The ATSC Digital Television System

MARK S. RICHER, SENIOR MEMBER, IEEE, GLENN REITMEIER, MEMBER, IEEE,
TOM GURLEY, SENIOR MEMBER, IEEE, GRAHAM A. JONES, JERRY WHITAKER, MEMBER, IEEE,
AND ROBERT RAST, SENIOR MEMBER, IEEE

Invited Paper

The ATSC digital television standard describes a system designed to transmit high-quality video and audio, and ancillary data within a single 6-MHz terrestrial television broadcast channel. This paper outlines the overall architecture of the system and serves as an introduction to the papers that follow in this special issue of the PROCEEDINGS OF THE IEEE.

Keywords—*Advanced Common Application Platform (ACAP), Advanced Television Systems Committee (ATSC), compression, digital television, interactive television, MPEG-2, Program and System Information Protocol (PSIP), 8-VSB.*

I. INTRODUCTION

Digital television (DTV) has ushered in a new era in television broadcasting. The impact of DTV is more significant than simply moving from an analog system to a digital system. Rather, DTV permits a level of quality and flexibility wholly unattainable with analog broadcasting.

Analog television systems, by their nature, are rigidly defined and constrained to a narrow range of performance that offers few choices. Analog systems also have fundamental quality limitations. The move to a digital broadcasting system has enabled a significant step up in performance, quality, and a wider range of services. DTV can deliver programs free of transmission impairments throughout the service area while still occupying a 6-MHz transmission channel. In terms of performance, the ability to provide high-definition pictures with high-quality surround sound audio is essential to the future of broadcasting, as consumers are increasingly offered such enhancements with other forms of delivery. An important element of the Advanced Television Systems Committee (ATSC) system is the flexibility to expand functions by building upon the technical foundations specified in standards such as ATSC Digital Television Standard A/53 [1] and Digital Audio Compression (AC-3) Standard A/52 [2]. These ATSC standards, established in 1995, were the world's first standards for DTV, and they established the precedent for system quality and flexibility that separates DTV from all the existing analog television systems.

With the NTSC analog system, and its PAL and SECAM counterparts used in other countries, the video, audio, and some limited data information (e.g., closed captioning) are conveyed by modulating an RF carrier in such a way that a receiver of relatively simple design, by today's technology, can easily demodulate and reproduce the video and audio elements of the signal, and related data. As such, a complete program is transmitted by the broadcaster that is essentially in finished form. In analog television, camera, transmission, and display parameters are tightly coupled as part of an end-to-end system, which limits the ability to modify many of the basic system choices (e.g., picture resolution). The ATSC digital system design, for the first time, anticipated and enabled the separation of camera, transmission, and display properties. The ATSC standard pioneered a layered architecture that separates picture formats, compression coding, data transport, and transmission, as illustrated in Fig. 1. This means that additional levels of processing are required after an ATSC receiver demodulates the RF signal, before a complete program can be assembled and presented. The receiver first processes the digital bitstream extracted from the received signal to yield a collection of program elements (video, audio, and/or data) that match the service(s) that the consumer selected. This selection is made using system and service information, transmitted as part of the digital signal. The audio based on the ATSC A/52B standard and video elements based on the ISO/IEC

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M. S. Richer and J. Whitaker are with the Advanced Television Systems Committee, Washington, DC 20006 USA (e-mail: mricher@atsc.org).
G. Reitmeier is with NBC Universal, New York, NY 10112 USA.
T. Gurley is at 229 Old Colony Way, Rocky Mount, NC 27804 USA.
G. A Jones is with the National Association of Broadcasters, Washington, DC 20036 USA..
R. Rast is with Micronas Semiconductors, Poway, CA 92064 USA.
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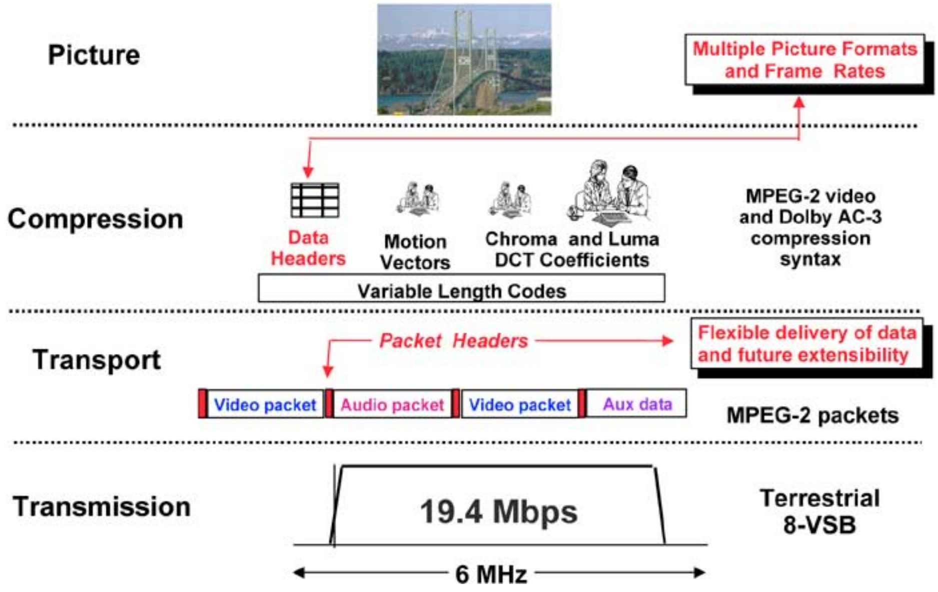

Fig. 1. Layered architecture of the ATSC DTV system.

MPEG-2 standard are delivered in digitally compressed form and must be decoded for presentation. Video may be high definition (HDTV) or standard definition (SDTV). HDTV has a resolution of approximately twice that of conventional television and a picture aspect ratio of 16 : 9 (horizontal:vertical). Audio may be monophonic, stereo, or multichannel. Various forms of data may supplement the main video/audio program (e.g., closed captioning, descriptive text, or commentary) or may be one or more stand-alone services (e.g., a stock or news ticker).

The nature of the ATSC DTV system is such that it is possible to provide new features that build upon the infrastructure within the broadcast plant and the receiver. One of the major enabling developments of digital television, in fact, is the integration of significant processing power in the receiving device itself. Historically, in the design of any broadcast system—be it radio or television—the goal has always been to concentrate technical sophistication (when needed) at the transmission end and thereby facilitate simpler and lower cost receivers. Because there are far more receivers than transmitters, this approach has obvious business advantages. While this concept still applies, the complexity of the transmitted bitstream and compression of the audio and video components require a significant amount of processing power in the receiver, which is now practical because of the enormous advancements made in digital IC technology. Analog television served the public well, but had reached the limits of its capability to improve. The capability of digital television to evolve may be its greatest asset.

II. Overview of the ATSC Digital Television System

The ATSC digital television standard describes a system designed to transmit high-quality video and audio, and ancillary data, within a single 6-MHz terrestrial television broadcast channel. The design emphasis on quality resulted in the advent of digital HDTV and multichannel surround sound.

The system can deliver about 19 Mb/s in a 6-MHz terrestrial broadcasting channel and about 38 Mb/s in a 6-MHz cable television channel. This means that encoding HD video essence at 1.106 Gb/s[1] (highest rate progressive input) or 1.244 Gb/s[2] (highest rate interlaced picture input) requires a bitrate reduction by about a factor of 60.[3] To achieve this bitrate reduction, the system uses complex video and audio compression technologies.

These compression schemes optimize the scarce resource of the transmission channel by representing the video, audio, and data sources with as few bits as possible while preserving the level of quality required for the given application.

The RF/transmission system of the ATSC DTV standard is designed specifically for terrestrial as well as cable applications. The layered structure is such that the video, audio, and service multiplex/transport subsystems are useful in other applications as well. Companion papers in this section describe the digital satellite and cable systems in North America and demonstrate the close relationship with ATSC standards.

A. *System Flexibility*

The ATSC DTV standard provides a huge data "pipeline" to the receiver that can support a wide variety of applications. For example, in a 6-MHz channel, a broadcaster can transmit one high-definition program, or an HDTV program with one or more simultaneous standard-definition programs, or multiple simultaneous SDTV programs, or a virtually limitless array of data services, or various combinations of all three. This flexibility in program services is a key benefit of the ATSC DTV standard for both broadcasters and consumers.

The capability to change services depending upon the needs of the consumer is critically important given the

[1] $720 \times 1280 \times 60 \times 2 \times 10 = 1.105\,920$ Gb/s (the 2 represents the factor needed for 4 : 2 : 2 color subsampling, and the 10 is 10 bits/sample).

[2] $1080 \times 1920 \times 30 \times 2 \times 10 = 1.244\,160$ Gb/s (the 2 represents the factor needed for 4 : 2 : 2 color subsampling, and the 10 is 10 bits/sample).

[3] Note that that when the overhead numbers are added, the progressive-versus-interlaced numbers quoted above become closer.

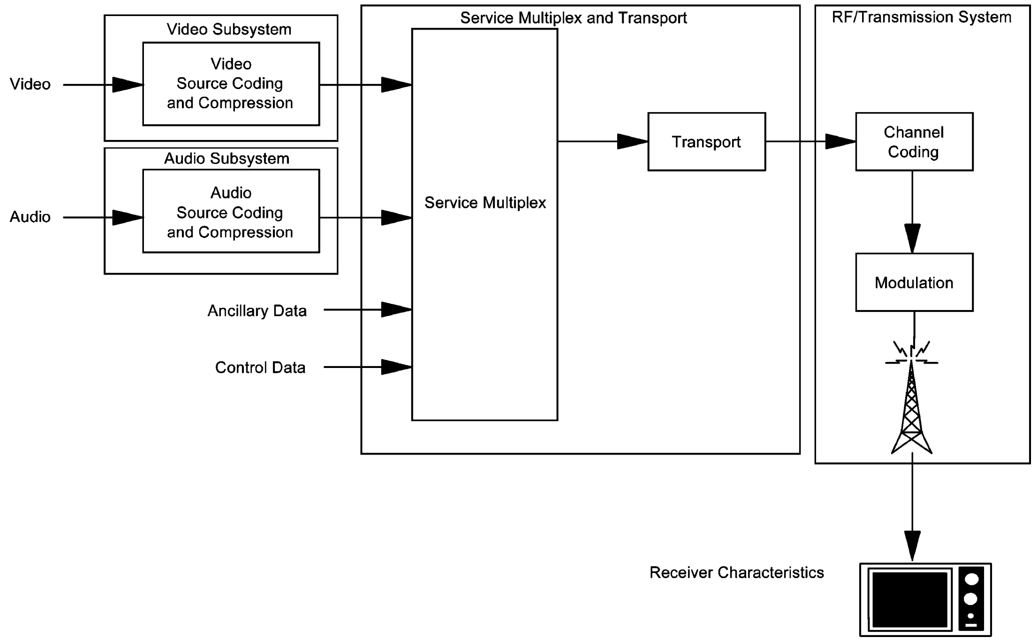

Fig. 2. ITU-R digital terrestrial television broadcasting model.

interrelationship of terrestrial, cable, and satellite distribution systems today. In markets such as North America, for example, it is not uncommon for a television broadcast network to operate local TV stations, have affiliated cable services, and provide content to satellite distributors. Given this interrelationship, it is important that commonality and interoperability among the various media is maintained to the greatest extent possible.

B. *DTV System Block Diagram*

A basic block diagram representation of the ATSC DTV system is shown in Fig. 2. This representation is based on one adopted by the International Telecommunication Union, Radiocommunication Sector (ITU-R), Task Group 11/3 (Digital Terrestrial Television Broadcasting) [3]. According to this model, the digital television system can be seen to consist of four major elements, three within the broadcast plant plus the receiver.

1) Source Formats: The source formats for the ATSC standard were carefully selected for their interoperability characteristics with film [wide aspect ratio and 24 frames per second (fps)], computers (square pixels and progressive scanning), and legacy television systems (480 lines and ITU-601 sampling), as illustrated in Fig. 3. In addition, the HDTV formats and the square pixel SDTV format are related by simple 3 : 2 ratios, allowing high quality yet economical conversion among these formats with relatively low-order interpolating filters. The legacy ITU-601 related formats maintain the 3 : 2 ratio vertically, but require slightly more complex relationships horizontally.

2) Video/Audio System: The video/audio system, as shown in Fig. 2, refers to the bitrate reduction methods appropriate for application to the video, audio, and ancillary digital data streams. The purpose of compression is to reduce the number of bits needed to represent the audio and video information to a level that can be contained within the

Vertical Lines	Pixels	Aspect Ratio	Picture Rate
1080	1920	16:9	60 interlaced 30 progressive 24 progressive
720	1280	16:9	60 progressive 30 progressive 24 progressive
480	704	16:9 and 4:3	60 progressive 60 interlaced 30 progressive 24 progressive
480	640	4:3	60 progressive 60 interlaced 30 progressive 24 progressive

Fig. 3. Video formats and frame rates specified by the ATSC system. (Note that the frame rates include both 60.0 and 59.94 Hz, and 30.0 and 29.97 variations).

transmission channel capacity. ATSC employs the MPEG-2 video stream syntax (Main Profile at High Level) for the coding of video and the ATSC standard "Digital Audio Compression (AC-3)" for the coding of audio. The ATSC DTV standard defines the video formats for HDTV and SDTV as shown in Fig. 3. ATSC consumer receivers are designed to decode all HDTV and SDTV streams providing program service providers with maximum flexibility.

The term "ancillary data" dates from the original drafting of A/53 and is a broad term that includes control data and supplementary data, including data associated with the program audio and video services. As standards were developed to define how to transport and process data, it became clear that different forms of data served very different purposes and different standards were needed for metadata and essence. Data delivered as a separate payload can provide independent services as well as data elements related to an audio- or video-based service, as described in a later section.

3) Service Multiplex and Transport: The service multiplex and transport system, as shown in Fig. 2, refers to the means of dividing each bitstream into "packets" of information, the means of uniquely identifying each packet including packet type, and the appropriate methods of interleaving or multiplexing video bitstream packets, audio bitstream packets, and data bitstream packets into a single transport mechanism. The structure and relationships of these essence bitstreams is carried in service information bitstreams, also multiplexed in the single transport mechanism. In developing the transport mechanism, interoperability among digital media—such as terrestrial broadcasting, cable distribution, satellite distribution, recording media, and computer interfaces—was of prime consideration. The ATSC system employs the MPEG-2 transport stream (TS) syntax for the packetization and multiplexing of video, audio, and data signals for digital broadcasting systems. The MPEG-2 TS syntax was developed for applications where channel bandwidth or recording media capacity is limited and the requirement for an efficient transport mechanism is paramount. It also provides the critical timing information for the receiver to perform video and audio synchronization.

a) Program and System Information Protocol (PSIP): PSIP, defined in ATSC Standard A/65, is a small collection of tables designed to operate within every TS for terrestrial broadcast of digital television. Its purpose is to describe the information at the system and event levels for all virtual channels (channel numbers are not tied directly to the actual RF channel frequency) carried in a particular TS. Additionally, information for analog channels as well as digital channels from other TSs may be incorporated.

There are two main categories of information in the ATSC PSIP standard: system information and program data. System information allows navigation and access of the channels within the DTV TS, and the program data provides necessary information for efficient browsing and event selection. Some tables announce future events and some are used to locate the digital streams than make up an event. The PSIP data are carried via a collection of hierarchically arranged tables, repeated in the packet stream at frequent intervals.

4) RF Transmission System: The RF transmission system, as shown in Fig. 2, refers to channel coding and modulation. The channel coder takes the packetized digital bitstream, reformats it, and adds additional information that assists the receiver in extracting the original data from the received signal, which due to transmission impairments may contain errors. In order to protect against both burst and random errors, the packet data is interleaved before transmission and Reed–Solomon forward error correcting codes are added. The modulation (or physical layer) uses the digital bitstream information to modulate a carrier for the transmitted signal. The basic modulation system offers two modes: an 8-VSB mode for terrestrial broadcasting and a 16-VSB mode intended for cable applications. The 8-VSB mode was designed for spectral efficiency, maximizing the data throughput with a low receiver carrier-to-noise (C/N) threshold requirement, high immunity to both cochannel and adjacent channel interference and a high robustness to transmission errors. The attributes of 8-VSB allow DTV channels to coexist in a crowded spectrum environment that contains both analog and digital television signals. In addition, the lower power requirements (typically, 12 dB lower than analog NTSC) of 8-VSB allow ATSC DTV stations to exist on channels where analog stations cannot due to interference constraints. The spectral efficiency and power requirement characteristics of 8-VSB are essential to the conversion of terrestrial broadcast transmission from analog to digital since new spectrum is not allotted during the transition phase.

The recently developed "Enhanced-VSB" (E-VSB) mode involves the transmission of a backward-compatible signal within the standard 8-VSB symbol stream that can be received at a lower carrier-to-noise ratio than conventional 8-VSB. The E-VSB mode allows broadcasters to trade off some of their data capacity for additional robustness. With an E-VSB transmission, some of the approximately 19.4 Mb/s data is allocated to the robust mode and some is allocated to the normal 8-VSB mode. However, the amount of delivered data (payload) is reduced for the robust mode because part of the payload is traded for additional forward error correction (FEC) bits to correct bit errors that occur with reception under weaker signal conditions (resulting in up to a 6-dB improvement).

5) Receiver: The ATSC receiver recovers the bits representing the original video, audio, and other data from the modulated signal. In particular, the receiver performs the following functions:

- tunes the selected 6-MHz channel;
- rejects adjacent channels and other sources of interference;
- demodulate (equalize as necessary) the received signal, applying error correction to produce a transport bitstream;
- identifies the elements of the bitstream using a transport layer processor;
- select each desired element and send it to its appropriate processor;
- decodes and synchronizes each element;
- performs product-specific video, audio, and data processing;
- presents the programming to the appropriate video or audio transducer.

Noise, interference, and multipath are elements of the terrestrial transmission path with which receiver circuits are designed to deal. Innovations in equalization, automatic gain control, interference cancellation, and carrier and timing recovery improve signal reception and create product performance differentiation. In fact, current ATSC receivers have demonstrated remarkable improvements in reception performance compared to initial receiver implementations.

The decoding of transport elements that make up the programming is usually considered to be a straightforward implementation of the MPEG and AC-3 specifications, although significant opportunities for innovation in circuit efficiency or power usage exist. Innovations in video decoding offer opportunities for savings in memory and circuit speed and complexity. Product differentiation based on picture quality is also widespread, resulting from innovations in error concealment, format conversions, perceptual picture processing, and specific display related processing. The user interface and new data-based services are other important areas for product differentiation.

The development of large-screen consumer displays has played an important role in the evolution of receivers. Whether intended for use in an integrated receiver or as a stand-alone display, the rapid deployment of new large, high-resolution flat panel displays has substantially changed the video landscape.

For example, one of the first concerns of technologists with regard to HDTV in the home was the size of the display device. In order to fully appreciate the image quality of HDTV at typical viewing distances, it is necessary to view the image on a large screen. However, with CRT technology a large screen also means a large, heavy enclosure. Flat panel displays and projection systems with HDTV resolution have essentially eliminated this physical constraint.

III. Data Broadcast and Interactive Capability

The rollout of the digital television infrastructure opens up a new frontier in communication. This is leading to powerful new applications extending beyond regular television programming, with possibilities that hold considerable commercial potential.

Recognizing the interest in data broadcast applications, the ATSC developed a suite of data broadcast standards (Documents A/90–A/97) to enable a wide variety of data services, which may be related to one or more video programs being broadcast or stand alone services. Applications range from streaming audio, video, or text services to private data delivery services. Data broadcast receivers may include personal computers, televisions, set-top boxes, or other devices.

Generally speaking, data broadcast applications targeted to consumers can be classified by the degree of *coupling* to the main video programming, specifically the following.

- *Tightly coupled* data are intended to enhance the TV programming in real time. The viewer tunes to the TV program and simultaneously receives the data enhancement along with it.
- *Loosely coupled* data are related to the program, but are not closely synchronized with it in time. For example, an educational program might send supplementary reading materials or self-test quizzes within the broadcast stream.
- *Noncoupled* data are typically contained in separate "data-only" virtual channels. They may be data intended for real-time viewing, such as a 24-hour news headline or stock ticker service.

1) Advanced Common Application Platform (ACAP): The ACAP standard (A/101) is a platform for interactive television services. ACAP was developed as the result of a landmark harmonization effort between the ATSC DTV Application Software Environment (DASE) Standard and Cable Television Laboratory's ("CableLabs") Open Cable Application Platform (OCAP) specification.

In essence, ACAP makes it appear to interactive programming content that it is running on a single platform, the so-called common receiver. This common receiver contains a well-defined architecture, execution model, syntax, and semantics. As a "middleware" specification for interactive applications, ACAP gives content and application authors assurance that their programs and data will be received and run uniformly on all brands and models of receivers.

The term *interactive television* (ITV) is broad and includes a vast array of applications, including:

- customized news, weather, and traffic;
- stock market data, including personal investment portfolio performance in real time;
- enhanced sports scores and statistics on a user-selective basis;
- games associated with program;
- online real-time purchase of everything from groceries to software without leaving home;
- video on demand (VOD).

There is no shortage of reasons why ITV is viewed with considerable interest around the world. With the rapid adoption of digital video technology in the cable, satellite, and terrestrial broadcasting industries, the stage is set for the creation of an ITV segment that introduces to a mass consumer market a whole new range of possibilities.

ACAP is intended to provide consumers with advanced interactive services while providing content providers, broadcasters, cable and satellite operators, and consumer electronics manufacturers with the technical details necessary to develop interoperable services and products.

IV. Future Improvements

The basic design of the ATSC DTV system both anticipates and facilitates continuing improvements in performance in many ways.

- By specifying the *transmitted* picture formats, camera resolutions and frame rates in production can continue to improve, and display processing technology can continue to improve the overall quality delivered to the viewer. The recent introduction of 1080P displays is an excellent example, where receivers can deinterlace 1080/60I and upconvert 720/60P formats. In addition, flexible frame rate displays with 72-Hz refresh have been demonstrated that allow an outstanding rendition of film-based content (transmitted at 1080/24P or 720/24P) by eliminating the artifacts of the traditional 3 : 2 sequencing that is used to display 24-fps film at 60-Hz television rates.
- By specifying the MPEG *decoder* syntax, encoders can continue to improve the quality of ATSC signals (or further reduce bitrates to allow the introduction of additional services) as processing power improves. Increased motion search range, noise reduction preprocessing and multipass encoding algorithms are examples that have already contributed to improved

quality and are now commercially available in ATSC encoders.
- Through the flexibility of the MPEG transport protocol, the ATSC standard can deliver multiple simultaneous services and new services can be added without disrupting the installed base of receivers
- By specifying the *transmitted* VSB signal, receivers can continue to improve their ability to reject interference and deal with transmission impairments such as multipath. Recent improvements in adaptive equalization, carrier recovery, and cochannel interference rejection are clearly evident in the performance of the latest ATSC receivers.

In addition, the ATSC continues to develop new capabilities that can result in the introduction of new services, such as data broadcasting and ACAP, as described in the previous section of this paper.

V. Overview of ATSC DTV Section

Coverage of the ATSC DTV system in this special issue of the Proceedings of the IEEE is divided logically into the following topics:
- RF, modulation, and transmission;
- video and audio coding;
- packetized transport and multiplex, including program and system information protocol;
- data broadcasting and interactive television;
- receiver implementation.

This section also includes closely related systems for cable and satellite delivery as implemented in North America:
- carriage of digital video and other services by cable in North America;
- satellite direct to home.

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Mark S. Richer (Senior Member, IEEE) received the B.S. degree from the Rochester Institute of Technology, Rochester, NY.

He was Vice President and General Manager, CDS, a division of Thomcast Communications. For 16 years, he was with with the Public Broadcasting Service (PBS), where, as Vice President of Engineering and Computer Services, he was responsible for development of new technologies for PBS and its member stations, design of audio/video systems, and management of computer operations. He was instrumental in the development of technological innovations, including the Line 21 closed captioning for the deaf system and selection and implementation of digital video compression and transmission technology. He also led PBS efforts in the area of digital and high definition television. He is currently the President of the Advanced Television Systems Committee (ATSC), Washington, DC. The ATSC is an international, nonprofit organization developing voluntary standards for digital television. He holds two patents.

Mr. Richer is a Fellow of the Society of Motion Picture and Television Engineers (SMPTE). He served as Chairman of the System Subcommittee Working Party on Test and Evaluation for the FCC Advisory Committee on Advanced Television Service.

Glenn Reitmeier (Member, IEEE) received the B.E.E degree (*summa cum laude*) from Villanova University, Villanova, PA, and the M.S.E. degree in systems engineering from the University of Pennsylvania, Philadelphia.

He is Vice President of Technology Standards, Policy and Strategy at NBC Universal, New York. Since joining NBC in 2002, he was involved in the creation and launch of NBC's new high-definition cable channel, Universal-HD and the new DTV multicast channel, NBC Weather Plus. He is widely recognized as a pioneering visionary, creator, and architect of digital television. Early in his career, he was instrumental in establishing the ITU 601 component digital video standard. During the competitive phase of HDTV standardization, he led the Sarnoff-Thomson-Philips-NBC development of Advanced Digital HDTV, which pioneered the use of MPEG compression, packetized transport, and multiple video formats. He was a key member of the Digital HDTV Grand Alliance, taking a leadership role in its formation and in all of its all technical decisions, communications with government and industry, and interoperability efforts that lead to establishing the ATSC digital television standard.

Mr. Reitmeier is the recipient of the Society of Motion Picture and Television Engineers' Progress Medal and the Leitch Gold Medal and holds over 50 patents in digital video technology.

Tom Gurley (Senior Member, IEEE) graduated with distinction from Duke University, Durham, NC, and received the M.S.E. degree from the University of Pennsylvania, Philadelphia.

He is a consultant to the broadcast industry and a pioneer in digital television technology. He served as Director of Testing for the Advanced Television Test Center, responsible for laboratory testing of the "Grand Alliance" system and its six predecessors. Subsequently, he joined the Association for Maximum Service Television (MSTV) as Vice President of Technology and served as Technical Director of the all-industry Model DTV Station Project (WHD-TV). He has been active in the work of several ATSC committees. Previously in his career, he managed advanced development for RCA Broadcast Systems, leading early work in digital video and solid-state camera technologies, and served in production, operations, and engineering capacities for radio and television stations and a private satellite network. He holds three U.S. patents in digital video and has authored numerous papers and presentations on television technology.

Mr. Gurley is a Fellow of the SMPTE, and a member of Tau Beta Pi and Eta Kappa Nu. He currently serves as President of the IEEE Broadcast Technology Society.

Graham A. Jones was born in Stoke-on-Trent, U.K., in 1944. He received the B.Sc. degree in physics from Nottingham University, U.K., in 1964.

He started his career with the BBC and for 18 years was a partner of International Broadcasting Consultants. Previously with Harris Corporation, he was Engineering Director for the Harris/PBS DTV Express road show. He is currently Director of Communications Engineering with the National Association of Broadcasters, Washington, DC, working on advanced television issues, standards, and education. He is author of *A Broadcast Engineering Tutorial for Non-Engineers* (Elsevier, 2005), and editor for the forthcoming *10th NAB Engineering Handbook*.

Mr. Jones is a Fellow and Governor of the Society of Motion Picture and Television Engineers. He is a Chartered Engineer and a member of the Institution of Electrical Engineers, the Society of Broadcast Engineers, and the Royal Television Society. He was chair of the ATSC TSG/S1 specialist group on PSIP Metadata Communications and chairs the SMPTE S22 working groups on lip sync and image formatting. In 2004 he received the ATSC Bernard J. Lechner Outstanding Contributor Award.

Jerry Whitaker (Member, IEEE) is the Vice President for Standards Development of the Advanced Television Systems Committee (ATSC). He supports the work of the various ATSC technology and planning committees and assists in the development of ATSC standards and related documents. He currently serves as Secretary of the Technology and Standards Group and Secretary of the Planning Committee, and is closely involved in work relating to educational programs. He is the author and editor of more than 35 books on technical topics, including *The Standard Handbook of Video and Television Engineering*, 4th ed. (McGraw-Hill, 2003); *NAB Engineering Handbook*, 9th ed. (National Association of Broadcasters, 1999), *DTV Handbook*, 3rd ed. (McGraw-Hill, 2001), and *The Electronics Handbook*, 2nd ed (CRC, 2005). Prior to joining the ATSC, he headed the publishing company Technical Press, Morgan Hill, CA.

Mr. Whitaker is a Fellow the Society of Broadcast Engineers and a Fellow of the Society of Motion Picture and Television Engineers. He has served as a Board member and Vice President of the Society of Broadcast Engineers.

Robert Rast (Senior Member, IEEE) is industry liaison for Micronas Semiconductors and chairman of the board of the Advanced Television Systems Committee, an international standards-setting body. In the 1990s, he was General Instrument's digital HDTV evangelist. When the Digital HDTV Grand Alliance formed in 1993, he became one of its leaders. More recently, he has been an executive at Dolby Laboratories and at two emerging digital technology companies, DemoGraFX and LINX Electronics.