Abstract

The emerging technologies of digital video and high-speed networks are combined together in a set-top box to provide a wide variety of value-added services to consumers. The control software in set-top boxes includes a real-time multi-tasking operating system with extensive multimedia support. Along with digital TV functionality, the control software provides an easy to use functional interface for set-top capabilities, such as MPEG decoding, high-speed broadband network interface, 2-way communications and graphics. An application-level software called the navigator performs basic TV functions and has the ability to download and execute interactive multimedia applications from network servers.

Keywords: digital set-top box, interactive TV, multimedia operating systems, video dial-tone networks, embedded software.

1. Introduction

In the fast changing world of home entertainment, the next revolution is being heralded by digital television. Digital televisions provide improved video and audio quality and open up opportunities for many interactive services. These value-added services are particularly appealing to consumers who want more than just additional channels of television programming. Interactive information service providers also see many new business opportunities with digital television.

The delivery of high-quality digital video to consumer homes requires considerable network bandwidth. Many different network media such as fibre, cable, satellite, broadcast and computer networks can be used to deliver digital video. Broadband video dial-tone networks with a hybrid fibre and coaxial medium are being planned across the world to offer high-bandwidth network
connections to homes. These networks will have the capacity for a large number of channels with television programming and many personalized interactive multimedia services [1,2]. The enabling technologies for interactive digital television are broadband networks and a common digital transport mechanism that can be used to simultaneously transport compressed video, audio and digital data. Video compression technology and lower memory prices have also played an important role in making interactive digital television a reality.

Many interactive services are being planned by service providers to use the broadband network for innovative multimedia applications, such as interactive games, home shopping, video telephony, movies on demand and interactive education. These applications require interactive digital set-top boxes and televisions to integrate many functions traditionally performed by computers. Interactive digital set-top boxes combine the video and audio decoding capabilities of televisions with a multimedia application execution environment.

The embedded software on interactive digital set-top boxes provides the flexibility to adapt a generic set-top box platform to specific network environments. The software component of digital set-top boxes and televisions is likely to increase in the future because of fewer but more programmable hardware components. Such flexibility can bring down manufacturing costs for digital set-top boxes and televisions and open up opportunities for value added custom applications.

This paper describes the operating system and application software required to manage the many different tasks that can be performed by an interactive digital set-top box. The operating system hides many of the hardware specific details of the set-top box and provides a clean functional interface to the set-top box’s capabilities [3]. The set-top box hardware needs to be managed efficiently so that applications executing on the set-top can simultaneously use many of its resources.

One of the main advantages of a digital set-top box is the capability to execute user-specific applications. Application development is greatly simplified by having an operating system because of the programming interface and library that is supported by the operating system. In a network with set-top boxes from multiple vendors, a uniform operating system is also essential to assure portability of applications across set-top boxes from different vendors.

Section 2 gives an overview of the video dial-tone network in which a digital set-top box operates. The different components of a video dial-tone network, the head-end equipment, level 1 & 2 gateways and the set-top box are described. Section 3 discusses the hardware architecture of a set-top box.
Set-top box control software

Section 4 describes the architecture of the digital set-top software in detail. The application programming interface and the operating system, including the kernel, device drivers, and file managers, are described in this section. Section 5 describes the default application of the set-top box that performs basic cable TV functions. This application also controls user access to the network and is used to download applications from network servers and execute them on the set-top box. The application programming interface and other applications resident on the set-top box are also discussed in this section.

2. Digital video networks

Delivering digital video requires a high-bandwidth channel from the content provider to a consumer's home. Cable networks have provided this capability with analogue systems for many years. These networks have traditionally provided a fixed programming content to the consumer using a primarily uni-directional network with a very limited polled back-path capability. Now, with the demand for individualized programming and interactive services there is a need for bi-directional networks with the help of which a user can communicate programming choices and interact with network server based applications.

Some cable networks have recently switched to compressed digital technology on the coaxial networks. This provides some flexibility in video delivery but is still inadequate for interactive services because of the limitations in the upstream data transport mechanism.

Satellite and terrestrial broadcast networks are also uni-directional and have the same problems with interactive services as analogue cable networks. These networks need to be augmented with a separate network that can be used to transport user requests to service providers.

The Internet [4] is a very wide area computer network that is well suited for bursty computer data but is not a good choice for digital video transport [5]. Digital video networks need to deliver a high bandwidth data stream into consumer homes and a low bandwidth communication layer for interaction between the set-top box user and the service provider [6,7].

2.1. Video dial-tone networks

There are two different architectures being advocated for digital video networks by two different industries. Analogue cable operators want to extend their uni-directional coaxial networks with a communication path from
subscriber homes to cable service gateways that can control the content being sent to the subscriber. Current video compression technology can also multiply the capacity of their analogue cable networks by a factor of 10 [8]. Cable networks were designed for broadcast services and will have to incorporate complex service gateways to provide point-to-point services such as video-on-demand.

Telephone companies are approaching digital video networks from a different direction. Current telephone networks already provide point-to-point communication and have the technology for the control and service gateways to manage wide-area switched star networks. The main problem with telephone networks is the bandwidth between the head-end equipment and the consumer's home.

Video dial-tone networks are being designed with a fibre-optic backbone with coaxial cable or fibre-optic cable to the home. Such a network with a packet-switched star topology can sustain high data rates required for digital video transport. Let us now consider the video dial-tone network architecture shown in Fig. 1. The video dial-tone network consists of two logical networks, a uni-directional broadband network (shown with thicker lines in Fig. 1) and a bi-directional signalling network (shown with thinner lines in Fig. 1). The broadband network is used to distribute video and audio programming as MPEG-2 transport packets over ATM (Asynchronous Transfer Mode) with AAL5 adaptation layer [9,10]. The signalling network is a low speed bi-directional X.25 [11] or TCP/IP network [12,13].
Bell Atlantic, a large telephone company in the United States, is currently deploying a video dial-tone network using equipment from many different vendors [14]. Philips is providing the set-top boxes for the network and Broadband Technology is providing the switching equipment for it. This video dial-tone network is capable of a 180 Mbps downstream channel and a 10Kbps upstream signalling channel to/from the set-top box. Part of the downstream channel capacity (135 Mbps) is allocated to three video channels and the remaining capacity (45 Mbps) is allocated to the downstream signalling channel. The fibre-optic network is terminated on the curb-side by an optical network unit that can support 8 such connections, or a total of 24 set-top boxes per optical network unit. The head-end equipment that is stationed in a neighbourhood can support 32 optical network units.

The digital set-top box (labelled STB in Fig. 1) is connected to the head-end equipment (Level 0 gateway). The broadcast cable programs are encoded using real-time encoders and presented as inputs to the head-end equipment. The Level 1 gateway serves as a network manager for the broadband and signalling networks [15]. It allocates bandwidth for video and audio connections between set-top boxes and video information providers based on service requests from set-top users. Packets of data with signalling information are also routed to their proper destinations by the Level 1 gateway. The Level 1 gateway provides directory services for video information providers that are clustered around Level 2 gateways. Video information providers are listed in a Level 1 gateway menu, which is displayed when a user connects to it. A user request to connect to a specific video information service is then validated by the Level 1 gateway, which allocates the required network resources for the service and then establishes virtual connections between the user’s set-top box and the video information service provider.

3. Hardware architecture

The digital set-top box is a customer premises equipment, which converts a normal NTSC or PAL television into a digital cable TV. The digital cable TV feed for the set-top box is provided through a coaxial cable connection from a Level 0 gateway. Video dial-tone services are also provided through the same physical connection.

The set-top box should be capable of decoding MPEG-2 video and audio which requires an MPEG sub-system in the architecture. It should also enable a user to download custom applications and execute them on the set-top box. This requires a general purpose microprocessor in the set-top box with an architecture that supports software control of the different devices.
The hardware architecture of a set-top box is shown in Fig. 2. Similar architectures have been proposed by different researchers for use in cable networks as well as video dial-tone networks [7,8,16,17].

The set-top described in this article is connected to the network through a communication module (also called a network interface module). This module is provided by Broadband Technologies for the Bell Atlantic video dial-tone network [14]. The communication module terminates the ATM network at the set-top end. It strips off the ATM/AAL5 headers [10] from the incoming broadband stream and provides a serial MPEG-2 transport stream [9] to the transport demultiplexer. It is also connected to the set-top system bus and can be controlled by the main microprocessor.

The set-top uses a Motorola 68341 as its main microprocessor. An external RS232 serial port and an auxiliary microprocessor are connected directly to the internal UART in the main microprocessor. The microprocessor also has 2MB of DRAM and 1MB of NVRAM on its system bus. Other devices on the system bus include a CD-i graphics processor with 1MB of DRAM, a transport demultiplexer with 32KB of SRAM and a PCMCIA port.

The auxiliary microprocessor (AUX) controls an infra-red remote control unit, a keypad on the front panel of the set-top box and a magnetic card reader. Using the AUX minimizes the numbers of I/O interrupts that need to be serviced by the main microprocessor and keeps it free to perform other
real-time tasks. The AUX also has 256 bytes of EEPROM storage available to store parameters across power cycles.

The transport demultiplexer ASIC (also known as the ANV AAL) demultiplexes the MPEG transport stream into audio, video, program-specific and private data streams. The DRAM controller for the system is built into the ANV AAL, which also provides a bridge to the MPEG sub-system.

The MPEG sub-system consists of MPEG audio and video decoders as well as encoders to provide NTSC and audio outputs for a television. This sub-system also has its own dedicated 'application bus' to feed MPEG elementary data from the ANV AAL. The audio and video decoders have 128KB and 2MB of DRAM, respectively, for their internal buffers. The NTSC encoder and the DAC convert the outputs of the video and audio decoders, respectively, for use by television sets. The NTSC encoder also serves as a mixer for video and graphics before being displayed on the television.

4. Interactive TV software architecture

The control software on the set-top box ties together all the hardware components into a functioning unit. An interactive digital set-top box is required to provide a user friendly interface to a video dial-tone network offering personalized multimedia services and regular cable TV service [8]. It should be capable of decoding video and audio, and provide simple graphics capability for on-screen displays.

For personalized interactive services, a set-top box should be addressable in the video dial-tone network, thus providing point-to-point communications between a video information provider and a user. It should also have the ability to download client applications and execute them locally.

As shown in Fig. 3, the set-top software has two parts, the system software that provides the DAVID application programming interface [18] and application software that provides cable TV functionality or some other personalized multimedia service. Section 5 describes the application software layer in detail.

The DAVID system software includes the operating system (OS-9) kernel, device drivers and file managers. The operating system kernel is responsible for scheduling different tasks for the microprocessor in the set-top box. The OS-9 kernel also manages inter-process communication between the different tasks and processes in the set-top box. It performs memory management for the multi-tasking operating system and maintains the real-time clock for the system.

The set-top box architecture consists of several components (Fig. 2), namely, a video decoder, an audio decoder, a CD-i graphics processor, a transport
demultiplexer, a network interface module, a serial port, a PCMCIA port and an auxiliary processor. These hardware components have programmable registers that can be used to control the behaviour of the component. Each one of these devices has a device driver task associated with it that allows the main microprocessor to manage the device. The device drivers also perform interrupt servicing for the components and hide the details about device addresses and actual register values. DAVID also includes a file manager for each device driver that has a 'file like' interface for the device. A file like interface provides a uniform layer of abstraction and is generic to all the capabilities of the set-top box. For example, a device can be initialized by an application by opening the file corresponding to the device, or an application can start video decoding by using a system call such as \texttt{mpeg\_play}. Figure 4 shows the different processes at the application and system layers.

Let us consider the RTNFM (real-time network file manager) [18] task which controls the transport demultiplexer device. This device is capable of demultiplexing an MPEG transport stream [9] into MPEG elementary streams for audio, video and private data. RTNFM includes a file manager and a device driver that provide access to data on a downstream broadband channel. Applications use system calls to capture data on the different streams using their packet identification number (PID) and are far removed from the specifics of the device.

The SPF (sequential packet file manager) task and its associated drivers control the set-top end of the bi-directional signalling channel. It is used to send user requests (e.g. channel changes) to the head-end equipment and receive replies from it that are passed on to applications. The transport driver
Set-top box control software

consists of send and receive engines that handle all transport protocol details such as message sequence numbers and lost or repeated messages. A lower level driver implements the network layer and sends (receives) data to (from) the network interface device.

The audio and video decoders in the set-top box are controlled by the MPFM (MPEG file manager) task. It uses RTNFM to set up the broadband audio and video data streams between the transport demultiplexer and the decoder devices. The SCF (sequential character file manager) task manages the RS232 serial port on the set-top box that can be connected to a terminal. It is also used to download data into the set-top through the serial port.

The CD-i graphics processor is managed by the UCM (user communication manager) task. This task generates the on-screen displays that are overlaid on the video. The AUXMAN (auxiliary processor file manager) controls the interface with the auxiliary microprocessor which in turn controls the remote control and the keypad. It also controls a small EEPROM bank that stores the system parameters across power cycles. The PCMCIA port on the set-top box is managed by its own driver called PCFM. This driver is dynamically configurable and expects a device-specific module to be loaded into the set-top box corresponding to the device connected to the PCMCIA port.

These tasks and the OS-9 kernel are together called the DAVID [18] application programming interface. DAVID specifies a set of functions and system calls that are available to application programs to use different capabilities of
the set-top box effectively. Application software developed for a DAVID compliant set-top box can be ported easily to all platforms that support DAVID or similar application programming interfaces.

5. Application software

From a user's perspective, the most important part of a set-top box is its user interface. A user would like to use the set-top box for many different services, e.g. cable TV, premium channels, video-on-demand and custom applications. The default application on the set-top, called the navigator, enables a user to access these services. In this section, we describe the navigator and other application software on the set-top box.

5.1. Interoperability

Interactive digital set-top boxes are being developed to operate in video dial-tone networks wherein many different vendors are co-developing different parts of the network. Interoperability between equipment and software is a big issue in such multi-vendor efforts which fosters the need for standards and well defined interfaces. ATM [10] and MPEG-2 [9] have been chosen as the data-link and video transport standards in most video dial-tone networks. Many standards bodies such as the ATM Forum and the Digital Audio-Visual Council (DAVIC) are finalizing other interfaces, e.g. the session signalling interface, the application programming interface. In the absence of a standard application programming interface, the DAVID application programming interface plays an important role in application software development for the set-top box. It is a proprietary interface [18] that has been widely adopted for many video dial-tone networks in the United States.
The navigator is the main DAVID application resident in the set-top box. Other custom DAVID applications can also be downloaded from video information providers for use by individual set-top users.

5.2. Navigator

The navigator is the primary user interface software on the set-top box. It is also called a 'player shell' because it encapsulates all the functionality of the set-top box and provides an abstract interface to users. The navigator processes the user commands to the set-top box and calls the appropriate file manager to perform the functions requested by the user.

The primary function of the navigator is to provide basic cable TV functionality (labelled 'CATV' in Fig. 4). The navigator maintains a list of channels available for viewing by the user and can service basic user requests for channel changes and volume control. Cable TV service requires the navigator to 'tune' to the requested channel. Depending on the type of network, this request can be serviced in the set-top box or the Level 0 gateway. The set-top box can choose one of the streams in a multiplexed data stream by assigning the correct virtual-circuit/virtual-program indicator (VCI/VPI) [10] to the network interface module or the correct packet identifier (PID) to the transport demultiplexer [9]. If the requested channel is not available to the set-top box then the channel change request needs to be passed on to the head-end equipment that can switch the requested channel to the set-top box. Once the correct data stream is available, the audio and video decoders are called to decode the data stream.

Another important function of the navigator is to display electronic program guides and menus that allow a user to make informed choices about which program to view. It can also be used to set viewing and recording alarms through a menu system.

As we have seen above, the navigator is a distributed application that can process some user commands locally and some commands have to be forwarded to the appropriate network element. Figure 5 depicts the interactions of the navigator with the Level 0 gateway. On boot-up, the navigator requests the SPF task to establish a link between the set-top box and the Level 0 gateway. After the low-level link has been established, several virtual circuits are created for the Level 0 gateway to communicate with the navigator and other resident applications. These circuits are then used to send messages between the applications and the Level 0 gateway.

5.3. Downloaded applications

The feature that distinguishes digital set-top boxes from analogue
television set. The ability to download custom applications from video information providers and execute them locally is a crucial feature. Such applications can transform a generic television set into a specialized information and entertainment terminal. Services like video-on-demand, home shopping, and virtual travel agency are enabled due to this capability of the set-top box.

A resident application, called LIGW, can be invoked by the navigator to establish connections to a Level 1 gateway server. This application is responsible for downloading and displaying a menu of services available through the specified Level 1 gateway. The Level 1 gateway serves as an access node for Level 2 gateways and provides a directory for services available from video information providers.

Once a video information provider is chosen by a user, a Level 2 application is downloaded into the set-top box and a virtual circuit with the required bandwidth is established between the downloaded application and the Level 2 gateway. This application is then invoked by the navigator to provide the requested service.

5.4. Operating system upgrade

The operating system on the set-top box can be upgraded to a new version by two mechanisms, using the PCMCIA port or through the network. The PCMCIA port supports battery powered memory (SRAM) cards that are directly addressable from the main microprocessor in the set-top box. A new version of the operating system is loaded into such a card on a development computer. The PCMCIA card is then plugged into the set-top box and the set-top is rebooted. During boot-up, the PCMCIA card
is checked for a new version of the operating system. If it is found to contain a valid operating system then the new operating system is programmed into the NVRAM on the set-top. The program that modifies the NVRAM contents is located in memory outside the NVRAM. The set-top is rebooted after the upgrade.

The operating system on the set-top box can also be upgraded through the network on user request or automatically on a periodic basis. The UPGR application downloads a new version of the operating system by tuning to a diagnostic channel that carries the operating system as MPEG-2 private data [9]. Network operating system upgrade is performed in two stages. First, all the packets corresponding to a complete operating system are captured by the UPGR application and the operating system is extracted from the packets. Then, the new operating system is programmed onto the NVRAM using the same method as the PCMCIA operating system upgrade.

5.5. Other resident applications

There are a few other resident applications in the set-top box that perform specific services. The user configurable addresses and parameters in the set-top box are modified using the config application. This application allows a user to set-up the network address of the set-top box and select preferred service providers. The config application can also be used to request an upgrade of the operating system on the set-top box and to set program alarms like a VCR.

The display process is responsible for interpreting VT100 messages from other applications and calling the UCM file manager to display them on the TV screen. Emergency broadcast messages from a Level 0 gateway are handled by an EBS application that overlays the emergency message on the TV.

The digital set-top box supports simple low-bandwidth text messaging between an interactive text server and a user via overlay on specified broadcast channels. This user initiated service can be used to solicit user responses to programmes such as game shows and advertisements. The IAT application provides the user interface for this service.

6. Conclusions

Digital video networks are poised to play a major role in shaping the future of information and entertainment services. Interactive digital set-top boxes bring the services provided by these networks to the user's home. The embedded control software within the set-top box provides the flexibility to
adapt a generic set-top box architecture to the requirements of a specific network. The set-top software also has a modular design so that it can be used in a new network environment by changing the protocol and interface modules without having to design and manufacture a new set-top box. The control software also hides the machine and network specific features of a set-top box under a layer of abstraction and provides a user-friendly interface to access cable television and video information services.

In the future, the software component in set-top boxes is likely to increase with more integration and more programmable components. These changes will also increase the flexibility of set-top boxes because it will be possible to move a set-top across networks and download a new version of the control software for the programmable components for use in the new environment. The finalization of standards for the various protocols and interfaces in digital video networks will foster interoperability which is important for the success of such products.

Value-added software and services for the set-top environment have a big potential for growth in the future. Such services include video-on-demand, video conferencing, home shopping, virtual travel agencies and remote banking services. Today, users are willing to pay for such services over the Internet [4] even though the Internet is not capable of providing real-time multimedia services. The multimedia capabilities of a set-top box are far superior to that of an average home computer and that will unleash a new generation of value-added applications.

REFERENCES

Set-top box control software


Authors

**Kamlesh Rath** is a Senior Member of Research Staff at Philips Laboratories, Briarcliff Manor, NY, USA. He got his PhD in Computer Science from Indiana University in 1995. His research interests are in multimedia operating systems, digital video networks, embedded system design and hardware software codesign. He is currently involved in developing COMPASS, the COMmon Philips Architecture for Scalable Set-Top System Software.

**James Wendorf** is Research Department Head, Software Systems and Architecture, at Philips Laboratories, Briarcliff Manor, NY, USA. He obtained his PhD in Computer Science from Carnegie Mellon University in 1987, in the areas of operating systems, real-time systems, and computer architectures. Since joining Philips in 1987 he has worked on multiprocessor operating systems, including porting the Mach operating system to the Philips Research DOOM/POOL machine, television control systems, including the development of a PC controllable TV, and most recently the control software for interactive digital TV receivers. Jim currently leads the Set-Top Software group that was responsible for developing the control software for the Bell Atlantic Digital Entertainment Terminal product, and is currently developing COMPASS, the COMmon Philips Architecture for Scalable Set-Top System Software, in close cooperation with the product divisions.