Chapter 1

The Evolution of Television Technology

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Abstract: The historical evolution and progression of television technology is reviewed as a framework for understanding the developments that are occurring today in television technology. New developments in television technology—such as high definition, wide-screen. digital, and interactive—are described. The various technological uncertainties that will help shape the future of television technology are discussed.

1. INTRODUCTION

The future of television is facing a wide variety of technological alternatives. Although the specifics may be controversial and cloudy, it is much more important to understand and clarify the overall bigger picture. If many of the paths facing the future of television technology all lead to the same technological destination, then that destination and the environment it represents are far more important than the specific paths.

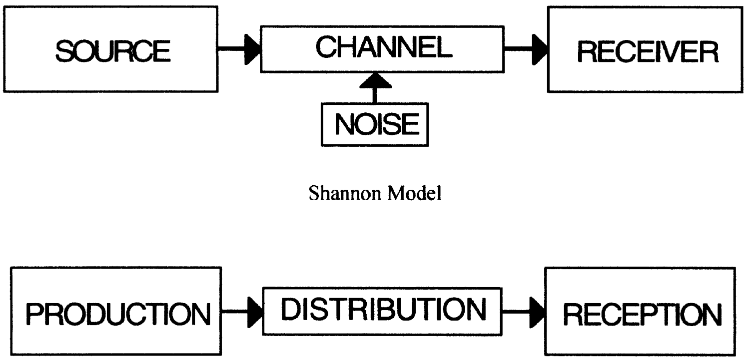
The continued progress and evolution of television technology has stimulated many policy issues, such as the importation of distant signals on CATV systems, copyright and ownership, protection of network affiliates, and black-outs of sporting events. Thus, a consideration and discussion of television technology, in such terms as its history and technological uncertainties, are relevant to understanding the future of television in general. To focus this discussion, an overall system model of television and video is first presented in the following section of this article. The model is

D. Gerbarg (ed.), *The Economics, Technology and Content of Digital TV*

then followed by a description of the historical progression of television and video technology.

2. TELEVISION AS A SYSTEM

A model for a communication system was proposed by Claude E. Shannon in 1948 as a framework for his mathematical studies of communication systems in the presence of noise.[1] The Shannon model, in its simplest form, consists of a source, a channel (corrupted by additive noise), and a receiver, as shown in Fig. 1.



TV Model

Figure1. Shannon's model of a communication system applied to television.

The Shannon model adapted to television consists of production (the source), distribution (the channel), and reception (the receiver). Progress in television technology is having much impact on all three of these elements in the chain of television as a system.

Production includes the origination, packaging, and branding of video material that is created in a studio, obtained from film and other sources, and distributed over networks. This material (programming) is delivered to consumers in their homes over a variety of distribution methods.

The various distribution methods can be categorized as (1) over-the-air radio waves, (2) wired, and (3) physically delivered.

Over-the-air radio waves can be used in terrestrial systems or in geostationary orbit, communication-satellite systems. Over-the-air terrestrial broadcasting occurs in the VHF and UHF bands, either at conventional high power or at low-power VHF and UHF broadcast (LPTV). Terrestrial high-frequency microwave broadcast, which is line-of-sight, is used for microwave multichannel multipoint distribution service (MMDS). Over-the-air radio waves are used for communication satellite systems, such as direct broadcast satellite (DBS) in the Ku microwave band (12 GHz) to small dish antennas; satellite broadcasts in the C band (4-6 GHz) to large dish antennas; and satellite master antenna systems (SMATV) for distribution over coaxial cable in apartment buildings .

The major form of wired delivery of television is cable television (CATV) over coaxial cable. The coaxial cable forms a tree architecture, and amplifiers are required every few thousand feet. Cable television first started as a form of community antenna television, hence the acronym CATV. Newer CATV systems utilize optical fiber in the backbone network. Television and video is delivered over physical media, including video cassette tape (VCR), laser video disk, and digital video (or versatile) disk (DVD).

There thus are a wide variety of ways for delivering television signals to homes and also to television broadcast network affiliates and to cable distributors and firms. What this means is that television has become world-wide and instantaneous with much program variety and abundance. Television programming is funded by a variety of means, including advertising, viewer payments (pay TV), viewer voluntary contributions, license fees, government funding, and viewer purchase of physical media (VCR tape, disks).

New ways for delivering television to homes are emerging, though thus far their emergence has encountered delivery pains. A few years ago, the use of a switched network was suggested as a way to deliver television to homes. Such switched systems were known as video dial tone (VDT) or video-on-demand (VOD). These newer emerging approaches have thus far been far too technologically complex and costly to achieve commercial viability.

3. THE PROGRESS OF TELEVISION TECHNOLOGY

The technical standards for television were developed five decades ago. The very fact that these standards have remained virtually unchanged for such a lengthy period attests to how well chosen they were. The original standards for monochrome television were expanded to accommodate color television, as implemented in the NTSC (National Television System Committee) standard for North America and in the European PAL (phase alternation line) and SECAM (séquentiel couleur avec mémoire) standards. The standards for color television were chosen to be backwards compatible with the older monochrome standard, thereby assuring an orderly diffusion of the newer color system. Although television standards have remained unchanged, television technology has progressed greatly over these decades.

The basic idea of scanning an image to create a serial signal was devised in 1884 by the German Paul Nipkow with his invention of a mechanical scanning disk. But electromechanical television was not practical and had to await the invention of an all electronic system utilizing a cathode ray tube for display—first proposed by Boris Rossing in Russia in 1907—and the invention of an electronic camera. The camera tube was invented decades later, with credit shared by Vladimir K. Zworykin's iconoscope (demonstrated in 1924) and Philo T. Farnsworth's image dissector tube (demonstrated in 1927). Camera tubes progressed from these early inventions to the image orthicon and the vidicon tubes. But vacuum tubes were large and bulky and required large voltages to operate. Solid state image sensors have today replaced camera tubes.

The cathode ray tube (CRT) continues—after well over a half century—to be the display technology of choice for television, and also for desk-top personal computers. The high resolution, high contrast, brightness, and robustness of this technology are some of the reasons for its long life. Cathode ray tube technology has continued to progress over its long life, however. Monochrome displays with a single electron beam expanded to become color displays with three electron beams and a shadow mask. Color phosphors have continued to improve. A black matrix increases the contrast, particularly in high ambient light conditions. The face plate has become nearly flat. Wide screen tubes are available in Japan. But, the cathode ray tube is heavy and bulky and requires very high voltages to accelerate the electron beams and high currents to deflect the electron beams. These disadvantages could be eliminated by the development of an alternative display technology, such as flat-screen, thin, liquid crystal displays (LCD) and plasma panels. But these replacement technologies have been long in coming and still seem to be in the future.

Television—it has been postulated—is little more than radio with pictures. It has been also postulated that the sound quality is more important than the picture quality. The early inventors of television must have well understood these claims since they decided on the use of high-fidelity sound transmission to give a wide frequency range and the use of wide-band frequency modulation of the radio wave to give noise immunity. Television audio has progressed with its expansion to include stereophonic, two-channel sound. A secondary audio program (SAP) has also been added and is frequently used for a second language on news broadcasts.

In the early days of television, programs were recorded on film. All that changed in 1976 with the development and introduction of magnetic tape recording of television for the studio with the Ampex Corporation's invention of quadruplex transverse recording on two-inch wide tape. This technology was then expanded into the home with the invention of slant recording using helical scanning, as implemented by Sony with its Betamax™ system in 1976 and shortly later by the Victor Company of Japan, JVC, with its Video Home System VHS™ technology. Two incompatible systems for the home were too confusing for consumers, and in the end, the Sony system did not survive. The Super VHS™ home system is an improvement on the VHS technology, but has not replaced the older system. Helical scanning has been adopted and is standard for professional use in the studio.

Television receivers were costly appliances in their early years, and many consumers purchased them with weekly time payments spread over years. The many vacuum tubes in these early sets were frequently burning out and had to be repaired by television repair people who made home calls. Vacuum tubes were replaced by transistors and then by integrated circuits. The result has been lower cost—and price—along with greatly increased reliability and quality. Television's role as a passive entertainment medium was assured with the invention of the remote control. No longer did the viewer have to raise from the couch to change a channel. Channel surfing from the comfort of the couch was assured. Knobs have been replaced with on-screen control.

Technology has progressed greatly in the television studio. Computers are used to automate much of the scheduling and switching of program sources. Computers are used to create graphics and text, particularly for news programs. The professional camcorder has simplified and increased the flexibility of news gathering in the field. Solid-state cameras with increased light sensitivity have reduced the need for high-intensity studio lighting. Computer processing has resulted in the creation and use of virtual sets, thereby increasing production flexibility and lowering costs.

The vertical blanking interval (VBI) is the time allowed for the electron beam to move from the bottom of the screen back to the top to begin another picture. During a portion of the VBI, the beam is at the top of the screen but has not yet begun to display a visible picture. During this time, the VBI scan lines can be used to transmit data or other information. In effect, a 6 MHz channel is available for a short time to transmit any kind of information. It is during the VBI that teletext data is transmitted. In the United States, the VBI is used to transmit information used for closed captioning text that appears on the screen as an aid to the hearing impaired.

4. TECHNOLOGICAL UNCERTAINTIES

4.1 High Definition Television (HDTV)

In the early 1980s, high definition television (HDTV) was promised as the television of the 1990s. The 1990s are now coming to their close, but HDTV still seems far away. HDTV promises television with a picture with improved spatial resolution, achieved by doubling the number of scan lines to about 1000. However, consumers show little interest in HDTV, and some studies show that consumers actually prefer low-definition TV for some types of programs.[2]

Whether the increased resolution of HDTV is noticeable depends on viewing distance. The present 500-line standard was chosen based on the resolution of human vision with a viewing distance no closer than four times the picture height. Increasing the number of lines for this assumed viewing distance would not be noticeable. The HDTV improvement would only be noticeable for large-screen television receivers that are viewed closely. But, then again, program quality is far more important than image quality. The end result may be that HDTV will only allow viewers to see more clearly how poor the quality of program content really is.

One-thousand line television is an old idea and has been an industrial standard for many decades. What is relatively new is use of a 1000-line standard for broadcast television. HDTV started in Japan by the Japan Broadcasting Corporation (NHK) and is still being broadcast there using an analog standard sent over a 30-MHz channel. Analog standards that would be backwards compatible with the existing NTSC standard were proposed for the United States by both RCA and CBS in the 1980s, but were never implemented. The rush to digital television overcame analog HDTV.

If improved image quality is important to consumers, processing in the television receiver using the existing NTSC signal can greatly achieve much improvement. Ghosts could be eliminated using adaptive digital filters and a known reference signal sent during the vertical blanking interval. Noise could be greatly reduced through comparison of adjacent fields and frames. One-thousand line display could be achieved by interpolating additional lines between the adjacent 500 lines. Flicker could be eliminated by increasing the display rate with the use of a buffer memory. The separation of the color information could be improved through the use of digital comb filters.

In fact, the television receiver would increasingly use digital technology. In some ways, the television receiver would resemble a digital computer. However, since the functions of a television receiver are very different from a computer, the two products are not converging. Computers use cathode ray tubes for display, but are not television sets.

4.2 Wide-Screen Television

Standard television (STV) has an image that is four units wide and three units high—an aspect ratio of 4:3. This choice was made decades ago to give an aspect ratio similar to that of a motion picture image of that day. Today's motion pictures offer wide-screen images. Hence, it is believed that television of the future must likewise offer wide-screen images with a wider aspect ratio. The aspect ratio that seems to be the accepted possible new standard is 16:9.

The problem is too many aspect rations makes it very difficult from an artistic perspective to create video content. The overall artistic "feel" and dramatic impact of an image depends on its aspect ratio. Video content must today be created with a variety of distribution outlets in mind, including wide-screen motion pictures, standard television, and airlines—all with different aspect ratios. The addition of yet one more aspect ratio complicates an already complicated situation.

4.3 Digital Television

Although so promoted as "the" technology of the future, digital is actually many decades old. The use of a digital representation of a signal transmitted as a series of "on" and "off" bits as a form of pulse code modulation was described by Claude E. Shannon, Bernard M. Oliver, and John R. Pierce of Bell Labs in 1948.[3] The earliest practical use of their invention was the T1 multiplex system first used in 1962 to multiplex 24 voice telephone circuits on a single pair of copper wires. The digital compact disc for audio is now fifteen years old, and indeed is worthy of the term "revolutionary" in its impact on forcing the phonograph record into oblivion within much less than a decade.

Digital offers immunity to noise and signal degradation, but at the expense of bandwidth. In this way, digital is akin to wide-band frequency modulation, which also offers noise immunity at the expense of bandwidth. Wide-band frequency modulation was invented by Major Edwin Howard Armstrong, with patents issued in 1933. Broadcast television has used Armstrong's wide-band FM for the audio signal since the earliest days. However, the use of digital for reproducing sound had to await the invention of a medium with sufficient bandwidth. That medium was the laser disk.

The conversion of a standard NTSC signal to a digital format using 720 pixels per scan line and encoding each pixel with 16 bits (8 bits for luminance and 4 bits each for the two color difference signals) results in a digital signal at a bit rate of 168 Mbps. This digital signal would require a bandwidth in the order of 80 MHz—far more than could be carried over a conventional 6-MHz TV channel.

The solution to the digital bandwidth problem is to compress the digital signal by reducing spatial detail and by exploiting the redundancy of information both within a frame and between adjacent frames. The standard that achieves the necessary compression was chosen by the Moving Pictures Expert Group (MPEG), formed in 1988 under the International Standards Organization (ISO). Spatial detail can be reduced because the human eye is less sensitive to higher spatial frequencies in the luminance and chrominance information.[4] The use of MPEG compression reduces the bit rate to about 4 Mbps. Since a 6 MHz channel can carry about 19 Mbps, about four standard TV (STV) signals, each in a MPEG digital format, can be combined—or multiplexed—together in a single 6-MHz channel.

4.4 Interactive Television

For most viewers of television, television is a passive entertainment medium, and the last thing these viewers would want to do is interact with their television set. This conclusion was confirmed in trials of videotex conducted in the United States by AT&T in Florida and in Southern California in the early and mid 1980s.[5] Videotex used the home TV set to display text and graphic information accessed over a telephone line from a centrally located data base. Trial participants complained that using videotex prevented them from watching television programs and that the data base was too difficult to search. The videotex service was most used to send text messages—an early form of today's e-mail.

Perhaps in ignorance of the lessons learned from videotex, WebTV uses the home TV set to give access to the Internet. Not surprisingly, the consumer response to WebTV has not been that positive, even though Bill Gates is reported to have spent about $1 billion in purchasing and promoting it. Other companies are attempting to use the vertical blanking interval to give access to the Internet. The problem with all these attempts to use the home TV set as a computer terminal is that the home TV set is positioned in the home entertainment center as a passive display device. The only success in using the home TV set to display information has been teletext in Europe.

Why is teletext so successful in Europe, yet nonexistent in the United States? Teletext sends a few hundred pages of text and simple-graphic information during the vertical blanking interval. The information is timely and of general interest, thereby assuring a mass appeal. The small size of the recirculating information means that users can comprehend its totality. The access is simply from the hand-held remote control through entry of a page number. Information about television program selection is also contained in the data base. One can only wonder whether WebTV and other similar systems ultimately will evolve into a form of teletext for the United States.

A television channel can be used fully to send digital data as a broadband medium to download information from the Internet. Another option, possible with multicasting, is to send three compressed digital TV programs and then use the remaining capacity for Internet data. Although this gives consumers high-speed access from the Internet, the access is shared which would reduce the average speed with increased usage. Furthermore, television is one-way enabling communication only from the Internet, and thus the telephone would need to be used to send information to the Internet. What this all means is that the use of broadcast television to enable access to the Internet faces many difficult challenges.

5. DISCUSSION

5.1 Many Uncertainties

The future of digital television is much more cloudy and uncertain that was originally thought. Questions and uncertainties abound. Is digital television a form of high-definition, wide-screen television or is it more programs on a single broadcast channel? Is digital television a linking of television to the Internet to create a new form of an interactive television experience? Will television be watched over an appliance that is also a personal computer, and perhaps also a digital audio player? Will terrestrial broadcast television disappear altogether?

How important is image quality over program variety and content? Why not employ digital processing in analog TV sets to improve image quality? Does the fact that such technology exists already but has not been implemented imply that consumers really care little about image quality? How do improvements in image stability (flicker) compare with improvements in resolution (high definition) and wide-screen formats (aspect ratio)? What should be the aspect ratio, resolution, and compression algorithm for digital television? Does digital television have the noticeable improvements in image quality that are necessary to make consumers want it enthusiastically? Will one or two distribution media (for example, terrestrial radio, optical fiber, satellite microwave radio, phone lines, disk) dominate in the future? The success of teletext in Europe stimulates the question of whether Web-TV will evolve into teletext in the United States.

In addition to these technological and consumer uncertainties, there are many questions regarding economics and finance. What will be the cost of new digital TV sets? Where will TV stations find the capital necessary to finance the conversion to digital?

Creative examination of the possible impact of unexpected future innovations is needed. These "what ifs" could have major unexpected changes in direction. As one example, consider the impact of the use of optical fiber for the provision of CATV service. This would eliminate the need for amplifiers because of the low loss of fiber. But more importantly, the tremendous bandwidth of fiber would make it possible to deliver hundreds of digital TV signals at rates of 1 Gbps per program. Compression (such as MPEG) with its compromises with quality would not be needed. Similarly, if the capacity of laser disk technology continues to expand, there soon will be little need for compression to record and play a digital TV signal.

A "what if" in the policy dimension would be a government mandate for all CATV systems to supply basic programming for free as a common carrier. This would mean that over-the-air, terrestrial broadcasting would no longer be needed with its artificial technological restriction of 6 Mhz per channel.

5.2 Digital Certainties

Digital technology offers immunity against noise, distortion, and deterioration both over time and over successive copying. Program content will increasingly be produced, captured, and stored in a digital format. Therefore, the production side of television must continue—as is already occurring—to convert to a digital modality as a common platform for delivery over a variety of media.

The digital technology used for production must offer as much technical quality as possible. For audio, this means at least 20 bit quantization and possibly even over-sampling. For video, this means accommodation of a wide-screen format, high-definition over scanning, and full resolution at bit rates in the order of 1 giga bit/sec. Studio facilities (audio and video) need to be converted to fully digital as quickly as possible.

All the advantages of digital are at the expense of bandwidth. One solution is the use of compression to save bandwidth. However, compression costs quality. Another solution is to increase the available bandwidth, such as the increase that occurs when optical fiber replaces coaxial cable for CATV distribution or the increase that occurred when the laser disc replaced the phonograph record.

5.3 A Changing Environment

Media synergies—such as those supposed between Paramount and Blockbuster by Viacom and between Disney and Cap Cities—seem illusionary. CATV firms are not providing telephone service, although they now talk of providing Internet access, nor are telephone companies providing video-on-demand service. Media and industry convergence have come to be synonyms for industry consolidation and mergers.

Many high-tech products have encountered consumer apathy. Digital audio tape, the AT&T Videophone 2500, and the CD mini disc are just a few of recent products that failed to gain mass-market consumer acceptance. The future of today's Digital Video Disk (DVD) seems fraught with difficulties, one of which is whether the "V" stands for video or for versatile. Meanwhile, Time Warner's trial in Florida of futuristic new interactive services has closed, and Pacific Bell has terminated its trial of video dial tone services. It now seems that the country will not be wired in the foreseeable future with fiber to homes and curbs for a convergence of telephone, video, and data services.

Television seems to be moving toward a television of abundance in terms of an ever increasing variety of programming delivered over an increasing variety of distribution channels. However, program quantity does not necessarily relate to program quality. Audiences will be more fragmented and specialized, possibly leading to the end of television as a culturally integrative medium. Except for major sporting events, television seems destined to continue to decrease as a mass medium with large audiences for a small number of programs.

Today, only about 20 percent of TV households in the United States obtain their television directly from over-the-air, VHF and UHF, terrestrial radio broadcasts. For most people in the United States, television is obtained from cable and from direct-broadcast communication satellites. Technology has created many more channels of distribution other than only terrestrial radio broadcast. Meanwhile, the program capacity of CATV and DBS systems is increasing. On-demand viewing is mostly in the use of the VCR to view rented and purchased tapes. All this creates a great demand for program content to fill all the distribution media.

5.4 A Strategy

Considerable confusion is generated by the hype created by the press and also by a fascination, based mostly on ignorance, with technology. This is confounded by the prospects for great profits and also by a fear of being left behind because of the rapid pace of technological change. Thus a wise strategy for the future is to avoid all the hype about digital television and instead concentrate on the production of branded content which is distributed worldwide through a variety of existing and evolving transmission media (satellites, fiber, physical media, cable) and modalities—analogue or digital.

BIBLIOGRAPHY

Bhatt, Bhavesh: David Birks; & David Hermreck, "Digital Television: Making It Work," *IEEE Spectrum*, October 1997, pp. 19-28.

Neuman, W. Russell, "The Mass Audience Looks At HDTV: An Early Experiment," Research Panel. National Association of Broadcasters, Las Vegas, NV, April 11, 1988.

Noll, A. Michael, "Digital Television, Analog Consumers," *Telecommunications*, Vol. 31, No. 9, September, 1997, p. 18.

Noll, A. Michael, *Television Technology: Fundamentals and Future Prospects*, Artech House, Inc. (Norwood, MA), 1988.

Noll, A. Michael, "Videotex: Anatomy of a Failure," *Information & Management*, 1985, pp. 99-109.

Pierce, John R. and A. Michael Noll, *Signals: The Science of Telecommunications*, Scientific American Library (New York), 1990.

Shannon, C. E., "A Mathematical Theory of Communication," *Bell System Technical Journal*, Vol. 27, No. 3, July, 1948, pp. 379-423.

Strachan, David, "Video Compression," *SMPTE Journal*, February 1996, pp. 68-73.

Table 1. Television system elements

PRODUCTION	DISTRIBUTION	RECEPTION
• Origination:	• Over-the-air (radio waves):	• TV Receiver:
- studio (live)	- terrestrial --	- conventional
- recorded	VHF/UHF	- home theater
tape	low-power (LPTV)	
disk	microwave (MMDS)	• Set-Top Box:
	- satellite --	- CATV converter
• Packaging	DBS	- DBS decoder
	C-band	
• Branding	satellite master antenna (SMATV)	• Player/Recorder:
		-VCR machine
	• Wired:	- disk player
	- coaxial cable (CATV)	
	- "emerging"	• "Emerging:"
	- switched	- personal computer
	Video On Demand	
	Video Dial Tone	
	- Internet	
	- optical fiber	
	fiber-to-the-home (FTTH)	
	fiber-to-the-curb (FTTC)	
	hybrid fiber-coax (HFC)	
	• Physically-Delivered:	
	- tape (VCR)	
	- laser disk	
	- digital video disk (DVD)	

Table 2. A Chronology of Television Technology

1884	Patent granted to Paul Nipkow (German) -- scanning-disk system over wires.
1906	Max Diekmann (German) invents cold cathode ray tube (CRT).
1907	Prof. Boris Rosing (St. Petersburg. Russia) applies for patent for TV system using CRT & mechanical scanner.
1911	Demo by Rosing of TV system using rotating-mirror imager & cold CRT.
1922	Patent filed by Charles Francis Jenkins (American) for crude TV system using rotating prismatic disks.
1923	Patent filed by Vladimir Kosmo Zworykin (at Westinghouse).
1924	Demo by Zworykin of iconoscope electronic camera.
1925	John L. Baird (in London) demonstrates wire transmission of TV.
1925	Ernst Fredrik Werner Alexanderson (Swede at General Electric) initiates work in radio transmission of moving pictures.
1926	Bell Labs telecast over wire between New York City and Washington, DC – first use of term "television."
1927	Philo T. Farnsworth develops image dissector electronic camera.
1927	General Electric Company experiments in TV.
1927	First TV license issued by FCC to Jenkins, station W3XK.
1928	Bell Labs demonstrates color TV.
1929	Farnsworth demo of all-electronic TV system (Philco in 1931).
1929	Zworykin applies for patent on Kinescope CRT.
1932	10,000 TV receivers in use in United Kingdom -- BBC broadcasts TV using Nipkow disks with 30-line resolution.
1939	First regularly-scheduled TV broadcasts in US by NBC (in NYC, Schenectady, & LA) & sale of TV sets by RCA.
1941	NTSC adopts 525-line and 30 frames/sec standard.
1941	FCC licenses NBC and CBS TV stations in NYC.
1945	FCC allocates 13 VHF channels.
1948	Ed Parsons of Astoria, Oregon installs coaxial cable system to deliver distant TV received over-the-air from Seattle.
1949	Robert J. Tarlton of Lansford, Pennsylvania installs cable TV system to deliver TV signals received from Philadelphia.
1950	FCC adopts field-sequential color TV standard.
1952	FCC allocates 70 UHF channels.
1953	49% TV penetration in U.S.
1953	FCC adopts NTSC color TV standard.
1980s	HDTV in Japan.
1996	Telecommunications Act (U.S.) promotes advanced TV broadcasting.

Table 3. Digital-TV Bit Rates & Bandwidths

SERVICE	BIT RATE	BANDWIDTH
NTSC Professional	≈ 70 million bps	≈ 80 MHz
NTSC Home Quality	≈ 84 million bps	≈ 40 MHz
HDTV	≈ 1 billion bps	≈ 500 MHz
TV Channel	≈ 19 million bps	≈ 6 MHz
MPEG Compression	≈ 4 million bps	≈ 2 MHz

[1] Shannon 1948
[2] Neuman 1988
[3] Pierce 1990, pp. 78 & 99
[4] Strachan 1996; Bhatt 1997
[5] Noll 1985