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International Society of Broadband Experts

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From the Editors

Welcome to the December issue of the *Journal of Digital Video*, a publication of collected papers by the Society of Cable Telecommunications Engineers (SCTE) and its global arm, the International Society of Broadband Experts (ISBE). This Volume 3, Number 1/December 2018 issue focuses on a timely and important topic: high dynamic range (HDR) video.

December sets a fitting tone for the HDR topic – 'tis the season we are all bombarded with marketing messages (bordering on hype) that proclaim must-have status on everything from automotive tailgates to some miracle drug that will cure you – but, maybe not -- if you carefully read the disclaimers.

As one of the next-great-things, the benefits of HDR are probably aligned with the automotive claims "your mileage may vary" and "Professional Driver on Closed Course – do not attempt." Yet, just about every mid-range consumer display now claims some form of HDR capability with various operating points and functions. Where are the disclaimers?

How could that be? Consumer technology is supposed to be simple and close-to "auto-magic."

Metaphorically breaking the glass-ceiling, HDR, in one combined blow, smashes through decades of the consistency (perhaps complacency and inertia) that kept the consumer display environment at the known quantities of 100-nits and a color-palette matching a 1960's witches' brew of phosphors and cathode-ray tube (CRT) technology.

Let us not forget that video is not about technology, *per se*, it is about storytelling and content. And there are healthy debates in the HDR community between vendors and storytellers. Decades of analog-to-digital evolution removed knobs from video displays – gone are horizontal and vertical hold, hue is also unnecessary, but, alas, brightness and contrast remain – should they?

HDR expands brightness and color and now provides the ability for consumers to "turn 'em to eleven"-- but is that the right thing to do? Having a good knowledge of HDR is a good place to start – and that's the SCTE•ISBE role in this edition.

The two papers in this issue each address separate but important new parts of HDR.

First, keeping an automotive theme, an excellent under-the-hood overview of the technology that is HDR. Messrs. Goldman and Davis look at HDR from both the "what is it" perspective as well as a view toward making HDR work on cable – a document that should also be a learning companion to *SCTE 247 High Dynamic Range (HDR) Video: System Requirements for Cable Phase 1 – Initial Deployment.*

Secondly, there are several HDR system proponents and the Technicolor/Philips paper provides background into the SL-HDR1 system and also provides excellent detail for readers to build their knowledge-base of HDR systems.

We thank the individuals who contributed to this issue of the *Journal of Digital Video*, including the authors, peer reviewers, and the SCTE•ISBE publications and marketing staff. We hope you enjoy this issue and that the selected papers spark innovative ideas and further cement essential knowledge in digital video.

In closing, if there is any editorial information or topics that you would like us to consider for the fifth issue of *SCTE•ISBE Journal of Digital Video*, please refer to the "editorial correspondence" and "submissions" sections at the bottom of the table of contents for instructions.

SCTE•ISBE Journal of Digital Video Editors,

Paul Hearty, Ph.D. (Senior Editor)
Vice President- Technology Standards Office, Sony Electronics, Inc.
SCTE Member

Craig Cuttner (Guest Editor)
Cuttner Tech
SCTE Member

High Dynamic Range Video for Cable

A Technical Paper prepared for SCTE•ISBE by

Matthew S Goldman, SVP of Technology, MediaKind
(formerly known as Ericsson Media Solutions)
SCTE•ISBE Member
matthew.goldman@mediakind.com

Scott M Davis, Technology, Entertainment, & Innovation, Charter,
SCTE•ISBE Member
Scott.Davis1@charter.com

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1. Introduction

In the past decade, many new technologies have been implemented to improve the consumer experience for watching video. While innovation in the video industry has accelerated in the last decade, the cable telecommunications industry has faced the challenge to remain relevant against this rapid change in technology and viewing habits. While many subscribers have migrated to other services available to them, millions of consumers enjoy the simplicity of sitting down at the end of the day and simply turning on their TV to passively consume news, sports, and movies. However, change is constant; in the last decade, we have seen the return (and decline) of 3D, the advent of 4K Ultra-HD, improved streaming, increased VOD titles, and more presentation options for consumers to acquire and enjoy content. While the cable industry faces a new field of challengers that are struggling against the bottom line to retain customers (http://variety.com/2018/digital/news/hulu-2017-losses-920-million-1202692000/), it must continue to engage new technologies to stay relevant to the consumer.

Since the early origins of providing an “amplified pipe” for the distribution of off-air television signals, the cable industry has successfully demonstrated the aptitude to adopt, evolve, and innovate distribution technologies used to provide information and entertainment services to its consumers. Like with the transition from analog to digital audio and video formats, the nature of the cable industry has been to embrace potentially disruptive and different technologies – but deploy those technologies to consumers in a more measured evolution.

Next-Generation video services and related consumer product offerings are disruptive and quite varied in their technical nature. As such, one should use care to understand the context of the advanced services – High Dynamic Range (HDR) video services are potentially only one component of a next-generation consumer offering, perhaps combined with the higher-spatial resolution of 4K Ultra High Definition (UHD) video as well as new immersive audio options to provide a more compelling user experience.

2. What is meant by HDR?

HDR video offers consumers a much-improved viewing experience compared to traditional TV programming, episodic, motion pictures, etc. The dynamic range of current television/video images, now referred to as having standard dynamic range (SDR), is governed by cathode ray tube (CRT) physics first documented over eighty years ago.

The human visual system (HVS) is much more sensitive to luminance (brightness) than it is to chrominance (color), with an extremely wide dynamic range of approximately one million to one (a contrast ratio of the luminance of the brightest object to that of the darkest). The HVS dynamic range can discern from 105 cd/m2 (candelas per square meter or “nits” of luminance) of bright sunlight to 10-4 nits of dim starlight. Unlike increased spatial resolution, which has its effect when the viewer is within the “proper viewing distance” of a very large display (proper viewing distance refers to being within the acuity limits of the HVS, which is approximately 3 picture heights back from a HD display or 1.5 picture heights back from a 4K Ultra-HD display), increasing the dynamic range of the video is a visual improvement that is applicable across any screen size, regardless of the spatial resolution of the image (i.e., it applies to standard definition [SD], HD or Ultra-HD resolutions). This improvement is in large part due to the limit in dynamic range of legacy (SDR) displays that gives the viewer the feeling that he/she is watching a reproduction versus looking out a window of reality, so to speak.

Until recently, the production standard for consumer video had not been changed since the physics of CRTs were first documented in the 1930s, including setting the peak white level to 100 nits. Although modern video cameras can capture a very wide dynamic range and flat panel TVs have claimed maximum peak white levels above 400 nits for many years, almost all TV production is still done using SDR, following Rec. ITU-R BT.709 [10] and BT.1886 [11]. This, of course, has been done to ensure full backwards compatibility with hundreds of millions what are now called SDR TVs.

Reduced dynamic range visually translates to the inability to see both lowlights (e.g., details in deep shadows) and highlights (e.g., clouds in a bright sunny day) simultaneously; one or the other will be “lost” in the reproduction of the images on the display. The impact of reduced dynamic range particularly is noticeable for specular highlights, both direct and reflected (such as sunlight reflecting off of the surface of water or the metal body of an automobile). Today’s TV viewing looks rather “muted” per se; not real. With the increased dynamic range of HDR – which much more closely maps to the HVS – highlights will appear to “pop” in vividness, due to the greatly increased delta between the average light level in the image and the highlight, and low-lights will be resolvable simultaneously in any deep shadow areas.

In most cases when one is referring to HDR, what is really meant is the combination of three technologies: HDR, wide color gamut (WCG [7]) and 10-bit sample bit depth (quantization). Unless referring specifically to an HDR transfer function itself (see later on), HDR as used in this article refers to the combination of HDR + WCG + 10-bit. Furthermore, it is important to note that HDR use is not limted to UHD spatial resolutions (4K and 8K) only. In fact, many content and service providers seriously are considering the use of HDR with 1080p “full HD” resolution and the Ultra HD Forum has defined 1080p HDR as an Ultra-HD format [18].

Figure 1 is a two-dimentional representation of the visible color space that the HVS is able to perceive. The inner triangle represents the subset of the BT.709 color space that HDTV implements (now commonly referred to in the industry as narrow color gamut) As you can see, much of the color space that the HVS can perceive is not included in the HDTV color palette. As such, when UHD spatial resolution standards were being developed, the color space was expanded as well (defined in Rec. ITU-R BT.2020 [7] – as represented by the outer triangle – and this became known as WCG.

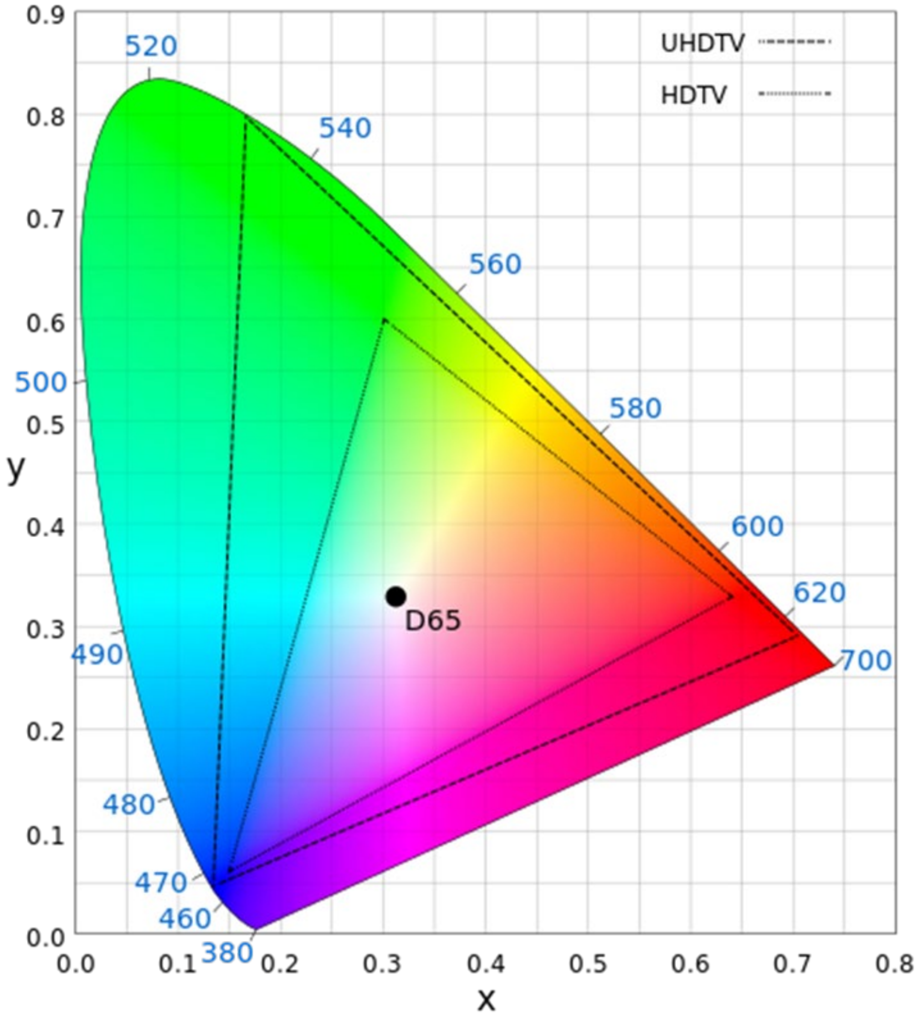

Figure 1 - CIE 1931 Chromaticity Diagram [21] showing perceivable human vision versus HDTV (internal triangle) and UHDTV (dotted triangle) color representation.

All direct-to-consumer TV production and transmission/delivery is in a digital format; analog waveform formats have gone the way of the dinosaur. Until very recently, all direct-to-consumer content was represented by digital data values with 8-bit precision (code word length for the sample bit depths). This results in a maximum of 2^8 or 256 levels for both luminance (brightness) and chrominance (color). With the relatively closer viewing distances of larger displays, another artifact that will be noticed more readily is image banding. Image banding is commonly seen in TV today, particularly in large areas of backgrounds where there is a shallow ramp in chrominance/luminance accompanied by low or still motion, as well as during fades. If 10-bit data precision were used instead (2^{10}), up to 1024 levels of gradient would become available, resulting in much smoother contouring. As such, UHDTV specifications, such as SMPTE ST 2036 [20], define 10-bit code words as the minimum data precision values.[1] Existing production workflows use 10-bit code words throughout and it is only when the direct-to-consumer format is created that the 10-bit code words are truncated to 8 bits during final stage compression. The High Efficiency Video Coding (HEVC) standard [12] is the first consumer compression technology to define a 10-bit consumer format (Main 10 Profile) specifically for this reason, and the latest HDR displays and other consumer devices support it.

3. The Problem

Modern cable systems must support many different, highly complex ways in which content must flow in real-time among various subsystems within a cable operators' plant. Moreover, cable operators exist in the middle of an entire end-to-end ecosystem in which many aspects of content production and consumer devices are beyond their control, but which impose certain technological constraints and limitations based on consumer expectations, business arrangements, and equipment resources. It is clear that the requirements for any next generation technology for any cable system must take into account many important complexities and differences that are not contemplated in the far simpler situation of purely on-demand delivery of pre-recorded content; yet, these next generation cable systems must provide a competitive viewing experience in more complex real-time deliveries. In order to develop the requirements for HDR, several companies scrutinized both live linear channels and on-demand content delivery on an end-to-end basis – from content production through various stages of delivery, all the way to the consumer display – to understand the impacts on the cable provider.

HDR video must be considered in the context of this complex ecosystem, in which cable operators deliver a variety of video services (e.g., live linear channels and on-demand content) to a variety of consumer devices (e.g., cable STBs, smart TVs, PCs, tablets and smart phones) over different network infrastructures (e.g., the cable HFC plant, in-home DOSCIS/Wi-Fi IP delivery, and external internet connections including mobile network operators' cellular networks). In addition, the complexity and technical requirements of enhanced services such as DVR, "cloud DVR" and "start-over viewing" add to the not-so-simple case of live linear channels.

The linear television signals that cable operators deliver to their subscribers comes from many sources, including cable programmers; TV broadcast networks; over-the-air local TV stations (network-affiliated and independent); and cable operator-produced programming such as sports and news. A content owner or programmer worries about one or only a few channels/services. At that scale, one can tolerate format conversions from a variety of input formats to a common output format (aka, the "house format"). Cable operators, however, have to deal with thousands of live linear channels/services. With thousands of services, format conversions become burdensome, from both operational and economic point of views, and hands-on quality control is nearly impossible. In particular, the production of live television programming has many considerations related to producing content for both next-generation distribution and audiences, and legacy HD and SD distribution and audiences. Although production is outside of SCTE's scope, some of the many considerations regarding proper camera shading, lighting, conversion between the different HDR systems (see later), SDR to HDR upconversion and HDR to SDR downconversion needed to intermix HDR and SDR cameras, and graphics generation for both signals are described in [9].

[1] For more information see https://www.broadcastingcable.com/blog/understanding-gamma-and-high-dynamic-range-part-1-159024

Live television cameras transform the HDR linear light Red, Green and Blue signals into a non-linear transfer characteristic luminance signal and subsampled color difference signals representation (typically Y′CrCb) with a 10-bit code word space (although more bits may be used in the future). This signal representation is the basis for subsequent signal interfaces in programmer playout and ad insertion systems and for linear signal distribution to cable operators. The details of these HDR signal representations are described in [16] and [1].

4. The Different HDR Systems

There are many options for HDR systems in the industry today.

Perceptual Quantizer (PQ), which was first standardized as SMPTE ST 2084 [15] and is now also part of Rec. ITU-R BT.2100 [16], is an electro-optical transfer function (EOTF) that specifies a much more non-linear conversion of signal level to display light than the transfer function of traditional SDR televisions (known as the gamma curve, see Rec. ITU-R BT.1886 [11]. PQ defines a peak white luminance of 10,000 cd/m2 (or nits). The peak white level for SDR production – which was standardized as the peak white output of a CRT-based display –was severely limited at 100 nits. When PQ is combined with UHD color gamut [16] and 10-bit coefficients for the sample depth, the resulting HDR system is known as PQ10 [18].

Another HDR system is known as HDR10, which is also based on PQ. Although this name was not used explicitly by the Blu-Ray® Disc Association, their Ultra HD Blu-Ray video characteristics were the source of the Consumer Technology Association's HDR10 Media Profile. Essentially, HDR10 is PQ10 with the addition of optional static mastering display color volume metadata. The optional static metadata consists of SMPTE ST 2086 [17] plus two additional parameters, MaxCLL (maximum content light level) and MaxFALL (maximum frame average light level).

Another PQ-based HDR system is known as HDR10+. This Samsung-created system starts with HDR10 then adds dynamic content-dependent metadata. The metadata is descriptive in nature; that is, it gives information about what is contained in the bitstream which a rendering device may use to improve its results as opposed to telling a rendering device what to do. Dynamic indicates that the metadata may change as often as every video frame, with the idea that a better image result can be rendered than possible with only static metadata or without any metadata describing the associated video images. The dynamic metadata used is standardized in SMPTE ST 2094-40 [4] and SMPTE ST 2094-1 [14].

Dolby Vision, from Dolby Laboratories, is another PQ-based HDR system that leverages off of HDR10 and adds its own optional and descriptive dynamic content-dependent metadata to improve the rendered image. The dynamic metadata used by Dolby Vision is standardized in SMPTE ST 2094-10 [5] and SMPTE ST 2094-1 [14].

Technicolor and Philips have jointly developed SL-HDR1 and standardized it under ETSI [19]. Unlike other dynamic metadata systems that use descriptive metadata, SL-HDR1 uses a much different workflow: it converts the native HDR stream to SDR and generates prescriptive "HDR reconstruction" metadata. Prescriptive metadata is required to recreate the HDR image. The claimed reason for converting the bitstream in this fashion is to provide backward compatibility to SDR displays while providing HDR to an HDR compatible display, without the need for simulcasting. The backward compatibility, however, is of limited value in actual implementations because the large population of legacy SDR displays use 8-bit code words, while proper HDR fidelity requires 10-bit code words. When video compression is used, it is not a simple truncation or expansion of 8-bits.

Hybrid Log-Gamma (HLG) is an alternate HDR transfer function to PQ that is also specified in [16]. HLG was jointly developed by the BBC and NHK to be backwards compatible with SDR displays (assuming the same color space is used). HLG defines a non-linear curve in terms of relative scene light, an opto-electronic transfer function (OETF), in which the signal values that correspond to the traditional SDR range (up to 100 nits) use a compatible gamma curve while the higher signal values use a logarithmic curve. Because the scale is relative light level – as opposed to PQ's absolute light levels of the mastering display), no metadata is defined. HLG10 (HLG combined with WCG and 10-bit quantization) has emerged as an early favorite among the HDR formats for live TV production, partially because it does not use metadata and therefore none of the complications around maintaining metadata exist. Time will tell, however, if this trend will continue. There is work going on to determine the behavior of HLG when highlights are created far above the 1000 nits of the standard HLG curve.

So here we are: six different HDR systems. While the Ultra HD Forum has worked diligently to create and publish guidelines on how to implement these systems, having six major options for HDR has created industry confusion nonetheless and, in fact, has delayed HDR deployments. Some of the key questions remaining include:

- Which format is the best to use for the use case being considered?
- Which format will survive in the long run?
- Which format produces the most compelling HDR quality? Or are they all relatively the same?

Many of the above systems are completely duplicative in functional results. Moreover, it is simply impractical for a cable operator to support all the options available. As an example, when ads are inserted into a stream, the ad insertion needs to take place in SD and HD (and now 4K UHD!), and as linear and adaptive bit-rate (ABR) streams. HD already has two spatial-temporal options (720p and 1080i) and there are a plethora of ABR representations to manage (both in format and profiles) to address the wide market of receiver types. Attempting to support a multitude of HDR formats greatly exacerbates implementation complexities. Each representation needs to be stored and managed. Each HDR system is signaled differently and while the metadata carriage format within the video-compressed bitstream domain all use HEVC's Supplemental Enhancement Information (SEI) messages, the SEI containers are different. Moreover, interactions between client and server need to ensure a single delivery type to the consumer because switching between HDR modes has been shown to cause HDMI resets in testing – resulting in a very poor consumer experience. Additionally, in discussions with content providers, it was clear that the effort to create and maintain an option for every HDR system was not considered cost effective, and that it would slow down the move to HDR for the consumer in the cable ecosystem. Likewise, maintaining many versions of the ads would be cost prohibitive, and must be avoided.

The cable industry is not alone in the challenge of adopting HDR. Camera manufacturers, production and broadcast teams, multichannel video programming distributors (MVPDs), and other content providers all have a place in the workflow. The ATSC has adopted a plurality of the HDR systems in the ATSC 3.0 standards. While having options may seem like a benefit to a broadcaster, it adds needless complexity to an equipment provider (with all the associated economic impact) and it seriously complicates a service aggregator who needs to manage and deliver hundreds if not thousands of video stream. Cable operators manage hundreds to thousands of streams. Operationally, it makes sense to limit the number of options to as small a group as possible. Actually, is this not the paramount purpose of standardizing interfaces and protocols? To select one option or minimize options in order to enhance interoperability and enable economic scale of deployments? While conversion options exist between different formats of HDR, initial discussions with content providers has indicated a lack of interest in allowing cable operators to convert

HDR formats due to the possible impact to the creative intent of the content producers. Per a SMPTE report on HDR imaging ecosystem [6], the "[l]ack of standards (luminance level, transfer function, black level) for HDR display devices and its ecosystem is probably the biggest issue facing filmmakers at this moment. Without standards one must provide a separate color corrected version for each HDR ecosystem." This is a cost that must be borne somewhere in the feed chain. As there is a great deal of concern about changing artistic content, it is likely that content creators will bear that cost, which will be put forward to the cable operator and eventually could impact consumers. This aligns with the guidance that "[w]hile HDR metadata should be signaled in interfaces, the use of multiple HDR metadata sets should be discouraged. Such fragmentation will introduce complications to HDR workflows, and may lead to requirements for multiple HDR deliverables. This in turn could lead to a delay or even a barrier in adoption of HDR technologies by content creators and users. [6]

5. Other HDR Considerations

Many content producers are experimenting with various types of HDR production. Camera manufacturers have endeavored to ensure they are able to manage HDR in several formats, while production switchers and other broadcast equipment have emerged as well. Where technology does not exist to do HDR natively in production, several very good SDR->HDR production options have emerged for fixed asset cameras or graphics options that have not matured yet or where there is no cost value in replacing.

One aspect that continues to develop is the improvement in "creating" HDR from SDR material (so called inverse tone mapping), including in real-time. Additionally, several companies have done a very reasonable job of creating options that convert SDR to HDR with a reasonable level of quality (e.g., 3D lookup tables). While not as accurate as shooting natively in HDR, upconverting SDR to HDR does provide an option to let consumers acquire more quality content that takes advantage of their display technologies.

6. The Use Cases

The HDR drafting group within SCTE Digital Video Subcommittee – including content producers, programmers, broadcasters, vendors and cable operators – engaged in extensive discussion of both the large-scale content ecosystem and the specifics of modern cable systems and developed the use cases and associated requirements necessary to successfully deploy next generation video services to cable subscribers. These requirements are intended to serve as the basis for selecting an initial approach for an SCTE HDR video standard. As stated in the introduction to this document, the technology is evolving at a rapid rate, and we anticipate that standards and deployments will follow a crawl/walk/run level of technical and economic complexity to accomplish an early deployment but need to take precautions not to exclude future improvements.

Cable needs to provide the highest quality HDR delivery to consumers. Cable needs to attract content owners and programmers' best content and ensure that cable remains competitive with other delivery systems. Cable also needs to ensure that it supports the content provider / MVPD trusted relationship, in terms of cooperatively conforming the content to a minimum number of HDR systems, to decrease the costs in the delivery chain, and bound the operational complexity. HDR quality on cable services shall be commensurate with the best other sources of HDR content (e.g., Blu-ray Disc, OTT services) while working with the constraints of bandwidth to offer subscribers a wide variety of HDR services. Additionally, the cable operator should deliver programmers HDR content without substantial degradation. Any cable HDR standard should not substantially degrade content production transfer characteristics (S-Log3, PQ, HLG). HDR systems should also align (where possible) with other standards to ensure that there are fewer conversions required. Consideration of the UHD Forum Guidelines as well as MovieLabs commentary were additional drivers. Since many titles in the Blu-ray world are already available in HDR10, it made sense as a group to consider this as a primary target. While the drafting group is aware that HLG is being used for many live HDR productions, the near unanimity of movie and episodic content in North America is available in PQ EOTF rather than HLG.

Cable must support distribution of both SDR and HDR content that preserves "creative intent" of both renderings. SDR content should be integrated into an HDR program feed for cable transmission purposes with no perceptible change from the original SDR visual quality. For example the viewer may see two SDR feeds for a live presidential television debate, where both HDR and SDR signals were sourced from a single truck HDR color-graded production process and compared against a second SDR channel that uses a separate SDR color-graded process for the channel. Live linear channels must be simulcasted alongside legacy services/formats (in order to grow a new HDR user base while still supporting the existing SDR user base for video services) as well as "inside" an HDR service (using real-time inverse tone mapping) to complete a full schedule for programming. While SDR and HDR video will look different (else why bother with HDR) the consumer should not have a sense of unease or oddity of switching between the two. This asserts that HDMI resets shall be avoided as they are detrimental to the consumer experience.

MVPDs provide ad insertion into linear channels, and there is complexity and additional cost involved when considering maintaining multiple versions of the same asset for the purpose of that insertion. Cable systems already face this with two different types of HD video, SD video, and alternate ad options based on different profiles provided by different agencies. In the past, several MVPDs have gone through the process of standardizing the bit-rate, resolutions, etc. to ensure that they can decrease the number of variances that they would have in their ad inventory. Thus, to support more than one version of HDR would undo the work done to simplify the processing.

The difficulty of maintaining a consistent user experience across not only an MVPD-provided decoder box, but also customer owned and maintained (COAM) boxes makes clear that cable needs to simplify the number of options to make this viable as a starting point. This is not say that additional formats could not be added in the future, but rather that to foster implementations of HDR, the facility needs to follow the "crawl, walk, run" approach to make sure that cable launches something well, something right, and something fast. In the midst of this, the drafting committee is aware that the HDR ecosystem continues to improve. While HLG10 has made inroads into live productions, and some of the other PQ-based systems also are being used, HDR10 is ubiquitous for pre-produced content. Therefore, in the interest of launching an HDR service as quickly as possible, the drafting committee chose the HDR10 system for initial deployments.

The drafting group also determined that the encoding must be consistent with the expectations in the industry. Irrespective of the EOTF or metadata systems, the drafting group has identified HEVC Main 10 Profile as the target for compression within this domain. While there are many discussions about whether or not it is the right path forward in the future for all providers, with cable's requirement to do live content as well as on demand content, a compression profile that is consistent for the decoders available today is needed, and with profiles and technologies that will assist us in both domains. Ergo HEVC was the logical choice for compression.

When considering HDR, metadata is a significant part of several of the systems in play. There was a great deal of concern about the viability of metadata surviving the end-to-end delivery of the content. It was made clear that the reliance upon metadata to ensure an HDR experience should not be a requirement at this time. To that end, the drafting group determined it was appropriate to state that if metadata should be part of the system then its loss should not result in an SDR experience. Specifically, as we look at live systems for HDR, HDR10 without its metadata (equivalent to PQ10) was determined to be acceptable for our use at this time.

Consideration was given to which color space to use for HDR. While there are options in different industry forums presenting commentary today about color, the decision was made that should Cable go to HDR, it was time to ensure that the WCG BT.2020 color space was used as well. In the process of doing this work, while EOTF options were somewhat contentious, there was no argument that the color space should be WCG.

There is no requirement at this time to deliver 4K for HDR, and many sports programs talk specifically about using 1080p60 instead of 2160p60 (4K) for delivery of content. There’s been a great deal of discussion about frame rates, but at this time many forums including the ATSC have indicated they will continue to support fractional frame rates even in high frame rate video.

7. The Proposition

The majority opinion of the members of the HDR drafting group is that HDR10 meets the current requirements of the cable industry for an HDR video distribution standard against the broad ecosystem the cable industry desires to support. Note that this was not unanimous; there are members of the drafting group with varied and well thought out differing opinions. The majority believes that HDR10 provides appropriate brightness and color volume representations, and it exists in a place where other HDR formats used for content production have defined conversion methods [1]. HDR10 has been used by both Blu-ray Disc and internet streaming providers, which ensures the consistent availability of high-quality content in the format and the availability of technical solutions that will meet the needs of the cable industry, and MovieLabs prefers the use of the PQ curve. HDR10’s processing and display is supported across the widest variety of currently available and next-generation television, computer, tablet, and phone devices [2]. HDR10’s performance may be improved and easily extended in the future with the optional inclusion of dynamic metadata [3, 4, 5], as the ability to create and deliver it becomes a practical possibility in the content production and distribution ecosystem. SCTE should proceed expeditiously to standardize HDR10 for cable systems at this time, but this effort should not preclude the option to introduce other HDR systems in the future that may better meet the industry’s needs.

8. Conclusion

There is a great deal of industry effort to provide HDR to consumers. In an effort to provide flexibility and options, SMPTE has provided many options to the industry. The ATSC has adopted almost all of the options into the ATSC 3.0 standards. Now, there are more options than can be supported. To be responsible to the operations and to the consumer, MVPDs have moved to limit the options down to a starting place that is reasonable against the expression of the decoders available, the coding desires of many content producers, the extensibility of the technology, stability of service operations, and the value to the consumer.

9. Abbreviations

ABR	adaptive bit rate
COAM	customer owned and maintained
CRT	cathode ray tube
HDR	high dynamic range
HEVC	high efficiency video coding
HLG	hybrid log-gamma
HVS	human visual system
ISBE	International Society of Broadband Experts
OETF	opto-electronic transfer function
PQ	perceptual quantizer
SCTE	Society of Cable Telecommunications Engineers
SDR	standard dynamic range
SEI	supplemental enhancement information [HEVC]
MaxCLL	maximum content light level
MaxFALL	maximum frame average light level
MVPD	multichannel video programming distributor
WCG	wide color gamut

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[2] https://www.flatpanelshd.com/focus.php?subaction=showfull&id=1505390780

[3] ATSC Standard A/341 Amendment for “2094-10”, ATSC, 2018.

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Single-Layer HDR Video Coding with SDR Backward Compatibility

A Technical Paper prepared for SCTE•ISBE by

David Touze
Senior Research Engineer
Technicolor
975 avenue des Champs Blancs - ZAC des Champs Blancs - 35576 Cesson Sevigné, France
+33 2 99 27 31 08
david.touze@technicolor.com

Leon van de Kerkhof
Chief Architect
Philips
leon.van.de.kerkhof@philips.com

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1. Introduction

The arrival of the High Efficiency Video Coding (HEVC) standard enables the deployment of new video services with enhanced viewing experience, such as Ultra HD broadcast services. In addition to an increased spatial resolution, Ultra HD will bring a wider color gamut (WCG) and a higher dynamic range (HDR) than the standard dynamic range (SDR) HD-TV currently deployed. Increasing of dynamic range, i.e. the luminance ratio of bright over dark pixels, has been shown to dramatically improve the user experience. Increasing gamut and dynamic range are two faces of the same coin as they basically augment the color volume to which pixels belong. Furthermore, luminance and colors are intrinsically linked in legacy workflows that are non-constant luminance: the signal non-linearity is not applied directly to the luminance, but instead the non-linear luminance is a combination of non-linear quantities (typically RGB).

Different solutions for representing and coding HDR/WCG video have been proposed [1][2][3][4]. As stated in [5][6][7][8], SDR backward compatibility with decoding and rendering devices is an important feature in video distribution systems, such as broadcasting or multicasting systems. The coming American broadcast standard ATSC 3.0 is expected to emit both SDR BT.709/2020 and HDR BT.2020 streams. The European DVB standard has already introduced SDR UHDTV in the BT.2020 color space and will extend it to HDR BT.2020 soon. Peak brightness is expected to migrate from legacy 100 nits to about 1000 nits, but compression solutions should be flexible enough to handle future higher brightness as well as non-broadcast applications that may take advantage of more nits.

Dual-layer coding, for instance using the scalable extension of HEVC (a.k.a. SHVC) is one solution to support SDR backward compatibility. However, due to its multi-layer design, this solution is not adapted to all distribution workflows. An alternative is to transmit HDR content and to apply at the receiving device an HDR-to-SDR adaptation process (tone mapping). One issue in this scenario is that the tone mapped content may be out of control of the content provider or creator. Another issue is that a new HDR-capable receiving device is needed to apply this tone mapping for existing SDR displays. Alternatively, the Hybrid Log Gamma (HLG) transfer function [2] has been designed as a straightforward solution to address the SDR backward compatibility, that is, an HDR video graded on a display using the HLG transfer function can be in principle directly displayed on an SDR display (using the BT.1886 transfer function [9]) without any adaptation. However, this solution may result in color shifting when the HLG-graded video is displayed on an SDR rendering device, especially when dealing with content with high dynamic range and peak luminance [10][11][12]. Also, there is no way to optimize the brightness and contrast of the SDR image.

The proposed Single Layer SDR backward compatible HDR video distribution solution detailed in this paper, named SL-HDR1, and standardized in ETSI TS 103 433 specification [13], aims at addressing these issues. SL-HDR1 leverages SDR distribution networks and services already in place. It enables both high quality HDR rendering on HDR-enabled CE devices, while also offering high quality SDR rendering on SDR CE devices.

The main features of the HDR distribution system are as follows:

- Single layer with metadata: SL-HDR1 is based on a single layer coding process, with side metadata that can be used at post-processing stage. The metadata payload corresponds to a few bytes per picture, GOP (Group Of Pictures) or scene.
- Codec agnostic: SL-HDR1 does not impact the core codec technology and is codec independent. SL-HDR1 is based on an encoding pre-processing applied to the HDR input, and on a corresponding decoding post-processing (functional inverse of the pre-processing) applied to the reconstructed video from decoding. Use of a 10-bit codec is recommended, since an 8-bit codec could introduce artefacts such as banding effects, due to having too few codewords available for the precision required for HDR content.
- Enable SDR backward compatibility: a decoded bitstream can be displayed as is on an SDR display. The color fidelity is preserved compared to the HDR version. An additional post-processing is applied to convert the decoded SDR version to HDR, thanks to the metadata, with preservation of the HDR artistic intent.
- Enable preserved quality of HDR content: there is no penalty due to the SDR backward compatibility feature; coding performance compared to HLG are improved, in particular in terms of color impairments.
- Enable adaptation of the HDR content to the HDR display capabilities: if the HDR content peak brightness is higher than the HDR display peak brightness, the post-processing adapts the HDR content to display peak brightness, preserving all details and HDR artistic intent.
- Limited additional complexity: the pre- and post-processing steps are of limited added complexity; in particular the involved operations are only sample-based, without inter-sample dependency.
- Independent from the input OETF (optical to electrical transfer function): the pre- and post-processing operate in linear-light domain, and are therefore independent from the input OETF.

The document is organized as follows. The solution overview is presented in section 2.1. Section 2.2 describes the HDR-to-SDR decomposition and section 2.3 defines the HDR reconstruction process. Section 2.4 relates to the metadata signaling. Section 2.5 details the display adaptation feature. Section 2.6 presents tests results, assessing the SDR quality and the HDR compression performance of SL-HDR1 comparatively to distribution solutions just based on PQ and HLG transfer functions. Lastly, the Conclusion section provides closing remarks.

2. SL-HDR1 Codec

2.1. SL-HDR1 System Overview

Figure 1 shows an end-to-end workflow supporting content production and delivery to HDR and SDR rendering devices. The core of the HDR distribution solution SL-HDR1 corresponds to yellow and green boxes. SL-HDR1 involves a single-layer SDR/HDR encoding-decoding, with side dynamic metadata. At the distribution stage, an incoming HDR signal is decomposed into an SDR signal and content-dependent dynamic metadata. The SDR signal is encoded with any distribution codec (e.g. HEVC Main 10) and carried throughout the existing SDR distribution network with accompanying metadata conveyed on a specific channel or embedded in the SDR bitstream. The dynamic metadata are typically carried in an SEI message when used in conjunction with an HEVC codec. The dynamic metadata are associated per frame or can be associated to multiple frames, such as GOP for instance. The post-processing stage is functionally the inverse of the pre-processing and performs the HDR reconstruction. It occurs just after

SDR bitstream decoding. The post-processing takes as input an SDR video frame and associated dynamic metadata in order to reconstruct an HDR picture. Single-layer encoding/decoding requires only one encoder instance at HDR encoding side, and one decoder instance at player/display side. It supports the real-time workflow requirements of broadcast applications. The dynamic metadata is produced by the HDR decomposition process and remain internal to the distribution process. They do not need to be conveyed to the rendering device. Additional metadata, originated from the production/post-production, can optionally be distributed and conveyed to the rendering device.

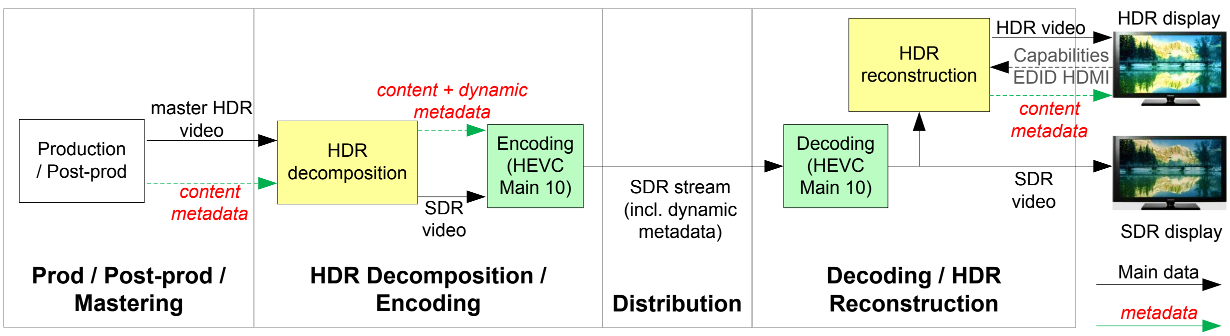

Figure 1 - Example of HDR end-to-end system.

The block diagram in Figure 2 depicts in more details the HDR decomposition and reconstruction processes. The center block included in red dashed box corresponds to the distribution encoding and decoding stages. The left and right grey-colored boxes respectively enable format adaptation to the input video signal of the HDR system and to the targeted system (e.g. a STB, a connected TV). The yellow boxes show the HDR specific processing. The first step of the HDR decomposition process linearizes the input HDR content, allowing the system to ingest every HDR production format such as PQ (display referred), HLG (scene referred) or any other production format. For the HLG case, as it is a relative format, the peak brightness of the HLG content needs to be provided to the system. The linearized content is then independent from the input format and allows the system to always work in the same consistent linear-light domain. The core component of the HDR decomposition stage is the HDR-to-SDR conversion that generates an SDR video from the linear-light HDR signal. Optionally, gamut mapping may be used when the input HDR and output SDR signals are represented in different color spaces. This optional gamut mapping may be introduced either before or after the HDR-to-SDR conversion. The decoder side implements the inverse processes, in particular the SDR-to-HDR reconstruction step that inputs the SDR video provided by the decoder and that transforms it back to an HDR video at a peak luminance adapted to the HDR display capabilities.

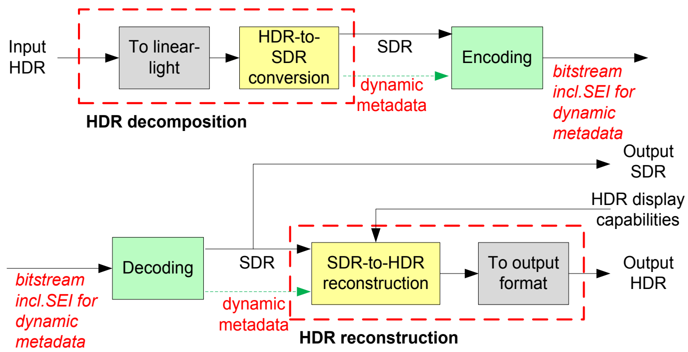

Figure 2 - HDR system architecture overview.

2.2. HDR-to-SDR Decomposition Process

The HDR-to-SDR decomposition process aims at converting the input linear-light 4:4:4 RGB HDR signal to an SDR Y'CbCr 4:2:0 compatible version. The process uses side information such as the color primaries and gamut of the container of the HDR and SDR pictures. The process operates without color gamut change: the HDR and SDR pictures are defined in the same color gamut. If needed, a gamut mapping processing may be applied either on the HDR pictures or on the SDR pictures. In the former case the HDR picture is converted from its native color gamut to the target color gamut before the HDR-to-SDR decomposition process. And in the latter case the SDR picture generated by the HDR-to-SDR decomposition process is converted from its native color space to the target SDR color gamut.

The HDR-to-SDR decomposition process is depicted in Figure 3. It is primarily based on the HDR content analysis (picture per picture) in order to derive a set of mapping parameters that will be further used to convert the HDR signal into SDR (step 1). Once the mapping parameters have been derived, a luminance mapping function, noted *TM*, is obtained. Next, the linear-light luminance *L*, derived from the HDR linear-light RGB signal, is mapped to an SDR luma signal, i.e. a gammatized version of the linear-light SDR luminance, using the luminance mapping function *TM* (step 2). The chroma components are then derived (step 3). A final color correction is applied in order to match the SDR colors to the input HDR signal colors (step 4). Steps 2 to 4 are detailed in the following sub-sections.

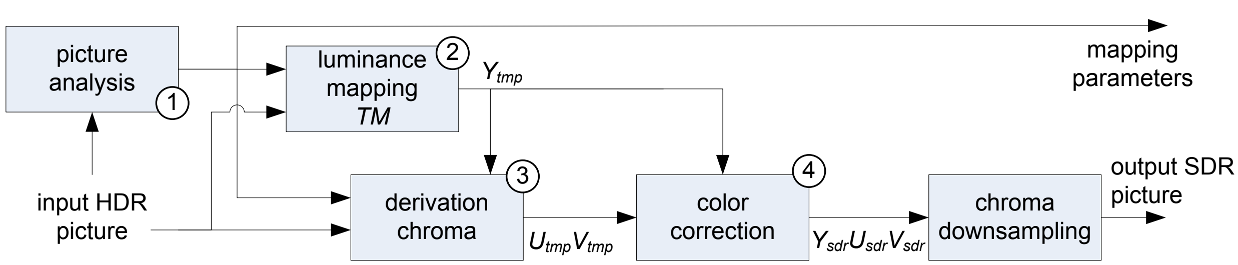

Figure 3 - Synoptic of HDR-to-SDR decomposition process.

2.2.1. Luminance mapping

The luminance mapping (step 2) aims at converting the input linear-light luminance signal, derived from the HDR linear-light RGB signal, into an SDR luma signal using a luminance mapping function *TM*. This is done according to the following equations:

$$L = A_1 \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

$$Y_{tmp} = (LUT_{TM}(L))^{\frac{1}{2,4}} \tag{2}$$

where $A = [A_1 A_2 A_3]^T$ is the conventional 3x3 R'G'B'-to-Y'CbCr conversion matrix (e.g. BT.2020 or BT.709 depending on the color space), A_1, A_2, A_3 being 1x3 matrices.

The mapping function or look-up-table *TM* is built as follows. The mapping is based on a perceptual transfer function, and uses a limited set of control parameters, that have to be further conveyed to the post-processing in order to be able to invert the luminance mapping process. The input linear-light luminance signal *L* is first converted to the perceptually-uniform domain based on the mastering display peak luminance, using a perceptual transfer function illustrated in left picture of Figure 4. This process is controlled by the mastering display peak luminance parameter. To better control the black and white levels, a signal stretching between content-dependent black and white levels (parameters *blackLevelOffset* and *whiteLevelOffset*) is applied. Then the signal is tone mapped using a piece-wise curve constructed out of three parts, as illustrated in Figure 5. The lower and upper sections are linear, the steepness being determined by the *shadowGain* and *highlightGain* parameters. The mid-section is a parabola providing a smooth bridge between the two linear sections. The width of the cross-over is determined by the *midToneWidthAdjFactor* parameter. The curve can be further fine-tuned using a piece-wise linear corrective function. Then the signal is converted back to the linear light domain based on the targeted SDR display maximum luminance of 100 cd/m2, as illustrated in the right picture of Figure 4. The resulting signal is the SDR luma.

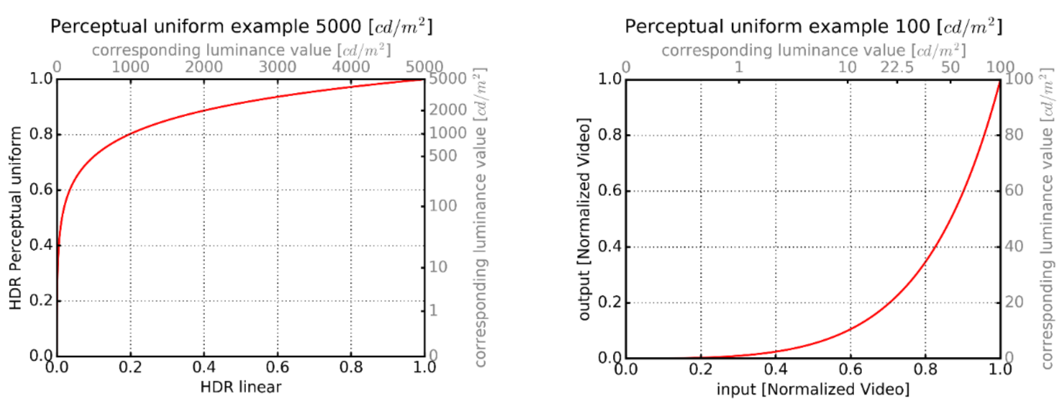

Figure 4 - Example conversion curves for converting from linear light to perceptual domain (left, with peak luminance 5000 cd/m2) and back to SDR linear light (right).

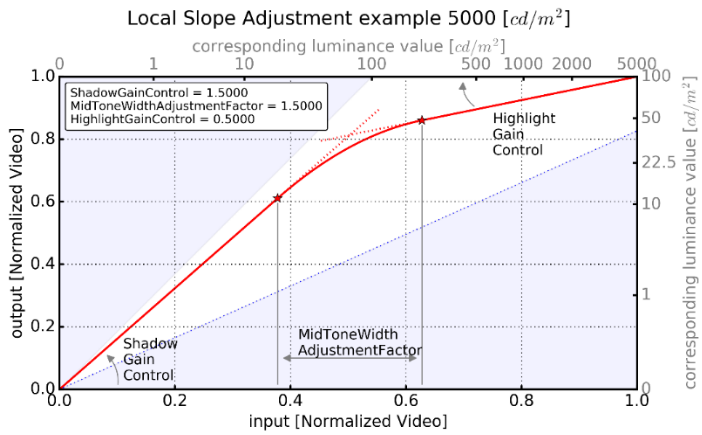

Figure 5 - Tone mapping curve shape example.

2.2.2. Chroma components derivation

The chroma components are derived as follows (step 3). First a square root is applied to input HDR linear-light R, G, B and L values to reproduce a transfer function close to the BT.709/BT.2020 OETF (the usage of a square root guarantees the reversibility of the process). Then the resulting squared-root R, G, B values are scaled by the squared-root L value, which results in a gamma-tized SDR version of the input R, G, B signals. The resulting R, G, B signal is converted to chroma components U_{tmp}, V_{tmp}:

$$\begin{bmatrix} U_{tmp} \\ V_{tmp} \end{bmatrix} = \frac{1}{\sqrt{L}} \times \begin{bmatrix} A_2 \\ A_3 \end{bmatrix} \times \begin{bmatrix} \sqrt{R} \\ \sqrt{G} \\ \sqrt{B} \end{bmatrix} \tag{3}$$

2.2.3. Color correction

A final color correction is applied in order to match the SDR colors to the input HDR signal colors (step 4). First the chroma components are adjusted by a scaling factor $1/\beta(Y_{tmp})$, where $\beta(Y_{tmp})$ is a function that enables to control the color saturation and hue and that is constructed by matching primaries and white points between the SDR and the HDR gamut.

$$\begin{bmatrix} U_{sdr} \\ V_{sdr} \end{bmatrix} = \frac{1}{\beta(Y_{tmp})} \times \begin{bmatrix} U_{tmp} \\ V_{tmp} \end{bmatrix} \tag{4}$$

Then the luma component is adjusted to further control the perceived saturation, as follows:

$$Y_{sdr} = Y_{tmp} - Max(0, a \times U_{sdr} + b \times V_{sdr}) \tag{5}$$

where a and b are two control parameters. This luma adjustment step helps in recovering the color perception difference that occurs when a specific color is rendered at different luminance level.

As demonstrated in [13], this color correction step is fundamental to control the SDR colors and to guarantee their matching to the HDR colors. This is in general not possible when using a fixed transfer function.

2.3. HDR Reconstruction

The HDR reconstruction process takes place after the stream decoding process and is therefore codec agnostic. This process is depicted in Figure 6. This section describes the revertible process without taking into account the display adaptation feature that is detailed in section 5. From the input dynamic metadata (detailed in section 2.4) a luma-related look-up table, *lutMapY*, and a color correction look-up table, *lutCC*, are derived. The next step consists in applying the SDR-to-HDR reconstruction from the input SDR picture, the derived luma-related look-up table and color correction look-up table. This process produces an output linear-light HDR picture. An optional gamut mapping can be applied when the color spaces of the SDR picture and of the HDR picture are different (either before or after the SDR-to-HDR reconstruction).

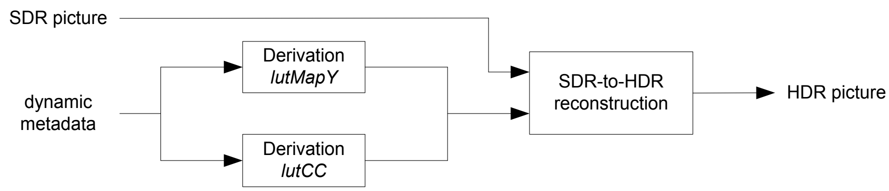

Figure 6 - Overview of the HDR reconstruction process.

The SDR-to-HDR reconstruction process is the functional inverse of the decomposition process. However, for implementation complexity reasons, some operations are concatenated or applied in a different order. This is the case for the final R, G, B reconstruction step described below. The operation reordering and concatenation allows this step to be implemented as a single “output” LUT and this method optionally allows the addition of an output EOTF (such as PQ or HLG) in the same “output” LUT. The LUT *lutMapY* actually corresponds to the inverse of the square-root of the mapping LUT *TM*. The post-processing color correction LUT *lutCC* is actually linked to the pre-processing color correction LUT β and the tone mapping LUT *lutMapY* by the following equation:

$$\beta[Y] = 2^B \times \; lutMapY[Y] \times lutCC[Y] \qquad (6)$$

where B is the bit-depth of the luma signal. It can be demonstrated that the inverse of $lutCC$ is close to a linear function.

The HDR reconstruction process performs the following successive steps for each sample Y, U (Cb component), V (Cr component), of the SDR picture. First U and V are centered (by subtracting the chroma offset, e.g. 512 for a 10 bit signal). Then the variables Y_{post} U_{post} and V_{post} are derived as:

$$Y_{post} = Clamp(0, 2^B - 1, Y + Max(0, a \times U + b \times V) \qquad (7)$$

$$\begin{bmatrix} U_{post} \\ V_{post} \end{bmatrix} = lutCC[Y_{post}] \times \begin{bmatrix} U \\ V \end{bmatrix} \tag{8}$$

The reconstruction of the HDR linear-light *R*, *G*, *B* values is made up of the following steps. A parameter *T* is first computed as:

$$T = k0 \times U_{post} \times V_{post} + k1 \times U_{post} \times U_{post} + k2 \times V_{post} \times V_{post} \tag{9}$$

where *k0*, *k1*, *k2* are predefined parameters that depend on the coefficients of the R'G'B'-to-Y'CbCr conversion matrix *A*. The intermediate values R_{im}, G_{im}, B_{im} are derived as follows:

$$\begin{bmatrix} R_{im} \\ G_{im} \\ B_{im} \end{bmatrix} = A^{-1} \times \begin{bmatrix} \sqrt{1-T} \\ U_{post} \\ V_{post} \end{bmatrix} \tag{10}$$

A clamping is done to 0, $\sqrt{L_{HDR}}$, where L_{HDR} is the HDR mastering display peak luminance.

Then, linear-light *R*, *G*, *B* values are obtained by the following equation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \left(lutMapY[Y_{post}]\right)^2 \times \begin{bmatrix} R_{im}^2 \\ G_{im}^2 \\ B_{im}^2 \end{bmatrix} \tag{11}$$

It can be demonstrated that equations (9) to (11) invert the pre-processing operation of (1) to (3), that is, the conversion of the HDR version *R*, *G*, *B* into chroma components. When *T* is larger than 1 (which is in principle not possible, but may happen because of quantization and compression), U_{post} and V_{post} are scaled by $1/\sqrt{T}$, the resulting *T* becoming equal to 1. As this scaling applies simultaneously on the two chroma components, the resulting hue remains stable.

2.4. Metadata Description

The post-processing uses the LUTs *lutMapY* and *lutCC*, and the parameters *a, b, k0, k1 and k2*, as dynamic data. These data enable to finely control the texture and colors of the SDR version, and to ensure a good fit to the HDR intent. The LUTs *lutMapY* and *lutCC* are conveyed either using a limited set of parameters (parameter-based mode), or explicitly coded (table-based mode). In both cases, the metadata payload corresponds to a few bytes per video frame or scene. The parameter-based mode may be of interest for distribution workflows which primary goal is to provide direct SDR backward compatible services with very low additional payload or bandwidth usage for carrying the dynamic metadata. The table-based mode may be of interest for workflows equipped with low-end terminals or when a higher level of adaptation is required for representing properly both HDR and SDR streams.

Next to the dynamic metadata, the system uses information that define the properties of the mastering display used when grading the HDR content, as defined in Mastering Display Colour Volume (MDCV) message. This is static information (typically fixed per program) required by the post-processing. It comprises the color gamut of the SDR/HDR signal and the mastering display peak luminance.

In the parameter-based mode, the metadata for reconstructing *lutMapY* consist of the parameters mentioned in section 2.2.1. For reconstructing *lutCC*, a default pre-defined LUT is used at the post-processing side, and a piece-wise linear table made of at most 6 points is used as a scaling function to adjust the default table. These parameters are conveyed using the parameters defined in the SMPTE ST 2094-20 specification. Typical payload is about 70 bytes per scene, including Mastering Display Colour Volume (MDCV) message. In the table-based mode, *lutMapY* and *lutCC* are explicitly coded using the parameters defined in the SMPTE ST 2094-30 specifications. Typical payload is about 186 bytes per scene, including Mastering Display Colour Volume (MDCV) message. In both cases, the metadata are limited to the codec space. They do not come from the production side, and do not need to be conveyed outside the decoding platform. They are conveyed using standardized metadata containers.

The usage of dynamic metadata allows a fine control of the SDR texture (using the tone mapping LUT *lutMapY*) and of colors (using the color correction LUT *lutCC* and the parameters *a, b, k0, k1* and *k2*). This guarantees the preservation of the HDR texture and intended colors in the SDR version, as illustrated in pictures in next section. High SDR and HDR video quality is obtained, without any strong limitation of the dynamic range and peak luminance (no limitation to peak luminance of around 1000-1500 nits). This also gives high flexibility which enables to easily adapt the system (for instance thanks to the easy control of the dynamic metadata payload) to the distribution workflow.

2.5. Display Adaptation

The display adaptation feature is only active with parameter-based metadata mode and is based on the Tone Mapping and Inverse Tone Mapping computation blocks of the system.

On the HDR decomposition side (see Figure 3), the luminance mapping block (step 2) computes a Tone Mapping curve based on the dynamic parameters described in section 2.2.1 and based on the mastering display peak luminance and the targeted SDR display maximum luminance of 100 cd/m2.

On the HDR reconstruction side (see Figure 6), the *lutMapY* derivation block computes an Inverse Tone Mapping curve based on the same dynamic parameters, the same SDR display maximum luminance of 100 cd/m2 and the same HDR mastering display peak luminance. The resulting Inverse Tone Mapping curve is the inverse of the Tone Mapping curve computed by the HDR decomposition block, as depicted in Figure 7.

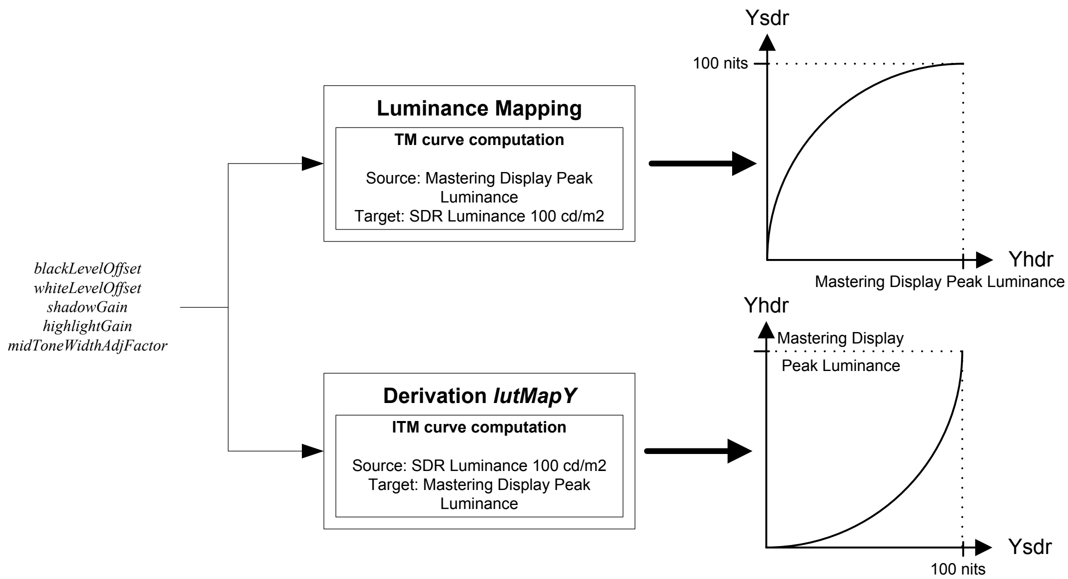

Figure 7 - Tone Mapping and Inverse Tone Mapping computation blocks

The display adaptation feature is an extension of the HDR reconstruction process and takes place in the *lutMapY* derivation and *lutCC* computation process, as shown in Figure 8.

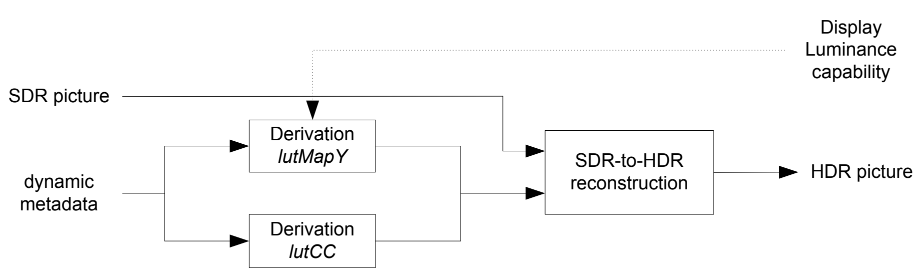

Figure 8 - Overview of the HDR reconstruction process with display adaptation

The feature relies on the attached display luminance capability that is provided either through the EDID data of the HDMI connection to the display or inherently when the processing is integrated in the display device. When EDID information can't be trusted, the feature could be either disabled or optionnally be driven by the system firmware. The solution consists of a cascaded calculation of the previously described Inverse Tone Mapping curve and an adapted Tone Mapping curve. This added Tone Mapping block uses the same dynamic parameters and the same input mastering display peak luminance but now relies on the provided presentation display peak luminance capability as the target output peak luminance, as shown in Figure 9:

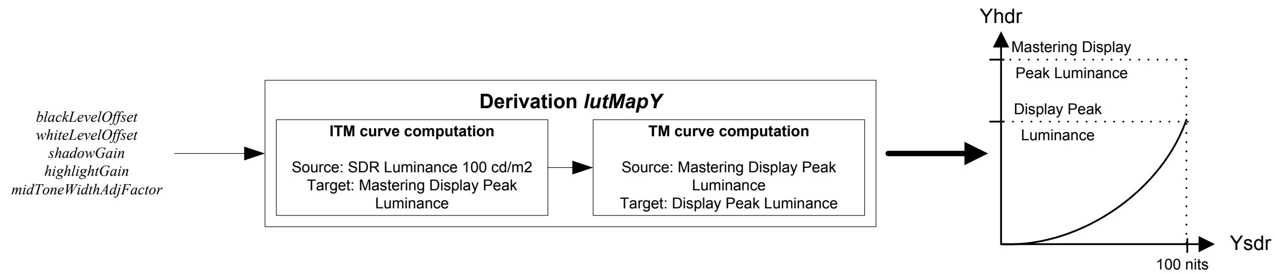

Figure 9 - Inverse Tone Mapping curve computation with display adaptation

The cascading of these two processes is easily implemented in the *lutMapY* LUT with no added complexity.

This process in essence only adapts the luminance of the signal and aims to preserve the artistic intent for a presentation display with a different peak luminance than the targeted SDR or the original HDR peak luminance by means of a reconstructed adapted signal.

2.6. Performance evaluations

Two reference distribution solutions, PQ and HLG, can be considered for evaluating an HDR video distribution solution. PQ [14] is a non-SDR backward compatible transfer function, based on the human contrast sensitivity model developed by Barten [15] more adapted to HDR than the usual gamma. HLG [2] is a new transfer function aiming at offering some level of SDR backward compatibility. The two next sections report comparative results of SL-HDR1 vs. distribution solutions using these two transfer functions.

2.6.1. HDR compression comparison with PQ transfer function

This section reports HDR compression results of SL-HDR1, compared to the non-SDR backward compatible solution HDR10 based on the PQ transfer function. The considered test sequences, selected for the MPEG HDR and WCG Call for Evidence [5], are natively in RGB, 4:4:4, linear-light format, represented in BT.2020 color primaries container. The complete conversion and coding, decoding and back-conversion chain, for all tested solutions has been performed in BT.2020 color primaries container. All contents have been compressed using the MPEG reference HEVC encoder HM 16.2.

Several metrics to assess HDR image objective quality have been proposed at MPEG [5]. Unfortunately, none of them is very satisfactory in the sense that better metric values do not necessarily imply better subjective quality. For this reason, metric values have to be considered with care and are provided in Table 1 is more color oriented and the metric L100 evaluates the luminance quality only. Both metrics are based on an extension of the well-known Lab 2000 color space [17]. It is observed that high metric gains are possible, but subjectively optimized compressed videos show much less gains, proving once again the inconsistency of the objective metrics. In this test, it has been verified by subjective tests performed by non-naïve viewers that all visually optimized videos have a quality at least comparable to the best proponents of the MPEG HDR and WCG Call for Evidence [16]. The artifacts observed on the reconstructed HDR content include typical compression artefacts already observed in SDR compression such as blocking artefacts and inconsistent color patches generation especially for color areas reaching the color gamut boundaries.

Table 1 for both 4:2:0 subjectively optimized luminance mapping parameters (the automatic tuning is adjusted to get optimal visual SDR quality, left column) and 4:4:4 metric oriented parameter optimization (the automatic tuning is adjusted to get high objective metric DE100 values, right column). The gains are expressed in average bitrate savings compared to the HDR10 reference using the Bjøntegaard-Delta-rate measure [16] and do include the overhead due to the metadata (encoded in dedicated SEI message) associated to the proposed method. A negative value of x% indicates that SL-HDR1 requires x% less bitrate than the reference (PQ/HDR10) for a similar quality.

The metric DE100 is more color oriented and the metric L100 evaluates the luminance quality only. Both metrics are based on an extension of the well-known Lab 2000 color space [17]. It is observed that high metric gains are possible, but subjectively optimized compressed videos show much less gains, proving once again the inconsistency of the objective metrics. In this test, it has been verified by subjective tests performed by non-naïve viewers that all visually optimized videos have a quality at least comparable to the best proponents of the MPEG HDR and WCG Call for Evidence [5]. The artifacts observed on the reconstructed HDR content include typical compression artefacts already observed in SDR compression such as blocking artefacts and also inconsistent color patches generation especially for color areas reaching the color gamut boundaries.

Table 1 - HDR compression performance on MPEG metrics compared to HDR10.

			420 subjective optim.		**444 DE100 optim.**
Sequence	Resolution	Peak luminance	DE100	L100	DE100
Market3	HD	4000 nits	-30.4%	-25.1%	-71.8%
AutoWelding	HD	4000 nits	-14.8%	-2.8%	-38.8%
ShowGirl2Teaser	HD	4000 nits	-34.1%	-8.9%	-56.8%
StEM_WarmNight	HD	4000 nits	-17.7%	-2.8%	-41.1%
BalloonFestival	HD	5000 nits	-3.1%	-13.6%	-61.3%
		Average	-20.0%	-10.6%	-53.9%

It should be noted that SDR backward compatibility imposes a natural balance, but not optimal for HDR compression, between chroma and luma. The balance may be compensated by an adequate adjustment of the chroma quantization parameter (controlled by syntax element QPChromaOffSet in HEVC). It has been observed that the tuning of this parameter also improves the quality of HDR10 anchors and it may as well improve the proposed solution. However this raises the issue of having to develop, for HDR content, particular encoders significantly different from encoders optimized for SDR video. An extra-advantage of SDR backward compatible solutions is that existing SDR encoders can be re-used.

2.6.2. HDR compression comparison with HLG transfer function

This section reports SDR quality evaluation and HDR compression results of SL-HDR1, compared to the SDR backward compatible solution based on the HLG transfer function. For these tests, visual evaluations made by an independent lab, under supervision of V. Baroncini (MPEG tests chair), have been performed. Two different tests were performed. First tests aimed at evaluating the SDR backward compatibility feature, by checking the quality of the SDR video generated from the HDR content. Second tests aimed at evaluating the HDR compression performance. For these two tests, comparative evaluation was performed between three solutions: HLG, SL-HDR1 with first tuning, SL-HDR1 with second tuning.

First tuning tends to generate brighter pictures, i.e. picture with a higher average luminance level, than second tuning. In both cases, the tuning is fully automatic, but is performed according to one of these two different modes.

In the experiments, the HLG implementation from HDRTools software, version 0.12 (accessible at link https://gitlab.com/standards/HDRTools/tags/v0.12), made by the HLG designers, has been used to generate the HLG results. As recommended by the HLG designers, a system gamma correction was applied to the input linear-light RGB HDR content prior to converting it with HLG. The value of the system gamma γ in the HLG pre-processing depends on the peak luminance L_{peak} of the HDR mastering display, and is derived as follows:

$$\gamma = 1.2 + 0.42 \text{ x } \text{Log10}(L_{peak} \ / \ 1000) \tag{12}$$

2.6.2.1. Test sequences

In order to have a future-proof evaluation, and to anticipate the evolution of HDR displays capabilities, sequences with various peak luminance have been used. The content color gamut is either BT.709 or P3D65, but all sequences are represented in BT.2020 color primaries container. All sequences are natively represented in EXR RGB 4:4:4 linear-light half-float format. The complete conversion and coding, decoding and back-conversion chain, for all tested solutions has been performed in BT.2020 color primaries container.

The test sequences are listed in Table 2.

Table 2 - Test sequences for comparative tests with HLG.

Name	Sequence	Peak luminance	Content gamut	Container gamut	fps	Size	duration
S0	Market3	4000	709	2020	50	HD	8s
S1	EBU_04_Hurdles	3000	709	2020	50	HD	10s
S2	EBU_04_Starting	3000	709	2020	50	HD	10s
S3	EBU_13_LongJump	3000	709	2020	50	HD	10s
S4	HdM ShowGirl	5000	P3D65	2020	24	HD	10s
S7	CableLabs Rope	5000	709	2020	24	HD	10s

2.6.2.2. Evaluation of SDR quality

The goal of these tests is to verify that colors and texture of the SDR generated by HLG and SL-HDR1 conform to those of the HDR content. The methodology described in [18] is used. For each solution, the viewers have to assess the conformity of the SDR displayed on an SDR monitor to the HDR displayed on an HDR monitor (Sim2). In particular, they have to check the conformity of colors and the texture preservation. This test set-up uses two displays that, when driven with a “black” input signal, become not visible to the viewing subjects. Furthermore, an opaque non reflective curtain is placed between the displays, in a way that, even if the viewer can still watch both displays, any visible interference due to reflections and indirect illumination among the displays is avoided.

Test results are depicted in the graphs of Figure 10 and Figure 11. The vertical axis depicts the Mean Opinion Score (MOS). A score of 10 corresponds to quality of reproduction that is perfectly faithful to the original. A score of 0 denotes a quality of reproduction that has no similarity to the original. A worse quality cannot be imagined. 5 corresponds to a fair quality. The average score value, with related confidence interval, is depicted for each tested solution. In all cases but one, SL-HDR1, with any tuning, was judged much better than HLG. Only for sequence S7, SL-HDR1 tuning1 and HLG are equivalent, and better than SL-HDR1 tuning2. The average scores and confidence intervals for the 6 sequences, and for the three methods, are depicted in Table 3. SL-HDR1 with both tuning outperforms HLG by around 1.7 MOS points.

Illustrative SDR pictures resulting from the HDR conversion by HLG (left) and by SL-HDR1, with first tuning (right) are depicted in Figure 12. Color hue and contrast issues can be observed in HLG versions. In general, texture losses are observed in HLG, especially in bright areas (wall in Market, ground track in Hurdles). And saturated colors (such as red and purple colors) suffer from noticeable hue shifts.

Table 3 - Average MOS and confidence intervals.

	Average MOS	Confidence interval
HLG	4.82	0.35
SL-HDR1 tuning1	6.56	0.26
SL-HDR1 tuning2	6.54	0.22

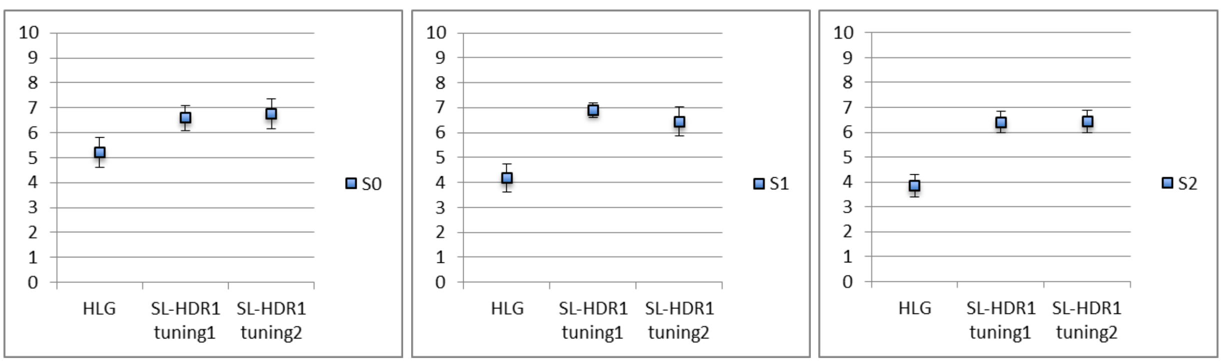

Figure 10 - Average MOS values per sequence, with corresponding confidence interval.

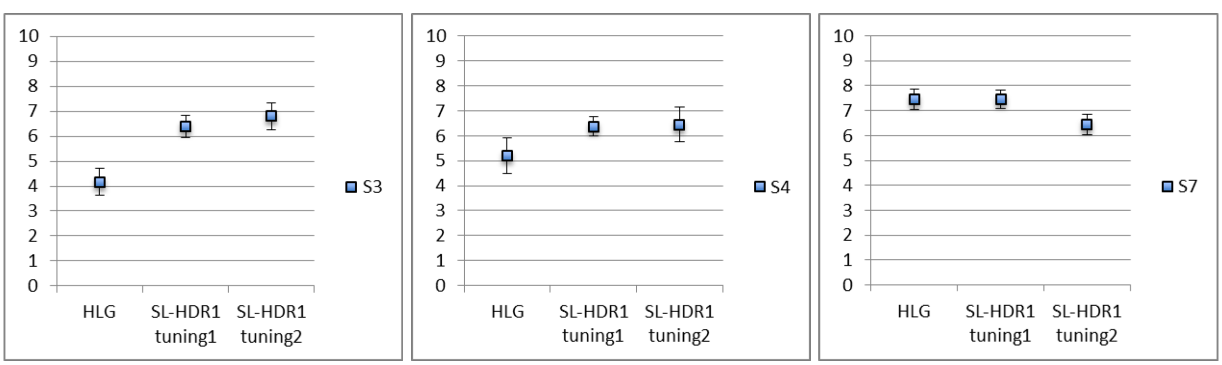

Figure 11 - Average MOS values per sequence, with corresponding confidence interval.

Figure 12 - SDR version from HLG (left) and SL-HDR1 (right) of Market (top) an EBU Hurdles (bottom) HDR first picture.

2.6.2.3. Evaluation of HDR compression performance

The goal of these tests is to evaluate the quality of the reconstructed HDR using SL-HDR1 compared to the reconstructed HDR using HLG (that is, HDR coded with HLG transfer function, compressed then decompressed with HEVC Main10). The test procedure for the formal subjective evaluation uses one of the test methods described in [19], specifically the Degradation Category Rating (DCR) method. Four bitrates were used, adapted to each test sequence, as listed in Table 4. The encoding was performed using a professional HEVC file encoder from Elemental, Main 10 profile, with same settings for the three tested solutions. The Intra period was set around 1s (24 for 24 fps content, 48 to 50 fps content). The hierarchical-B GOP structure was of size 8, with 4 reference pictures, and B-pictures used as reference.

The average bitrate savings of SL-HDR1 compared to HLG for each sequence have been computed from the MOS vs. bitrate data to quantify the achieved bitrates savings. Table 5 shows the MOS Bjøntegaard-Delta-rate (BD-rate) for each sequence. BD-rate measures as described in40were used with MOS scores taking the place of the peak signal-to-noise ratio (PSNR) values that have been typically used with BD-rate measurements, with negative numbers indicating percentage of rate reduction at the same MOS quality. The estimated rate saving by using SL-HDR1 in place of HLG is quite significant. Only in one case (sequence S7), the compression performance with SL-HDR1 tuning 1 is similar to HLG. The average MOS BD-rate gain (that gives an estimation of the bitrate saving) of SL-HDR1 compared to HLG is of 24.6% for tuning 1, and 26.7% for tuning 2.

Table 4 - Bitrates (kbps) per sequence.

Sequence	R1	R2	R3	R4
S0	8000	5000	3000	2000
S1	8000	5000	3000	2000
S2	8000	5000	3000	2000
S3	6000	4000	2000	1000
S4	6000	4000	3000	2000
S7	3000	1700	1000	0700

Table 5 - MOS BD-rate savings measurements.

	SL-HDR1 tuning1 vs HLG	SL-HDR1 tuning2 vs HLG
S0	-33.1%	-27.5%
S1	-13.9%	-9.6%
S2	-38.5%	-50.7%
S3	-37.1%	-17.9%
S4	-23.9%	-41.4%
S7	-1.2%	-13.1%
Avg	**-24.6%**	**-26.7%**

3. Conclusions

The co-existence of SDR and HDR on one hand, and BT.709 and BT.2020 contents on the other hand is likely to happen and last for at least a few years. Some applications, like broadcasting, will benefit from SDR backward compatible solutions that avoid simulcasting versions with various ranges and gamut. Backward compatibility would make the transition from SDR HDTV to HDR UHDTV smoother with increased interoperability.

The proposed solution, SL-HDR1, addresses the SDR/HDR backward compatibility by offering a new dynamic reducer with consistent SDR/HDR colors. This solution also adapts to the wide range of HDR display brightness capabilities by tuning the content to the display capabilities while preserving the artistic intent. The solution has been compared to two alternative solutions, a non-backward compatible approach (HDR10) that is different in essence and an alternative backward-compatible approach (HLG). It shows solid compression gain compared to the conservative non-backward compatible HDR10 approach. Tests results also show that SL-HDR1 outperforms HLG in a statistically significant way. This holds for both tests, i.e. both the visual quality of the SDR and that of the reconstructed HDR are better for SL-HDR1 compared to HLG. For SDR visual quality, SL-HDR1 outperforms HLG by 1.7 points in Mean Opinion Score (MOS). For HDR compression, a bitrate saving of around 25% is obtained by SL-HDR1 compared to HLG. SL-HDR1 is compliant with a 4:2:0 distribution workflow as well as with existing HDR color spaces (namely BT.2020 CL CbCr), non-linearity (PQ or HLG EOTF) and bit-depth (10 bits) used as input to rendering devices.

The solution has been designed with a particular focus on low complexity and high performance. The pre- and post-processing are of very low added complexity. The involved operations are pixel-based, without inter-sample or temporal dependency. The complexity increase is very reasonable (a few operations and

LUTs) relatively to the HDR coding gain and the new backward compatible feature that are provided. Associated metadata can be encapsulated in the compressed bit-stream and would not require their transmission from the production to the display. The solution has been standardized as ETSI TS 103 433.

4. Abbreviations

ATSC	Advanced Television Systems Committee
BD-rate	Bjøntegaard-delta-rate
CE	Consumer Electronics
DCR	degradation category rating
EBU	European Broadcasting Union
EDID	Extended Display Identification Data
ETSI	European Telecommunications Standards Institute
fps	frame per second
GOP	group of pictures
HD	high definition
HDR	high dynamic range
HEVC	high efficiency video coding
HLG	hybrid log gamma
ITM	inverse tone mapping
kbps	kilo bits per second
LUT	look-up table
MDCV	mastering display color volume
MPEG	Moving Picture Experts Group
MOS	mean opinion score
OETF	optical to electrical transfer function
PQ	perceptual quantization
PSNR	peak signal to noise ratio
SCTE	Society of Cable Telecommunications Engineers
SDR	standard dynamic range
SEI	supplemental enhancement information
SHVC	scalabilty extension of HEVC
STB	set-top box
TM	tone mapping
TS	technical specification
TV	television
UHD	ultra high definition
UHDTV	ultra high definition television
WCG	Wide color gamut

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Reflections of Success and a Call to Teamwork and Collaboration from a Longstanding Standards Participant

Letter to the Editor prepared for SCTE•ISBE by

By Craig Cuttner, retired. (No longer affiliated with any premium network except by paying subscription fees (#LostPerks)).

Standards are not about being nostalgic – well, maybe they are – because, down in the details, SCTE•ISBE is a standards development organization – SDO for short. Development is a verb that, in my mind, includes the process of identifying a need, a trend, or seeing chaos on the horizon and trying to prevent a train wreck. I've seen all of those and, I guess, will be nostalgic about where the SCTE•ISBE Digital Video Subcommitte (DVS) has been and provide some thoughts for the future.

As lawyers would conclude, I have standing in this matter – I was a member of DVS since the beginning (20+ years) – including leadership roles such as chairing Working Group 1 (Audio and Video Encoding). I had the great benefit of working for a company that understood that an investment toward and participation in the SDO process yields many benefits. To name a few: less operational complexity, less cost and more efficiencies in bringing new products to consumers.

In the early days those lofty goals were secondary to just getting digital video on cable to work.

Digital video (and audio) was obviously the next-great-thing, and the resulting technology and vendor land-grab almost became one of those train wrecks I alluded to earlier. The precedent in the analog world: cable operators were regional and local islands – each with an individual choice of sync-suppression scrambling that became a permanent tie to a single vendor forever. As a programmer, those regional skirmishes didn't matter so long as one satellite feed of FM-TV at 10.75 MHz/V was sent to the entire country.

Early digital video was a completely different beast.

Different vendors had different customer alignments on the operator side – encoder A would work great with set-top A, but not so much with set-top B. MPEG-2 wasn't finished, but direct-to-consumer digital satellite was already launching without it -- as a closed-system. Cable compression couldn't be local, even moderate digital headends were impractical – costing more, in some cases than the capital worth of the entire plant.

Satellite programming could only practically be in one format, chips for STBs wouldn't scale for cost reduction and operators that were merging and interconnecting could not afford in-home box-swaps to align digital vendor technologies.

The DVS took a rolled-up-sleeve approach and worked through the technological differences… first, the audio and video would actually work between vendor equipment! Then enhancements such as multiplex grooming, digital ad-insertion, video on demand, emergency alerts, and the big leap into high definition.

To look back on it now, one would be tempted to presume – of course it works… Not so fast vector-quantization (VQ) fans.

None of today's baseline should be taken for granted. Nor should you make assumptions about the future being smooth – high dynamic range video and object audio are new technologies with multiple, competing vendors and the current version of digital satellite (i.e. over the top (OTT)) already launching in their own closed end-to-end system. Encoder A only has to talk to Client Software A – no muss, no fuss, right?

Wrong…

Looking toward the future, programmers, cable operators and the consumer are more tightly integrated than ever. Set-top boxes are now customer owned and managed (COAM); Netflix is integrated to play on operator boxes; program networks are now distributed via OTT and cable operators have their own TV Everywhere and OTT offerings.

The need for standards development is as important as ever. And there is no time like the present to remember the investments of the past -- the process of identifying a need, a trend, or seeing chaos on the horizon and trying to prevent a train wreck.

SCTE•ISBE, the Engineering Committee and the subcommittees continue to be worth the investment in making information and entertainment services relevant and cost-effective to produce and distribute.

I'm glad to have played a role in the early foundations of DVS and digital cable – but the call-to-arms is as strong as ever – participate in the development process – think big picture and solve problems with like-minded colleagues. Join a committee, participate in a drafting group. That process will provide you with personal satisfaction and, even more so, you will learn a lot and make industry friends.

SCTE•ISBE doesn't do "defacto" standards, every one of the SCTE standards, recommended practices and other documents were developed by a team working together from different companies, perspectives and contribution.

It is exactly that teamwork and collaboration that kept me coming back and gave me the ability to look over my 20+ years on DVS and be proud for the team itself, the individual people (especially chair Paul Hearty) and all the contributions large and small by so many – but not with nostalgia, but a proud anticipation of what can (and will) be accomplished in the NEXT 20 years.

[-end-]

Craig Cuttner recently retired after 36-years at HBO (expressing his own opinions) and was the recipent of the SCTE•ISBE 2018 Excellence in Standards award, a Cable TV Pioneer, and a Fellow of the Society of Motion Picture and Television Engineers (SMPTE) and has over a dozen patents issued or pending – and, apparently, hasn't figured out how to get free cable (#LostPerks).

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140 Philips Road | Exton, PA 19341-1318 | T: 800.542.5040 | F: 610.884.7237 | scte.org • isbe.org