Digital Signal Processing in Home Entertainment

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Abstract In the last decade or so, audio and video media switched from analog to digital and so did consumer electronics. In this chapter we explore how digital signal processing has affected the creation, distribution, and consumption of digital media in the home. By using "photos", "music", and "video" as the three core media of home entertainment, we explore how advances in digital signal processing, such as audio and video compression schemes, have affected the various steps in the digital photo, music, and video pipelines. The emphasis in this chapter is more on demonstrating how applications in the digital home drive and apply state-of-the art methods for the design and implementation of signal processing systems, rather than describing in detail any of the underlying algorithms or architectures, which we expect to be covered in more detail in other chapters. We also explore how media can be shared in the home, and provide a short review the principles of the DLNA stack. We conclude with a discussion on digital rights management (DRM) and a short overview of the Microsoft Windows DRM.

1 Introduction

Only a few years ago, the most complex electronic devices in the home were probably the radio and the television, all built using traditional analog electronic components such as transistors, resistors, and capacitors. However, in the late 1990s we witnessed a major change in home entertainment. Media began to go digital and so did consumer electronics, like cameras, music players, and TVs. Today, a typical home may have more than a half-dozen electronic devices, built using both traditional electronic components and sophisticated microprocessors or digital signal processors. This chapter will try to showcase how digital signal processing

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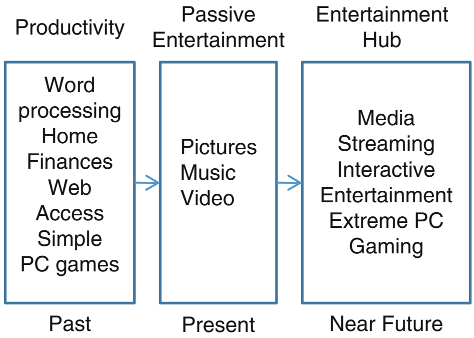


Fig. 1 The evolution of the home PC

(DSP) has affected the creation, distribution, and consumption of digital media in the home. We will use "photos", "music", and "video" as the three core media of home entertainment. The emphasis in this chapter is more on demonstrating how applications in the digital home drive and apply state-of-the art methods for the design and implementation of signal processing systems, rather than describing in detail any of the underlying algorithms or architectures. We expect these details to be exciting topics of future chapters in this book. For example, while we discuss the need for efficient image and video compression in the home, there is no plan to explain the details of either the JPEG or MPEG compression standards in this chapter.

1.1 The Personal Computer and the Digital Home

There are many contributing factors for the transition from analog to digital home entertainment, including advances in semiconductors, DSP theory, and communications. For example, submicron technologies allowed more powerful and cheaper processors. New developments in coding and communications led the way to new standards for the efficient coding and transmission of photos, videos, and audio. Finally, an ever-growing world-wide Web offered new alternatives for the distribution and sharing of digital content. One may debate which device in the home is the center of home entertainment—the personal computer (PC), the TV, and the set-top box, are all competing for the title—however, nobody can dispute the effects of the PC in the world of digital entertainment.

Figure 1 shows the functional evolution of the home PC. In the early days, a PC was used mostly for such tasks as word processing, home finances, Web access, and playing simple PC games. Today, PCs are also the main interfaces to digital cameras and portable music players, and are being used for passive entertainment, such as listening to Internet radio and watching Internet videos. However, the integration of media server capabilities allows now a PC to also become an entertainment hub. Windows Media Player 11 (WMP11), Tiversity, and other popular media server applications allow now users to stream pictures, music, and videos, from any PC to a new generation of devices called digital media receivers (DMRs). DMRs integrate wired and wireless networking and powerful processors to play HD content in real time. An example of DMRs includes connected-TVs and gaming devices, such as the Xbox360 or the PlayStation 3. Many DMRs can also operate as Extenders for Windows Media Center, which allows users to access remotely any PC with Windows Media Center. This service allows users to interact with their PCs at both the four feet level (personal computing using a keyboard and a mouse) and the ten feet level (personal entertainment using a remote control).

This PC evolution has changed completely the way consumer-electronics (CE) manufacturers design new devices for the home. Instead of designing isolated islands of entertainment, they now design devices that can be interconnected and share media over the home network or the Internet. In the next few sections we will examine in more details the processing pipelines for photos, music, and videos, the Digital Living Network Alliance (DLNA) interoperability standard for content sharing in the home, and digital rights management issues, and how all these together influence the design and implementation of future signal processing systems.

2 The Digital Photo Pipeline

If you ask people what non-living item they would try to rescue from a burning home, the most common answer will be "our photos". Photos touch people like very view other items in a home. They provide a visual archive of a family's past and present, memories most of us would like to preserve for the future generations as well.

Figure 2 shows the photo pipelines for both an analog (film-based) and a digital camera. In the past, taking photos was a relatively simple process. As shown in Fig. 2a, you took photos using a traditional film camera, you gave the film for developing, and you received a set of either prints or slides. In most cases, you would store your best pictures in a photo album and the rest in a shoe box. Unless you were a professional photographer, you had very little influence on how your printed pictures would look. Digital photography changed all that. Figure 2b shows a typical digital photo processing pipeline, and as we are going to see, digital signal processing is now part of every stage.

2.1 Image Capture and Compression

Using a digital camera, digital signal processing begins with image capture. A new generation of integrated camera processors and DSP algorithms make sure that captured raw sensor data are translated to color-corrected image data that can be

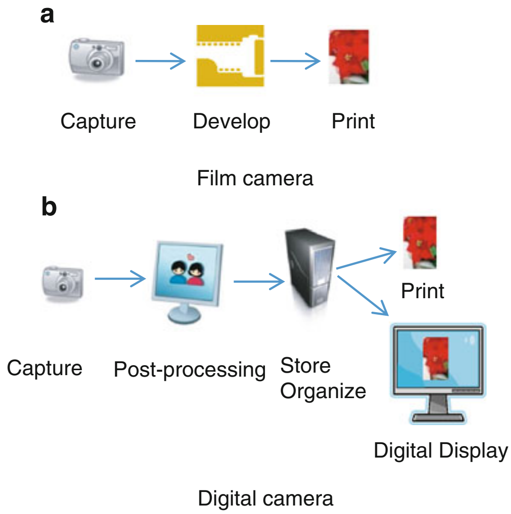


Fig. 2 Photo processing pipeline

stored either in raw pixels or as compressed images. Inside the camera, the following image processing algorithms are usually involved:

2.1.1 Focus and Exposure Control

Based on the content of the scene, camera controls determine the aperture size, the shutter speed, the automatic gain control, and the focal position of the lens.

2.1.2 Pre-Processing of CCD Data

In this step, the camera processor removes noise and other artifacts to produce an accurate representation of the captured scene.

2.1.3 White Balance

The goal of this step is to remove unwanted color casts from the image and colors that are perceived as "white" by the human visual system are rendered as white colors in the photo as well.

2.1.4 Demosaicing

Most digital cameras have a single sensor, which is overlaid with a color filter array (CFA). For example, a CFA with a Bayer pattern alternates red and green filters for odd rows with green and blue filters for odd rows. During demosaicing the camera uses interpolation algorithms to reconstruct a full-color image from the incomplete color samples.

2.1.5 Color Transformations

Color transformations transform color data from the sensor's color space to one that betters matches the colors perceived by the human visual system, such as CIE XYZ.

2.1.6 Post Processing

Demosaicing and color transformations may introduce color artifacts that are usually removed during this phase. In addition, a camera may also perform edge enhancement and other post-processing algorithms that improve picture quality.

2.1.7 Preview Display

The camera scales the captured image and renders it in a manner suitable to be previewed on the camera's preview display.

2.1.8 Compression and Storage

The image is finally compressed and stored in the camera's storage medium, such as flash memory. Compression is defined as the process of reducing the size of the digital representation of a signal and is an inherent operation in every digital camera. Consider a typical 8 Mega pixel image. Assuming 24-bits per pixel, un-compressed, such an image will take about 24 MB. In contrast, a compressed version of the same picture can take less than 1.2 MB in space, with no loss in perceptual quality. This difference means that if your camera has 500 MB of storage you can either store about 20 uncompressed pictures or about 400 compressed ones. In 1991, JPEG was introduced as an international standard for the coding of digital images, and remains among the most popular image-compression schemes.

2.2 Photo Post-Processing

The ability to have access to the raw bits of a picture allowed users for the first time to manipulate and post-process their pictures. Even the simplest of photo processing software allows users to perform a number of image processing operations, such as:

- Crop, rotate, and resize images
- Automatically fix brightness and contrast
- Remove red-eye
- Adjust color and light
- Do special effects, or perform other sophisticated image processing algorithms

While early versions of image processing software depended heavily on user input, for example, a user had to select the eye area before doing red-eye removal, newer tools may use automatic face recognition algorithms and require minimal user interaction.

2.3 Storage and Search

Digital pictures can be stored in a variety of media, including CD-ROMs, DVDs, PC hard drives, or network-attached storage (NAS) devices, both at home or on remote backup servers. These digital libraries not only provide a better alternative to shoe boxes, but also allow users to use new algorithms for the easy storage, organization, and retrieval of their photos. For example, new face recognition algorithms allow users to retrieve all photos that include "John" with a click of a button, instead of pouring through all the family albums. Similarly, photos can be automatically organized according to a variety of metadata, such as date, time, or even (GPS-based) location.

2.4 Digital Display

Low-cost digital printers allow now for at home print-on-demand services, but photo display is not constrained any more by the covers of a photo album or the borders of the traditional photo frame. PCs, digital frames, and digital media receivers, like the Apple TV or the xbox360, allow users to display their photos into a variety of devices, including wall-mounted LCD monitors, digital frames, or even HDTVs. Display algorithms allow users to create custom slide shows with sophisticated transition effects that include rotations, zooming, blending and panning. For example, many display devices support now "Ken Burns effects," a combination of display algorithms that combine slow zooming with panning, fading, and smooth transitions, similar to effects Ken Burns is using in his documentaries.

All in all, the model digital photo pipeline integrates a variety of sophisticated digital image processing algorithms, from the time you take a picture all the way to the time you may display them on your HDTV.

3 The Digital Music Pipeline

Music is the oldest form of home entertainment but in the last few years, thanks to digital signal processing, we have seen dramatic changes on how we acquire and consume music.

In 1980, Philips and Sony introduced the first commercial audio CD and opened a new world of digital audio recordings and entertainment. Audio CDs offered clear sound, random access to audio tracks, and more than 60 min of continuous audio playback, so they quickly dominated the music market. But that was only the beginning. By mid-1990s audio compression and the popular MP3 format allowed for a new generation of players and music distribution services.

Figure 3 shows a simplified view of the digital music processing pipeline from a master recording to a player. As in the digital photo pipeline, digital signal processing is part of every stage.

3.1 Compression

In most cases, music post-production processing begins with compression. Hardcore audiophiles will usually select a lossless audio compression scheme, which

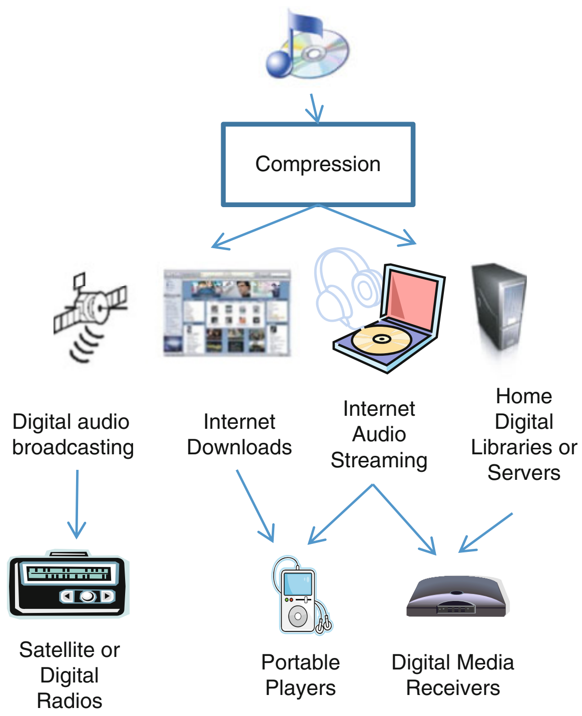


Fig. 3 Music processing pipeline

allows for the exact reconstruction of the original data. Examples of lossless audio codecs include WMA lossless, Meridian lossless (used in the DVD-Audio format), or FLAC (Free Lossless Audio Codec), to name just a few. However, in most cases, audio is being compressed using a lossy audio codec, such as MPEG-audio Layer III, also known as MP3, or the Advanced Audio Codec (AAC). Compared to the 1.4 Mbits/s bit rate from a stereo CD, compression allows for CD-quality music at about 128 kbits/s per audio channel. Music codecs achieve these levels of compression by taking into consideration both the characteristics of the audio signal and the human auditory perception system.

3.2 Broadcast Radio

While AM/FM radios are still part of almost every household, they are complemented by other sources of broadcasted music to the home, including Satellite radio, HD Radio, and streamed Internet radio.

Digital Audio Broadcasting (DAB), a European standard developed under the Eureka program, is being used in several countries in Europe, Canada, and Asia, and can use both MPEG-audio Layer II and AAC audio codecs. In North America, Sirius Satellite and XM Satellite Radio started offering subscription-based radio services in 2002.

In the United States, in 2002 the Federal Communications Commission (FCC) selected the "HD Radio" from iBiquity Digital Corporation as the method for digital terrestrial broadcasting for off-the-air AM or FM programming. Unlike DAB, HD Radio does not require any additional bandwidth or new channels. It uses In-band On-Channel (IBOC) technology, which allows the simultaneous transmission of analog and digital broadcasts using the same bandwidth as existing AM/FM stations. HD Radio is a trademark of iBiquity Digital Corporation, which develops all HD Radio transmitters and licenses HD Radio receiver technology. HD Radio is officially known as the NRSC-5 specification. Unlike DAB, NRSC-5 does not specify the audio codec. Today HD Radio uses a proprietary audio codec developed by iBiquity.

In 1995, Real Networks introduced the RealAudio player and we entered the world of Internet-based radio. Today, Internet audio streaming is an integral part of any media player and allows users to access thousands of radio stations around the world.

3.3 Audio Processing

Access to digital music allowed not only a new generation of music services, like the iTunes store from Apple Inc., but also created new opportunities for new tools for the storage, processing, organization, and distribution of music inside the home.

Digital media servers allow us to store and organize our whole music collections like never before. Metadata in the audio files allows us to organize and view music files by genre, artist, album, and multiple other categories. In addition, new audio tools allow us to edit, mix, and create new audio tracks with the simplicity of “cut” and “paste.” But what if a track has no metadata? What if you just listened to a song and you would like to know more about it? New audio processing algorithms can use “digital signatures” in each song to automatically recognize a song while it is being played (see for example the Shazam service). Similar tools can automatically extract tempo and other music characteristics from a song or a selection of songs and automatically create a playlists with similar songs. For example, the “Genius” tool in Apple’s iTunes can automatically generate a playlist from a user’s library based on a single song selection.

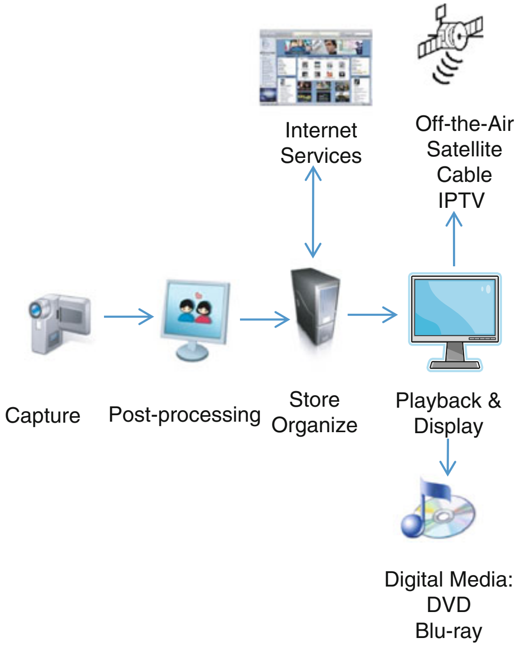
4 The Digital Video Pipeline

We have already discussed the importance of efficient coding in both the digital photo and music pipelines. Therefore, it will not come as a surprise that compression plays a key role in digital video entertainment as well. As early as 1988, the International Standards Organization (ISO) established the Moving Pictures Expert group (MPEG) with the mission to develop standards for the coded representation of moving pictures and associated audio. Since then, MPEG delivered a variety of video coding standards, including MPEG-1, MPEG-2, MPEG-4 (part 2), and more recently MPEG-4, part 10, or H.264. These standards opened the way to a variety of new digital media, including the VCD, the DVD, and more recently HDTV, HD-DVD and Blu-ray. However, compression is only a small part of the video processing pipeline in home entertainment. From Fig. 4, the home can receive digital video content from a variety of sources, including digital video broadcasting, portable digital storage media, and portable video capture devices.

4.1 Digital Video Broadcasting

As of June of 2009, in the United States, all television stations are required to broadcast only in digital format. In the next few years, similar transitions from analog to digital TV broadcasting will continue in countries all over the world. In addition to these changes, new Internet Protocol Television (IPTV) providers continue to challenge and get more market share from the traditional cable and satellite providers. Digital video broadcasting led to new developments in coding and communications and allowed a more efficient use of the communication spectrum. In addition, it influenced a new generation of set-top boxes and HDTVs with advanced video processing, personal video recording capabilities, and Internet connectivity.

Fig. 4 Digital video processing pipeline



4.2 New Portable Digital Media

It is not a surprise that the DVD player is considered by many the most successful product in the history of consumer electronics. By providing excellent video quality, random access to video recordings, and multi-channel audio, it allowed consumers to experience movies in the home like never before. DVD movies combine MPEG-2 video with Dolby Digital audio compression; however, a DVD is more than a collection of MPEG-coded files. Digital video and audio algorithms are being used in the whole DVD-creation pipeline, inside digital video cameras, in the editing room for the creation of special effects and post processing, and finally in the DVD authoring house, where bit rate-control algorithms apply rate-distortion principles to preserve the best video quality while using the minimum amount of bits. As we transition from standard definition to high definition, these challenges become even greater and the development of new digital signal processing algorithms and architectures is more important than ever. For example, the Blu-Ray specification not only allows for new coding schemes for high-definition video, but also provides advanced interactivity through Java-based programming and “BD Live.”

4.3 Digital Video Recording

In 1999, Replay TV and Tivo launched the first digital video recorders or DVRs and changed forever the way people watch TV. DVRs offered far more than the

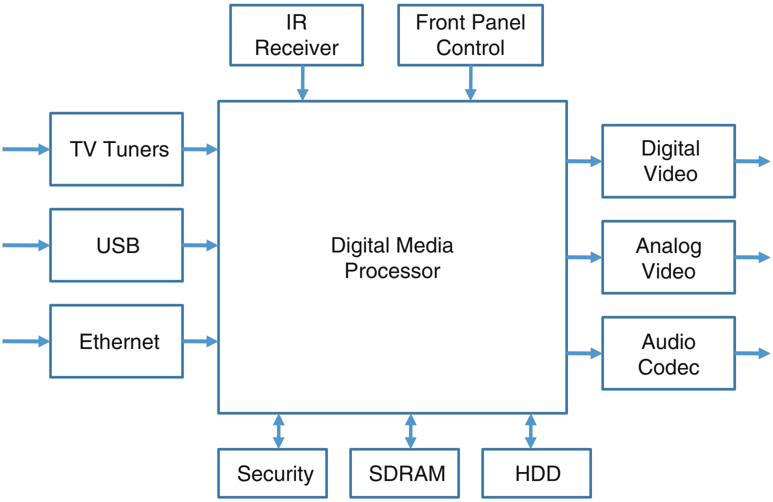


Fig. 5 Block diagram of a typical DVR

traditional "time shifting" feature of a VCR. Hard disk drive-based recordings allowed numerous other features, including random access to recordings, instant replay, and commercial skip. More recently DVRs became complete entertainment centers with access to the Internet for remote access and Internet-based video streaming. In addition, USB-based ports allow users to connect personal media for instant access to their personal photos, music, and videos. Like modern Blu-ray players, DVRs integrate advanced digital media processors that allow for enhanced video processing and control.

Figure 5 shows the simplified block diagram of a typical DVR. At the core of the DVR is a digital media processor that can perform multiple operations, including:

- Interfaces with all the DVR peripherals, such as the IR controller and the hard disk drive,
- For digital video, it extracts a Program Stream from the input Transport Stream and either stores it in the HDD or decodes it and passes it to the output,
- For analog video, it passes it through to the output or compresses it and stores it in the HDD,
- Performs all DVR controls, communicates with the service provider to update the TV Guide, maintains the recording schedules, and performs all playback trick modes (such as, pause, fast forward, reverse play, and skip), and
- Performs multiple digital video and image-related operations, such as scaling and deinterlacing.

In addition to the media processor, a DVR includes at least one TV tuner, Infrared (IR) and/or RF interfaces for the remote control, a front panel control, security-related controls, such as Smart Card or CableCard interfaces, and audio and video output interfaces. DVRs may also include additional interfaces, including USB and Ethernet ports, so they can play media from external devices or for adding external peripherals, such as an external hard disk drive.

4.4 Digital Video Processing

Comparing Figs. 2 and 4, we see that the digital video processing pipeline for personal camcorders is not that much different from the digital camera pipeline. After video capture using a CCD, video processing algorithms take the raw censor data, color correct them, and translate them in real-time to a compressed digital video bit stream. Alternatively, one can use any PC-based video capture card to capture and translate any analog video signal to digital. Regardless of the input, PC-based video editing tools allow us to apply a variety of post-processing imaging algorithms to the videos and create custom videos in a variety of formats. User videos can be stored either on DVDs or NAS-based media libraries. In addition, many users upload their videos into social networking sites, where videos are automatically transcoded to formats suitable for video streaming over the Internet, such as Adobe's Flash video or H.264. Modern video servers allow for the seamless integration of video with Internet content, allowing users to search within video clips using either metadata or by automatically extracting data from the associated audio and video data.

4.5 Digital Video Playback and Display

Every video eventually needs to be displayed on a screen, and modern High-definition monitors or TVs were never more sophisticated than now. Starting from their input ports, they need to interface with a variety of analog and digital ports; from the traditional RF input to DVI or HDMI. Sophisticated deinterlacing, motion compensation, and scaling algorithms are able to take any input, at any resolution, and convert it to the TV's native resolution. For example, more recently, 100/120 Hz HDTVs need to apply advanced motion estimation and interpolation techniques to interpolate traditional 50/60 Hz video sequences to their higher frame rate. LED-based LCD displays use also advanced algorithms to adjust the LED backlight according to the input video for the best possible dynamic contrast.

In summary, digital signal processing is involved in every aspect of the capture, post-processing, and playback of photos, music, and videos, but that's only the beginning. In the next section we will examine how our digital media can be shared anywhere in our home, using existing coding and communication technologies.

5 Sharing Digital Media in the Home

In the previous sections we discussed how digital signal processing is associated with almost every aspect of the digital entertainment in the home. In most homes we see multiple islands of entertainment. For example, the living room may be one such island with a TV, a set-top box, a DVD player, and a gaming platform. The office may be another island with a PC and a NAS. In other rooms we may find a laptop or a second PC or even additional TVs. In addition, each family may have a variety of mobiles or smart phones, a camera, and a camcorder. Each of these islands is able to create, store, or playback content. Ideally, consumers would like to share media from any of these devices with any other device. For example, say you download a movie from the Internet on a PC but you really want to view it on the big TV in the living room, wouldn't be nice to be able to stream that movie from the PC in the office to your TV via your home network? You definitely can, and the role of the Digital Living Network Alliance (DLNA) is to make this as easy as possible.

5.1 DLNA

DLNA is a cross-industry association that was established in 2003 and includes now more than 250 companies from consumer electronics, the computer industry, and mobile device companies. The vision of DLNA is to create a wired or wireless interoperable network where digital content, such as photos, music, and videos can be shared by all home-entertainment devices.

Figure 6 shows the DLNA interoperability stack for audio-visual devices. From Fig. 6, DLNA uses established standards, such as IEEE 802.11 for wireless networking, HTTP for media transport, universal plug and play (UPnP) for device discovery and control, and standard media formats, such as JPEG and MPEG for digital media. DLNA defines more than 10 device classes, but for the purposes of this discussion we will only cover the two key classes: digital media server and digital media player.

5.2 Digital Media Server

A digital media server is any device that can acquire, record, store, and stream digital media to digital media players. Examples include PCs, advanced set-top boxes, music or video servers, and NAS devices.

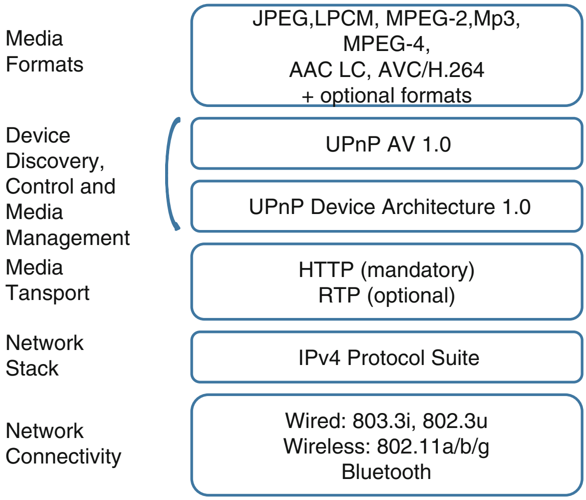


Fig. 6 DLNA audio–video interoperability stack

5.3 *Digital Media Player*

Digital media players (also known as digital media receivers) find content on digital media servers and provide playback capabilities. Figure 7 shows a typical interaction between a DLNA client and a DLNA server. The devices use HTTP for media transport and may also include a local user interface for setup and control. Examples of digital media players include connected TVs and game consoles. Today, digital media players combine wired and wireless connectivity and a powerful digital signal processor. However, despite the efforts of the standardization committees to establish standards for the coding of pictures, audio, and video, this did not stop the proliferation of other coding formats. For example, just for video, the coding alphabet soup for audio/video codecs includes DivX, xvid, Real Video, Windows Media Video (WMV), Adobe Flash video, and Matroska video, to name just a few. This proliferation of coding formats is a major challenge for consumer electronics manufacturers who strive to provide their customers a seamless experience. However, while it is rather easy to upload a new codec on a PC, this may not be the case for a set-top box, a DMR, or a mobile client. While manufacturers work on the next generation of multi-format players, it is not uncommon to see now PC-based media transcoders. These transcoders interact with media servers and allow for on-the-fly transcoding of any media format to the most commonly used formats, like MPEG-2 or WMV.

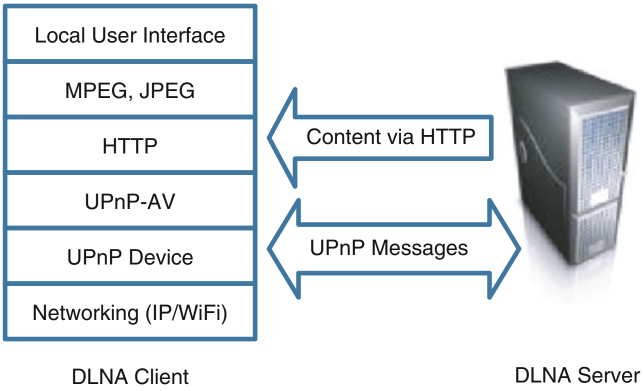


Fig. 7 Typical DLNA client–server interaction

6 Copy Protection and DRM

The digital distribution of media content opened new opportunities to consumers but also created a digital rights management nightmare for content creators and copyright holders. The Serial Copy Management System (SCMS) was one of the first schemes that attempted to control the number of second-generation digital copies one could make from a master copy. For example, while one can make a copy from an original CD, a special SCMS flag in the copy may indicate that one cannot make a copy of a copy. SCMS does not stopping you making unlimited copies from the original, but you cannot make a copy of the copy. SCMS was first introduced in digital audio tapes, but it is also available in audio CDs and other digital media. CSS (content scrambling system) is another copy protection scheme, used by almost every commercially available DVD-Video disc and controls the digital copying and playback of DVDs.

DRM or digital rights management refers to technologies that control how digital media can be consumed. While, Fairplay from Apple Inc. and Windows DRM from Microsoft are the most commonly used DRM schemes, the development of alternative copy protection and DRM schemes is always an active area of research and development in digital signal processing.

6.1 Microsoft Windows DRM

Microsoft provides two popular DRM kits; one for portable devices and one for networked devices.

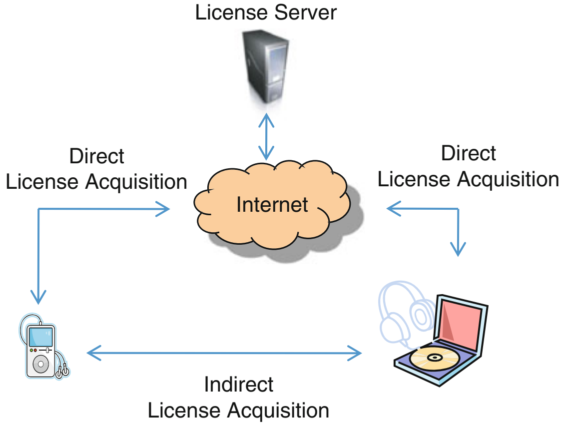


Fig. 8 License acquisition for portable devices

Figure 8 shows that under Windows Media DRM portable devices can acquire licenses either directly from a license server through an Internet connection, or indirectly, from a local media server (for example a user's computer).

Figure 9 shows license acquisition scenarios when two devices support the Windows Media DRM for Network devices. In this scenario, in addition to the basic DLNA stack, the digital media receiver integrates the Windows Media DRM layer (WMDRM) and has also the capability to play Windows Media Video (WMV) content.

Using Windows Media DRM for network devices, the two devices exchange keys and data as follows:

- The first time a device is used it must be registered and authorized by the server through UPnP. A special certificate identifies the device and contains information used to ensure secure communication.
- During the initial registration, the server performs a proximity detection to verify that it is close enough to be considered inside the home.
- Periodically, the server repeats the proximity detection to revalidate the device.
- The device requests content for playback from the server.
- If the server determines that the device is validated and has the right to play the content, it sends a response containing a new, encrypted session key, a rights policy statement specifying the security restrictions that the device must enforce, and finally the content. The content is encrypted by the session key. Each time content is requested, a new session is established.
- The network device must parse the rights policy and determine if it can adhere to the required rights. If it can, it may render the content.

As digital content is shared among multiple devices, most made by different manufacturers, an open DRM standard or DRM-free content seem to be the only ways to achieve inter-operability.

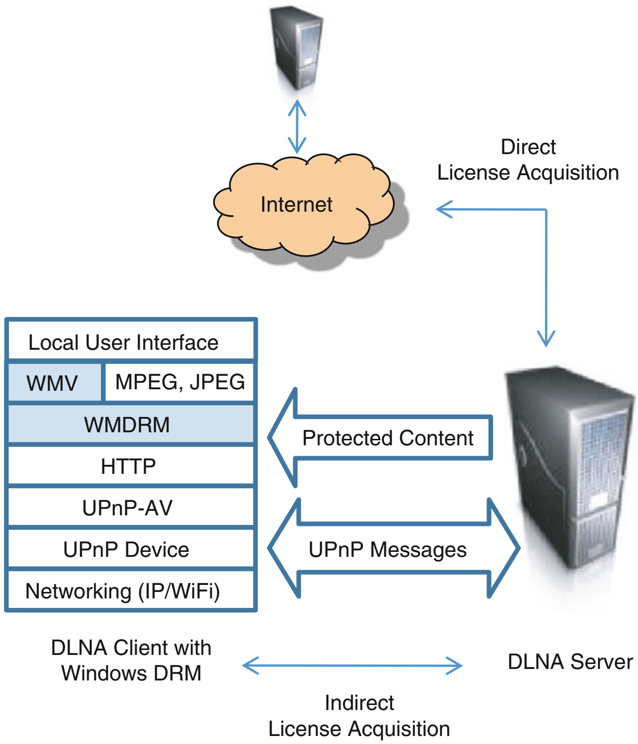


Fig. 9 License acquisition and data transfer for networked devices

7 Summary and Conclusions

The home entertainment ecosystem is transitioning from isolated analog devices into a network of interconnected digital devices. Driven by new developments in semiconductors, coding and digital communications, these devices can share photos, music, and videos using a home network, enhance the user experience, and continue to drive the development of new digital signal processing algorithms and architectures.

8 To Probe Further

A good overview of the digital camera processing pipeline is given by [16]. An overview of image and video compression standards, covering both theory and architectures, including the JPEG [7], MPEG-1 [8], MPEG-2 [9], AAC [10], and MPEG-4 [6] standards, can be found in [2]. The H.264 standard, also known as

MPEG-4, part 10, is defined in [11]. Other chapters of this Handbook [3, 13] provide additional details on video coding. The DAB specification can be found in [5]. In [12], Maxson provides a very thorough description of the NRSC-5 specification [15] for HD radio transmission. For more information about DLNA, DLNA's web site, www.dlna.org, provides excellent information and tutorials. A nice overview of DLNA can also be found in a white paper on UPnP and DLNA by [1]. Most of the material on Windows DRM is from an excellent description of Microsoft's DRM by [4]. More details about Microsoft's Extenders for Windows Media Center can be found in Microsoft's Windows site [14].

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