmitter system discussed thus far assumes separate visual and aural PA stages. This configuration is normally used for high-power transmitters. Low-power designs often use a combined mode in which the aural and visual signals are added prior to the PA. This approach offers a simplified system, but at the cost of additional pre-correction of the input video signal.

PA stages are often configured so that the circuitries of the visual and aural amplifiers are identical. While this represents a good deal of "overkill" insofar as the aural PA is concerned, it provides backup protection in the event of a visual PA failure. The aural PA can then be reconfigured to amplify both the aural and visual signals at reduced power.

The aural output stage of a television transmitter is similar in basic design to an FM broadcast transmitter. Tetrode output devices generally operate class C, providing good efficiency. Klystron-based aural PAs are used in UHF transmitters.

Coupling/Filtering System

The output of the aural and visual power amplifiers must be combined and filtered to provide a signal that is electrically ready to be applied to the antenna system. The primary elements of the coupling and filtering system of a TV transmitter are:

- Color notch filter
- Aural and visual harmonic filters
- Diplexer

In a low-power transmitter (below 5 kW), this hardware may be included within the transmitter cabinet itself. Normally, however, it is located external to the transmitter.

Color Notch Filter

The color notch filter is used to attenuate the color subcarrier lower sideband to the –42 dB requirements of the FCC. The color notch filter is placed across the transmitter output feedline. The filter consists of a coax or waveguide stub tuned to 3.58 MHz below the picture carrier. The Q of the filter is high enough so that energy in the vestigial sideband is not materially affected, while still providing high attenuation at 3.58 MHz.

Harmonic Filters

Harmonic filters are used to attenuate out-of-band radiation of the aural and visual signals to ensure compliance with FCC requirements. Filter designs vary, depending on the manufacturer; however, most are of coaxial construction utilizing components housed within a prepackaged assembly. Stub filters are also used, typically adjusted to provide maximum attenuation at the second harmonic of the operating frequency of the visual carrier and the aural carrier.

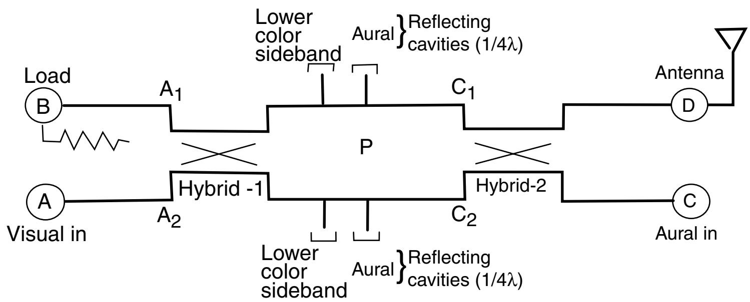

FIGURE 1.14 Functional diagram of a notch diplexer, used to combine the aural and visual outputs of a television transmitter for application to the antenna.

Diplexer/Combiner

The filtered visual and aural outputs are fed to a diplexer where the two signals are combined to feed the antenna (see Fig. 1.14). For installations that require dual-antenna feedlines, a hybrid combiner with quadrature-phased outputs is used. Depending on the design and operating power, the color notch filter, aural and visual harmonic filters, and diplexer can be combined into a single mechanical unit.

A hybrid combiner serves as the building block of the notch diplexer, which combines the aural and visual RF signals to feed a single-line antenna system and provide a constant impedance load to each section of the transmitter.

The notch diplexer consists of two hybrid combiners and two sets of reject cavities. The system is configured so that all of the energy from the visual transmitter passes to the antenna (port D), and all of the energy from the aural transmitter passes to the antenna. The phase relationships are arranged so that the input signals cancel at the resistive load (port B). Because of the paths taken by the aural and visual signals through the notch diplexer, the amplitude and phase characteristics of each input do not change from the input ports (port A for the visual and port C for the aural) and the antenna (port D), thus preserving signal purity.

1.3 Nonbroadcast Applications

Radio and television broadcasting are the most obvious applications of RF technology. In total numbers of installations, however, nonbroadcast uses for RF far outdistance radio and TV stations. Applications range from microwave communications to induction heating. Power levels range from a few tens of watts to a million watts or more. The areas of nonbroadcast RF technology covered in this section include:

- Satellite transmission
- Radar
- Electronic navigation
- Induction heating

Satellite Transmission

Commercial satellite communication began on July 10, 1962, when television pictures were first beamed across the Atlantic Ocean through the Telstar 1 satellite. Three years later, the INTELSAT system of *geostationary* relay satellites saw its initial craft, Early Bird 1, launched into a rapidly growing communications industry. In the same year, the U.S.S.R. inaugurated the Molnya series of satellites traveling in an elliptical orbit to better meet the needs of that nation. The Molnya satellites were placed in an orbit inclined about 64° relative to the equator, with an orbital period half that of the Earth.

All commercial satellites in use today operate in a geostationary orbit. A geostationary satellite is one that maintains a fixed position in space relative to Earth because of its altitude, roughly 22,300 miles above the Earth. Two primary frequency bands are used: the *C-band* (4–6 GHz) and the *Ku-band* (11–14 GHz). Any satellite relay system involves three basic sections:

- An *uplink* transmitting station, which beams signals toward the satellite in its equatorial geostationary orbit
- The satellite (the space segment of the system), which receives, amplifies, and retransmits the signals back to Earth
- The *downlink* receiving station, which completes the relay path

Because of the frequencies involved, satellite communication is designated as a microwave radio service. As such, certain requirements are placed on the system. Like terrestrial microwave, the path between transmitter and receiver must be line-of-sight. Meteorological conditions, such as rain and fog, result in detrimental attenuation of the signal. Arrangements must be made to shield satellite receive antennas from terrestrial interference. Because received signal strength is based on the inverse square law, highly directional transmit and receive parabolic antennas are used, which in turn requires a high degree of aiming accuracy. To counteract the effects of galactic and thermal noise sources on low-level signals, amplifiers are designed for exceptionally low noise characteristics. Figure 1.15 shows the primary elements of a satellite relay system.

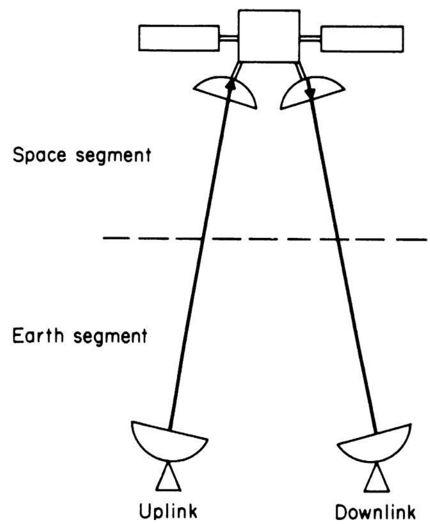

FIGURE 1.15 A satellite communications link consists of an uplink, the satellite (as the space segment), and a downlink.

Satellite Communications

The first satellites launched for INTELSAT and other users contained only one or two radio relay units (*transponders*). Pressure for increased satellite link services has driven engineers to develop more economical systems with multiple transponder designs. Generally, C-band satellites placed in orbit now typically have 24 transponders, each with 36-MHz bandwidths. Ku-band systems often use fewer transponders with wider bandwidths.

Users of satellite communication links are assigned to transponders generally on a lease basis, although it may be possible to purchase a transponder. Assignments usually leave one or more spare transponders aboard each craft, allowing for standby capabilities in the event a transponder should fail.

By assigning transponders to users, the satellite operator simplifies the design of uplink and downlink facilities. The Earth station controller can be programmed according to the transponder of interest. For example, a corporate video facility may need to access four or five different transponders from one satellite. To do so, the operator needs only to enter the transponder number (or carrier frequency) of interest. The receiver handles retuning and automatic switching of signals from a dual-polarity feedhorn on the antenna.

Each transponder has a fixed center frequency and a specific signal polarization. For example, according to one frequency plan, all odd-numbered transponders use horizontal polarization while the even-numbered ones use vertical polarization. Excessive deviation from the center carrier frequency by one signal does not cause interference between two transponders and signals because of the isolation provided by cross-polarization. This concept is extended to satellites in adjacent parking spaces in *geosynchronous* orbit. Center frequencies for transponders on adjacent satellites are offset in frequency from those on the first craft. In addition, an angular offset of polarization is employed. The even and odd transponder assignments are still offset by 90° from one another. As spacing is decreased between satellites, the polarization offset must be increased to reduce the potential for interference.

Satellite Uplink

The ground-based transmitting equipment of the satellite system consists of three sections: baseband, intermediate frequency (IF), and radio frequency (RF).

The baseband section interfaces various incoming signals with the transmission format of the satellite being used. Signals provided to the baseband section may already be in a modulated form with modulation characteristics (digital, analog, or some other format) determined by the terrestrial media that brings the signals to the uplink site. Depending on the nature of the incoming signal (voice, data, or video), some degree of processing will be applied. In many cases, multiple incoming signals will be combined into a single composite uplink signal through multiplexing.

When the incoming signals are in the correct format for transmission to the satellite, they are applied to an FM modulator, which converts the composite signal upward to a 70-MHz intermediate frequency. The use of an IF section has several advantages:

- A direct conversion between baseband and the output frequency presents difficulties in maintaining frequency stability of the output signal.
- Any mixing or modulation step has the potential of introducing unwanted by-products. Filtering at the IF may be used to remove spurious signals resulting from the mixing process.
- Many terrestrial microwave systems include a 70 MHz IF section. If a signal is brought into the uplink site by terrestrial microwave, it becomes a simple matter to connect the signal directly into the IF section of the uplink system.

From the 70-MHz IF, the signal is converted upward again, this time to the output frequency of 6 GHz (for C-band) or 14 GHz (for Ku-band) before application to a high-power amplifier (HPA). Conventional Earth station transmitters operate over a wide power range, from a few tens of watts to 12 kW or more. Transmitters designed for deep space research can operate at up to 400 kW.

Several amplifying devices are used in HPA designs, depending on the power output and frequency requirements. For the highest power level in C- or Ku-band, klystrons are employed. Devices are available with pulsed outputs ranging from 500 W to 5 kW, and a bandwidth capability of 40-MHz. This means that a separate klystron is required for each 40 MHz wide signal to be beamed upward to a transponder.

The *traveling wave tube* (TWT) is another type of vacuum power device used for HPA transmitters. While similar in some areas of operation to klystrons, the TWT is capable of amplifying a band of signals at least ten times wider than the klystron. Thus, one TWT system can be used to amplify the signals sent to several transponders on the satellite. With output powers from 100 W to 2.5 kW, the bandwidth capability of the TWT offsets its much higher price than the klystron in some applications.

Solid-state amplifiers based on MOSFET technology can be used for both C- and Ku-band uplink HPA systems. The power capabilities of solid-state units are limited, 5 to 50 W or so for C-band and 1 to 6 W for Ku-band. Such systems, however, offer wideband performance and good reliability.

Uplink Antennas

The output of the HPA, when applied to a parabolic reflector antenna, experiences a high degree of gain when referenced to an ideal isotropic antenna (dBi). For example, large reflector antennas approximately 10 m in diameter offer gains as high as 55 dB, increasing the output of a 3-kW klystron or TWT amplifier to an effective radiated power of 57 to 86 dBW. Smaller reflector sizes (6 to 8 m) can also be used, with the observation of certain restrictions in regard to interference with other satellites and other services. Not surprisingly, smaller antennas provide lower gain. For a 30-m reflector, such as those used for international satellite communications, approximately 58 dB gain can be achieved. Several variations of parabolic antenna designs are used for satellite communications services, including the following (see Fig. 1.16):

- *Prime focus, single parabolic reflector:* places the source of the signal to be transmitted in front of the reflector precisely at the focal point of the parabola. Large antennas of this type commonly employ a feedhorn supported with a tripod of struts. Because the struts, the waveguide to the feedhorn, and the horn assembly itself are located directly within the transmitted beam, every effort is made to design these components with as little bulk as possible, yet physically strong enough to withstand adverse weather conditions.

- *Offset reflector:* removes the feedhorn and its support from the radiated beam. Although the reflector maintains the shape of a section of a parabola, the closed end of the curve is not included. The feedhorn, while still located at the focal point of the curve, points at an angle from the vertex of the parabola shape.
- *Double reflector:* the primary reflector is parabolic in shape while the subreflector surface, mounted in front of the focal point of the parabola, is hyperbolic in shape. One focus of the hyperbolic reflector is located at the parabolic focal point, while the second focal point of the subreflector defines the position for the feedhorn signal source. Signals reflected from the hyperbolic subreflector are spread across the parabolic prime reflector, which then directs them as a parallel beam toward the satellite. This two-reflector antenna provides several advantages over a single-reflector type: (1) the overall front-to-back dimension of the two-reflector system is shorter, which simplifies mounting and decreases wind-loading; (2) placement of the subreflector closer to the main reflector generates less spillover signal because energy is not directed as closely to the edge of the main reflector; and (3) the accuracy of the reflector surfaces is not as stringent as with a single-reflector type of structure.

The antenna used for signal transmission to the satellite can also be used to receive signals from the satellite. The major change needed to provide this capability is the addition of directional switching or coupling to prevent energy from the transmitter HPA from entering the receiver system. Switching devices or *circulators* use waveguide characteristics to create a signal path linking the transmitter signal to the antenna feedhorn, while simultaneously providing a received signal path from the feedhorn to the receiver input.

Signal Formats

The signal transmitted from the uplink site (or from the satellite, for that matter) is in the form of frequency modulation. Limitations are placed on uplinked signals to avoid interference problems resulting from excessive bandwidth. For example, a satellite relay channel for television use typically contains

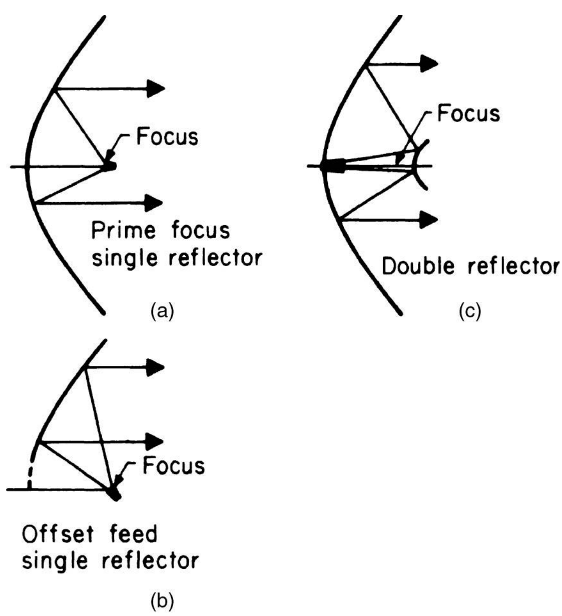

FIGURE 1.16 Satellite transmitting/receiving antennas: (a) prime focus, single reflector; (b) offset feed, single reflector; (c) double reflector.

only a single video signal and its associated audio. Audio is carried on one or more subcarriers that are stacked onto the video signal. To develop the composite signal, each audio channel is first modulated onto its subcarrier frequency. Then, each of the subcarriers and the main channel of video are applied as modulation to the uplink carrier. The maximum level of each component is controlled to avoid overmodulation.

In the case of telephone relay circuits, the same subcarrier concept is used. A number of individual voice circuits are combined into groups, which are then multiplexed to subcarriers through various digital means. The result is that thousands of telephone conversations can occur simultaneously through a single satellite.

Satellite Link

Like other relay stations, the communications spacecraft contains antennas for receiving and retransmission. From the antenna, signals pass through a low-noise amplifier before frequency conversion to the transmit band. A high-power amplifier feeds the received signal to a directional antenna, which beams the information to a predetermined area of the Earth to be served by the satellite (see Fig. 1.17).

Power to operate the electronics hardware is generated by solar cells. Inside the satellite, storage batteries, kept recharged by the solar cell arrays, carry the electronic load, particularly when the satellite is eclipsed by the Earth. Figure 1.18 shows the two most common solar cell configurations.

Power to the electronics on the craft requires protective regulation to maintain consistent signal levels. Most of the equipment operates at low voltages, but the final stage of each transponder chain ends in a high-power amplifier. The HPA of C-band satellite channels may include a traveling wave tube or a solid-state power amplifier (SSPA). Ku-band systems typically rely on TWT devices. Klystrons and TWTs require multiple voltages levels. The filaments operate at low voltages but beam focus and electron collection electrodes require voltages in the hundreds and thousands of volts. To develop such a range of voltages, the satellite power supply includes voltage converters.

From these potentials, the klystron or TWT produces output powers in the range of 8.5 to 20 W. Most systems are operated at the lower end of the range to increase reliability and life expectancy. In general, the lifetime of the spacecraft is assumed to be 7 years.

A guidance system is included to stabilize the attitude of the craft as it rotates around the earth. Small rocket engines are provided for maintaining an exact position in the assigned geostationary arc (see Fig. 1.19). This work is known as *station-keeping*.

Satellite Antennas

The antenna system for a communications satellite is really several antennas combined into a single assembly. One is for receiving signals from Earth. Another, obviously, is for transmitting those signals

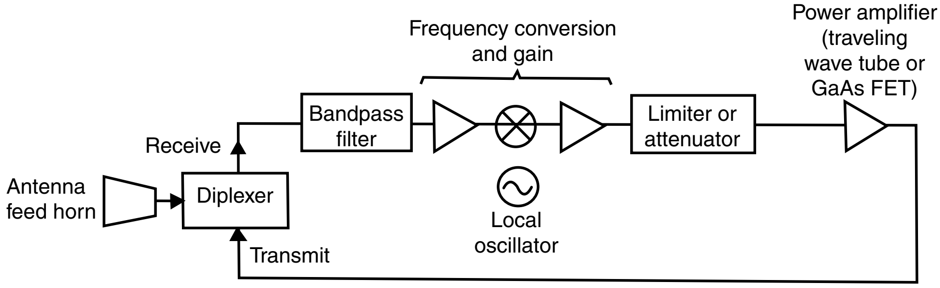

FIGURE 1.17 Block diagram of a satellite transponder channel.

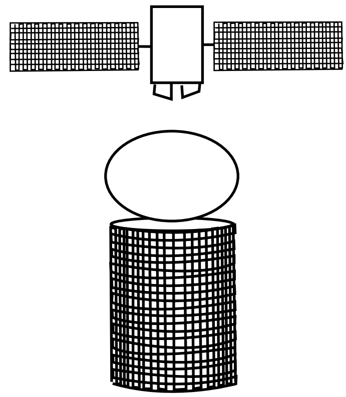

FIGURE 1.18 The two most common types of solar cell arrays used for communications satellites.

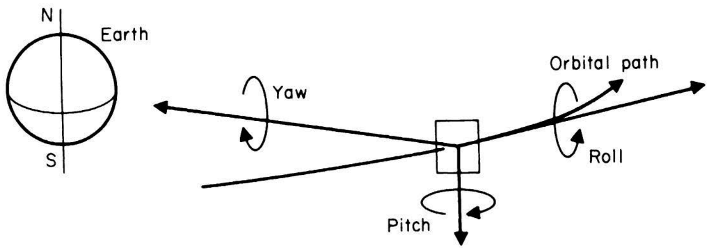

FIGURE 1.19 Attitude of the spacecraft is determined by pitch, roll, and yaw rotations around three reference axes.

back to Earth. The transmitting antenna can be made of more than one section to handle the needs of multiple signal beams. Finally, a receive-transmit beacon antenna provides communication with the ground-based satellite control station.

At the receiving end of the transponder, signals coming from the antenna are split into separate bands through a channelizing network, allowing each input signal to be directed to its own receiver, processing amplifier, and HPA. At the output, a combiner brings all channels together again into one signal to be fed to the transmitting antenna.

The approach to designing the complex antenna system for a relay satellite depends a good deal on horizontal and vertical polarization of the signals as a means to keep incoming and outgoing information separated. Multilayer, dichroic reflectors that are sensitive to the polarizations can be used for such purposes. Also, multiple feedhorns may be needed to develop one or more beams back to Earth. Antennas for different requirements may combine several antenna designs, but nearly all are based on the parabolic reflector. The parabolic design offers a number of unique properties. First, rays received by such a structure that are parallel to the feed axis are reflected and converged at the focus. Second, rays emitted from the focal point are reflected and emerge parallel to the feed axis. Special cases may involve some use of spherical and elliptical reflector shapes, but the parabolic is of most importance.

Satellite Downlink

Satellite receiving stations, like uplink equipment, perform the function of interfacing ground-based equipment to satellite transponders. Earth stations consist of a receiving antenna, *low noise amplifier* (LNA), 4-GHz (C-band) or 11-GHz (Ku-band) tuner, 70-MHz IF section, and baseband output stage.

Downlink Antennas

Antenna type and size for any application are determined by the mode of transmission, band of operation, location of the receiving station, typical weather in the receiving station locale, and the

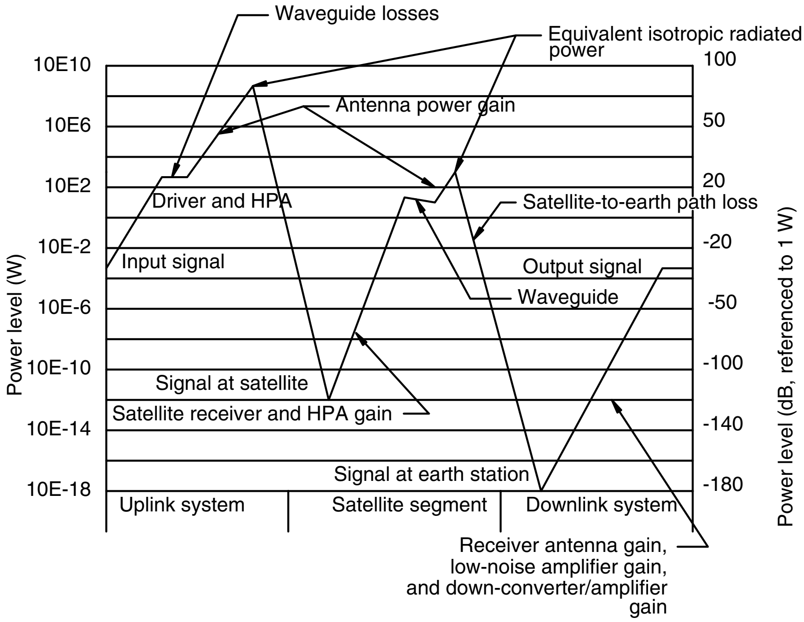

FIGURE 1.20 The power levels in transmission of an analog TV signal via satellite.

required quality of the output signal. Digital transmissions allow a smaller main reflector to be used because the decoding equipment is usually designed to provide error correction. The data stream periodically includes information to check the accuracy of the data and, if errors are found, to make corrections. Sophisticated error concealment techniques make it possible to correct errors to a certain extent. Greater emphasis is placed on error correction for applications involving financial transactions or life-critical data, such as might be involved with a manned space flight. For entertainment programming, such as TV broadcasts and telephone audio, absolute correction is less critical and gives way primarily to concealment techniques.

Receiving antennas for commercial applications, such as radio/TV networks, cable TV networks, and special services or teleconferencing centers, generally fall into the 7- to 10-m range for C-band operation. Ku-band units can be smaller. Antennas for consumer and business use may be even more compact, depending on the type of signal being received and the quality of the signal to be provided by the downlink. The nature of the application also helps determine if the antenna will be strictly parabolic, or if one of the spherical types, generally designed for consumer use, will be sufficient.

In general, the gain and directivity of a large reflector are greater than for a small reflector. The size of the reflector required depends on the level of signal that can be reliably received at a specific location under the worst-possible conditions. Gain must be adequate to bring the RF signal from the satellite to a level that is acceptable to the electronics equipment. The output signal must maintain a signal-to-noise ratio sufficiently high that the receiver electronics can recover the desired signal without significant degradation from noise.

It is instructive to consider the power budget of the downlink, that is, a calculation of positive and negative factors determining signal level. Figure 1.20 shows an analysis of both the uplink and downlink functions, as well as typical values of gain or loss. From this figure the need for receiving equipment with exceptional low noise performance becomes more obvious. One of the most critical parts of the receiver is the low noise amplifier (LNA) or *low noise conversion* unit (LNC), which is the first component following the antenna to process the signal. Such devices are rated by their *noise temperature*, usually a number around 211 K. The cost of an LNA or LNC increases significantly as the temperature figure goes down.

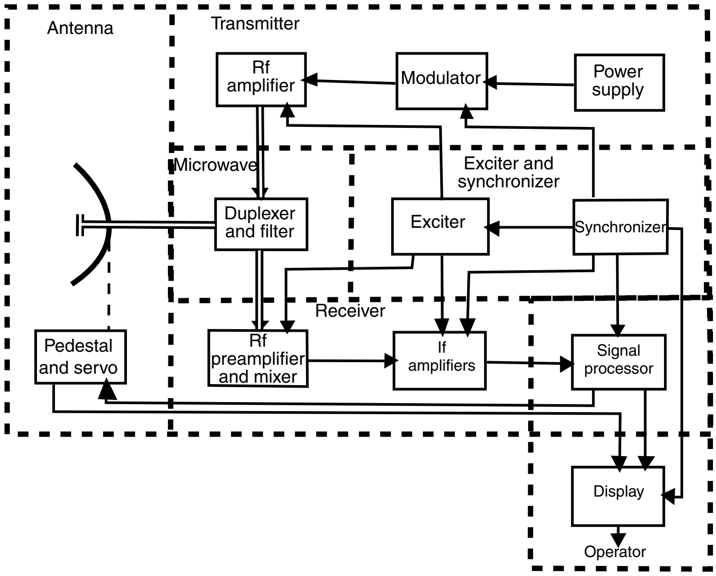

FIGURE 1.21 Simplified block diagram of a pulsed radar system.

Radar

The word "radar" is an acronym for *radio detection and ranging*. The name accurately spells out the basic function of a radar system. The measurement of target angles is an additional function of most radar equipment. Doppler velocity can also be measured as an important parameter. A block diagram of a typical pulsed radar system is shown in Fig. 1.21. Any system can be divided into six basic subsections:

- *Exciter and synchronizer:* controls the sequence of transmission and reception
- *Transmitter:* generates a high-power RF pulse of specified frequency and shape
- *Microwave network:* couples the transmitter and receiver sections to the antenna
- *Antenna system:* consists of a radiating/receiving structure mounted on a mechanically steered, servo-driven pedestal. A *stationary array*, which uses electrical steering of the antenna system, can be used in place of the mechanical system shown in Fig. 1.21.
- *Receiver:* selects and amplifies the return pulse picked up by the antenna
- *Signal processor and display:* integrates the detected echo pulse, synchronizer data, and antenna pointing data for presentation to an operator

Radar technology is used for countless applications. Table 1.3 lists some of the more common uses.

Radar Parameters

Because radar systems have many diverse applications, the parameters of frequency, power, and transmission format also vary widely. There are no fundamental bounds on the operating frequencies of radar. In fact, any system that locates objects by detecting echoes scattered from a target that has been illuminated with electromagnetic energy can be considered radar. While the principles of operation are similar regardless of the frequency, the functions and circuit parameters of most radar systems can be divided into specific operating bands. Table 1.4 shows the primary bands in use today. As shown in this table, letter designations have been developed for most of the operating bands.

Radar frequencies have been selected to minimize atmospheric attenuation by rain and snow, clouds, and fog, and (at some frequencies) electrons in the air. The frequency bands must also support wide bandwidth radiation and high antenna gain.

TABLE 1.3 Typical Radar Applications

Air surveillance	Long-range early warning, ground-controlled intercept, acquisition for weapon system, height finding and three-dimensional radar, airport and air-route surveillance
Space and missile surveillance	Ballistic missile warning, missile acquisition, satellite surveillance
Surface-search and battlefield surveillance	Sea search and navigation, ground mapping, mortar and artillery location, airport taxiway control
Weather radar	Observation and prediction, weather avoidance (aircraft), cloud-visibility indicators
Tracking and guidance	Antiaircraft fire control, surface fire control, missile guidance, range instrumentation, satellite instrumentation, precision approach and landing
Astronomy and geodesy	Planetary observation, earth survey, ionospheric sounding

Source: Fink, D. and Christiansen, Eds., *Electronics Engineers' Handbook*, 3rd ed., McGraw-Hill, New York, 1989, Table 302. IEEE standard 521–1976.

TABLE 1.4 Radar Frequency Bands

Name	Frequency Range	Radiolocation Bands based on ITU Assignments in Region II
VHF	30–300 MHz	137–144 MHz
UHF	300–1,000 MHz	216–225 MHz
P-band[b]	230–1,000 MHz	420–450 MHz
		890–940[a] MHz
L-band	1,000–2,000 MHz	1,215–1,400 MHz
S-band	2,000–4,000 MHz	2,300–2,550 MHz
		2,700–3,700 MHz
C-band	4,000–8,000 MHz	5,255–5,925 MHz
X-band	8,000–12,500 MHz	8,500–10,700 MHz
Ku-band	12.5–18 GHz	13.4–14.4 GHz
		15.7–17.7 GHz
K-band	18–26.5 GHz	23–24.25 MHz
Ka-band	26.5–40 GHz	33.4–36 MHz
Millimeter	>40 GHz	

[a] Sometimes included in L-band.
[b] Seldom used nomenclature.
Source: Fink, D. and Christiansen, Eds., *Electronics Engineers' Handbook*, 3rd ed., McGraw-Hill, New York, 1989, Table 302. IEEE standard 521–1976.

Transmission Equipment

The operating parameters of a radar transmitter are entirely different from the other transmitters discussed thus far. Broadcast and satellite systems are characterized by medium-power, continuous-duty applications. Radar, on the other hand, is characterized by high-power, pulsed transmissions of relatively low duty cycle. The unique requirements of radar have led to the development of technology that is foreign to most communications systems.

Improvements in semiconductor design and fabrication have made solid-state radar sets practical. Systems producing kilowatts of output power at frequencies of 2 GHz and above have been installed. Higher operating powers are achieved using parallel amplification.

A typical radar system consists of the following stages:

- *Exciter:* generates the necessary RF and local-oscillator frequencies for the system
- *Power supply:* provides the needed operating voltages for the system
- *Modulator:* triggers the power output device into operation; pulse-shaping of the transmitted signal is performed in the modulator stage.
- *RF amplifier:* converts the dc input from the power supply and the trigger signals from the modulator into a high-energy, short-duration pulse

Antenna Systems

Because the applications for radar vary widely, so do antenna designs. Sizes range from less than one foot to hundreds of feet in diameter. An antenna intended for radar applications must direct radiated power from the transmitter to the azimuth and elevation coordinates of the target. It must also serve as a receiver antenna for the echo.

There are three basic antenna designs for radar:

- *Search antenna:* available in a wide variety of sizes, depending on the application. Most conventional search antennas use mechanically scanned hornfeed reflectors. The horn radiates a spherical wavefront that illuminates the antenna reflector, the shape of which is designed to focus the radiated energy at infinity. The radiated beam is usually narrow in azimuth and wide in elevation (fan shaped).
- *Tracking antenna:* intended primarily to make accurate range and angle measurements of the position of a particular target. Such antennas use circular apertures to form a pencil beam of about 1° in the X and Y coordinates. Operating frequencies in the S, C, and X bands are preferred because they allow a smaller aperture for the same transmitted beamwidth. The tracking antenna is physically smaller than most other types of comparable gain and directivity. This permits more accurate pointing at a given target.
- *Multifunction array:* an electrically steered antenna used for both airborne and ground-based applications. An array antenna consists of individual radiating elements that are driven together to produce a plane wavefront in front of the antenna aperture. Most arrays are flat, with the radiating elements spaced about 0.6 wavelength apart. Steering is accomplished by changing the phase relationships of groups of radiating elements with respect to the array.

Electronic Navigation

Navigation systems based on radio transmissions are used every day by commercial airlines, general aviation aircraft, ships, and the military. Electronic position-fixing systems are also used in surveying work. While the known speed of propagation of radio waves allows good accuracies to be obtained in free space, multipath effects along the surface of the Earth are the primary enemies of practical airborne and shipborne systems. A number of different navigation tools, therefore, have evolved to obtain the needed accuracy and coverage area.

Electronic navigation systems can be divided into three primary categories:

- *Long-range systems:* useful for distances of greater than 200 mi, are primarily used for transoceanic navigation.
- *Medium-range systems:* useful for distances of 20 to 200 mi, are mainly employed in coastal areas and above populated land masses.
- *Short-range systems:* useful for distances of less than 20 mi, are used for approach, docking, or landing applications.

Electronic navigation systems can be further divided into *cooperative* or *self-contained*. Cooperative systems depend on transmission, one- or two-way, between one or more ground stations and the vehicle. Such systems are capable of providing the vehicle with a location fix, independent of its previous position. Self-contained systems are entirely contained in the vehicle and may be radiating or nonradiating. In general, they measure the distance traveled and have errors that increase with time or distance. The type of system chosen for a particular application depends on a number of considerations, including how often the location of the vehicle must be determined and the accuracy required.

Because aircraft and ships may travel to any part of the world, many electronic navigation systems have received standardization on an international scale.

Virtually all radio frequencies have been used in navigation at one point or another. Systems operating at low frequencies typically use high-power transmitters with massive antenna systems. With few exceptions, frequencies and technologies have been chosen to avoid dependence on ionospheric reflection. Such reflections can be valuable in communications systems but are usually unpredictable.

Direction Finding

Direction finding (DF) is the oldest and most widely used navigation aid. The position of a transmitter can be determined by comparing the arrival coordinates of the radiated energy at two or more known points. Conversely, the position of a receiving point can be determined by comparing the direction coordinates from two or more known transmitters.

The weakness of this system is its susceptibility to site errors. The chief weapon against error is the use of a large DF antenna aperture. In many cases, a multiplicity of antennas, suitably combined, can be made to favor the direct path and discriminate against indirect paths (see Fig. 1.22).

Ship navigation is a common application of DF. Coastal beacons operate in the 285- to 325-kHz band specifically for ship navigation. This low frequency provides ground-wave coverage over seawater to about 1000 mi. Operating powers vary from 100 W to 10 kW. A well-designed shipboard DF system can provide accuracies of about ±2° under typical conditions.

Two-Way Distance Ranging

By placing a transponder on a given target, automatic distance measuring can be accomplished, as illustrated in Fig. 1.23. The system receives an interrogator pulse and replies to it with another pulse, usually on a different frequency. Various codes can be employed to limit responses to a single target or class of target.

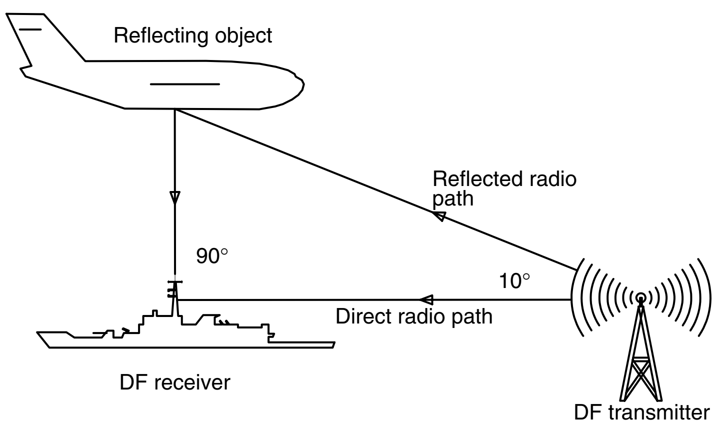

FIGURE 1.22 Direction finding error resulting from beacon reflections.

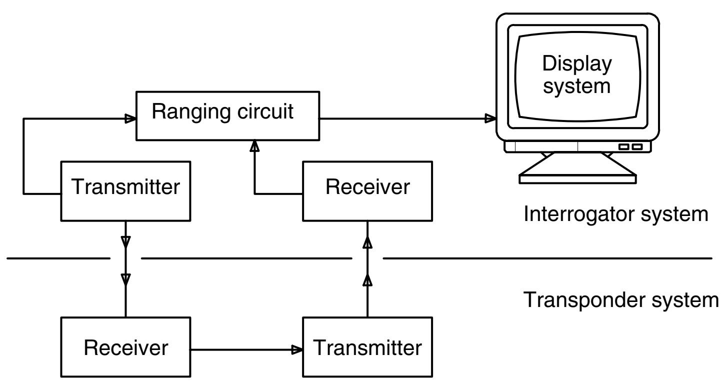

FIGURE 1.23 The concept of two-way distance ranging.

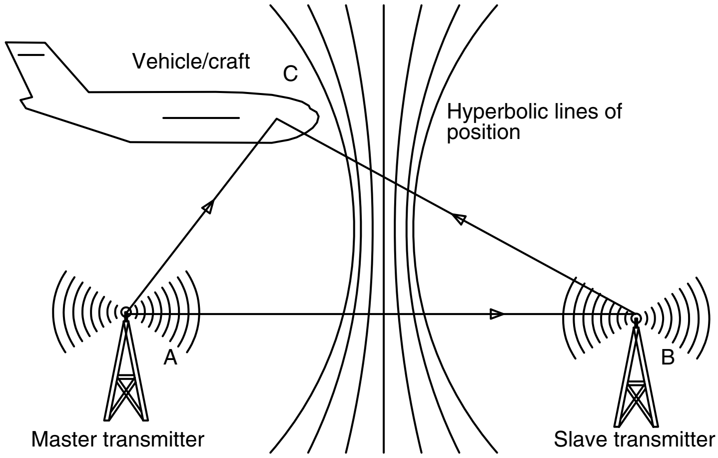

FIGURE 1.24 The concept of differential distance ranging (hyperbolic).

Distance-measuring equipment (DME) systems are one application of two-way distance ranging. An airborne interrogator transmits 1-kW pulses at a 30-Hz rate on one of 126 channels spaced 1 MHz apart. (The operating band is 1.025 to 1.150 GHz). A ground transponder responds with similar pulses on another channel 63 MHz above or below the interrogating channel.

In the airborne set, the received signal is compared with the transmitted signal, their time difference derived, and a direct digital reading of miles is displayed with a typical accuracy of ±0.2 mi.

Ground transponders are arranged to handle interrogation from up to 100 aircraft simultaneously.

Differential Distance Ranging

Two-way ranging requires a transmitter at both ends of the link. The differential distance ranging system avoids carrying a transmitter on the vehicle by placing two on the ground. One is a master and the other a slave repeating the master (see Fig. 1.24). The receiver measures the difference in the arrival of the two signals. For each time difference, there is a *hyperbolic line of position* that defines the target location. (Such systems are known as *hyperbolic* systems.) The transmissions may be either pulsed or continuous-wave using different carrier frequencies. At least two pairs of stations are needed to produce a fix.

If both stations in a differential distance ranging system are provided with stable, synchronized clocks, distance measurements can be accomplished through one-way transmissions whose elapsed time is measured with reference to the clocks. This mode of operation is referred to as *one-way distance ranging*. The concept is illustrated in Fig. 1.25.

Loran C

Hyperbolic positioning is used in the Loran C navigation system. Chains of transmitters, located along coastal waters, radiate pulses at a carrier frequency of 100 kHz. Because all stations operate on the same frequency, discrimination between chains is accomplished by different pulse-repetition frequencies. A typical chain consists of a master station and two slaves, about 600 mi from the master. Each antenna is 1300 ft high and is fed 5-MW pulses, which build up to peak amplitude in about 50 μsec and then decay to zero in approximately 100 μsec. The slow rise and decay times are necessary to keep the radiated spectrum within the assigned band limits of 90 to 100 kHz.

To obtain greater average power at the receiver without resorting to higher peak power, the master station transmits groups of nine pulses, 1 msec apart. These groups are repeated at rates ranging from 10 to 25 per second. Within each pulse, the RF phase can be varied for communications purposes.

Coverage of Loran C extends to all U.S. coastal areas, plus certain areas of the North Pacific, North Atlantic, and Mediterranean. There are currently 17 chains employing about 50 transmitters.

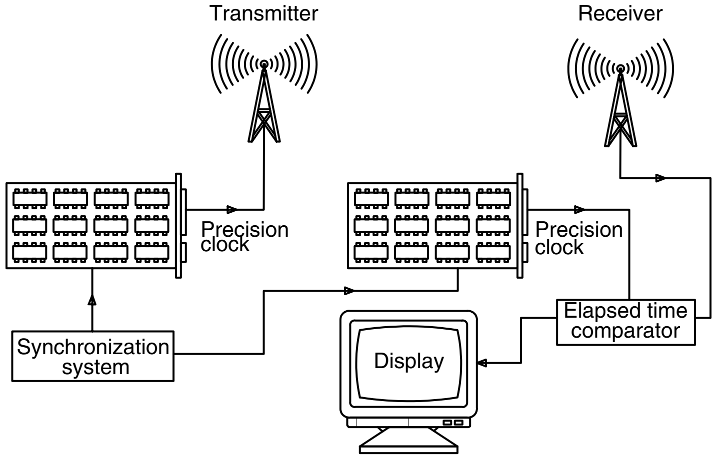

FIGURE 1.25 The concept of one-way distance ranging.

Omega

Omega is another navigation system based on the hyperbolic concept. The system is designed to provide worldwide coverage from just eight stations. Omega operates on the VLF band, from 10 to 13 kHz. At this low frequency, skywave propagation is relatively stable. Overall accuracy is on the order of 1 mi, even at ranges of 5000 mi.

There are no masters or slaves; each station transmits according to its own standard. Each station has its own operating code and transmits on one frequency at a time for a minimum of about 1 sec. The cycle is repeated every 10 sec. These slow rates are necessary because of the high *Q*s of the transmitting antennas. A simple Omega receiver monitors for signals at 10.2 kHz and compares emissions from one station against those of another by using an internal oscillator. The phase difference data are transferred to a map with hyperbolic coordinates.

Most Omega receivers are also able to use VLF communications stations for navigation. There are about ten such facilities operating between 16 and 24 kHz. Output powers range from 50 kW to 1 MW. Frequency stability is maintained to 1 part in 10^{12}. This allows one-way DME to be accomplished with a high degree of accuracy.

Microwave Radio

Microwave radio relay systems carry considerable long-haul telecommunications in the United States and other countries. The major common-carrier bands and their applications are shown in Table 1.5. The goal of microwave relay technology has been to increase channel capacity and lower costs. Solid-state

TABLE 1.5 Common-Carrier Microwave Frequencies Used in the U.S.

Band (GHz)	Allotted Frequencies (MHz)	Bandwidth (MHz)	Application
2	2,110–2,130 2,160–2,180	20	Limited
4	3,700–4,200	20	Major long-haul microwave relay band
6	5,925–6,425	500	Long and short haul
11	10,700–11,700	500	Short haul
18	17,700–19,700	1,000	Short haul, limited use
30	27,500–29,500	2,000	Short haul, experimental

devices have provided the means to accomplish this goal. Current efforts focus on the use of fiber-optic landlines for terrestrial long-haul communications systems. Satellite circuits have also been used extensively for long-haul, common-carrier applications.

Single-sideband amplitude modulation is used for microwave systems because of its spectrum efficiency. Single-sideband systems, however, require a high degree of linearity in amplifying circuits. Several techniques have been used to provide the needed channel linearity. The most popular is amplitude predistortion to cancel the inherent nonlinearity of the power amplifier.

Induction Heating

Induction heating is achieved by placing a coil carrying alternating current adjacent to a metal workpiece so that the magnetic flux produced induces a voltage in the workpiece. This causes current flow and heats the workpiece. Power sources for induction heating include:

- Motor-generator sets, which operate at low frequencies and provide outputs from 1 kW to more than 1 MW.
- Vacuum-tube oscillators, which operate at 3 kHz to several hundred MHz at power levels of 1 kW to several hundred kilowatts. Figure 1.26 shows a 20-kW induction heater using a vacuum tube as the power generating device.
- Inverters, which operate at 10 kHz or more at power levels of as much as several megawatts. Inverters utilizing thyristors (silicon controlled rectifiers) are replacing motor-generator sets in high-power applications.

Dielectric Heating

Dielectric heating is a related application for RF technology. Instead of heating a conductor, as in induction heating, dielectric heating relies on the capacitor principle to heat an insulating material. The material to be heated forms the dielectric of a capacitor, to which power is applied. The heat generated is proportional to the *loss factor* (the product of the dielectric constant and the power factor) of the material. Because the power factor of most dielectrics is low at low frequencies, the range of frequencies employed for dielectric heating is higher than for induction heating. Frequencies of a few megahertz to several gigahertz are common.

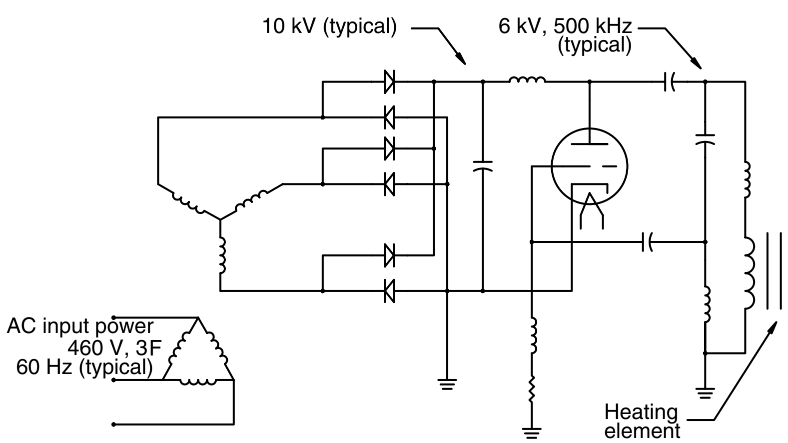

FIGURE 1.26 A 20-kW induction heater circuit.

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