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Streamlining Cable System HDR Deployment with HLG (Hybrid Log-Gamma)

A Technical Paper prepared for SCTE•ISBE by

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Introduction

CBS, BBC, NHK and others now have years of high-end production experience utilizing the Hybrid Log-Gamma (HLG) format for live high dynamic range (HDR) production of premier news and sporting events. They are enthusiastic supporters of HLG for production, and for its use as a distribution format in terrestrial broadcasting and for its subsequent retransmission by multichannel video programming distributors (MVPDs), as well as for transmission of non-broadcast linear cable channels. The goal of this presentation is to explain why HLG is the best format to streamline and optimize deployment of HDR for both broadcast and cable systems.

HLG was invented by two of the world's leading broadcasters: the BBC and NHK (Japan Broadcasting Corporation). They developed HLG specifically to provide high quality HDR video, and to allow an easy migration to live HDR production and distribution. Whether in the home or outside, Hybrid Log-Gamma provides consistent results on TV screens and devices, because it is optimized for the human visual system in all TV viewing environments.

High dynamic range television is destined to be an important service type for broadcasters and cable operators because it delivers more natural and beautiful images. HDR video is an imaging system that provides a greater contrast ratio; in other words, it provides a higher variation in displayed luminance values with respect to its average luminance. This provides brighter highlights and specular reflections, extends visible detail in shadow and dark parts of the picture, and also gives a greater impression of sharpness. Coupled with the wide color gamut used in HDR formats, this greater contrast ratio provides a video experience that is far more lifelike and compelling.

HDR has become possible because the contrast capabilities of today's video cameras and displays far exceed what can be represented by the limited signal standards for traditional video. To enable delivery of these improved imaging characteristics, two HDR video signal types have been developed and standardized, known as Perceptual Quantization (PQ) and Hybrid Log-Gamma (HLG) – both with the ability to convey greatly improved shadow detail at the dark end of the tone scale, and extended highlights at the bright end.

Content

1. The Two Approaches to HDR – PQ and HLG

The focus of this paper is two-fold: To describe some of the key advantages of the Hybrid Log-Gamma solution, which requires no metadata of any kind, and to review the undesirable aspects of using the PQ-based format known as "HDR10" for broadcasting or cable transmission.

By way of background, I am prompted to review HDR10 issues because the 2018 publication of *SCTE 247 (High Dynamic Range Video: System Requirements for Cable Phase 1 – Initial Deployment)* suggests that the HDR10 format ought to be of foremost interest to cable operators for launching HDR services. The contrary view in this presentation is that launching HDR linear channels in HLG format is a considerably better choice for emission in terrestrial broadcasting and for cable retransmission. HLG transmission will better preserve the creative intent of linear HDR channels, and it requires no conversion from what CBS and most broadcasters expect to be the dominant HLG format in broadcast emissions. It is a format that will deploy far more quickly on cable, with less effort, and with better quality than HDR10.

HDR services based on the PQ signal (based on the name "Perceptual Quantization"), in order to perform optimally for home television service, requires dynamic metadata to be sent along with the video signal to guide processing for displaying the PQ signal on the wide range of peak luminance levels in various makes and models of consumer HDR TV receivers. This process is generally referred to as display adaptation. The "HDR10" format recommended in SCTE 247 is a PQ HDR signal with no such dynamic metadata, however. HDR10 can optionally include a few bits of static metadata; "static" meaning that this metadata does not vary during the entire PQ-encoded program, i.e., it does not vary with specific frames or scenes. This static metadata is often ignored by consumer HDR10 display processing, because there is confusion about its meaning and utility.

Though not a topic for this paper, I expect cable operators will want to study another key issue, which is that HDR TV deployed in HDR10 format will, at some point, require a second deployment phase to add dynamic metadata to HDR10 channel transmissions. Cable transmissions in HLG format will not require any second step. I note also that CBS experience leads it to oppose having HLG broadcast signals converted to HDR10 for carriage over cable systems, as is unfortunately encouraged in SCTE 247.

2. HLG: The Prevailing HDR Format

There is no better endorsement of HLG than that it has already become the predominant format for HDR production and distribution of live and linear television. First, HLG was designed to be *evolutionary* in nature, in part because it is a "scene-referred" signal like all conventional video, including today's HDTV (BT.709) and regular UHDTV (BT.2020). This means the signal represents the relative light within the scene as detected and output by the camera. The word *relative* connotes the *ratio* of the intensity of light relative to the peak output of the camera's image sensor, without signifying any absolute light levels to appear on a display. Scene-referred *relative* video signals are also used in other high-end camera capture formats such as Sony S-Log3, ARRI Log C, Panavision Panalog, and others.

So, HLG is a dimensionless signal that embodies no information about specific brightness levels on a display, and it is designed to be scaled and rendered (adjusted for visual consistency) to displays of any brightness. When presented to displays of differing peak luminance capabilities, a gamma adjustment is applied at the display in accordance with that screen's peak brightness to yield a consistent perceptual appearance. This rendering approach was thoroughly researched in subjective tests by BBC R&D and NHK, and the final method is published by the ITU-R. This method requires no metadata to guide it, which results in highly significant simplifications in deployment all the way from camera or grading suite to the home display.

By contrast, a PQ signal is meant to be revolutionary in nature and is the first "display-referred" video encoding approach for television. A PQ signal represents the absolute light output for each pixel on a display, in units of candelas per square meter (cd/m^2, or "nits"). This has advantages in situations where the viewing display and environment matches the content production or mastering environment, but has distinct disadvantages in the varying circumstances common in consumer television viewing, requiring dynamic metadata streams to also be sent to compensate.

3. About the HLG Signal

A Hybrid Log-Gamma video camera applies an opto-electronic transfer function (OETF), which is a camera encoding to convert the linear output of the camera light sensor(s) into a non-linear video signal – the non-linearity being necessary to represent its high dynamic range image with only 10-bit quantization. As the "H" in HLG states, the HLG signal is a *hybrid* of two types of functions in one.

In the lower half of the HLG signal's excursion, the function closely emulates a conventional standard dynamic range (SDR) camera's gamma encoding (in which an SDR signal is encoded as a power function with an exponent of about 0.5, with the exponent represented by the Greek letter "gamma"). In HLG, this gamma portion of the OETF is modified to provide additional dynamic range in the lowest levels approaching black.

In the upper half of the HLG camera encoding function (OETF), the signal seamlessly transitions from the gamma portion to a logarithmic encoding of relative scene light levels in order to represent the large range of brighter tones up to diffuse white and well beyond – for highlights such as specular reflections and emissive light sources that may be in the scene. The 10-bit HLG signal (sometimes called "HLG10") comfortably exceeds the simultaneous dynamic range of the human visual system at any state of adaption (in this case, to a given peak displayed luminance and the surrounding TV viewing environment).

Importantly, HLG requires no metadata (by design, none is defined for HLG) to guide display adaptation for screens of differing peak brightness capabilities. For this and other reasons HLG is compatible with existing 10-bit television plant infrastructure, equipment and codecs. When presented to a standard dynamic range (SDR) display the HLG HDR signal, with its gamma-like and log portions, closely resembles a standard dynamic range signal with a gamma function and a "knee" for highlight handling at the upper end. Therefore, a standard dynamic range display interprets an HLG HDR signal as an SDR signal and displays a compatible image without any HDR-to-SDR conversion required. It does this differently in two circumstances:

> 1. An HLG signal yields a usable compatible picture on existing, in-place SDR (BT.709) monitors, which is of great value to non-critical HLG monitoring in existing studio and remote production facilities. By comparison, PQ HDR signals do not present a usable image. In HLG production or transmission applications, for simple confirmation of the presence or absence of a signal or assessing what's "on camera", BT.709 color monitoring of HLG is often sufficient, though the image is a bit de-saturated and has some visible hue shifts because in this case, BT.2020 color decoding is not present.
>
> 2. When BT.2020 color decoding is present in an SDR display, a full quality SDR image is presented as a backward-compatible response to an HLG input.

In production, dynamic (or static) metadata (PQ) prevents image mixing in existing production switchers for such functions as dissolves, image resizing and other digital video effects. It is obvious, for example, that a dissolve between two images from different sources, each with different dynamic metadata, will at some point have to decide when to switch from one set of metadata to the other, and would have to do so without a noticeable impact on the video image. This is not practical. Metadata also complicates production graphics overlays in similar ways – if the dynamic metadata is related to the background video image, is it still correct metadta when graphics are inserted or superimposed on that image? Obviously not. By design, HLG avoids all of these difficulties. The extent to which these issues help cable operators depends on whether such processing is part of their operations.

Therefore, production migration to HDR using HLG requires little more than HDR cameras (for which HLG signal encoding is now universally available) and HLG displays – with the latter only needed in critical HDR quality monitoring areas such as preview and line monitors in a production control room. As just mentioned, it is common in mobile production units to monitor many HLG input signals with existing conventional SDR (BT.709) displays, because the designed-in backward-compatible nature of the HLG signal provides a satisfactory picture for content display when the image need not appear perfect. Interestingly, BBC has reported that the HLG signal also provides a useful picture signal on sRGB computer desktop monitors, and has been used in this way for certain monitoring applications in sports field productions. Cable operators can take advantage of this approximate BT.709 and sRGB display compatibility to streamline the deployment of signal continuity monitoring in cable systems, with far less investment than for PQ signals which in all cases demands new PQ-capable monitors, or PQ to BT.709 content mapping units at the input side of existing SDR monitors. For full-quality HLG HDR monitoring, true HLG monitors would be used, of course.

The HLG signal is fully commercially backward-compatible when fed to SDR displays that handle BT.2020 color, as is done for the U.K. user base by the BBC's OTT *iPlayer* streaming service, and for other services in Europe, where early DVB specifications have assured that all SDR UHDTV receivers have built-in BT.2020 color processing.

Note also that HLG is supported by High Efficiency Video Coding (HEVC) compression at mezzanine and consumer bit rates and is carried and signaled by High-Definition Multimedia Interface (HDMI) links from set-top boxes to consumer TVs. HLG is widely supported in HDR TVs due to its open published standards, high performance, and its non-proprietary nature.

These are just some of the reasons HLG has become the dominant format in live, linear HDR television production and distribution around the world.

Following is a relevant listing compiled by BBC R&D in June, 2019.

All current broadcast HDR TV services use HLG

Operator	Territory	HDR Technology
beIN Sports	Qatar	HLG10
Canal+	Poland	HLG10
CCTV	China	HLG10
DirecTV	US	HLG10
DISH	US	HLG10
Insight	Netherlands	HLG10
KPN	Netherlands	HLG10
RTL	Germany	HLG10
Sky Italia	Italy	HLG10
Sky Perfect	Japan	HLG10
NHK	Japan	HLG10
TravelXP	India/Europe/US	HLG10

Distributing HDR Television — BBC | Research & Development

Figure 1 – All Current Broadcast HDRTV Services use HLG

4. Shortfalls with HDR10 for Broadcast and Cable Transmission

Having explained a bit about HLG, let me cite some specific sources that demonstrate why CBS has serious concerns about performance of PQ HDR on broadcast and cable.

As I said, in 2018 SCTE published document *SCTE 247 High Dynamic Range (HDR) Video: System Requirements for Cable Phase 1 – Initial Deployment*. This document plainly states there are many unsolved problems with deploying dynamic metadata in cable's complex end-to-end workflow as will be needed in order to optimize PQ picture quality.

In its *Section 6.5 Metadata*, SCTE 247 states, "Within the context of existing MPVD systems, there is a practical concern that metadata is not consistently passed by intermediate segments of the delivery chain. This reality may have severe consequences for downstream decoders."

Further, in its final *Section 9.2 Drafting Group Consensus Recommendation,* SCTE 247 states with regard to HDR10 that, "Its performance may be improved in the future with the optional inclusion of dynamic metadata, as the ability to create and deliver it becomes a practical possibility in the content production and distribution ecosystem."

SCTE 247 also states that "HDR10 is appropriate for use in the cable industry for a 'first pass' HDR video distribution option against the time constraints larger operators desire to meet."

In summary, SCTE 247 recommends use of HDR10 for cable transmission despite its acknowledgement that it delivers compromised HDR service quality. It does so on the grounds that HDR10 is acceptable to some "larger operators", where it is justified by unresolved workflow complications. You can imagine that content providers will have considerable discomfort with such an approach.

For CBS, this raises the question, "If PQ HDR with dynamic metadata is good, how bad is HDR10 without that metadata?" The answer: not good enough.

Before leaving SCTE 247, note that in its concluding paragraph, SCTE 247 makes the following positive comment about HLG: "The HLG HDR system, which operates simply without HDR metadata of any kind to complicate the various cable system workflow and processing systems, is also a potentially valid solution to some of the issues identified in this document, and should be evaluated along with other HDR systems and metadata based enhancements to HDR10 in future phases of HDR standardization."

5. Important References in SMPTE Standard ST 2084 for PQ

The limitations of the HDR10 approach are also evident in some key statements in SMPTE standard *ST 2084:2014*, the document in which the PQ "Perceptual Quantization" electro-optic transfer function (EOTF) was defined five years ago without reference to metadata. These statements make clear that the PQ transfer function alone does not define how it should be rendered on displays that differ in peak brightness from that of the mastering reference display, or in viewing environments different from that used in the mastering suite. Though dynamic metadata was likely anticipated as an eventual solution at the time ST 2084 was developed, the following qualifications about the PQ signal, without dynamic metadata, do not reflect well on the notion that cable operators might deploy HDR10.

Here are three excerpts from the ST 2084 *Introduction:*

- "Because this EOTF is referenced to absolute luminance, the display is assumed to be operating in a specified reference viewing environment…"

- "The EOTF does not impart a preferred rendering appearance for any particular viewing environment. Image modifications needed for viewer contrast, colorfulness, highlight details, and visible detail in shadows at any particular output level must be chosen as part of the mastering process."

- "The reference EOTF and its inverse represent an efficient encoding system for high luminance range data. Though an idealized display device could follow this EOTF exactly, in real world displays the EOTF can be thought of as a nominal target. Actual displays can vary from the absolute curve due to output limitations and effects of non-ideal viewing environments."

6. The Trouble with HDR10

The PQ transfer function defined in SMPTE standard ST 2084 is defined as an "EOTF", an electro-optical transfer function, meaning that it defines the characteristic function in a PQ <u>reference display</u> that maps electronic digital code values in a PQ signal to absolute luminance values on that reference display in order to match the image seen on the reference display used for production or color grading/mastering. This emphasis on EOTF is why PQ is referred to as a "display referred" video signal – unlike for all prior television standards (BT.601, BT.709 and BT.2020) and for HLG (per BT.2100), which are all "scene-referred."

The PQ transfer function was designed to allow encoding that, as a practical matter, can represent video using *a chosen subset* (at best, about 14-stops in range) from within its potential 28 stops of screen luminance coding range, and to do so in a 10-bit (or 12-bit) displayed signal without visible contouring ("banding") caused by quantization of HDR signal levels. In television use, assuming black level display is typically limited to about .01 nits, some of both the lower end of the PQ encoding function is not usable, so the PQ range is then closer to 21 stops of dynamic range; but even then, all of this cannot in fact be used in television service.

The reason is that the dynamic range of the human visual system in any state of *visual adaptation* is about 14 stops.[1] Today's best video cameras also have a similar 14-stop range. So, a real-world PQ signal cannot, in practice, deliver a visible contrast range exceeding this same 14-stop limit. In a motion picture theater, or with uninterrupted Blu-ray movie viewing, careful scene brightness planning (over time as the story proceeds) can take advantage of viewers' ability to visually adapt to allow more than a 14-stop range to be exploited, but this is not possible for television service, because television content is frequently interrupted by ads and other interstitial materials which would disrupt any attempt to take advantage of slow audience changes in visual adaptation.

The 28-stop PQ signal range definition does offer flexibility for applications in special situations; an example of which might be outdoor and stadium displays in daylight that need very high peak levels (perhaps near or at 10,000 nits) and where low black levels can't be seen due to high ambient surround

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[1] Visual adaptations are temporary changes in sensitivity or perception when exposed to a new stimulus, sometimes with after-effects that may linger after the stimulus is removed. The human visual system can adapt to different light level ranges, but it takes time to do so, with adaptation to increased luminance happening more quickly than adaptation to darker conditions. This presents an important constraint in commercial HDR television service.

light levels). But in the consumer television application, HDR video must be generally be produced to occupy a luminance dynamic range selected in a particular "window" of about 14 stops from among the total possible range of 28 (or 21) stops. For these reasons, it is important not to accept the occasionally expressed but erroneous notion that the possible top-end 10,000 nit displayed luminance of the PQ signal specification represents a "brightness" advantage for PQ over HLG for television applications. HLG signals can be displayed and rendered for correct appearance on any screen brightness, and is not limited to 1,000 nits (another common misunderstanding about the mean of this chosen "bridge level" for conversions between PQ an HLG in ITU-R Recommendations and Reports).

The PQ transfer function was conceived in its "display referred" and "absolute luminance-preserving" manner (where its digital code values represent specific, absolute luminance levels on a display) because its design philosophy was in part that, for theatrical movies finished in non-real-time in color-grading suites, it is the absolute luminance levels of the image on the colorist's reference monitor that reflects the final, approved look of the content, and that this needs to be preserved and reproduced in a cinema. This is of real value when the final display capabilities and viewing environment match those with which the content was mastered, as can be done via grading in conditions that will be matched to those of the standardized dark theater environment. Viewing environment means the lighting conditions surrounding the consumer's view of the display but still within his field of vision. The uniform movie theatre "cinema" environment was an initial and ideal target for PQ-based HDR imaging, because its peak screen brightness is standardized at 48 nits, and the environment in all theaters is uniformly dark. In such a case, the conveyance of the absolute luminance levels from mastering monitor to cinema screen works very well to reproduce what the colorist saw on the reference monitor, because both situations have matching display peak luminance and viewing environment, so that the viewers' state of adaptation is the same as that of the colorist's. But television viewing varies dramatically when compared to that in theatrical movie exhibition.

7. The Television Environment Challenge for HDR

So, the challenge with HDR for *home television service* is that the peak brightness of consumer HDR receivers varies depending on what model the consumer owns, as do viewing conditions in the home. We watch TV in many situations: at night in dim (or dark) lighting; at night but with room lights on, and in bright rooms in daytime with the drapes open. These variances require adjustment of on-screen tonal rendering of the HDR image in order to preserve the creative intent of the content. In short, the goal is for the content to look "as intended", despite these variations. HLG achieves this in a sound, research-proven and standardized way (again, without metadata).

The shortcoming with HDR10 is that a PQ receiver's alteration of the content's tone curve without dynamic metadata guiding it, is a process that is neither defined nor standardized. In theory, since the PQ signal defines an absolute brightness for each pixel, an HDR10 receiver's display might simply comply with this meaning. There is evidence that at least one early consumer HDR10 receiver's processing did so, but it was then recognized by a U.K. TV product reviewer that the pictures produced (from HDR10 Blu-ray disc playback) were displayed too dark in consumer viewing conditions brighter than the mastering reference conditions. This resulted in lowlights ('shadow details') being invisible and mid-tones that were too dark.[2]

Therefore today, for HDR10 display in its definitional "no-metadata" mode, CE manufacturers have to design their own HDR10 receiver processing to adjust the on-screen tonal rendering of the HDR10 signal to fit the display's full dynamic range capabilities, even though doing so contradicts the PQ signal's

[2] See: http://www.hdtvtest.co.uk/news/4k-vs-201604104279.htm

explicit absolute brightness meaning (when brighter display is demanded by brighter viewing environments). Some TVs provide manual "Bright Mode" selections for the viewer to select with his or her remote control, with labels like "Dark" and "Bright" to allow the viewer to tell the receiver about the viewing environment. This starts with applying some undisclosed gain factor to brighten the video for a better match to the viewing environment, and probably other undisclosed picture processing. However, on some lower-brightness receivers this can require associated compression or clipping of highlights to keep the signal within the capabilities of the display. There remains no agreed, standardized or published method for such HDR10 gain-up or tone mapping adjustments. Presumably, licensed dynamic range tone mapping solutions also provide HDR10 tone mapping for cases where no metadata is received, but these are also proprietary and undisclosed. Each CE manufacturer implements its own techniques – and they do vary substantially. Therefore, broadcasters and cable operators providing HDR10 services have no way of knowing how the painstakingly-produced HDR images will appear to customers, nor how much the appearance will vary. In other words, creative intent will be degraded for some percentage of home viewers. For the majority of HDR content, HLG handles the display rendering challenge in a much better way, which I will describe later.

It must be acknowledged that PQ signals, when accompanied by dynamic metadata, are improved in their tone mapping for displays in the home. Indeed, this makes the point that HDR10 content is in need of improvement and is not optimal for delivery on its own. Such display adaptation is the central purpose of dynamic metadata, though it comes with a cost of implementation complexity in professional plants and in home receivers.[3] In an OTT environment, where an offline-graded program with its dynamic metadata can be delivered and placed on a streaming server, dynamic metadata PQ system can and have been implemented in a simple fashion, so there's no problem with these deployments, to the extent that enough receivers exist to process their metadata. But live and linear television with all of its workflow complexity, insertion of ads and other interstitial material, presents a much greater challenge. It must be noted that there are two dynamic metadata systems for PQ HDR video, neither of which can be expected to gain 100 percent market share in receivers. If the necessary receiver metadata processing is not present, the display reverts to CE-manufacturer specific processing of only the HDR10 signal, which as stated above, is unreliable in its quality or consistency. By comparison, consider that HLG decoding and rendering is present in nearly all HDR receivers already, and can be expected to be in 100 percent of consumer receivers soon (because its operation is standardized, simple, and non-proprietary).

It is not unreasonable for broadcasters and cable operators to ask if it is worth the trouble, for linear cable channels in particular, to forever feed receiver tone-mapping processing circuitry with streams of dynamic metadata originated at the production, channel assembly or cable transmission end. Even assuming the doubtful universal-deployment in receivers, one should certainly investigate whether this approach will yield an appreciable quality improvement when compared to the display rendering done by HLG linear channels that require no metadata.

It is important to recognize that HDR10 signals, partly as the result of the PQ signal's absolute luminance nature, are adapted to differing displays largely through what are called tone-mapping techniques. Though "mapping" suggests that all the levels are cleverly moved about, the fact is that the action happens mostly at the extremes of the signal. The dark shadow areas are compressed or clipped, as are bright highlights when the PQ program has been mastered with a contrast range that exceeds that of any given home HDR display. This means that tone-mapping to fit wide-range PQ content to displays with

[3] For clarity, no judgment is made in this presentation about either of the *dynamic metadata-based systems* or the acceptability of their result, rather, this paper is pointing out that the *HDR10 format* is a poor choice for broadcast or cable transmission, because it is missing the necessary dynamic metadata that is essential for the PQ signal to mapped well to in-home HDR displays. Here, HLG is proposed as the superior zero-metadata solution for linear cable channel transmission, and a solution that once deployed, is fully deployed, with no later upgrade step.

less dynamic range will degrade the producer's creative intent. PQ content mastered to include highlights up to 2,000 or 4,000 nits or more (and lower-level shadow details) will thus appear differently on various home displays. The PQ system concept's intent is to show higher level highlights on receivers that can produce such levels. This creates visible variation in creative intent. Such highlights will be highly compressed or omitted entirely on lower-brightness home displays. All elements in a "high-grade" mastered PQ program may be visible if the consumer receiver has a high-end PQ HDR display, but on many, lowlights and highlights will be soft-clipped or hard-clipped. These image changes occur even when the tone mapping is guided by dynamic metadata

It is interesting to see some data on the range of peak brightness levels of consumer HDR television displays: A look at this Montreal-based web site: https://www.rtings.com/tv/tests/picture-quality/peak-brightness shows that for the sixty-seven 2019 models of HDR consumer receivers they had tested as of the writing of this paper (mid-August 2019), peak brightness of these products (using their "Real Scene Brightness" test) range from 178 nits to 1640 nits. Nineteen units had peaks lower than 300 nits, six were in the 300-400 nit range, thirteen were in the 400-600 nit range, nine were in the 700-900 nit range, and seven were in the 900-1,640 nit range. PQ tone-mapping will necessarily compress or clip highlights and/or lowlights on many of the lower brightness consumer HDR sets, while HLG, for all but some the lowest luminance displays (which are really more like SDR displays) will render to each display's full luminance range with no highlight or lowlight clipping, allowing viewers to let their eyes adapt and have a full HDR experience.

8. HLG Display Rendering is Done Differently

Video in the HLG format will scale the signal to the peak highlight capability of each of these receivers, anchoring the black level of the signal to the display's minimum, and the peak white level to the display's maximum (or to a lower brightness setting if the viewer sets the contrast control lower for more comfortable viewing in dimmer ambient conditions). An HLG receiver will also apply a correction to the display gamma based on the specific peak brightness, ideally according to the formulae published in ITU-R Report BT.2390, HLG receivers, if provided with ambient light sensors, will also be able to fine-tune their correction room viewing conditions (i.e., surround lighting and ambient lighting). This is a secondary factor in terms of significance, but it is documented in the ITU-R standards. Please read ITU-R Report BT.2390, section 6.2., for a full explanation of this complex topic that led to the metadata-free HLG solution for HDR TV. Only in the case of low-end, dim HDR displays in bright viewing conditions will an HLG display need to roll off highlights or lowlights.

Thus, HLG rendering, in most cases, will allow the on-screen rendering of diffuse white and mid-tone scene elements to rise or fall with screen brightness. Visual adaptation then allows the full high dynamic range (~14 stops) to be fully enjoyed by the viewer. As mentioned above, if the display has a very high peak luminance capability in dark or dim viewing conditions, the user can simply turn down the contrast control to reduce image brightness to a comfortable level (and the HLG rendering will also adjust display gamma in concert).

To make this concept clear, it is helpful to think about the case where cinema projections of feature films, for many decades, have been able to represent a substantial dynamic range, including stunningly bright scenes, even with a standard peak brightness of only 48 nits (just half of what the capability of now obsolete classical CRTs). Consider the splendidly bright desert scenes in a film like Lawrence of Arabia, released in 1962! So, absolute brightness levels are not as important as they might seem. As long as human vision is adapted for viewing of an HDR TV receiver with a reasonable luminance dynamic range, one can see a 14-stop dynamic range. This is at the heart of the "relative" HLG HDR TV rendering approach: display the full range of the signal in most cases, let the viewer adapt to that range and have a full HDR experience. PQ by comparison relies on tone mapping (modifying) lowlights, midtones and highlights.

9. CBS Lab Demonstrations of HDR10 Display Rendering Variation

In summary then, the variations in HDR10 delivered image quality is of concern to CBS, as it contemplates its future production of premium events of all kinds, such as GRAMMY Awards ceremonies, to golf tournaments, NCAA football and basketball, NFL regular season and Super Bowl games, and the like. How can a broadcaster or MVPD commit to a system that introduces inconsistency in the delivered quality to the home viewer?

CBS recently demonstrated the problems that arise with converting programs produced in HLG to the HDR10 format, with no standardized, accepted methods, but only via processing choices made by individual receiver manufacturers for specific product models. These demonstrations were presented to members of the SCTE Digital Video Subcommittee at a special presentation and demo session on June 12, 2019 at the CBS engineering laboratory in New York. HLG inventors Tim Borer and Andrew Cotton from BBC Research & Development presented HLG technology and its advantages, and Greg Coppa of CBS presented the HLG-to-HDR10 demonstrations in the engineering laboratory.

In the demos, segments of high-quality HLG video programming from CBS Sports and from the BBC were converted from HLG to HDR10. For reference, a pair of professional HDR reference monitors (1,000 nits peak, OLED) were placed side-by-side showing the original HLG video and its real-time LUT-based conversion to HDR10. The video on these two reference monitors were visually identical, as expected, because the conversion was performed with the HLG signal rendered for the reference monitor's 1,000 nit peak level and the converted HDR10 signals delivered the same displayed absolute pixel levels on an identical 1,000 nit reference screen.

The HLG programs and the converted HDR10 signals were simultaneously displayed side-by-side on identical pairs of consumer receivers – three different models; two LCD, one OLED. All of these displays had peak brightness values other than 1,000 nits. For a substantial percentage of the test sequences, the pictures converted to HDR10 format looked worse in various aspects, most frequently with a lack of detail and clipping in the highlights, and color distortions as well. In no case was the picture rendering *improved* by the conversion from HLG to HDR10. BBC R&D had originally conceived this comparison demonstration, having earlier presented a similar demo for a European Broadcasting Union (EBU) audience, where the same deteriorations were seen, as well as a loss of shadow detail in brighter environments. The CBS New York demonstration was separately engineered in its laboratory with different, U.S. model consumer receivers.

Conclusion

High dynamic range television is a complex topic, with implications not easily understood at first glance. This paper, and the further information in its Annex below, has presented a few of the key issues indicating that HLG signals will be superior and more consistent than the HDR10 format for cable distribution of linear channels, including retransmission of broadcast HLG channels. The reader is urged to explore further via the References listed at the end of this paper..

ANNEX: HLG Rendering – Better Preservation of Creative Intent

Following is some additional background that may be useful in reviewing the complex topic of "rendering" for visual consistency, which underlies the HLG approach.

First, it is worth reviewing why "rendering" for different display brightness levels is necessary, and how it works. In general, the range of luminance levels in an image on any TV display are typically substantially lower than those of the original scene. To accurately represent the real scene, this reduced range of light levels on a display cannot be created by a simple linear downscaling of the scene light levels, due to a number of complex characteristics of the human visual system. If pure linear downscaling were done, the image would lack contrast; mid-tones would look too bright and "washed out", and the image would also be less colorful. When presenting on a display at luminance levels substantially lower than in the real scene, the tonal scale must be modified for it to look visually correct, a process called "rendering". Such rendering has always been implemented in all standard dynamic range (SDR) TV systems. Tonal rendering is a well-studied field with a very long history that is practiced for photographic prints, for theatrical film projection, in conventional TV, and now by HLG over a large range of display brightness levels for HDR TV, thanks for research and innovation by BBC Research and Development and NHK.

Proper rendering of the tone scale to produce satisfying visual results is particularly important for HDR TV because HDR displays vary greatly in their luminance range capabilities, requiring a range of different compensations for correct rendering. This was not the case in standard dynamic range TV where the rendering (tone curve adjustment via a gamma exponent in a power function) was fixed at a single value because standard CRT brightness was always at or near 100 nits.

It is well known that in traditional standard dynamic range (SDR) TV, a non-linear transformation is applied to the linear signal from a video camera's image sensor. This is known as "gamma correction" because is pre-corrects for the inverse non-linear function the signal will encounter in a CRT (or in a modern flat panel SDR display, which emulates the characteristic of a CRT) when it converts the video signal back into displayed light. The camera's gamma correction function is approximately the inverse of the CRT display's inherent transfer function (its display gamma) The overall goal is to render the image's tonal scale on the display so that it is presents a perceptually consistent version that evokes the a highly similar look to that of the original scene (or the imaging of the scene as intended by the creator). However, to achieve this, the two functions are actually arranged to *not completely cancel one another*, lest the tonal scale be a just linear downscaling with visibly misty mid-tones, as noted above. The SDR system's concatenation of a camera gamma correction function and the display's gamma function is arranged to yield a tone curve that is a bit darker in the lower mid-tones. In numerical terms, this "system gamma" is slightly greater than 1; for SDR TV, the "gamma exponent" of the power function is 1.2. Roughly speaking this "pulls" the middle of the tonal curve downward, restoring contrast to the image so that it looks perceptually correct.

Courtesy of BBC R&D, the following is a generalized illustration (representing no particular case, other than the concept of "gamma"), showing how varying the value of the gamma non-linearity affects the appearance of video images:

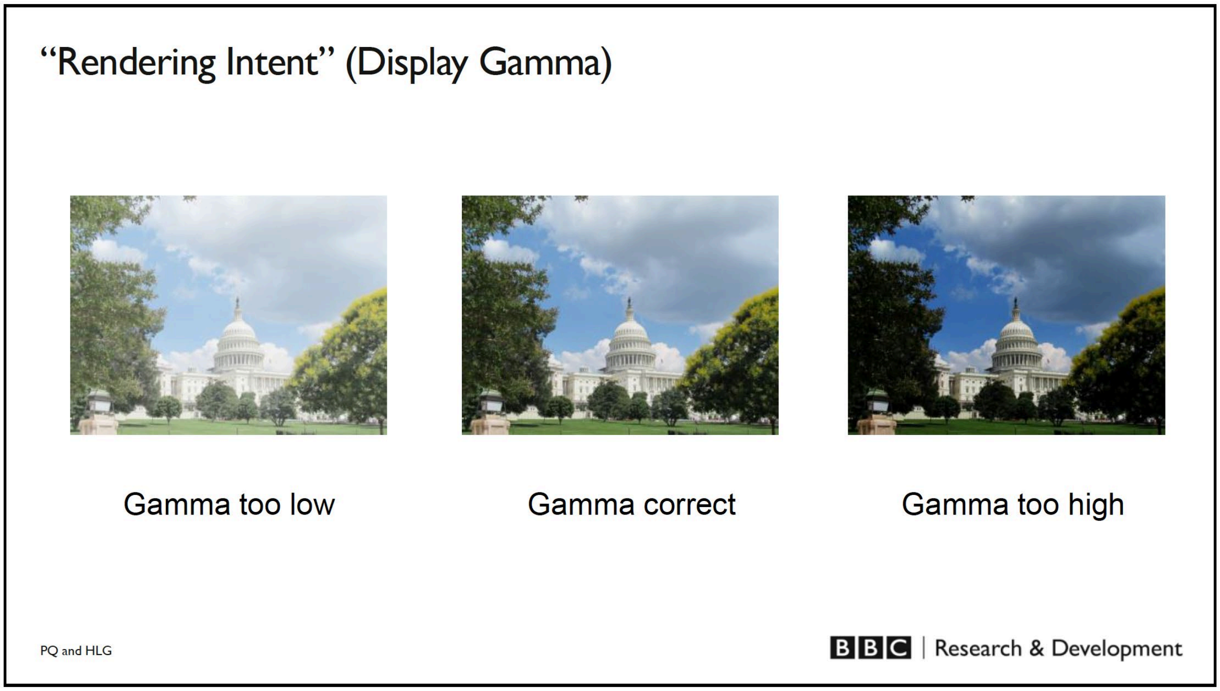

Figure 2 – Rendering Intent (Display Gamma)

The net tone curve's departure from linear is often referred to as the "system gamma" (meaning the end-to-end net gamma of the entire chain, resulting from camera gamma correction concatenated with the display's gamma characteristic.) In HDR terminology, this is typically referred to as the opto-optical transfer function (OOTF), denoting the total path from the OPTICAL characteristics of the scene to the OPTICAL output of the display. Another way to say it is that the OOTF maps relative scene linear light to display linear light.

Because they sought to design an HDR solution that avoids the complications introduced by dynamic metadata, BBC R&D and NHK designed the HLG system to perform picture rendering without it. They conducted research to determine how system gamma needs to vary according to display peak brightness (in initial research with displays ranging from 500 nits to 4,000 nits peak). Test subjects were asked to perceptually match as closely as possible an image displayed at a reference peak brightness to the same image with a non-reference peak brightness by adjusting the system gamma applied to the non-reference brightness image. A description of this research is published in *ITU-R Report BT.2390 High dynamic range television for production and international programme exchange*. (See in particular Figure 23).

BBC R&D also conducted further subjective tests to extend this model to include the effect of different viewing environments for various display brightness levels. The resulting HLG system gamma adjustment function is published graphically and as mathematical formulae as well. For more details, please read *BT.2390 Section 6.2 System gamma and the opto-optical transfer function*.

That's a bit of further background on how the HLG HDR *signal* is arranged to be display-independent, and how it can be rendered with excellent creative consistency without any dynamic metadata needing to be sent along with it. This is an intensely important HLG capability that will provide high performance with operational simplicity in deployment of HDR in multi-channel distribution.

Following is a useful summary provided by BBC R&D showing the four basic combinations of display brightness and viewing environment, and the superiority of HLG over HDR10 in preserving image quality and creative intent.

HDR10 & HLG10 in the Home (and elsewhere)

- High Quality (Bright) TV, Dim Viewing Environment
  - Both HLG and HDR10 produce beautiful HDR pictures!
  - Both formats fully preserve creative intent.
- Dimmer TV, Dim Viewing Environment
  - HDR10: Highlights reduced to fit display brightness (blacks & mid-tones unaffected)
  - HLG10: Whole picture dimmer, eye adjusts, full HDR picture preserving creative intent
- Dimmer Display, Bright Viewing Environment
  - Insufficient display dynamic range for HDR
  - Both HDR10 and HLG10 must be tone mapped to a lower dynamic range (SDR)
- Bright Display, Bright Viewing Environment.
  - HDR10: Requires explicit tone mapping.
  - HLG10: Whole picture brighter (to see blacks), full HDR picture preserving creative intent.

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Figure 3 – HDR10 & HLG10 in the Home (and elsewhere)

The author wishes to acknowledge those who have in recent years greatly assisted in his understanding of the HLG solution for HDR, including BBC R&D developers of the HLG HDR system Dr. Tim Borer and Andrew Cotton; and Greg Coppa of CBS. Any errors that may appear in this paper are the author's alone.

Abbreviations

cd/m^2	candelas per square meter, the SI unit of luminance (also "nit")
EBU	European Broadcasting Union
EOTF	electro-optic transfer function
HDMI	High-Definition Multimedia Interface
HDR	high dynamic range
HEVC	High Efficiency Video Coding
HLG	Hybrid Log-Gamma (an OETF at the core of the HLG system)
ITU-R	International Telecommunications Union – Radiocommunications sector. www.itu.int
LUT	lookup table
MVPD	multichannel video programming distributor
nit	frequently used non-SI term for luminance (1 nit = 1 cd/m^2)
OETF	opto-electronic transfer function
OOTF	opto-optical transfer function
PQ	Perceptual Quantization (an EOTF upon which HDR10 is based)
SDR	standard dynamic range (as in BT.601, BT.709, BT.2020)

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