This application note discusses the use of high dynamic range (HDR) in broadcasting as well as the implementation of a broadcast chain for UHD.
## Contents

1. The UHD-1 Format – 4K at Home .................................................. 3
2. High Dynamic Range (HDR) .......................................................... 4
   2.1 Wide color gamut (ITU-R Rec. 2020) .................................... 4
   2.1.1 Chroma Subsampling ...................................................... 4
   2.1.2 Color Depth ................................................................. 4
   2.1.3 Color Space ................................................................. 6
   2.2 Increased Dynamic Range of Luminosity .............................. 7
   2.2.1 EOTF vs. OETF ............................................................ 8
   2.3 HDR Metadata Standards ................................................... 10
   2.4 Downward Compatibility ................................................... 10
3. The HDR-UHD Broadcast Chain with the R&S®AVHE100 ............ 11
4. References .................................................................................. 13
1 The UHD-1 Format – 4K at Home

Ultra high definition (UHD-1) is a broadcast video format that contains four times more pixels than a broadcast high definition (HD) frame (3840x2160 pixels vs. 1920x1080 pixels). Unlike the current two HD broadcast formats (1920x1080i 50/60 and 1280x720p 50), pictures are no longer transmitted as fields in interlaced scanning mode but rather in progressive mode at 50 or 60 frames per second (3840x2160p 50/60).

UHD-1 is commonly also known as 4K, but this term originates from the fields of professional production and cinema, where digital projection requires a resolution of 4096x2160 pixels (so about 4000 pixels horizontally) and a refresh rate of 24 frames per second for standard films or 48 frames per second for high frame rate (HFR).
2 High Dynamic Range (HDR)

Many Ultra high definition televisions will include HDR functionality, which provide a more realistic and immersive viewing experience. This is achieved by increasing the color space representation with wide color gamut and increasing the range of luminosity.

2.1 Wide color gamut (ITU-R Rec. 2020)

ITU-R Rec. 2020 (also called BT. 2020) defines the screen resolution, refresh rate, chroma subsampling, color depth, and color space that are used for the various UHD formats.

2.1.1 Chroma Subsampling

The 4:2:0 chroma subsampling scheme used for SD and HD will continue to be used for UHD. This data reduction method takes advantage of the human eye’s relatively low sensitivity in terms of color resolution, as well as its high sensitivity with respect to luminance.

The camera image in RGB format is converted to luminance and color difference data (RGB --> YCbCr), after which every second chroma component is removed both horizontally and vertically.

<table>
<thead>
<tr>
<th>Chroma subsampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Luminance data</td>
</tr>
<tr>
<td>CbCr Color difference data</td>
</tr>
<tr>
<td>YCbCr</td>
</tr>
</tbody>
</table>

2.1.2 Color Depth

Color depth refers to the number of luminance or chroma components per pixel. UHD TV broadcast increases the color depth to 10 bits (1024 shades) for luminance (Y) and for the two color difference signals (Cb and Cr) because otherwise the
transitions would be visible if only 8 bits (256 shades) were used on the latest UHD TV displays. This effect is known as banding or posterization.

Fig. 1 - Banding effect.

Rec. 2020 provides for enhancement up to 12 bits (4096 shades). In contrast, SD and HDTV use a color depth of only 8 bits.

![Color depth diagram]

<table>
<thead>
<tr>
<th>Color depth</th>
<th>1 bit (2 gradations)</th>
<th>2 bit (4 gradations)</th>
<th>4 bit (16 gradations)</th>
<th>8 bit (256 gradations)</th>
<th>10 bit (1024 gradations)</th>
<th>12 bit (4096 gradations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 bit</td>
<td>2 gradations</td>
<td>4 gradations</td>
<td>16 gradations</td>
<td>256 gradations</td>
<td>1024 gradations</td>
<td>4096 gradations</td>
</tr>
</tbody>
</table>
2.1.3 Color Space

The color space defines the displayable or visible colors in a color model. Both of the figures below show color space CIE1931 with the positions of the primary colors, while the triangle represents the colors that can be displayed. Rec. 601 represents standard definition (SD) and Rec. 709 high definition (HD).

The white point is defined in line with D65 and corresponds to about 6500 Kelvin, or average daylight.

As a result, the color space from Rec. 2020 can display colors that cannot be displayed with Rec. 601/709, and it covers about 75.8 % of the CIE1931 color space as compared to 35.9 % for Rec. 601/709.
Enlarging the color space while retaining the original 8-bit color depth would cause too much distance between adjacent chroma components and would result in a similar banding or posterization effect. The color depth must therefore be increased in parallel from 8 to 10 in order to maintain or increase the color accuracy.

### 2.2 Increased Dynamic Range of Luminosity

Besides color rendition, contrast is also critical for HDR to allow dark and bright details to be seen in the picture that would otherwise be invisible. As shown in the following figure, HDR-ready TVs can achieve darker black levels and brighter white levels, making details visible that would normally disappear in a gray or white picture area on legacy TVs.
The luminance of a HDR television is significantly increased without turning the black areas into gray areas which is what typically happens on legacy TVs if the background illumination is simply increased. UHD TV manufacturers instead use techniques such as local backlight dimming and new types of crystals or coatings in LCDs or OLEDs. Today's flat screen TVs are capable of up to 400 nits (cd/m²), 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.

2.2.1 EOTF vs. OETF

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. The EOTFs for Rec. 601 (SD) and Rec. 709 (HD) represent a gamma function with a gamma of 2.2. This describes the characteristics of phosphor in legacy cathode ray tube (CRT) TVs and is therefore known as standard gamma.

On the input (camera) side, an inverse function (opto-electrical transfer function, or OETF) is used on the data after reading the camera sensor. This provides a linear relationship between the electrical signal and the luminance.

These standard gamma curves are still used today in broadcasting for the recording and playback of SD and HD signals.
Modern TVs no longer use CRTs and so allow the use of different EOT functions for recording, postprocessing and playback with better rendition and utilization of the displayable color space and dynamic range. The standard gamma curve can display up to 7 f-stops (100%). Modern CMOS image converters on the recording side can capture a dynamic range of up to 14 f-stops (1300%). However, clipping in the bright picture areas can become a problem in this situation. A number of different EOTFs have therefore been developed for different camera and display combinations and applications.

One group of these EOTFs, based on hyper-gamma curves (HG), have a dynamic range of up to 800% and are already widely used in digital cinematography.

The class of S-Log curves (Sony) can display up to 14 f-stops, which corresponds to about 1300% of the dynamic range of the standard gamma curve.

Dolby’s perceptual quantizer (PQ) curve was defined for the DolbyVision HDR process. A dynamic range of up to 10 000 nits should be possible with a color depth of 10 bits to
12 bits. This curve takes advantage of the fact that the eye cannot perceive details in very light areas.

2.3 HDR Metadata Standards

The following documents describe the HDR extensions for the entire broadcast chain:

- SMPTE ST 2084 - High Dynamic Range ElectroOptical Transfer Function of Mastering Reference Displays
- SMPTE ST 2085 - Color Differencing for High Luminance and Wide Color Gamut Images
- SMPTE ST 2086 - Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images
- SMPTE ST 2094 - Content-Dependent Metadata for Color Volume Transformation of High Luminance and Wide Color Gamut Images

2.4 Downward Compatibility

The encoded data stream should be transmitted only once during the broadcast and should be compatible with both normal and HDR-ready TVs. This is possible by embedding additional metadata alongside the compressed video data in the transport data stream as specified by the HEVC.

This metadata includes the color space being used (Rec. 709 or Rec. 2020), the maximum luminance of the mastering display in nits and the white point being used (D65 or DCI-P3). The electro-optical transfer functions, which determine the conversion from an input signal to the display, can also be signaled. A TV that can interpret this ancillary data displays the video signal in HDR, whereas a TV that cannot interpret the data displays the video in the old Rec. 709 standard. However the non-HDR display will typically look washed out and dull and not as brilliant and colorful as the HDR display.
3 The HDR-UHD Broadcast Chain with the R&S®AVHE100

In order to create a complete broadcast chain, all components from the camera to the video mixer and encoder to the TV must support and transmit the signals in accordance with Rec. 2020. As soon as a component cannot correctly interpret the signal, the entire signaling is lost resulting in the video signal interpreted and displayed in standard mode, even on HDR-ready TVs.

Modern broadcast cameras can record in RAW mode with up to 16-bit color depth in 4:4:4 mode. In live operation the video is typically output from the camera via four separate 3G-SDI signals, with each 3G-SDI cable carrying one quadrant of the UHD picture at 1920x1080 and up to 60 frames per second. These 4 HD quadrants are then combined to make one UHD picture by the video mixer.

The color artist evaluates the camera settings via a reference monitor that is directly connected to a camera control unit (CCU). From the CCU, all essential operating parameters for the camera can be set remotely from the outside broadcast vehicle, allowing the cameraman to concentrate on the video composition. These parameters include white balance, color level, gamma curve, shutter, lighting, f-stop, etc.

The video signals are then enriched with overlays for soccer games (broadcaster logos, game stats, tables, and so on).

The edited 4x 3G SDI signals then go from the mixer to the R&S®AVHE100 – an encoding and multiplexing solution from Rohde and Schwarz. Here, the four HD
quadrants are combined back into a UHD picture for encoding ensuring that picture in each quadrant has the same timing as the other quadrants.

Fig. 3 - The R&S®AVHE100 encoding and multiplexing solution.

This UHD picture is then encoded by the highly efficient HEVC (H.265) video codec which compresses the input 12 Gbit/s UHD signal down to about 30 Mbit/s. Additional HDR metadata is then inserted into the video data stream. This metadata can include the EOTF being used, the maximum light density for the reference monitor, the white point, etc.

The encoded video data stream is then multiplexed with one or more compressed audio tracks and other ancillary data streams such as HbbTV, teletext and DVB subtitles, into a MPEG-2 transport stream and then sent to a satellite modulator.

The signal generated by the satellite modulator is then uplinked to the satellite and then back to earth to a suitable satellite receiver.

UHD TVs are already equipped with one or more DVB-S2 tuners and the ability to decode HEVC encoded video streams.

A non-HDR UHD TV decodes the raw video and sends it to the display using the preprogrammed standard Rec. 709 EOTF.

On the other hand, a state-of-the-art HDR-ready TV can interpret the additional embedded ancillary data and display the video signal as a brilliant, intense picture using the embedded Rec. 2020 compatible EOTF.

HDR thus permits complete control of the video data displayed on TVs throughout the entire production chain.
4 Bibliography


Glossary

C

CCU: Camera control unit

CIE1931: CIE Norm Valence System or CIE standard color system as defined by the Commission internationale de l'éclairage

Clipping: The application of input signals outside of the allowed input range on signal processing units

EOTF: Electro-optical transfer function

HD: High definition

HEVC: High efficiency video coding (HEVC), also known as H.265 or MPEG-H Part 2

HFR: High frame rate

HG: Hyper gamma

LCD: Liquid crystal display


Nits: Unit of luminance; also candela per square meter

OETF: Opto-electrical transfer function

OLED: Organic light emitting diode

PQ: Perceptual quantizer

Rec. 2020: ITU-R Recommendation BT.2020, more commonly known by the abbreviations Rec. 2020 or BT.2020 was approved in 2012

Rec. 601: ITU-R Recommendation BT.601, more commonly known by the abbreviations Rec. 601 or BT.601 (or its former name, CCIR 601) is a standard originally issued in 1982 by the CCIR

Rec. 709: ITU-R Recommendation BT.709, more commonly known by the abbreviations Rec. 709 or BT.709 was approved in 1990

RGB: Colors red, green, and blue

SD: Standard definition

Shutter: Lightproof, mechanically movable part lies in the optical path before the focal plane in a camera

UHD: Ultra high definition
Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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