CABLE TELEVISION SYSTEMS

HISTORY AND OVERVIEW

Historical Background

Television was introduced to the American public at the 1939 New York World's Fair, with considerable flourish and fanfare. By 1954, scarcely 100 television broadcasting stations were in operation across the entire country, stymied by the wartime freeze and a six-year hiatus while the Federal Communications Commission (FCC) sorted out the difficult policy issues attending the establishment of a nationwide television service. Cable television originated in the late 1940s to extend the excitement of television reception to the small cities and rural towns beyond the "fringe" area of the few existing TV stations. TV signals received at favorable locations outside the town were transmitted on coaxial cable (or twin-lead cable in some cases) from high-gain antennas installed on tall towers or mountain tops to residences in the shadowed valleys. Amateur hobbyists and ambitious entrepreneurs enabled entire communities to share reception from common antennas, using war surplus coaxial cable and homemade amplifiers or "boosters" developed for master antenna systems (MATV) in multiple dwelling buildings. This was called community antenna TV, or CATV. A broader designation, cable TV or simply "cable," embracing locally generated and other video and audio signals not received over the air from terrestrial broadcasting stations, has replaced the earlier terms in popular usage.

Pioneers probed the mountains and hilltops for suitable receiving sites, by Jeep, airplane, or helicopter and on foot or horseback, packing a TV set, antenna, mast, and portable generator. They set up phased arrays of Yagi antennas to overcome cochannel interference. They built huge rhombics with sides 10 wavelengths (10λ) long, large curtain (bedspring) arrays, corner reflectors, and even a gigantic wire mesh very-high-frequency (VHF) horn. Several large parabolic reflectors, up to 100 m wide, were built with horizontal wires strung on 20 m wood poles to approximate the parabolic shape. A single-channel FM microwave relay at 7 GHz was used to relay programs from distant TV stations. In recent years, satellite relay and optical fiber have replaced most of these heroic efforts.

Cable TV spread rapidly from its rural origins to metropolitan America after the 1975 Ali–Frazier heavyweight prize fight was relayed by satellite from Manila to cable TV subscribers in Florida and Mississippi, on a pay-per-view basis. This event demonstrated, in a dramatic and highly publicized way, how satellites and cable TV networks could be employed to distribute subscription movies and other programming not already broadcast over the air in the major urban areas. Scores of new, nonbroadcast programming networks were quickly established for distribution solely by cable TV systems. Enhanced conditional access with addressable authorization soon developed to protect the security of premium charges for movies distributed by satellite relay.

Even before the 1975 satellite event, channel capacity on cable TV networks had grown from its original one to five low-band VHF channel base (channels 2 to 6; 54 MHz to 88 MHz), first to the full 12-channel allotment by the Federal Communications Commission (54 MHz to 88 MHz; 174 MHz to 216 MHz), then to 35 VHF channels in the VHF band below 300 MHz. With the prospect of satellite programming, new solid-state hybrid gain blocks were developed in 1978 to increase bandwidth to 400 MHz with 54 channels. By the 1990s, with the introduction of analog amplitude-modulated (AM) transmission on optical fiber trunks, channel capacity was expanded to 77 channels at 550 MHz bandwidth and 110 channels at 750 MHz. Technology is currently under development for expanding to 150 channels at 1 GHz bandwidth, and as many as a dozen or more compressed digital television programs may be carried in each 6 MHz channel.

Overview of Cable Television Systems

Television programs are collected from many sources, assembled, processed, and frequency-division-multiplexed (FDM) at the headend of the cable television system, for distribution to subscribers. Yagi or log-periodic antennas are employed to receive off-air signals from terrestrial television broadcasting stations. Most of the programs are relayed by geostationary satellites, received with TV receive only (TVRO) parabolic reflector antennas, typically 7 m or less in diameter. In some cases, signals from remote TV stations and local production studios may still be relayed by frequency-modulated (FM) microwave transmission at 7 GHz. Multichannel AM microwave transmission at 13 GHz may be employed to relay the entire multiplexed complement of programming to distribution hubs or neighboring communities. Selected analog television programs may be digitized at the headend and compressed to eliminate redundant information. Several compressed digital programs can be time-division-multiplexed (TDM) and modulated on a special carrier with high spectral efficiency [e.g., quadrature amplitude modulation (64-QAM, 8 levels on each axis)] in a single 6 MHz channel and combined with the multiplexed analog signals.

The headend facility houses the modulators, demodulators, heterodyne processors, satellite receivers, conditional access facilities, microwave transmitters and receivers, and the downstream laser transmitters as well as the optical receivers and processing facilities for return transmissions. Video tape players, character generators, and computer-controlled routing switches are provided for commercial insertion and various locally originated messages. Network management facilities generally provided at the headend include various monitoring, remote testing, and status alarm systems, as well as customer billing and remote authorization of premium program descramblers.

The hybrid-fiber-coaxial (HFC) distribution network architecture (Fig. 1) is based on optical fibers arranged in star, or ring-star, configuration, carrying light beams modulated with the multiplexed stream of AM analog television signals from the headend to multiple nodes, where optoelectronic transducers recover the multiplexed analog signals. Each such optical node is the hub of a separate, small network of coaxial cables, broadband RF amplifiers, and various passive devices, arranged in classical "tree and branch" configuration. The coaxial networks are typically designed to cover from 500 to a few thousand residences. Subscribers are connected through directional couplers, called *taps,* through small, flexible service drop cables, and, in most cases, through a customer interface device called a *set-top converter.* In addition to the primary function of channel selection, the converter includes circuits to restore scrambled premium programs to normal condition upon receipt of an authorization signal transmitted with a unique address code from the headend.

Bidirectional operation, for telephony, high-speed modem connections to the Internet, and various other interactive functions, is provided by allocating the spectrum above 54 MHz for transmission downstream from the headend or forward, while reserving the spectrum below about 42 MHz for return or upstream transmissions from customers.

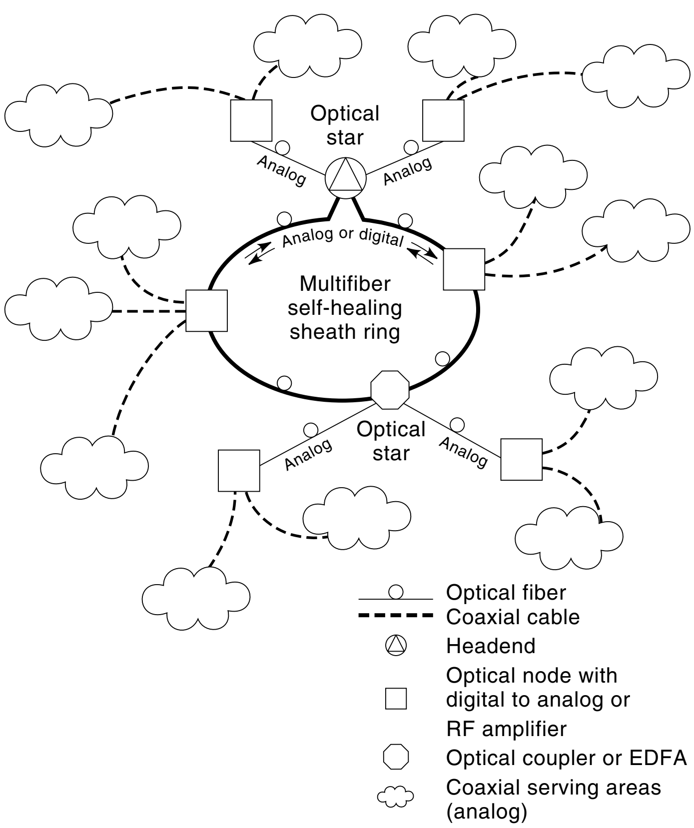


Figure 1. HFC architecture, showing both generic ring and star fiber topologies.

A growing number of programs are being relayed by satellite to cable TV headends in compressed digital format for distribution to subscribers. Terrestrial broadcasting in accordance with the recently adopted rules for digital television (DTV) has already begun at two locations on an experimental basis.

By 1996, 93 million households had access to cable television, representing 97% of all television households. Moreover, 63 million, or 65%, of those households are paying subscribers. There were about 1.4 million plant miles of coaxial cable installed, with an estimated 562,000 miles of fiber in place, along 28,000 route miles. Approximately 140 nationwide television program networks and dozens of regional networks, mostly sports and news, are already relayed by satellite to cable TV headends, and the list is growing. Additionally, a score or more local networks deliver mostly news and targeted ethnic programming by microwave and fiber optics.

CABLE TELEVISION ENGINEERING

The Headend

Program Sources

Satellite Relay. Most cable television programming is relayed by satellite to the headend. Geostationary satellites are maintained in orbit at 35,786 km directly above the equator. The geostationary orbit is defined so that the satellite velocity exactly matches the earth's rotation, and the satellite appears to be stationary. In accordance with international agreements, national authorities assign each satellite to a specific longitude, or *orbital slot,* often separated by no more than 2°. Most of the programs relayed by satellite to cable TV systems are transmitted in the C band at 3.7 GHz to 4.2 GHz downlink and 5.925 GHz to 6.425 GHz uplink. Because of the limited C-band capacity, program providers are increasingly turning to the Ku band at 11.7 GHz to 12.2 GHz downlink and 14.0 GHz to 14.5 GHz uplink. Most C-band satellites available for cable TV relay are equipped with 24 transponders. Generally they are frequency modulated with analog NTSC signals, although many are being converted to quadrature phase-shift keyed modulated with Moving Picture Experts Group–II (MPEG-II) compressed digital signals. Center frequencies are assigned in two cross-polarized groups of 12 channels, each occupying 40 MHz. Oppositely polarized groups are also offset by 20 MHz to minimize adjacent channel interference, as shown in Fig. 2. Ku-band transponders often occupy wider bandwidth. Satellite transponders are generally equipped to transmit program audio either on the 4.5 MHz intercarrier frequency or on special subcarrier frequencies commonly at 6.2 MHz and 6.8 MHz.

TVRO earth stations for cable TV are typically 4.6 m to 7.0 m diameter parabolic reflectors. Prime focus feed, with the receiving antenna located at the focal point of the parabola, is more commonly used than the Cassegrain feed, in which the antenna is at the vertex of the parabola with a convex reflector between the focal point and the vertex of the parabola. For convenience in the initial setup, the azimuth-over-elevation mount arrangement is generally preferred, in which the azimuth bearing to the point on the equator directly under the satellite and the angle of elevation are independently adjustable. An alternative polar mount is arranged so that the antenna structure rotates around an axis that is parallel

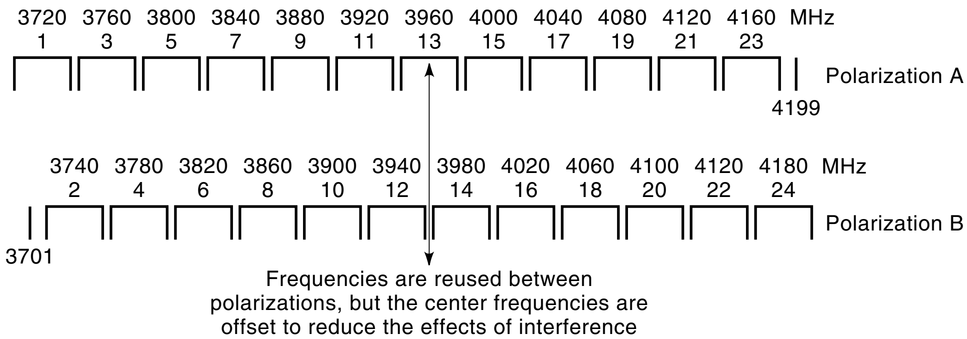


Figure 2. Satellite transponder channel allocations. © Morgan Kaufman Publishers.

to the earth's rotational axis. Once the proper declination has been set, only the azimuth need be adjusted to reorient toward another satellite. Offset and multiple feeds may be used to receive two or three satellites in nearby orbital slots. A large, specially designed reflector, circular in one plane and parabolic in the other, is used in some installations to receive signals from any satellite in the visible equatorial arc.

The preferred location for TVRO antennas would be close to the headend facility. However, interference from terrestrial microwave transmissions, a long-line telephone relay, for example, may require a more remote location, linked to the headend by optical fiber or coaxial cable. FCC licensing of TVRO earth stations is optional. However, only licensed stations are eligible for frequency coordination and interference protection.

Off-Air Reception. For receiving local signals from nearby terrestrial broadcasting stations, many cable TV systems still use some version of the Yagi antenna. The Yagi–Uda antenna, developed in the late 1920s by two professors at Tohoku University in Japan, is the simplest and lowest-cost antenna generally used in cable TV systems. It comprises a half-wave dipole coupled directly to the down-lead transmission line, with a parasitic half-wave "reflector" dipole spaced approximately $\frac{1}{4}\lambda$ behind it, and five or ten parasitic "director" dipoles in front, generally spaced considerably less than $\frac{1}{4}\lambda$, and somewhat less than a half-wave length long. Gain in the forward direction is between about 8 dBi and 13 dBi. The half-power beamwidth is 50° to 60°. Front-to-back ratios in the horizontal plane are likely to be between about 15 dB and 25 dB. Yagi antennas are inherently frequency dependent, and impedance match, represented by the voltage standing-wave ratio (VSWR), is not uniform across a 6 MHz channel. Unless the dimensions have been optimized for color, the chrominance subcarrier may be significantly attenuated. "All-band" Yagi antennas include more than one driven element and several directors of different lengths and spacing in order to provide reception for all TV channels. Yagi antennas may be stacked in various configurations for increased gain and directivity. Since the characteristics of the Yagi-type antenna are inherently parasitic, they are strongly influenced by metallic structures to which the antenna is mounted. The best mounting is on a vertical steel pipe long enough to separate the antenna structure by several wavelengths from any other metallic objects.

The log-periodic antenna was developed at the University of Illinois about 1957 as one of a family of frequency-independent antenna arrays. Although models manufactured by Scientific Atlanta, adapted for cable television about three years later, are not completely frequency independent, they do function well over much greater bandwidth than Yagi antennas. As used in cable TV, the dipole elements attached to a boom on the axis of the array are directly driven, with the polarity reversed between adjacent elements. None of the elements are parasitic. Forward gain for single log-periodic antennas is about 9 dBi to 12 dBi. The half-power beamwidth is 50° for the channel 7 to 13 model; 70° for the channel 2 to 6 model. Front-to-back ratios are greater than 25 dB, typically greater than 30 dB. The antenna is designed for cantilever mounting to the tower or other structure, and its performance is virtually unaffected by the supporting structure. VSWR is less than 1.5 : 1, with negligible attenuation of chrominance sidebands.

Four single log-periodic antennas may also be stacked at the corners of a diamond (Fig. 3), with axes parallel, for about 5 dB of additional gain and a half-power beamwidth reduced to between 20° and 30°. Diamond arrays are quite large and heavy, ranging from 7 m × 10 m at 475 kg for channel 2 to about one-third as much for channels 7 to 13. When properly designed and installed structurally, however, both the single and stacked arrays of log-periodic antennas have proven to be exceptionally satisfactory for both VHF and UHF reception of broadcast TV signals for distribution on cable TV networks.

By agreement with the local TV station, it may be feasible to provide a direct baseband connection, by microwave, coaxial cable, or optical fiber, from the video input at the broadcast transmitter to the cable TV headend. This direct video feed arrangement avoids the outages, propagation vagaries, ignition noise, and other problems likely to be experienced in the over-the-air path as well as in the high-power broadcast transmission facility.

Off-air signals may be received from FM radio broadcasting stations and processed with filters, automatic gain control (AGC), or frequency conversion, and carried in the conventional FM radio band at 88 MHz to 108 MHz. Digital music programs may be received by satellite, usually on satellite transponder subcarriers, to be remodulated and transmitted to subscribers in frequency bands designated by the operator, generally not the standard FM radio band. Digital music programs are encrypted as premium services.

Microwave Relay. Multichannel microwave relay systems were developed especially for cable TV and are identified in FCC rules as the Community Antenna Relay Service (CARS) using frequencies assigned in the band 12.7 GHz to 13.2 GHz. Four groups of channels in this band (C, D, E, and F) are

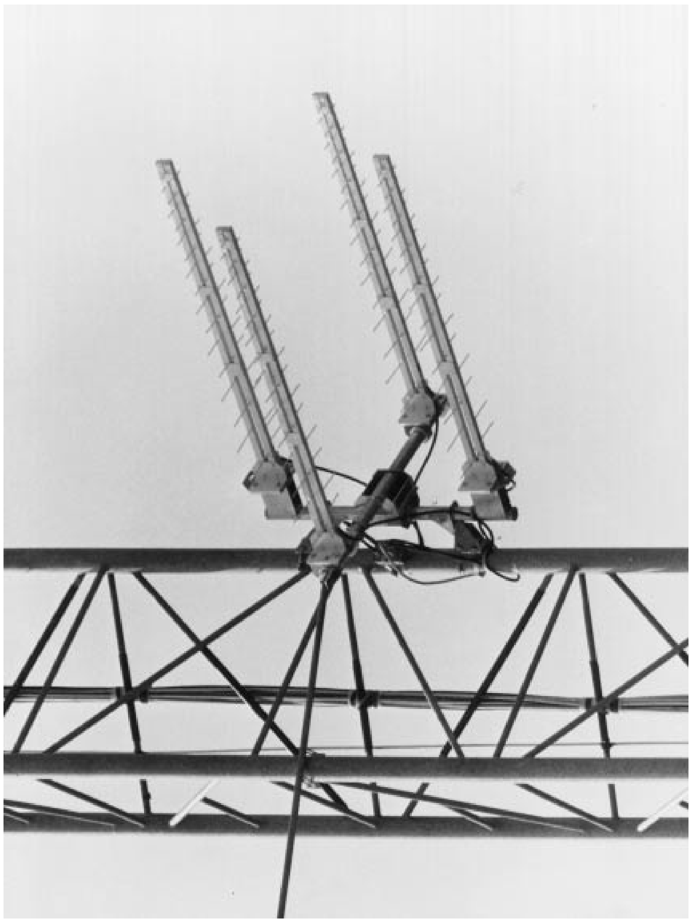


Figure 3. The log–periodic diamond (binomial) array. © Scientific Atlanta.

allocated for transmitting 6 MHz vestigial sideband (VSB) amplitude-modulated (AM) television channels. Groups C, D, and E provide for up to 40 adjacent channels; group F, up to 30. Two groups (A and B) are designated for transmitting 20 adjacent 25 MHz channels with frequency modulation. Group K is designated for AM and FM transmissions requiring 12.5 MHz bandwidth. Additional frequencies are assigned in the 17.7 GHz to 19.7 GHz band for two-way links and other purposes. Re-use of frequencies in the 13 GHz band may be facilitated by means of cross-polarization, elliptical polarization, frequency offsets, geographic separation, and directional beam orientation. Multichannel AM microwave has been used extensively for distribution of the entire frequency-division-multiplexed (FDM) channel complex between the headend and various hubs and nearby communities. Parabolic antennas up to 3 m in diameter are used for paths typically less than 25 km. Broadband receivers with a klystron local oscillator, phase-locked to a pilot signal, are housed in weatherproof enclosures. Transmitters are generally single channel, with a klystron or solid-state oscillator, although the earlier models used block conversion for up to eight channels. Many, but by no means all, of the multichannel microwave links installed are being replaced with optical fibers, partly because of outages during heavy rainfall.

Production studios and other remote pickup facilities for local programming may be linked to the headend by means of a single-channel CARS band (13 GHz) relay, optical fiber, or coaxial cable. Video tape or disk playback facilities for commercial insertion in various programs and character generators for local announcements are also provided at the headend.

A single-channel FM microwave transmitter at 7 GHz is used primarily to relay signals to cable television headends from distant terrestrial broadcasting stations. However, satellite-relayed programs have substantially reduced the need for acquiring distant terrestrial broadcast program signals. Consequently, many of these links have been deactivated or replaced with optical fiber links.

Operational Functions and Equipment

Satellite Receivers. A separate Low-Noise preamplifier with built-in Block down-converter (LNB) in a flanged waveguide mount are attached directly at the focal point of the TVRO antenna for each polarization. Noise temperatures are generally in the range 45 K to 90 K (noise figures 0.628 dB to 1.177 dB). Output of the LNB is generally at L-band frequencies, approximately 1.0 GHz to 1.5 GHz, or in older equipment, 0.27 GHz to 0.77 GHz. The LNB outputs are divided and connected to the appropriate H- and V-polarized input terminals of one or more L-band satellite receivers. Synthesized tuning controls, in some cases preset, provide for selecting one of the 24 transponder channels. The selected channel, including subcarriers, is processed at intermediate frequencies (IF) with AGC and appropriate band-pass filter shaping, then demodulated to baseband video and audio. The 4.5 MHz aural intercarrier signal may be provided as an optional output. Signals received by satellite relay or off-air from terrestrial broadcasting stations may include a number of FCC authorized subcarriers for multichannel television sound (MTS), such as stereophonic or multilingual sound, a second audio program (SAP), or a variety of unrelated subsidiary communications. The most common MTS application encountered in cable television is stereophonic sound, in accordance with the standards established by the Broadcast Television Systems Committee (BTSC) of the Electronic Industries Association (EIA) in North America or the Near Instantaneous Compounded Audio Multiplex (NICAM) standards in Europe.

Heterodyne Signal Processors and Demodulators. Off-air signals may be received with heterodyne signal processors, comprising (1) a down-converter, fixed-tuned to a specified input channel frequency, heterodyned to an IF band, normally 41 MHz to 47 MHz, (2) an IF amplifier, and (3) an up-converter in which the IF band is heterodyned to a specified output channel frequency, not necessarily the same as the input channel. At the output of the tuner or down-converter, the 41.25 MHz aural carrier is separated from the 45.25 MHz visual carrier. The aural and visual carriers are amplified separately, with independent manual and automatic gain control. When receiving weak terrestrial TV signals from great distances, separate aural and visual level control is often necessary to counteract frequency-dependent fading patterns. Although satellite relay has largely superseded long-distance off-air reception of terrestrial signals, independent level control is still necessary for maintaining the proper aural-to-visual carrier ratio in compliance with FCC rules.

Alternatively, terrestrial off-air signals may be demodulated to baseband video and audio, and routed to a bank of modulators, along with other baseband signals from satellite-relayed and locally originated programming. Flexibility and convenience in switching, monitoring, testing, emergency substitution, and maintenance are enhanced when all program signals are in the same baseband format. In the demodulator, the input RF channel is converted to the IF band, 41 MHz to 47 MHz, at which the visual carrier at 45.75 MHz is demodulated to baseband video, with either envelope detection or synchronous demodulation. The 4.5 MHz intercarrier aural subcarrier is demodulated to baseband audio, with standard 75 μs deemphasis, by a discriminator or other FM detector circuit. The 4.5 MHz subcarrier is also available at an output port before detection. The video IF filter is shaped to provide the standard Nyquist response between 0.75 MHz above and below the visual carrier and to complement the predistorted envelope delay characteristic specified by FCC.

Modulators. The baseband video and audio, or 4.5 MHz intercarrier sound from a satellite or microwave receiver, or demodulator, are applied to the input of a modulator, which is, in effect, a very-low-power television transmitter with less than 13 mW (11.25 dBm) output. The baseband video is amplitude-modulated on an IF carrier at 45.75 MHz. The IF filter uses surface acoustic wave (SAW) technology to shape the vestigial sideband response and envelope delay characteristics in accordance with the standard for television broadcast transmitters. Baseband audio is frequency-modulated on the IF subcarrier at 41.25 MHz with the standard 75 μs preemphasis. Alternatively, a 4.5 MHz aural subcarrier input may be combined with the video to bypass the audio modulator. The IF output is then up-converted to the specified TV channel frequency. For a comprehensive treatment of modulators and demodulaters, see Ref. 1.

Multiplexer

The RF channel outputs of all the modulators and processors are frequency-division multiplexed (FDM) by means of directional couplers and splitters in a device commonly called a *channel combiner.* The directivity of the couplers provides the isolation between individual channel modulators and processors necessary to avoid intermodulation and beat interference. A launching amplifier is generally required at the headend to offset insertion losses for a multichannel combiner. Inputs are provided for sweep generators and other test equipment as well as test points for monitoring the multiplexed signals.

Conditional Access. Many of the analog program signals relayed by satellite have been purposely scrambled as a preventive measure to prevent unauthorized reception by privately owned, "backyard" antennas. When appropriate arrangements have been made by the cable operator, an authorization signal with a unique address code is transmitted by a special control agency to activate descramblers at the headend so as to restore protected signals to normal viewability.

Another completely separate and independent security system is required to protect programs for which individual subscribers must pay a premium fee, on a monthly or per program [pay-per-view (PPV)] basis. Various methods have been used for this purpose, including notch filter traps, fixed-frequency and frequency-hopping jamming, RF synchronization suppression, and systematic disruption of the baseband scanning waveform. In addition to the jamming or scrambling equipment for each protected channel, software-controlled facilities are provided at the headend to transmit the uniquely addressed authorization codes and descrambling signals and to store billing information. (For more information on scrambling technology, see the section on customer premises interface in the following.)

Network Management. Network management facilities provided at the headend include picture and waveform monitors, facilities for testing, program routing switches, commercial insertion, redundancy protection, billing, and computer control of addressable authorization. Cable TV headends serving large populations are likely to be continuously staffed. As distribution networks become larger and the services offered become more sophisticated and sensitive to down time and rapid response, increasing importance is attached to facilities for automated monitoring, testing, and operation, centered at the headend. Sensors may be installed to provide information about visual and aural carrier levels, dc and ac voltages, internal temperature, and other relevant conditions in the distribution network. Remote sensors may be used to provide information regarding the status and condition of battery standby power supplies and outage occurrences at optical nodes or other critical locations in the coaxial networks. Sensors can be programmed to transmit alarms for out-of-limits conditions. Complete performance tests for compliance with FCC or other standards can be managed by computer, with a proper selection of sophisticated monitors.

The Distribution Network

CATV Architecture

Hybrid Fiber Coaxial Cable. The dominant network architecture for new construction, as well as rebuilding and upgrading existing cable TV networks, is hybrid fiber coaxial cable (HFC). A common form of HFC architecture comprises a fiber-optic star-configured network with optical fiber *supertrunk* lines radiating outward from the headend terminating in optical nodes. Alternative HFC designs utilize various adaptations of ring topology, as depicted in Fig. 1, as well as various combinations of multiple-star and ring-star topologies for connecting optical nodes to multiple headends or distribution hubs. Transmission in the ring architecture is typically analog, but in very large networks may be digital, requiring that each channel be separately converted to analog at hub sites. The optical nodes are necessarily analog and may include one or more photodetector receivers, RF amplifiers, power pack, redundancy modules, various ancillary and control facilities, as well as distributed feedback or Fabry–Perot lasers for return transmission. Each optical node is the center of a relatively small coaxial "tree-and-branch" distribution network, currently designed to serve between about 500 to a few thousand households.

Tree-and-Branch Architecture. Many older systems, especially in small towns outside the urban and suburban communities, have not yet upgraded by adding optical fiber supertrunks to the original all-coaxial "tree-and-branch" architecture. The basic tree-and-branch architecture of coaxial cable TV networks provides one or more trunk cables (sometimes called "express" lines) extending radially from the headend (or optical node) with branch lines leading off the main lines. The network operates at nominal 75 Ω throughout. No subscribers are connected directly to trunk or express cables. Depending on the length of the trunk cable, a series string, or cascade of trunk amplifiers, sometimes called trunk repeaters, is generally required to offset frequency-dependent cable losses, as well as various frequency-independent losses. In typical HFC networks, such series strings require fewer than five to ten repeaters, spaced about 500 m to 600 m. Without optical fiber, trunk lines often required up to 30 or more repeaters, spaced at 300 m to 400 m and typically limited to 60 National Television Systems Committee (NTSC) channels and 450 MHz. Relatively short feeder lines (sometimes called distribution lines) are bridged across the trunk lines. Subscriber service drops are connected through power-splitting devices called *taps* (or multitaps) to the feeder lines. Repeater amplifiers used to overcome tap-insertion losses and feeder-cable attenuation are commonly called *line extenders*. Before the development of directional coupler tap devices, subscribers were connected to distribution lines with *pressure taps* in which a *stinger* was inserted in a hole cut through the shield and insulation, not only causing mismatch reflections but signal leakage and moisture contamination as well.

Bidirectional Operation. Two-way operation in cable TV networks is made possible by frequency-division multiplex. Forward or downstream transmission normally occupies the spectrum above 54 MHz (47 MHz in Europe and elsewhere), extending to 750 MHz or higher (860 MHz in Europe, and other PAL regions). Return or upstream transmission is restricted to the spectrum below about 42 MHz (30 MHz in Europe), allowing for a guard band between 42 MHz and 54 MHz for the diplex crossover high–low-pass filters needed to isolate the forward and return transmissions. The feasibility of bidirectional operation of HFC networks for interactive programming and telephony has been amply demonstrated. Successful operation, however, requires special attention to the design, construction, and operation of the return network to overcome limitations in the coaxial portions of the HFC network due to ingress interference from strong local transmitters or electrical noise, aggregate noise funneled to the headend from the entire coaxial network, and restricted bandwidth.

Performance Objectives. The design of an HFC distribution network has two important primary objectives. Although not entirely unrelated, they are generally treated separately.

1. To meet predesignated technical performance standards at any subscriber tap port as to (a) carrier-to-noise ratio (C/N), and (b) carrier-to-composite intermodulation ratio [carrier-to-composite triple-beat ratio (C/CTB) and carrier-to-composite second-order ratio (C/CSO)].
2. To meet predesignated technical performance standards at any subscriber terminal as to (a) minimum signal level and (b) acceptable range of signal levels over frequency and time.

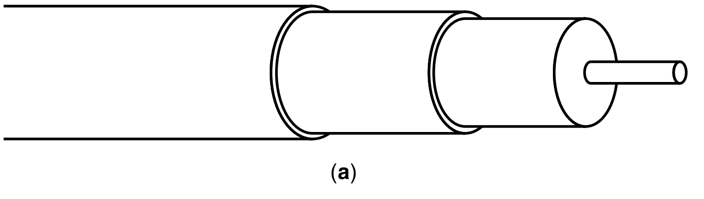
Network design performance projections are generally calculated at the highest-frequency visual carrier to be transmitted on the network, based on "worst case" equipment performance specified by manufacturers. Initial determinations of C/N, C/CTB, and C/CSO are used to represent the worst-case performance capability of the network, although this may not necessarily occur at the highest frequencies. Determinations of performance at other channels may be made as appropriate to determine the range of the critical operational parameters of the amplifiers and other devices in the network. For the coaxial portion of the network, the C/N and C/CTB ratios are controlling. For the optical fiber portion, however, C/CSO is usually significant, and may be controlling.

Coaxial Cable Construction

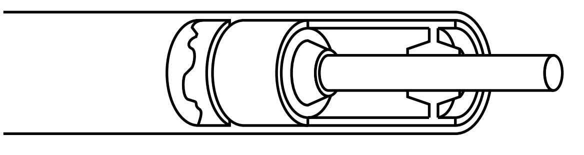
Trunk and Feeder Cable. The most commonly used coaxial cable for trunk and feeder is constructed with a seamless aluminum tubing outer conductor, with a solid copper-clad aluminum wire center conductor. The dielectric is expanded polyethylene, sometimes referenced as foam-filled or gas-injected; Fig. 4(a). The characteristic, or surge, impedance is $75 \pm 2\ \Omega$. Cables may be covered with a protective polyethylene jacket, or left unjacketed with the bare aluminum exposed. The most commonly used sizes for solid sheath aluminum cables are designated as 500 to 1000 (412 and 1125 sizes are also available), representing the outside diameter of the aluminum sheath in thousandths of an inch. Attenuation (in decibels) is approximately proportional to the square root of frequency, and inversely to the diameter of the dielectric (ID of the outer conductor).

Another type of cable that has been used successfully is constructed with air dielectric cells, separated by polyethylene disks fused to a polyethylene tubing to seal the individual cells (Trilogy MC^2); Fig. 4(b). The dielectric constant of the insulation in this cable more closely approximates that of air. Consequently, the attenuation is about 15% lower than that of the foam dielectric cable. Coaxial cable manufactured in Europe with air-cell insulation and copper conductors is known colloquially as "bamboo" cable. Aluminum- sheath coaxial cables are used exclusively in the United States, and increasingly in Europe and elsewhere. Some users, mostly outside North and South America, prefer the copper cables, which they consider to be less vulnerable to corrosion. However, the solid-sheath aluminum cable is less susceptible to leakage and ingress than the butt- or lapped-joint copper-sheath cable and less costly than welded- or soldered-seam copper cable. With proper care in cable and connector design and installation, aluminum cable has proven to be quite satisfactory with respect to corrosion and moisture contamination but is not suitable for cable powering with direct current.

Customer Service Drop Cable. Cables used to connect subscriber equipment to the distribution taps are smaller in di-



(a)



(b)

Figure 4. Construction of coaxial cable for trunk and feeder. (a) Foamed polyethylene dielectric. © Commscope. (b) Polyethylene air-cell dielectric. © Trilogy Communications Inc.

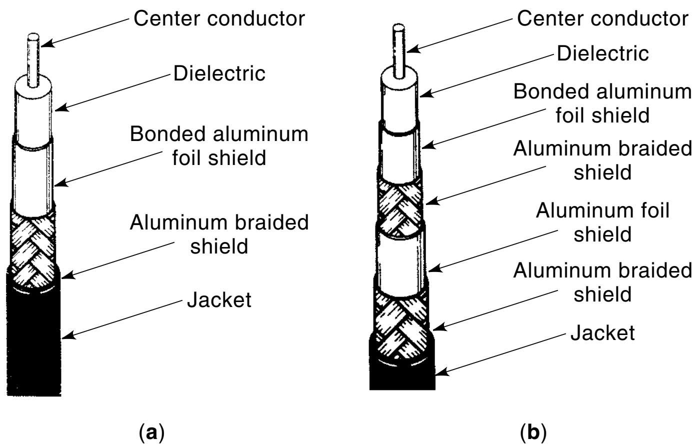


Figure 5. Drop cable construction. (a) Standard shield. (b) Quad shield. (Courtesy of Commscope.)

ameter and much more flexible than the semirigid trunk and feeder cables. Characteristic impedance is 75 ± 3 Ω. The preferred construction employs a copper-coated steel center conductor insulated with foamed polyethylene dielectric. The outer conductor is a laminated aluminum–polypropylene–aluminum foil tape applied longitudinally with bonded overlap. The bonded aluminum foil shield is covered with a braided shield of 34 AWG bare aluminum wire, providing roughly two-thirds coverage; Fig. 5(a). For additional shielding efficiency, a nonbonded laminated aluminum-foil shield may be applied over the shield braid. For greater mechanical durability, an additional low-coverage shield braid may be laid on top of the second aluminum-foil tape shield, forming the quad shield; Fig. 5(b). Many variations are available for special applications, such as code compliance for risers and plenum installations or for headend wiring. For dual installations, two cables may be molded together in a common jacket, designated "Siamese." For additional strength, a solid-steel messenger wire may be imbedded in the outer jacket, designated "figure-8." Separate copper wires may also be imbedded in the jacket to carry signaling or other electrical currents. The most commonly used drop cables are the 59 series and 6 series, with overall diameters of 6.1 mm and 6.9 mm, respectively. The larger 7 series and 11 series, at 8 mm and 10 mm O.D., are used for extra long runs. The size nomenclature is derived from the military Joint Army–Navy (JAN) designations RG-59/U, RG-6/U, and RG-11/U, although the drop cables manufactured for cable television are not designed to comply with the military specifications.

Coaxial Splices and Connectors. Coaxial cable splices and housing connectors for use with solid-sheath aluminum cables are fabricated with threaded caps and wedge rings arranged to clamp the connector body securely against the aluminum cable sheath. A steel sleeve (mandrel) is an integral part of the connector, arranged to fit snugly under the aluminum sheath to provide a firm backing for the wedged clamp. A special coring tool is required to remove a layer of dielectric sufficient to permit the integral sleeve to slide into place. Neoprene O-rings are used to seal against moisture penetration. Standard $\frac{5}{8} \times 24$ male thread is provided for attaching to the device housing. In one arrangement, called feed-through, a 5 cm length of the center conductor extends through the threaded entry port to be seized inside the device housing; Fig. 6(a). In an alternative arrangement, called pin type, the center conductor is pressed into a spring-bronze grip at one end of a pin extending through the threaded entry port to be seized inside the device housing; Fig. 6(b). Tightening the backing nut of two-part, pin-type connector bodies grips the aluminum sheath and the center conductor at the same time. In three-part, pin-type connectors, the center conductor is gripped independently of the outer sheath.

Splices generally consist of two housing connectors joined through a cylindrical shell with female threads at each end; Fig. 6(c). Slotted, tubular, spring-bronze grips with sharp internal ridges are provided to join the two center conductors for in-line splices. Alternatively, the housing connectors may be attached to a metal block with accessible, insulated clamps for seizing the center conductors.

Electrical Characteristics of Coaxial Cable

Characteristic Impedance. The characteristic impedance of a coaxial transmission line is the ratio of voltage to current on a transmission line when there are no reflections (2) and is defined by the well known equation (3):

$$\begin{aligned} Z_0 &= [(R + j\omega L)/(G + j\omega C)]^{1/2} \\ &= (L/C)^{1/2}[(1 + R/j\omega L)/(1 + G/j\omega C)]^{1/2} \end{aligned} \tag{1}$$

where R, G, L, and C are, respectively, the series resistance, shunt conductance, inductance, and capacitance per unit length. For cable TV, R and G are much smaller than ωL and ωC and may be quantified in terms of permeability (μ), dielectric constant (ϵ), and the conductor diameters:

$$Z_0 \cong (L/C)^{1/2} = [\ln(d_o/d_i)/2\pi](\mu\mu_0/\epsilon\epsilon_0)^{1/2} \tag{2}$$

$$\begin{aligned} &= (1/2\pi)(376.730373)(v)\ln(10)\log_{10}(d_o/d_i) \\ &= 59.958501(v)\ln 10\ \log(d_o/d_i) \end{aligned}$$

$$= 138.059551(v)\ \log(d_o/d_i) \tag{3}$$

where $L = [\mu\mu_0 \ln(d_o/d_i)]/2\pi$; $C = 2\pi\epsilon\epsilon_0/\ln(d_o/d_i)$; the permeability of free space (vacuum) $\mu_0 = 4\pi \times 10^{-7}$ H/m (by definition); μ is the relative permeability of conductors, which is

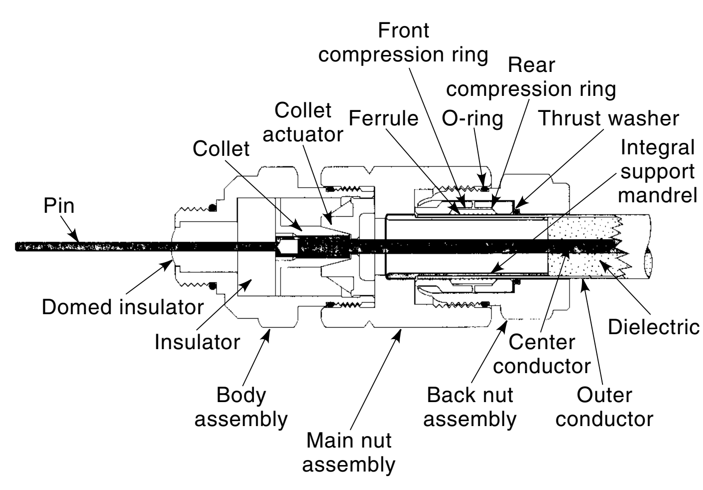


Figure 6. Three-piece pin-type coaxial connector. © Gilbert Engineering.

unity for nonferrous conductors; the permittivity (dielectric constant) of free space (vacuum) $\epsilon_0 = 8.854185 \times 10^{-12}$ F/m (derived from the velocity of light $c = 2.997930 \times 10^8$ m/s $= 1/\sqrt{\mu_0\epsilon_0}$); ϵ is the relative dielectric constant of the insulating material; v $(=1/\epsilon^{1/2})$ is the velocity of propagation relative to the velocity of light; the impedance of free space (vacuum) $(\mu_0/\epsilon_0)^{1/2} = (4\pi \times 10^{-7}/8.854185 \times 10^{-12})^{1/2} = 376.730373\ \Omega$; $\ln(N)$ denotes $\log_e(N)$, the natural or Napierian logarithm $[\ln(10) \times \log_{10}(N)]$; d_o is the inner diameter of the outer conductor; and d_i is the outer diameter of the inner conductor. At 87% velocity, $Z_0 = 75\ \Omega$ for $d_o/d_i = 4.21$.

Attenuation. Attenuation (4,5) on a matched transmission line is the ratio of power at the sending end relative to power at the receiving end. Attenuation is the real part of the complex exponential propagation constant per unit length, $e^{(\alpha+j\beta)l}$, expressing the current and voltage relationships in transmission lines (α = attenuation constant, β = phase constant, j = complex operator, and l is the length between sending and receiving ends of the line). The attenuation constant α is expressed in nepers per meter, neper being the natural logarithm (to the base e) of two scalar currents, or voltages. Attenuation in decibels per meter is equal to $[20 \log_{10}(e)]\alpha = 8.686\alpha$. Power *loss,* on the other hand, is the numerical (scalar) difference between power at the sending end P_s and power received P_r, relative to power at the sending end, and should not be confused with attenuation.

$$\begin{aligned}\text{Attenuation in decibels} &= \log_{10} P_s/P_r = 20 \log E_s/E_r\\ &= 8.686\alpha l\\ \text{Relative power loss} &= (P_s - P_r)/P_s = 1 - P_r/P_s\end{aligned}$$

where E_s = sending end voltage and E_r = receiving end voltage. To the extent that $\omega L \gg R$ and $\omega C \gg G$, the attenuation constant α is given by the following expression:

$$\alpha = \tfrac{1}{2}(R/Z_0 + GZ_0)\ \text{N/m} \tag{4}$$

The outer conductor of the coaxial cable is an extruded aluminum tubing, drawn down to fit over the foamed dielectric. The center conductor comprises a thin copper skin bonded to an aluminum wire. The resistance per unit length (R) of these conductors at radio frequencies is determined by the *"skin effect"* by which the current flow is concentrated in the very thin copper surface layer of the center conductor and the inner aluminum surface of the outer conductor. The distance below the surface of a conductor at which the current density has diminished to $1/e$ of its value at the surface is defined as the skin depth, δ (2.4 μm at 750 MHz), determined as follows:

$$\delta = (2\rho/\omega\mu\mu_0)^{1/2} = (\rho/\pi f\mu\mu_0)^{1/2}\ \text{m} \tag{5}$$

where ρ is the resistivity in $\Omega \cdot$ m (i.e., ohms between opposite faces of a 1 m cube) The distributed series resistance R per meter in Eq. (1) is given by

$$R = \rho/\delta\pi d = [(f\mu\mu_0/\pi)^{1/2}(\rho^{1/2}/d)]\ \Omega/\text{m} \tag{6}$$

The shunt conductance per unit length is calculated in terms of a dissipation factor D and is a specific characteristic of the dielectric material. D is defined as arctan $G/\omega C$ and since $G \ll \omega C$, $D \cong G/\omega C$. Thus, D is equivalent to the dielectric power factor. The shunt conductance is given by

$$\begin{aligned}G &= D\omega 2\pi\epsilon\epsilon_0/\ln(d_o/d_i)\\ &= D4\pi^2 f(\epsilon_0/v^2)/\ln 10 \times \log_{10}(d_o/d_i)\ \Omega^{-1}/\text{m}\end{aligned} \tag{7}$$

From Eqs. (2), (6), and (7), the general equation for attenuation in N/m is

$$\begin{aligned}\alpha = {} & [\tfrac{1}{2}\underbrace{(f\mu\mu_0/\pi)^{1/2}(\rho^{1/2}/d_o + \rho^{1/2}/d_i)}_{R}]\\ & \underbrace{[1/138.059551v \log_{10}(d_o/d_i)]}_{Z_0}\\ & + [\tfrac{1}{2}\underbrace{D4\pi^2 f(\epsilon_0/v^2)\ln 10 \log_{10}(d_o/d_i)}_{0.00011G}]\\ & \underbrace{[138.059551v \log_{10}(d_o/d_i)]}_{Z_0}\end{aligned} \tag{8}$$

Substituting numerical values with $D = 0.00011$ and appropriate unit conversions gives the following working formulas, for f in MHz, d_o and d_i in mm, and ρ in $\mu\Omega \cdot$ cm.

For $Z_0 = 60\ v\ \ln(10)\log_{10}(d_o/d_i)$:

$$\begin{aligned}\alpha = {} & 0.198952 f^{1/2}[\rho_0^{1/2}/d_o + \rho_i^{1/2}/d_i][1/v \log_{10}(d_o/d_i)]\\ & + 9.102138D/v\ \text{dB}/100\ \text{m}\end{aligned} \tag{9}$$

For $Z_0 = 75\ \Omega$:

$$\begin{aligned}\alpha_{75} = {} & 0.366229 f^{1/2}[\rho_0^{1/2}/d_o + \rho_i^{1/2}/d_i]\\ & + 4.944681 fD/v^2 \log_{10}(d_o/d_i)\ \text{dB}/100\ \text{m}\end{aligned} \tag{10}$$

The dissipation factor D is a characteristic of the dielectric and may be somewhat dependent on the conditions under which it was processed. A reasonable value for the foamed polyethylene cable is $D = 0.00011$. Typically, d_o and d_i are given in the specifications, and the velocity v is determined by the nature of the dielectric. If $138v \log(d_o/d_i) \neq 75\ \Omega$, Eq. (10) misstates the attenuation by about 1% per ohm deviation. Conductor resistance is responsible for 92% of the total attenuation at VHF, below 300 MHz, and about 86% at 1 GHz. Ignoring the dielectric dissipation component for a first approximation, the attenuation of coaxial cables is seen to be roughly proportional to the square root of frequency, because the skin effect causes the series resistance component to be proportional to the square root of frequency.

The attenuation of coaxial cables varies significantly with temperature, primarily because of the thermal coefficient of conductor resistance. The empirical finding that attenuation changes approximately 0.18% per degree Celsius closely confirms calculations based on thermal coefficients of resistivity for aluminum and copper.

Cutoff Frequency. At the frequencies generally employed in wired cable TV distribution networks, the coaxial cable operates in the transverse electric and magnetic (TEM) mode. This means that both the electric and magnetic fields are transverse to the direction of propagation. The TEM mode cannot be sustained, however, if the effective wavelength in the cable is less than the mean circumference of the dielectric crosssection. The cutoff frequency is given by

$$\begin{aligned} f_{\mathrm{c}} &= 2cv_{\mathrm{rel}}/\pi(d_{\mathrm{i}} + d_{\mathrm{o}}) \\ f_{\mathrm{c(GHz)}} &= 2cv_{\mathrm{rel}}10^{-9}/\pi(d_{\mathrm{i}} + d_{\mathrm{o}}) = 19.1v_{\mathrm{rel}}/(d_{\mathrm{i}} + d_{\mathrm{o}}) \end{aligned} \tag{11}$$

where the velocity of light $c = 3 \times 10^{10}$ cm/sec; the relative velocity $v_{\mathrm{rel}} = 1/\epsilon^{1/2}$; d_{i} is the inside diameter of the outer conductor in cm; and d_{o} is the diameter of the inner conductor in cm.

The cutoff frequency is between 5 GHz and 12 GHz for the solid-sheath cables normally used for distribution in cable TV networks. For the smaller-service drop cables, the cutoff frequency is generally well above 20 GHz.

Reflection and Return Loss. Unless a transmission line is terminated in a load the complex impedance of which is the conjugate of the characteristic impedance of the line (i.e., a reactive component of opposite sign), some of the incident signal will be reflected. Reflections are quantified in various ways, according to particular manifestations. Perhaps the oldest and most common is the voltage standing wave ratio: VSWR = $E_{\max}/E_{\min}$. Here $E_{\max}$ is the point along the line where the incident wave and reflected waves are in phase; $E_{\min}$ is the point at which they are totally out of phase. Another form is the voltage reflection coefficient $\rho = E_{\mathrm{r}}/E_{\mathrm{i}}$, where E_{r} and E_{i} represent the scalar amplitudes of the reflected and incident RF waves. It should be noted that these expressions are voltage related. Power ratios are derived by squaring the voltage ratios. The decibel power ratio corresponding to the reflection coefficient is designated return loss (RL). The following formulas indicate the relation among the reflection coefficient, VSWR, and return loss:

$$\rho = (\mathrm{VSWR} - 1)/(\mathrm{VSWR} + 1) \tag{12}$$

$$\mathrm{VSWR} = (1 + E_{\mathrm{r}}/E_{\mathrm{i}})/(1 - E_{\mathrm{r}}/E_{\mathrm{i}}) = (1 + \rho)/(1 - \rho) \tag{13}$$

$$\mathrm{RL} = \log_{10}\rho^2 \qquad \text{or} \qquad \log_{20}\rho \tag{14}$$

The reflection coefficient ρ, however, has both phase and amplitude, depending on the phase and amplitude of the complex impedance of the load, Z_{L}, terminating the line and of the characteristic impedance Z_0 of the line itself.

$$\rho = (Z_{\mathrm{L}}/Z_0 - 1)/(Z_{\mathrm{L}}/Z_0 + 1) = (Z_{\mathrm{L}} - Z_0)/(Z_{\mathrm{L}} + Z_0) \tag{15}$$

where the load impedance $Z_{\mathrm{L}} = R_{\mathrm{L}} + jX_{\mathrm{L}}$ and the characteristic impedance $Z_0 = R_0 + jX_0$.

Network analyzers displaying complex reflection coefficients (or scattering matrices) are commonly used in the design and manufacture of equipment. However, for design, installation, and maintenance of systems in the field, the measure of reflection most commonly used in cable TV is the scalar RL = $\log_{20}|\rho|$.

Structural Return Loss. Coaxial cables are manufactured by machines that extrude the aluminum tubing and dielectric and apply the laminated mylar tape and shield braid to drop cable. Minor deviations in one or more of the critical dimensions, especially of service drop cables, may occur at precisely repetitive intervals for every revolution of some wheel or roller that is slightly eccentric or otherwise imperfect. At the frequency for which the spacing of such minor deviations is a multiple of a half wavelength, the cumulative effect is a sharp increase in attenuation and decrease in return loss. This effect is seen on a sweep display of return loss versus frequency as one or more "spikes" with very narrow spectral width. Unless the line is precisely terminated in the conjugate of its complex characteristic impedance, the magnitude of the spikes may be obscured by inherent mismatch reflections. With the resistance and reactance of the bridge termination adjusted for minimum reflection (maximum RL) at all frequencies, the sweep trace represents the structural return loss (SRL) for the cable. Swept SRL testing is a more sensitive indicator of structural defects than attenuation sweep testing.

Before recurrent discontinuities had been virtually eliminated by improved manufacturing processes, spikes due to repetitive discontinuities with reflections 5 dB or so above the noise floor were not uncommon. By reducing the size of the offending wheels, the discontinuities could be made to occur at higher frequency for expanded bandwidth and channel capacity. Thus, specifications for coaxial cables indicate the highest frequency for which a minimum SRL is guaranteed. Modern cables are swept to 1 GHz for at least 30 dB SRL.

Shielding Efficiency. A critical characteristic of the drop cable is its shielding efficiency, or transfer impedance, for both signal leakage and signal ingress, as estimated in one of several different types of special multishield jigs that compare the field strength produced outside the cable with current flow inside. As a rough idea of relative shielding efficiency, tested in a particular jig, the rating for a drop cable with a single laminated tape and braid is about 80 dB. The addition of a second tape on top of the first braid increases the rating by about 20 dB. The outer braid, constituting a fourth layer, still further increases the rating by another 20 dB or so. Simulated flexure testing demonstrates that additional shielding layers add substantially to freedom from deterioration over time.

RF Amplifier Characteristics

Enclosures. Cable TV amplifiers are housed in cast metal housings, designed to conduct heat from the hybrid RF power devices to specially designed convection fins from which it is dissipated into the atmosphere; see Fig. 7. RF circuits are mounted in the body of the housing and a dc power pack is mounted in the cover, generally with a switching mode regulation. The two parts of the enclosure are secured with bolted clamps and sealed against both moisture and signal leakage with neoprene and metalized conductive gaskets.

Slope is defined as the decibel ratio between the gain (or loss) at the highest and lowest frequencies in the pass band of the amplifier or other device. The intrinsic gain of many amplifiers is independent of frequency across the entire pass band, within a fraction of a decibel. Passive filters, called *equalizers,* are inserted generally at the input but for some purposes also between the stages of a multistage amplifier, to reduce the effective gain at low frequencies corresponding to the lower loss in the associated cable. Ideally, the slope of a repeater amplifier, with equalizer in place, should be such that at any frequency in the pass band, the net gain of the combined amplifier and associated coaxial cable would be unity (0 dB). Automatic gain and slope control (AGSC) circuits are designed to maintain constant output levels at two designated pilot frequencies over the anticipated range of temperature and supply-voltage variation. Overall frequency-independent gain is generally controlled by the low-frequency pilot. The high-frequency pilot adjusts the slope with voltage-

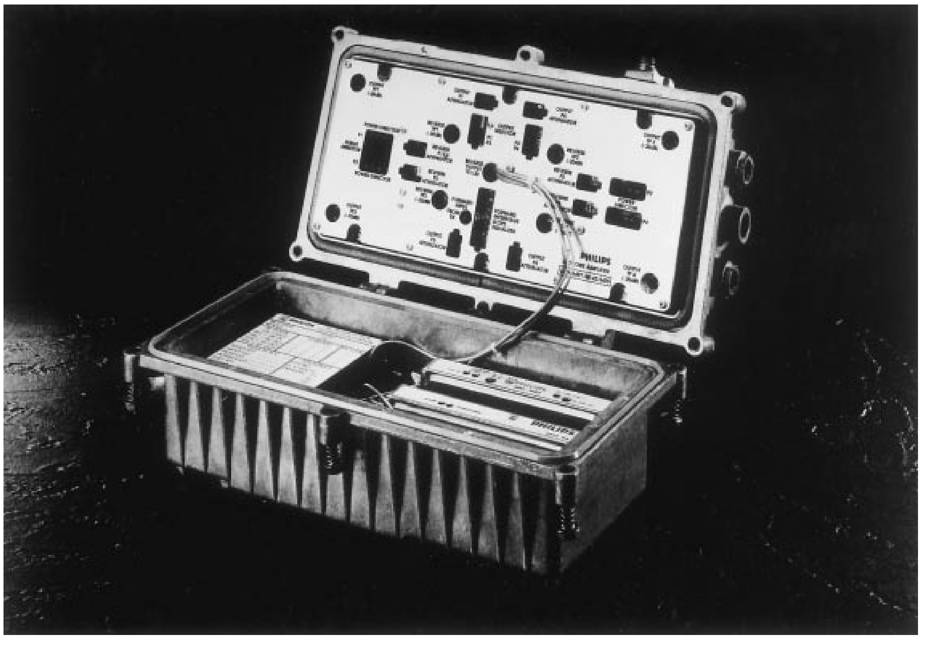


Figure 7. Amplifier housing. © Philips Broadband Networks Inc.

sensitive reactors, while maintaining the high-frequency pilot at a designated output level.

Tilt on the other hand, is not a characteristic of the amplifier itself, although it has a significant impact on performance. *Tilt* is the decibel ratio between the signal power level at the highest and lowest frequencies in the pass band and necessarily has different values at different points in the network.

It is important to recognize that slope represents the relationship between gain or loss and various frequencies in the pass band. Tilt represents the relationships between *signal levels* and various frequencies in the pass band. Slope represents the gain or loss characteristic between the input and output ports of an amplifier, passive device, or section of cable. Tilt describes the signal-level characteristic and may be affected by the gain or loss characteristic of preceding amplifiers, cable, and other devices, as well as signal-level settings at the headend. Slope is basically independent of signal level, except as it may be adjusted by AGSC circuits.

Cable television networks are based, almost exclusively, on cable-amplifier spans with unity net gain (0 dB) across the pass band. The cable span may be either at the input or the output of the associated amplifier and includes frequency-independent losses (such as splitters, couplers, and directional taps) as well as the frequency-dependent coaxial cable. If all channels are at the same level (zero tilt) at the input to the cable connected to an amplifier input port, the tilt at the end of the cable span would be sharply negative, since the cable attenuation is much greater at high frequency than at low frequency. In order to compensate, a passive equalizer is inserted at the amplifier input port, so designed that the combined attenuation of cable plus equalizer is constant across the entire pass band. Thus, the signal levels at the amplifier output will also have zero tilt.

On the other hand, with zero tilt at the input to an amplifier with such an equalizer in place, the signal levels at the amplifier output port will be tilted, with the higher values at the high-frequency end of the pass band. Thus, all channels will be at the same level (zero tilt) at the end of the following length of cable. This is a condition called *full tilt.* Since the output signal power, averaged over the pass band, is lower with full tilt than zero tilt, composite triple-beat (CTB) intermodulation distortion due to overload will be lower. However, the full-tilt condition also means that signal levels at the amplifier first stage input, following the equalizer, will also be full tilt, resulting in reduced carrier-to-noise ratios at the lower frequencies.

This dilemma has led to an arrangement called *half-tilt,* which splits the difference between zero tilt and full tilt. Half-tilt is further simplified for operational convenience by an arrangement called *block tilt,* by which the pass band is split in two or three segments to simulate the half-tilt, piecewise. With half-tilt or blocktilt, the amplifier output signal level at the highest frequency is greater than at the lowest frequency. However, the input to the next amplifier is lower at the highest frequency and greater at the lowest frequency, because of the difference in attenuation in the cable. Amplifier performance specifications are generally based on recommended operating levels, typically with 5 dB to 7 dB block tilt. Optimizing amplifier performance with respect to noise and distortion as functions of gain and slope, signal level, and tilt is a sophisticated task involving strategic analysis of the characteristics and interrelationships of various components such as the interstage coupling networks, automatic gain and slope control, fixed and variable equalization, noise figure, and linearity.

Gaussian Noise. Noise power, in cable TV, is defined as the average Gaussian noise (i.e., Johnson or random noise) power within 4.0 MHz noise power bandwidth (NPBW). Television signal levels are defined as the peak modulated RF envelope power during the synchronizing interval. The noise power level and RF signal carrier power level in cable television networks are expressed in decibels relative to 1 mV rms across a 75 Ω resistance or 13.33 nW. The value of 0 dBmV is equivalent to −48.75 dBm (dB re 1 mW). It is particularly important to recognize that, without exception, dBmV always refers to relative signal power delivered to a 75 Ω termination.

The numerical *noise factor* (f) is the ratio of total white-noise power in bandwidth (B) available at the output to the available Johnson noise power engendered by the input impedance. The *noise figure* (NF) is 10 times the logarithm of the noise factor (f). The available noise power at the input is given by the formula

$$10 \log kTB + 30\,\text{dB} = -107.95\,\text{dBm}$$

where k is Boltzmann's constant (1.3806×10^{-23} J/K), $T = 290$ K, and B is the NPBW (4.0 MHz).

Converting to dBmV, therefore, the available input noise power is

$$-107.95 + 48.75 = -59.2\,\text{dBmV} \tag{16}$$

The available output noise power is

$$-59.2 + (NF)_0 + G\,\text{dBmV} \tag{17}$$

where G is the gain. The combined, uncoordinated noise factor for n cascaded stages is (in numerical terms, not decibels):

$$\begin{aligned} f_{\text{total}} = f_1 + (f_2 - 1)/g_1 + (f_3 - 1)/g_1 g_2 \\ + \cdots + (f_n - 1)/g_1 g_2 \cdots g_{(n-1)} \end{aligned} \tag{18}$$

Each cascaded stage comprises an amplifier and its associated cable span, with unity gain (i.e., 0 dB) and identical noise figures, typically about 8.5 dB to 10 dB (a noise factor of 7 to 10). Since $f \gg 1$ and $g = 1$, it follows that $f_{\text{total}} \cong (n)f$. Thus, in decibels,

$$\text{NF}_{\text{total}} = (\text{NF})_0 + \log_{10} n \tag{19}$$

Nonlinear Distortion. In its broad sense, noise is any undesirable effect. In an electronic communication system, noise includes not only Gaussian, or randomly distributed electrical signals, but also various undesired nonlinear distortions of the desired signal, discrete interfering signals, hum, and impulsive electrical noise. Nonlinear distortion, resulting in intermodulation in a multicarrier FDM/AM network, has been thoroughly analyzed by Simons (6) and others, based on the assumption that the transfer characteristic of the amplifier can be represented by a power series with three terms. *First-order* terms of the power-series expansion for waves of three frequencies (f_a, f_b, f_c) represent the input signals with increased amplitude.

Second-order terms represent the second harmonics and sums and differences of pairs of input signal waves, in addition to dc components that indicate a shift in average level. Second harmonics and sums and differences appear generally at 1.25 MHz above or below a visual carrier. Because channels 5 and 6 are offset by 2 MHz below the standard assignments, some second-order products may occur at 0.75 MHz above or below a visual carrier or at 2.75 MHz above or below a carrier.

Third-order terms represent the third harmonics and two types of intermodulation. In one case, called *two-tone third order,* the frequency of the product is in the form $2f_a \pm f_b$. In the other case, the frequency of the product is in the form $f_a \pm f_b \pm f_c$. Products resulting from the $2f_a - f_b$ term are sometimes loosely identified simply as *intermodulation.* Products resulting from the $f_a + f_b - f_c$ term are called *triple beat.* The $2f_a - f_b$ and $f_a - f_b + f_c$ products are in the form $n\Delta f$ + 1.25 MHz, where n is an integer and Δf is the uniform 6 MHz FDM carrier spacing (except for channels 5 and 6) approximately coinciding with nominal FDM carrier frequencies. These products represent, in effect, a "near-zero" beat, comparable to cochannel interference. Third harmonics and some of the two-tone and triple-beat permutations also result in products at 2.5 MHz and 3.5 MHz above an FDM visual carrier (i.e., 2.5 MHz below the next higher channel). A few products involving channels 5 and 6 occur at various frequencies, but with little clustering. However, the very large number of near-zero-beat products represents by far the highest proportion of all third-order products falling within the pass band.

The third-order terms also include several products the frequencies of which are the same as the input signals, resulting in expansion or compression of the input signal. The amplitude of certain of these components is determined in part by the square of the modulated amplitude of one of the other signal waves. Thus, the modulation on one signal wave affects the amplitude of another. This group of third-order products represents cross-modulation.

The number of permutations of 50 to 150 FDM frequencies, taken three at a time, can be very large, even after filtering those that fall outside the pass band. The number of triple beats, Q, in the Mth channel of a total of N channels, is given as

$$Q = N^2/4 + \tfrac{1}{2}(N - M)(M - 1) \tag{20}$$

(obtained from Ref. 7).

For example, near the midpoint of a 450 MHz fully loaded pass band (60 channels), 1335 triple-beat products fall at frequencies close to a visual carrier frequency. This increases to 2217 near-zero beats for a 550 MHz pass band (77 channels) and 4538 near-zero beats for a 750 MHz pass band (110 channels). Theoretically, the largest number of triple beats falls within the channels just above the middle of the system pass band. The peak occurrence is broad and, because of system tilt and the gain–frequency characteristics of the amplifiers, the maximum number may occur elsewhere.

The number of second-order products falling on a specific channel is given in Ref. 1 as follows:

$$N_{\text{L}} = n - m - x + 1 \qquad \text{and} \qquad N_{\text{U}} = (x - 2m + 1)/2 \tag{21}$$

where N_{L} is the number of lower beats ($A - B$), N_{U} is the number of upper beats ($A + B$) (note: the 0.5 number represents the 2nd harmonic), n is the harmonic number of the highest carrier, m is the harmonic number of the lowest carrier, and x is the harmonic number of the carrier being evaluated [note: $(m - 1) < x < n - (m - 1)$].

From this, it is apparent that the number of second-order products is very much less than third order. Second-order products are significant, particularly in the optical fiber portion of the HFC network because of the special characteristics of lasers and optical fibers other than transmission nonlinearity.

The frequency tolerance established by the FCC for television broadcast visual carriers is ± 1 kHz. In general, the FCC requires only that cable television channels delivered to the subscriber's terminal be capable of being received and displayed by TV broadcast receivers used for off-air reception of TV broadcast signals. Visual carrier frequencies assigned to some broadcast television stations are offset by 10 kHz or 20 kHz to minimize terrestrial co-channel interference. Moreover, visual carrier frequencies for cable TV must be offset from nominal assignments by 12.5 kHz ± 5 kHz in the aviation radio bands to minimize interference, and 25 kHz ± 5 kHz in the aeronautical navigation bands. Typically, however, the triple-beat products tend to cluster within about ± 60 kHz around the nominal assignments at intervals of 6 MHz (NTSC) with almost random phase. The average power of this cluster consisting of a few thousand primarily triple-beat and third-order two-tone products is the most reliable measure of intermodulation distortion and is defined as the composite triple beat (CTB).

Similarly, second-order intermodulation products cluster primarily at ±1.25 MHz around visual carriers. The average power of the cluster at +1.25 MHz above a visual carrier is defined as the composite second-order (CSO) power. The worst CSO is likely to occur toward the upper end of the pass band. Second-order products at −1.25 MHz, below visual carrier, are of little importance, because of the substantial vestigial sideband attenuation.

Cross-modulation is still specified by manufacturers, on request. In the early days when CATV carried only a few TV channels, cross-modulation was the primary indicator of overload distortion, since so few channels were carried on the network. As network capacity increased to 30 channels and beyond, however, the number of triple-beat products in each cluster increased rapidly. The composite beat is now generally considered to be the most reliable indicator of overload distortion. Cross-modulation was found to be susceptible to anomalous performance in the presence of higher-order (fifth, seventh, ninth, etc.) products which under certain circumstances tended to cancel the lower orders, causing an anomalous reduction in cross-modulation with increasing signal levels. Although cross-modulation ratios in “well behaved” amplifiers tend to track the triple-beat ratios, they are no longer considered primary indicators of third-order distortion.

The power-series analysis shows that the power level of individual second harmonics nominally is 6 dB lower than that of the second-order sum and difference products. The power level of individual two-tone third-order products is nominally 6 dB lower and third-harmonic products 15.5 dB lower than that of individual triple-beat products. Moreover, for every 1 dB increase in output level of the fundamental signal, the level of the second-order intermodulation products also increases by 1 dB, while the level of third-order products, including third harmonics, triple-beat, two-tone, and cross-modulation, increases by 2 dB. This is the classic “two for one” rule for third-order products, which has been reasonably confirmed empirically. Second-order intermodulation products are effectively suppressed in the coaxial portions of the network by the use of push–pull circuitry. Distortion due to nonlinearity in the amplifiers in the coaxial portion of the network is dominated by the triple-beat products generated in the hybrid gain blocks. However, in the fiber-optic portion, second-order products are likely to be of considerable importance, often dominant. The upstream network is also vulnerable to distortion products due to rectification in contacts that may have become slightly oxidized and are common to both directions of signal flow such as the center conductor seizure clamps. Thus, the thousands of triple beats generated by the downstream carriers are likely also to be transmitted in the upstream direction.

Spectrum Allocation Plans for Cable Television

Offsets and Power Limits. All carriers and signal components carried on a cable TV network at greater than 10^{-4} W (+38.75 dBmV) are required to be offset from frequencies available for assignment in the aeronautical frequency bands. In addition, cable TV carriers at greater than 10^{-5} W (28.75 dBmV) are prohibited to operate within 50 kHz or 100 kHz of frequencies designated for emergency and distress calling. The offsets listed in Table 1 are specified by the FCC as a precaution against interference with aeronautical radio as a result of inadvertent leakage from malfunctioning or damaged coaxial television distribution lines. The offsets are designed to interleave cable TV carrier frequencies between the aviation frequency assignments spaced at 25 kHz for communication and 50 kHz for air navigation.

The ANSI/EIA-542 Standard. The American National Standards Institute (ANSI) and the Electronic Industries Association (EIA) have adopted the ANSI/EIA 542 Standard entitled “Cable Television Channel Identification Plan,” developed jointly with the National Cable Telecommunications Association (NCTA). The FCC has adopted the EIA-542 Plan by reference, effective June 30, 1997. Channel identification plans from 54 MHz to 1002 MHz (or higher) are provided for (1) standard frequencies, (2) harmonically related carriers (HRC), and (3) incrementally related carriers (IRC).

The Standard Plan. From the beginning, cable TV channels have conformed with the VHF channels designated by the FCC for television broadcasting: 54 MHz to 88 MHz, with a gap at 72 MHz to 76 MHz, and 174 MHz to 216 MHz. Except for channels 5 and 6 (76 MHz to 88 MHz), the lower-frequency boundary of the FCC channels is a multiple of 6 MHz. However, the Standard Plan designates additional cable TV channels in the same pattern of continuous 6 MHz channels up to 1002 MHz (or higher), with the lower-frequency boundary at a multiple of 6 MHz and the only gap being at 88 MHz to 90 MHz. Channels 5 and 6 and the FCC channel designations for UHF broadcasting (470 MHz to 806 MHz) are offset 2 MHz below the 6 MHz multiple. As a result, cable channel numbers 14 and above do not conform with the corresponding UHF broadcast channel numbers assigned by the FCC. Channel 1 is undesignated in the Standard Plan, but is assigned in the 72 MHz to 78 MHz gap between channels 4 and 5 in the HRC and IRC plans. [*Historical note:* In 1940, the FCC deleted channel 1 (44 MHz to 50 MHz) from television and

Table 1. Required Frequency Offsets (except Harmonically Related Carriers)

Service	Frequency Band	Required Offset
Communication	118 MHz to 137 MHz	12.5 kHz ± 5 kHz
Communication	225 MHz to 400 MHz	12.5 kHz ± 5 kHz
Navigation	108 MHz to 118 MHz	25 kHz ± 5 kHz
Glide path	328.6 MHz to 335.4 MHz	25 kHz ± 5 kHz
Aero. emergency	121.5 MHz	100 kHz
Marine distress	156.8 MHz	50 kHz
Aero. emergency	243.0 MHz	50 kHz

reallocated it, first to FM radio, and later, in 1948, to land mobile radio]. Three TV channels are identified in the FM radio band, 90 MHz to 108 MHz.

HRC and IRC Plans. In the early 1970s, Israel (Sruki) Switzer, a Canadian engineer, proposed to convert all visual carrier frequencies to an integral multiple of 6 MHz, phase-locked to a 6 MHz comb generator in order to minimize intermodulation distortion (8). The fundamental separation was set by the FCC at 6.0003 MHz $\pm$ 1 Hz to ensure acceptable offsets in the aviation radio bands. This arrangement is designated in the ANSI/EIA-542 Standard as harmonic related carriers.

A similar alternative arrangement, designated Incremental related carriers (IRC), depends on phase-locking all visual carriers to a comb generator at $6n$ MHz + 1.2625 MHz (n is an integer). Both arrangements are labeled *coherent,* although the intermodulation products are inherently frequency coherent but generally not phase coherent.

In the HRC arrangement, all harmonics as well as all second- and third-order intermodulation products coincide precisely with a visual carrier frequency. Since television receivers are not responsive to frequencies within about 10 Hz of the visual carrier, such zero-beat products would not generally be visible, although cross-modulated sidebands may still be visible. In the IRC arrangement, the precise constant frequency spacing between visual carriers causes the principal third-order intermodulation products to coincide precisely with other visual carriers. However, the harmonic and second-order products do not coincide with other carriers and are not as well hidden from view on the TV screen as in the HRC plan. In the coaxial network, second-order products are substantially suppressed by push–pull circuits, and the subjective improvement with IRC is only slightly less than with HRC. However, with HFC architecture, the IRC format may not be as effective as HRC because of substantial second-order effects in the optical network.

In the HRC plan, all visual carriers are shifted to ~1.25 MHz below their standard frequency assignments (except that channels 5 and 6 are at ~0.75 MHz above the standard assignment). In the IRC plan, all visual carrier frequencies (except channels 5 and 6) are the same as the standard frequency assignments, including the required aeronautical offsets. The automatic frequency control (AFC) circuits in most modern TV and VCR equipment are capable of capturing either HRC or IRC. However, without a set-top converter, the offset HRC channels are more vulnerable to direct pickup interference in the strong radiated fields of nearby TV transmitters.

Bidirectional and Digital Transmission. The ANSI/EIA-542 Standard makes no special provision for either bidirectional or digital program transmissions. It is the general practice in North America to allocate return, or upstream, transmissions in the band between about 5 MHz and an upper limit as close to TV channel 2 (54 MHz) as practical diplex filters permit, typically in the neighborhood of 30 MHz to 42 MHz. The corresponding allocation for forward, or downstream, transmission depends entirely on the individual situation. A plan for allocating forward transmissions in the band 750 MHz to 850 MHz and the corresponding return in the band 900 MHz to 1000 MHz has been considered but has not been put into practice. Most plans for migration to digital transmission on the subscriber network contemplate allocating a block of 100 MHz to 200 MHz for 64-QAM digital programs, retaining frequencies below about 550 MHz for conventional analog program channels.

Coaxial Network Calculations

CNR, C/CTB, and C/CSO Performance. The following symbols are used in calculating RF performance for the coaxial network.

CNR	C/N ratio (dB)
C/CTB	The ratio of the carrier to the average power of the cluster of triple-beat products
C/CTB_0	The rated C/CTB for a single amplifier at output level A_0
C/CSO	The ratio of the carrier to the average power of the largest second-order cluster
C/CSO_0	The rated C/CSO for a single amplifier at output level A_0
A	Operational output of each amplifier at the highest frequency (dBmV)
A_0	Output level at specified CTB and CSO performance levels (dBmV)
G	Operational gain of each amplifier at the highest frequency in the pass band (dB)
NF	Noise figure
L	Cascade length (dB), $L = nG$ dB
n	Number of identical amplifiers in series cascade

Idealized design computations make several important assumptions, subject to adjustment for predictable variants. Performance may be calculated for other conditions through logical extensions of the fundamental relationships. Assumptions are as follows:

1. All amplifiers in the cascade have identical characteristics.
2. The net gain for each span comprising amplifier, equalizer, cable, and frequency-independent loss is constant and uniformly 0 dB at all frequencies in the pass band.
3. The temperature of the entire span is constant and uniform.
4. The noise figure for the amplifier is not a function of the gain of the amplifier.
5. The amplifiers are sufficiently linear that the magnitude of the fourth and higher orders of the power-series expansion are relatively insignificant.

The relationships between the basic performance criteria and network specifications are set forth in the following equations. Note that both CNR and C/CTB are used here in the positive form, as carrier-to-interference ratios. Larger ratios mean *better* performance. Distortion ratios are commonly specified elsewhere as the interference-to-carrier decibel ratio, indicating the magnitude of the distortion relative to the carrier level, designated "dBc." This results in negative ratios that are algebraically larger (i.e., a smaller absolute number without regard to sign) for *poorer* performance:

$$\mathrm{CNR} = A - (-59.2 + \mathrm{NF} + G + 10\log n)\,\mathrm{dB} \tag{22}$$

$$\mathrm{C/CTB} = \mathrm{C/CTB}_0 - [2(A - A_0) + 20\log n]\,\mathrm{dB} \tag{23}$$

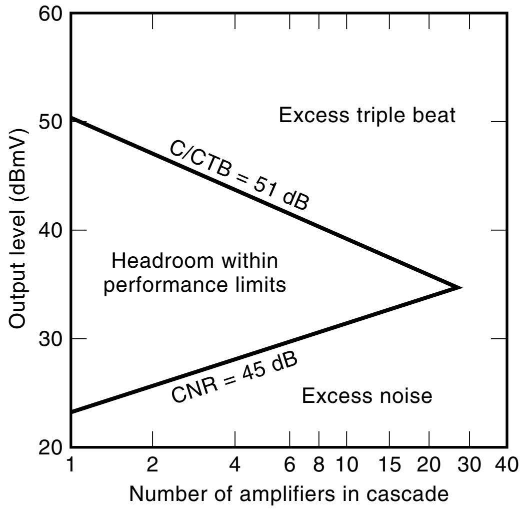


Figure 8. Wedge diagram showing headroom between C/CTB and CNR objectives versus cascade length.

These relationships may be rearranged to show the amplifier output levels (A_{CNR} and $A_{\mathrm{C/CTB}}$) required to achieve specified CNR and C/CTB objectives as a function of cascade length. The "wedge" diagram in Fig. 8 is a plot of the following equations:

$$\begin{aligned} A_{\mathrm{CNR}} &= \mathrm{CNR} - 59.2 + \mathrm{NF} + G + 10 \log n \\ &= K_{\mathrm{CNR}} + G + 10 \log n \end{aligned} \tag{24}$$

$$\begin{aligned} A_{\mathrm{C/CTB}} &= A_0 + \tfrac{1}{2}(\mathrm{C/CTB}_0 - \mathrm{C/CTB}) - 10 \log n \\ &= K_{\mathrm{C/CTB}} - 10 \log n \end{aligned} \tag{25}$$

Headroom and Optimum Gain. The *headroom,* or tolerance, between the maximum permissible C/CTB ratio and minimum allowable C/N ratio is the difference between $A_{\mathrm{C/CTB}}$ and A_{CNR}:

$$\begin{aligned} \text{Headroom } &= A_{\mathrm{C/CTB}} - A_{\mathrm{CNR}} \\ &= (K_{\mathrm{C/CTB}} - K_{\mathrm{CNR}}) - G - 20 \log n \end{aligned} \tag{26}$$

For relatively short cascades, the performance objectives are met with a substantial margin or headroom. The maximum "reach" for a cascade of n identical amplifiers is the total attenuation for which the headroom vanishes. Since $n = L/G$, or $20 \log n = 20 \log L - 20 \log G$, the maximum reach, L, for zero headroom is given by

$$20 \log L = 20 \log G - G + (K_1 - K_2) \tag{27}$$

The optimum gain (G) for maximum reach (L) is obtained by setting to zero the derivative of Eq. (27), with respect to G:

$$d(20 \log L)/dG = [(20 \log \epsilon)/G] - 1 \tag{28}$$

Therefore, L is maximum when

$$G = 20 \log \epsilon = 8.6859\,\mathrm{dB} \tag{29}$$

Ideally, maximum reach would occur at the Napierian gain, $G = 8.69$ dB per amplifier. However, deviations from the ideal assumptions are unavoidable in practice. Simons (6) has shown that because of uncertainties in signal level due to variations in temperature and other conditions, minor nonuniformities in gain across the pass band, and noise figure variation with gain, the achievable reach is actually much less than ideal. Maximum reach actually occurs at higher gain per amplifier and is quite broad. For many operational reasons, amplifier gain in practical designs is likely to be in the range of 20 dB to 25 dB rather than the theoretical optimum value of 8.69 dB. Minimizing down time in the network, controlling aggregate noise and ingress in the return path, and providing for efficient two-way traffic management may require higher priority in design than maximizing reach. Coaxial distribution lines in HFC networks are inherently much shorter than would be required without the optical fiber links, and amplifiers with as much as 40 dB gain are not unrealistic in HFC.

Feedforward. All amplifiers for coaxial cables in HFC networks utilize classical push–pull circuitry to minimize second order distortions by cancellation. Feedforward (FF) is another circuit arrangement for canceling distortion, originally developed by H. S. Black at Bell Laboratories in the late 1920s.

The operation of the feedforward integrated circuit hybrid chip is illustrated in Fig. 9. For the first loop cancellation, the input signal is divided at the input directional coupler DC1. The main portion passes through a broadband, microstrip delay line to directional coupler DC3. A sample of the input signal goes to the input of a push–pull cascode hybrid gain block. The output of the gain block contains the amplified signal shifted 180° by the cascode circuit plus the distortion and noise added by the gain block. This output is sampled in directional coupler DC2 and passed through an attenuator to be combined, in directional coupler DC3, with the delayed input signal, which has not been shifted 180°. If the delay precisely matches the delay in the gain block, the attenuator pad equals the amplification of the gain block, and the attenuation of DC1 is the same as DC2, only the error signal containing noise and distortion will remain in the output of DC3.

For the second loop cancellation, the error signal is amplified with 180° phase reversal, and combined with the delayed output of DC2 canceling the error signal, and leaving only the amplified, undistorted signal at the output. In practice, of course, these conditions cannot be met precisely. Although noise in the main amplifier is canceled, the effective noise figure is increased somewhat due to noise generated in the error amplifier. Feedforward technology is used primarily to

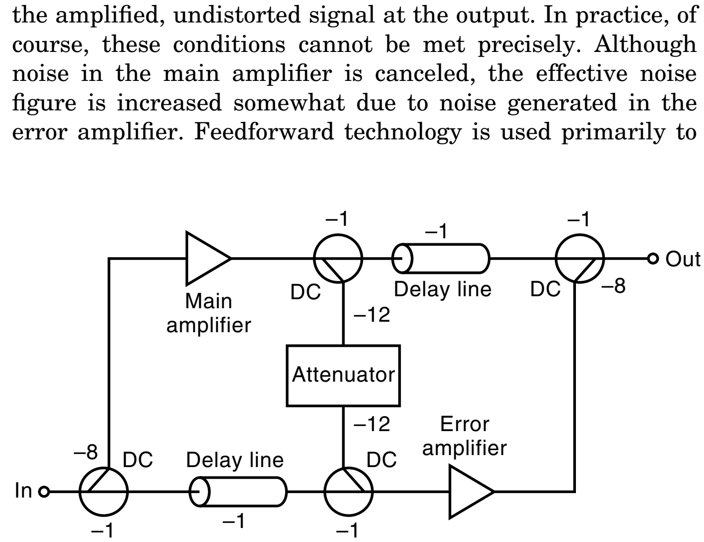


Figure 9. Functional block diagram for feedforward (FF) RF amplifier. DC = directional coupler. © National Cable Television Association.

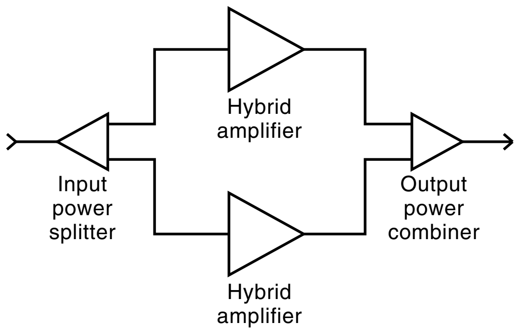


Figure 10. Schematic circuit diagram for amplifier using parallel hybrid device (PHD). © National Cable Television Association.

extend the reach of long cascades, and is not normally used in the short coaxial cascade portions of the HFC networks (9–11).

Parallel Hybrid Devices. (Power Doubling™). Another technique for improving CTB performance with heavy channel loading is the parallel hybrid device (PHD), developed by affiliates of the Philips Broadband Networks, Inc. (successor to Magnavox), using Amperex integrated-circuit chips. The PHD is essentially two push–pull hybrid gain blocks connected in parallel. Power Doubling is the proprietary term used by Philips for the generic PHD. For a given output power, each hybrid operates at half power (−3 dB), thereby increasing the C/CTB ratio for each hybrid by 6 dB. Since the triple beats are generated in different hybrid gain blocks, they are not phase coherent. When combined, the resulting C/CTB ratio is theoretically 6 dB higher than it would have been for a single hybrid operating at the designated output power level, with only a slight reduction in noise figure. Figure 10 shows how the two hybrids are driven through a power divider (splitter) at the input and recombined in another power divider, reversed. Uniform phase delay through the two legs of the splitter and combiner and good isolation are essential for proper operation (12).

Reflections and Group Delay

Visual Echoes. Phantom images, sometimes called "ghosts," may be caused by multipath radio wave propagation in space, reflections within the coaxial or fiber cable, phase distortions in various filters, or variations in transit time for signals of different baseband video frequency. Multipath propagation in space is not unique to cable TV operations and has been treated in many references, both from a theoretical and empirical point of view.

Reflections within the coaxial cable are caused by impedance discontinuities, primarily due to mismatch between the characteristic impedance of the cable and the source or load impedance of active or passive devices, including amplifiers, power dividers and combiners, multitaps, connectors, and splices. Return loss for active equipment ranges from about 14 dB to 16 dB, and for passive devices, from about 16 dB to 18 dB (with all ports properly terminated). Reflections at the input of a device travel in the reverse direction and are attenuated by cable loss until again being reflected at the output of another device to become an echo of the direct signal. The echo delay is the time required to travel back to the preceding device and return. The signal-level ratio between the desired signal and the twice-reflected signal, with which it travels, is the sum of the return loss of the two devices plus twice the cable loss. The echo delay is approximately 2×2.9 ns/m (at 87% velocity ratio). Cable losses are relatively small, between about 0.01 dB/m and 0.07 dB/m. The classical study by Pierre Mertz of the Bell Laboratories in 1953 found that echoes delayed less than about 2 μs are not perceptible if the amplitude ratio of the echo to the direct signal is less than $35 + 20 \log(t_{\mu s})$ dB, or 40 dB for any echo delayed more than about 2 μs. Except in a few situations, main-line reflections are not likely to exceed the Mertz threshold. However, the single reflection from the input port of one tap, traveling back through the output port of the previous tap, may produce an echo of the desired signal on the subscriber service drop that exceeds the Mertz threshold. This is most likely to occur with tap values greater than about 30 dB that have very little directivity, especially at frequencies for which return loss is less than 18 dB.

Nominal return loss is only achieved when all ports are properly terminated. Tapped feeder lines are vulnerable to more severe reflections from unterminated tap ports. A directional coupler with four equal outputs, sometimes used as a "terminating tap," may have only 5 dB of return loss when unterminated, coupling reflections into nearby service drops that may exceed the threshold.

Chroma Delay. The diplexing filters separating forward and return transmissions in the distribution network introduce phase errors (group-delay inequality) at the low end of the forward spectrum and at the upper end of the return spectrum. The principal effect is to introduce *chroma delay,* defined as the difference in time delay between the luminance information (at 200 kHz) and chrominance (at 3.58 MHz). The resulting color misregistration is sometimes called the *comic book* effect. Typical chroma delay at channel 2 (55.25 MHz) for individual amplifiers may be less than 10 ns per amplifier for guard bands between 30 MHz and 54 MHz, but as much as 30 ns when the upstream band cutoff is increased to 42 MHz. However, the delay is cumulative across the cascade of several amplifiers and may exceed the maximum of 170 ns currently set by the FCC or 100 ns as recommended by the International Electrotechnical Commission (IEC).

Chroma delay at the upper end of the return spectrum may be at least 20 ns close to 30 MHz, or more than 60 ns close to 42 MHz. At the low end of the return spectrum (close to 5 MHz), chroma delay due to the 60 Hz power filters may be less than about 15 ns. For return data transmissions occupying much less bandwidth than the television signal, the effective group-delay inequality across the occupied bandwidth is much less than chroma-delay inequality.

Effect on Data Transmissions. The impact of "micro-reflections" on digital transmissions is a different matter. Data rates are likely to be as high as 27 megabits per second (Mbps), using modulation schemes with spectral efficiency of 4 to 5 bits per hertz. The undesirable effect of microreflections is intersymbol interference (ISI) as a result of group-delay deviations. Preliminary tests in existing networks indicate that bit error rates caused by microreflections are likely to be within tolerable limits in properly designed and maintained HFC networks. However, specific design criteria necessary to ensure satisfactory digital transmission have not yet been established on the basis of actual operating experience.

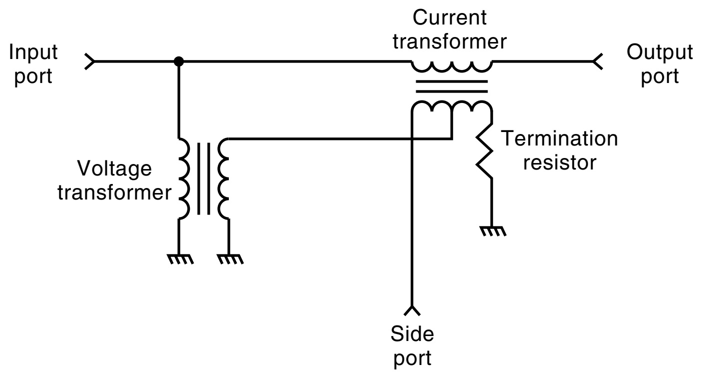


Figure 11. Schematic diagram of directional coupler.

Passive Devices

Line Splitters and Couplers. Most passive devices are directional couplers. Early attempts based on resonant coaxial stubs were abandoned when the introduction of ferrite cores for RF transformers made possible the modern directional coupler. Figure 11 is a typical diagram. A line splitter, or power divider, generally has one input and two equal signal outputs, or it may be turned around to combine two equal input signals into a single output, as combiners or multiplexers. A line coupler is a power divider with unequal outputs used to extract a small amount of signal from the main line or to inject a signal into the main line.

Directivity in a three-port passive device is the difference between the input-to-tap loss (tap value) and the tap-to-output loss (isolation). In the theoretical, lossless, case, the total power delivered to the output ports is equal to the power at the input port. In practice, however, the available devices realize about 75% to 90% power efficiency at frequencies up to 550 MHz, dropping to about 60% at 1 GHz. For example, the theoretical 3 dB attenuation in each leg of a typical two-way splitter may actually be 3.5 dB or 4.0 dB at frequencies up to 300 MHz but as much as 4.5 dB or 5.5 dB above 550 MHz. Efficiency and attenuation between input and output ports when used as a signal combiner is the same as when used as a divider. The most common couplers provide 3 dB (splitter), 8 dB, 12 dB, 16 dB, or 20 dB nominal attenuation at the tap leg, and from 3 dB to less than 1 dB on the through leg with 10 dB to 15 dB directivity. Signal power dividers are also available with three-output ports, configured either with three equal outputs or two high-level and one lower-level outputs.

Splitters and couplers for use in trunk and feeder lines are arranged to pass 60 Hz ac power at up to 10 A between the input and output ports. Nonterminating multitaps are rated to pass 60 Hz ac power in the through line, but traditionally have not been equipped to pass 60 Hz power to the tap ports. However, in anticipation of the prospective use of HFC cable television networks for delivery of telephony services, a new series of multitaps is offered with arrangements for passing 60 Hz ac power to individual coaxial (or auxiliary twisted copper pair) service drops, generally current-limited to 2 A per tap leg.

The ferrite transformers in devices using the directional coupler circuit are potential sources of interference due to hum modulation. This is a function of the extent to which currents related to the 60 Hz power source are blocked from the ferrite transformer windings. For a sinusoidal supply waveform, a blocking capacitor may be sufficient. However, the rise and fall times of trapezoidal or square waveforms are likely to be considerably shorter than those for the fundamental sine wave, making the blocking capacitor substantially less effective. Moreover, impedance shifts due to saturation of the ferrite core are likely to modulate the RF wave. Thus 60 Hz current flowing through the ferrite transformer winding may impress spurious waveforms on the RF signal at power-source-related frequencies.

Multitaps. Asymmetrical directional couplers, connected to two-, four-, or eight-way splitters are called multitaps and are used for connecting subscribers to the distribution lines (see Fig. 12). Multitap installation requires cutting the feeder cable and inserting a ferrite-based power divider to tap off a small portion of the signal power, with insertion loss in the through leg typically 1 dB to 4 dB, while maintaining a proper 75 Ω impedance match. Deviation from nominal values of attenuation and return loss is likely to occur unless all ports are properly terminated, either in a terminated coaxial drop cable or a well shielded 75 Ω resistor. Attenuation between multitap subscriber output ports, or *isolation,* is typically between about 20 dB and 30 dB, although some European suppliers specify up to 40 dB (at higher cost) in response to government-mandated standards. The two- or four-way taps that are sometimes connected at the end of a feeder line without a directional coupler are called *terminating taps,* since they do not provide a through leg. Terminating taps are more likely than directional taps to couple reflections and other disturbances caused by subscriber equipment back into the distribution system and are avoided by some designers. For tap values of 32 dB or less, directivity ranges between about 8 dB and 15 dB. For tap values larger than 32 dB, however, directivity may be as low as 1 or 2 dB.

Ac Power Sources

Cable Powering. 60 Hz ac power is transmitted through the coaxial cable for the operation of active devices, such as amplifiers and in some cases the electro-optical transducers in the optical nodes. Initially, cable power was limited at 30 V rms. Since the early 1970s, however, cable power has been distributed primarily at 60 V rms. By the mid-1990s, the current required for expanded bandwidth and channel capacity, closer amplifier spacing, and the introduction of additional functions has increased to such an extent as to require increasing to 90 V or even higher to avoid excessive IR voltage drops across the inherent resistance of the coaxial conductors.

Power drawn from the supply mains at 60 Hz, usually 120 V ac, is provided with disconnect and overcurrent protection facilities required by safety codes at the point of connection. Because energy use by the cable TV network is nearly constant over time, some utilities have waived the normal metering requirement. A 120/60 (or 90) V ferroresonant transformer provides surge and overload protection as well as inherent current limitation and constant voltage regulation for varying input voltage and output load. The 60 Hz waveform may be “quasi-square-wave” (trapezoidal) or sine-wave filtered for low harmonic content. These power supplies are generally mounted on utility poles or in above-ground cabinets or vaults and operate at better than 90% efficiency. 60 Hz ac power is inserted into the coaxial cable through a pas-

Figure 12. Typical multitaps: 2-way; 4-way; 8-way. © General Instrument Corp.

sive device called a power inserter, comprising a low-pass filter in a housing not unlike the housing used for line couplers.

Emergency Standby Power. A standby power supply with a 12 V to 36 V dc storage battery drives a solid-state dc–ac inverter with automatic transfer when the main power source fails (see Fig. 13). The battery is continuously trickle-charged off the main power. When an outage occurs, the transfer interval is short, typically not more than a half cycle (8 ms). Loss of the 60 Hz ac cable power during the brief transfer interval is likely to cause a transient disturbance in the current and voltage relationships at regulated power packs in the individual amplifiers, especially where switching-mode regulators are used. The resulting disturbance rippling through the affected stations could last for several periods of the 60 Hz voltage before reaching stability. In some models, therefore, separate primary windings for commercial power and inverter power enable the tank circuit to provide sufficient electronic momentum to maintain the 60 Hz supply voltage during the transfer. Standby power supplies may be mounted on a utility pole, installed on a concrete slab, or located within a convenient building.

The design and maintenance of batteries for use in emergency standby power supplies are critically important. Sealed gel cells are desirable to minimize corrosion and loss of electrolyte. Cells should automatically be maintained at full charge, without overcharging, even during long idle periods. Cell design should be optimized for the range of expected discharge rates, over the expected ambient temperature range. Continuous monitoring of the status of standby power supplies is essential. If the battery should discharge completely during a long outage without the operator's knowledge, the outage would merely be postponed. Unless required by utility codes or local jurisdictions to provide all power-supply locations with emergency standby facilities, some operators prefer

Figure 13. Emergency ac power supply with battery standby. © Alpha Technologies.

to protect only key locations, such as optical nodes, where outages are most likely to cause the greatest loss of service.

Because the headend is the critical heart of a cable TV network, it is commonly protected against loss of primary power by means of one or more motor-driven generators, fueled with gasoline, diesel, or propane, with automatic start and load transfer switching. Effective maintenance and routine cycling are needed to ensure availability in emergency conditions. Unless the headend is continuously staffed, the status of the emergency facility should be monitored and appropriately alarmed.

To preserve the memory associated with microprocessors used for various control and management functions during the transfer from primary to emergency power, an uninterruptible standby power supply (UPS) is commonly provided. A storage battery, typically 12 V to 36 V, is used to drive a solid-state dc–ac inverter that is the sole source of ac voltage for the protected equipment. The primary power is used only to maintain charge on the battery. Should the primary power fail, the inverter continues to power the cable network until the battery is completely discharged without transferring the load between the primary power and battery supply.

Power Distribution. Designing the ac power distribution for a coaxial cable network is a complex exercise in Ohm's and Kirchhoff's Laws. The dc 60 Hz loop resistance for coaxial cables of various sizes and construction are readily available from manufacturer's technical data sheets. Typical loop resistance for 500 size (12.7 mm OD) with a copper-clad center conductor is 5.64 Ω/km. The range of ac voltage over which the regulated power pack in each amplifier may operate is specified in the manufacturer's data sheets. Amplifier loads are sited at various positions in the network with diverse lengths of cable. The actual length of cable must be accurately determined in advance by an on-site survey. The size and type of cable are specified by the designer, based on the RF requirements for the network. The computations are necessarily iterative, since the current drain for each individual amplifier varies with the voltage at its input, which in turn depends on the IR voltage drop caused, at least in part, by its own current drain.

The Optical Fiber Network

Network Topology. The optical fiber network is most commonly configured as a star, with separate fibers between the headend and each of the optical nodes. Optical power dividers are commonly used at the headend to drive multiple fibers from a single laser transmitter but are not generally used in the field to create branch lines. To serve larger areas, various forms of ring topology may be utilized, including self-healing configurations to provide redundant transmission paths. The primary transmission mode for analog TV is frequency-division multiplexed VSB AM carriers, directly or externally modulated on laser transmitters. For transmitting digital TV along with the analog VSB AM carriers in the same transmission path, the 64-QAM carriers are FDM with the analog carriers, at about 10 dB reduced peak power.

Fibers and Connectors. Optical fibers for cable TV are almost exclusively single mode, whose diameter is so small (~10 μm) that the light path is parallel to the axis of the fiber without reflection [Fig. 14(c)]. Cable TV optical fiber architecture is based primarily on utilization of the optical window at 1310 nm wavelength. The nominal attenuation of available fibers is 0.35 dB per kilometer at 1310 nm, and 0.25 dB per km at 1550 nm. Chromatic (wavelength-dependent) dispersion is virtually negligible at 1310 nm, but significantly restricts transmission speed in the 1550 nm window as fiber length increases. Dispersion-shifted single-mode fibers are available, using a special refractive index profile, with negligible net chromatic dispersion at 1550 nm [Fig. 14(d)]. However, external modulation of the 1550 nm light beam avoids the spectral linewidth spreading, or "chirping," caused by direct modulation of the laser and therefore minimizes the adverse effect of chromatic dispersion on transmission speed. The 1550 nm window is increasingly being used, with external modulation, in order to take advantage of lower attenuation and the availability of photonic amplification, using segments of erbium-doped fiber.

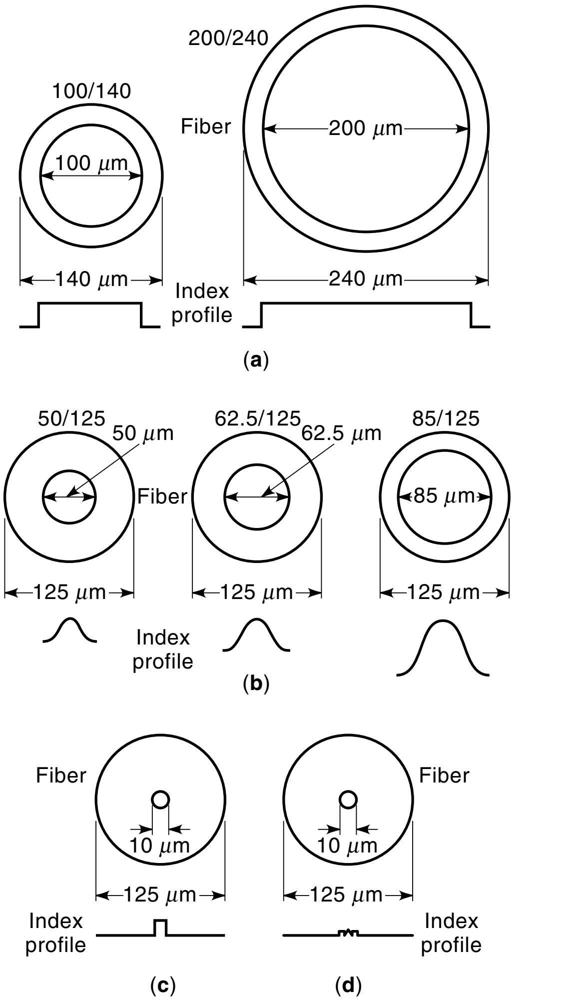


Figure 14. Typical dimensions of major types of optical fibers. © Howard W. Sams & Co.

As many as several hundred optical fibers may be bundled into cables for convenience in installation and protection from external damage. A dozen or so individual fibers are laid loosely in a gentle helix in buffer tubes filled with air, inert gas, or a soft viscous gel. Several buffer tubes are generally stranded around a central core. The buffer tubes are covered with a moisture barrier, a protective jacket, and where warranted, a steel armor cover. Special strength members of steel or Kevlar (dielectric) may be incorporated in optical fiber cables to protect the tiny silica fibers from the stresses of installation and the environment. With dielectric strength members, unarmored optical fiber cables are electrically nonconductive. Outside diameter of optical fiber cables is generally between 12.5 mm and 20 mm, slightly larger for armored cable. Optical fiber cable is normally supplied on reels in continuous lengths of 2.5 km to 5 km.

Connectors for optical fiber are more demanding and, in many ways, more sophisticated than those for coaxial cable. Optical fiber transmission paths may extend up to 30 km at 1310 nm, to 40 km at 1550 nm, or to 100 km or more with photonic repeaters. For up to 12 dB optical loss budgets, perhaps as many as 5 to 10 splices may be required between terminations. Optical fibers may be joined either by fusion splice or a reusable mechanical connector. For the fusion splice, the cladding must first be stripped away, the silica "cleaved" cleanly at a designated angle to the axis, and the cleaved ends carefully aligned before applying precisely the right amount and duration of heat required to fuse the two ends together properly. This process is generally accomplished with a special splicing machine to facilitate preparation of the fiber ends, holding them securely in place for inspection with a microscope while being accurately positioned. When properly aligned, pressing a button automatically applies the proper heat for fusion. Fusion splices are difficult to make under adverse environmental field conditions. However, when properly made, the additional splice attenuation is typically between 0.05 dB and 0.1 dB. On the other hand, reusable mechanical splices are more practical, for which attenuation of 0.2 to 0.5 dB (or more) per splice can be tolerated.

Laser Transmitters. The most commonly used light source for analog optical transmission is the distributed feedback (DFB) laser, either directly or externally modulated. Because of its much wider spectral bandwidth, the less expensive Fabry-Perot laser produces more noise than the DFB laser, but may be used for upstream data applications for which C/N requirements are not as severe as for analog or digital video. The neodymium-doped yttrium–aluminum–garnet (Nd : YAG) laser is used where a high-intensity light source is required at 1310 nm. The externally modulated DFB is used at 1550 nm, with photonic amplification using erbium-doped fiber amplifiers (EDFA), as described elsewhere.

The optical power of direct-intensity-modulated DFB lasers commonly ranges from about 4 dBm up to 14 dBm (2.5 mW to 25 mW). DFB lasers with photonic amplification (at 1550 nm), and YAG lasers with optical power up to 16 dBm (40 mW) and higher may be used with external modulators, such as a lithium niobate ($LiNbO_3$) Mach-Zehnder modulator, generally with feedforward or predistortion techniques to achieve satisfactory linearization. The use of externally modulated DFB lasers at greater than about 10 dBm may be subject to excess attenuation and second-order distortion as a consequence of stimulated Brillouin scattering (SBS), depending on the spectral width and "chirp" characteristics of the particular laser, as well as the composition of the glass. External modulation avoids the chirp and spectral linewidth spreading caused by direct intensity modulation of DFB lasers, minimizing the effects of chromatic dispersion but increasing the risk of Brillouin scattering.

Optical Receivers. Avalanche and p–i–n diodes at each optical node are used as electro-optical transducers to recover the FDM stream of analog and digital TV signals from the light beam. The multiplexed signals are amplified and applied to the coaxial network associated with that node. The rated sensitivity for analog AM design purposes is approximately 0 dBm, with optimized modulation depth for 77 channel loading at 51 dB to 53 dB CNR, 65 dB C/CTB, and 60 dB C/CSO (unmodulated carriers). As a general rule of thumb, the optical power required at the sending end of the analog fiber link should be approximately equal to the optical loss budget. Allowances for internal isolation and source coupler losses are included in rated transmitter output and receiver sensitivity. The optical link loss budget includes fiber loss, connector–splice loss, and power divider loss. Typical budgets for fiber and splice losses may be calculated at 0.4 dB per km at 1310 nm, or 0.3 dB per km at 1550 nm. Typical link budgets may be in the neighborhood of 10 dB to 13 dB for DFB lasers operating at +10 dBm (10 mW) to 13 dBm (20 mW), resulting in link lengths at 1310 nm between 25 km and 35 km. With externally modulated high-power lasers operating at up to 40 mW or 50 mW, link budgets may be as high as 17 dB (50 mW), with link lengths of at least 40 km at 1310 nm and 53 km at 1550 nm. For transmission of TDM uncompressed digital video signals, link-loss budgets may be as much as 30 dB, representing link lengths of 75 km at 1310 nm and 100 km at 1550 nm. Larger loss budgets may require electro-optic repeaters or greater optical power at the sending end with external modulation. Noise and distortion performance for analog AM fiber links with loss budgets less than 10 dB may be projected on the basis of manufacturer's specifications. However, for longer links, a more comprehensive and detailed analysis of each individual case may be appropriate.

One option to overcome losses that exceed the feasible optical budget limitations, is photonic amplification. Erbium-doped fiber amplifiers, when pumped optically at 980 nm or 1480 nm, provide up to 20 dB optical gain at 1550 nm. The noise figure is somewhat dependent on input power, typically 6 dB to 8 dB with input power between 0 dBm and +10 dBm. No measurable distortion is added to the optical link due to the EDFA. Another option, especially in the ring topology, is transmission of up to 16 TDM uncompressed digital TV (picture and sound) signals without an RF carrier. Converting such transmissions from digital to analog format for driving analog AM fiber or coaxial lines requires demultiplexing, decoding, decryption, and channel-by-channel VSB AM modulation. Because of the high cost of converting a large number of channels, digital links and rings are generally limited to very large networks. Still another option is the electro-optical analog repeater, comprising essentially a back-to-back optical receiver–transmitter combination. The disadvantage of this arrangement is that each repeater may reduce the CNR by approximately 3 dB and C/CTB by about 6 dB.

The lasers and photodiodes used as electro-optic transducers are operated over a linear portion of the light intensity versus electric current transfer curve. The optical power (OP) output of the laser is a linear function of the driving current and the current produced by the photodiode is a linear function of the incident optical power. Since the electrical power (EP) is proportional to the square of the current in both cases, it is also proportional to the square of the optical power. Thus, in terms of power transfer, both devices are square law. The decibel ratio of electrical power driving the laser to the electrical power output of the photodiode detector is

$$10 \log(\mathrm{EP})_{\mathrm{las}}/(\mathrm{EP})_{\mathrm{det}} = 20 \log(\mathrm{OP})_{\mathrm{las}}/(\mathrm{OP})_{\mathrm{det}} + 10 \log K$$

where K is a constant function of the driving resistance of the laser, the load resistance of the photodetector, and the constants relating optical power and current. Because of the square-law relationship, it can be said that "one optical dB is equivalent to two electrical dBs."

Customer Premises Interface

Set-Top Converter

Direct Pickup Interference. The dual heterodyne set-top converter was patented in 1967 by Ronald Mandell and George Brownstein to accomplish two objectives: (1) to overcome multipath, direct pickup interference, and (2) to provide for reception of TV channels that could not be tuned on conventional TV receivers at that time. Direct pickup interference results in a "leading ghost" when the inadequately shielded subscriber's TV set responds to the strong signal broadcast over the air, as well as the signal received through the cable a few microseconds later.

The objectives were accomplished by first changing the frequency of the channel selected to the standard 41 MHz to 47 MHz intermediate frequency (IF), in a manner, and with equipment, identical to that used in conventional television receivers, but better isolated from ambient fields. Then the IF is changed to a channel not used for broadcasting in the area, most often channel 3 (or 4). Thus, with a moderately well-shielded dual-heterodyne converter, strong local broadcast programs could be received without direct pickup interference.

Expanded Channel Capacity. Since all programs transmitted on cable were converted to channel 3 (for example), the TV set need not be tuned to the actual frequency transmitted on cable. This enabled the use of nonstandard channels that could be selected by the converter for reception on normal TV sets already in the home. Because the best place for the converter was on top of the TV set with which it is interfaced, the converter is widely called a "set-top." Because TV sets at the time were designed to tune only the twelve VHF channels 2 to 13, it is often said that the dual-heterodyne, set-top converter opened the door to the "13th channel" and beyond.

Many changes have occurred since the introduction of the set-top converter. The mechanical, "turret" channel selector with vacuum-tube tuners were replaced with voltage-controlled oscillators (VCO) and, currently, with phase-locked synthesizers and software-controlled channel selection capable of operation at UHF frequencies up to at least 1 GHz. The FCC requires that TV receivers marketed as being "cable ready" must be capable of selecting the 125 cable TV channels designated in Standard EIA-542 as well as the 12 VHF and 56 UHF channels designated by the FCC for terrestrial broadcasting. Cable-ready receivers must also meet technical performance requirements with respect to interference, overload, and signal leakage, but are not required to provide means to descramble premium channels.

Premium Channel Security. The carriage of movie programs relayed by satellite required that reception be limited to subscribers committed to pay a premium fee, either for a particular channel on a monthly basis or for a designated movie showing or other event. Various means were devised to deny reception to subscribers who were not committed to pay the additional fee.

Traps. The earliest security system used to deny reception of channels carrying movies for which a premium fee would be required was a sharp-notch filter, or "trap," at the visual carrier frequency. The trap was to be inserted in the service drop of customers who were *not authorized* to receive the program and for this reason was called a *negative trap.* To prevent unauthorized removal, the trap is generally installed with locking connecters that can only be disconnected with a special tool. It is still in use in some older systems in which more than half the subscribers are authorized to receive the movie program.

In another trapping arrangement, a sharp-notch filter is placed in the service drop to trap out a "jamming" or interfering carrier deliberately introduced at the headend. Because it is to be inserted only in the service drops of customers authorized to receive the program, it is called a *positive trap.* The jamming signal is frequency modulated with an annoying waveform and is located precisely halfway between the visual and aural carriers so that its second harmonic interferes with both the picture and the sound. The video sidebands are predistorted at the headend in order to compensate for the effect of the notch filter at frequencies close to the interfering carrier. The amplitude of the interfering carrier relative to the visual carrier is critical. If the level is lower than the visual carrier, the picture may be insufficiently obscured. However, if the level is set much higher at the headend, there is risk of adjacent channel interference affecting all subscribers. In some places, the traps were surrreptitiously removed by nonauthorized persons for use elsewhere, destroying the tap itself and leaving the authorized customer without service. Notwithstanding, the positive trap is still in service in many older and smaller systems.

Interdiction. In a different sort of jamming arrangement, premium programs are sent "in the clear" from the headend. A frequency-hopping interfering signal, located at the subscriber tap, "interdicts" the program before it enters the premises of a subscriber not authorized to receive the program. The interfering carrier hops from channel to channel so fast that the picture and sound are rendered unusable. An authorization signal from the headend, with unique address code, causes the frequency-hopping interfering signal to bypass the authorized program channel. Interdiction is technically successful but has not been widely deployed.

RF Synchronizing Pulse Suppression. By far, the most common security system is the separate scrambler provided at the headend to distort and degrade the signals for each premium program to be protected, in a reversible manner. Many of the older RF scramblers are still in service. RF scramblers are designed primarily to suppress the horizontal synchronizing pulse. In order to make the system more difficult to defeat, the degree of suppression and the timing of the restoration pulse may be varied in a systematic, pseudorandom pattern. Without proper synchronization, the scanning line generators in most TV sets are triggered at various incorrect and generally chaotic intervals, depending in random fashion on scene content and related signal waveforms. Normal pictures are restored by means of a timing signal transmitted from the headend, usually out of band. The restoration signal is applied only to authorized channels, controlled either by a preset programmable read only memory (PROM) chip, or a uniquely addressed authorization signal from the headend. Other modifications of the RF synchronization suppression technique have been developed to inhibit defeat, but at best, RF scrambling is vulnerable, at modest cost, requiring a minimum of technical skill and sophistication. In fact, synchronization suppression may be ineffective with those modern TV receivers that derive synchronization timing from the chrominance frequency instead of the horizontal synchronization pulse.

Baseband Scrambling. The current generation of scramblers operates at baseband and is significantly more secure than RF scrambling, because so many more options are available to render the picture unviewable. For example, the analog video waveform can be modified, in reversible fashion, by polarity inversion, line splitting and rearrangement, pseudorandom time shifting, and synchronization suppression, separately or in combination, continuously or time switched.

When proper arrangements have been made with the subscriber, a descrambling signal with unique address code is transmitted out of band, on a separate channel, or in-band, in the vertical blanking interval (VBI), to restore the scrambled picture to its original condition, a procedure known as *addressable* descrambling. Unauthorized use of services protected by sophisticated, addressable baseband scrambling depends primarily on stealing or cloning authorized set-top boxes. Nevertheless, the degree of security provided by analog scrambling, whether RF or baseband, must generally be supplemented with tight inventory control, tap audits, and other techniques, both technological and forensic.

Descrambler Compatibility. The most satisfactory place to descramble the signal is at the IF of the set-top converter. This has an unfortunate side effect, since even the advanced cable-ready sets would require a converter, not for tuning channels but for descrambling premium channels. Moreover, since even a cable-ready TV set would always be tuned to channel 3 when connected to the cable, convenience features such as "picture-in-picture" and recording programs for later viewing or while watching another program became difficult or impossible. These compatibility issues were addressed in the 1992 Cable Act, and are the subject of FCC regulations. An interface standard has been developed jointly by EIA and NCTA (EIA/IS-105) to enable a separate descrambler to be plugged into properly designed TV sets without a set-top converter. It is too early to tell whether this will solve the problem.

Advanced Interface Boxes

Interactivity. The set-top interface (i.e., converter) is also being adapted to provide a host of interactive and new service features. On-screen tools for navigating the 150-channel cable environment are becoming important features. Order lines for pay-per-view (PPV) programs may be provided by the upstream facilities. Competitive local exchange (CLE) services are being provided in a few locations. Migration to digital transmission of video programming is currently in progress, with facilities incorporated into the advanced set-top box for demodulation, demultiplexing, and converting to analog. Other changes in the set-top box can be anticipated in 1998 or 1999 with the availability in the consumer market of TV sets equipped to receive digital TV (DTV) broadcasts.

Internet Access. High-speed modems for access to the Internet are being deployed in an increasing number of cable TV networks. Both symmetric and asymmetric modems are now available, many of which comply with the recently adopted Multimedia Cable Network Standard (MCNS). The downstream side operates at speeds above the traditional high speed 128 kilobits per second (kbps) rate or 144 kbps for integrated services digital network (ISDN), and up to 10 Mbps or 30 Mbps. The upstream rates are typically much less, in the range of 64 kbps to 3 Mbps. Because of the lag in preparing cable TV networks for upstream transmission, a number of systems are providing modems for high-speed access to downstream signals but using the public switched telephone network (PSTN) for upstream transmission.

Compressed Digital Television

Current Status

The "Grand Alliance" of the Advanced Television Systems Committee. Until recently, television has been almost entirely an analog medium, both for terrestrial broadcasting and wired distribution. Worldwide, more than one billion television receiving sets and at least 100 million VCRs are available to receive vestigial sideband, amplitude-modulated (VSB AM) analog visual signals, National Television System Committee (NTSC), Phase Alteration Line (PAL), and Sequential Couleur avec Memoire (SECAM), broadcast by more than 75,000 television transmitters (13). In its Notice of Proposed Rule Making in May, 1996, the FCC proposed to adopt the digital TV (DTV) standards for broadcasting as proposed by the *Grand Alliance* of candidate systems. The Grand Alliance was sponsored by the Advanced Television Systems Committee (ATSC) to develop DTV standards combining the best features of the most promising proposals. It is projected that by the year 2000, terrestrial broadcast DTV signals will be available to more than half the population of the United States. Digital signals (to a different set of standards) are currently being transmitted direct-to-homes (DTH) in North America and elsewhere by direct broadcasting satellites (DBS). Cable TV systems are preparing to distribute to subscriber digital programs relayed by satellites.

Broadcast DTV Standards. Current NTSC television standards have remained in effect basically unchanged, except for the addition of compatible color, since adoption by the FCC in 1940. The new DTV standards provide various options, not necessarily incompatible, for different picture resolution and aspect ratio, ranging from conventional NTSC quality to enhanced or standard definition TV (SDTV) and high-definition TV (HDTV). The standards encompass both interlaced and progressive scanning. For interlaced scanning, as used in conventional NTSC, odd- and even-numbered lines are scanned consecutively as two separate fields, superimposed in one frame to create a single complete picture. For progressive scanning, the lines are scanned in sequence from top to bottom for a complete picture in each frame.

The principal features of the DTV standards proposed in 1997 for adoption by the FCC for terrestrial broadcasting are set forth in Table 2.

The 1080-line format with 60 interlaced frames per second (actually 30 interlaced fields per second) and the 720-line format with 60 progressive frames per second represent high-resolution wide-screen displays at 32,400 and 43,200 scan

Table 2. Digital TV (DTV) Standards

Resolution	Vertical Lines per Frame	Horiz. Pixels per Line	Aspect Ratio $W:H$	Frame Rate I = Interlaced; P = Progressive
High	1080	1920	16 : 9	60I 30P 24P
High	720	1280	16 : 9	60P 30P 24P
Standard	480	704	16 : 9 or 4 : 3	60I 60P 30P 24P
IBM VGA	480	640	4 : 3	60I 60P 30P 24P

Source: FCC NOPRM Docket No. 87-268.

lines per second, respectively. The 480-line format, with 60 interlaced frames per second at 4 : 3 aspect ratio closely approximates the current NTSC format at 14,400 active scan lines per second. The 480-line format with 60 progressive frames per second represents what has been called standard or enhanced resolution at 28,800 scan lines per second and could be displayed with either wide-screen or NTSC aspect ratio. The 480-line, 640 pixel format corresponds with the IBM Video Graphics Array (VGA) graphics format but is not related to any current video production format.

The Dolby Digital Audio Compression (AC-3) standard is specified for DTV sound. The AC-3 standard encodes a complete main audio service, including left, center, right, left surround, right surround, and low-frequency enhancement channels into a bit stream at a rate of 384 kbps. Multiple audio bit streams may be delivered simultaneously for multiple languages or for services for the visually or hearing impaired. The system also contains features that could allow viewers to control fluctuations in audio level between programs or to select the full dynamic range of the original audio program.

Source Coding

MPEG-II. Broadcast DTV as well as satellite DTH transmissions are encoded in accordance with the main profile syntax of the MPEG-II video standard, established by the Moving Picture Experts Group (MPEG) of the International Organization for Standardization (ISO). MPEG-II video encoding uses the discrete cosine Fourier transform (DCT) to reduce the serial interface data rate substantially from the nominal 144 Mbps for NTSC analog signals. The discrete cosine Fourier transform is a motion-compensated compression algorithm with bidirectional-frame (B-frame) prediction. DCT provides a numerical measure of the repetitive character of the information across blocks of 64 pixels. From this it is possible to drop those pixels in the block that represents zero, or very low, amplitude of the repetitive frequency and add little or nothing to the total image. Motion compensation identifies portions of an image that have shifted position from one field, or frame, to the next. B-frame prediction uses both past and expected future frames as reference. Source compression ratios based on the DCT algorithm range from about 25 : 1 or 30 : 1 up to nearly 100 : :1. The compressed data rate may be as low as 1.5 Mbps for NTSC scenes with little change from frame to frame, or 4 Mbps to 6 Mbps for live, active NTSC program material. It appears that high-resolution programs may require data rates between 9 Mbps and 19 Mbps. Digital video programs will probably also be encrypted, with various decryption key arrangements by which authorized subscribers may be enabled to receive premium or other programs.

Channel Coding

64-QAM and 8-VSB. RF transmission for television in North America, most of South America, Japan, and some other Asian countries, is restricted to 6 MHz per channel for terrestrial broadcasting, and therefore cable TV as well. High efficiency, multilevel (M-ary) modulation schemes are employed to enable transmission of video data streams at up to 30 Mbps data rate within the bandwidth of each 6 MHz channel, based on the efficiency factors shown in Table 3.

The ATSC standards specify 8-VSB (vestigial sideband) for terrestrial broadcast transmission (16-VSB for HDTV). Cable TV has adopted *de facto* 64-QAM. Tests have shown performance to be virtually identical to 8-VSB in all respects. Spectral efficiency for either 64-QAM or 8-VSB modulation permits the transmission of source-compressed digital video data rates up to about 27 Mbps or 30 Mbps in any 6 MHz cable TV channel. This means that from 7 to 14 or more compressed digital programs derived from NTSC analog sources, as many as two high-resolution programs, or some combination of digitally compressed and time-division-multiplexed (TDM) programs could be transmitted in each available 6 MHz cable TV channel.

It is important to recognize that 64-QAM and 8-VSB actually describe the sidebands of an amplitude-modulated, suppressed RF carrier. The modulating waveform is digital, but the RF waveform is subject to the same amplitude and phase distortions affecting analog modulation. Unlike baseband (or pulse code modulation (PCM)) transmissions, the digital signal modulated on a carrier cannot simply be regenerated. Weak signals may be amplified photonically, with EDFA, or converted to RF and retransmitted on another laser. As an alternative for very long or critical point-to-point service, up to 16 multiplexed, uncompressed digital video streams could be transmitted on an optical fiber without being modulated on an RF carrier. However, conversion to analog could be quite expensive. The data rate for 16 time-domain-multiplexed NTSC signals is in the range of 2 gigabits per second (Gbps) to 3 Gbps, with 4 : 2 : 2 sampling and 8 or 10 bit encoding.

Quadrature Phase-Shift Keyed (QPSK) Modulation. Transmissions with high spectral efficiency (i.e., bps/Hz) require higher transmission power in order to produce the higher-energy per bit–to–noise density ratios (E_b/N) needed for satisfactory re-

Table 3. Spectral Efficiency

Modulation Technique	Nyquist Rate Efficiency (bps per Hz)	Practical Efficiency (bps per Hz)	CNR for 10^{-8} ber[a] (theoretical)
QPSK[b]	2	1.2–2	15 dB
9 QPRS	2	2–2.8	17.5 dB
64-QAM	6	4.5–5	28.5 dB
8-VSB	6	4.5–5	28.5 dB
256 QAM	8	5–7	34.5 dB
16 VSB	8	5–7	34.5 dB

Source: Kamilo Feher, *Advanced Digital Communications,* Englewood Cliffs, NJ: Prentice-Hall, 1987, Table 7.3 and Fig. 7.5.

[a] Bit error rate per second.

[b] QPSK denotes quadrature phase-shift keyed modulation.

ception in restricted bandwidth. High-efficiency 8-VSB modulation is employed for terrestrial broadcast and 64-QAM for most cable transmissions, both of which are bandwidth-limited. Satellite transmissions are power-limited and therefore employ variations of phase shift keying for digital signals, principally QPSK modulation.

In order to distribute digital programs received by satellite, cable TV networks need to demodulate the QPSK transmission, demultiplex if necessary to repackage the programs, and decrypt in order to recover the serial bit stream for each program. The data would then be reencrypted, perhaps time-division-multiplexed and modulated as 64-QAM on an assigned carrier for the designated 6 MHz channel to be frequency-division-multiplexed with other analog and digital channels for distribution to subscribers.

PERFORMANCE STANDARDS AND TEST METHODS

Guidelines and Standards

Subjective Evaluation

Television Allocation Study Organization. In 1957, at the request of the FCC, the television industry established the Television Allocations Study Organization (TASO) to conduct a study of "the technical principles which should be applied in television channel allocations." The TASO Working Panel VI was charged with the task of determining "the numerical specifications of the various objective measures of picture quality which result in specified degrees of viewer satisfaction when television pictures are viewed in the presence of various types of interference." The panel investigated the impact of random noise, cochannel and adjacent channel interference, and the combined impact of cochannel and random noise simultaneously present, using a six-point rating scale:

Excellent	The picture is of extremely high quality, as good as you could desire.
Fine	The picture is of high quality, providing enjoyable viewing. Interference is perceptible.
Passable	The picture is of acceptable quality. Interference is not objectionable.
Marginal	The picture is poor in quality and you wish you could improve it. Interference is somewhat objectionable.
Inferior	The picture is very poor but you could watch it. Definitely objectionable interference is present.
Unusable	The picture is so bad that you could not watch it.

The TASO studies in 1959 were based on CNR, adjusted to 6 MHz NPBW, yielding values 1.75 dB below the corresponding 4 MHz values specified for measurements on cable TV networks. The TASO report provided a substantial basis for setting the criteria for channel assignment according to geographic location, transmission frequency, and radiated power. Except for random noise, TASO did not investigate other types of impairment encountered in cable TV networks. Moreover, the six grades of service were defined so as to include the effect of what was loosely described as subjective "enjoyment" of the scene, thereby potentially masking the effect of objectively measurable impairments.

Bell System Telephone Laboratories (BTL). Subjective impact investigations at the Bell Telephone Laboratories in 1951 and the early 1970s used a seven-point impairment scale:

Not perceptible
Just perceptible
Definitely perceptible but only slight impairment to picture
Impairment to picture but not objectionable
Somewhat objectionable
Definitely objectionable
Extremely objectionable

Bell Laboratories investigated video cross-talk, low frequency (hum), echoes, chroma delay, differential gain, and phase, as well as random noise.

Cable Television Laboratories. The most useful investigation of the specific impairments encountered in cable television were conducted in 1991 by Dr. Bronwyn Jones for the Cable Television Laboratories (CableLabs) (14). The CableLabs study investigated composite triple beat and phase noise as well as random noise, using the impairment rating scale recommended by the International Radio Consultative Committee (CCIR), based on extensive international psychometric studies.

Grade 5	Imperceptible
Grade 4	Perceptible but not annoying
Grade 3	Somewhat annoying
Grade 2	Annoying
Grade 1	Very annoying

Objective Guidelines and Standards

Federal Communications Commission (FCC). Subjective judgments regarding perceived picture quality of television signal waveform were important considerations in establishing the objective interoperability specifications recommended in 1941 and 1954 by the National Television Systems Committee (NTSC) and adopted by the FCC. Nevertheless, subjective standards of end-user acceptability have not been established by federal agencies. FCC specifications for cable TV include a sampling of the visual and aural carrier signal levels throughout the network. The objectively measurable characteristics of the video signal waveforms are specified only at the headend for two such characteristics: (1) chrominance–luminance delay inequality, and (2) differential gain and phase of the chrominance subcarrier. The audio characteristics of television sound are not designated by FCC specifically for cable TV, but may generally comply with audio standards for terrestrial television broadcasting.

Network Transmission Committee (NTC). The performance goals set forth in a report prepared by the Network Transmission Committee, known as NTC-7, represent the best objective technical performance that can be expected for NTSC television signals transmitted over facilities leased by the major television networks in the United States from the former Bell Telephone System. The NTC-7 performance goals are presented as technically achievable in practice but are not related in any way to the subjective impact of picture impairment, nor do they define thresholds of observer tolerance. While a modern NTSC cable TV headend may be able to comply substantially with the relevant performance goals of NTC-

7, full compliance is more than necessary to provide television images generally perceived to be of high quality.

International Electrotechnical Commission (IEC). The IEC is an affiliate of the International Standards Organization (ISO) with headquarters in Geneva. The technical standards set forth in IEC Publication 728-1 were prepared by Subcommittee 12G: Cabled Distribution Systems, of IEC Technical Committee 12: Radiocommunications, as recommendations for international use. Delegates with active technical background and experience in cable television in many countries participated in the deliberations.

Measurement Methods and Objectives

Reference Guidelines

NCTA Recommended Practices. The official reference guideline for the cable television industry is the *NCTA Recommended Practices for Measurements on Cable Television Systems* (7). Performance standards for the forward (downstream) HFC distribution network are based on end-to-end measurements in an operational network, including both optical fiber and coaxial segments. The input is the normal FDM complement of analog television program signals at the combiner (multiplexer) output port. Certain types of swept-frequency test signals, as well as RF carriers modulated with special test waveform signals, may be added to the normal complement. Specific carriers may be disabled momentarily for test purposes. Output test ports are generally at the output of an amplifier or in some cases at the output of a tap port, subscriber terminal, or a simulated service drop cable. The standards apply to analog signals even when multiplexed with QAM carriers modulated with TDM digital program signals operating at peak power levels 10 dB below normal for analog TV signals. Performance standards have not been officially established for the return (upstream) HFC distribution network nor for the QAM modulated digital signals. Performance of the optical fiber segment is not specified independent of the overall operation of the HFC network.

Headend

Test Signals and Objectives. Video waveform test procedures are based on observation at baseband of standard test signals on a waveform monitor with a graticule calibrated in IRE (Institute of Radio Engineers) units, such that 100 IRE units represents the spread between reference white and blanking level, as shown in Fig. 15. Negative modulation, as specified by the FCC for terrestrial broadcasting, means that a decrease in initial light intensity causes an increase in radiated power. The principal video test signals are as follows:

1. Multiburst: Six bursts at discrete frequencies: 0.5, 1.0, 2.0, 3.0, 3.58, and 4.2 MHz.
2. Five-riser staircase: Five luminance risers 18 IRE each, modulated with a 3.58 MHz chrominance subcarrier, 40 IRE peak-to-peak on each step. Alternative: Ten-riser staircase or modulated ramp.
3. $2T \sin^2$ pulse: Half-amplitude duration (HAD) 250 ns; amplitude 100 IRE. Usually displayed with a T-step line time bar; rise time 125 ns. $T = \frac{1}{2}f_c$, where f_c is the nominal video bandwidth (typically 4.0 MHz for NTSC), i.e., $T = \frac{1}{2} \times 4.0 \times 10^6$.

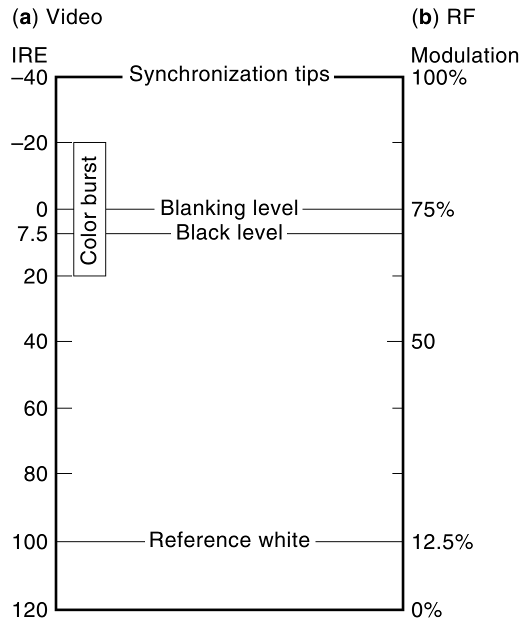


Figure 15. IRE graticule scale for: (a) video waveform; and (b) RF percent modulation.

4. $12.5T$ Modulated $\sin^2$ pulse: HAD, 1562.5 ns; modulation 3.58 MHz (Fig. 16).

Table 4 is a partial summary of the objectives as set forth in the NTC-7 report, with certain FCC and IEC provisions included for comparison.

IEC also specifies a maximum 7% "Echo rating," based on use of the $2T \sin^2$ pulse with the E-rating graticule shown in Fig. 17. The E-rating is adapted from the K-rating system originally developed by N. W. Lewis of the BBC in 1954 for quantifying short time distortions. Echo ratings are not widely used in the United States, although K-rating graticules (removable transparent scales attached to face of oscilloscope display) may be provided with waveform instruments intended for use in the United States.

Another useful test, specified by IEC but not specifically covered in the NTC-7 document, is single-channel intermodu-

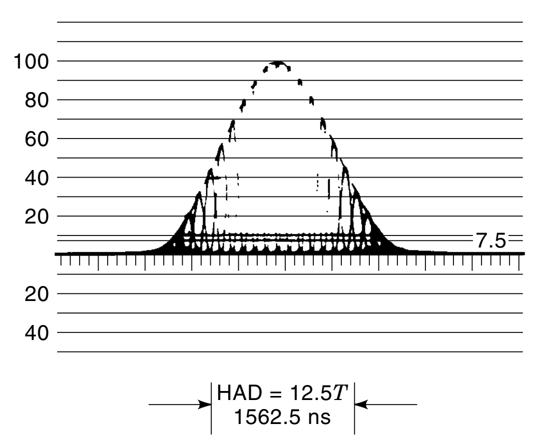


Figure 16. Chrominance delay test signal. 12.5-T modulated $\sin^2$ pulse. © Tektronix Inc.

Table 4. Performance Objectives for NTSC Video at Cable TV Headends

Parameter	Test Signal	NTC-7 Objective
Chrominance–luminance gain inequality	12.5T modulated pulse	100 ± 3 IRE
Chrominance–luminance delay inequality	12.5T modulated pulse	±75 ns (FCC maximum: 170 ns; IEC maximum: 100 ns)
Gain–frequency distortion	Multiburst; color burst	Each burst within 45–53 IRE, 40 IRE ± 4 IRE (FCC: ±2 dB between 0.75 and 5.0 MHz above lower channel boundary; IEC ± 2 dB re visual carrier, and <0.5 dB in any 0.5 MHz segment)
Differential gain	Modulated five-riser stairstep	<15% (FCC maximum: ±20%; IEC max.: NTSC 10%; PAL 10%; SECAM 40%)
Differential phase	Modulated five-riser staircase	<5° (FCC maximum: ±10°; IEC max.: NTSC 5°; PAL 12°; SECAM 32°)
Short-time waveform distortion	2T pulse; T-step line bar	Amplitude: 100 ± 6 IRE; overshoot < 10 IRE peak to peak
Line time waveform distortion (due to inadequate low-frequency response)	Line bar	4 IRE (baseband); 3% (−30 dB) of visual carrier level in the distribution network

Note: The NTC-7 report provides numerous other performance objectives, many of which are related to camera and videotape recording (VTR) performance.

lation. The triple beat between the visual carrier and the aural and chrominance subcarriers is about 920 kHz (the difference between 4.50 MHz and 3.58 MHz) above the visual carrier (1066 kHz in the PAL format), and causes a dot pattern to be seen in the displayed picture. The IEC specification is suitable for laboratory use, but not for in-service testing. The test is based on three unmodulated carriers. For NTSC, the level specified by IEC for the test carrier at visual frequency is 8 dB below the normal operating level; chrominance, 17 dB below; and aural, 6 dB below. At these levels, IEC specifies that the 920 kHz beat should be 54 dB below normal operating level. While the specified carrier and triple-beat levels are not included in US test procedures, the 920 kHz beat is an impairment primarily generated in single-channel equipment such as that used in cable TV headends, and should not be overlooked.

±T	Maximum amplitude for a given E rating		
	3	6	9
0	+100.–12	+100.–24	+100.–36
2	±12	±24	±36
4	±6	±12	±18
8	±3	±6	±9
12	±1.5	±3	±4.5

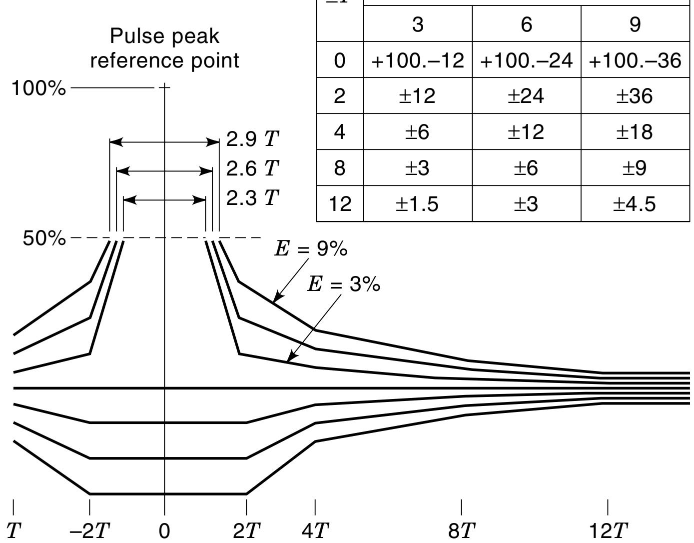


Figure 17. "E-Rating" graticule (IEC). © International Electrotechnical Commission.

Since the headend performance objectives are established for baseband video, the RF output of modulators or heterodyne processors must be demodulated for the test. The characteristic displayed on the waveform monitor represents the combined performance of the test demodulator and the system under test. The specified performance of the test demodulator should be significantly better than the expected performance of the system under test. The effect of the test demodulator may be evaluated by first feeding the video test signals to the test demodulator through a simple double-sideband (DSB) bridge modulator, without filters, and comparing the results with those from the system under test. With reasonable care, waveform distortion in the DSB modulator may be assumed to be negligible.

HFC Network Signal Levels

Frequency Sweeping. The proper alignment of signal levels across the pass band, to conform with the engineering design for a cable TV network, is generally accomplished by sweep frequency techniques. Modern sweep-frequency systems utilize microprocessors to measure and analyze the gain–frequency response across the pass band for presentation either in graphic or numerical form. Various calibration and operational features are incorporated in the instrument to ensure reliable results and convenience. Software-controlled automation with remote recording and analysis of the data have effectively reduced frequency sweeping to a routine procedure.

Sweep testing is primarily used for setting up and maintaining proper peak-to-valley performance. The peak-to-valley characteristic is defined as the maximum deviation from a straight line reference representing the trend line for the plot of net gain versus frequency recorded by the sweep receiver. The reference line may be flat with respect to frequency or it may display a definite slope, depending on the output characteristic of the sweep generator at the insertion point and the intrinsic slope characteristic of the network at the test point. Whether the reference line is simply a subjective estimate of the trend or a straight line drawn between the two end points of the sweep display (as recommended by the Society of Cable Telecommunications Engineers), the peak-to-valley characteristic is defined as the sum of the maximum deviation above and below the reference. While there is no specific regulatory requirement for overall network response, a generally accepted guideline is that peak-to-valley response should be no greater than $2 + N/10$ dB for trunk lines, or $3 + N/10$ dB for feeder lines, where N is the number of identical cascaded amplifiers preceding the test point).

Signal-Level Meter. The RF signal level for each analog television channel or digitally modulated carrier band is defined as the *peak envelope power* of the amplitude-modulated carrier wave, expressed in dBmV, represented by the maximum rms voltage across 75 Ω. For television signals, peak power occurs during the synchronizing interval. Signal levels for each visual carrier and aural subcarrier are generally measured individually with a signal-level meter (SLM), sometimes incorrectly called "field strength meter" (FSM). The SLM is a tunable, selective, peak-indicating RF voltmeter with calibrated detector, attenuator, and noise power bandwidth. The input impedance is 75 Ω, so that voltage readings relative to 1 mV can properly be calibrated in terms of dBmV. The actual effective bandwidth of typical SLMs is of the order of 0.3 MHz to 0.5 MHz. Performance characteristics for signal levels at any point within the network are determined by the engineering design and are not specified as standards.

FCC and IEC Signal-Level Standards. The subscriber terminal is defined by the FCC as "The cable television terminal to which a subscriber's equipment is connected." The set-top converter is treated as part of the distribution network. IEC specifies measurement at the "system outlet" or the end of the "subscriber's feeder."

The FCC specifies a minimum 0 dBmV at each subscriber terminal. In order to ensure sufficient level to accommodate at least a two-way splitter in all cases, there is an additional requirement for a minimum of +3 dBmV at the end of a 30 m simulated cable drop connected to the subscriber tap port in the network. This additional requirement also ensures that adequate signal levels will be available at the subscriber's television receiver without depending on gain in the converter. IEC requires 57 dBμV (−3 dBmV) minimum signal level at system outlets in the band 30 MHz to 300 MHz; 60 dBμV (0 dBmV), at 300 MHz to 1000 MHz.

Other requirements related to signal levels at the subscriber terminal are summarized below:

1. The visual signal level at the end of the 30 m simulated drop shall not vary more than 8 dB over 24 hours within any six-month period. IEC does not specify the time stability of signal levels.
2. The visual signal level shall be maintained within 3 dB of the level of adjacent channels within a 6 MHz frequency separation. IEC specifies a maximum 3 dB difference in levels between adjacent channels.
3. The visual signal level shall differ by no more than 10 dB between any channels in the band up to 300 MHz, with a 1 dB increase for each additional 100 MHz bandwidth. IEC specifies a maximum 12 dB difference in levels between channels in the band 30 MHz to 300 MHz; 15 dB, 300 MHz to 1000 MHz. In addition, IEC specifies no more than an 8 dB difference in any 60 MHz range, nor 9 dB in any 100 MHz range.
4. The FCC specifies maximum visual signal levels at subscriber terminals only to the extent that overload degradation does not occur in the subscriber's equipment. However, the FCC also specifies that cable-ready television receivers shall not generate objectionable spurious signals due to overload with input no greater than 15 dBmV at frequencies below 550 MHz. IEC specifies an 83 dBμV (23 dBmV) maximum visual signal level on any channel in the range 30 MHz to 1000 MHz.
5. The aural subcarrier signal level shall be maintained between 10 and 17 dB below the associated visual carrier signal level. For subscriber terminals using baseband type converters, the range is between 6.5 and 17 dB below the visual carrier. IEC notes that the relative level of the sound carrier should be established by each country according to its television system.

HFC Network Noise and Distortion

Carrier-to-Noise Ratio. System noise level is defined as the mean power level in a 4 MHz bandwidth. The FCC specifies the particular 4 MHz band immediately above the visual carrier, although the exact location of the bandwidth generally is not critical. The definition includes Gaussian or random noise as well as modulation noise, although the latter is specified separately. By definition, undesired discrete frequency disturbances (e.g., hum and interfering carriers) should be excluded. In practice, however, noise power is generally measured in a relatively narrow band (~0.5 MHz) that effectively excludes carriers and intermodulation products. Therefore, calculations and measurements of noise are generally assumed to be in accordance with random noise theory. The FCC specifies not less than 45 dB CNR; IEC specifies not less than 42 dB at 3.33 MHz NPBW, for which intrinsic thermal noise, $kTB = 0$ dBμV. While the 3.33 MHz bandwidth provides a convenient reference noise level, it has not been adopted for any other standards or commercial applications.

Measurement of noise power or carrier-to-noise ratio (CNR) may be made with several different types of instrumentation: (1) properly calibrated SLM; (2) properly calibrated RF spectrum analyzer; (3) baseband noise meter; (4) calibrated waveform monitor; or (5) power meter with bandpass filter calibrated at 4.0 MHz NPBW. Calibration against a certified noise source generator is recommended and is usually provided by the instrument manufacturer. Some spectrum and network analyzers include internal calibration and automated measurements arranged to display CNR directly. Various techniques are available for measuring CNR without interrupting service to customers. Since the bandwidth of the SLM is typically about 0.5 MHz, it is usually possible to find a quiet spot between channels, or in vacant channels, in which to measure noise power levels. With a spectrum analyzer set for narrow IF bandwidth, the noise floor in quiet spots between carriers can be measured and adjusted to 4.0 MHz. For baseband measurements, noise levels in blank synchronizing intervals can be compared with the power level generated by a calibrated noise generator. Instrumentation is available to accomplish similar calibration procedures automatically.

Signal-to-Noise Ratio. CNR is defined for cable television in the RF domain, while the signal-to-noise ratio (SNR) is baseband. The principal differences between CNR and SNR are in the *weighting* of the visual impact of baseband noise power as a function of frequency and the effect of noise in the vestigial sideband. For NTSC television, CNR, at 4 MHz NPBW, is virtually identical with SNR, weighted as defined by the EIA and International Radio Consultative Committee (CCIR). SNR studies by Bell Telephone Laboratories in 1971 used a different weighting curve, resulting in SNR values 2.7 dB greater than the 4 MHz CNR. (For a detailed discussion, see Ref. 15.)

Carrier to Composite Intermodulation Interference. Composite triple-beat (C/CTB) and composite second-order product (C/CSO) are generally measured with a spectrum analyzer. The composite triple-beat cluster at or close to a visual carrier frequency provides by far the dominant measure of third-order distortion. The most significant composite second-order sums are found at 1.25 MHz above a visual carrier. Differences are found at 1.25 MHz below a visual carrier, but since this is the lower boundary of the channel, it is substantially attenuated in the receiver.

With the IF resolution bandwidth and scan width of the spectrum analyzer set high enough to display the synchronizing pulse in the channel under test, the tip of the synchronization pulse is set at a convenient reference level. For the measurement, the IF resolution bandwidth of the analyzer is reduced to 30 kHz. With the carrier and its modulation turned off at the source, the remaining trace on the analyzer at the frequency of the desired carrier represents the CTB amplitude, Fig. 18. The amplitude of the CSO products can be observed in the same manner at 1.25 MHz above the desired visual carrier. The magnitude of the distortion is the difference (in decibels) between the reference carrier level and the amplitude of the composite trace, that is, C/CTB and C/CSO.

The most reliable measurements of composite distortion products are made in the laboratory using unmodulated [continuous wave (CW)] carriers. However, removing the modulation from all carriers in an operating system would cause intolerable disruption of service to many thousands of subscribers. Therefore, in-service measurements must be made with normally modulated carriers. To measure CTB, it is necessary to interrupt one carrier at a time just long enough to read the residual composite distortion amplitude.

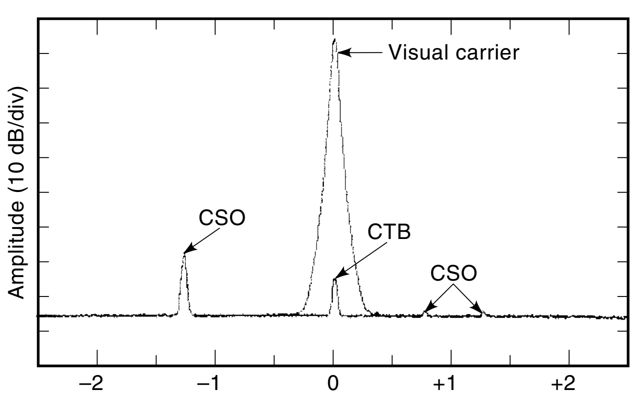


Figure 18. Spectral power distribution of the composite triple-beat cluster. Double exposure showing the reference carrier. Resolution BW: 30 kHz.

At 60% average picture level (APL), the mean power of the television signal is about 6 dB below the peak power in the synchronizing interval. Thus, the composite triple-beat level measured with modulated carriers should be about 12 dB lower than with CW carriers at the same peak power. Experimental confirmation was provided in an unpublished 1991 report by Oleh Sniezko, then of Rogers Engineering, Ontario, Canada. Composite second-order beats measured with modulated carriers should be about 6 dB lower than with CW carriers. The FCC requires that C/CTB and C/CSO ratios be not less than 51 dB for noncoherent channel cable television systems measured with modulated carriers. For coherent channel cable television systems, the ratio of carrier to intermodulation products that are frequency-coincident with the visual carrier shall not be less than 47 dB measured with modulated carriers. It is noted that in the IRC coherent channel system, the CSO products are not frequency-coincident with the visual carrier and must therefore meet the more stringent 51 dB requirement. The IEC specification is 54 dB with incoherent CW carriers.

Cross-Modulation. Multichannel cross-modulation is measured in the laboratory with all carriers, except the one under test, synchronously modulated to a depth of 85% to 90% with a square wave at approximately 15 kHz. The depth of modulation on the CW test carrier is a measure of the carrier-to-cross-modulation (C/XM) ratio. The C/XM ratio is not specified in the FCC rules and is no longer widely used in the industry. IEC specifies a two-channel method for measuring cross-modulation, with a formula based on unproven theory to adjust for multiple channels. (See Ref. 16.)

Phase Noise. The local oscillators in modulators, signal processors, satellite receivers, and low-noise converters, set-top converters, and consumer television receivers may introduce phase-noise impairment in the picture signal. As described by Pidgeon and Pike (17), "phase noise is distinguished from thermal noise by its low frequency character. Generally, demodulated phase noise decreases slowly to 1 MHz, and follows the roll-off in the RF spectrum above that." The measure of phase noise is the ratio between the RF carrier level and the sideband spectral power density of the CW carrier at 20 kHz frequency modulation, measured in a 1 kHz bandwidth, stated in dB/Hz.

Hum and Low-Frequency Transients. The FCC requires that the peak-to-peak variation in the RF visual signal voltage level caused by hum or repetitive transients generated within the network shall not exceed 3% (−30 dB) of the visual carrier signal voltage level. For NTSC, the IEC specification is −35 dB (1.8%). Note that 3% *peak-to-peak* variation is equivalent to 1.5% (−36 dB) sinusoidal hum modulation of the visual carrier. Power-source-related hum may be at 60 Hz or 120 Hz, with harmonics in the case of trapezoidal (i.e., "quasi-square-wave") waveform. Hum, typically 120 Hz for full-wave rectification, may be caused by low voltage, below the threshold level required for proper regulation in the power pack, or by inadequate or defective filtering in the power pack. A more perplexing source of hum is the displacement current in the blocking capacitor that allows RF to pass to the directional coupler/multitap circuits while blocking the 60 Hz currents. The displacement current is small but finite and may saturate the ferrite transformer core. But because the rise time of the "quasi-square waveform" is considerably greater than that of the 60 Hz sine wave, short bursts of current are al-

Table 5. Subjective Rating of Signal Impairments

Subjective Rating	C/CTB Ratio	C/N Ratio	Phase Noise C/N_φ
Not perceptible	>55 dB	>50 dB	>94 dB/Hz
Perceptible but not annoying	44.8 dB	47.7 dB	88.3 dB/Hz
Somewhat annoying	37.8 dB	44.5 dB	82.4 dB/Hz
Annoying	31.8 dB	40.6 dB	76.9 dB/Hz
Very annoying	<27 dB	<35 dB	<72 dB/Hz

Source: CableLabs (Bronwyn Jones).

lowed to flow through the ferrite transformers. These current bursts are likely to result in parametric modulation of the RF signal.

Hum is likely to be seen on the TV screen either as a wide horizontal shading moving slowly up the screen or as one or two fairly sharp, uniformly spaced, horizontal lines, also moving slowly up the screen.

CableLabs Subjective Guidelines. A preliminary report (14) describes a study of the subjective impact of the principal picture impairments, conducted in 1991 for the Cable Television Laboratories (CableLabs). Dr. Bronwyn Jones, formerly director of psychophysical studies for the CBS Laboratories, directed the study for CableLabs. Except for one chart on impairment due to random noise, most of the findings are available only in the unpublished version of the report. The findings, covering distortion and phase noise as well as random noise under a variety of viewing conditions, are summarized in Table 5. A description of the test facilities and procedures is provided in Ref. 18.

Comparison of random noise measurements in 1991 with the results of other studies over the past 40 years suggest that viewers may have become somewhat more critical. CTB distortion was measured with 64 noncoherent, normally modulated carriers. Other formal studies of the intermodulation and phase-noise thresholds have not been reported. However, several studies have shown that carrier-to-interference (C/I) ratios at the threshold of perceptibility for discrete single-frequency interference at 1.25 MHz above the visual carrier (for 6 MHz, system M) is approximately 50 dB to 53 dB [Fig. 19 (19,20)].

Other Measurements

Signal Leakage. Ideally, a coaxial network is a completely closed system, with zero transfer impedance to the environment. However, accidental damage or defects in manufacture, installation, or maintenance can interrupt the shielding integrity, causing both leakage interference outside the network and ingress interference to signals within. The spectrum used in cable TV networks is shared by many services depending on direct reception of signals radiated in space. Because of the potential but highly unlikely risk of interference to aeronautical communication or navigation radio as a result of damaged coaxial cable, regulations have been adopted to minimize the risk and provide for prompt detection and repair of leakage. The cable operator is required to eliminate harmful interference caused to any authorized service, regardless of preventive steps taken. Regulations also require notification to ensure that appropriate authorities are fully informed regarding the transmission on cable of frequencies allocated for sensitive services.

The regulations provide protection in three ways:

1. Carrier frequency offsets and power limits
2. Continuous monitoring for leaks
3. Annual determination of a cumulative leakage field strength

In addition to specified frequency offsets, cable TV network operators are required to establish a program of regular monitoring, substantially covering the plant every three months, using equipment and methods capable of detecting a leakage source producing more than 20 μV/m field strength at a distance of 3 m. At least once a year, a cumulative leakage index (CLI) must be determined, either by ground-based measurements adjusted to a 3 m distance from each leakage source or by flyover at 450 m above the average plane of the network. Threshold standards were developed by the FCC Advisory Committee on Cable Signal Leakage based on findings from extensive ground-based and airborne measurements conducted in 1979 by the FCC, the Federal Aviation Administration, and the Institute for Telecommunication Science of the U.S. Department of Commerce (21). The airborne flyover is designed to demonstrate that the composite field strength generated by the cable system, at any point at an altitude of 450 m above the system, does not exceed 10 μV/m. The CLI is calculated from ground-based measurement of the field strength (E) in μV/m for all leakage sources, producing at least 50 μV/m at any point in the system. The CLI is 10 log $(1/\varphi)\ \Sigma\ E^2$, where φ is the ratio of the miles of plant actually examined to the total system plant miles. The CLI must be

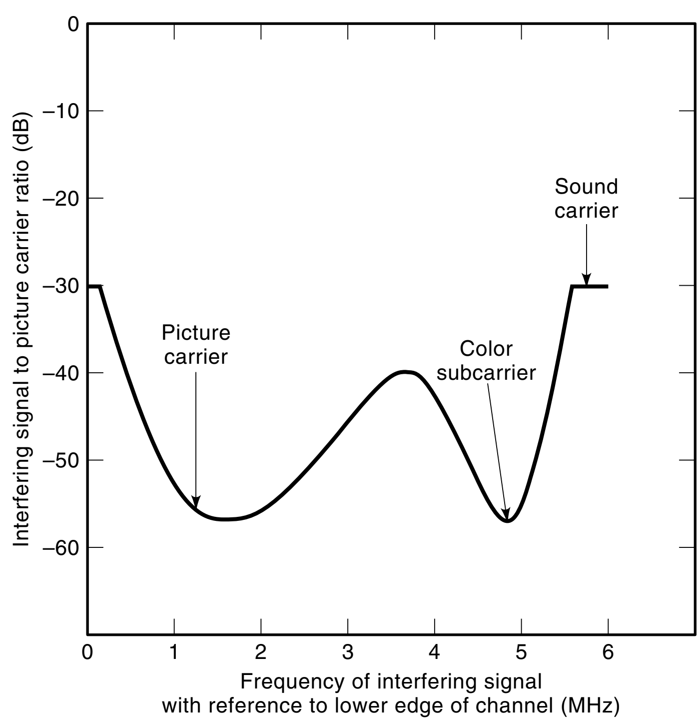


Figure 19. Maximum C/I ratio for intermodulation and other single-frequency signals. © Canadian Department of Communications, BP-23.

less than 64 dB, and φ must exceed 0.75. Leakage sources must be repaired within a reasonable period of time.

Optical and RF Time-Domain Reflectometry. Various types of instrumentation for time-domain reflectometry (TDR) are available to provide information as to the location and characteristics of transmission discontinuities in coaxial or optical fiber cables, based on the reflection of a pulse or step signal waveform. Depending on the rise time and duration of the pulse or step signal, sensitivity, and calibration procedures, TDR may be useful in precisely locating open or short circuits, determining the VSWR or impedance mismatch of coaxial or optical fiber connectors or splices, and determining the length and attenuation of a segment of coaxial or optical fiber cable. The signal-level meter (SLM), sweep generator and detector, spectrum analyzer, waveform monitor, and TDR are the principal instruments for RF performance measurements in coaxial networks. The optical power meter and optical time-domain reflectometer (OTDR) are the principal instruments for measurements in optical fiber links.

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