PATHPARTNER

HDR Technical Paper

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1. Introduction

Ultra-High-Definition ('Ultra-HD' or 'UHD') represents the next big step in the evolution of video recording, processing, and display technology. It is the logical successor to HD and offers marked improvements over current video technologies[9]. UHD video offers immersive viewing experience with enhanced video characteristics as shown in Figure 1-1.

- Picture resolution: The greater the number of pixels, the greater the level of detail we are able to draw out. Higher spatial resolution was the first promoted feature of UHDTV. A UHD TV's native resolution will be 3840x2160 pixels.
- Higher frame rate: With high motion content, such as many sports and some nature documentaries, the standard frame rate of conventional TV systems is not high enough, resulting in a stuttering or strobing effect in the motion. New UHD standards increase the frame rate from 50 or 60 fps to 100/120 fps resulting in smoother motion.
- Higher Dynamic Range (striking contrast) and Wide Color Gamut (much greater range of colors) with Higher bit depth of pixels.

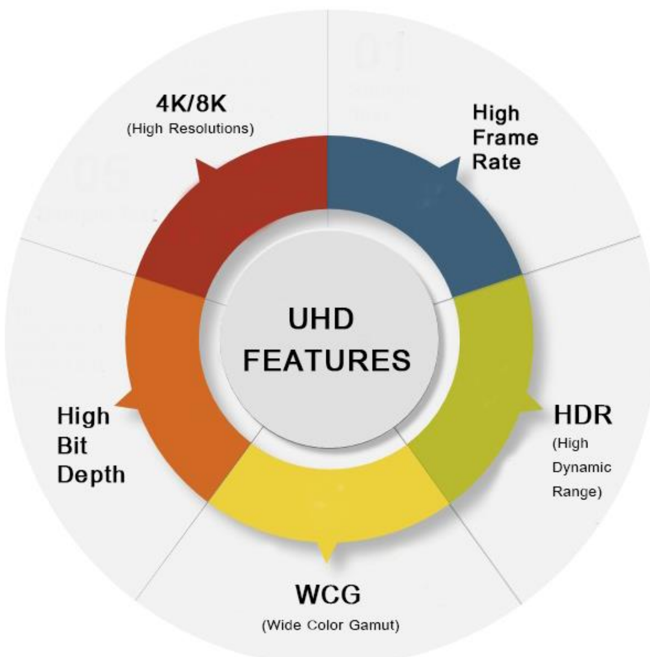

Figure 1-1 UHD Features

2. What is HDR

Increased picture resolution and higher frame rate are the key features of UHD but these features alone are not enough to make each pixel able to better represent the full range of brightness we see in reality. They alone cannot increase perceived quality to justify initiating a new broadcast service. And also the picture resolution improvement over HDTV could be less pronounced in a home environment, due to the limitations of human visual acuity, screen size, and home viewing distances. All these issues are addressed by the HDR technology which is a combination of High Dynamic Range, Wide Color Gamut and Higher Bit-depth (10/12-bit sampling). HDR components[10] are shown in Figure 2-1. HDR improves the pixels and enables viewer to see a more realistic image and have an immersive visual experience.

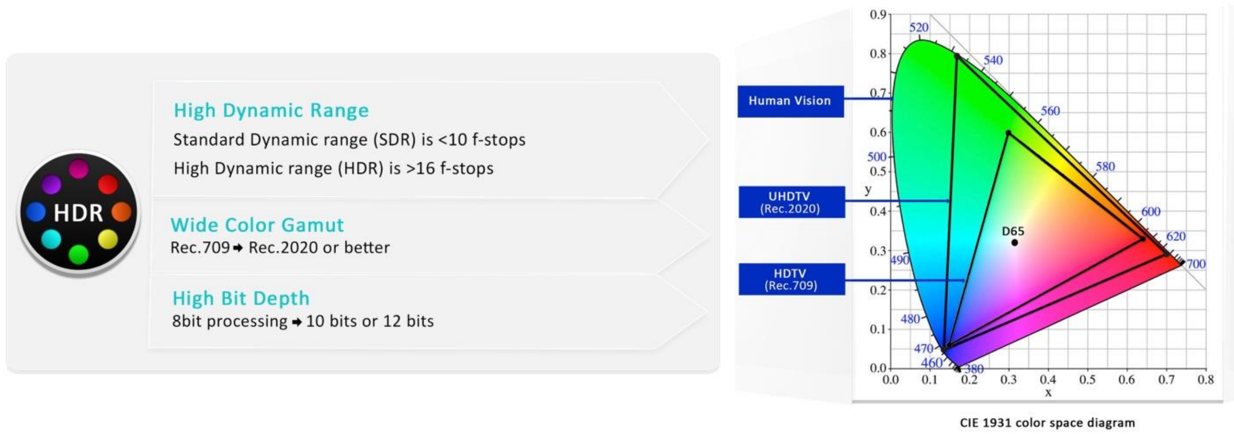

Figure 2-1 Component of HDR technology

HDR brings life to natural scenes, with vivid colors, it enables higher contrast in the scenes which allow better artistic representations and of course it enables visible content even under challenging lighting conditions. A few scenarios where HDR is required[11] are shown in Figure 2-2.

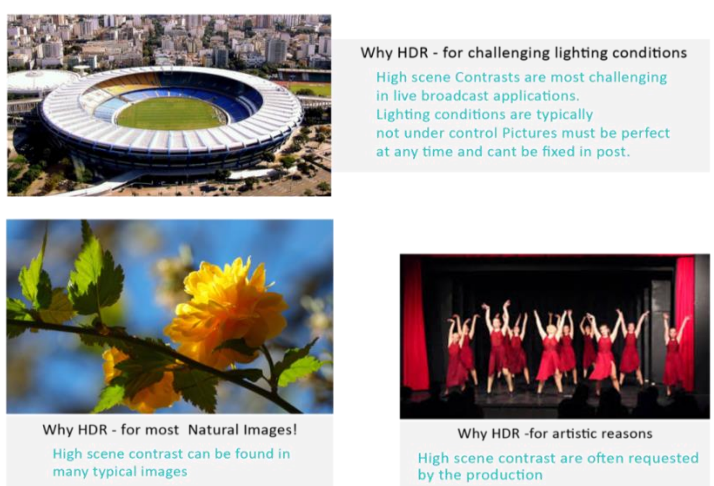

Figure 2-2 Need of HDR

2.1. High Dynamic Range (HDR)

High Dynamic Range is the capability to represent a large luminance variation in the video signal, i.e., from very dark values (less than 0.01 cd/m^2) to very bright values (greater than 1000 cd/m^2). Human eye can adapt to an enormous range of light intensity levels. It can detect a luminance range of 10^{14} (about 46.5 f-stops), from 10^{-6} cd/m^2 to 10^8 cd/m^2. This range does not include looking at the midday sun 10^9 cd/m^2) or lightning discharge. The retina has a static contrast ratio of around 100000:1 (about 6.5 f-stops). As soon as the eye moves it re-adjusts its exposure by adjusting the iris which regulates the size of the pupil[12]. This adaptation mechanism provides an automatic gain to the visual system. The brightness range that people can see is much greater than the available simultaneous contrast range of current displays as shown in Figure 2-3.

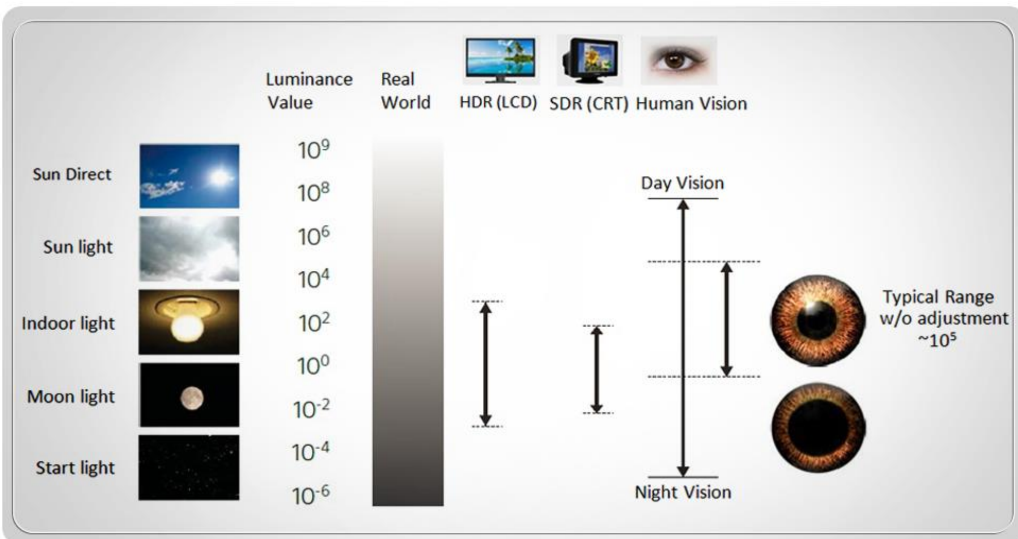

Figure 2-3 Luminance Dynamic Range (Source: Sony)

High dynamic range is specified and designed for capturing, processing, and reproducing scene imagery, with increased shadow and highlight detail beyond current SDR video and cinema systems capabilities. HDR systems are intended to present more perceptible details in shadows and high lights thus better matching human visual system capabilities under the several image viewing conditions typically found in consumer environments. In particular, HDR allows distinguishing bright details in high lights that are often compressed in traditional video systems, including allowing separation of color details in diffuse near-white colors and in strongly chromatic parts of the image[3].

Existing systems that utilize the Standard Dynamic Range (SDR) typically support brightness values only in the range of 0.01 to 100cd/m^2. Due to the physical characteristics of CRT TVs, video transmission has limited the brightness of pictures to about 100 nits (cd/m^2). With the advent of new TV technologies such as LCD, it is now possible to reproduce brighter pictures and lower levels of black; therefore allowing a substantial increase of the overall dynamic range or contrast ratio of the picture. Today's flat screen TVs are capable of up to 400 nits (cd/m^2), while HDR-ready TVs should manage up to 1400 nits. Display systems TVs compliant with Dolby Vision will be even brighter at up to 4000 nits.

2.2. Wide Color Gamut (WCG)

Wide Color Gamut is the capability of representing a wide range of colors than have been supported by conventional systems. Existing systems are been based on Rec.709 color space, which only capture a relatively small percentage (35.9%) of all visible chromaticity values, according to CIE 1931. This legacy color space leaves a large set of visible colors that cannot be rendered on SDTV or HDTV displays. Wider color spaces, such as Rec.2020 can represent a much larger percentage of visible chromaticities (~75.8 %) and can render more colorful and realistic pictures and enhance the viewer's experience and impression of reality. Figure 2-5 shows comparison of Rec.709 and Rec.2020 color spaces.

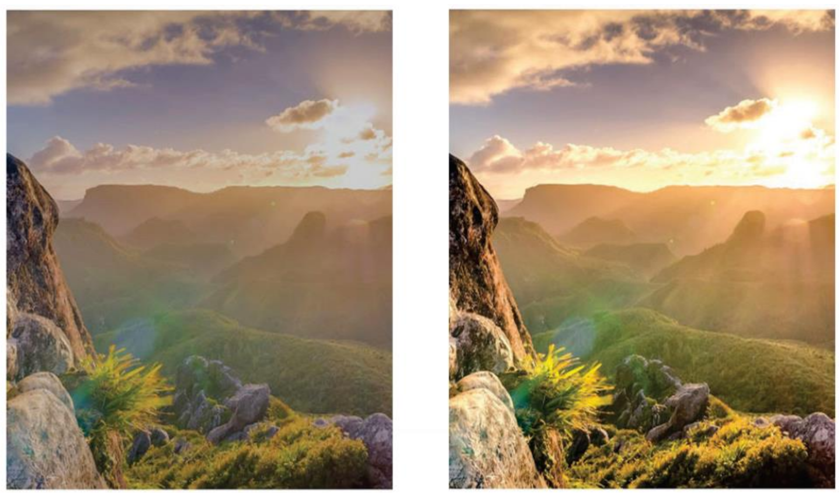

Figure 2-4 SDR Vs HDR Image (Source: 20th Century Fox)

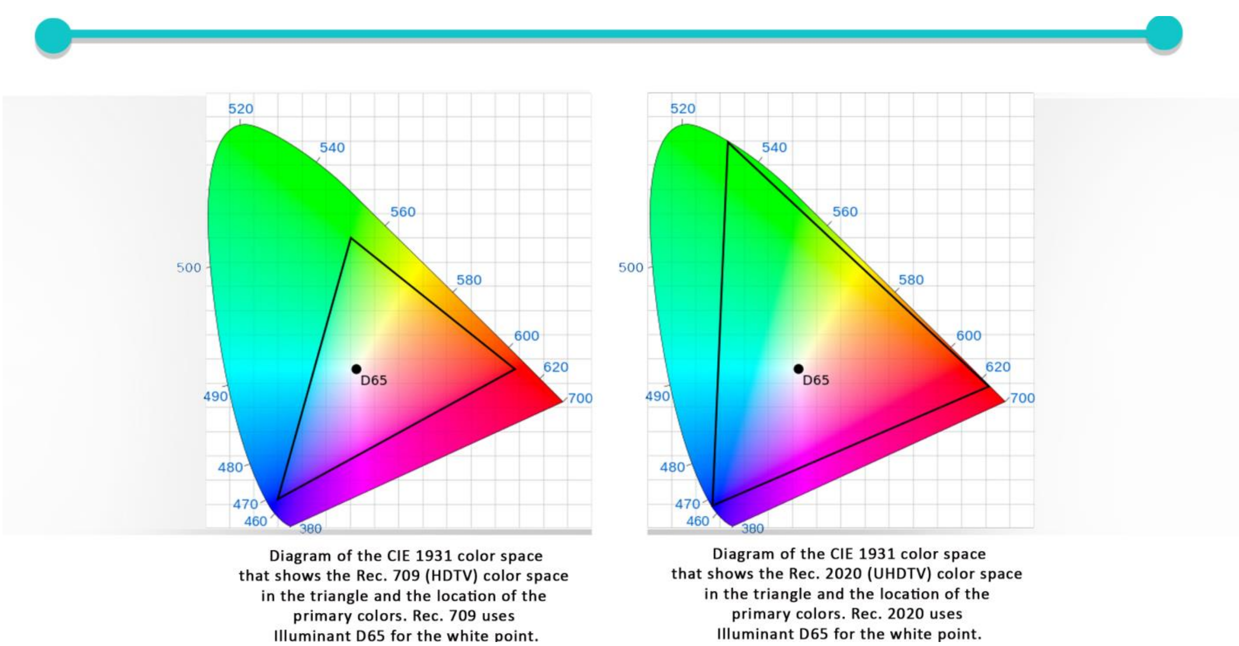

Figure 2-5 Wide Color Gamut: Rec2020 Vs Rec709

2.3. High Bit-depth

Conventional TV systems use 8-bit sample precision and does not provide sufficient brightness or color levels, which could result in the viewer seeing artifacts such as visible banding in the TV image. This limitation is exacerbated with WCG and HDR[13]. Though camera can capture a very high dynamic range and the LCD can display a reasonably high dynamic range, unfortunately the processing of the video during workflow and transmission still follows Rec.709 standard using 8-bits per component and a maximum brightness level of 100-120 nits. The expansion of brightness levels performed by the LCD will yield brighter colors, but it cannot add any of the information lost when the dynamic range was compressed into the REC 709 standard. The expansion can even yield unwanted artifacts such as color banding as shown in Figure 2-6. If the LCD monitor tries to expand the color dynamic range, then even worse effects may become visible with actual color distortions from the original intended colors[14].

Higher sample precision, such as 10-bit or 12-bit, represents more colors and brightness levels and greatly improves the ability to represent smoother transitions between hues or brightness to reduce banding effects.

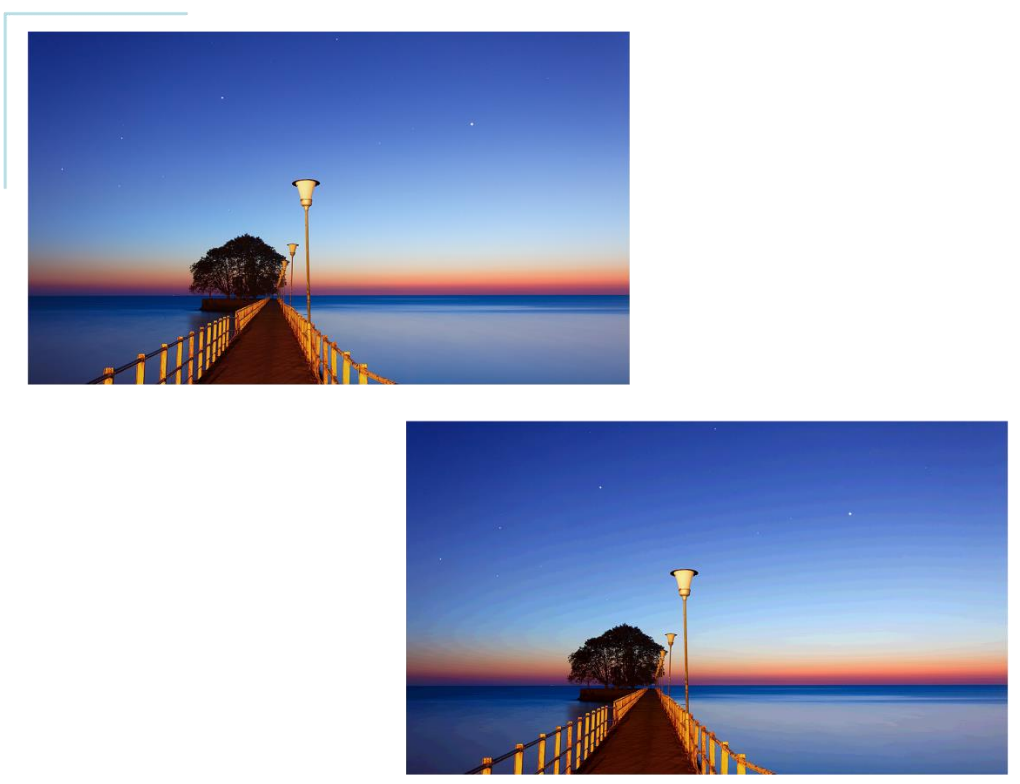

Figure 2-6 Color Banding Effect

3. OETF/EOTF Transfer functions

OETF (Optical Electrical Transfer Function) refers to the way the optical signal gets translated into voltage at the capture (camera) side and EOTF (Electrical Optical Transfer Function) refers to the way the electrical signal gets translated into optical signal at the display (TV) side. TVs contain lookup tables that describe an electro-optical transfer function (EOTF) which defines at what electrical input level the display should be illuminated, and how strongly[15]. These transfer functions are based on gamma, power functions, logarithmic functions and also on perceptual models to mimic the non-linear behavior of the human visual system.

Need for OETF/EOTF Transfer functions:

Human eyes do not perceive the light the way cameras do. Digital cameras produce a linear output w.r.t input light intensities. The magnitude of the output signal is doubled when twice the number of photons hit the camera sensor. But Human vision follows an approximate gamma or power function, with greater sensitivity to relative differences between darker tones than between the lighter ones.

Gamma encoded images store tones more efficiently. If images are not gamma-encoded, allocates too many bits or bandwidth to highlights that humans cannot differentiate and allocates too few bits or bandwidth to shadow values that humans are sensitive to. Hence requires more bits/bandwidth to maintain the same visual quality.

The Figure 3-1 shows how the linear encoding uses insufficient levels to describe the dark tones. On the other hand, the gamma encoded gradient distributes the tones roughly evenly across the entire range ("perceptually uniform"). However, real-world images typically have at least 256 levels (8 bits), which is enough to make tones appear smooth and continuous. If linear encoding were used instead, 8X as many levels (11 bits) would've been required to avoid image posterization[16].

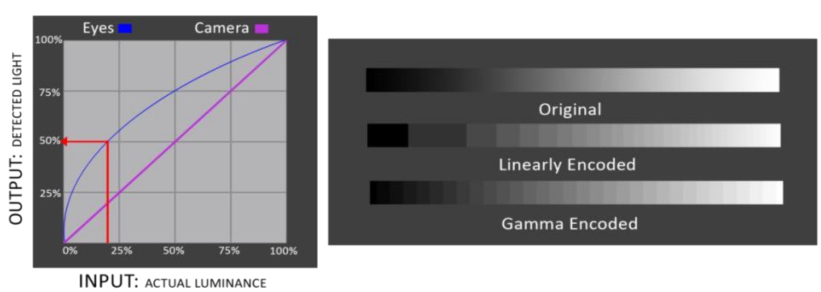

Figure 3-1 Need of Gamma Encoding

Gamma encoding of images is used to optimize the usage of bits when encoding an image, or bandwidth used to transport an image, by taking advantage of the non-linear manner in which humans perceive light and color. However, the gamma characteristics of the display device do not play a factor in the gamma encoding of images and video. They need gamma encoding to maximize the visual quality of the signal, regardless of the gamma characteristics of the display device.

Gamma encoding is a nonlinear operation used to code and decode luminance or tristimulus values in video or still image systems.

$$V_{\text{out}} = AV_{\text{in}}^{\gamma}$$

Gamma correction refers to the way the optical signal is translated into voltage at the capture/camera side. A gamma value $\gamma < 1$ is sometimes called an encoding gamma, and the process of encoding with this compressive power-law nonlinearity is called gamma compression. Gamma expansion refers to the way the electrical signal gets translated into optical signal at the display (TV) side. A gamma value $\gamma > 1$ is called a decoding gamma and the application of the expansive power-law nonlinearity is called gamma expansion[17]. The effect of gamma correction on an image[16] is shown in Figure 3-2.

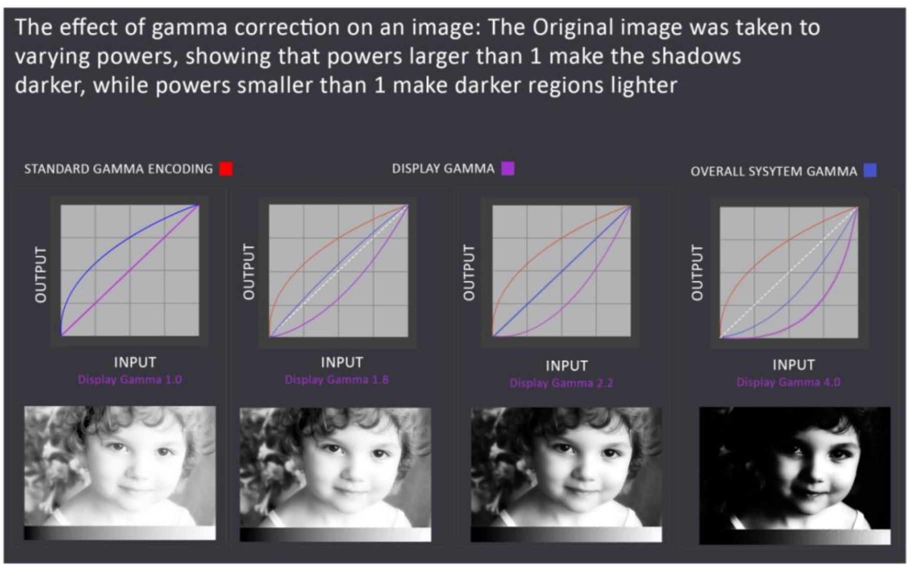

Figure 3-2 Effect of Gamma Correction

Examples of OETF/EOTF transfer functions:

- Standard Gamma (CRT TVs, Transfer functions for Rec.709/Rec.601)
- Hybrid Log-Gamma (ARIB STD-B67, developed by BBC & NHK)
- Perceptual Quantization (SMPTE ST 2084)
- Hyper Gamma (Digital cinematography)
- Log (Sony S-Log)

3.1. Standard Gamma

In CRT TVs or displays, the light intensity varies nonlinearly with the electron-gun voltage. Altering the input signal by gamma compression can cancel this nonlinearity, such that the output picture has the intended luminance. Although gamma encoding was developed originally to compensate for the input–output characteristic of cathode ray tube (CRT) displays, that is not its main purpose or advantage in modern systems[17].

The EOTFs for Rec. 601 and Rec. 709 represent a gamma function with a gamma of 2.2. This describes the characteristics of phosphor in legacy cathode rate tube (CRT) TVs and is therefore known as standard gamma (shown in Figure **3**-**3**). These standard gamma curves are still used today in broadcasting for the recording and playback of SD and HD signals. Supports brightness values up to 100 cd/m^2, low luminance levels, and limited dynamic range. Modern TVs no longer use CRTs and so allow the use of different EOTFs functions for recording, post processing and playback with better rendition and utilization of the displayable color space and dynamic range[15].

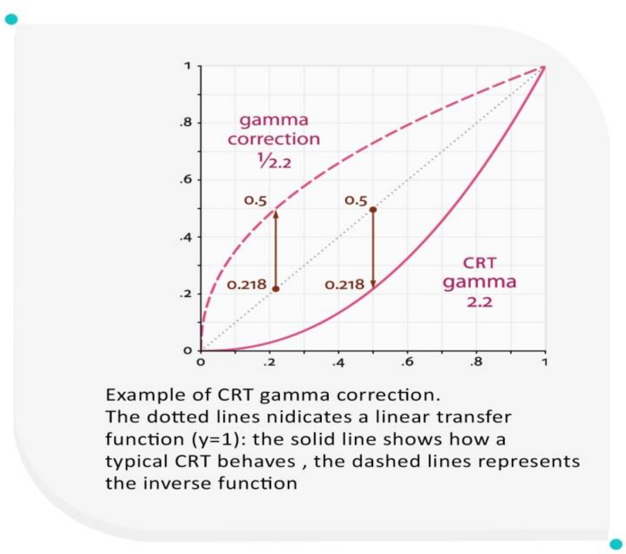

Figure 3-3 CRT Gamma Correction

3.2. SMPTE ST 2084

Unlike the traditional power law gamma curves, e.g. BT.709 or BT.1886, that have been designed to cover brightness values of up to 100 cd/m^2 this transfer function is designed to cover a much wider range of brightness values in the range of 0.001 to 10,000 cd/m^2. It exploits the characteristics of the human visual system and is able to represent a wide dynamic range of brightness with little loss of information using 12 or 10 bits. Even though existing consumer displays can only support much more limited dynamic ranges, e.g. <2,000cd/m^2, it was designed with future consumer equipment as well as professional applications, such as post-production and archiving, and display interfaces (e.g. HDMI) in mind[18]. It is an absolute luminance function, requiring the EOTF of the playback display to exactly match the EOTF of the mastering reference display. It maps each video signal code word to the same absolute luminance and chromaticity in every display (i.e. 10-bit code word 691 always maps to 500 nits). This allows each playback display to exactly match the luminance and chromaticity of the mastering reference display[19]. Comparison of SMPTE ST2084 EOTF and Gamma EOTF is shown in Figure **3**-**4**.

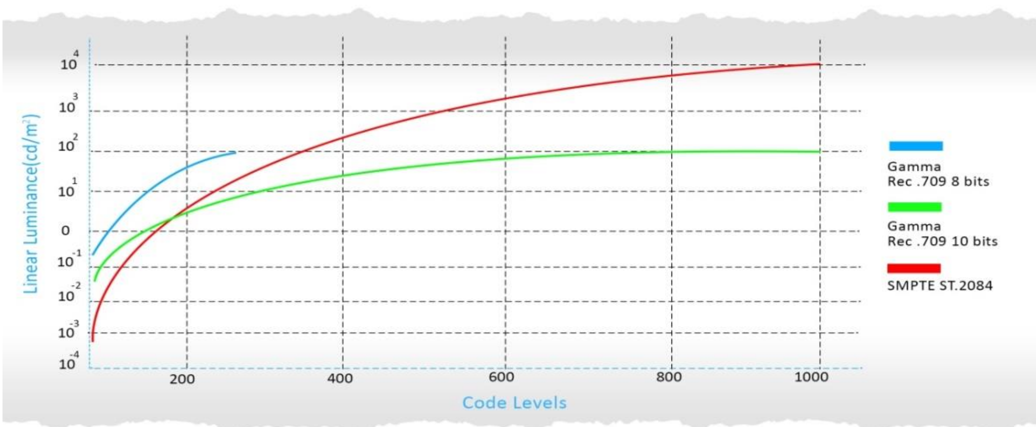

Figure 3-4 Comparison of SMPTE ST2084 and Gamma EOTFs

This HDR EOTF is standardized by SMPTE and is based on the Barten law which indicates that the contrast sensitivity of the human eye is a non-linear law, roughly in the form of ΔL/L, where the noticeable increase in luminance depends on the average luminance value. Based on these experiments, the Barten model (Figure 3-5) has been used for determining a new EOTF representing luminance (cd/m²) vs. the digital code over 12 bits (4096 levels) as shown in Figure 3-4. This law is known as "PERCEPTUAL CODING" (PC) and is associated with non-linear quantization called "Perceptual Quantization (PQ)". This standard specifies the reference monitor to be used for studio mastering in the range of 10,000 cd/m² for peak white. This represents a factor of x100 on dynamics compared to the previous specification of 100 cd/m² which had been the reference for studio mastering monitors with CRTs for decades[20]. Gamma functions wastes bits in bright regions and Log functions wastes bits in dark regions[21]. Since SMPTE ST2084 corresponds closely to the human perceptual model, it makes the most efficient use of signal bits throughout the entire luminance range (as shown in Figure 3-5).

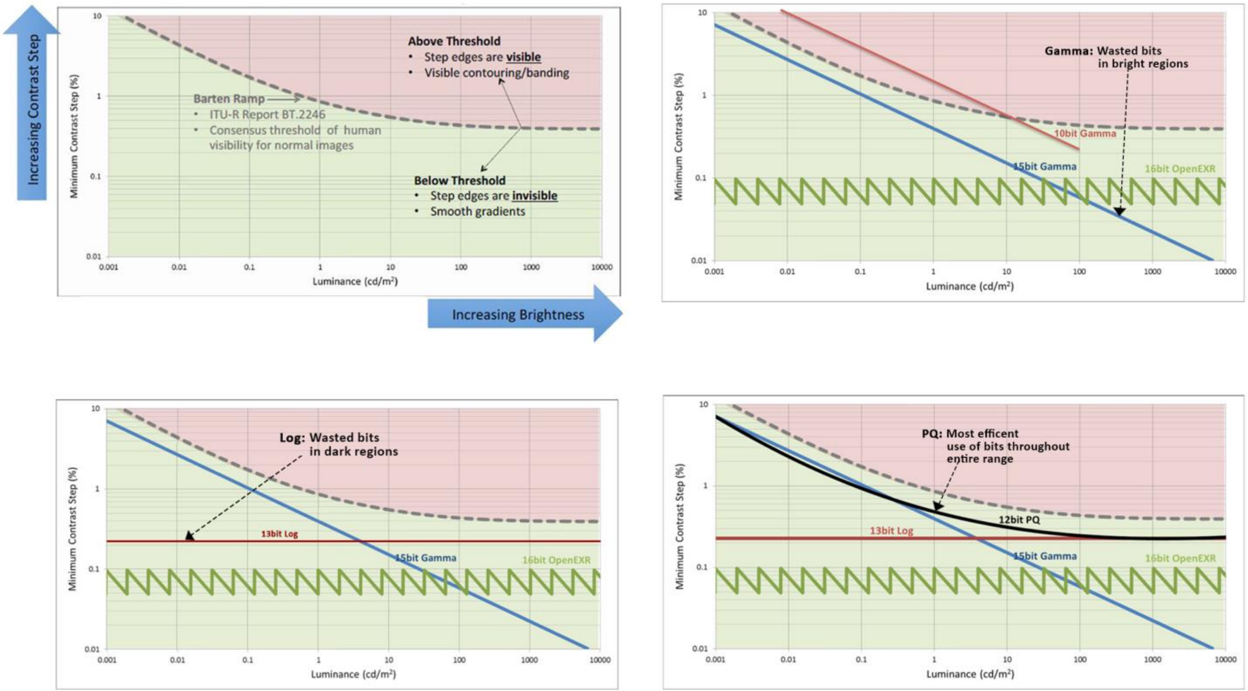

Figure 3-5 Barten Ramp and Contrast Step Curves

An ST2084 encoded signal can represent luminance levels up to 10,000 nits at the cost of relatively few extra code words. A majority of the ST2084 codes represent lower luminance levels, to complement the human visual system's greater contrast sensitivity at lower luminance levels and to minimize visible banding at those lower levels. Half of the HDR codes are in the SDR range, meaning that 10-bit HDR doubles the number of code values in the SDR range, compared to traditional 8-bit video[19].

If a display system were to simply reproduce a linear representation of the scene light, it would produce low contrast, washed out images. This is because scenes that are viewed at brightness levels much lower than the original scene are perceived to have much lower contrast than the original scene. To optimize the images, an S-curve function is used to map scene light to display light. This Optical to Optical Transfer Function (OOTF - often referred to as rendering intent or system gamma) compresses/clips the extreme highlights and dark areas and contrast enhances the mid-range light levels with a gamma >1 characteristic[19] (typically 1.1 to 1.6). The SMPTE ST2084 PQ system, which is defined by its EOTF, was designed to have the OOTF applied in the camera or the production process (as shown in Figure 3-6).

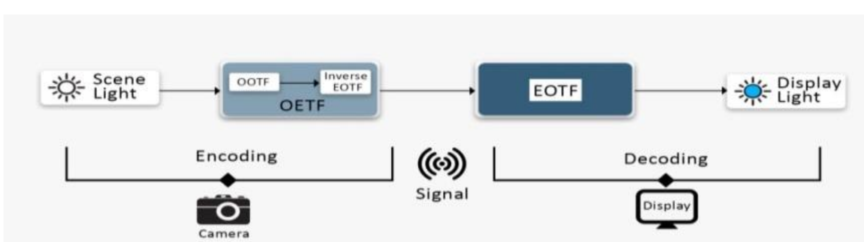

Figure 3-6 OOTF in Production in SMPTE ST 2084 PQ System (Source: ITU)

3.3. Hybrid Log Gamma (HLG)

It is a hybrid curve that applies a standard gamma curve for darker pixels in the legacy SDR range and a logarithmic curve for higher brightness highlights (Figure 3-7). The hybrid OETF makes it possible to broadcast a single stream that is compatible with both SDR and HDR televisions. Association of Radio Industries and Businesses (ARIB) adopted hybrid log gamma OETF, which was jointly developed by the BBC and NHK for their UHDTV service that is to be deployed in Japan. This transfer function is specified in ARIB STDB67, and apart from being able to represent higher dynamic range content also claims a form of backward compatibility, when the content is decoded and displayed on a BT.1886 capable system. In such a system, the content, although not perfect, would still look reasonable to the casual viewer, without the need of any additional processing[18].

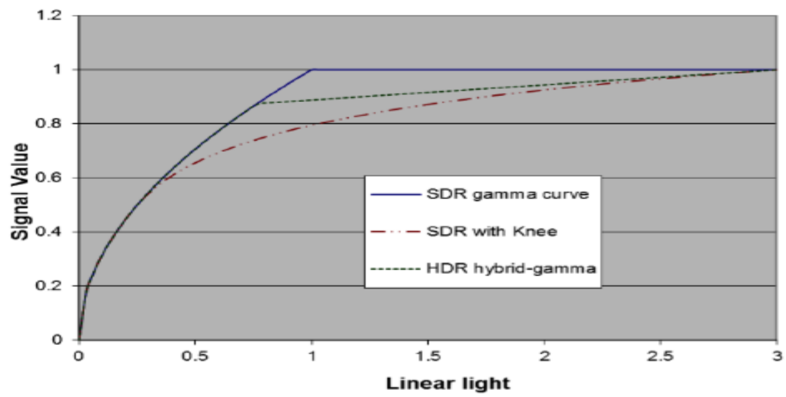

Figure 3-7 Hybrid Log Gamma OETF Vs SDR OETF (Source: BBC/NHK)

A major difference of this transfer function versus ST 2084 is that this transfer function is considered to be a scene referred transfer function, like BT.709, allowing a system to invert it based on the target display capabilities. On the other hand, ST 2084 is a display referred transfer function and requires the exact inverse process to be applied so as to allow the display to match the exact intent of the grading display. Another difference is that this transfer function can only cover a considerably narrower dynamic range than ST 2084 (<2,000cd/m2). Nevertheless, there is considerable interest in using this transfer function for several live production applications, especially for TV broadcast applications[18]. Comparison of various EOTF and OETF transfer functions is shown in Figure 3-8.

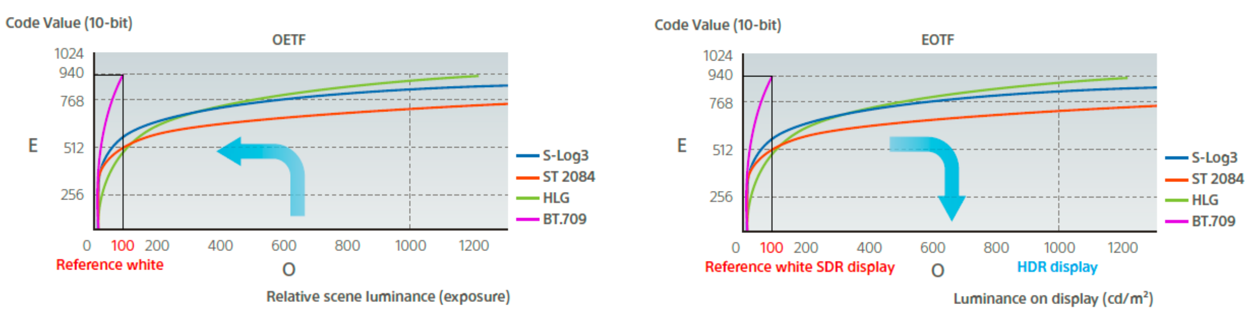

Figure 3-8 Comparison of EOTF and OETF transfer functions (Source: Sony)

4. HDR Effects

Today's high-performance camera systems including cinematography cameras and studio cameras can capture high dynamic range and wide color gamut images. But due to technological limitations of conventional CRT displays, current standard-dynamic-range (SDR) production restricts luminance levels to a maximum of 100 cd/m^2(nit) and supports only the ITU-R BT.709 standard color space. In recent years, LCD and OLED displays have become widely used, and the technology of these devices enables higher luminance and wide color gamut reproduction. Extending beyond this most recent technological evolution, you can now achieve HDR image reproduction by using the most appropriate transfer functions (OETF/EOTF) for both the production side and the consumer side. This section provides an explanation about effects of HDR, using the example of a video scene in which sunshine extends into a room[22].

SDR System

At the production stage, the camera-captured scene image retains a high dynamic range, from the window's high-luminance level to the room's low brightness image (left picture). However, the current transmission path with 8-bit depth compromises image quality (center picture). Furthermore, as the display limits maximum luminance to 100 cd/m^2(nit), the system loses both the camera-captured luminance levels and the dynamic range (right picture).

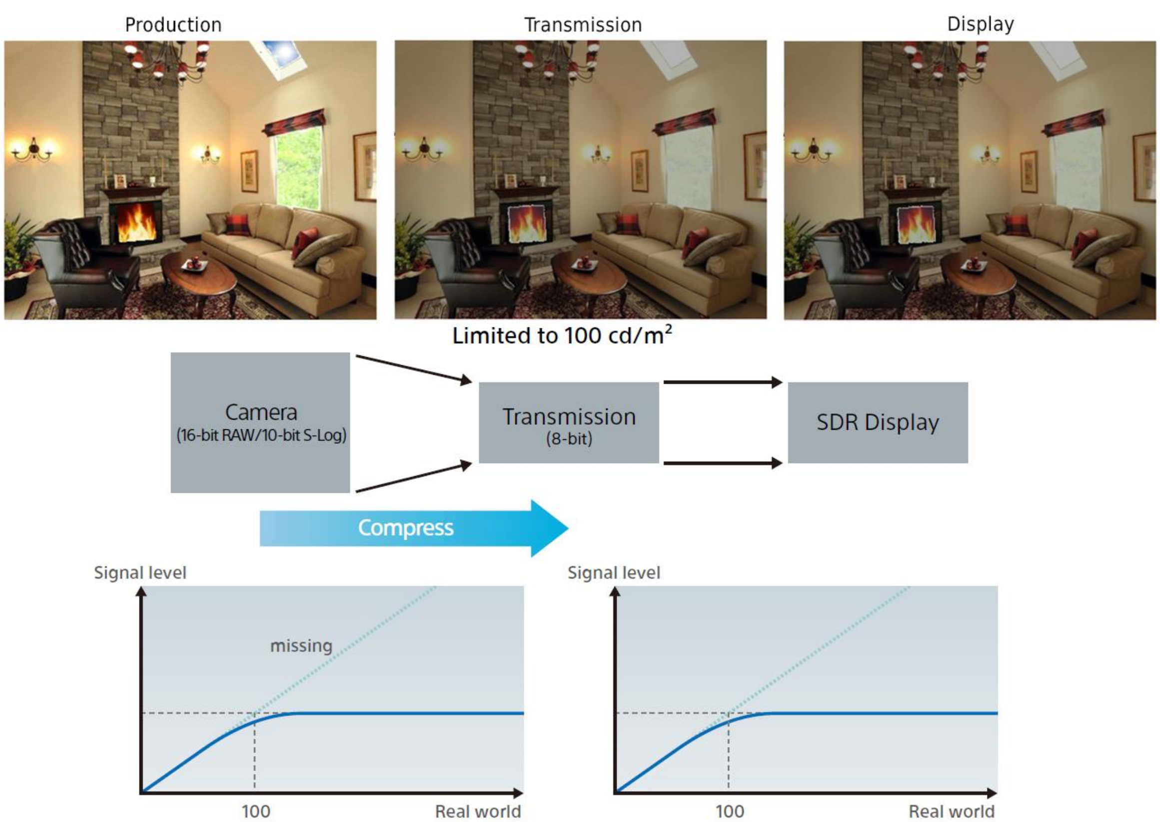

Figure 4-1 SDR System with SDR Transmission and Display (Source: Sony)

This means that, in the SDR system, the camera-captured dynamic range of luminance levels is compressed and, consequently, the high-light portion of the window is white-clipped while detail is lost in other parts of the image (as shown in Figure 4-1)[22].

SDR System with a High-Luminance Display

This system features a high-luminance display instead of a conventional SDR display. Although, this system delivers the same image reproduction as an SDR-equipped system in the transmission process, it is able with the high-luminance display to increase the luminance levels of the whole image. This means that the high-light portion of the window is washed out while some details in gradation are lost. In addition, the luminance level inside the room is increased (as shown in Figure 4-2)[22].

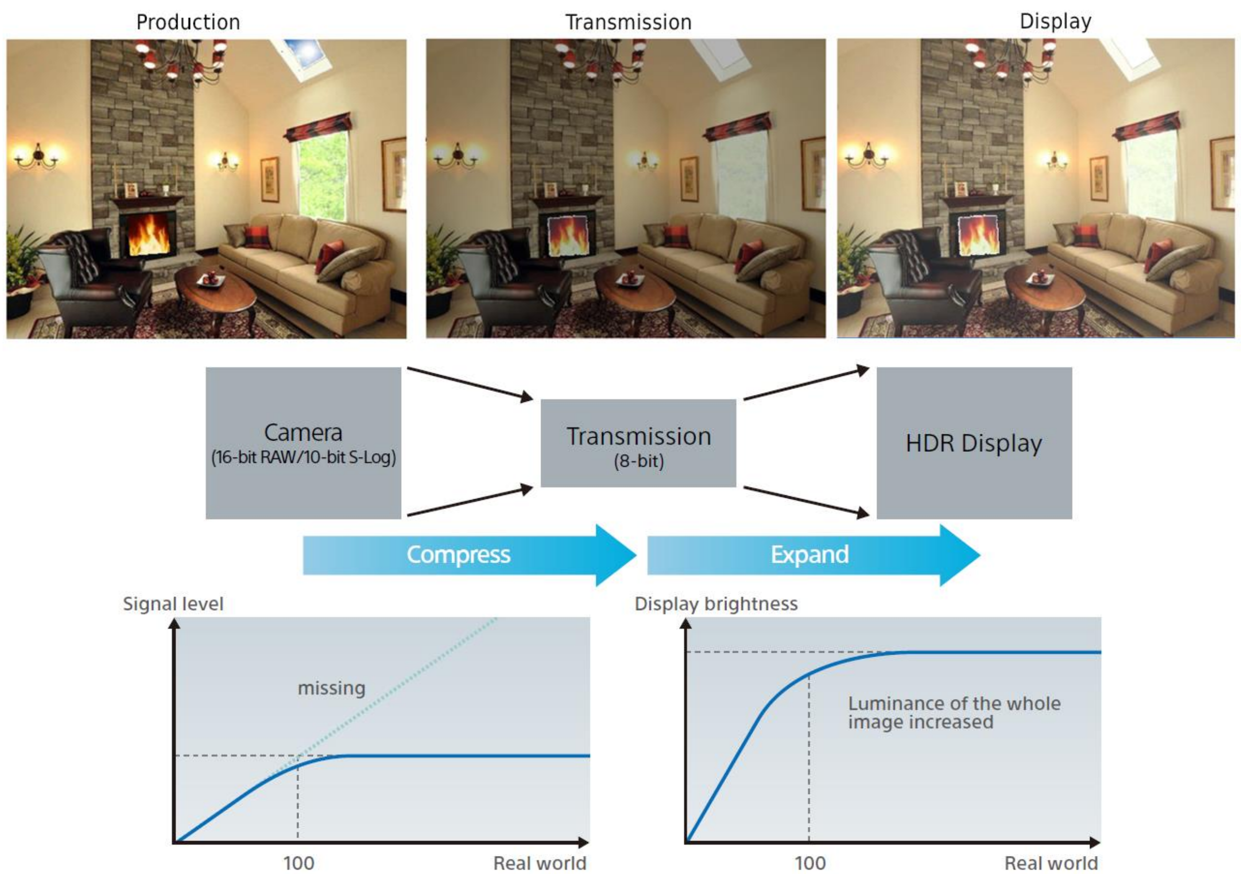

Figure 4-2 SDR System with SDR Transmission and HDR Display (Source: Sony)

HDR System

A system with end-to-end HDR from the camera, through transmission, and to the display can deliver an HDR image from the high-light portion right through to the dark portion. This means that the scene image on the window is reproduced correctly without white-clipping, and also the luminance level inside the room is also reproduced correctly (as shown in Figure 4-3)[22].

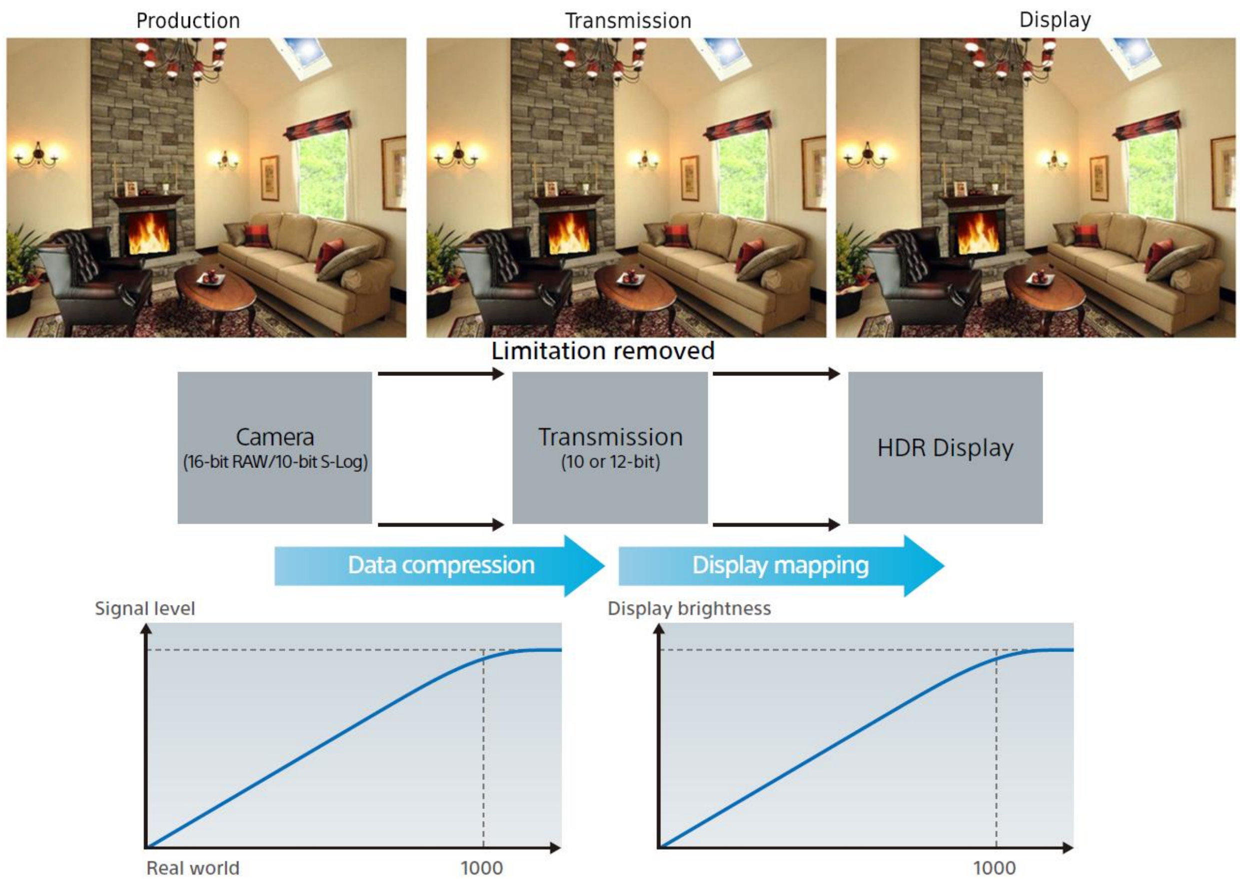

Figure 4-3 HDR System with HDR Transmission and Display (Source: Sony)

5. Content production workflow

Today's cameras are able to capture content with high dynamic range and extended color gamut, sometimes using proprietary transfer functions and color gamut that can vary from one vendor to another. Content production workflows are used to modify the colors based on the artistic intent and also carry out dynamic range adjustment as needed. Production workflows produce the HDR master using an OETF such as ST.2084 or another OETF that was selected for content delivery. The production workflow can also include an HDR to SDR conversion to ensure backward compatibility as needed. The characteristics of the reference display within the content production workflow can be carried as additional metadata in the HDR content. This mechanism was standardized in SMPTE ST 2086. It is used to carry information such as color primaries and luminance range of the reference display which can be fed to the HDR TV on the receive side to accurately render the content by preserving the artistic intent[10]. Content production workflow is shown in Figure **5**-**1**.

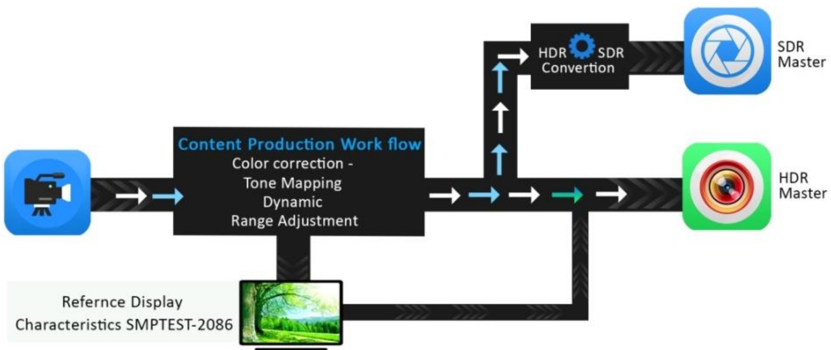

Figure 5-1 Content Production Workflow

Color grading is the process of altering and enhancing the color of an image (shown in Figure 5-2). Main functions of color grading are reproducing accurately what was shot, establish a desired 'look' (stylized looks), enhance and/or alter the mood of a scene. The major color correction tools are (brightness, contrast, saturation, masks, mattes, power windows, motion tracking). If you change the colors, you could call it your artistic expression (grading) or correction. Grading was used so that night scenes could be filmed more cheaply in daylight[23].

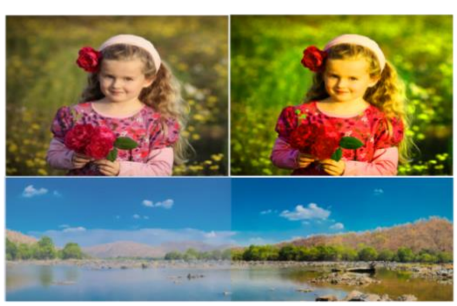

Figure 5-2 Color Grading

6. HDR Systems

HDR systems may be or may not be backward compatible with legacy SDR systems.

6.1. Non-backward compatible HDR systems

The Blu-ray HDR technology is an example for non-backward compatible HDR system and is referred to as HDR-10 (for 10 bit content) or HDR-12 (for 12 bit content).

6.2. Backward compatible HDR systems

As there are a large number of displays and TV sets that are not capable of displaying HDR content, it is important to have some backward compatibility that allows an HDR signal to be displayed on existing SDR systems. Backward compatibility is important in broadcast and OTT environments as service providers need to ensure that content can be viewed on legacy SDR TVs. A variety of backward compatible HDR solutions have been put forward by companies such as BBC, Dolby, Philips, and Technicolor[10].

Backward compatibility with traditional SDR systems can be achieved in three ways.

- Simulcast both HDR and SDR content
- Dual layer approach
- Single layer approach

Simulcast both HDR and SDR content

This option is not practical in broadcast/OTT environments as it consumes extra bandwidth. It can be envisaged for VOD or packaged content (Blu-ray discs) by selecting the proper format based on the capabilities of the TV[10].

Dual layer approach

HDR to SDR conversion operation produces a backward compatible base layer which includes the SDR content as well as an enhancement layer that carries extra dynamic range and color information. Both layers are encoded and transmitted. On the receiver side, the base layer is decoded to retrieve an SDR compatible content that can be directly displayed on legacy TVs. The enhancement layer is decoded and combined with the base layer to produce the HDR version of the content. On average, the dual layer approach requires 15% to 30% extra bandwidth to transmit the enhancement layer[10].

Single layer approach

HDR to SDR conversion operation produces a single layer stream and a set of metadata that carries extra dynamic range and color information. The single layer includes the SDR content and gets carried throughout the delivery chain. In parallel, metadata is inserted as part of the single layer stream. Legacy systems retrieve the SDR content and ignore the metadata to produce a version of content that can be displayed on SDR TVs. HDR receivers use the metadata to reconstruct the HDR content for delivery to HDR TVs. Typically, bandwidth overhead due to metadata insertion is limited to a few hundreds of kbits/s[10].

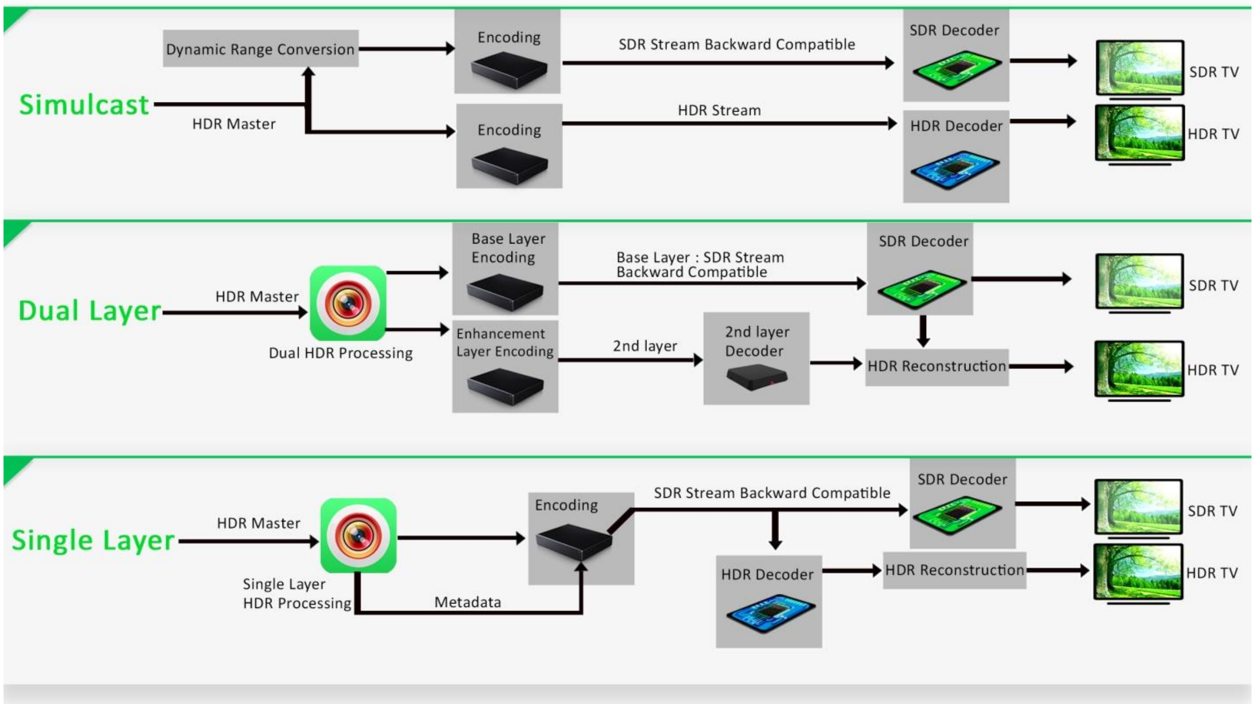

Figure 6-1 HDR Systems with SDR Backward Compatibility

7. HDR Metada

- Static metadata
- Content dependent metadata (dynamic metadata)

7.1. Static metadata

Static metadata is included with the authored content to describe the possible range of colors and dynamic range that are used by each encoded content[3]. SMPTE ST2086 defines static metadata that is supported by HDMI 2.0a, and is included with mastered HDR content to convey the color volume of the mastering display and the luminance of the content. This is described by the chromaticity of the red, green, and blue display primaries and white point of the mastering display, plus its black level and peak luminance level[19]. ST2086 may be included in the encoded stream for both SDR and HDR contents. MaxFALL and MaxCLL are the additional static metadata items that applies to HDR content only and can be carried on the Ultra HD Blu-ray format.

Maximum Content Light Level (MaxCLL) corresponds to the brightest pixel in the entire stream. The max(R,G,B) operator is applied to all pixels in all frames of the content to determine the maximum value (MaxCLL) for that particular content. If a simple tone mapping approach is used by the consumer display to replace pixel values in the content that are not representable on the consumer display with pixel values that are representable, then the MaxCLL could be used to define the upper bound of the value of the pixels that will be encountered in that particular content[24].

Maximum Frame Average Light Level (MaxFALL) corresponds to the highest frame average brightness per frame in the entire stream. HDR Content for Blu-ray Format Extension will be created while considering the authoring guideline that the Maximum Frame Average Light Level not to exceed 400 nits[3]. Since MaxCLL only describes the brightest pixel, it does not provide any indication of the overall brightness of a specific frame, or the entire video stream. As such, considering an image of a sky at night, the stars in the sky may appear very bright, but also cover a very small area of the frame. Since the remainder of the frame is dark, the overall average luminance for this frame may be much lower than compared with a regular daylight scene. However, this increase in dynamic range (dark sky with accented bright stars) is exactly what makes HDR an interesting tool.

Further, considering the challenges within consumer electronics devices, the frame average luminance is much more important from a power management perspective than the peak luminance within a given frame. Therefore, the Frame-Average Light Level of a given piece of content is an important parameter for consumer display devices to understand. The computation of the MaxFALL values only considers the active image areas of the frame, which is relevant when for example a 2.40:1 aspect ratio content is stored in a 16x9 frame with letterbox mattes for distribution to the home, so the MaxFALL value can remain valid if cropping or zooming is applied to the image[24].

7.2. Content dependent metadata

It can vary dynamically throughout the source content. When the source content mastered with HDR/WCG is transformed for presentation on a display having a smaller color volume such as a SDR display, the color transformation process can be optimized through the use of content dependent, dynamic color transform metadata rather than using only display color volume metadata. As the content characteristics change from scene to scene, the optimal transform processing that best reproduces the content creators' artistic intent can change. For example, the color volume transformation parameters used for a very dark scene could be quite different from those used for a very bright scene. As an alternative to archiving and managing multiple, transformed masters, one for each targeted video system, the transforms can be represented as metadata synchronized with the frames of one master. The metadata can be captured or generated as part of the mastering process, when images are creatively approved, and later applied in media conversions during the distribution stage[3].

SMPTE ST2094 defines content-dependent (dynamic) metadata, to be supported in HDMI 2.1. Dynamic metadata will convey frame-by-frame or scene-by-scene Color Remapping Information (CRI), which will enable color transformation to be variable along the content timeline.

Samsung has also proposed a standard for content-dependent dynamic metadata called "Scene--based Color Volume Mapping" in which dynamic metadata is defined for each scene (or clip) to best reproduce the creative intent of HDR contents as much as possible on displays with a smaller dynamic range and narrower color gamut[19]. The proposed technology, beside metadata from SMPT ST 2086, uses the following metadata: Average picture level (APL) based peak luminance characteristics of the mastering and the target monitors, and Scene-wise maximum of the color components {R,G,B}, Scene-wise average of maximum of color component values {R,G,B}, and Scene-wise area of the brightest pixels from HDR contents[3].

HDMI 2.0a covers HDR EOTF signaling and static metadata. The next version of the popular interface standard will be HDMI 2.1 that adds support for "dynamic metadata" for HDR, according to Philips. The new DisplayPort 1.4 standard will also add support for dynamic metadata for HDR.

The current TVs have different picture characteristics for maximum brightness, color gamut etc. With dynamic metadata signaling a specific TV would be able to optimize picture performance scene-by-scene based on its hardware/picture capabilities. Dynamic metadata will allow a HDR TV to move up and down the average picture brightness level on a scene-by-scene (or even frame-by-frame) basis during a movie. It will allow TVs to get more details out of the HDR picture and potentially improve HDR reproduction in brightly lit environments. Currently HDR video is graded to be quite dark through the use of static metadata.

The open HDR10 format, which is mandatory in the UHD Blu-ray standard and supported by streaming services, currently relies on static metadata. UHD Blu-ray movie with static metadata would use one overall HDR grade for the entire movie. With dynamic metadata it is possible for the studio mastering team to change the HDR grade on a scene-to scene basis to improve the picture experience. The Dolby Vision format, on the other hand, is created with dynamic metadata in mind.

Complex sets of content dependent metadata with Look Up Tables (LUT's), matrices, masks etc. which can be scene based or even frame based (in case of frame based switching of content) could require substantial, additional bandwidth in a transport channel[3].

Color Volume Mapping

Color volume is solid in colorimetric space containing all possible colors a display can produce. Color volume of a display is specified by its color primaries, white point, and luminance[3]. The higher the luminance range and the wider the color space, the larger the overall color volume. Color volume mapping denotes the process of mapping content that is created on a large color volume mastering display down to a playback display that has a reduced color volume ('color gamut' often evokes a 2D area). In some HDR systems, this mapping is being called "display adaptation" or "display tuning."

Luminance - The peak luminance of a playback HDR display will often be lower than the peak luminance of the reference display that was used to master video content that is being played back. In this case, the higher content luminance can be tone mapped to the lower dynamic range of the playback display, with a luminance roll-off of the brightest highlights that avoids hard clipping. Tone mapping needs to be done in a fashion that minimizes the perceptual effects of the luminance roll-off[19].

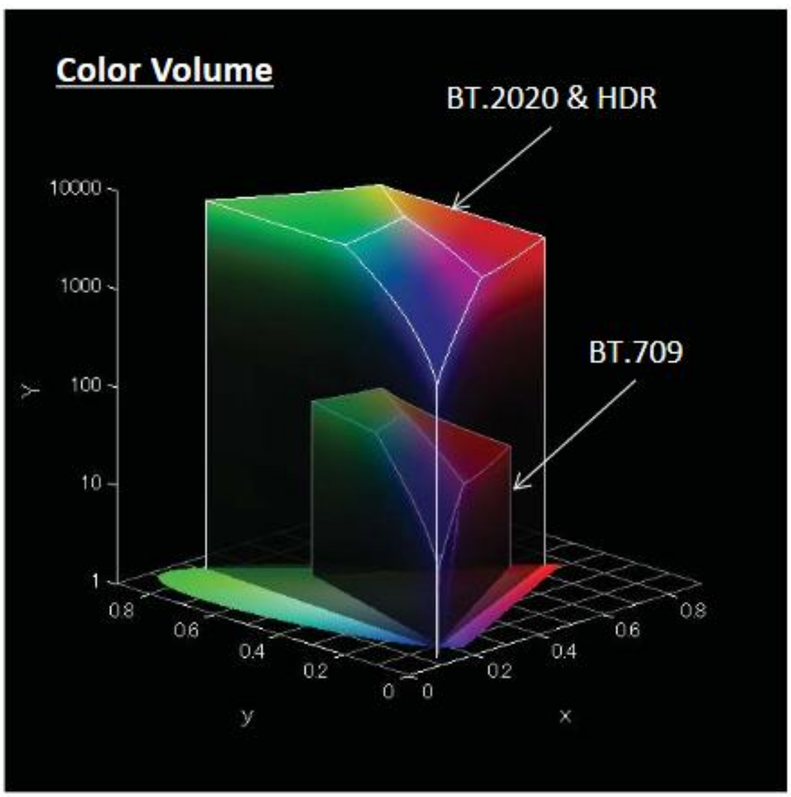

Figure 7-1 Color Volume: BT.2020 Vs BT.709 (Source: Sony)

Chromaticity - The primary colors of a playback HDR display will often be less saturated than the primaries of the reference HDR display that was used to master video content. In this case, the wider content gamut can be gamut mapped to the narrower gamut of the playback display. Gamut mapping needs to be done in a perceptual fashion to maintain relative saturation differences but also not desaturate lower saturation images and wash out the image.

Luminance and Chromaticity - Because of the perceptual interaction of luminance and chromaticity, when a lower dynamic range display rolls off the top end of higher luminance content, that also affects the chromaticity of brighter pixels, and both need to be taken into account in a display's color volume mapping strategy.

For tone mapping and gamut mapping to be achieved in the playback display, the display needs to be informed by static metadata of the luminance and chromaticity attributes of both the mastering display and the content. These attributes are represented by the static metadata fields that are defined in the SMPTE ST2086 standard. However, if color volume mapping is performed without scene-by-scene content information, the mapping will be based only on the brightest scene and the widest gamut scene in the content. The majority of the content will have greater compression of dynamic range and color gamut than would be necessary. Dynamic metadata allows a compatible display to map the content to a smaller color volume only as needed, when the content exceeds the capability of the playback display. The perception model can change dynamically, based on the luminance and gamut requirements of each scene.

Color volume mapping is more important the more difference there is between the mastering display and the playback display and will be an essential part of the future proofing of HDR technology. It ensures that playback displays that can do accurate mapping will still show content well when mastering displays are at or near the BT.2020 gamut limits, with many thousands of nits[19].

ICtCp Color Representation

Y’C’bC’r is SDR’s legacy color-opponent based encoding scheme that separates luma from chroma information for the purposes of chroma subsampling. With the large color volume that results from high dynamic range and wider color gamut, the shortcomings in using Y’C’bC’r to map luminance, hue, and saturation differences from one color volume to another have become magnified, also yielding larger color crosstalk encoding errors and amplification of noise near the edges of the RGB color space. The shortcomings are due to the perceptual crosstalk between the Y’, C’b, and C’r signal channels.

As saturation changes in this color space, the luminance changes and the hue shifts, especially in the blue region. Because the Y’C’bC’r space is not constant luminance, saturated colors (especially red and blue) are rendered too bright. Also, as Y’C’bC’r chroma is subsampled to 4:2:2 or 4:2:0, quantization errors due to bit depth limitations are introduced in the chroma.

The BT.2020 standard provides the Y'cC'bcC'rc constant luminance format as an alternative to Y’C’bC’r (see ITU-R Report BT.2246-5). This format resolves the issue of chroma leakage into the Y’c luma signal, yielding improved tone mapping and luminance encoding. It does not, however, solve the problem of luminance leakage into the C’bc and C’rc signals.

Dolby has proposed the use of an alternate ICtCp color representation, approved by ITU-R SG 6, that better conforms to the neural processing characteristics of the human visual system than either Y’C’bC’r or Y'cC'bcC'rc. ICtCp is a color-opponent space that represents color in terms of an Intensity (black-white) channel (I), a Tritan (blue-yellow) channel (Ct), and a Protan (red-green) channel (Cp). As saturation changes in the ICtCp color space, luminance and hue remain almost constant; no crosstalk.

The ICtCp color representation results in constant intensity, hue linearity, and perceptual uniformity. This yields efficient encoding of high dynamic range and wide gamut color difference signals with lower quantization error, as well as more accurate color volume mapping[19].

8. HDR Standardization

Efforts are underway to define new standards for delivering HDR content. Industry standards are needed to ensure interoperability between all the components of the delivery chain starting from content capture, content production, encoding, transport, decoding and finally display. However, getting the industry to agree on one across-the-board approach is proving difficult given the business implications that are on stake. The following provides an overview of standardization activities for the HDR technologies[10].

Society of Motion Picture and Television Engineers (SMPTE)

- SMPTE ST.2084: High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays
- SMPTE ST.2086: Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images
- SMPTE ST.2094: Content Dependent (Dynamic) Metadata for Color Volume Transformation of High Luminance and Wide Color Gamut Images.

SMPTE ST.2084: Defines 'display referred' EOTF curve with absolute luminance values based on human visual model, called Perceptual Quantizer (PQ).

SMPTE ST.2086: This standard is used to describe the capabilities of the display used to master the content, which includes the CIE (x, y) chromaticity coordinates of the RGB Primaries and White Point of the mastering display, in addition to the minimum and maximum luminance of the mastering display. If traditional mastering practices are followed during content creation, the range of colors and luminance values encoded in the mastered video signal will be limited to the range of colors and luminance values that can be shown on the mastering display. ST2086 may be included in the encoded stream for both SDR and HDR contents[3]. This standard helps the final screen at the consumer end to locate itself in the color volume of the mastering display in order to adapt its rendering according to its own attainable color volume (i.e. its own color primaries)[20]. SMPTE ST 2084 and ST 2086 were added to HEVC as part of an extension update in 2014 so it is included in the compressed HEVC file.

SMPTE ST.2094: The color transformation process can be optimized through the use of content-dependent, dynamic color transform metadata rather than using only display color volume metadata[3].

MPEG (Moving Picture Experts Group)

Several supplemental enhancement information (SEI) messages are added in the second version of HEVC standard to support HDR signaling.

- Mastering display color volume SEI message
- Knee function information SEI message
- Color remapping information SEI message
- Chroma resampling filter hint SEI message

Mastering display color volume SEI message: This message provides information on the color volume (color primaries, white point and luminance range) of the mastering display that is used to author the video. This information is necessary to build the Knee function information SEI message to map the source luminance and chrominance intent to the best possible match on an output display[14]. Display primaries specify the normalized x and y chromaticity coordinates of the color primaries (red, green, and blue) of the mastering display according to the CIE1931 definition of x and y as specified in ISO 11664-1 (see also ISO 11664-3 and CIE 15). White point specify the normalized x and y chromaticity coordinates of the white point of the mastering display according to the CIE 1931 definition of x and y as specified in ISO 11664-1 (see also ISO 11664-3 and CIE 15). Luminance range specify the nominal maximum and minimum luminance of the mastering display.

This SEI message does not specify the measurement methodologies and procedures used for determining the indicated values or any description of the mastering environment. It also does not provide information on colour transformations that would be appropriate to preserve creative intent on displays with colour volumes different from that of the described mastering display.

The information conveyed in this SEI message is intended to be adequate for purposes corresponding to the use of SMPTE ST 2086[4].

Knee function information SEI message: This message provides information on how to convert from one dynamic range to a different dynamic range for customization to particular display environments. An example would be to compress the upper range of high dynamic range (HDR) video that has a luminance level of 800 cd/m^2 for output on a 100 cd/m^2 display[5]. Some dynamic range compression function needs to be specified to minimize contrast distortions. Since the human eye perceives contrast differently in bright areas as compared to darker areas, the transformation of luminance dynamic range will generally be non-linear. To simplify transformation functions, the concept of "knees" is introduced so that multiple line segments can be joined together to approximate a non-linear curve[14]. A knee function is a piecewise linear function specified by knee points maps the input luminance level to the output luminance level. An example of a knee function is shown in Figure 8-1 with three knee points[4]. Multiple knee function processes can be supported for different display scenarios.

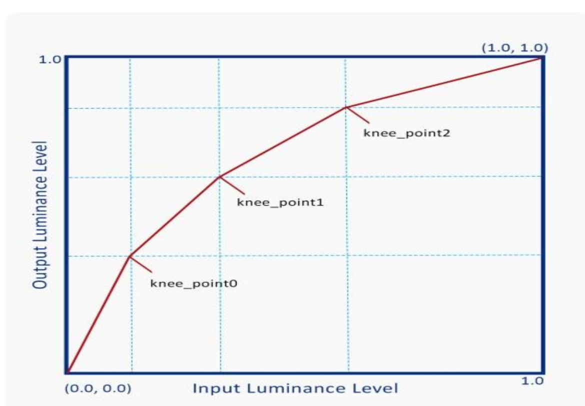

Figure 8-1 A Knee Function with three knee points

Color remapping information SEI message: This message provides information on remapping from one color space to a different color space. An example would be to preserve the artistic intent when converting wide color gamut (WCG) video from the Rec. 2020 color space for output on a Rec. 709 display[5]. In this example, data from the source will be lost through a compression of the color space. To minimize artifacts and to respect the source's colors as much as possible, this SEI message can be used to specify a desirable transformation that is optimal to the source's content[14]. The color remapping information SEI message was proposed for future UHDTV applications. The colour remapping information may be applied directly to the decoded sample values, regardless of whether they are in the luma and chroma domain or the RGB domain. Multiple color remapping processes can be supported for different display scenarios[4].

Chroma resampling filter hint SEI message: This message provides information on converting from one chroma sampling format to another. The message signals one downsampling process and one upsampling process for the chroma components of decoded pictures. When the sampling processes signalled in the chroma resampling filter hint SEI message are used, for any number of upsampling and downsampling iterations performed on the decoded pictures, the degradation of the colour components is expected to be minimized[4].

Test Model (TM) for the HDR and WCG extension of HEVC

Test Model framework overview: A functional diagram of the proposed TM is shown in Figure 8-2. The proposed system uses HEVC Main 10 profile for the bitstream generation and bitstream decoding, and uses meta-data provided by the decoder to control decoder side processing used to reconstruct an HDR and WCG representation. The input HDR signal is pre-processed to produce a modified HDR signal that is provided to the HEVC main 10 encoder. The HEVC main 10 decoder output is used to reconstruct the HDR signal. The pre-processing and post-processing steps primarily aim at improving the coding efficiency of HDR content, and at providing support of SDR backward compatibility. Efficient delivery of HDR and WCG content is achieved with the tool described in this proposed TM. The only normative tool in the HDR reconstruction process proposed in this TM is inverse reshaper. Non-normative technologies including SEI and VUI changes are not presented in this TM[29].

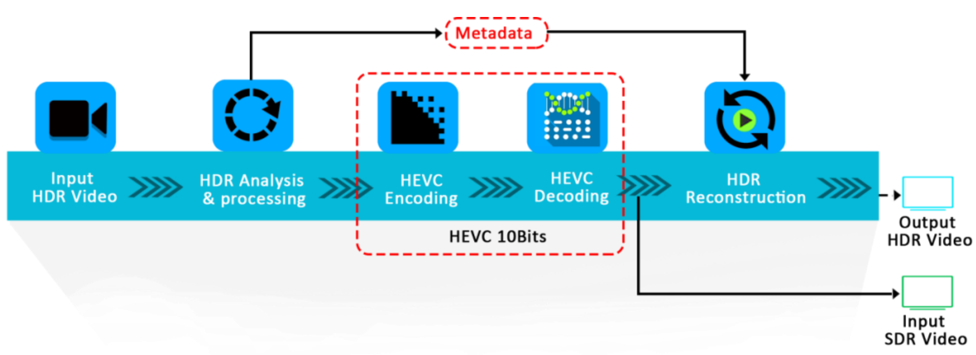

Figure 8-2 Test Model (TM) for the HDR and WCG extension of HEVC

HDR video analysis and processing: HDR analysis and processing applies prior to the HEVC encoding. It maps the input HDR signal to a format adapted to the HEVC Main 10 profile. Figure 8-3 represents a block diagram of the encoding.

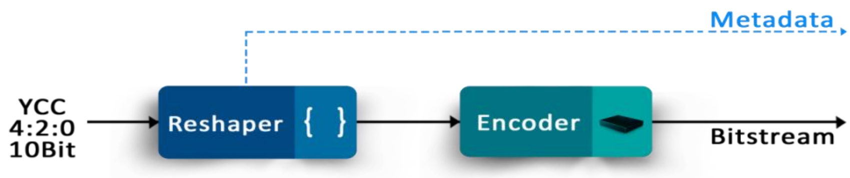

Figure 8-3 HDR Encoding Process

The normative encoding process utilizes the adaptive reshaper module after the HDR signal is converted from 4:4:4 to 4:2:0. The purpose of reshaper is to change the signal characteristics of YCbCr to improve the coding efficiency of the existing HEVC Main 10 codec, and also to potentially enable producing an SDR compatible reshaped version. The motivation of reshaper has three aspects:

- PQ is designed to cover the full range of HDR signal from 0 to 10,000 nits. However, due to the display limitation and director's intent, the video range might be smaller than the full range.
- For HDR and WCG signal, we are dealing with a much larger color volume than SDR which includes both color and intensity.
- In case of SDR-backward compatibility, reshaper performs dynamic range reduction with control of color shift resulting from this dynamic range reduction.

Reshaper is designed to simultaneously improve texture sharpness and improve color performance. It can additionally enable SDR backward-compatible support. For luma, reshaper is modeled using a piecewise 2nd order polynomial or piecewise linear model. The maximum number of pieces is 8. The use of 8 segments allows approximation of most “reasonable” curves, i.e., continuous, and bounded derivative. The 2nd order polynomial model is used to approximate complex, non-linear smooth curves efficiently without the need to use a large number of segments. For chroma, reshaper is based on piecewise linear model reshaper functions with up to 32 pieces. In some implementation, reshaper piece-wise linear functions can be implemented through a LUT. Parameters of the luma and chroma reshaper models are signaled in the PPS syntax and usually updated when there is a scene change or IRAP[29].

HDR video reconstruction process: Figure 8-4 provides an illustration of the normative HDR signal reconstruction process from the YCbCr 4:2:0 decoded samples. The 10-bit output signal from the HEVC Main 10 decoder is given as the input to the inverse reshaper process. For luma, the inverse reshaper is based on piece-wise second-order polynomial model. For chroma, the inverse reshaper is based on a piece-wise linear model[29].

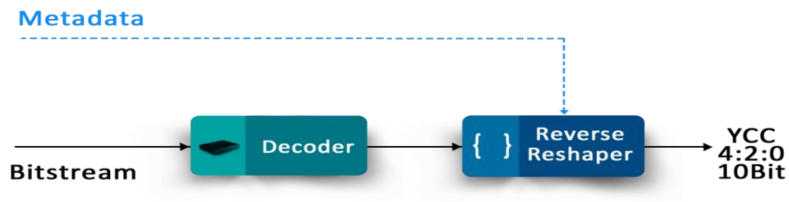

Figure 8-4 HDR Decoding Process

ARIB (Association of Radio Industries and Businesses)

ARIB, the Japanese organization that's the equivalent of DVB in Europe and ATSC in North America, has standardized upon HLG for UHD HDR broadcasts[25]. The HLG standard is royalty-free and was approved as ARIB STD-B67 by the Association of Radio Industries and Businesses (ARIB). Hybrid Log-Gamma (HLG) is a HDR standard jointly developed by the BBC and NHK.

BDA (Blu-ray Disc Association)

The Blu-ray Disc Association has released its new Ultra HD Blu-ray Disc specification with HDR10 media profile as mandatory for players and discs. This specification also includes Dolby Vision and Philips HDR formats as optional HDR video technologies for players as well as discs.

CTA (Consumer Technology Association)

The Consumer Technology Association (CTA), formerly the Consumer Electronics Association (CEA), has defined the following minimum guidelines for a TV, monitor, or projector to be referred to as an HDR-Compatible Display:

- Includes at least one interface that supports HDR signaling as defined in CEA-861-F, as extended by CEA-861.3
- Receives and processes static HDR metadata compliant with CEA-861.3 for uncompressed video.
- Receives and processes HDR10 Media Profile from IP, HDMI or other video delivery sources. Additionally, other media profiles may be supported.
- Applies an appropriate Electro-Optical Transfer Function (EOTF), before rendering the image[25].

HDMI/CEA (Consumer Electronics Association)

HDMI (High Definition Multimedia Interface) Forum released the new HDMI2.0a specification with extensions to enable transmission of HDR formats. This new version allows transmission of SMPTE ST 2086 static metadata based on CEA-861.3 (HDR Static Metadata Extensions) [10].

UHD Alliance

The UHD Alliance mostly is focused on content creation and playback, guidelines for CE devices, branding and consumer experience. It develops branding and logos in order to distinguish products that allow consumers to view content in Ultra-HD. UHD Alliance has announced a set of norms for displays, content end 'distribution' to deliver UHD with HDR, and an associated logo program. The norm is called 'Ultra HD Premium'[25]. The UHD Alliance has defined this Ultra HD Premium certification and logo for devices, content and services that meet the following minimum UHD specifications[19].

- Image Resolution: 3840x2160 for content, distribution, and playback displays
- Color bit depth: 10 bits minimum for content and distribution, 10 bits for playback displays
- Color representation: BT.2020 for content, distribution, and playback displays.
- Mastering display: SMPTE ST2084 inverse EOTF transfer function, minimum of DCI-P3 color space, peak luminance more than 1,000 nits, black level less than 0.03 nits.
- Content transfer function: SMPTE ST2084
- Playback display: SMPTE ST2084 EOTF transfer function, more than 90% of P3 color space, peak luminance more than 1,000 nits and black level less than 0.05 nits or peak luminance more than 540 nits and black level less than 0.0005 nits[19].

Ultra HD Forum

The Ultra HD Forum focuses on developing guidelines and best practices for the implementation of the end-to-end content delivery chain including production workflow and distribution infrastructure for Ultra-HD systems. The forum will also facilitate interoperability tests between vendors throughout the complete delivery chain[10].

ATSC (Advanced Television Systems Committee)

ATSC has started working on ATSC3.0, a new standard for terrestrial broadcast which includes support for Ultra-HD, HDR and immersive audio[10].

ITU-R (ITU - Radiocommunication Sector)

ITU-R Recommendation BT.2100 specifies HDR-TV image parameters for use in production and international programme exchange using the Perceptual Quantization (PQ) and Hybrid Log-Gamma (HLG) methods[28].

9. HDR Solutions

- HDR 10
- Dolby Vision
- Philips HDR
- Technicolor HDR
- BBC/NHK HDR

9.1. HDR10

The MPEG group studied HDR requirements and concluded that the HEVC Main 10 profile compression (H.265) provided the efficiency and signal quality needed for HDR delivery. Other industry groups also determined that an optimum implementation of a 10-bit 4:2:0 format base video signal would meet the requirements for delivering HDR and WCG.

Based on these conclusions, the Blu-ray Disc Association (BDA), the High-Definition Multimedia Interface (HDMI) Forum, and the UHD Alliance (UHDA) adopted a delivery format, based on HEVC Main 10, for the compression and delivery of HDR and WCG content. This base-level HDR delivery format is now commonly referred to as "HDR10". The CTA (former CEA) mandated the HDR10 media profile in their HDR-compatible display spec[19]. This is an open platform version of HDR that has been adopted by the Blu-ray Disc Association (BDA) for 4K UHD. Bit-depth 10-bit, Rec.2020 color space, SMPTE ST 2084 EOTFs, SMPTE ST 2086 metadata for delivering the extended dynamic range, which is mastered using a peak brightness of 1000 Nits. This version of HDR has been adopted by Twentieth Century Fox for the 4K Ultra HD Blu-rays that they announced recently and it is also being used by both Amazon Instant and Netflix to deliver HDR content. This version of HDR is not yet a complete standard. It is a collection of technologies and specifications, but it is incomplete as an end-to-end system.

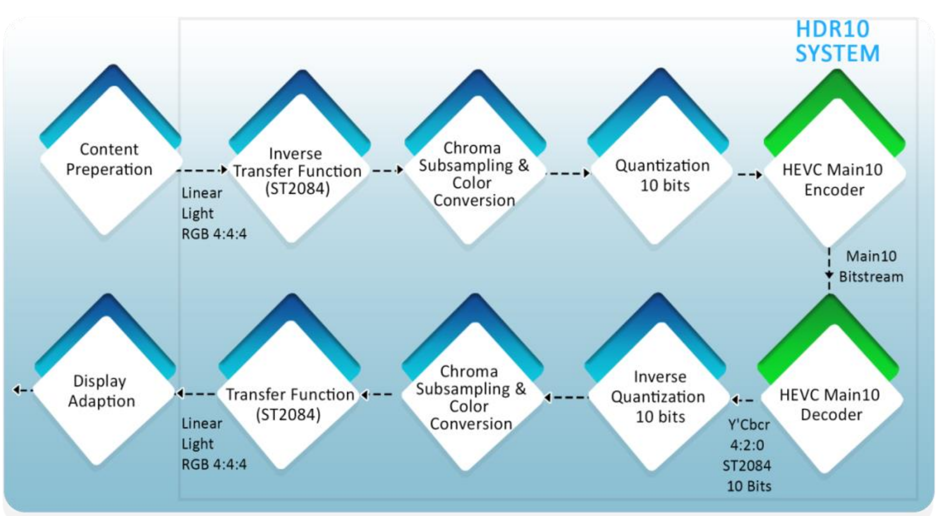

Figure 9-1 HDR10 System (Source: NGCODEC)

HDR10 is a non-backward compatible HDR system and is shown in the Figure 9-1. Linear light image data from a camera is first subject to some form of live or off-line grading, as judged by the visual results on an HDR-compatible mastering display.

The color volume of the content is always represented within a BT.2020 color space container. The RGB 4:4:4 image data is then encoded to video signal code words that best exploit human vision characteristics by using the SMPTE ST2084 PQ curve and able to represent a rather wide dynamic range of brightness with little loss of information. Color conversion and chroma sub-sampling is performed to convert the signal to non-constant luminance (NCL) Y’Cb’Cr’, 4:2:0 format and is then quantized to 10 bits per channel before it is sent to an encoder for HEVC compression.

The compressed signal is decoded and the color conversion and sub-sampling are then reversed to recover an RGB 4:4:4 signal. The signal is then applied to the SMPTE ST2084 playback transfer function (EOTF) to recover linear light values from the encoded video signal values.

The ST2086 metadata conveys the black level and peak luminance level of the mastering display, plus luminance attributes of the mastered content. If the color gamut of a playback display is narrower than that of the video content or if the peak luminance of the display is lower than that of the content, the content can be perceptually mapped to the narrower gamut or lower luminance display. The playback display should follow ST2084 as much as possible for luminance, and then roll off smoothly from some point below the playback display’s peak luminance to not clip the highest luminance levels in the mastered signal. Because, with metadata, the playback display can know the peak luminance of the content, the playback display only needs to remap to the peak luminance of the content, not to the ST2084 10,000 nits maximum.

For HDR10, though, this perceptual luminance and gamut mapping is not defined. There is currently no industry standard for the method of color volume mapping an HDR signal’s tonal range or color gamut to playback displays with a smaller dynamic range or narrower color gamut. The playback attributes of an HDR10 display can be tested, but there is currently no way to validate accurate image rendering of an HDR10 display against a standard. Some current HDR10 displays seem to ignore parts of the ST2086 metadata, which is concerning[19].

HDR10 is defined as the combination of the following container and coding characteristics[18]:

- Color container/primaries: BT.2020
- Transfer function (OETF/EOTF): SMPTE ST 2084 (with peak brightness of 10,000cd/m2)
- Representation: Non Constant Luminance (NCL) YCbCr
- Sampling: 4:2:0
- Bit Depth: 10 bits
- Metadata: SMPTE ST 2086, MaxFALL, MaxCLL, HEVC SEI messages
  MaxFALL (Maximum Frame Average Light Level): Highest frame average brightness per frame in the entire stream. Blu-ray guideline that it not to exceed 400 nits.
  MaxCLL (Maximum content light level): Brightest pixel in the entire stream.
- Encoding using HEVC Main 10 profile

9.2. Philips HDR

It is included in the specifications for 4K Ultra HD Blu-ray. It is designed to deliver a high quality HDR source over a single layer/stream using very low additional bandwidth. It uses 10-bit HEVC encode/decode, combined with the Philips HDR EOTF and display tuning to optimize the image for the display's peak luminance. The idea is that a single layer/stream combined with metadata can deliver HDR by adding low bit rate information to allow the transformation of content to the optimal grade for any display peak luminance and dynamic range. There is also a compatible mode, where the SDR video plus parameters is transmitted and the decoder uses the parameters to up convert the SDR video to HDR.

HDR delivery chain with HDR encoding: Figure 9-2 shows single layer HDR video transmission system with HDR encoding in the delivery chain.

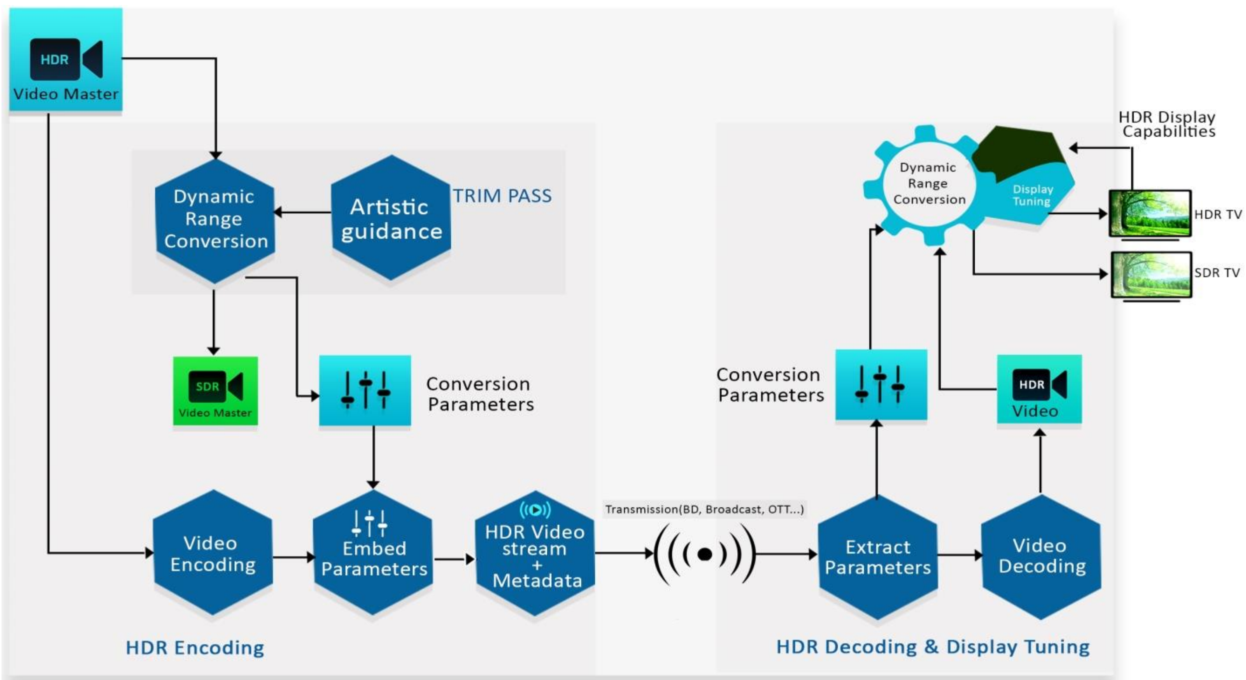

Figure 9-2 HDR Video Transmission System (Source: Philips)

The process starts from a HDR master video, graded on a reference HDR monitor (high brightness, low black levels). In the case of live production, such display should be used to monitor the HDR video master. The HDR video master is encoded. Typically, an HEVC video encoder will be used, with SMPTE ST 2084 as EOTF. An SDR video master is derived in the decoder in a semi-automatic way from the HDR master. First, an initial tone mapping is proposed. This may be based upon an average tone mapping curve, or may be created by an automatic analysis of the input image. A colorist then adds corrections to this initial to optimize the SDR master. This is typically done on a scene-by-scene basis, but may be done on a frame-by-frame basis if desired. This 'artistic guidance' process is typically done in a trim-pass. The corrections by the colorist are captured in conversion parameters, which are transmitted as content-dependent metadata along with the encoded HDR video using SEI messages embedded in the video stream. The content-dependent metadata is defined in SMPTE standard ST 2094-20. The HDR to SDR conversion operation produces a single layer stream and a set of metadata that carries extra dynamic range and color information. The characteristics of the display used for grading or monitoring, such as peak luminance and black level, are added as SMPTE ST 2086 metadata to the video stream.

At the receiving side, the video stream is decoded, producing HDR video. The conversion parameters are extracted from the SEI messages. If an SDR output signal is desired, exactly the same dynamic range conversion process as set by the colorist on the encoder side is repeated in the decoder, producing an SDR signal. If an HDR display is connected, the conversion parameters are used to produce an HDR output signal optimized for the specific display capabilities of the display[26].

HDR delivery chain with SDR encoding: For applications that require an SDR compatible transmission signal, a compatible mode is available, in which not the HDR master but the SDR master video is (HEVC) encoded and transmitted along with the conversion parameters (as shown in Figure 9-3).

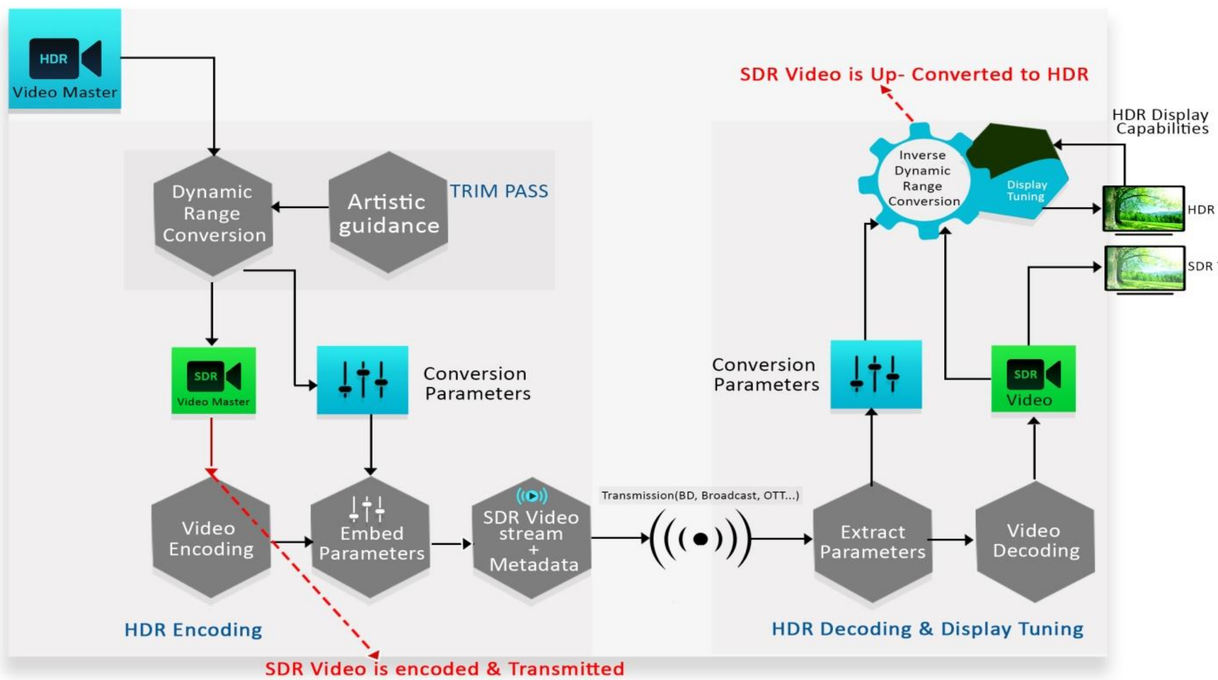

Figure 9-3 HDR System with SDR Transmission (Source: Philips)

The decoder receives the SDR signal that can go directly to an SDR display. An 'HDR-aware' decoder retrieves the conversion parameters from the video stream. Inverse dynamic range conversion is applied to the video to obtain the HDR video. In this compatible mode, the conversion needs to be invertible. This puts some constraints on the HDR to SDR conversion, e.g. hard clipping is not allowed. In a recent MPEG test, it was shown that the Philips HDR system using this SDR-compatible mode of operation actually provides better video quality than straightforward encoding of the HDR video[26].

9.3. Dolby Vision

Dolby Vision™ is based on extensive research to identify the practical limits of the human visual system dynamic/color range for entertainment purposes and then develop a flexible, scalable, end--to--end solution to increase the capability of each pixel to represent more and brighter colors as well as increased dynamic range (aka "better pixels").The research concluded a system which is capable of delivering content with a dynamic range from 0.001 to 10,000 nits, would satisfy the vast majority of viewers (~84%) on a range of consumer devices from tablets to very large TVs and even theatrical displays. However, for a dynamic range of 10,000 nits, gamma 2.4 does not accurately match the contrast sensitivity nonlinearity derived from the light--adaptive function of the human eye. Consequently, a new perceptually--based quantizer EOTF called PQ was developed following the contrast sensitivity function of the human eye as measured by Barten and referenced in Report ITU--R BT.2246--2 and subsequently standardized as SMPTE ST--2084. As for precision: For noise--free images such as animation, CGI, or graphics, using 12--bit PQ ensures that both monochromatic and color--banding artifacts are below the visible threshold. For natural images that contain some noise, using a 10--bit PQ representation is adequate, but care needs to be taken, especially with graphics. For simplicity, we refer to images with higher dynamic range/wider color gamut than SDR as High Dynamic Range (HDR) [3].

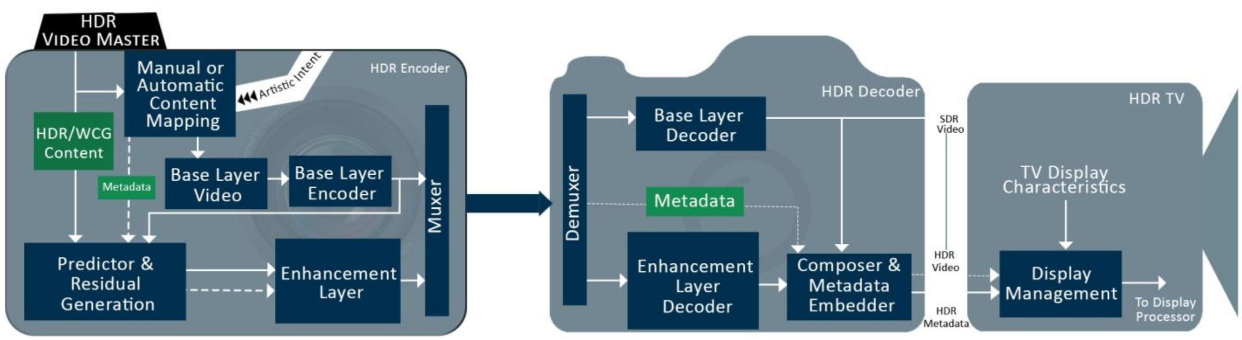

Figure 9-4 Dolby Vision HDR System (Source: Dolby)

Dolby's "Pulsar" professional reference display with a 4000 nit (D65)/P3 color volume, plus a set of plug--ins for off--line production suites, enable creatives to master in the largest available color volume. During HDR mastering, metadata is generated based on creative input. This metadata is used downstream to guide the display management in the consumer device. For backwards compatibility with BT.709, BT.2020, etc., a dual--layer codec architecture has been developed which transmits existing standards either SDR HDTV or HDR10 (optional on Ultra HD Blu-ray) as a backward compatible 10-bit base layer while a 2-bit HDR Enhancement Layer (EL) provides information necessary to recreate the Dolby Vision HDR. This dual layer codec works outside of the coding loop so that no changes are required to legacy encoders or decoders. The solution works with any spatial resolution, bit depth, color primaries, and color volumes up to 10,000 nits for either an 8--bit AVC or an 8/10--bit HEVC base layer. 10 or 12 bit PQ inputs will be faithfully reconstructed at the dual decoder output. The Dolby Vision enhancement layer increases the bitrate by only ~20--25% above the backwards--compatible base layer. Dolby has also developed a single layer non--backwards compatible 10 bit solution for broadcast or OTT applications which provides even greater bitrate efficiency in use cases where backwards compatibility is not required and works with legacy dual layer decoder implementations[3]. This single layer offers the ability to use dynamic metadata and, with the Dolby proprietary tunneling technology, retains the 12-bit mastering fidelity, even though the transport is 10-bit HEVC.

Dolby Vision is a proprietary HDR system requiring display manufacturer licensing. Dolby developed RGB tunneling over HDMI, with the metadata embedded in the signal itself, to allow proprietary Dolby Vision 12-bit video and metadata to travel through HDMI 2.0 interfaces, without having to wait for the standardization of HDMI 2.0a. Dolby Vision uses proprietary end-to-end dynamic metadata to precisely define image luminance and chromaticity. It conveys the black level and peak luminance level of the mastering display plus overall luminance attributes of the mastered content. It also conveys color volume attributes for each new scene[19]. During HDR mastering, dynamic metadata for Dolby Vision is generated to reflect the relationship between the HDR and SDR versions of each video frame. This dynamic metadata is carried in the Dolby Vision enhancement layer.

All Dolby Vision playback devices are compatible with both single-layer and dual-layer profile content.

A Dolby Vision dual-layer stream with an SDR base-layer and an enhancement layer can be decoded, combining the SDR stream with the enhancement layer stream and dynamic metadata, to produce Dolby Vision HDR video, with dynamic metadata, to drive a Dolby Vision display. Or, the SDR stream can simply be decoded to produce SDR video to drive an SDR display.

A Dolby Vision dual-layer stream with an HDR10 base-layer and an enhancement layer can be decoded to produce Dolby Vision HDR video, HDR10 video, or SDR video.

In a Dolby Vision HDR decoder, the original mastered 12-bit PQ content is reconstructed by combining the 10-bit SDR or HDR10 stream, the 2-bit enhancement layer stream, and the dynamic metadata to produce 12-bit HDR video at the decoder output, with dynamic metadata.

A Dolby Vision display uses the dynamic metadata, along with the display characteristics, to map the HDR video to the capabilities of each particular playback display[19].

Dolby Vision Decoder, Composer and Display Manager

Dolby Vision is compatible with a wide range of video codecs. It’s currently qualified with HEVC and AVC decoders. There are multiple ways to encode and decode Dolby Vision signals. Depending on the needs of the content creator and on the capabilities of the target display hardware, Dolby Vision signals can be delivered using a single HEVC Main-10 stream or as two AVC-8 or HEVC-8 or HEVC-10 streams[27].

Single Layer Dolby Vision: The single layer HEVC Main-10 profile of Dolby Vision can be decoded by a standard HEVC decoder, then post-processed using a Dolby Vision module to produce the full range 12 bit Dolby Vision signal[27].

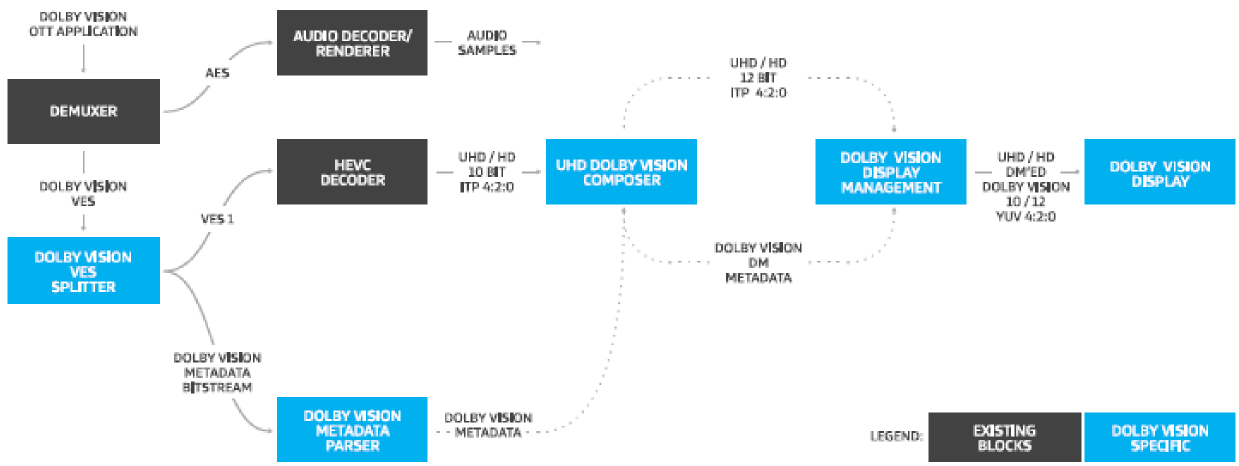

Figure 9-5 Single Layer Dolby Vision (Source: Dolby)

Dual Layer Dolby Vision: For dual layer AVC or HEVC Dolby Vision profiles, the source stream (typically a video elementary stream with interleaved base-layer AUs, enhancement-layer AUs, and metadata RPUs) is split, and the base and enhancement streams are fed through separate decoders[27].

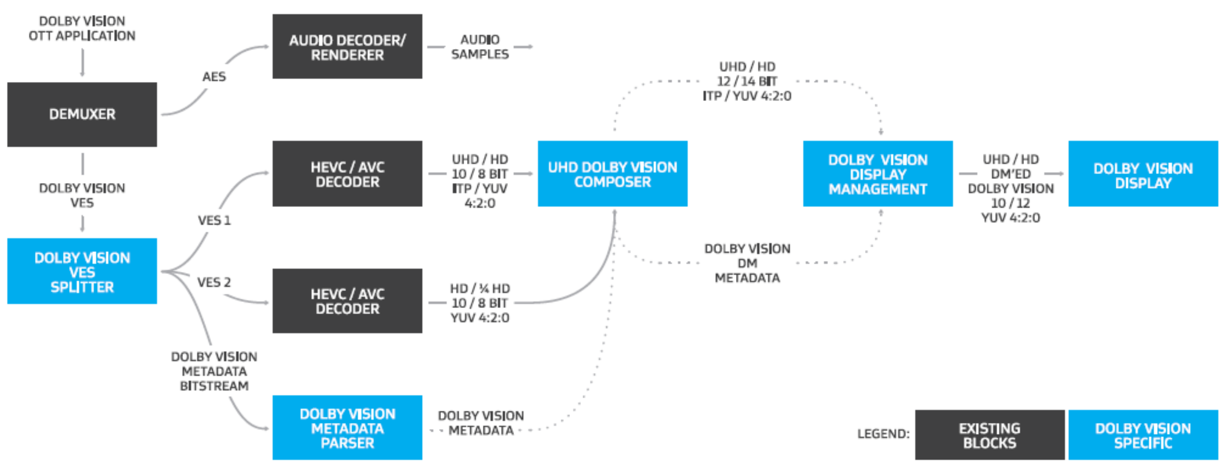

Figure 9-6 Dual Layer Dolby Vision (Source: Dolby)

Composer: The Dolby Vision composer is responsible for reassembling the full-range signal from the base layer, the enhancement layer, and the metadata[27].

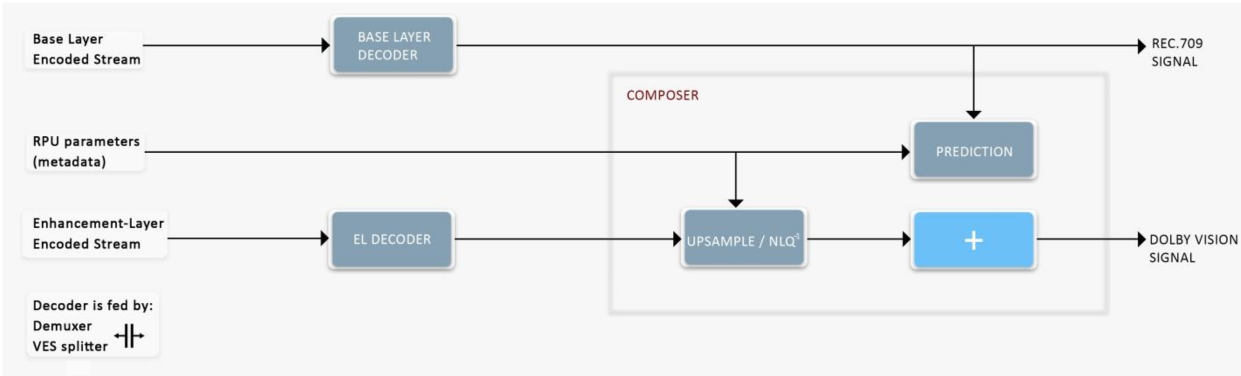

Figure 9-7 Composer - Dolby Vision (Source: Dolby)

Display Manager: The Display manager is tuned for the target display device: it knows the maximum and minimum brightness, color gamut, and other characteristics of that device. Metadata that accompanies the full-range Dolby Vision video signal carries information about the original system used to grade the content and any special information about the signal. Using this metadata, the display manager intelligently transforms the full-range signal to produce the best possible output on the target device[27].

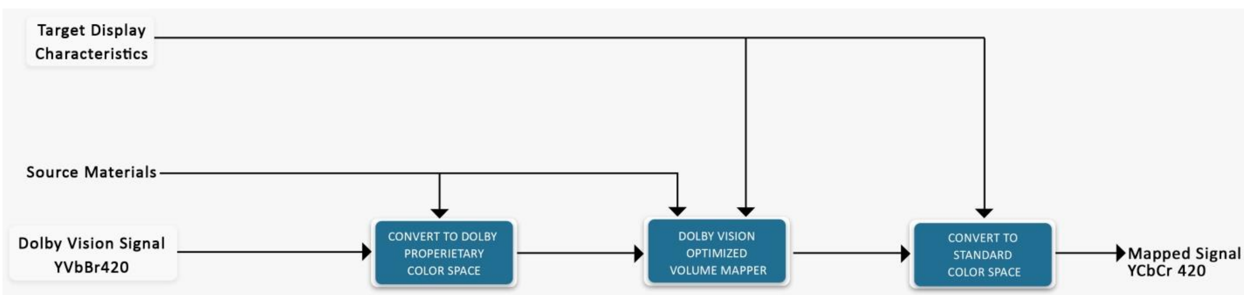

Figure 9-8 Display Manager - Dolby Vision (Source: Dolby)

A major difference between the Dolby Vision approach and other HDR solutions is the metadata that accompanies each frame of the video all the way to the display manager in the consumer-playback device. Systems with generic HDR carry only static metadata that describes the properties of the color-grading monitor that was used to create the content and some very basic information about the brightness properties (maximum and average light levels) for the entire piece of content. Dolby Vision adds dynamic metadata that is produced during content creation; the dynamic properties of each scene are captured. With this information, the Dolby Vision display manager is able to adapt the content to the properties of the display much more accurately. It allows hues to be preserved properly, which is critical for display of skin tones. Even with mass market edge-lit TVs, the overall impression of colors is preserved much more accurately.

Guided by the Dolby Vision metadata, the Dolby Vision display manager enables great visual experiences on a wide range of display devices ranging from higher-end OLED TVs with stunning black levels to LCD TVs with advanced technologies like quantum dot, all the way down to mass-market edge-lit TVs[27].

9.4. Technicolor HDR

Figure 9-9 shows an end-to-end workflow supporting content production and delivery to HDR and legacy SDR displays. This HDR workflow is based on technologies and standards that facilitate an open approach, including a single layer SDR/HDR HEVC encoding, the MPEG standardized Color Remapping Information metadata (CRI) for HDR to SDR conversion, a Parameterized Electro--Optical Transfer Function (P-EOTF), and SHVC. This ensures that consumers at home experience what the filmmaker intended[3]. Technicolor proposes that SMPTE consider standardization of a future proof P-EOTF based on simple parameters and powerful enough to represent SMPTE ST 2084 and other EOTF curve shapes more suited for television as proposed by the BBC, NHK, (Hybrid Log-Gamma) and others.

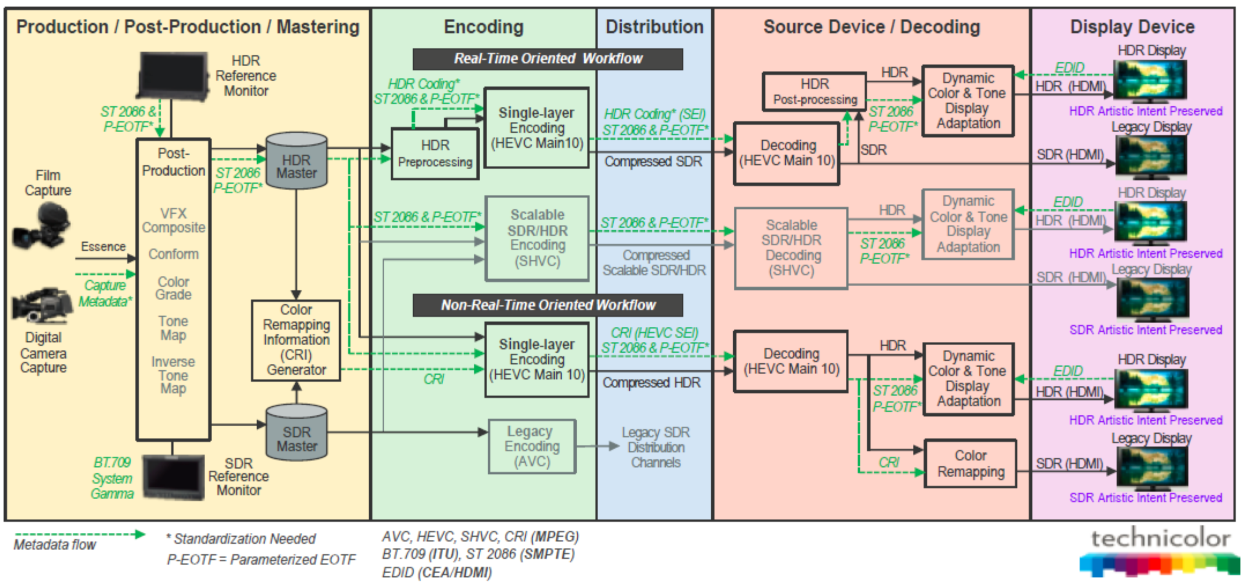

Figure 9-9 Technicolor HDR Ecosystem workflow

Technicolor identified three ways to deliver content in both HDR and SDR: (1) Backward compatible single layer SDR/HDR encoding with mastering metadata, (2) Single layer HDR Encoding with CRI to support SDR displays, and (3) A future dual layer scalable SDR/HDR encoding. Single layer encoding requires only one HEVC decoder in the player/display and supports the real-time workflow requirements of broadcast applications. For non real-time applications, single layer HDR encoding with CRI preserves quality and creative intent on HDR and SDR displays.

HEVC Version 2, standardized by the ITU-T/ISO/IEC JCT on video coding, specifies CRI carried in the HEVC stream as an SEI message to enable remapping of reconstructed color samples to match another grade having a different color gamut and dynamic range. The HDR grade(s) and SDR grade produced by content creators are available as input to a CRI generator to produce the CRI. A CRI capable source device (e.g., a UHD Blu-ray player or Set Top Box) remaps the tone scale and color gamut of the HDR content to produce SDR output matching the artistic intent approved by the filmmaker in the SDR master[3].

9.5. BBC/NHK HDR

Hybrid Log-Gamma (HLG) is a high dynamic range (HDR) standard that was jointly developed by the BBC and NHK (Japan Broadcasting Corporation). The HLG standard is royalty-free and was approved as ARIB STD-B67 by the Association of Radio Industries and Businesses (ARIB). HLG is based on open standards to promote maximum access and free and fair competition within the industry. This standard has been optimized for both dynamic range and for compatibility with existing SDR standards. The BBC feels that the SMPTE ST 2084 EOTF isn't best suited to broadcast and, in conjunction with NHK, they have developed a revised EOTF called 'Hybrid Log Gamma' that has been standardized by ARIB (STD-B67). The BBC approach is designed to incorporate many of the attributes of HDR already mentioned but to deliver them in the most efficient and cost-effective manner possible.

Hybrid Log Gamma (HLG): The BBC's proposal is to replace the conventional gamma curve, specified in ITU Recommendations 601, 709 and 2020, with an HDR alternative. Simply increasing the bit depth of the conventional gamma curve would not provide a sufficient increase in dynamic range. BBC proposes to retain more or less the conventional gamma curve for low lights and use a logarithmic curve for highlights. In the low lights we propose to use a pure gamma curve for the electro optic transfer function (i.e. the "gamma" curve" in the camera), without the linear part used hitherto. The linear part of the curve was, previously, used to limit camera noise in dark parts of the picture. However, HDR cameras necessarily have lower noise and so the linear part of the curve is no longer appropriate and removing it increases the dynamic range. In the highlights, the bright parts of the picture, BBC propose to use a logarithmic curve, which increases the dynamic range in a psycho-visually optimum way when Weber's law of vision applies. The logarithmic curve is chosen to be continuous with the conventional gamma curve, and the slope of the curve is also continuous, providing a smooth OETF overall[3]. This hybrid curve is referred as Hybrid Log Gamma (HLG) as it applies a standard gamma curve for darker pixels in the legacy SDR range and a logarithmic curve for higher brightness highlights as shown in Figure 3-7. The HLG technology is royalty free and does not require licensing by either broadcasters or display equipment manufacturers. The HLG proposal is fully specified from end to end. It has a complete mastering spec and a complete playback spec, so proper playback can be validated.

On the display side BBC proposed a parameterized electro--optical transfer function (EOTF) which allows the signal to be displayed on a wide range of displays, with varying peak luminance, black level and viewing environments, to produce a high quality picture. This feature is essential to support the conventional model of video production and distribution. In addition to allowing for variations in black level and peak white the BBC EOTF also supports variable end-to-end system gamma to support varying viewing environments.

8 bit signal is inadequate for HDR either in production or for distribution but 10 bits is sufficient for both production and distribution and has the advantage of being compatible with existing production infrastructure. According to BBC and NHK, HLG is compatible with existing 10-bit production workflow infrastructure such as 10 bit SDI interconnects, compressed links and existing SDR monitoring. With ten bits it can support dynamic range about 100 fold greater than SDR television. 12 bits might also beneficially be used in production[3]. In distribution only a single compressed 10 bit signal would be transmitted, to feed both SDR and HDR receivers rather than requiring a complex layered coding solution. When HLG HDR content is decoded and displayed on an SDR display, the image may look a bit different from a non-HLG

HDR image, but it will be perceptibly HDR-looking according to BBC/NHK. However, this backward compatibility of HLG with SDR displays applies only to SDR displays implementing the BT.2020 color space. To receive an HLG broadcast, a TV needs to switch to high brightness mode and use the HLG EOTF, rather than a gamma power, BT.1886, or ST2084 EOTF. The HLG system takes a relative luminance approach to its HDR transfer function, like BT.709, allowing each playback display to map a video signal's maximum code word to the peak luminance of that specific display, rather than to a specific luminance level.

This HDR system does not require end to end metadata during the production process and avoids maintaining the integrity of metadata throughout the chain which is extremely difficult (it is difficult even to ensure correct audio visual sync!). So the signal is display-independent and can be rendered unprocessed on an SDR display.

Traditional SDR video systems have a capture OETF and a display EOTF that aren't exact inverses of each other, to provide a system gamma (OOTF) of approximately 1.1 to 1.2. This system gamma, referred to as the rendering intent, compensates for the effects of ambient light in the viewing environment. A byproduct of variable system gamma is that image saturation depends on the system gamma produced by each particular display. Higher system gamma creates a more saturated image[19].

In the HLG system, the system gamma is automatically adjusted in each playback display, based on its dynamic range and the ambient lighting surrounding the display. A playback display with very high dynamic range and low ambient surround might produce a system gamma as high as 1.6. A display with just better than SDR capability might produce a system gamma of only 1.3.

To avoid saturation differences with the differences in system gamma, an HLG-compliant display first inverts the capture OETF and calculates the relative Y value for each pixel. A rendering intent gamma is then developed for each pixel, based on the pixel's derived Y value, plus the display's black level, peak luminance, and surround light level. The rendering intent gamma is applied to each of the pixel's RGB components in unison.

This inclusion of each pixel's relative Y value in the rendering intent preserves the colorimetry of each pixel value despite different rendering intents (system gamma). This amounts to HLG displays doing a limited form of color volume mapping, despite metadata not being used by the system. Unlike HDR systems that use the SMPTE ST2084 PQ curve, the HLG system is defined by its OETF[19]. It was designed to have the OOTF (rendering intent) applied in the display as shown in Figure 9-10.

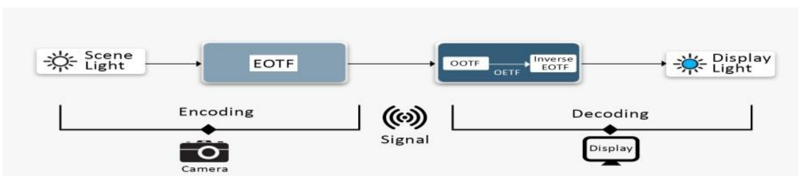

Figure 9-10 OOTF in Display in HLG System (Source: ITU)

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