White Paper

The Status of Wide Color Gamut UHD-TVs

January 2016

By

Chris Chinnock
Insight Media
3 Morgan Ave.
Norwalk, CT 06851 USA
203-831-8464
www.insightmedia.info

Table of Contents

Table of Figures

Table of Tables

Introduction

UHD TVs with a resolution of 3840x2160 are now common in the market place and will soon surpass sales of 1080p TVs. But the roll out of UHD TVs and UHD content will not be uniform. There are several aspects to improved image quality besides more pixels. These enhancements, producing what are sometimes called "better pixels", include:

- Wider Color Gamut (WCG)
- High Dynamic Range (HDR)
- Higher Frame Rate (HFR)

TVs and content will be offered that feature various combinations of the above features. And, these features have variations within them that offer different levels of performance. It is a complex matrix of content offering and display capabilities that is sure to be very confusing to the end user.

In this white paper, we will focus on the improvements that wide color gamut will bring to new content and to TVs that have this capability. Since WCG will also be coupled to HDR in many cases, we need to discuss this to some degree as well. HFR will not be discussed.

The report will discuss what wide color gamut is, the challenges to creating and delivering wide color gamut content to TVs, what platforms are now ready to deliver this content and what TVs are ready to receive and display WCG content. In addition, we will dive into the various approaches to creating WCG TVs as there are several methods with various trade-offs.

Market research suggests that WCG displays are desired by consumers. According to a recent IHS Technology forecast, WCG flat-panel displays – from smartphones to TVs - will grow from 2.8% of the display market in 2015 to 25% by 2020 in terms of display area shipped. In 2015, TV displays will constitute 52% of the WCG market, rising to 86% in 2020.

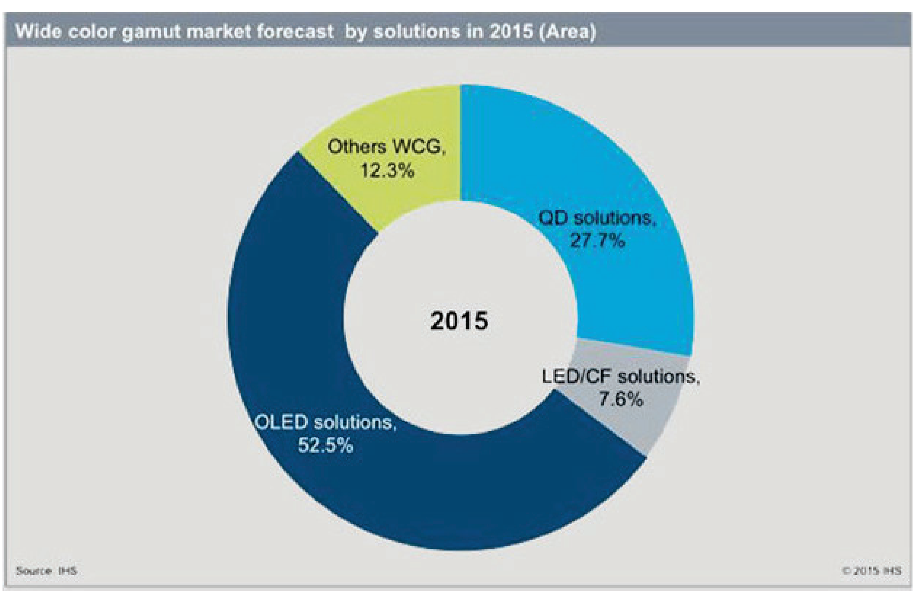


Figure 1: Wide Color Gamut Flat-Panel Forecast for 2015 by Technology (Source: IHS)

Quantum Dot technology will be adopted strongly by TV makers. According to IHS, the market share of the QD solution will grow from less than 1% in 2015 to more than 9% in 2020, driving the growth of the wide color gamut display market.

IHS also published a forecast on High Dynamic Range (HDR) TVs. As we will see, wide color gamut and high dynamic range will be closely coupled in content and display. This forecast offers unit shipments of around 2.9 M sets in 2016 growing to about 32.6M sets. Adoption really starts to take off in 2017 with China taking the lead on unit sales and Japan running up a high percentage of sales over the forecast period.

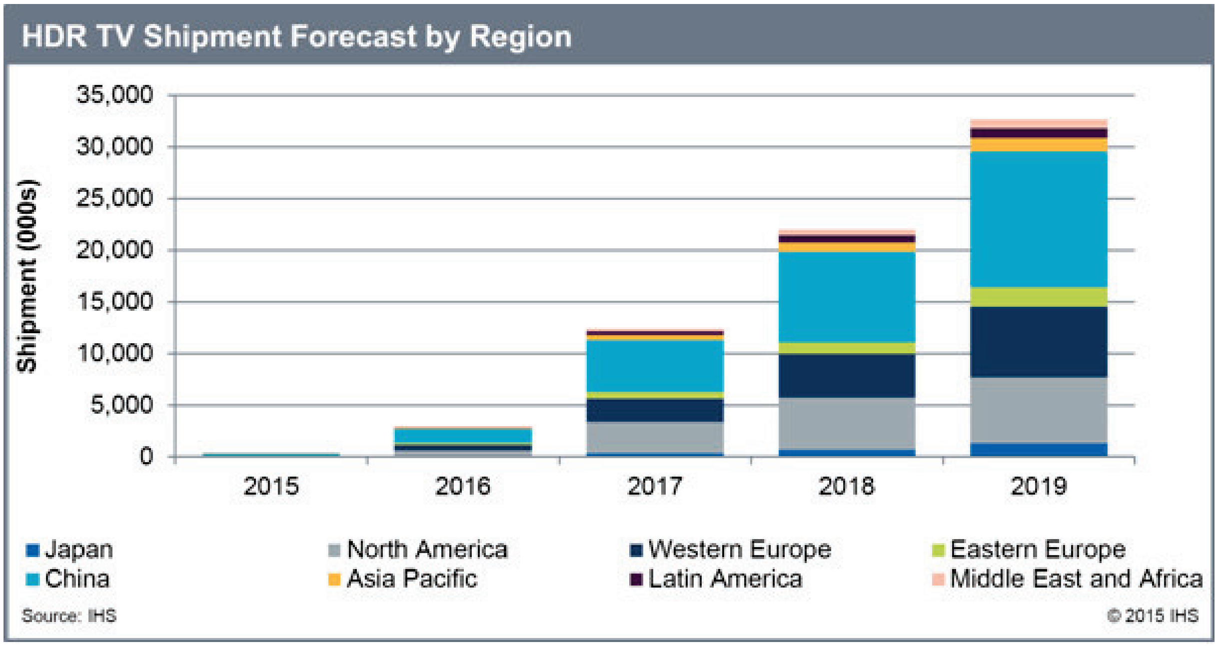


Figure 2: IHS HDR Forecast by Region

Color and Color Gamuts

What is Wide Color Gamut?

Color science is a complicated topic that we will attempt to simplify here (with apologies to the color scientists). Color science must describe:

- The naturally-occurring colors in the world
- The total volume of colors (natural and artificially generated) - What our eyes can see

In addition, there are aspects of color engineering that were developed to help capture color images, prepare them for distribution to end users and to present them on electronic displays. These aspects are captured in standards for:

- Color encoding

- Color sub-sampling
- Color gamut

The presentation of color images on display devices is done with a number of technologies. The choices of these technologies have an impact on how the human eye and brain perceives these images.

Color Volume

Color is best described as a three-dimensional volume. But most of the time, color is discussed as a region of a two-dimensional plane. 2D charts describe the color performance of the display at a single luminance (brightness) level, but not all of the luminance levels the display can create, and the color performance may differ with luminance; it can be hard to maintain a very saturated color at low luminance, for example. Thus luminance is the third dimension in the color volume representation of color.

Figure 3 shows a common 2D method for showing the color capabilities of the display - the 1976 CIE *u'v'* chromaticity diagram. The horseshoe shaped area of the diagram represents all the colors that the human eye can see. Interestingly, nature does not create colors to fill this horseshoe. The irregularly shaped circle (Pointer's Gamut) represents the surface of natural colors in the world. Artificial light sources like neon, LED lights, and laser sources have colors that extend beyond the surface colors boundary. In addition, color can be computer-generated as cartoons and graphics that can be anywhere in the horseshoe – even extending to its edges (the spectral locus).

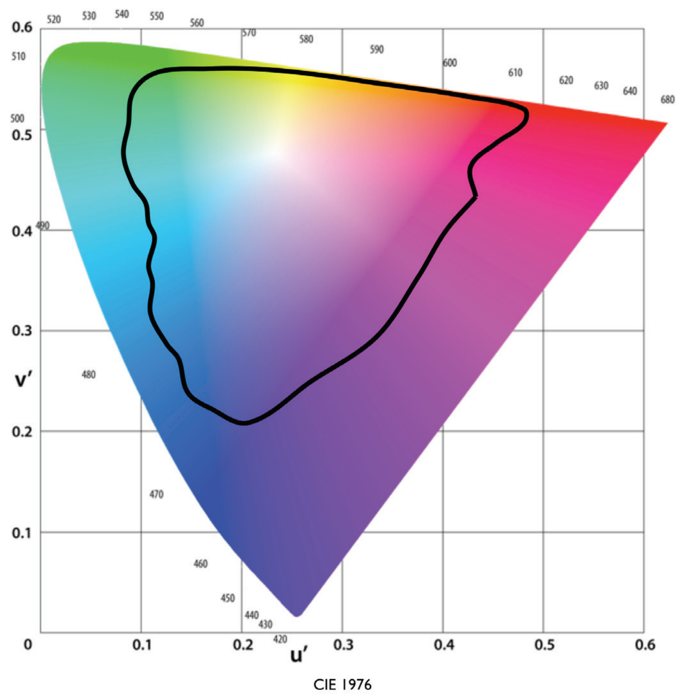


Figure 3: Surface Colors (Pointer's Gamut) within the 1976 CIE Chromaticity Diagram

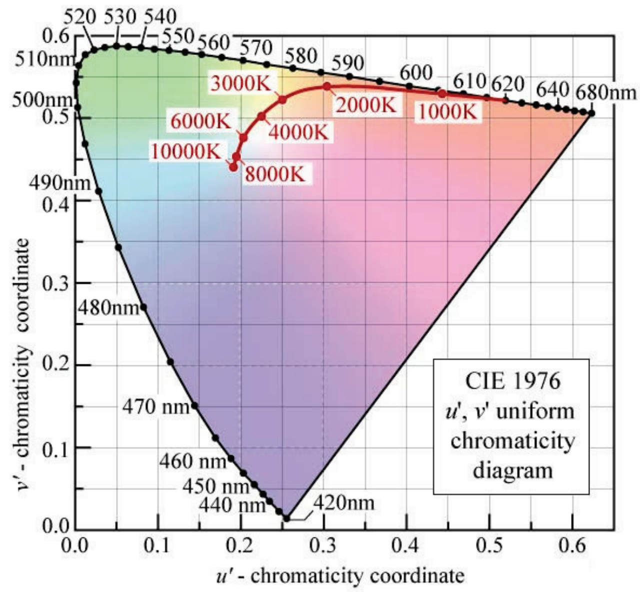


Figure 4: The u'v' Chromaticity Diagram

The 2D version of color representation using u’v’ coordinates (Figure 3 & Figure 4) was developed so that the perceived distance between two color points was more linear and consistent versus the 1931 version that used *x,y* coordinates.

But the best way to describe all possible perceived colors is a three-dimensional coordinate system. Many different coordinate system exists, one of which is CIELUV. Figure 5 shows the color volume of the Rec. 709 color standard, which is the one used for HDTV. The horizontal axes are x and y*’* chromaticity coordinates while the vertical axis is luminance or brightness (Y). The left graphic shows Rec. 709 as a 2D representation, while the other two show two different views of the 3D representation.

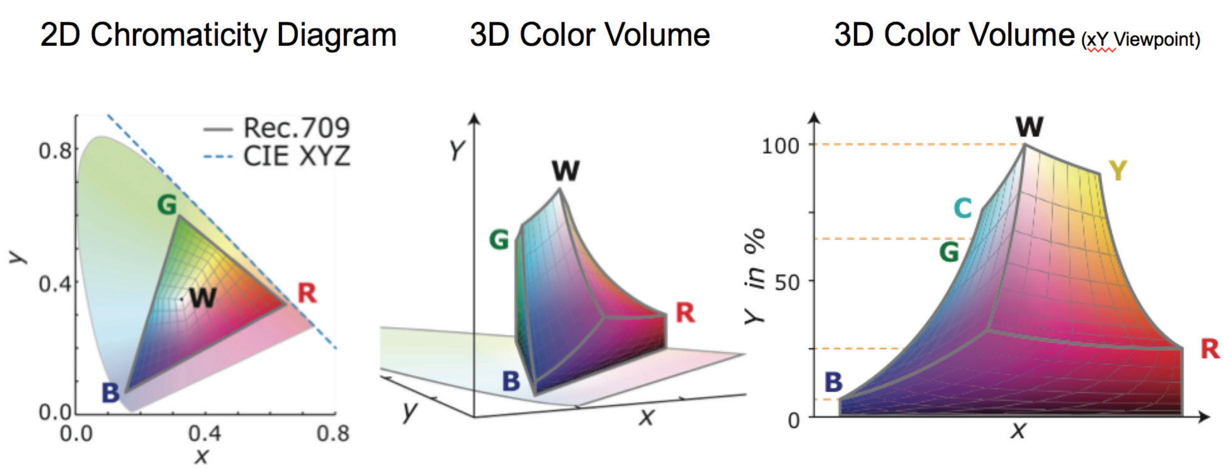


Figure 5: Color Volume of the Rec. 709 Standard (Source: Dolby)

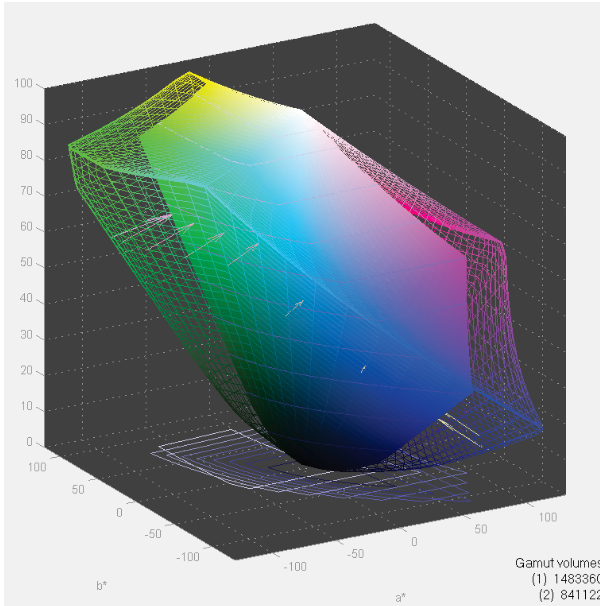


Figure 6: Comparison of the Display Color Volume (wire grid) vs. the rec 709 Color Gamut

Color volumes are often used to compare the volume of a color standard to what a particular device can display. Figure 6 shows typical comparison with the monitor color volume represented by the wire grid and the ITU-BT 709 (Rec 709) standard represented by the solid volume. Note that the monitor's color space completely envelops the 709 standard meaning it can display all of those colors in the 709 standard. (If you rotated this color volume around so that you could see "the back of it", you would find the wire grid continued to always enclose the solid volume.) The color volume of this monitor is 176% of the 709 volume. *However, note that this measurement does not say how accurately the monitor displays the incoming colors – only that the monitor has the capability of displaying them accurately.* That is why calibration is needed.

Also note that at low luminance levels (the bottom of the shapes) and high luminance levels (top), the color volume is smaller than it is at the middle. That is why the 2D xy or u'v' representations are not as accurate as color volume. Most likely, any marketing materials' specification of a device's color gamut using a 2D metric will choose a luminance level that yields the biggest horizontal cross section of the volume – which will only be accurate for that single luminance level!

To illustrate this point consider Figure 7. The orange color of the volcano lava is shown in a 2D and color volume representation. The 2D representation suggests that the color is within the Rec. 709 gamut. The 3D representation shows that this point is actually outside of the Rec. 709 gamut. The reason is that the luminance value is not considered in the 2D representation. As noted earlier, the 2D values are the best case which occurs at lower luminance values. For the fairly bright lava content, the luminance level now places it outside of the Rec. 709 color volume. How this is rendered depends completely on the capabilities of the display and color processing.

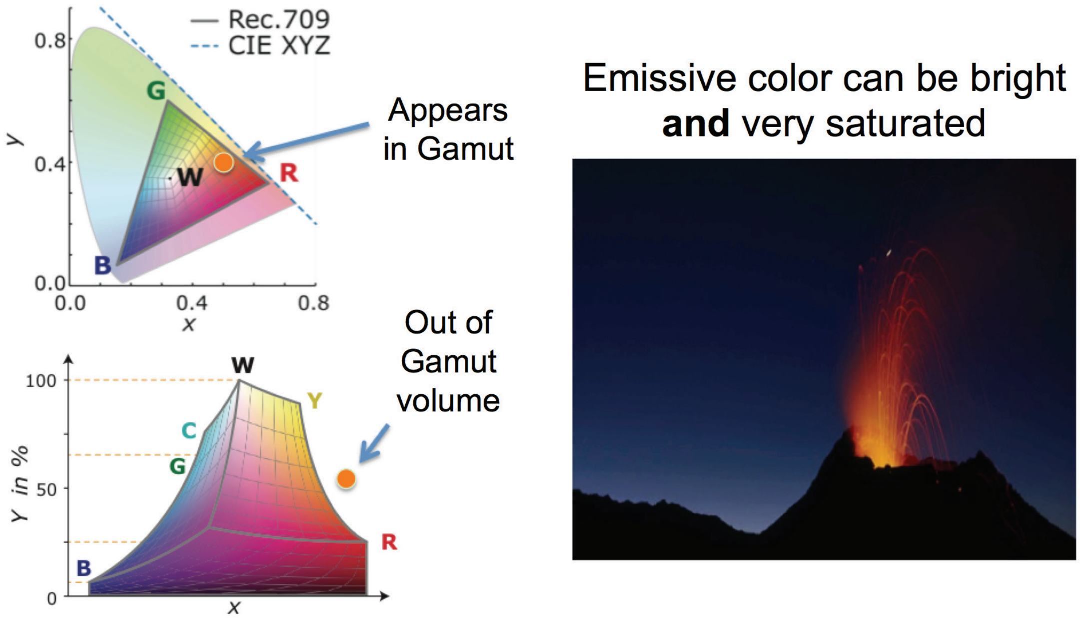


Figure 7: Misleading Use of 2D Color Gamut Representation (Source: Dolby)

Color Standards

There are many color standards that have been developed. These standards are needed to provide an agreed-upon set of colors to master content to so that it can be faithfully recreated on a display.

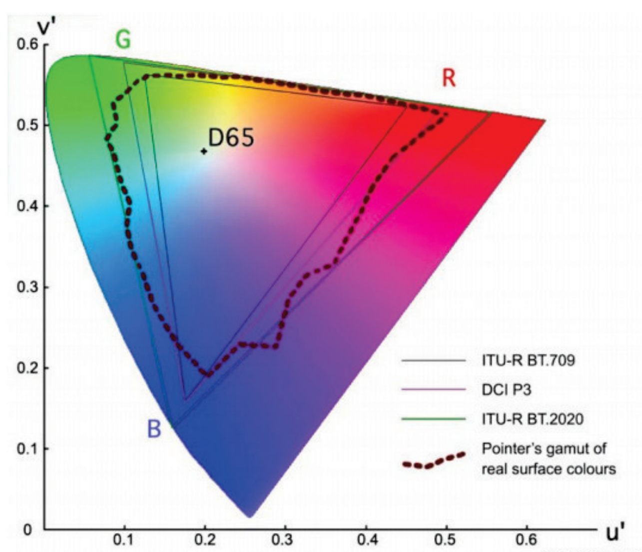


Figure 8: Various 2D Color Standards using u'v' Coordinates

The sRGB color space is the primary standard used in the majority of input devices, such as cameras and scanners, as well as display devices such as computer monitors, printers, and smartphones. The sRGB color space uses the RGB primaries (not shown in Figure 8), with a specific gamma curve to determine the steps between gray levels. Most Internet content is rendered using the sRGB color space.

The HDTV specification for color is represented by ITU-R BT.709, sometime called simply 709 or Rec. 709 (Figure 8). This is typically referenced in televisions and home theater projectors, and uses the same RGB primaries as sRGB but a different gamma curve. In other words, a comparison of series of red blocks with increasing levels of brightness between sRGB and Rec. 709 will show many identical levels, with only some slight differences in the darker regions.

The DCI (P3) color space is used in digital cinema, while the ITU-R BT.2020 standard is the new color space for Ultra-High Definition TVs. Rec 2020 is the largest color space being used for video content today. It does the best job of showing all of the colors available in nature, plus many additional colors (neon lights, LED lights, computer generated colors, etc.). The largest triangle in Figure 8 represents the coverage of BT.2020, showing Pointer's gamut for reference as well.

The white point of the display is that combination of red, green and blue light that creates white light. But white light has a "color temperature". Movie and TV content is typically graded and should be displayed using a D65 white point. This is supposed to have a relationship to the white light from a blackbody radiator at 6500 degrees Kelvin (although it is more complicated than that).

Almost all TVs ship with a default mode white point color temperature of 9,000 to 11,000 degrees Kelvin. These displays will appear distinctly bluish in their white point. This setting is mostly about selling the TVs. In a showroom environment for example, the whites look brighter and crisper than a set tuned to movie/TV mastering standard of 6500 Kelvin (D65). But for home TV, a D65 white point is needed for accurate color rendition as the content is mastered on a display with a D65 white point and specific color standard (709 in the case of HDTV). That is why most TVs also have a "cinema" or "movie" mode that tunes the white point to D65 and should offer the closest color gamut to Rec. 709 it can.

Wide color gamut TVs are capable of producing colors that are outside of the Rec. 709 standard. *In the TV market, this is generally meant to apply to TVs that have a color gamut capability that includes the 709 standard as well as additional colors outside of this standard.*

Benefits of Wide Color Gamut

Additional and More Saturated Colors

A WCG TV will be able to show more colors than a traditional TV that supports the rec. 709 color space. This will enable content captured and mastered in a wider color gamut to be displayed with these wider colors.

The P3 and 2020 color gamuts are the ones of interest to the TV market. Content produced and displayed in these color standards will:

- Allow additional colors to be displayed vs. rec 709
- Allow more accurately saturated color to be displayed vs. rec. 709

The additional colors that can be shown are represented by the colors that are outside of the rec.709 triangle but within the P3 or 2020 triangle (see Figure 8). These colors are particularly helpful in creating deeper reds, cyans, purples, magentas and greens. WCG displays can show Coke red or Ferrari red more accurately and portray the aqua color of a Caribbean ocean or glacier ice much more naturally.

WCG displays can also create more saturated colors. The saturation or pureness of the color is related to how close the color is to the spectral locus, or edge of the horseshoe as in Figure 8. With a calibrated 709 display, attempting to show the purest possible yellow displays a color on the edge of the 709 triangle between the red and green primaries. Attempting to show that same purest possible yellow color on a P3 or 2020 calibrated display, yields a more saturated color, closer to the spectral locus, this time on a line between the red and green P3 or 2020 primaries. Note that as 709 and 2020 share the D65 white point, you could draw a line extending from the D65 white point, to the rec 709 yellow, to the 2020 yellow, and finally to the yellow point on the spectral locus.

Consumers often prefer more saturated colors because they appear richer and more emotional than less saturated colors. More saturated colors can be created in non-WCG displays as well by using electronic methods to exaggerate colors. Such methods do not expand the color gamut of the display – they push the colors of the content closer to the saturation limit of the display – but still within the color capabilities of the display. This is what happens when you turn up the “saturation” control on your TV.

Unfortunately, the image quality deteriorates doing this and the colors become unnatural looking. For example, adding a little more blue to the image can impact other colors like flesh tones. That’s why it is best to calibrate the display for optimal performance. That means colors are limited to the optical color capabilities of the display and they will be accurate. *A WCG display has the native optical technology to create a larger gamut of colors than a typical 709 display. This enables the display of more deeply saturated colors and color accurate images compared to a 709 display.*

Another side benefit of more deeply saturated colors is the apparent increase in brightness of these colors. This is known as the Hemlholtz-Kohlrausch (HK) effect and is illustrated in Figure 9. The top row has five color squares, all fully-saturated, with equal luminance. The bottom row has 5 gray squares as well, all at the same luminance level as the colored squares above them. This uniform luminance level shared by all 10 squares was chosen to be the same as the luminance level of the background, so the gray squares all blend in equally well. The colored squares, though they have the same luminance (a physical measure) do not all appear to be the same brightness (a perceptual measure).

The ability to present a larger, more saturated color palette to the consumer is also very enticing for content creators. The UHD specification ratified by the ITU specifies a 2020 color gamut for content and specifies a “container” for carrying the color information. 2020-capable TVs need to decode this color information.

Figure 9: The HK Effect Visualized (Source: Wikipedia)

Not all content will take advantage of the large color gamut offered by 2020 because of technical and market reasons we will explain later. But some content will take advantage of this bigger color volume. For example, with CGI or animated content it is easy to create colors that are deeply saturated and close to the 2020 boundary. New movies such as "Inside Out" took advantage of this capability specifically. "Tomorrowland" is another movie example of featuring WCG content. As we will see, all the major Hollywood studios are committed to producing WCG and High Dynamic Range content.

Coupling with High Dynamic Range (HDR)

Newer TV sets with the High Dynamic Range (HDR) capability will be WCG sets as well. This is a key point as WCG without HDR will not be as compelling – or popular. Therefore, it is useful to understand what HDR is and how this will impact contrast, brightness and colors.

The real world contains a wide range of luminance values – about 15 orders of magnitude in cd/m^2 or nits (Figure 10). The human visual system can cover most of this range, but not simultaneously. Our eyes adapt to the average light level so that our steady state luminance range is more like 3.7 orders of magnitude. That means our eyes in a steady state are like a camera with about 12.5 f-stops of dynamic range. Dynamic range is a measure of the ratio of the peak luminance (brightness) and dimmest black level.

So what happens when content is captured by a camera, processed, distributed and displayed on a TV or projector? Figure 11 shows how the colors and range of luminance (contrast) is reduced through this process. That is why a TV or projector doesn't look like the real world – the colors and range of luminance is greatly reduced.

Modern professional cameras can capture 11-14 f-stops of luminance, but this wide dynamic range is not preserved. In the production process, this range is "squeezed down" to a smaller dynamic range.

The specification for current standard dynamic range (SDR) content was developed in the CRT days where mastering CRTs had the same luminance range as consumer TVs. From a practical standpoint, a luminance range of 0.1 to 100 nits made sense as it matched the best display technology at the time.

Figure 10: Range of natural and human luminance values (Source: Dolby)

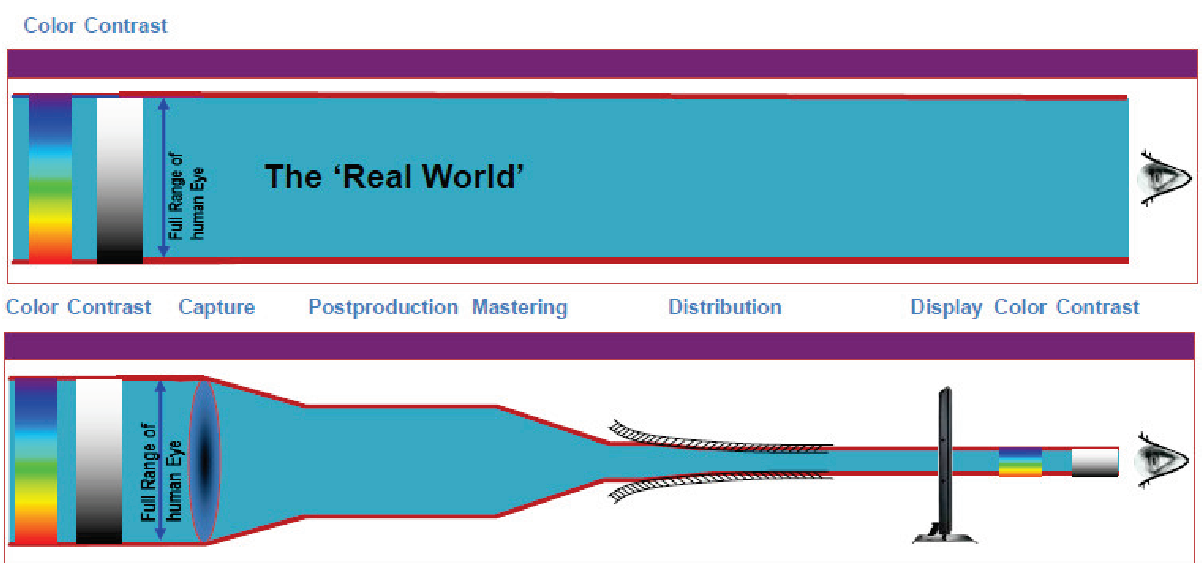


Figure 11: Reduction in dynamic range through the capture-to-display pipeline. HDR widens this pipeline to the end user (Source: Dolby)

As LCD TVs became more prevalent, this mastering range was not changed. LCDs offer higher peak luminance and initially higher black levels. These black levels are now at or even blow what CRTs could offer (with dynamic dimming) . What happens is that the content is simply scaled or stretched from the mastering dynamic range to the real dynamic range of the display device. *The dynamic range of the display has changed, but the basic dynamic range of the content remains the same.*

High Dynamic Range or HDR changes the way content is mastered so that it now has a greater range in luminance and color values. Then, HDR displays can show this wider range to great effect. This is illustrated in Figure 12.

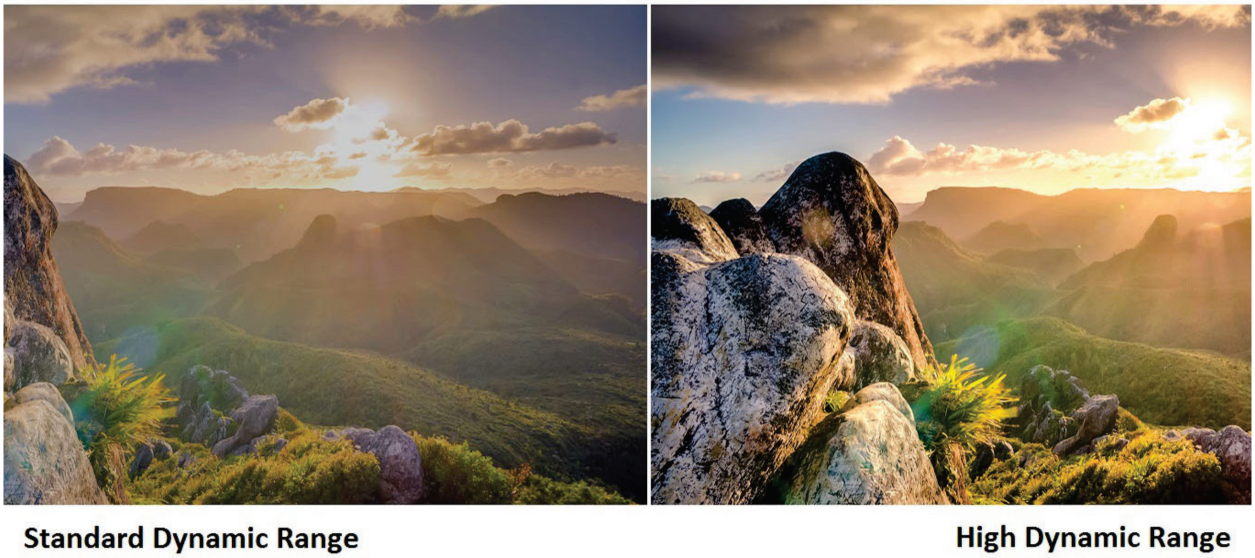


Figure 12: SDR vs. HDR Images (Simulation; Source: 20th Century Fox)

HDR is an increase in the contrast ratio. This often means an increase in the peak luminance as well as a decrease in the lowest luminance or black levels. In HDR LCD TVs, the peak luminance is achieved by adding more or higher brightness LEDs to the backlight while reduced black levels are achieved with the dimming of the backlight by zones. These zones can be one-dimensional using an edge-lit backlight – typically 8 to 16 zones, or two dimensional using a direct area-type backlight – sometimes hundreds or even thousands of zones. In OLED, the black levels are already quite good, so the challenge is to increase peak luminance.

The commonly accepted definition of HDR is any display that can display a broader range of light than the ITU's BT.1886 broadcast standard. Effectively, this means any device with a peak luminance above 100 nits. *Since many devices on the market today have already surpassed that mark, we will likely see a new definition emerge that reflects the realities of what is available in the market place. It is likely that most sets that are marketed as "HDR" in 2016 and beyond will have a peak luminance of at least 1,000 nits.*

Figure 13 shows the results of some testing that Dolby undertook to better understand what consumer prefer in terms of the range of luminance values. This testing was done with an experimental set up that could deliver very dark black levels and peak luminance up to 10,000 nits. What Figure 13 reveals is a clear preference for much higher dynamic range (especially higher luminances). And, once exposed to HDR, it also showed how dissatisfied people become with SDR content. As a result of this research and research conducted by others, we will see HDR TVs marketed that have a range of peak luminance and black level values, and therefore, a variety of dynamic ranges.

As consumers will experience, HDR content played on an HDR display is a WOW moment. The brightest parts of the image can be eye popping while simultaneously being able to see details in the darker parts of the image. Most people have not seen this before and the impact can be seen from across the room.

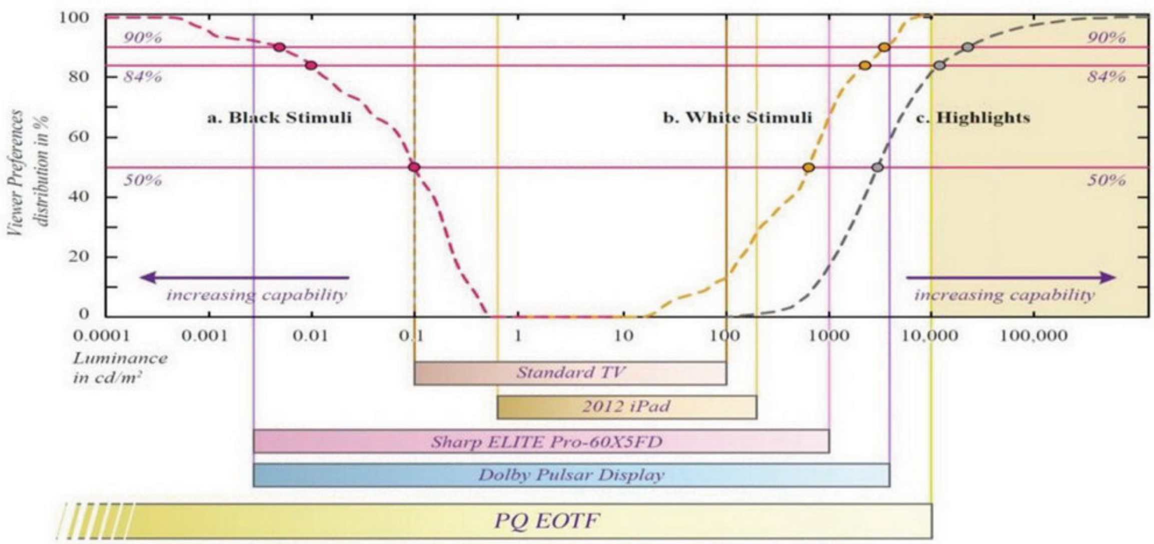


Figure 13: Consumer Preferences for Dynamic Range (Source: Dolby)

When HDR content is coupled with WCG content and display, the effect is even more amazing. Why? Because the higher luminance capabilities of the TVs allow bright elements to now have color, enabling point B to now be displayed as in Figure 5. This, coupled with the more saturated colors and the increase in apparent brightness (HK effect), leads to a big overall impact.

Many believe HDR and WCG will usher in the next big wave to video enhancements for consumers and professionals – and we agree. HDR & WCG may offer the biggest bang for the buck (or bit) - more so than increased spatial resolutions such as 5K and 8K, or HFR (high frame rate). And the combination of HDR, WCG and increased bit depth seems to be the winning combination for the near future for most content.

An Ideal HDR/WCG Display?

As we will discuss in the paper, there is no clear definition of what an "ideal" HDR/WCG display should look like. Organizations like the UHD Forum, UHD Alliance, CEA and others are all working on or have issued definitions of HDR displays that are not in alignment. We don't want to suggest another definition here, but it would be helpful to have a reference point for a best-of-class HDR/WCG display, we believe. Some suggestions are noted below.

- Near Term (1-2 years) "Ideal" HDR/WCG Display
  - DCI-P3 color gamut
  - Average peak luminance of 600 nits
  - Peak highlights luminance of 1000 nits

  - Black level of 0.1 nits
  - 10-bit display processing
  - At least 64 dimmable zones
- Mid-Term (2-3 years) "Ideal" HDR/WCG Display
  - 2020 color gamut
  - Average peak luminance of 800 nits
  - Peak highlights luminance of 1500 nits
  - Black level of 0.05 nits
  - 10- to 12-bit display processing
  - At least 128 dimmable zones

Challenges with Wide Color Gamut

Bit Depth

Bit depth refers to the number of digital bits devoted to image quality. It typically refers to the bit depth per color in an RGB video format, so 8-bits per color is a 24-bit video – standard today.

WCG and HDR content needs increased bit depth for both mastering and delivery. Today, content is mastered at 10-12 bits and delivered with 8 bits per color. HDR and WCG content needs to be mastered at 10-16 bits per color and delivered at 10-12 bits.

Why? Because the steps or code values available in 8-bit coding is not sufficient to cover the expanded range of luminance and color values of HDR and WCG content without creating artifacts. These artifacts will be most evident as posterization or banding layers in slowing changing shades of a color. You may have noticed this in representations of the sky in a video where there are clear bands of different blue shades (Figure 14). It is a particular problem in darker regions too.

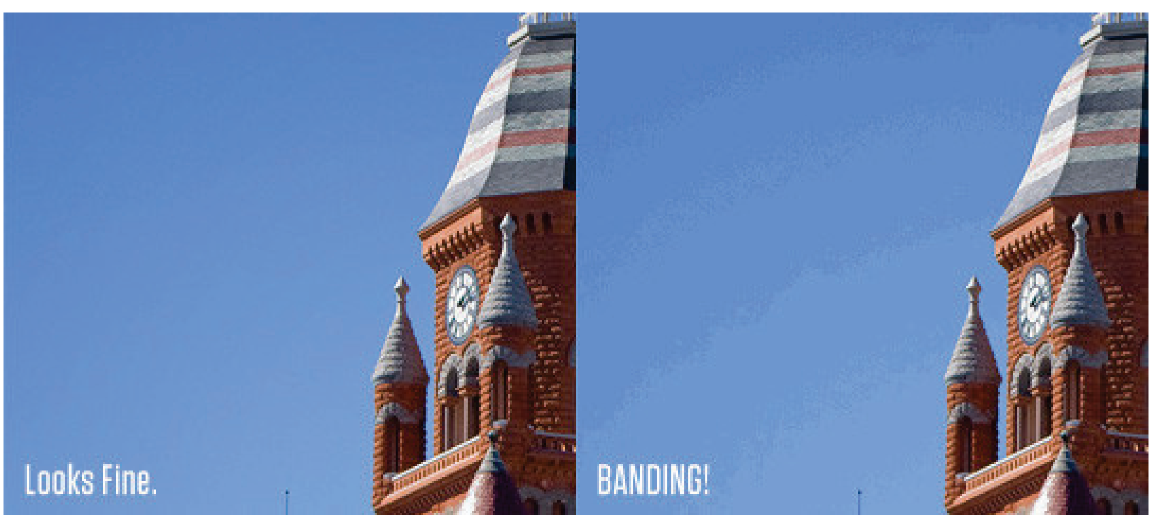


Figure 14: Banding or Posterization

Capture systems and some post production processes work with 12- or even 16-bits per color, but most professional broadcast TV work today is done at 10-bits per color, with the final rendering done at 8 bits for distribution to the end user in many consumer and professional applications.

The distribution of digital code values over the luminance ranges is called the "gamma curve". And for HDR in particular, new gamma curves are needed. That's because the existing curves were designed for standard dynamic range content and simply scaling these code values to an expanded range won't work. Why? Two reasons.

For one, the curves were designed to try to have steps between code values be about the same from a visual perception point of view. Stretching them messes up this relationship. Secondly, expanding the range with only 8 bits per color does not provide enough gradation between steps. The result is the banding of Figure 14.

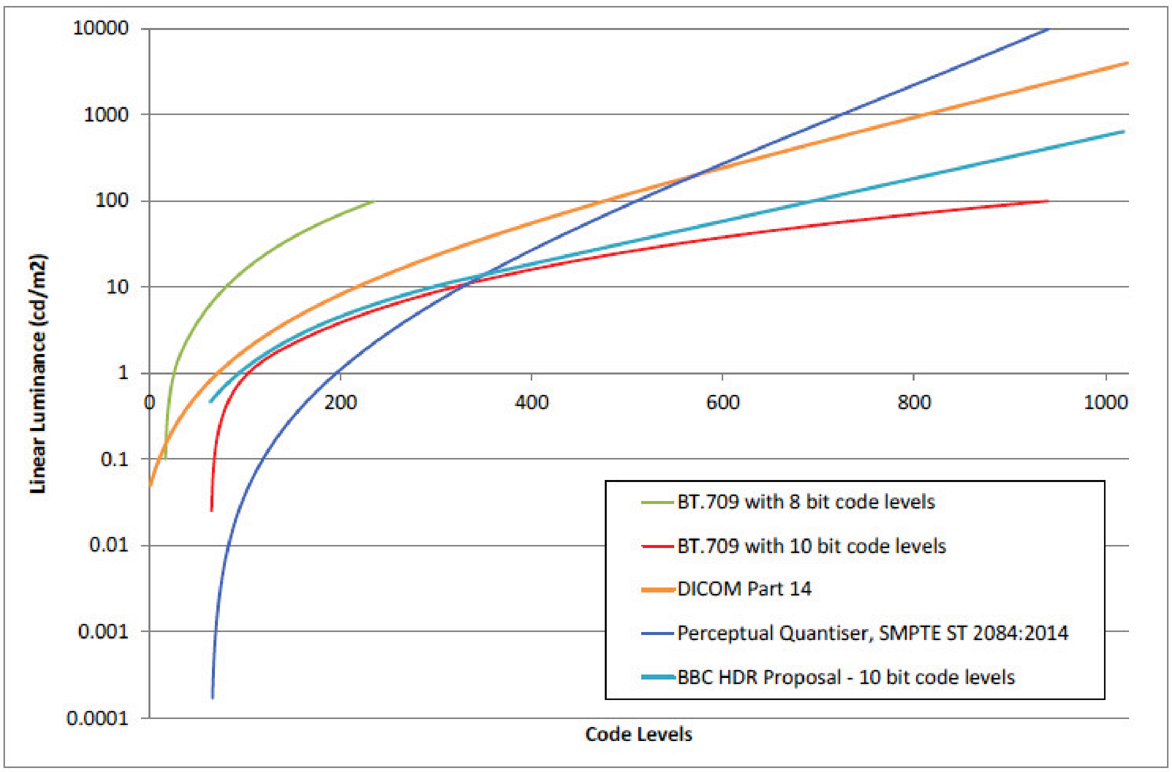


Figure 15: Various EOTF Curves being Considered for HDR Content and Display

As a result, HDR content needs at least 10-bits per color for the finished product. But the display gamma curve (now called the Electro-Optic Transfer Function or EOTF) issue is still a bit undecided.

So far, the leading candidate for wide adoption is the so-called "PQ" or Perceptual Quantizer curve. This has been standardized as SMPTE 2084 and is part of the new Blu-ray 4K specification and other groups are expected to adopt this as well. Figure 15 shows the PQ curve along with two 709 curves, and the BBC/NHK HDR proposed curve as well.

The shape of the PQ curve was designed to match human perception over a wide luminance range (0.0005 to 10,000 nits), with the bit depth extendable depending upon the range of luminance values covered. But most importantly, for the first time a code value is tied to a specific luminance level. That means when the content creator wants a certain pixel to be at 100 nits, a properly designed display will reproduce it at 100 nits – if it uses the PQ EOTF curve.

Multiple other HDR gamma curves have been developed as well. Some of them for cameras to be used at capture while others, such as the BBC/NHK Hybrid Log Gamma, have been standardized to resolve issues of backwards compatibility.

Moving to higher bit depth has ramifications throughout the acquisition, production, distribution and consumption pipeline. Delivering 10-bits per color to the home requires a major upgrade. Delivering it in professional applications will be challenging as well as equipment may have to be upgraded to support this.

Furthermore, this minimum 10-bit pipeline must include the TV. But not all of today's UHD TVs can do this. The TV electronics to create the HDR values need to offer 10 to 12-bit processing with the panel drivers also at 10-bits per color to maintain a 10-bit pipeline. Some TVs may try to shortcut this pipeline by offering sub-par electronics and 8-bit panel drivers that use frame rate control and dithering to achieve a 10-bit "look." This may produce unwanted artifacts, especially in dark areas of the picture. We anticipate that work being done by groups like the UHD Alliance, Blu Ray and CTA will help to standardize bit depth, giving consumers a way to at least identify content, devices and displays that deliver the full signal range.

Tolerance on 2020 Primaries

The ITU has ratified the UHD Phase 1 specification, which includes the 2020 color gamut. The specification calls out the red, green and blue primary wavelengths, but it does not give any tolerances. Since these are located on the spectral locus, only laser sources can produce the full color gamut – but with speckle, which is unacceptable. To fix the speckle means the primaries are no longer pure. What's the result? No display can claim to be "compliant" to the 2020 specification. That is why the addition of tolerances to the specification is needed.

To address this issue, 3M, a supplier of quantum dot films, has done some analysis and human testing to try to determine what those tolerances should be. The idea is to develop tolerances so that displays made within this range will show colors that are "perceptually indistinguishable" by human observers.

Current quantum dot TVs can achieve up to 93.7% of the 2020 color gamut. With a small change in the color filters used on these LCD TVs, 3M thinks QD TVs can reach up to 97% of the 2020 color gamut. But TV makers want to be able to say they are 100% 2020 compliant.

As a result, 3M has proposed new tolerances to SMPTE for consideration to become a standard. This would allow current quantum dot TVs to now claim they are 2020 compliant. Such a move would clearly help the quantum dot and laser-based display technology, but other wide color gamut technologies might not be able to meet the tolerances proposed by 3M. This is an on-going debate that needs to be monitored.

Five HDR/WCG Techniques to Consider

Today, there are a number of proposed methods to capture, process, deliver and display HDR/WCG content. These remain competing offering for standardization. The options are summarized in Table 1.

The first option, sometimes called HDR 10 (more formally, the Main 10 profile of ITU-T H.265), uses the PQ EOTF and static metadata. What is static metadata? It is information about the mastering of the content — details of the monitor used for mastering (chromaticities of the primaries, white point, max and min luminance as specified by SMPTE ST 2086) along with details about the content like the maximum content light level (MaxCLL) and maximum frame-average light level (MaxFALL)). This information, along with information about the capabilities of the TV's color space, min and max luminance capabilities, are then used to adjust the video (via tone mapping and chroma compression/mapping) to provide the best picture quality for that particular TV.

The single layer column of Table 1 means that a single compressed video stream, typically HEVC, can deliver the content so only one decoder is needed at the display. This is scheme implemented in the new Ultra HD Blu-ray format, but note that content in this format is not compatible with legacy SDR TVs or phase 1 UHD TVs (these TVs offer UHD resolution, but NOT WCG or HDR).

Approach	OETF/EOTF	Metadata	Backward Compatible?	Layers
HDR 10	PQ	Static	No	Single
BBC/NHK	HLG	Static	Yes	Single
Philips	PQ	Dynamic	Yes	Single
Technicolor	PQ or Proprietary	Dynamic	Yes	Single
Dolby Vision	PQ	Dynamic	Yes	Single or Dual

Table 1: Proposed HDR Options

The HLG approach is the one developed by the BBC and NHK and discussed above. Like the other approaches to be discussed below, it is backward compatible with legacy SDR displays but uses the Hybrid Log Gamma OETF/EOTF curves. Unlike the other approaches to be discussed below, it relies solely on static metadata.

The next three all feature delivery of dynamic metadata. Dynamic metadata is like static metadata, except it provides different parameters like max and min luminance, average frame luminance, etc. on a clip-by-clip, scene-by-scene or even frame-by-frame basis. Why is this better? Because it allows the optimization of the content on a much finer scale so the luminance and color mapping adjustments provide a better image. Static metadata may clip highlights and reduce visibility of shadow details, but with dynamic metadata, the tone mapping can be optimized for a bright or dark scene.

The development of dynamic metadata is much more complex than simple static metadata. In the proposals put forth by Philips and Technicolor, an HDR and SDR master has to be created up front. Then various methods can be used to compare the two grades and extract metadata about the differences. Technicolor calls their dynamic metadata processing scheme Reference-Based Color Volume Remapping Information. Key to their system is the carriage of Color Remapping Information (CRI).

Alternatively, Dolby believes that a single HDR grade can be completed and then algorithms can faithfully create an SDR grade from the HDR master along with metadata. Such solutions are in their early stage of deployment and evaluation, so changes are likely in the future.

Distribution of HDR/WCG content must also be considered. Both single and dual layer solutions have been proposed.

In the single layer options, metadata is coupled to the HDR version of the content for compression and distribution to the home. At the home, the content and metadata are uncompressed, and the hardware implementing the dynamic remapping system (a set-top box, a Blu-ray player, or the HDR firmware of a Smart TV) interrogates the display to capture its EDID data which reveals the resolution, peak brightness, etc. of the TV. This information, along with the metadata, is then used to construct an SDR version if the TV is SDR, or a range of HDR solutions depending upon the capabilities of the HDR TV and the approach being used. A block diagram describing one method to create, encode, deliver and process the dynamic metadata for SDR or HDR TVs is shown in Figure 16.

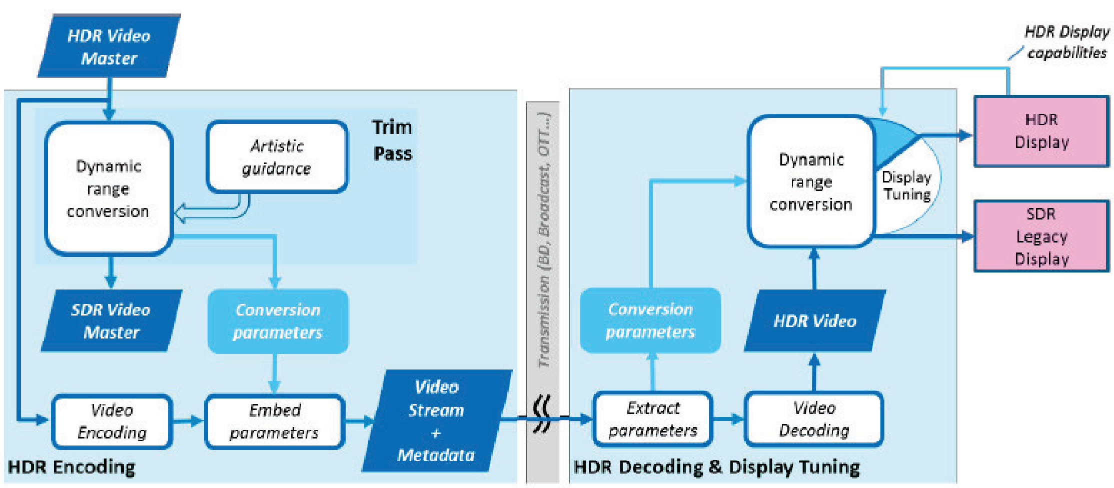


Figure 16: One Way to Create Dynamic Metadata, Package and Deliver for HDR or SDR Displays (Source: Philips)

Dolby offers a single layer version as well as a dual layer option. There are actually two dual layer options offering the 12-bit OETF/EOTF PQ for higher image quality. In one version, which is used for the Ultra HD Blu-ray spec, the HDR content is packaged as an HDR 10 base layer, which is sent as one stream, and a separate video stream containing an enhancement layer. The two are combined at the receiver to recreate the high fidelity HDR image.

The second Dolby Vision dual layer approach features a SDR base layer and an HDR enhancement layer, which is not allowed in Blu-ray discs.

HDR/WCG Content

HDR/WCG Content Creation

Issues with HDR/WCG Production

SMPTE has released a study group report that looked at the status of standards, equipment and workflow to capture, produce and distribute HDR/WCG UHD content. It highlighted its finding for both realtime live TV workflows and for file-based non-realtime workflows. The readiness and desire for HDR/WCG content in these two major production chains is quite different.

The real time, live TV workflow for HDR and WCG is less mature than the off-line, file-based workflow. First and foremost, there are few standards in place to support a workflow. At this time, only trials and one-offs have been done to understand what the issues are and what gaps exist.

Since few standards exist, it is anticipated that HDR/WCG content will be mastered without consistent colorimetery, peak luminance, maximum dynamic range and transfer function. HDR and SDR versions of the content may or may not exist and content may have to be converted to an in-house format.

Live contributions of HDR/WCG content will be needed, but little is known or specified about this yet. How will the HDR/WCG content signaling work? How will compression be applied? There is no time for a colorist to grade real time content, so what transfer curve and workflow is best? SDI does not support the carriage of metadata, so solutions like the OETF/EOTF from the BBC and NHK may find use here. Most remote facilities won't be ready to support HDR/WCG content so the equipment and infrastructure for HDR/WCG production will need to be brought to the venue for some time.

Insertion of advertisements and graphic overlays is a key part of the live TV workflow. The mechanics of inserting SDR or HDR ads and graphics into the live stream is non-trivial.

On the non real-time side, there are many needs at the production facility. The first concern will be ingest of HDR/WCG content in a wide variety of formats with different codecs and metadata. New storage and asset management tools will need development and new transcoders and processing facilities to support distribution for various formats must be developed. A full 10-bit pipeline is needed and interfaces to support HDR/WCG signaling need to be in place.

The tools to grade HDR content are maturing, but it seems likely that a HDR and SDR grade will be needed for some time (as with the transition from SD to HD or when 3D production was added in parallel). Methods to capture camera metadata and establish on-set workflows for dailies and editorial need development.

Much video production work still carries signals over SDI infrastructure. SDI has an identifier section in the payload header that can be used for providing information about the dynamic range, colorimetery, codec, etc of HDR/WCG content. The concern currently is that with many variations, there will not be enough bits in the identifier section to account for all these variations, thus requiring a modification to the standard.

It is also unclear how many final grades of HDR and SDR will be needed and how much conversion can help. Table 2 shows how complicated this can become. The report highlights recommendations for future activity including the needs for new SMPTE standards.

Production of HDR/WCG content is happening, but it is happening on specific movie projects today. As the tools expand and the installed base of HDR/WCG TVs expands, catalog content and more new productions will go to HDR/WCG. The major studios, Netflix and Amazon are leading the production of content using non real-time tools. Standards-setting groups like the UHD Alliance are also working to clarify this by establishing specifications not just for consumer devices but also content mastering and distribution. Realtime HDR production is probably 2-3 years ways and will come in slowly, we suspect.

Table 2: Signal conversions that could have preset transforms

From / To Input Format	HD_{100}Rec709	UHD_{100}Rec2020	HDR_{500}Rec709	HDR_{1000}Rec709	HDR_{500}Rec2020	HDR_{1000}Rec2020 Output format
HD_{100}Rec709	x	matrix only	*SDR->HDR*	*SDR->HDR*	*SDR->HDR*	*SDR->HDR*
UHD_{100}Rec2020	chroma compress	x	*SDR->HDR*	*SDR->HDR*	*SDR->HDR*	*SDR->HDR*
HDR_{500}Rec709	tone map	tone map & matrix	x	fits	matrix only	fits
HDR_{1000}Rec709	tone map	tone map & matrix	tone map	x	tone map	matrix only
HDR_{500}Rec2020	tone map & chroma compress	tone map	chroma compress	matrix & chroma compress	x	fits
HDR_{1000}Rec2020	tone map & chroma compress	tone map	tone map & chroma compress	matrix & chroma compress	tone map	x

Note- Subscripts indicate the peak luminance intended to be conveyed by the source or target format.

Table 2: Matrix of Possible Signal Conversions (Source: SMPTE Study on HDR)

Getting Studios to Master to 2020

Just because the UHD specification calls for content to be mastered in the 2020 color space, doesn't mean major content creators will do that. In reality, it is going to take time to build up a library of 2020 content – maybe quite some time.

There are a number of very practical reasons why the major Hollywood studios – who need to drive this transition – will be slow with 2020 content. For one, being able to master content to 2020 requires a 2020 display to review on. Today, any 2020 content needs to be mastered and reviewed using an RGB laser projector. That is a very expensive display, so studios are not going to buy many.

This will change as more professional monitors are released with wider color gamuts. But the tolerances need to be fixed, as noted above.

The WCG production monitors that are in service today support a P3 color gamut, which is in between 709 and 2020 in terms of color volume. Plus, these monitors typically need to be HDR capable as this feature is often coupled with WCG content. These are few and far between today and expensive. This need also extends to on-set requirements for review of dailies.

In theatrical, the standard gamut is P3, but new HDR/WCG theaters are coming on-line that use RGB laser projectors capable of showing 2020 in all its glory. But there are very few of these theaters today and they are very expensive to build.

Looking at the consumer side, while there are WCG TVs in the market today, it is a tiny fraction of the market. This does not represent much of an installed base for the studios, so they do not see a big need to do a rapid transition to mastering in 2020.

However, Hollywood does appear to be more excited about mastering in HDR and they are being aggressive here with all 7 major studios committed to the format. But, this HDR content is being graded to the P3 color standard in most cases. Why? For one, this is the same color space that they now grade for the theatrical release, so configuring the content for home release is a lot easier and less costly. Secondly, the monitors they have today support P3, and thirdly, many of the WCG TVs can support P3 quite well, whereas only quantum dot TV come close to supporting a 2020 gamut.

So, mastering in HDR and P3 within a 2020 container will be the near term path for most content – with some exceptions. Content will be mastered in 2020 where it is important, like animations where the colors can really pop, or major films where they will have good runs in the expanding line up of HDR/WCG theaters. This also creates a small flow of content to the home market over various distribution channels. However, these efforts may accelerate if Rec.2020 capable displays become more common in consumers' homes following the launch of the first such display in 2015 with Vizio's R65.

Accessing HDR/WCG Content

Ultra HD Blu-ray

The Blu-ray Disc Association has a new specification called Ultra HD Blu-ray which expands the resolution to UHD and adds support for HDR and WCG. The allowed video formats are shown in Table 3 with a comparison to legacy SDR.

Note that the BT 2020 WCG specification can apply to HDR or SDR content and that UHD and Full HD resolutions are supported. The maximum frame rate is 60 fps and 4:2:0 chroma sub-sampling is specified along with HEVC compression (Main 10 profile, high tier, level 5.1, 100 Mbps max bitrate). The EOTF is SMPTE 2084, the PQ curve discussed above.

video type	HDR	SDR	Legacy SDR
spatial resolution	3840x2160, 1920x1080	3840x2160, 1920x1080	1920x1080
video compression	HEVC	HEVC	AVC
picture format aspect ratio	16:9	16:9	16:9
bit depth	10	10	8
color encoding primaries	BT.2020	BT.709, BT.2020	BT.709
chroma sub sampling	4:2:0	4:2:0	4:2:0
frame rate	23.976p, 24p, 25p, 50p, 59.94p, 60p	23.976p, 24p, 25p, 50p, 59.94p, 60p	23.976p, 24p
peak video bitrate	100Mbps	100Mbps	40Mbps
EOTF	SMPTE ST2084	BT.1886	BT.1886
static metadata	SMPTE ST2086, MaxCLL, MaxFALL	SMPTE ST2086	N/A

Table 3: Allowed Combinations of Video Parameters on the Ultra HD Blu-ray Format

The high bit rate, HDR/WCG support and UHD resolution should help re-establish Blu-ray as the gold standard for image quality.

Support for static metadata is mandatory in the Ultra HD Blu-ray player, but optional for the disc. While HDR 10 is the baseline HDR/WCG format, the spec allows optional HDR formats as well, such as the Philips, Technicolor and dual stream Dolby Vision approaches. Of course, the disc and player must support this format as well. Block diagrams showing the Dolby Vision and Philips optional approaches for Blu-ray are shown in Figure 16, Figure 17 and Figure 18.

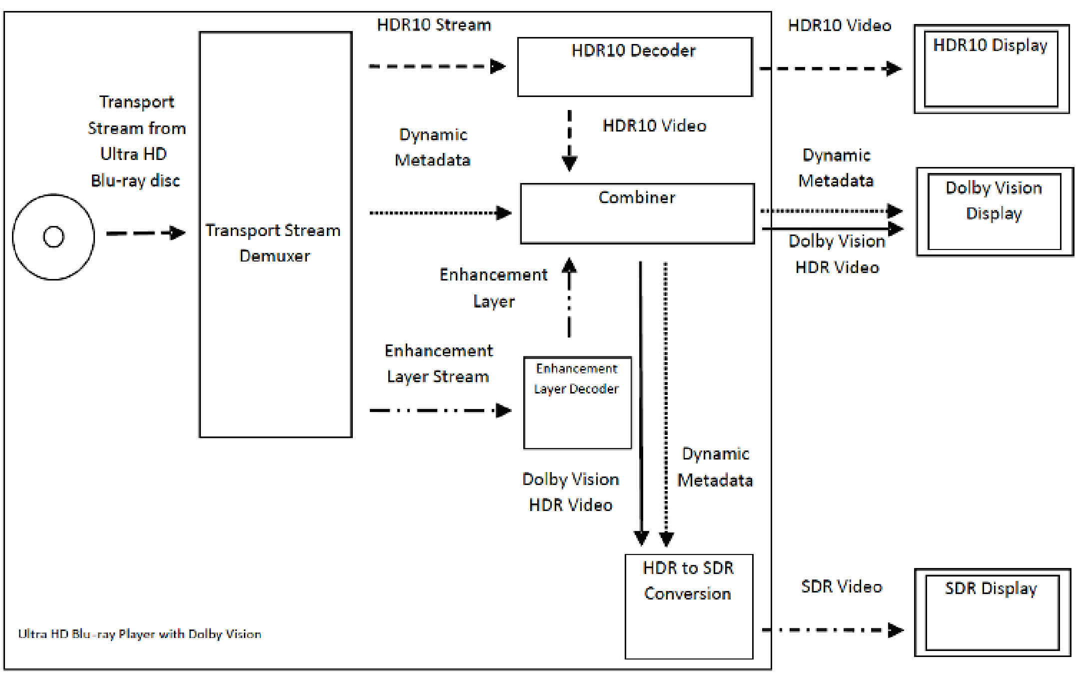


Figure 17: Optional Dolby Vision Block Diagram for Ultra HD Blu-ray

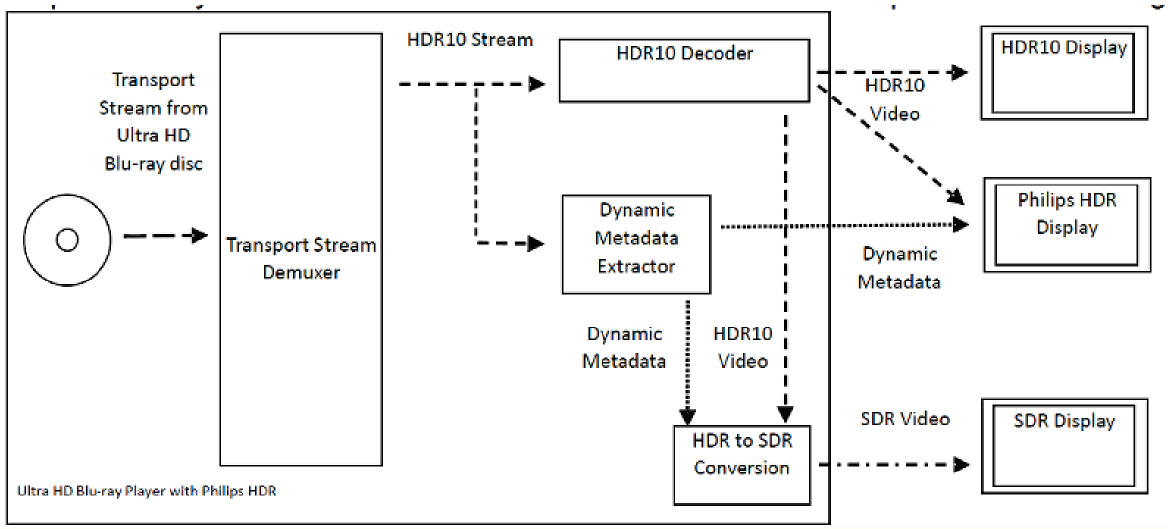


Figure 18: Optional Philips HDR Block Diagram for Ultra HD Blu-ray

Metadata is encoded in the SEI messages with the HEVC compression scheme. Once decoded, it is transported from the player to the TV using HDMI. The HDMI 2.0a and CEA-861.3 specs support this transmission.

The mastering and production of Ultra HD Blu-ray discs seems to be in place. Scenarist and BluFocus have both been certified for this process and content is expected before the end of the year, or early 2016.

Prototypes of Ultra HD Blu-ray players have been shown and the first products announced. For example, Panasonic has announced the DMR-UBZ1 will be offered in Japan by mid November 2015 for ¥380,000 ($3,165) ex VAT. It includes a 3TB hard drive, but there is no word if it will support the optional higher quality HDR/WCG formats.

Figure 19: Panasonic's New Ultra HD Blu-ray Player

Other Ultra HD Blu-ray players with HDR/WCG capabilities are expected to launch in 2016, including one from Samsung.

Over-the-Top

Over the top (OTT) providers use the public Internet to deliver video to any Internet-connected device. OTT services often complement an IPTV, cable or satellite service because they do not generally offer local programming or live TV feeds. The bandwidth may not be guaranteed either. Many of the OTT providers have worked hard over the last few years to help ensure a minimum quality of service, however. Key providers in this category include Netflix, Amazon Prime, VUDU, Hulu, M-Go, YouTube and many others.

Amazon Prime, VUDU, Ultraflix and Netflix are already streaming UHD resolution content with Amazon now also offering HDR/WCG UHD content as well. In 2015, Netflix announced that they were shooting 10 new shows in HDR/WCG UHD. Others are not expected to be far behind in rolling out their offerings of HDR/WCG UHD content.

In fact, just recently, Vimeo announced it plans to roll out an adaptive bit rate streaming service for the viewing of 4K video. This should be available in Q1'16. Support will be for iOS and Apple TV at launch with Amazon TV, Roku and Android to follow in the coming months. There is probably no support for HDR, but probably for WCG in the initial launch.

OTT providers have proved to be more flexible, agile and quicker to embrace new technologies for video viewing than their broadcasting counterparts. That is because they are not tied to legacy infrastructure, but rely on Internet service providers to deliver video over broadband connections. Of course, they have to make deals with broadband providers to assure minimum bandwidth to their customers for good video service.

They can also innovate at Internet speeds — if they want to try a new version of a dynamic remapping scheme, they can push that version to 10% of OTT-connected devices and see if those devices spend more time streaming content (for example). In contrast, innovation in the broadcast space occurs at the pace of international standards bodies, where a half-year cycle of proposal, testing and adoption is considered extraordinarily fast.

OTT services can be delivered to TVs that support an Internet connection, to Blu-ray players, AV receivers, set top boxes or streaming sticks. Roku, Google, Apple and others make boxes or sticks to support OTT services that they update regularly.

OTT providers also do something the cable, satellite and over-the-air providers don't do – they interrogate the TV or device to discover what type of display it has (via EDID data). They can also asses the Internet connection speed. That allows them to deliver a signal that is matched to the resolution, color space and bandwidth for that specific connection. What enables this is an App that resides on the consumer's TV, gateway or mobile device. Integration of the App requires some effort on the part of the device maker.

Vudu has announced it is rolling out 4K HDR services using Dolby Vision technology in a single layer service. The new Vizio Reference series 4K TVs have the Dolby Vision decoder built in.

Roku's new player, Roku 4, supports 4K video and WCG, but not HDR. Nor does the Amazon 4K Fire TV set top box support HDR, but both should support WCG if the content is encoded in 2020. Roku's and Amazon's companion stream sticks support 1080p, not 4K.

On the other hand, providers of such devices are iterating on updates very quickly – much faster than game consoles or set top box makers, so don't expect these deficiencies to last long.

Over the Air

ATSC 3.0 is the next generation over-the-air (OTA) standard that is still in development. The current OTA system in the U.S., ATSC 1.0, does not support broadcasting of UHD content.

ATSC 3.0 is a comprehensive standard that will include broadcast of UHD resolution plus enhancements like HDR and WCG. The standard should be completed soon with products expected in 2016. However, it will be 2-3 years before the FCC grants final approval for a full roll out.

ATSC 3.0 includes a variety of components as detailed in Figure 20. It also offers a lot of flexibility for broadcasters to configure many types of services. For example, a broadcaster can choose to offer 4K, HD, mobile formats, or any combination within the channel capacity. HEVC has been selected as the compression codec with the ability to offer HDR, WCG and high frame rate still in the discussion phase. 4K broadcasting can be offered a 8-15 Mbps or 15-25 Mbps for higher quality.

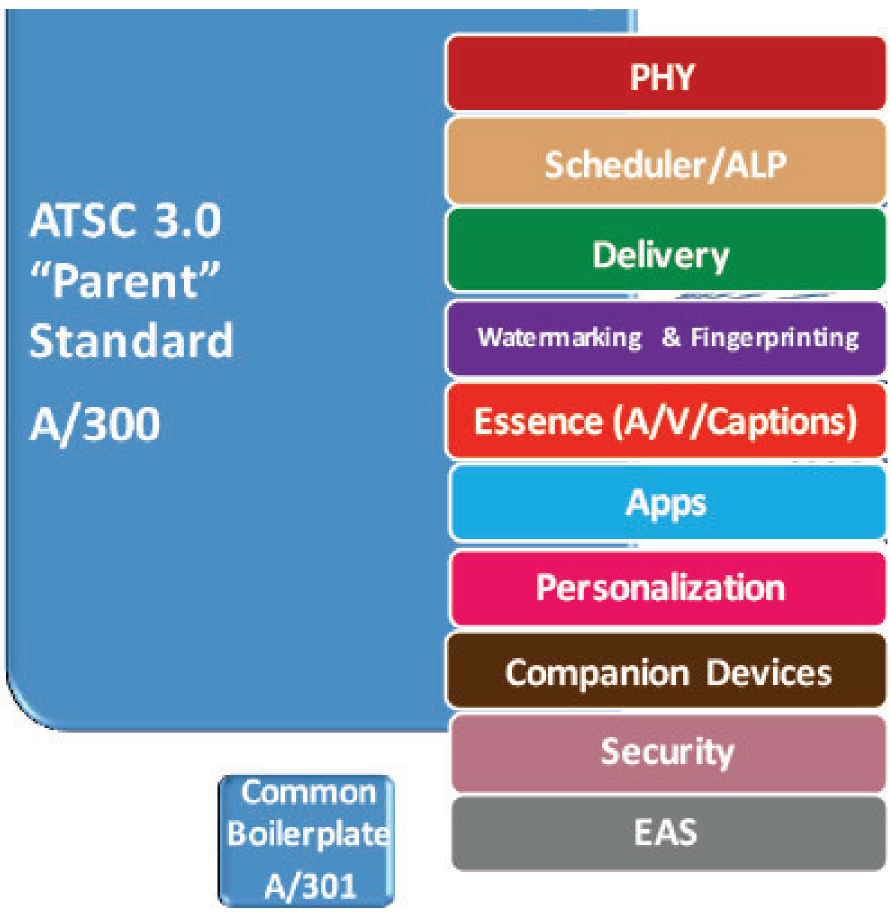


Figure 20: ATSC 3.0 Overview

Structurally, it is somewhat similar to the 7 layer IT protocol stack with an IP-based transport layer. It allows for channel bonding (to increase bandwidth), hybrid delivery (broadcast & broadband), emergency alerts and much more. The physical layer is quite flexible and has been designed to have extraordinary reach to stationary and mobile devices.

In 2018, Korea must host the Winter Olympics so they are on track to make a decision soon to use ATSC 3.0 or DVB-T2 to broadcast the Olympics in 4K. 30 MHz of broadcast spectrum has already been allocated in Korea for 5 new channels of mandatory 4K broadcasting.

Currently, there are four HDR proposals being evaluated by ATSC 3.0 study groups. In Q1'16, the organization should make a recommendation on one or more of these HDR/WCG carriage proposals. This means it will move to the candidate standard status and developers will begin equipment manufacture and field testing. Already, the first HDR ATYSC 3.0 trail broadcast was completed in December 2015 by Sinclair Broadcasting.

Cable

Cable companies are starting to embrace delivery of 4K content to homes on a global basis. They are even starting to offer services with HDR and WCG. For example, Canada-based Roger Communications has announced they will launch Rogers 4K TV with a commitment to live broadcasting with HDR starting in 2016. This will be supported by a new 4K set top box that offers gigabit connectivity.

Rogers says it plans to broadcast more than 100 live sporting events in 4K next year, including more than 20 NHL games. It will begin broadcasting with high dynamic range for the Toronto Blue Jays home opener in April 2016, and broadcast each Blue Jays home game in 4K with HDR for the entire 2016 season. Rogers Ignite Gigabit Internet service and set top box is needed for the 4K content. It features unlimited usage starting at $149.99. It will be rolled out in 2015 and by the end of 2016 is expected to be in more than 4 million homes.

In the U.S., Comcast says that it is preparing an HDR-capable Ultra HD set top box for launch in 2016. Called the Xi6, it will be more advanced than the current Ultra HD set top box, the Xi4.

Satellite

Satellite delivery of 4K-UHD content has started with the first announcements for HDR options now out in the public as well.

In Japan for example, SkyPerfect is expected to launch UHD content featuring HDR capabilities (and WCG). This service will use the BBC/NHK standardized Hybrid Log Gamma (HLG) method for encoding HDR/WCG content.

UK-based Sky says it will launch a new set top box dubbed SkyQ that will support UHD content with HDR and HFR capabilities (plus WCG). The STB is reported to offer multi-screen viewing so family members can each watch different shows on varying screens, allowing up to 4 different channels to be watched (or recorded) simultaneously. The box should also offer live TV and catch-up streaming in the same place so jumping between the two will appear seamless.

Additional UHD satellite-based channels are up and running now or soon – and these likely support the 2020 color space, but it is unclear if or when these channel might add support for HDR.

Global satellite provider SES has launched a couple of UHD TV channels and has done tests with HDR already. While it has not announced plans, it seems likely to launch or upgrade a channel to support HDR in 2016 or 2017.

Many other satellite providers like DirecTV, DISH, Eutelsat and others have been experimenting with and/or launching UHD TV channels. DirecTV now says it is now testing a UHD sports service and intends to launch it in early 2016. The firm has the capacity to launch 50 UHD channels at 30 Mbps in addition to its current HD and SD offerings. There is no word on support for WCG or HDR, however.

Figure 21 is the view of IHS in terms of UHD TV channel by 2025 – over 1000 UHD channels by then (all supporting WCG we suspect). While they do not specify how many might support HDR, many probably will.

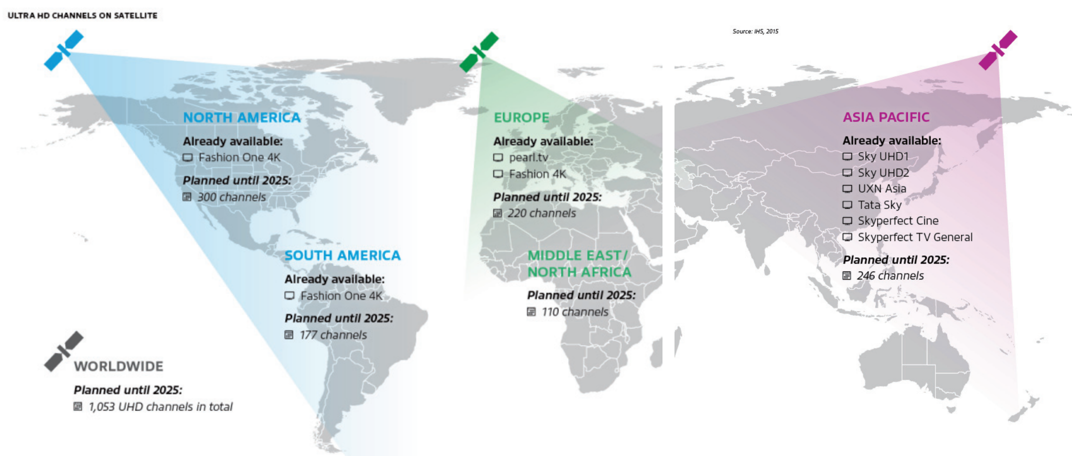


Figure 21: UHD TV Channels by 2025 (Source: IHS)

IPTV

IPTV providers use Internet protocol to deliver TV services, but not over the public Internet like OTT providers. Instead, they maintain their own private network that offers high levels of management and quality of service. Typical providers here include AT&T Uverse and Verizon FiOS.

Some of the IPTV providers have significant fiber optic infrastructure, which might sound like it means they can offer high bandwidth services. But that is not really true, at least in the U.S. That's because they use the same QAM modulation that the cable companies do. For decent quality, three HD channels can be packed into on QAM modulator. That's not enough bandwidth for decent 4K video quality, so next generation solutions will be needed. That's expensive as the networks and set top boxes need to be upgraded to support 4K. The DOCSIS 3.0 structure and HEVC compression should help, but it is being rolled out slowly.

In addition, both Verizon and AT&T are at capacity with their networks. Verizon just sold off its network in three states to Frontier. As a result, 4K will come slowly to IPTV in the U.S. and HDR will lag even further behind.

IPTV in other countries may fare better, however. For example, Telefonica Spain has launched a 4K IPTV channel that will focus on formula one racing. The content is HEVC encoded and transmitted at 30 Mbps.

Other companies are looking at IPv6 as the solution for transmission of 4K video content for IPTV networks.

Game Consoles

This platform, primarily Xbox and PlayStation, can also serve as gateways for delivering UHD content to TVs. Currently, neither platform supports playback of native UHD content, although support for 4K is expected in the next platform release. It is unclear if that will include WCG and HDR, however.

Playback of HDR/WCG Content

Once 4K/WCG content is in the home via one of the delivery methods above, it needs to be transported to the TV. The vast majority of the connections, except some OTT connections which access the Internet directly, will use HDMI.

There are three versions of HDMI that can support delivery of 4K content: HDMI 1.4, 2.0 and 2.0a. With HDMI 1.4, the transceivers are limited in bit rate to 10.2 Gbps, but HDMI 2.0 and 2.0a transceivers go up to 18 Gbps, before overhead. Table 4 summarizes the key specifications for these three versions while Table 5 shows the supported frame rates and chroma sub-sampling that is supported with HDMI 2.0/2.0a.

HDMI 1.4a can only support 4K or UHD resolution content 24, 25 or 30 fps, 4:4:4 and 8-bit or 12-bit, 4:2:2. HDMI 2.0/2.0a expands this considerably as noted in Table 5.

With HDMI 2.0, a new signaling method was introduced in addition to the big increase in bit rate to 18 Gbps. 2.0 also added support for BT 2020 wide color gamut content as well as other features as noted in Table 4. BT 2020 supported frame rates and chroma sampling in HDMI 2.0/2.0a are shown in blue in Table 5.

HDMI 2.0a has all the same features of 2.0 with the addition of support for HDR signaling and conforms to CEA-861-3. This signaling support today includes the so-called HDR 10 protocols which means SMPTE ST 2084 for the PQ EOTF gamma curve and ST 2086 static metadata information. This information is carried in the SEI blocks of the payload header in the HDMI bit stream. Some existing HDMI 2.0 devices can be firmware upgraded to 2.0a, but this varies by manufacturer. It does not require a cable upgrade either. Only a few UHD TVs support HDMI 2.0a so far such as Samsung's SUHD TVs, two of Sony's top of the line XBR models, Vizio's Reference series and the Panasonic CX850. This should change in 2016 as HDMI 2.0a gets more widely adopted in HDR/WCG sets.

Generation	1.4 (2009)	2.0 (2013)	2.0a (2015)
Base Data Rate (Gbps)	10.2	18	
Protocol	TMDS		
Color Space	rec 709, xvYCC, sYCC601, Adobe RGB, Adobe YCC601	rec 709, xvYCC, sYCC601, Adobe RGB, Adobe YCC601. BT 2020 (with 10 or more bits/color)	
Color Depth	48 bit/pixel (Deep Color)	48 bit/pixel (Deep Color)	
HDR Metadata Support	No		Yes
HDCP	1.4	1.4 & 2.2	
Audio Channels (LPCM)	8 @ 192 KHz	32 @ 1536KHz	
Audio return Channel	yes	yes	
HDMI Ethernet Channel (100 Mbps)	yes	yes	
3D support	yes	yes	
Dual Viewing	no	yes	
Multi-stream Audio	no	4 channels	
CEC Extensions	yes	Yes CEC 2.0	
21:9 support	No	Yes	

Table 4: Specifications for HDMI 1.4, 2.0 and 2.0a

	8bit	10bit	12bit	16bit
4K@24 4K@25 4K@30	RGB 4:4:4	RGB 4:4:4	RGB 4:4:4 4:2:2	RGB 4:4:4
4K@50 4K@60	RGB 4:4:4 4:2:0	RGB 4:2:0	RGB 4:2:2 4:2:0	RGB 4:2:0

Table 5: Supported Frame Rates and Chroma Sub-sampling for HDMI 2.0

Playback on HDR/WCG TVs

While the main focus of current WCG mastering and playback is on 2020 compliant signals, we need to start with a discussion of xvYCC and DeepColor.

xvYCC, sometimes called Extended-gamut YCC or x.v.Color is a color space that was proposed by Sony and standardized by IEC in 2006. xvYCC-encoded video retains the same color primaries and white point as BT.709, and uses either a BT.601 or BT.709 RGB-to-YCC conversion matrix and encoding. The xvYCC color space permits YCC chroma values outside the code value range of 16–240. That means negative RGB values which are not normally valid. These are used to encode more saturated colors. For example, a cyan that lies outside the basic gamut of the primaries can be encoded as "green plus blue minus red". These extra-gamut colors can then be displayed on a WCG device with primaries outside of BT 709.

A mechanism for signaling xvYCC support and transmitting the gamut boundary definition for xvYCC has been defined in the HDMI 1.3 specification and is compatible with HDMI's existing YCbCr formats. To properly decode and display xvYCC colors, the display needs to signal its readiness to accept the extra-gamut xvYCC values, and the source needs to signal the actual gamut in use to help the display to intelligently adapt extreme colors to its own gamut limitations.

DeepColor does not allow colors outside of 709 to be shown, so it is not really a WCG technology. Developed by HDMI and debuted in the 1.3 specification, it is really just about adding greater bit depth (10-, 12- or even 16-bits per color). If the content, player, display and HDMI interface support DeepColor, it may add more precision to the color processing and reduce the potential for banding or posterization – but it does not expand the color gamut. However, DeepColor in combination with xvYCC can enable display of colors beyond 709 without banding.

xvYCC and DeepColor is a complete WCG solution, so the full chain from lens to display must support it. However, to our knowledge, only a limited amount of content (some UHD content from Sony Pictures) is available with xvYCC encoding and a limited number of displays and playback devices support it or DeepColor other than some Sony products. Attention today is clearly on BT 2020 solutions.

Once 2020 content has been delivered to the display and properly decoded, it must be processed for display. Two critical operations are tone mapping and color volume remapping.

Tone mapping adjusts the luminance levels of the content to the luminance range of the display device. We discussed this a bit with regards to HDR content above.

The second operation is color volume mapping. Table 6 provides a summary for some of the basic options that will be popular going forward. This processing may or may not be done in combination with HDR tone mapping.

Along the diagonal of Table 6 is where the display has the native electro-optical characteristics required to recreate faithfully all colors that could possibly be present in the incoming signal. Theoretically, a calibrated display should be able to reproduce these colors quite accurately, matching the image's appearance as established by the colorist.

Now let's consider what happens with 2020-mastered content played back on a less capable TV or display. If the TV has only a P3 or 709 color gamut capability, it cannot display all the colors that might be in the 2020-mastered content. In most cases, proper color processing will accurately display colors that are with the native color gamut of the display. In other words, any color within the P3 gamut should display properly on the P3 display and any color within the 709 gamut should display properly on the 709-capable display.

Content mastered to	Played back on		
	2020-cabable TV	P3-capable TV	709-capable TV
2020	**shows 2020 colors**	clips out-of gamut to P3 or does perceptual rending to simulate out-of gamut colors	clips out-of gamut to 709 or does perceptual rending to simulate 2020 colors
P3	Can show P3 colors or may stretch to 2020	**shows P3 colors**	clips out-of gamut to P3 or does perceptual rending to simulate out-of gamut colors
709	Can show 709 colors or may stretch to P3 or 2020	Shows 709 colors or may stretch to P3	**shows 709 colors**
Bold is only mode where accurate, calibrated colors are possble			

Table 6: Matrix of Options for Color Mapping

Issues arise for colors that are outside of the native color capabilities of the display – i.e. that part of the color volume between 709 and 2020 or between 709 and P3, for a 709 display, or between P3 and 2020, for a P3 display. The techniques to handle these cases vary considerably and many proprietary methods exist. However, they generally fall into two types of solutions: clipping or perceptual rendering.

Clipping means the saturation of the color, which is beyond the capabilities of the display, are reduced to what the display can natively produce. This is usually done by reducing the saturation by calculating a vector from the color back to D65 and seeing where it intersects the edge of the display's native color volume. The color is then displayed with this reduced saturation level. In some schemes there can be a luminance shift as well.

Some algorithms implement this on a global scale which means all the colors are desaturated leading to a somewhat washed out and bland image. A better way to do it is pixel-specific color processing that only clips those pixels that are out-of-gamut, while leaving others that are within gamut untouched. This requires more sophisticated processing and has a cost. However, it appears that TV chip sets makers are implementing the capabilities to do this type processing.

Another trade-off with gamut clipping is the loss of details in the out-of-gamut colors. For example, if these are a variety of out-gamut green shades in the original image which reveal some fine details of the image, clipping may take all of these out-of-gamut colors to nearly the same color, resulting is a loss of detail.

A second method to deal with out-of-gamut colors is called perceptual rendering. In this case the fine details of the original are preserved by shifting the out-of-gamut color range to a similar color range that is within the native capabilities of the display. The perception of the green shades may be similar to the original, but the colors may change and are definitely less saturated. Again, this requires more sophisticated processing, but these techniques provide the freedom for display manufacturers to differentiate their performance.

Now let's look at the P3 row in Table 6. The concept we want to discuss here is the "stretching" idea. Here, the content is delivered in a color volume that is *less than* the capabilities of the display. The most 'faithful' way to handle content in this case is to show the colors accurately in their mastered color space. If accurate rendition of the original creative intent is not the highest priority, the colors can be 'stretched' towards the boundaries of the display's native color gamut.

With "stretching", the saturation of the colors is extended under user control or via pre-set modes. The "vivid" mode is an example where the saturation can become intense – something some people like and what helps sell TVs – but with the trade-off of inaccurate colors. The images can look cartoonish and just plain wrong as the saturation is often done on a global scale so everything is more saturated and distorted. This option does not expand the color volume of the mastered content, it just changes the color balance in a way that does not match what the colorists wanted.

Color stretching change the "creators intent" so it is not an accurate image. But, it may be more pleasing to some people, which is why such options will be offered.

The entries in the 709 row of Table 6 are extensions of the above concepts.

It is important to note that the pipeline from mastered content to display needs to support WCG and/or HDR technology. These standards are still emerging so creativity is sometimes necessary.

For example, Vizio's new 65" reference series TV uses a quantum dot film from Nanosys and 3M that can achieve 87% of Rec. 2020 or 120% of the P3 color gamut. It also includes the Dolby Vision HDR capability. VUDU will be the first to supply Dolby Vision HDR content to the display using the two layer approach. The base layer will have the SDR/709 grade so it is backwards compatible to legacy TVs, but it will also include static metadata for processing by non-Dolby Vision HDR sets. This metadata is embedded in the first two lines of the video. The second layer contains the enhancement information needed to reconstruct the Dolby Vision HDR/WCG signal.

Dolby Vision content is mastered at 12-bits per color with 4:2:2 color sampling. But this mode is not supported over HDMI. So, the signal must be converted to 8-bit 4:4:4 (same bandwidth) to go over HDMI 2.0 to the TV, where it is reconverted to 12-bit 4:2:2 for processing by the Dolby Vision chip. This is then delivered to the TV's TCON (Timing Controller) board, where it changes to 10-bits to drive the panel.

Vizio and Dolby are still evaluating whether the HDMI 2.0a version will properly support Dolby Vision HDR transfer from external sources like Ultra HD Blu-ray players or set top boxes.

Wide Color Gamut Display Technologies

A number of technologies now exist to move beyond the BT 709 color gamut that is the standard in HDTVs today. The UHD TV specification calls for BT 2020, which is a much larger color gamut. Below, we will discuss the current methods used to create larger color volume along with their current performance levels.

LCD Display System Considerations

There are two primary display technologies vying for use in WCG TVs: LCD and OLED. In this section we will talk about LCD structures and OLEDs will be covered in a separate section.

An LCD consists of several major subsystems

- Backlight
- TFT glass substrate
- Color filter substrate

The backlight creates white light over the entire surface area of the display. The TFT (Thin Film Transistor) substrate has transistors at each sub-pixel which controls how much light passes thru each sub-pixel. Generally, a full color pixel is composed of red, green and blue sub-pixels with the light of each sub-pixel individually controlled. The color filter substrate filters the white light coming through each sub-pixel into red, green and blue components. Since these subpixels are small and close together, we perceive the combination of the luminance as a single color from a single pixel.

There are two types of backlight architectures:

- Edge lit
- Direct lit

In edge lit, a row of LEDs is coupled to a lightguide with the LEDs emitting perpendicular to the display surface. The LEDs create white light (by several methods to be discussed soon) while the lightguide homogenizes the light so it is uniform (with the help of diffuser, prism and polarizing sheets).

In direct lit backlights, the LED are arranged in an two dimensional matrix with light emitting toward the display and the viewer. Again, various films help to homogenize and polarize the light prior to entering the TFT substrate.

In an HDR display, you need a broad range of contrast. In LCDs, this is typically done by creating dimmable “zones”. That means, the light output of the LEDs is also modulated in addition to the modulation at the sub-pixel level. That’s two levels of modulation, which enable the wide range of light levels, which only one level can’t achieve.

In an edge lit backlight, the dimmable zones are horizontal and only allow up to about 16 zones in current TVs. In direct lit backlight, you can create a 2D matrix of zones. The number varies by manufacturer and quality level of the TV, but current product TVs support up to 384 independently dimmable zones (and more in professional products). How many dimmable zones is adequate for good HDR rendition is still a matter of debate, but a 2D matrix is clearly better than a 1D matrix. A 2D matrix also offers additional benefits for power savings – something that is a non-trivial consideration with HDR TVs that seek to meet EnergyStar requirements.

As mentioned previously, the white light in the backlights can be generated using a number of different technologies. Each has its trade-offs in terms of performance, cost, design and manufacturability – including their ability to create wide color gamut displays.

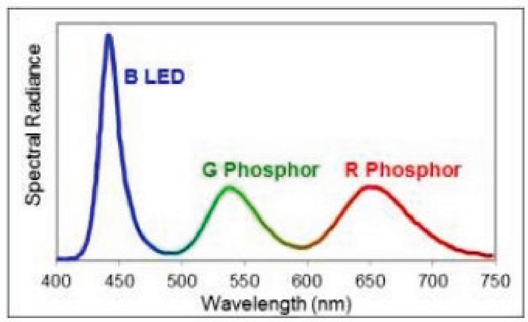
Phosphor Film

The phosphor film architecture features blue LEDs (in edge or direct lit orientation) illuminating a film embedded with phosphors. These phosphors are designed to absorb light at one wavelength (blue for display applications) and reemit at longer wavelengths (typically red and green).

Figure 22 shows the configuration in an edge lit LCD, plus the material properties and resultant spectrum of the backlight. This is filtered further by the color filter array on the front of the LCD.

This approach should produce fairly narrow RGB primaries and if the materials are chosen well, enable a color gamut of around 80% of BT 2020. However, some studies have suggested that going beyond 85% of BT 2020 with this approach will be difficult.

	Green	Red
Materials	$SrGa_2S_4$:Eu	CaS:Eu
Peak Wavelength	540 nm	653 nm
FWHM	47 nm	64 nm



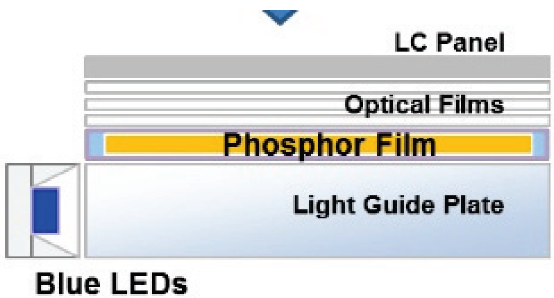


Figure 22: RG Phosphor Film Materials and Spectra (Source: Dexerials)

This approach is not very favorable from a cost perspective because for UHD displays, the display size is big meaning a full-sized phosphor sheet is needed. But the improved spectral performance comes at the expense of luminance reduction (in the 30-40% range), according to research reported by Dexerials using the materials in Figure 22. The phosphor film also requires a moisture barrier for lifetime maintenance. As a result, it may be more appropriate for small displays or lighting applications.

The phosphors used in these films need to be engineered for the emission wavelength, efficiency and manufacturability, which means it can be costly to engineer new ones. The film from Dexerials profiled below does not have ideal primaries for achieving a 2020 color gamut either. For example, the 653 nm red is a little too deep and inefficient while the green, at 540nm, is a little too yellow to be ideal. Since rec.2020 wavelengths are directly on the spectral locus, even a small deviation from the correct wavelength makes it impossible to achieve greater than 85% coverage of rec.2020 without very lossy color filters.

Quantum Dots

Quantum Dot Technology

Quantum dots are semi-conductor nanocrystals that also absorb light of higher energy and re-emit light at a longer wavelength, or down-convert it. The best materials on the market do so very efficiently, with a quantum efficiency of nearly 100%. Quantum dot (QD) materials can be used in a variety of applications such as lighting, medicine, solar cells and displays.

It is the size of the quantum dots that determines the down conversion wavelength (Figure 23) with smaller dots outputting shorter wavelengths and larger dots outputting longer wavelenghts. For display applications, two sizes of quantum dots are required: one for the green and one for the red. These are designed to absorb blue LED light, which also provides the light for third primary in the display.

The spectral width of the converted light is mainly determined by the range of sizes of quantum dots. Narrow spectrum is desired to get close to the 2020 primaries, so tight control of the manufacturing process is critical.

Quantum dot emission can be adjusted in the manufacturing process, enabling control of wavelengths with nanometer-level precision. This allows the quantum dots to be tuned to meet the needs of an application without changing the material system of the quantum dots or their surrounding matrix. This is an advantage in development, because the materials system can be developed, tested for performance and reliability, and qualified before fixing the final emission profile. It also allows the emission to be precisely optimized for a given display, enabling higher Rec. 2020 coverage.

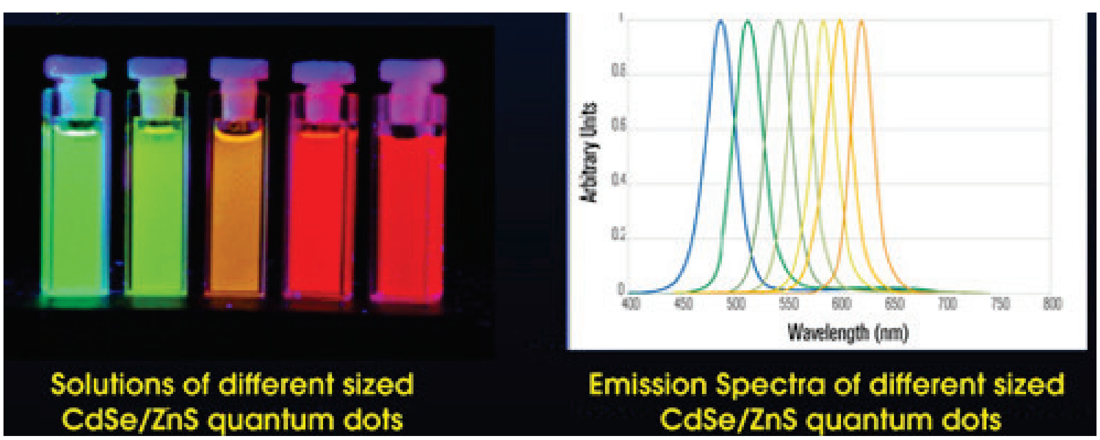


Figure 23: Quantum Dot Size Determines the Emission Wavelength

Two basic types of quantum dots are fabricated today: Cadmium-based and Cadmium-free (mainly based on Indium Phosphide). But the structure of these devices can vary and is the source of many of the different types of QDs offered by companies in the market (Figure 24).

Cadmium-free is desired in countries where there is more concern about the hazards of toxic materials like Cadmium such Japan and Europe. This seems to be less of an issue in other countries where independent research has shown that energy efficiency gains from Cadmium-based materials results in a net reduction in free Cadmium in the environment.

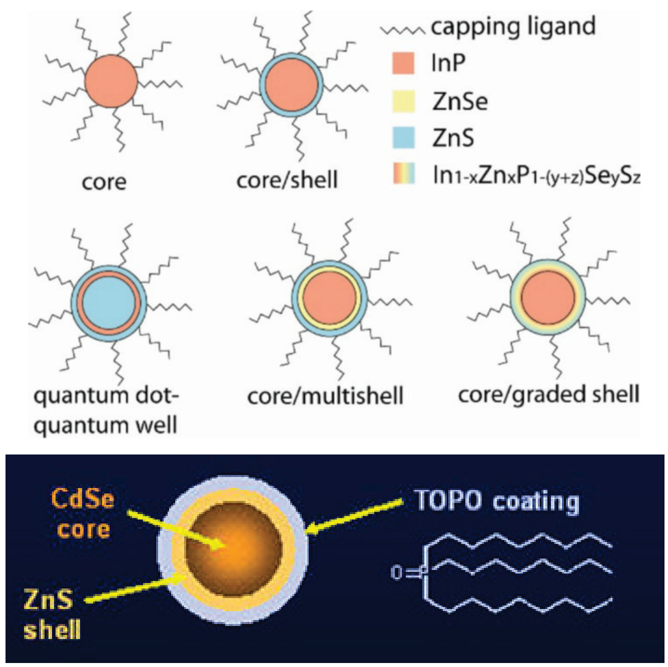


Figure 24: Structures of Cadmium-based and Cadmium-Free Quantum Dots

Cadmium-based quantum dots were commercialized first and offer higher efficiency overall. Cadmium-free is still behind in terms of efficiency (~10% less efficient than Cd-based) and color gamut coverage (less than 80% of 2020 vs. over 90% for Cd-based). Since Cadmium-based Quantum Dots offer better performance, the choice of which one to use is based on sensitivity to regulatory and environmental issues.

The CdSe quantum dots can deliver a bigger color gamut and more efficiently.

Quantum Dot Film

Film-based QD solutions mean that the red and green quantum dots are placed inside a film that is attached over the emitting surface of the backlight. Blue LEDs, either edge mounted or direct type, illuminate the film. The film is engineered to pass some blue light and convert the rest of the blue light to red and green in the right proportion to produce the specified white color point. This configuration offers the lowest optical power density, which is a factor in QD lifetime. But QD materials, like most semiconductor materials, need protection from oxygen, water and heat. That means the addition of barrier layers must be added to the film. Such films have seen significant improvement recently in terms of performance improvements and cost reduction.

Film-based QD solutions have been commercialized by 3M (quantum dot materials from Nanosys) and by Samsung (internal supply of quantum dots, developed with and licensed from Nanosys). Other companies are in development as well.

DisplayMate has measured the Samsung UN65JS9500 color gamut, which uses Samsung's QD technology. The result is shown in Figure 25 for several picture modes. Movie mode should be the calibrated 709/SDR mode with a D65 white point, which it achieves. Overall, principal Ray Soneira measured the color gamut as 104% of P3. While the gamut has a larger area than P3, there are some fully saturated colors on the edge of the P3 triangle it cannot show.

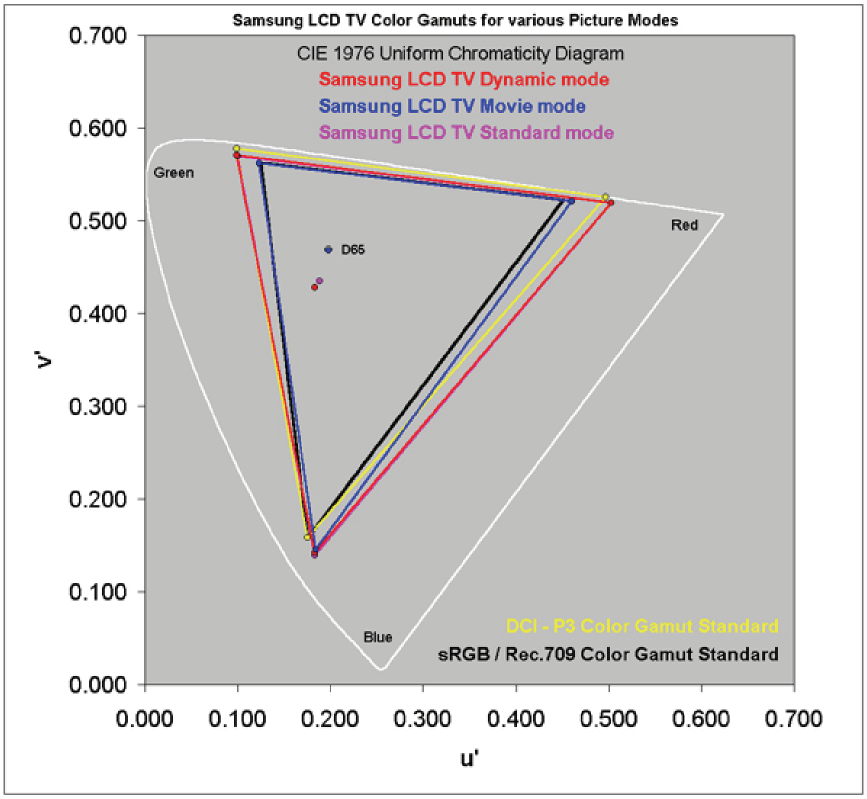


Figure 25: Color Gamut of the Samsung UN65JS9500 SUHD TV (Source: DisplayMate)

Samsung sets that offer wide color gamut are branded "nanocrystal." This is based upon their Cadmuim-free InP quantum dot technology. As we stated earlier, Cadmium-free quantum dots cannot create as large a color volume as Cadmium-based QDs (and Samsung does not publish its color space specification compared to the 2020 gamut).

On the other hand, the new Vizio 65" Reference Series TV (RS65-B2) uses the 3M/Nanosys QD film technology, which is Cadmium-based. The color space is speced at 120% of DCI-P3 (in black) or 87% of 2020, as shown in Figure 26.

Looking at the P3 diagram suggests it can create colors in the cyan and purple ranges that are outside P3, but it cannot create the fully saturated (closest to the edge of the spectral locus, the horseshoe-shaped range of visible colors) red, greens and yellow along the top of the P3 triangle.

A review of the 2020 diagram shows that it can reach 87% of the full color volume, again being a little deficient in showing the fullest saturated colors. Part of the reason for this coverage was the choice of primaries that Vizio made. 3M and Nanosys have shown the ability to get to 93.7% of 2020 with slight adjustments of these primaries.

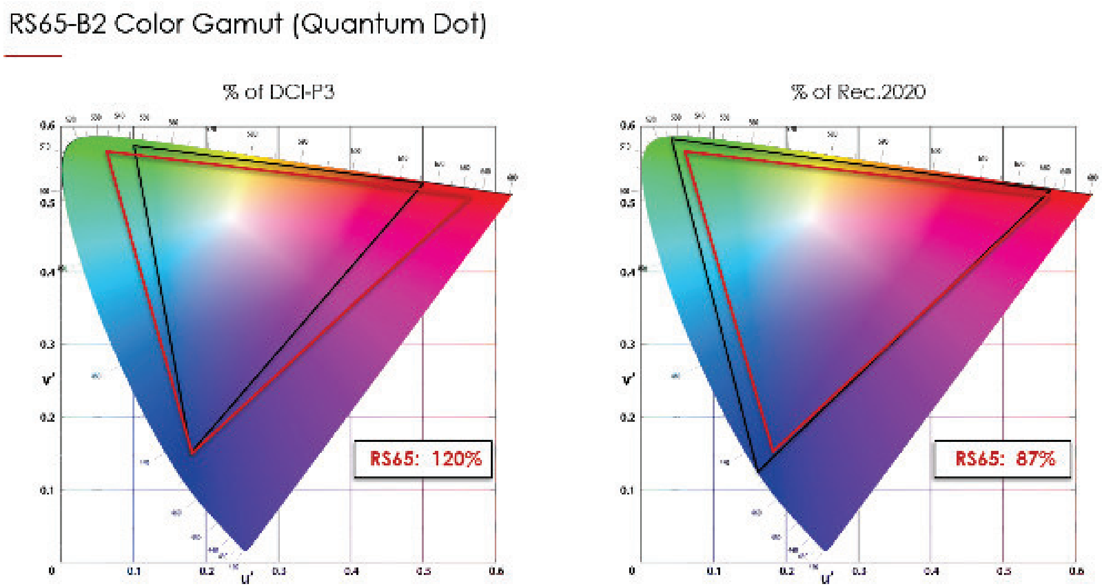


Figure 26: Color Space for Vizio 65" Reference TV (Source: Vizio)

Quantum Dot Edge Optic

Quantum dot resin can also be packaged inside a long slender glass tube that is placed between the blue LEDs and the light guide in the backlight. This is called the quantum dot edge optic option and has been commercialized by one company, QD Vision.

Again, the concentrations are engineered to pass some blue light and create red and green light in the proper proportions. The optic solution is sealed into a high precision glass tube, which acts as the barrier against moisture and oxygen, just like the film.

As blue light passes through the optic, some of it is converted to red and green and some passes through into the lightguide. Since the dots are isotropic emitters, meaning they emit light at random in all directions, a significant portion of the converted light does not make it into the lightguide. It is possible to recapture some, but not all of this light by adding reflectors around the optic. This results in a reduction in efficiency compared to the film approach, which benefits from integration into a part of the display stack that recycles light very efficiently. In the film implementation, photons that head the ‘wrong way’ are automatically captured and sent back through the film by the display’s back-reflector.

As mentioned previously, a film-based approach can support a direct lit backlight for a 2D matrix of dimmable zones whereas the QD edge optic can only support edge lit backlights and 1D dimmable zones. Most see a 2D dimmable matrix with excellent local contrast as a key element of high quality HDR, so HDR solutions will likely migrate toward the film solution over the optic solution for this reason. On the other hand, the amount of Quantum Dot materials required scales with area using a film solution while cost scales with height using the optic solution. This can have an impact on cost and, indeed, initial reports from the marketplace indicate that films have generally been more expensive to date. However, a number of other factors impact the cost of film based components.

- Companies focusing on the film approach have invested heavily in scaling-up automated manufacturing lines to handle the increased volume of material required by the film. This has lead to a significant cost advantage for material production with fully automated production, and very high production yields, these companies will have a cost advantage for the Quantum Dot material itself.
- High quality barrier films were initially supply-constrained but now several new sources of high quality barrier film are ramping up production. Also, there have been recent advances in the Quantum Dot material, matrix material and the coating process which allows for a lower grade (and lower cost) barrier film to be used. Multiple equipment companies have also been investing heavily in optimizing throughput and overall cost of ownership allowing their customers to produce barrier film at a lower cost.

It is also possible to contemplate a hybrid solution that places QD filled optic such as a film or glass optic only over the LED strips that compose the direct backlight. That would address the dimmable zone deficiency of the traditional edge optic approach and potentially scale less expensively than the film solution. We will have to see how this evolves, but it seems likely both solutions will continue in the market for some time.

QD Material Supplier	Film	Optic	LED	Cadmium-based	Cadmium-Free	Manufacturing Partner	Customers with Shipping Products (12/2015)
Nanoco	D		D		D	Dow Chemical (dots)	
QDVision	D	C	D	C	D		TPV/Philips (TV), TPV/AOC (monitor), TCL (TVs), Seiki (TV), Hisense (TV), Konka (TV)
Nanosys	C		D	C	C	3M (film); AUO (displays)	Vizio R65 (TV), Sharp UG30 (TV), ASUS (Laptop), Hisense 65H10B (TV), TCL 8800S (TV), Amazon Kindle Fire HDX (Tablet), Tianma (Medical Monitor)
Samsung	C				C	Nanosys (IP, development)	Samsung (TV)
Quantum Materials					D		
Pacific Light Technologies			D				
C = Commercialized							
D = Development							

Table 7: Summary of QD Suppliers, Partners and Customers

QD optic technology has been adopted by several TV makers including Hisense, Philips/TP Vision, Seiki and TCL. Reports of the color gamut vary by manufacturer running from 94% of P3 to 90% of 2020.

Quantum dot technology seems to offer the biggest color gamut of the various approaches today. Table 7 summaries the known suppliers of QD materials along with their known partners and customers.

Adjusting Color Filtering

Another method to increase the color gamut of a display is to redesign the TFT color filters or to add additional filters elsewhere in the TV. These changes always result in a loss in luminance unless compensated for with more brightness, for example.

At the panel level, manufacturers have the option to consider changing the bandpass characteristics of the color filters. Typically, there is a little cross over between the blue and green filters and between the green and red filters. This can be reduced to increase the gamut and allows greater native color saturation by trading off brightness and efficiency. We believe the LG UF 8300 series employs this approach.

At the product level, manufacturers can consider adding additional filters without changing the RGB color filter array. Samsung's 7000 series TVs do this by adding a filter sheet the size of the TV that essentially acts as a yellow notch filter. This does reduce brightness however, which appears to be compensated for with more powerful LEDs in the backlight.

Adjusting the color filtering can only take you so far, however. Achieving a P3 color gamut is possible, but power goes up. Achieving P3 and 1000 nits may not be very practical as the power goes way up. Achieving 2020 is not really practical at all – even at high power levels, which is not useful.

Perhaps the better use of color filter adjustments is in combination with quantum dot technology. For example, 3M and Nanosys have demonstrated that they can reach 93.7% of the 2020 color gamut with a slight change in the red and green color filter technology. The current color filters have a slight overlap in the blue and green, which is enough to desaturate the blue and reduce color space coverage. Modeling by 3M suggests that up to 97% of the 2020 gamut is possible with further blue filter modifications.

As we noted in a previous section, the 2020 RGB primaries are currently specified as single wavelengths with no tolerances. It seems likely this will change to allow some tolerances and enabling the production of 2020-compliant displays. Whether that includes a change in the primaries is unclear, however.

LEDs

Direct View RGB LEDs

LEDs can be fabricated in many wavelengths including red, green and blue. These devices can be used to create direct-view LED videowall displays, LCD displays using RGB LEDs in the backlight, and even projectors using high-power RGB LEDs.

In LED videowalls for example, a trio of RGB LED die (3-in-1 type) are packaged in a surface mount device (SMD). These are close packed together at various pixel pitches to form a module or cabinet. A series of modules are then built up to form a display. The display controller allows the driving of the red, green or blue LEDs at each pixel location.

While this sounds like an ideal solution for a WCG display, there are a number of practical issues. For example, the LEDs come from different material systems and have different driving, aging and temperature dependence characteristics. These are compensated for in the circuits to drive the LED (part of the LED board), but constant calibration is needed in practice.

Creating a 4K resolution display depends upon the pixel pitch of the RGB LEDs. The smallest commercially available pitch is about 1mm. So a display with 3840 pixels would be 3840mm wide or 12.6 feet wide. It would also cost more than $500K so is not very practical from a size and cost perspective. In addition, there are issues with the low fill factor and high power consumption.

On the positive side, they have a lot of luminance, high contrast and refresh rates and deep color saturation at the die level. But since there are so many LED die, they have to be binned into groups with similar peak wavelengths and emission bandwidths. This spread of peak wavelengths, even with tight binning, makes it difficult to get a display that can comply with a 2020 color gamut. That is why few LED video wall makers specify the color gamut.

Similar 3-in-1 LED packages can be used with LCD displays in direct-type or edge-lit backlights. Indeed Samsung and Sony commercialized some TVs using this approach, but they do not seem to be available any more.

The reasons would appear to be the cost, drive management issues, thermal control, differential lifetime, color gamut and stability, plus the rise of alternative technologies. While the approach is still viable, it seems unlikely to see much if any commercialization.

RGB LEDs in Projectors

RGB LED projectors on the other hand, are commercialized and prospering. Here, a single trio or maybe two sets of RGB LEDs are used to create the light. This confines the challenges to a much more manageable set of LEDs. Digital Projection for example, has an RGB LED projector that can achieve very close to the 2020 color gamut as shown in Figure 27.

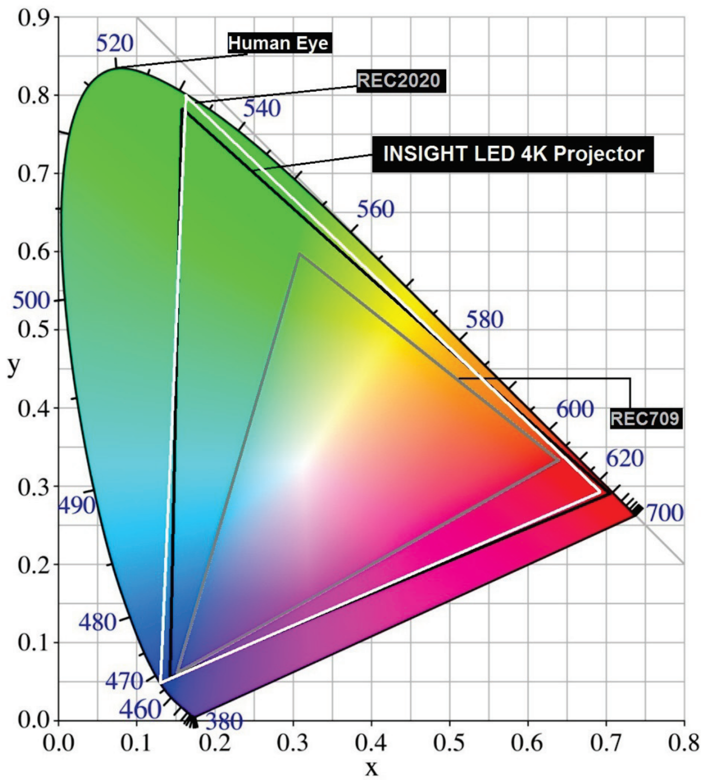


Figure 27: Color Gamut of the Insight 4K LED Projector from Digital Projection

Phosphor-Enhanced LEDs

The majority of LCD display using LED-based backlights use LEDs can create white light using a blue LED overcoated with a YAG yellow phosphor (Figure 28). The blue light acts as an optical pump to the phosphor which down-converts the light to a different spectrum.

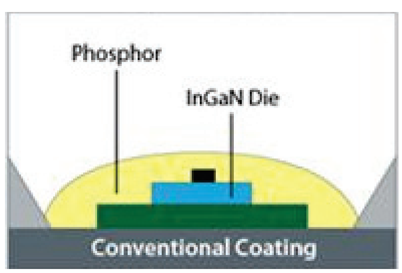


Figure 28: Phosphor Coated LED Structure

Optically-pumped phosphor conversion operates on a different principle than quantum dots. While the QD emission of often narrow (25-35 nm for Cd-based and 40-50 nm for Cd-free FWHM), the phosphor emission is usually much broader (100-150 nm for the YAG:Ce phosphor in Figure 29).

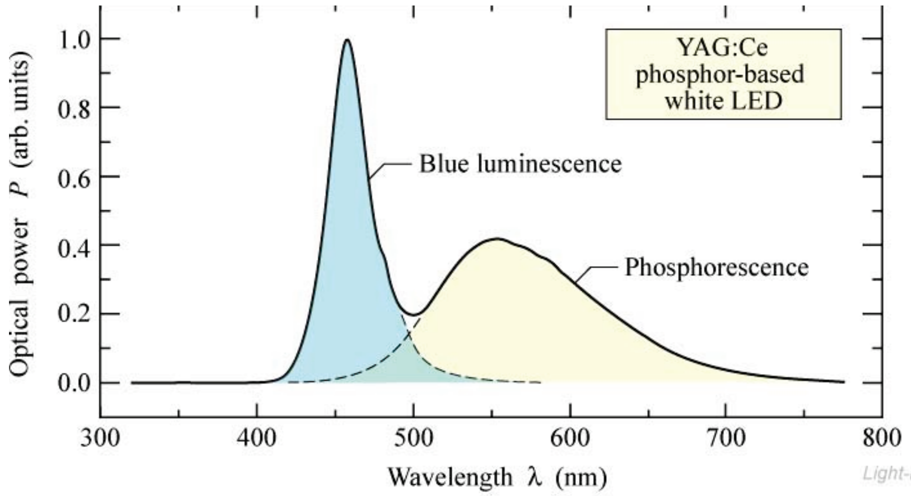


Figure 29: Spectral Profile of White LED with YAG Phosphor

Almost all mobile LCD displays and many LCD TVs use white LED made using the YAG phosphor as it is quite efficient, inexpensive and produces decent white light. But it is not optimal for achieving a wide color gamut. Typical LCD displays using this type of white LED can obtain 35-55% of rec.2020 or 45-75% DCI-P3 (in u'v') of color gamut.

One popular solution is adding red and green phosphors to the blue LED. As noted in the Phosphor Film section, an RG phosphor film pumped by blue LEDs can lose 30-40% of the light compared to a white YAG LED. Sharp has released a new RG phosphor blue LED that loses only 3% of the luminance compared to the YAG LED. More recently, Sharp and Nichia have licensed a new red phosphor material called PFS that appears to be better than europium doped nitride red phosphors.

The new material has been developed by GE and is called potassium fluorosilicate doped with manganese (PFS or KFS). This creates a narrow red line emission with a FWHM of less than 10nm! This allows a sharper red primary with less chroma bleed vs. the europium phosphor. These red phosphors can be combined with a yellow or a green phosphor to be blue-pumped by the LED.

We believe the Sony "Triluminous" WCG displays uses Blue +RG phosphors for the light source. It is unclear if they have yet migrated to LEDs with the new PFS phosphor. But we did see a comment on AV Forum where they reported measuring the spectrum of a X850 UHD TV and this spectrum suggests the use of the PFS red phosphor (Figure 30).

One concern with phosphors is their decay time which may be as long as 20 ms for some materials. For fast-moving content in an HDR display, this can be much longer than the length of the frame and cause blur/ghosting.

And, as noted previously, development of new color primaries is not so easy and requires development of new material systems. The wide FWHM of green is still a big problem in terms of reaching high coverage of rec.2020, for example.

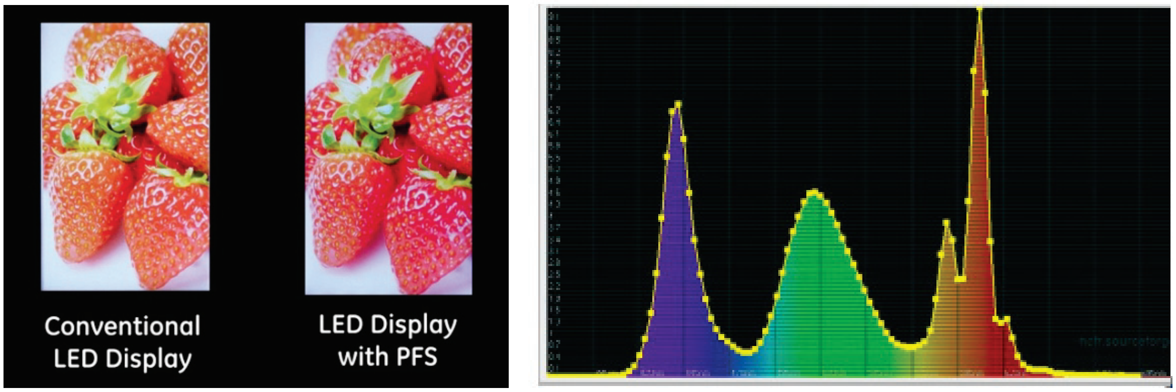


Figure 30: Spectrum of Sony WCG X850B TV based on Sharp LED with PSF Red Phosphor from GE (Source: AVS Forum)

While phosphor technology has a long history of development, the activation method has changed from CRT (electrons) to LCDs (blue light). Innovation continues here at a rapid pace so we can expect to see new materials and combinations of materials that will be considered for an optimized 2020 color gamut display.

QD-Phosphor Hybrid

In a very new development, Osram has announced that it has developed a phosphor hybrid LED. Called Quantum Colors LEDs (QC LEDs), the device is based upon a blue LED with a green quantum well structure and red phosphor (Figure 31). This is apparently NOT a quantum dot technology but a semiconductor quantum well that interferometrically emits green when pumped by blue light.

The technology was developed partly in the SSL4EU and Hi-Q-LED projects, funded by the EU and German Ministry of Education and Research (BMBF). LEDs using the technology have a narrow green peak, with full width half maximum of 30nm. Another claimed advantage is in lifetime. QC LEDs 'should' last for at least 30,000 hours and should be in use in TVs by the end of 2016.

The QC LED is said to cover 100% of the P3 gamut or 80% of the 2020 color gamut. However, Osram can tune the green to a peak of, for example, 530 nm rather than 540nm to optimize the gamut to maximize for the Rec. 2020 coverage. Osram also said that its choice of P3 in its release was just as an example.

The firm confirmed that the $58 that it quoted in its press release represents its estimated cost for a 55" direct-lit LED-backlit LCD. The LED design is "plug & play" with its existing white LEDs without any changes to the system and would work in direct-lit or edge-lit sets.

For phosphor-based solutions, the P3 gamut would need optimized filters because of the rather wide FWHM of the phosphors. Osram confirmed that it has testing samples now, with LED samples available to customers in the spring of 2016 and mass production towards the end of the year.

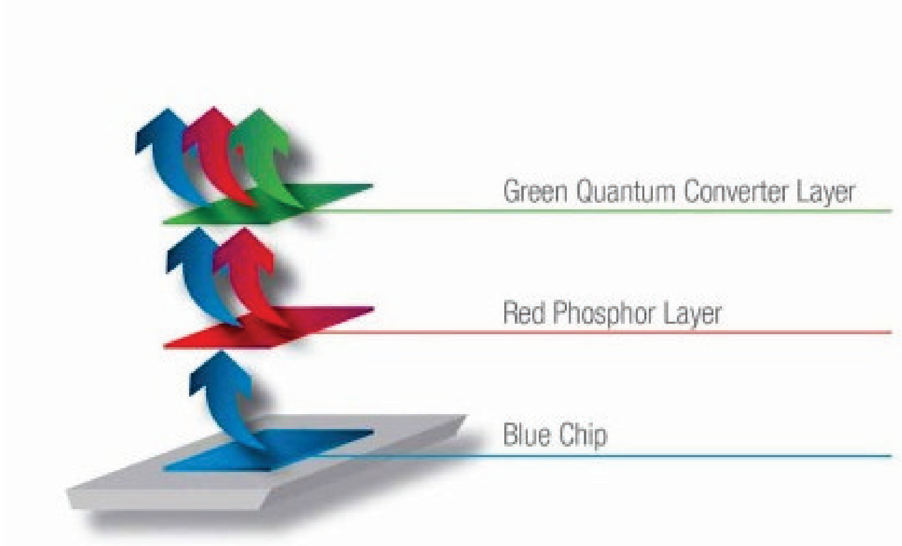


Figure 31: Osram's QC LED Schematic

OLED

Organic Light Emitting Diodes (OLEDs) have been commercialized as TVs, mainly led by LG Electronics. OLEDs are emissive displays which means they create their light at each pixel, like CRTs and PDPs. Each pixel has an electron and hole transport region that meet to create a diode junction. A series of control transistors for each pixel deliver current, which creates the light. More transistors are desired for better control and uniformity adjustments, but this also reduces the light emitting portion of each pixel.

OLEDs are even more sensitive to oxygen and moisture than quantum dots – much more sensitive. Even a tiny pin prick in the barrier layer can lead to complete display failure. While we are seeing improvements in barrier layers for OLEDs, this still remains a critical process and the displays are still more expensive than OLEDs.

There are two basic methods for OLED displays:

- Red, green and blue OLED subpixels – Championed by Samsung for mobile displays and LG in its premium TV
- White emitting OLED material with RGB color filters – Championed by LG for TVs

There are also concerns about the lifetime of the blue OLED material. The only commercial implementation of white OLEDs for displays uses a triple layer of blue fluorescent and yellow phosphorescent materials. Development of a longer lifetime blue phosphorescent material is needed (or something else).

OLEDs have the benefit of being able to create very low and well controlled black levels for great details in the black regions. This leads to very high contrast. But the peak emission of OLEDs is somewhat limited in comparison to LCDs, where it is much easier to increase the light output of the backlight. The best OLEDs today can achieve at most 40-50% (400-500nits) of the peak luminance of QD LCD displays (700-2,000 nits).

This brightness limitation also affects the color volume capabilities of the OLED display. At low luminance levels, the best OLED displays can show a P3 color gamut. But as luminance increases, the display is unable to maintain this color gamut. At the peak luminance levels, the color gamut is only a fraction of the low luminance gamut. That means fireworks could look white on an OLED but they may be properly displayed as green on a QD LCD TV.

There is no doubt that the great black levels, high contrast and P3 color gamut can produce some very compelling HDR images – especially those with a lot of dark content. But for brighter content, OLEDs may be quite challenged in competition with LCD. This may be particularly acute on the retail show floor where the ambient lighting is high and all the TVs are in the brightest and most saturated "vivid" mode.

LG has commercialized WCG/HDR TVs and the second major entry into the OLED TV field is Panasonic. The panel is sourced from LG, but Panasonic has developed its own electronics from driving the display and processing video images.

Panasonic says their TV can achieve close to the P3 color gamut. In independent testing by DisplayMate, Ray Soneira measured the color gamut of the LG OLED TV (model 65EG9600) in three picture modes (vivid, cinema and standard). This is shown in Figure 32.

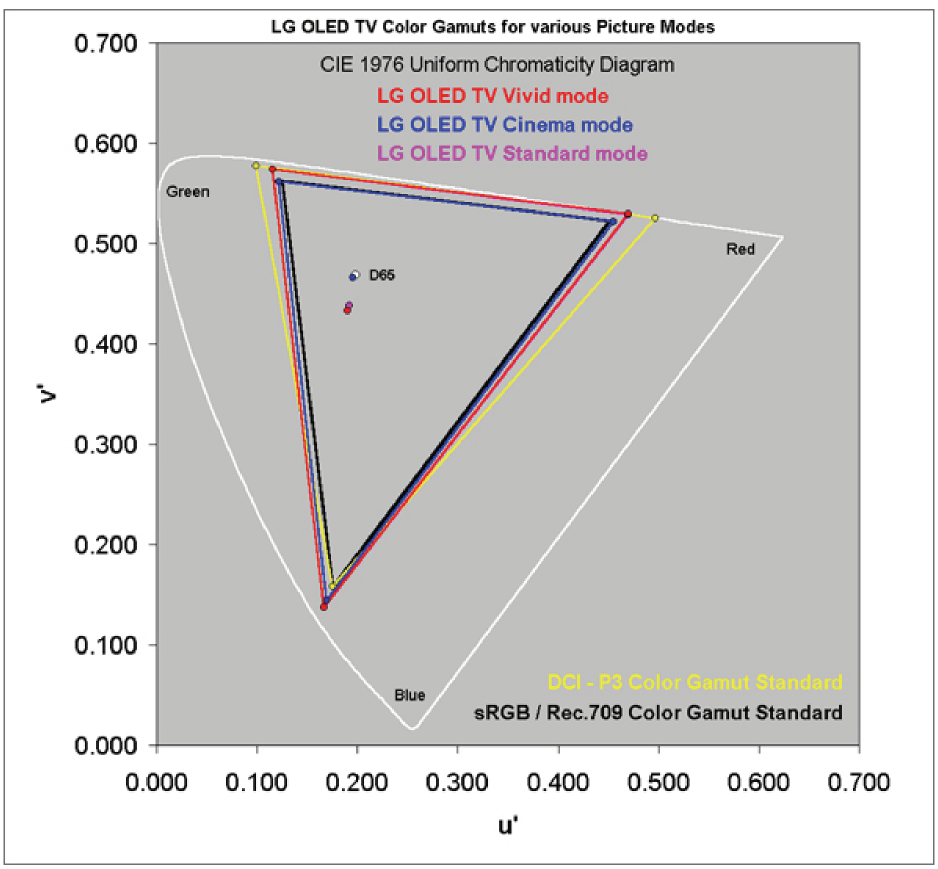


Figure 32: Color Gamut of LG's 65EG9600 OLED 4K TV (Source: DisplayMate)

As expected, cinema mode is the reference mode with a 709 gamut, standard dynamic range and a D65 white point. The LG display does a good job or reproducing reds and greens and is slightly bigger in the blues, which need to be remapped to the 709 color volume.

Vivid mode offers the highest saturation, but shifts the white point so colors may not be accurate. The red and green primaries are a little short of P3 but the blue is good. Overall, Soneira measured the OLED TV at 93% of P3.

Can OLEDs get to a 2020 color gamut? That remains unclear as new materials will have to be developed and this takes time and expense. Plus, OLEDs will need to have answer to their brightness limitations in the long run.

Emerging Technologies

QD-LEDs

So far, we have discussed the integration of quantum dots into films and into an optical element. The third approach, sometimes called QD-LEDs, is to fabricate the LED device using quantum dot materials. This is the highest optical density challenge, which is why it is not commercialized yet, plus there are many materials challenges to be solved. However, the QD-LED approach solves many issues allowing the elimination of the QD optic or film and simply using QD-LEDs in edge or direct type LCD backlights.

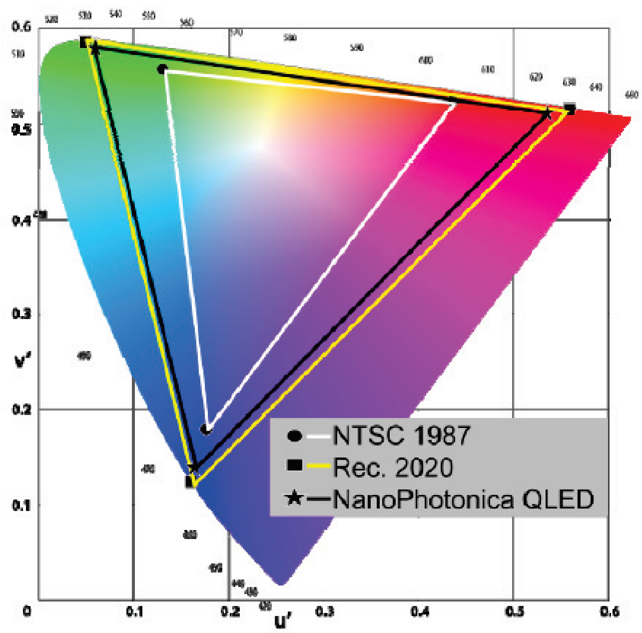


Figure 33: Color Gamut of a Prototype QD-LED Developed by NanoPhotonica

Figure 33 shows the color gamut of a QD-LED prototype from NanoPhotonica. As can be scene, it is covering about 90% of the 2020 color gamut. Solution printing of the QD-LEDs in a display-style matrix is the focus of their work. Many others are working on QD-LEDs as well.

Some research is also being directed toward creating an electroluminescent display with embedded quantum dots.

Hybrid and Multi-Primary

Because there are so many materials and packaging options to create a wide color gamut display, hybrid solutions are emerging too. In general, this can mean combinations of LEDs, phosphors, quantum dots and even lasers to create a WCG display. Here, we will discuss some known solutions or development efforts, but many more have undoubtedly have been, or will be proposed and potentially developed and commercialized.

One hybrid approach is to mix LEDs and lasers. This has been commercialized by Casio for projectors and by Mitsubishi for a rear-projection TV. Recently, Mitsubishi has also announced a hybrid LCD TV as well, but has not revealed any details of the architecture or performance. Others have suggested using a blue LED plus a green LED with red phosphor.

Another hybrid approach is to create a multi-primary display. That means adding more primaries than just RGB. This idea seems like a logical way to get better coverage of the all the colors humans can see in the CIE "horseshoe" as a triangle always excludes some colors.

Indeed multi-primary displays have been proposed and developed and they do offer wider color gamuts, but often at a cost that is not always just monetary.

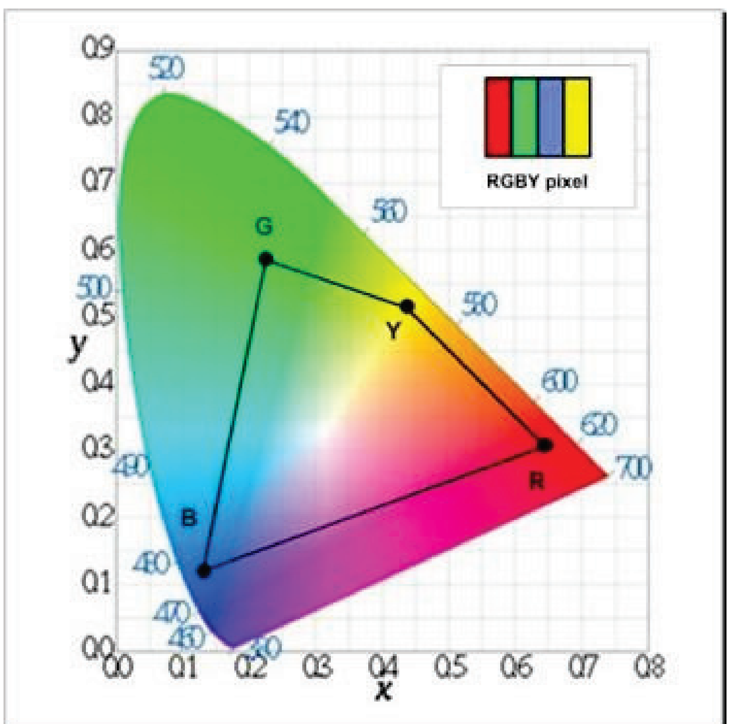


Figure 34: RGBY Pixel Pattern

Early efforts did not have the 2020 gamut as a target to meet, so any displays that had a color volume outside of 709 or 601 had to stretch these colors to the wider gamut. That is always tricky and can change the creative intent, so these efforts were not successful.

Sharp, for example, has developed a new pixel architecture: red, green, blue and yellow (RGBY), as shown in Figure 34. It uses the yellow sub-pixel to allow more of the medium and long wavelengths of light from the backlight to reach the viewer. This in turn allows the red, green, and blue primaries to be comprised of higher color-saturation filters.

Figure 34 shows that RGB primaries are chosen for BT 709 with the yellow primary allowing the TV to create more saturated yellows. Note that this requires Sharp to have algorithms to stretch the colors from the 709 master to accentuate the added color space. Sharp has a UHD version of the RGBY pixel design as well, but the color gamut is not known.

RGBW pixel architectures are also used in UHD TVs. The white pixel helps to boost peak luminance, which can help for HDR, but it also will reduce the color volume – sometimes significantly. The set needs to be run in a cinema mode that reduces the contribution from the white subpixel.

Creating a multi-primary display to reach the 2020 color gamut is actually quite hard. That's because the RGB primaries are on the spectral locus, so you essentially must include these anyway to come close to a 2020 color volume.

Another important issue with narrow-band primaries and multi-primary displays is Metamerism. Metamers are spectrally variant color stimuli that are perceived identically. In other words, if a certain color of red is perceived as the same color when created from a red LED, red laser or white light source with a red filter – these are metamers.

Metameric failure is when the same color is not perceived the same by two different observers. This can happen as we move from broadband light sources like blue + yellow phosphor LEDs to narrowband light sources like or quantum dots or lasers. The same color may measure the same with a spectrometer or colorimeter, but users perceive it differently.

At the Rochester Institute of Technology (RIT) they are developing models of multi-primary solutions to understand how different solutions impact the display of colors and the color volume, but also how these systems impact human perception and susceptibility to metameric failure.

For example, RIT has modeled an 8-primary display as well as a 7-primary display, which has actually been built as a prototype. Both do a great job of creating a very large color volume, but the 7-primary, called the MPD, does a better job of reducing metameric failure. Figure 35 show the color gamut coverage of the two multi-primary displays.

The results of their analysis are shown in Table 8. OM_s is the measure of metameric failure with a lower number being better. Note how poorly the 8-laser system performs, even with the largest color gamut. The RIT MPD display's primaries were chose to get a large color volume and to minimize metameric failure.

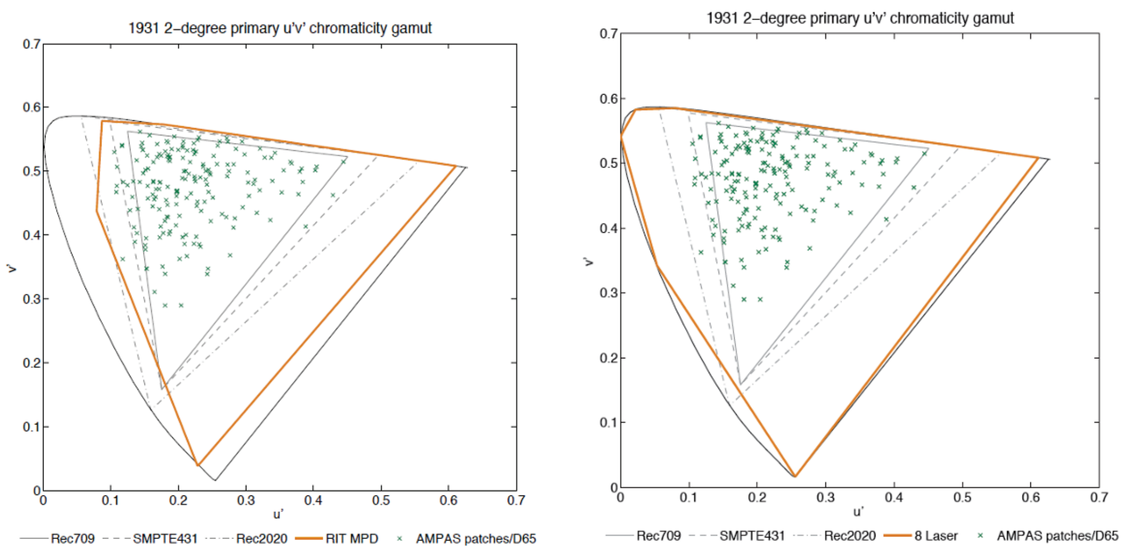


Figure 35: Color Gamuts of a 7-primary Display (MPD - left) and an 8-Primary Display (R) (Source: RIT)

CIE D65	**OM_s**	**$OM_{s,var}$**	**max DE00(31)**
MacBeth24			
Sony CRT (Rec. 709)	2.15	2.6E-03	0.44
NEC DLP (P3)	1.83	2.8E-04	0.00
Panasonic DLP (P3)	2.49	1.0E-03	0.00
Laser (Rec. 2020)	5.50	2.6E-01	0.00
8 laser	11.61	3.1E+02	0.00
RIT MPD	0.78	6.2E-06	0.00

*NOTE: Extra degrees of freedom used to further minimize OM_s for 8-laser and RIT MPD

R·I·T

Table 8: Metameric Analysis of Multi-Primary Displays (Source: RIT)

RIT Professor David Long said their research is also focused on how to optimize the primaries for the 2020 color gamut in order to reduce the potential for metameric failure. Recommendations could be coming soon, which could lead to a revised 2020 color standard with metameric-optimized primaries and tolerances so display makers can focus on creating 2020-certified displays.

Summary of Current Wide-Color-Capable TVs

The table below summarizes known specifications for commercially available and announced WCG TVs.

Brand	Model number	LCD or OLED?	WCG Tech	Edge or Direct BLU?	Number of Dimmable Zones	Color Space	Curved or Flat?	Screen Size	Resolution	ship date	MSRP	HDR Format support	connectivity support	Codec support	4K content support	peak luminance (nits)	Ultra HD Premium Certified?	Notes
Hisense	43H7c	LCD		Direct		DCI-P3 | 79.6%	Flat	43	UHD	Feb. 2016	$399	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	350	No	
Hisense	50H7C	LCD		Direct		DCI-P3 | 79.6%	Flat	50	UHD	Feb. 2016	$549	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	370	No	
Hisense	50H8C	LCD		Direct	10	DCI-P3 | 79.6%	Flat	50	UHD	Mar, 2016	$599	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Hisense	55H7C	LCD		Direct		DCI-P3 | 79.6%	Flat	55	UHD	Feb. 2016	$649	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	370	No	
Hisense	55H8C	LCD		Direct	12	DCI-P3 | 79.6%	Flat	55	UHD	Mar, 2016	$699	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Hisense	55H9B	LCD		Direct	85	DCI-P3 | 79.6%	Curved	55	UHD	Feb. 2016	$999	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	500	No	Hisense ULED™ - UltraLED 1.0
Hisense	65H10B	LCD	QD Film	Direct	240	DCI-P3 | 99.98% Rec.2020 | 91.2%	Curved	65	UHD	Feb. 2016	$2,799	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	800	No	Hisense ULED™ - UltraLED 2.0
Hisense	65H10C	LCD	QD Film	Direct	240	DCI-P3 | 99.98% Rec.2020 | 91.2%	Curved	65	UHD	Jul, 2016	TBA	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	1000	Yes	Hisense ULED™ - UltraLED 3.0
Hisense	65H7C	LCD		Edge		DCI-P3 | 79.6%	Flat	65	UHD	Feb. 2016	$1,299	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	380	No	
LeTV	85"	LCD	RG Phosphor	Direct			flat	85	UHD	Q3'16		Dolby Vision						
LeTV	uMax120	LCD	RG Phosphor	Direct	384	85% of NTSC	Flat	120	UHD	Q4'16		Dolby Vision						3D model with 120 Hz refresh rate
LG Electronics	B6	OLED	N/A	N/A	Pixel Dimming	99% of P3	Flat	55, 65	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu		yes	
LG Electronics	C6	OLED	N/A	N/A	Pixel Dimming	99% of P3	Curved	55, 65	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu		yes	
LG Electronics	E6	OLED	N/A	N/A	Pixel Dimming	99% of P3	Flat	55, 65	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu	800	yes	super slim design - 2.57 mm; webOS 3.0, picture-on-glass design with minimal bezels
LG Electronics	EC9300	OLED	N/A	N/A	Pixel Dimming	709 +	Curved	55	1080	2014	$1.8K	N/A						
LG Electronics	EF9500	OLED	N/A	N/A	Pixel Dimming	709 +	Flat	55, 65	UHD	Now	$3K, $5K	HDR 10 (SMPTE 2084/2086); BBC using HbbTV 2.0 in development	HDMI 2.0a with HDR signalling	HEVC, VP9	Amazon, Netflix			
LG Electronics	EG9100	OLED	N/A	N/A	Pixel Dimming	709 +	Curved	55	1080	Now	$2K	N/A						
LG Electronics	EG9600	OLED	N/A	N/A	Pixel Dimming	709 +	Curved	55, 65	UHD	1H 2015	$3K, $5K	HDR 10 (SMPTE 2084/2086); BBC using HbbTV 2.0 in development	HDMI 2.0	HEVC, VP9	Amazon, Netflix			firmware update to stream Amazon and future providers
LG Electronics	EG9700	OLED	N/A	N/A	Pixel Dimming	709 +	Curved	77	UHD	2014	$5K	N/A		HEVC				

Brand	Model number	LCD or OLED?	WCG Tech	Edge or Direct BLU?	Number of Dimmable Zones	Color Space	Curved or Flat?	Screen Size	Resolution	ship date	MSRP	HDR Format support	connectivity support	Codec support	4K content support	peak luminance (nits)	Ultra HD Premium Certified?	Notes
LG Electronics	Signature G6	OLED	N/A	N/A	Pixel Dimming	99% of P3	Flat	65, 77	UHD	March, 2016; June 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu	800	yes	super slim design - 2.57 mm; G6 slightly thinner than E6 at its thinnest point; webOS 3.0, picture-on-glass design with minimal bezels
LG Electronics	UF8300	LCD	Narrow Filter	Edge	6	709 +	flat	50	UHD	Summer 2015	$1.1K	N/A		HEVC, VP9				
LG Electronics	UF9500	LCD	Narrow Filter	Edge	12/32	709 +	flat	65,79	UHD	Summer 2015	$2.7K, $7K	N/A		HEVC, VP9				
LG Electronics	UH7700	LCD	RG Phosphor/Filter	?	?	84% of P3	Flat	49-65	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu			super slim design; harmon-Kardon speaker systemWeb OS 3.0; 240 hz refresh
LG Electronics	UH8500	LCD	RG Phosphor/Filter	?	?	90% of P3	Flat	49-75	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu			super slim design, harmon-Kardon speaker systemWeb OS 3.0; 240 hz refresh
LG Electronics	UH9500	LCD	RG Phosphor/Filter	?	?	91% of P3	Flat	55-86	UHD	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu			super slim design - 6.6 mm; harmon-Kardon speaker systemWeb OS 3.0; 240 hz refresh
LG Electronics	UH9800	LCD	RG Phosphor/Filter	?	?	91% of P3	Flat	98	8K	March, 2016	TBA	HDR-10, Dolby Vision working on Tech/Philips HDR	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Amazon, Netflix, YouTube, Vudu			super slim design; harmon-Kardon speaker systemWeb OS 3.0; 240 hz refresh
Panasonic	DX900	LCD	RG Phosphor	Direct	500	90% of P3	Flat	58, 65	UHD	Spring 2016	TBA	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	Amazon, Netflix	>1000	Yes	Firefox OS
Panasonic	TX-65CZ950 TX-65CZW954	OLED	N/A	N/A	N/A	90% of P3	Curved	65	UHD	Oct 2015; Europe	$11K	HDR 10 (SMPTE 2084/2086); BBC using HbbTV 2.0 in development	HDMI 2.0a with HDR signalling					specially modified version of Panasonic’s professional-level 4K Studio Master processor. First OLED 4K TV to be THX certified.
Philips/Funai	6000 series	LCD	?	Direct	?	?	Flat	43, 55 (direct) 65 (edge)	UHD	mid-2016	$0.75K, $0.9K, $1.4K	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	built-in apps including Netflix, YouTube, Vudu, Xumo and Pandora.			120 fps refresh rate
Philips/Funai	65PUS9600	LCD	RG phospor	Direct	256	94% P3	flat	65	UHD	Q4'15	$4.5K	HDR 10	HDMI 2.0a with HDR signalling			1000		with Ambilight. Android TV runs on a hexa-core processor. Resolution is UltraHD, and the TV can upscale content to this level. Philips has also built its
Philips/Funai	7000 series	LCD	?	Edge	?	?	flat	49, 55, 60	UHD	mid-2016	$0.85K, $1K, $1.4K	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	built-in apps including Netflix, YouTube, Vudu, Xumo and Pandora.			240 fps refresh rate
Philips/Funai	8600 series / F7	LCD	?	Direct	32	82% of 2020	Flat	55, 65	UHD	mid-2016	$1.2K, $1.7K	HDR-10, Dolby Vision	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	built-in apps including Netflix, YouTube, Vudu, Xumo and Pandora.			240 fps refresh rate
Philips/Funai	8909C	LCD	?	Direct	?	87% of 2020	Curved	55, 65	UHD	Oct. 2015		none mentioned				400		
Philips/Funai	PUS8601	LCD	?	Edge	N/A	709?	flat	55, 65	UHD	Q4'15	?			HEVC, VP-9		700		
Philips/Funai	PUS8700	LCD	?	Narrow Filter	Direct	709?	Curved	55, 65	UHD	Q4'15	?			HEVC, VP-9				
Philips/TPV	55PU	LCD	QD Edge	Edge	N/A	100% NTSC	Flat	55	UHD	2015	$ 1,449.00	N/A				400		
Samsung	JS7000 SUHD	LCD	Nano Crystal	Direct	?	P3	Flat	50, 55, 60	UHD	now	$1K, $1.2K,$1.5K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p				
Samsung	JS700D SUHD	LCD	Nano Crystal	Edge	?	P3	Flat	55, 60	UHD	now	Cosco model $1K, $1.2K,$1.5K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p				
Samsung	JS8500 SUHD	LCD	Nano Crystal	Edge	?	P3	Flat	48, 55, 65	UHD	now	$1.5K, $1.8K, $2.5K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p	Netflix, Amazon, Hulu Plus, Vudu, YouTube, Pandora, TuneIn			

Brand	Model number	LCD or OLED?	WCG Tech	Edge or Direct BLU?	Number of Dimmable Zones	Color Space	Curved or Flat?	Screen Size	Resolution	ship date	MSRP	HDR Format support	connectivity support	Codec support	4K content support	peak luminance (nits)	Ultra HD Premium Certified?	Notes
Samsung	JS850D SUHD	LCD	Nano Crystal	Edge	?	P3	Flat	65	UHD	now	Cosco model	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p	Netflix, Amazon, Hulu Plus, Vudu, YouTube, HBO Go, Pandora, Amazon Cloud Player, TuneIn, iHeart Radio, Milk Music, PlayStation Now, GameFly Streaming			
Samsung	JS8600 SUHD	LCD	Nano Crystal	Edge	?	P3	Flat	78	UHD	now	$7K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p				
Samsung	JS9000 SUHD	LCD	Nano Crystal	Edge	?	P3	Curved	48, 55, 65	UHD	now	$1.6K, $2K, $3K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p	Netflix, Amazon, Hulu Plus, Vudu, YouTube, Pandora, TuneIn			
Samsung	JS9100 SUHD	LCD	Nano Crystal	Edge	?	P3	Curved	78	UHD	now	$7K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p				
Samsung	JS9500 SUHD	LCD	Nano Crystal	Direct	?	P3	Curved	65, 78, 88	UHD	now	$4K, $10K, $20K	HDR-10	HMDI 2.0a with firmware upgradability	HECV, VP-9, UHD/30p	Netflix, Amazon, Hulu Plus, Vudu, YouTube, Pandora, TuneIn			
Samsung	KS9500	LCD	QD Film	Edge	?	P3	Curved	55, 65, 78	UHD	2016		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9, UHD/60p	Amazon, M-GO, Netflix and Neulion	1,000	yes	entire Samsung lineup of SUHD SKU's to be Ultra HD Premium certified for 2016
Samsung	KS9800	LCD	QD Film	Direct	?	P3	Curved	65, 78, 88	UHD	2016		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9, UHD/60p	Amazon, M-GO, Netflix and Neulion	1,000	yes	entire Samsung lineup of SUHD SKU's to be Ultra HD Premium certified for 2016
Seiki	?	LCD	QD Edge	Edge	?	?	?	55	UHD	2016								
Sharp	LC-43N6100U	LCD		Direct		DCI-P3 | 79.6%	Flat	43	UHD	Mar, 2016	$449	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	350	No	
Sharp	LC-43N7000U	LCD		Edge		DCI-P3 | 79.6%	Flat	43	UHD	Feb. 2016	$499	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	350	No	
Sharp	LC-50N6000U	LCD		Direct		DCI-P3 | 79.6%	Flat	50	UHD	Mar, 2016	$649	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Sharp	LC-50N7000U	OLED		Edge		DCI-P3 | 79.6%	Flat	50	UHD	Feb. 2016	$699	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Sharp	LC-55N6000U	LCD		Direct		DCI-P3 | 79.6%	Flat	55	UHD	Mar, 2016	$749	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Sharp	LC-55N7000U	LCD		Edge		DCI-P3 | 79.6%	Flat	55	UHD	Feb. 2016	$799	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	400	No	
Sharp	LC-60N6200U	LCD		Edge		DCI-P3 | 79.6%	Flat	60	UHD	Mar, 2016	$1,149	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	450	No	
Sharp	LC-60N7000U	LCD		Edge		DCI-P3 | 79.6%	Flat	60	UHD	Mar, 2016	$1,199	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	450	No	
Sharp	LC-65N7000U	LCD		Edge		DCI-P3 | 79.6%	Flat	65	UHD	Feb. 2016	$1,499	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	450	No	
Sharp	LC-65N9000U	LCD	QD Film	Direct	240	DCI-P3 | 99.98% Rec.2020 | 91.2%	Curved	65	UHD	Mar, 2016	$2,999	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	800	No	Sharp Spectros™ 2.0
Sharp	LC-65N9001U	LCD	QD Film	Direct	240	DCI-P3 | 99.98% Rec.2020 | 91.2%	Curved	65	UHD	Jul, 2016	TBA	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	1000	Yes	Sharp Spectros™ 2.0
Sharp	LC-70N7100U	LCD		Direct	192	DCI-P3 | 79.6%	Flat	70	UHD	Jul, 2016	$1,999	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	500	No	
Sharp	LC-70N8100U	LCD	WCG	Direct	192	DCI-P3 | 92.2%	Flat	70	UHD	Jul, 2016	$2,299	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	500	No	

Brand	Model number	LCD or OLED?	WCG Tech	Edge or Direct BLU?	Number of Dimmable Zones	Color Space	Curved or Flat?	Screen Size	Resolution	ship date	MSRP	HDR Format support	connectivity support	Codec support	4K content support	peak luminance (nits)	Ultra HD Premium Certified?	Notes
Sharp	LC-70N9100U	LCD	QD Film	Direct	192	DCI-P3 | 99.98% Rec.2020 | 91.2%	Flat	70	UHD	Jul, 2016	$3,199	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	1000	Yes	Sharp Spectros™ 2.0
Sharp	LC-75N8000U	LCD		Edge	32	DCI-P3 | 79.6%	Flat	75	UHD	Feb. 2016	$2,999	HDR-10 processing	HDMI 2.0a with HDCP 2.2	HEVC, VP9	Netflix 4K, Amazon 4K, YouTube 4K, UltraFlix 4K, Toon Goggles 4K	450	No	
Sony	X810C	LCD	RG Phosphor	Edge	?	P3	flat	43, 49	UHD	Now	$800, $900	none mentioned			firmware update to add Amazon HDR support			
Sony	X830C	LCD	RG Phosphor	Edge	?	P3	flat	43, 49	UHD	Now	$800, $900	none mentioned			firmware update to add Amazon HDR support			
Sony	X850C	LCD	RG Phosphor	Edge	?	P3	flat	55, 65, 75	UHD	Now	$1.4K, $2.2K, $3.5K	none mentioned			firmware update to add Amazon HDR support			
Sony	X850D	LCD	RG Phosphor	Edge	1	P3	Flat	55, 65, 75, 85	UHD	Q1'16		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9				full frame dimming of edgelights
Sony	X900C	LCD	RG Phosphor	Edge	?	P3	flat	55, 65	UHD	now	$1.8K, $2.8K	none mentioned	?	?	firmware update to add Amazon HDR support			
Sony	X910C	LCD	RG Phosphor	Edge	?	P3	flat	75	UHD	now	$5K	none mentioned	?	?	firmware update to add Amazon HDR support			
Sony	X930C	LCD	RG Phosphor	Edge	?	94% of P3	flat	65	UHD	now	$3.5K	EDR	HDMI 2.0 with HDR signalling	?	firmware update to add Amazon HDR support	The X-tended Dynamic Range feature in the Sony X930C provides up to twice the brightness range		
Sony	X930D	LCD	RG Phosphor	Edge	?	P3	Flat	55, 65	UHD	Q1'16		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9				very thin design (11mm) with near zero bezel; Slim Backlight Drive
Sony	X940C	LCD	RG Phosphor	Direct	?	94% of P3	flat	75	UHD	now	$7K	EDR	HDMI 2.0 with HDR signalling	?	firmware update to add Amazon HDR support	The X-tended Dynamic Range feature in the Sony X940C offers up to three times the brightness range		
Sony	X940D	LCD	RG Phosphor	Direct	?	100% of P3?	Flat	75	UHD	Q1'16		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP9	?			
Sony	X950B	LCD	RG Phosphor	Edge	?	?	flat	65, 85	UHD	Now	$5.5K	EDR	?	?	?			
TCL	C2	LCD	QD Edge	Edge	?	110% NTSC	Curved	55, 65	UHD	2016		Dolby Vision						
TCL	H8800S-CUD	LCD	QD Film	Direct	?	110% NTSC; 90% of 2020	Curved	65"	UHD	Spring 2016								
TCL	QLED 2.0 H8800	LCD	QD Film	Direct	?	110% NTSC; 90% of 2020	Curved	65"	UHD	Spring 2016		Dolby Vision	HDMI 2.0a		Amazon			
TCL	QLED H9700	LCD	QD Edge	Edge	?	110% NTSC; 90% of 2020	flat	55, 65	UHD	12/14, China	$1932, $3059					400, 450		
TCL	S88	LCD	QD Edge	Edge	?	97% P3	Curved	55, 65	UHD	now	1500, 2350 Euro							
TCL	US9806-55	LCD	?	Edge	?	85% of 2020	Curved	55	UHD	now	1680 Euro							
TCL	X1	LCD	QD Film	Direct	288	P3; 91% rec.2020	Curved	65	UHD	March in China; 2H'16 in US	$3.5K	Dolby Vision			Vudu	1000		4000R curvature; 6 Harmon Kardon speakers, 15.4 mm thickness, Quad-core CPU and hexa-core GPU
TCL/Thomson	55UA9806	LCD	QD Edge	Edge	N/A	110% NTSC; 90% of 2020	Flat	55	UHD	2015	1790 EURO	N/A				400		
TCL/Thomson	A87	LCD	?	Edge	?	96% of NTSC	Curved	55, 65, 78	UHD	Oct'15	1260, 2100, 5900 Euro			HEVC				
Vizio	RS120	LCD	RG Phosphor	Direct	384	96% P3; 73% 2020	flat	120	UHD	now	$130K	Dolby Vision				800		
Vizio	RS65-B2	LCD	QD Film	Direct	384	120% P3; 87% 2020	flat	65	UHD	now	$6K	Dolby Vision				800		HDR10 coming via firmware update in April
Westinghouse	Curved series	LCD					Curved	55, 65, 75	UHD	Q4'16	$700, ?, ?	HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	Netflix			
Westinghouse	Flat HDR series	LCD					Flat	43, 55, 65, 75, 85	UHD	Q4'16		HDR-10	HDMI 2.0a with HDCP 2.2	HEVC, VP-9	Netflix			

Table 9: Summary of HDR/WCG Commercially Available and Planned UHD TVs