UHDTV Ecosystem Study Group Report

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This report provides an overview of image and audio technology standards and requirements for UHDTV production in the professional broadcast domain. This report is the result of a SMPTE study primarily focused on real time broadcasting and distribution and therefore is not an exhaustive analysis of UHDTV.

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1. Introduction

This report represents the final considerations of the Society of Motion Pictures and Television Engineers (SMPTE) study group investigating the Ultra-High Definition Television (UHDTV) Ecosystem. The report provides recommendations for further work, which will be further analyzed within SMPTE.

The industry has developed technologies for increasing image pixel arrays, capturing higher frame rates, extended color gamut and other image parameters beyond those currently defined for High Definition Television (HDTV).

Image formats for UHDTV have been approved by, SMPTE[1] and the International Telecommunications Union (ITU)[2]. It has been indicated that commercial deployment of UHDTV could begin as early as 2014 for UHDTV1 and 2016 for UHDTV2. While the intent is distribution of the content to the home, overall questions for the professional industry sector are:

- How to interchange content with these new formats in the professional real-time and non-real-time domains (considering uncompressed, mezzanine and contribution quality)
- What exchange and interface standards are needed
- What issues need further investigation to provide compatible workflows with current HDTV and SDTV systems

To avoid confusion with terminology, a brief description of UHDTV terms is provided below.

1.1. Definition of Terms

UHDTV1: The 3840×2160 pixels -image format described in SMPTE ST 2036-1. UHDTV1 (ST 2036-1) also makes use of Recommendation ITU-R BT.2020 to describe the color encoding parameters for the image. Sometimes shortened to "UHD-1".

UHDTV2: The 7680×4320 pixels image format described in SMPTE ST 2036-1. UHDTV2 (ST 2036-1) also makes use of Recommendation ITU-R BT.2020 to describe the color encoding parameters for the image. Sometimes shortened to "UHD-2".

[1] SMPTE ST 2036-1:2013 Ultra High Definition Television – Image Parameter Values for Program Production
[2] Recommendation ITU-R BT.2020 (2012) Parameter values for ultra-high definition television systems for production and international programme exchange

"4K": A term used to describe images of 4096x2160 pixels although sometimes applied to UHDTV1 images of 3840×2160 pixels. ***This term should not be used when referring to UHDTV1.***

"8K": A casual term for UHDTV2 images of 7680×4320 pixels. ***This term should not be used when referring to UHDTV2.***

HDTV: The 1920×1080 imaged formats defined in SMPTE ST 274:2008 or 1280×720 image formats defined in SMPTE ST 296:2012. HDTV also makes use of Recommendation ITU-R BT.709 to describe the color encoding parameters for the image. Sometimes shortened to "HD".

"Quad-HD": A casual term sometimes meaning images of 3840×2160 pixels using the HDTV color space. ***Use of this term should be avoided.***

Digital Cinema: This term refers to the suite of standards produced by SMPTE 21DC (the SMPTE ST 428, ST 429, ST 430, ST 431, ST 432, and ST 433 suites along with the ST 2048 suite). Sometimes termed "D-Cinema." The image formats and workflows documented in these document suites are optimized for theatrical presentation and not television reproduction.

SDTV: The 720×486 or 720×576 pixels image formats described in SMPTE ST 125-2013. Sometimes shortened to "SD".

NOTE: *this report makes reference to a number of documents that are currently in development within SMPTE. Such documents - prefaced with the word "Proposed" – and may not be publically available at time of this writing.*

1.2. Scope of this Report

This report first provides a short overview of image and audio technology standards currently available for UHDTV. It is not an exhaustive analysis of UHDTV1 and UHDTV2 but rather it represents a SMPTE study primarily focused on real time broadcasting and distribution of UHDTV, intended to highlight available standards and to make recommendations for further development work on standards and technology.

It then explores the requirements for and the impacts on interface/exchange formats defined by SMPTE ST 2036-1 ("UHDTV1" and "UHDTV2") and Recommendation ITU-R BT.2020, in an end-to-end chain (e.g., with a reference diagram visualizing the areas where exchange standards are needed).

The report next focuses on the professional real-time infrastructure for producing and processing content for distribution via television and broadband distribution, with ancillary reference to non-real-time-infrastructures. Compatibility to interface technologies expected for the end user environment is taken into account. The report provides recommendations for future standardization work but does not define these new standards.

This report will have a primary focus on the 3840×2160-pixel array of UHDTV1 imaging described in SMPTE ST 2036-1. It should be noted that UHDTV2 has the same set of concerns, as well as added consideration for bandwidth requirements. Where there are differences between UHDTV1 and UHDTV2 they will be highlighted.

Consideration is also given to audio requirements and of the potential requirement for higher frame rates (beyond 60 Hz) for specific applications.

2. What is UHDTV

As with many new technology names and acronyms, there typically is a range of understanding and interpretation as to what a name means, and the term "UHDTV" is no exception.

It should be noted that the term "Ultra" is often prepended to new technology names to indicate an evolution to something higher in performance than the previous technology it expands upon. This is particularly evident in consumer products where a mix of similar terminologies, (e.g., “4K” and “Ultra”) are sometimes used to define diverse technologies.

The most formal use of the term Ultra High Definition Television is that used in the SMPTE Standards: ST 2036-1:2013 (program production image parameters, first published in 2009 and then revised); ST 2036-2:2008 (for audio) and ST 2036-3:2012 (digital interface and mapping). These documents define UHDTV1 (3840x2160 pixels) and UHDTV2 (7680x4320 pixels), and provide constraints on spatial and temporal resolution, color space, bit depth and audio channel structure to the specific parameters described in those standards.

This report chooses to place a "stake in the ground" and focus on a specific issues dealing with UHDTV1, although most are applicable to UHDTV2 as well. In order to move the work of the Study Group forward and provide recommendations in a timely fashion, the UHDTV Ecosystem discussed here is centered on the image format constraints listed in Table 1. What follows is this report's definition, and answer to, "What is UHDTV?"

3. Image

Image characteristics for UHDTV systems as currently defined in ST 2036-1 are as shown in Table 1 below.

System category	System nomenclature	Luma or R' G' B' samples per line	Lines per frame	Frame rate (Hz)
UHDTV1	3840 × 2160/23.98/P	3840	2160	24/1.001
	3840 × 2160/24/P	3840	2160	24
	3840 × 2160/25/P	3840	2160	25
	3840 × 2160/29.97/P	3840	2160	30/1.001
	3840 × 2160/30/P	3840	2160	30
	3840 × 2160/50/P	3840	2160	50
	3840 × 2160/59.94/P	3840	2160	60/1.001
	3840 × 2160/60/P	3840	2160	60
	3840 × 2160/120/P	3840	2160	120
UHDTV2	7680 × 4320/23.98/P	7680	4320	24/1.001
	7680 × 4320/24/P	7680	4320	24
	7680 × 4320/25/P	7680	4320	25
	7680 × 4320/29.97/P	7680	4320	30/1.001
	7680 × 4320/30/P	7680	4320	30
	7680 × 4320/50/P	7680	4320	50
	7680 × 4320/59.94/P	7680	4320	60/1.001
	7680 × 4320/60/P	7680	4320	60
	7680 × 4320/120/P	7680	4320	120

Table 1. Image sample structures and frame rates of UHDTV systems

Note: *A revision to ST 2036-1 is currently under consideration to include 100 fps and 120/1.001 fps.*

3.1. Image Structure

The following discussion is primarily applicable to serial digital interfaces, but may be applicable in some file formats.

3.1.1. Pixel Array

UHDTV1 having a pixel array of 3840 × 2160, and UHDTV2 having a pixel array of 7680×4320 which are uniformly spaced, orthogonal and have a pixel aspect ratio of 1:1 (square pixels). The aspect ratio of the pixel array is 16:9.

3.1.2. Image Sync and Blanking

When carried on a serial digital interface, horizontal ancillary data areas and vertical ancillary data area are appended to the UHDTV pixel array.

These areas or spaces are required for synchronization and are also used to carry audio and other ancillary data streams.

For file formats such as MXF, the information contained in horizontal ancillary data and vertical ancillary data areas are separated from the image raster and stored separately in a manner that permits reconstruction of a properly formatted serial digital signal as required.

3.2. Colorimetry

UHDTV reference primaries as defined in ST 2036-1 are shown in Table 2 below.

For backwards compatibility with HDTV systems, ST 2036-1 allows implementers to optionally adopt conventional reference primaries for UHDTV1, which are consistent with Recommendation ITU-R BT.709, as shown in Table 3. The colorimetry employed must be signaled on the interface.

(1) This study group recommends that further work be undertaken to ensure that the UHDTV colorimetry employed is signaled on the interface.

	CIE x	CIE y
Red primary	0.708	0.292
Green primary	0.170	0.797
Blue primary	0.131	0.046
Reference white	0.3127	0.3290

Table 2. UHDTV reference primaries and reference white[3]

	CIE x	CIE y
Red primary	0.640	0.330
Green primary	0.300	0.600
Blue primary	0.150	0.060
Reference white	0.3127	0.3290

Table 3. UHDTV Optional Conventional reference primaries and reference white[4]

[3] These values are consistent with Recommendation ITU-R BT.2020
[4] Conventional reference primaries may be used by UHDTV1. These reference primaries are consistent with Recommendation ITU-R BT.709.

The supported color gamut for each set of reference primaries is illustrated in the diagram of Figure 1.

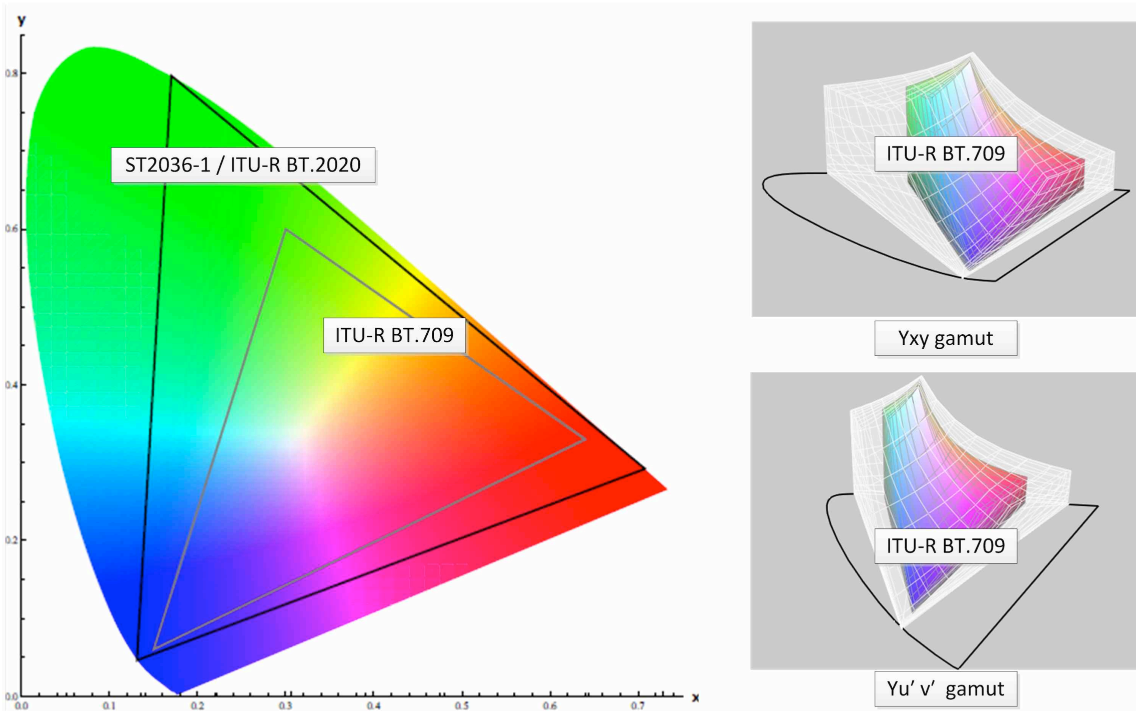

Figure 1. UHDTV supported color gamut in both x,y and u',v'

ST 2036-1 allows optional conventional encoding in $Y'C'_BC'_R$ format.

Recommendation ITU-R BT.2020 provides the option of constant luminance encoding in Y'_C, C'_{BC}, C'_{RC} format.

3.3. Transfer Function

The transfer function of UHDTV mimics that of Recommendation ITU-R BT.709.

This Study Group Report does not have the mandate to explore and study High Dynamic Range (HDR) UHDTV images. There are proponents who would like to make use of HDR in UHDTV. These proponents believe that the existing transfer function specified for HDTV and UHDTV will not support HDR images. Annex B provides more information on this subject.

3.4. Color Space Conversion

As previously noted, SMPTE ST 2036-1 and Recommendation ITU-R BT.2020 specify a common extended color space for UHDTV. ST 2036-1 optionally allows the conventional HDTV color space for backward compatibility with legacy equipment. To date UHDTV productions have been largely created using this legacy color space.

The UHDTV color gamut is significantly larger than those of either HDTV or SDTV. The new color gamut volume (in XYZ space) is twice the HDTV color gamut volume. Thus, compared to HDTV, UHDTV covers almost all Pointer's colors that represent existing real surface colors. UHDTV workflows and devices that support the UHDTV color space should be able to support an equivalent level of color interoperability and accuracy as HDTV workflows and devices do today.

It is envisioned, however, that the industry will experience a transition period when moving to the extended UHDTV color space for production and post-production. Color conversion to and from legacy HDTV and SDTV color space will be required.

(2) This study group recommends that SMPTE undertake further work to study the issues and requirements for color space conversion between UHDTV color space and legacy color space. This study should also consider the requirements to standardize color metadata.

Further information on color space conversion and gamut mapping is provided in Annex C.

3.4.1. Color Space Conversion Metadata

It is a tenet of today's SDTV and HDTV television systems that any capture device is able to completely fill the specified color gamut, that is the gamut of the content matches that of the container in which it is held.

For SMPTE ST 2036-1 UHDTV based systems, some capture devices and most displays are not capable of either capturing or displaying the full gamut of the UHDTV color space.

If naive color conversions were to be performed between the UHDTV and HDTV/SDTV color gamuts, the conversion algorithm could only assume that the content filled the UHDTV color gamut and reduce the color volume appropriately to create an HDTV or SDTV version.

Although, in principle, each display device could measure the content color gamut of the incoming signal and process the content appropriately. The content color gamut could vary according to the artistic choices on a scene-by-scene basis likely resulting in temporally unstable color conversion. The alternative is to send a metadata description of the color gamut of the images with the UHDTV content.

3.5. Frame Rates

UHDTV systems as specified in SMPTE ST 2036-1 are progressively captured at frame rates of 24/1.001 fps; 24 fps; 25 fps; 30/1.001 fps; 30 fps; 50 fps; 60/1.001 fps; 60 fps; or 120 fps.

A revision to ST 2036-1 is currently under consideration to include 100 fps and 120/1.001 fps.

Further information on higher-than-conventional UHDTV frame rates is provided in Annex D.

3.5.1. 120 fps Frame Rate

The maximum frame rate of 120 fps specified in ST 2036-1 was intended as a single worldwide high frame rate for UHDTV. Since the time of publication, proponents have asked to modify the standards to include 100 and 120/1.001. At the time of this writing, the SMPTE TC members were divided on whether to include 120 fps, 120/1.001, or both of these frame rates for UHDTV. The arguments for these positions are briefly summarized below.

3.5.1.1. Fractional Frame Rate Case

Many broadcasters embrace the 120/1.001 frame rate since they will be able to more readily interoperate with all of the nation's massive library of existing SDTV and HDTV productions in UHDTV productions without adding temporal artifacts, processing latency, special planning, and without introducing additional infrastructure complexity. It is also understood that, beyond the existing archive, the television industry will continue to produce countless hours of new, high value programming for many years or decades into the future, all based on existing fractional frame rates. Note that the original challenges of handling digital audio with fractional frame rate video have long since been resolved. These technical and operating techniques need only be applied in the UHDTV era.

Moreover, producing UHDTV material at fractional frame rates only will substantially simplify live productions such as sports, news and special events that are coordinated between broadcasters (as with pool feeds or co-productions), or between a single broadcaster's mixed feeds in HDTV and UHDTV formats, as well as any integration of archival material into the program.

For pragmatic and commercial reasons then, it is essential that UHDTV support 120/1.001 fps. Further, it will be advantageous if no integer higher frame rates are recommended for use in the current fractional frame rate geographical regions, thus avoiding complications in exchange of materials between broadcasters and other production entities.

3.5.1.2. Integer Frame Rate Case

There are significant technical and operational advantages to integer frame rate operation, including simplification of video and audio processing, enhancement of video and audio synchronization, simplification of time related labels (including elimination of daily jam sync for time code), and enhancement of global interoperability of video material. In particular, audio sampled at typical rates will never precisely map to video frames at 1/1.001 fractional frame rates.

Fractional frame rates exist solely because of one particular technical decision regarding the analog NTSC television standard, made over 50 years ago and having significant unintended consequences ever since. Fractional frame rates have been associated with a long history of technological and operational challenges requiring solutions and workarounds.

High-quality conversion between existing fractional frame rates (e.g. 24/1.001, 30/1.001, 60/1.001) and new, higher frame rates (e.g., 120 and 120/1.001) may not be achieved by the regular repeating or dropping of frames, but may instead require the use of more advanced techniques. Thus, there may be no inherent advantage to higher fractional frame rates vs. higher integer frame rates (e.g., 120/1.001 vs. 120). No scientific evidence has been presented to this Study Group regarding video quality, complexity of conversion, or any other aspect between existing fractional frame rate material and either 120 fps or 120/1.001 fps UHDTV material.

Given the potential historic opportunity to end the proliferation of new fractional frame rates and their attendant issues to future television operations, given the reasonable concerns about conversion between existing fractional-frame-rate material and new, higher-frame-rate material, and given that there is expected to be a significant time period before commercial, higher-frame-rate operations are expected to commence, it is necessary for SMPTE to perform further study before it standardizes additional higher frame rates, including 100 and 120/1.001.

For pragmatic and commercial reasons, then, it is essential that further study on the relative complexity of conversion between existing fractional frame rates (e.g. 24/1.001, 30/1.001, 60/1.001) and new higher frame rates (e.g. 120/1.001 and 120), in relation to the resultant video quality, be completed before SMPTE standardizes additional higher frame rates.

(3) This study group could not come to a consensus whether to include 120/1.001 fps in ST 2036-1 and recommends that further work be undertaken by SMPTE to consider the implications.

Further information on additional / alternate UHDTV frame rates is provided in Annex E.

3.6. Stereoscopic 3D

As UHDTV is an extension over existing HDTV which nowadays includes Stereoscope 3D, it is important to spend some time foreseeing potential impacts if any. SMPTE has a number of standards specific to stereoscopic 3D either published or in preparation. For example:

Full Resolution Contribution Links ST 2063:

Live Stereoscopic 3D events must be sent typically to a central distribution point or facility. This generally requires full (spatial) resolution images, because additional production is typically carried out before emission to viewers. This standard provides the important constraints for such systems.

Production Timing and Sync ST 2076:

Production timing and sync mechanisms were developed to achieve perfect synchronism between right and left cameras. This standard provides important foundational information that facilitates UHDTV and other formats for 3D production.

Disparity Map Representation ST 2066:

Document ST-2066 is a standard for data representation of Disparity Map for Stereoscopic 3D. This document already includes references and mechanisms to support UHDTV resolution. There is no foreseeable impact on the network.

Stereoscopic 3D in MXF ST 2070-1:

This document defines metadata and the index structure of stereoscopic 3D video streams in MXF for operational applications. This standard currently supports streams of stereoscopic images, either as uncompressed image pairs, inter-frame compressed formats as well as Long GOP formats.

4. Audio

With the enhanced visual experience of UHDTV, there is an opportunity to extend the accompanying audio experience to improve immersion, audio quality, and "wow factor" in order to give the consumer a premium overall experience.

While the current 5.1 and Stereo audio configurations will continue to be delivered, the overall quality and resolution of audio should aspire to the level of the UHDTV visual experience. In addition to these current audio configurations, newer audio systems are coming forward that should be considered for use in UHDTV.

SMPTE ST 2036-2 documents a 22.2 audio channel system for UHDTV, and since the time that document was written, additional "immersive audio" systems have come to market for cinema, such as 9.1, 11.1 and "object based" formats.

The manufacturers of these systems are working with other industry organizations to determine the best way to bring immersive audio to the home while insuring compatibility with current home systems. As of this writing, there are proposals being brought forward, but no set standard yet exists.

Additional information on extended or immersive audio requirements is included in Annex A.

5. Time Code

For most of the usual frame rates (i.e. 24, 24/1.001, 25, 30, 30/1.001, 50, 60 and 60/1.001) SMPTE ST 12-1 Linear Time Code and ST 12-2 Ancillary Time Code can support UHDTV frame rates. However for frame rates above 30 fps (50, 60, and 60/1.001) SMPTE ST12-1 does not allow for single frame identification using LTC. SMPTE ST 12-2 Ancillary Time Code carrying VITC payloads does have a field marker to identify "frame" one and "frame" two of a two "frame pair" sequence. This means that using LTC one can only edit accurately every two frames.

There presently is no time code support above 60 fps. SMPTE Technology Committee 32NF is working on a new method for time labeling content that should support all frame rates.

(4) This study group recommends that either a modification to SMPTE ST 12-1 to support higher frame rates or a new time labeling method needs to be standardized to support frame rates up to 120 fps.

6. UHDTV Ecosystem

The diagram of Figure 2 illustrates a notional television production / broadcast facility.

For the purposes of this report, the diagram is used to explore operational requirements for facilities and to identify any special needs relating to the interchange of material when transitioning to UHDTV production and for mixed UHDTV, HDTV and SDTV production.

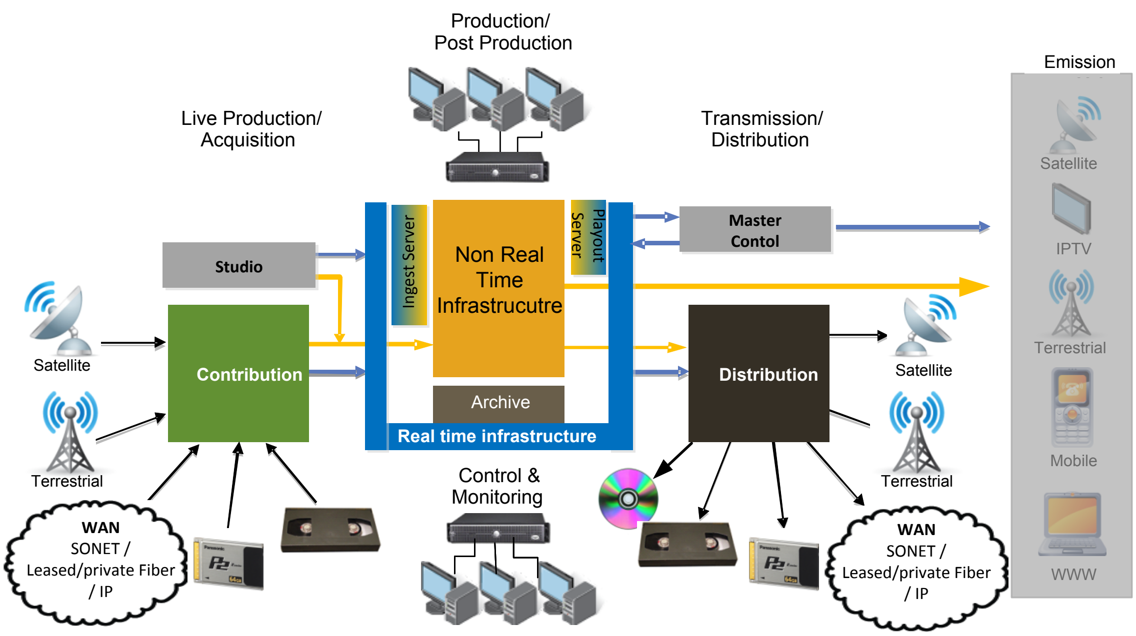

Figure 2. UHDTV Ecosystem Reference Diagram

6.1. Real-time Streaming Media Interfaces

As was the case with the introduction of HDTV the definition of interfaces normally relies upon the definition of the image formats before the documentation can be completed. To this end SMPTE is working on a number of proposed interfaces. A mix of optical and coaxial cable interfaces have been developed or are currently under development in support of UHDTV real-time Streaming Media Interfaces. Refer to Annex F for further details. The basic UHDTV uncompressed video payloads can be seen in Table 4 and Table 5. Multi-link solutions are required to cope with these high data rates.

NOTE: *Serial Digital Interface rates include additional bandwidth for coding, the carriage of timing signals and ancillary data such as audio etc.*

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	Total Payload (nominal)					
			10-bit 4:2:0	10-bit 4:2:2	10-bit 4:4:4	12-bit 4:2:0	12 Bit 4:2:2	12-bit 4:4:4
3840	2160	120	15Gbit/s	20Gbit/s	30Gbit/s	18Gbit/s	23Gbit/s	36Gbit/s
		60	7.5Gbit/s	10Gbit/s	15Gbit/s	9Gbit/s	12Gbit/s	18Gbit/s
		50	6Gbit/s	8Gbit/s	12Gbit/s	7.5Gbit/s	10Gbit/s	15Gbit/s
		30	3.7Gbit/s	5Gbit/s	7.5Gbit/s	4.5Gbit/s	6Gbit/s	9Gbit/s
		25	3.1Gbit/s	4 Gbit/s	6.2Gbit/s	3.7Gbit/s	5Gbit/s	7.5Gbit/s
		24	3Gbit/s	4Gbit/s	6Gbit/s	3.6Gbit/s	4.8Gbit/s	7.2Gbit/s

Table 4. UHDTV1 Image formats and payloads

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	Total Payload (nominal)					
			10-bit 4:2:0	10-bit 4:2:2	10-bit 4:4:4	12-bit 4:2:0	12-bit 4:2:2	12-bit 4:4:4
7680	4320	120	60Gbit/s	80Gbit/s	120Gbit/s	72Gbit/s	95.5Gbit/s	144Gbit/s
		60	30Gbit/s	40Gb/s	60Gbit/s	36Gbit/s	48Gbit/s	72Gbit/s
		50	25Gbit/s	33Gbit/s	50Gbit/s	30Gbit/s	40Gbit/s	60Gbit/s
		30	15Gbit/s	20Gbit/s	30Gbit/s	18Gbit/s	24Gbit/s	36Gbit/s
		25	12.4Gbit/s	16,6Gbit/s	25Gbit/s	15Gbit/s	20Gbit/s	30Gbit/s
		24	12Gbit/s	16Gb/s	24Gbit/s	14.4Gbit/s	19 Gbit/s	29Gbit/s

Table 5. UHDTV2 Image formats and payloads

As of this writing there are no standardized interfaces that deal with frame rates beyond 60Hz.

Eventually, as UHDTV production moves from "application and infrastructure islands" to mainstream production requirements, a new core-infrastructure and real-time media streaming interface data rate and build out will be required. This may well include some form of IP infrastructure.

In dealing with the high bandwidths of UHDTV signals the current costs of implementation may influence the choice of interface that an end user may make.

(5) This study group recommends that further work be undertaken to develop real-time streaming media interface standards in support of UHDTV1 image formats and payloads up to 120 fps.

6.2. Mezzanine Compression

To reduce the cost of the UHDTV infrastructure build out, the use of a mezzanine compression system to extend the life of existing major infrastructure items such as HDSDI routers and existing IP-based networks in production islands may be very attractive.

Modest levels of compression in the range 2:1 to 20:1 (depending on image format and interface bandwidth requirements) could be employed to provide sufficient bandwidth reduction to accommodate the transport of UHDTV production image formats over the existing SDI infrastructure.

For example, such a system would convert the UHDTV baseband signal data rate of ~12Gbit/Sec to 3G bit/s-HDSDI or even 1.5Gbit/Sec HDSDI.

The key attributes for a mezzanine codec to be used in live production are listed below:

- Low-delay coding and decoding (1 frame or less)
- Low-loss compression providing visually near-perfect reproduction.
- Multi-generation compression adds negligible concatenation errors and additional loss.
- A symmetrical encode / decode algorithm that should be relatively easy to implement both in hardware and software
- Support for full range of images (image sampling, resolution, frame-rate, bit depth and color gamut)
- Compression range ~ 2 to 20x
- Similarly such a codec can also be used to decrease file sizes to improve storage efficiency and download times during production.

(6) This study group recommends that SMPTE undertake work to define specific mezzanine image compression profiles and bit streams that can be mapped to the SDI interface.

6.2.1. Uncompressed Real-Time Networked Interface

As described earlier, the bandwidth requirements for the UHDTV image formats are at rates higher than existing single-link electrical SDI interfaces.

It is possible to carry uncompressed UHDTV1 images over multiple Ethernet interfaces. Ethernet interfaces have been defined by the IEEE 802.3 working group, at appropriate data rates for transmission.

SMPTE ST 2022-6 has standardized the carriage of high bit-rate media content (such as ST 259, ST 292-1 and ST 424 streams) using RTP over IP that can be carried over Ethernet connections.

(7) This study group recommends that SMPTE continue to work on standardization for the carriage of uncompressed UHDTV image streams over packetized real-time network interfaces.

6.2.2. Visually Lossless Real-Time Networked Interface

As previously discussed, the application of "visually lossless" compression to address the tremendous bandwidth requirements of UHDTV images may be useful in professional applications. The definition of visually lossless should be defined precisely by SMPTE, but in general it should refer to compression that is unable to be reliably differentiated by expert viewers when compared with the original image after a number of concatenated encode/decode cycles.

Latency of encoding/decoding of the compressed stream would be a significant issue for live production. A codec with a minimal latency that could provide the required compression with appropriate computational complexity would be required.

6.3. Infrastructure Requirements for Audio

The current infrastructure illustrated in Figure 2 may require updates in order to handle the extended requirements for audio in general and also for immersive audio. Some key areas to be considered may include:

- Audio mixing facilities and sound design rooms may require upgrades to provide higher quality audio. In order to create immersive audio, they must be outfitted with proper mixing and monitoring equipment. Mixing engineers and sound designers should be educated and well versed in the medium to create high quality content that will pass muster with talent.
- A new, file-based medium for the original UHDTV master may be needed. The Interoperable Master Format (IMF), as defined by the SMPTE ST 2067 suite of documents is one possible choice.
- Uncompressed audio transport and bandwidth requirements need to be defined for moving audio in a production environment. Care must be taken to ensure the phase-alignment of samples for a sound-field is kept intact.
- High quality immersive audio bandwidth requirements and realistic delivery payloads must be defined. In order to achieve that goal, baseband PCM, or very high quality audio codecs are likely to be used to transport immersive audio over broadcast infrastructure to maintain audio quality; any audio codec employed should meet the requirements for contribution/distribution specified in Annex 1 of Recommendation ITU-R BS.1548, *User requirements for audio coding systems for digital broadcasting*.

- New interfaces may be needed throughout the infrastructure, including production facilities, broadcast facilities and possibly in the home in order to handle immersive audio along with the higher bit rate video that will be required for UHDTV.
- New audio playback solutions may be needed in the home to play immersive audio. Realistic rendering of immersive audio into a variety of playback systems is required.

(8) This study group recommends that SMPTE undertake additional work to study extended requirements for audio and infrastructure with specific consideration to the following areas:

- ***Standardize additional immersive audio formats to be used for UHDTV. Consideration should be given to audio standards created by other organizations, such as the ITU.***
- ***Standardize a common file format to describe immersive audio to insure interoperability. [****Note that some of this work may already be underway in other SMPTE groups such as TC-25CSS)*
- ***Standardize the carriage of uncompressed immersive audio over packetized real-time network interfaces, with attention to the technical issues of maintaining the phase relationships between the coincident digital samples in a given sound-field.***
- ***Standardize audio characteristics for audibly lossless compression. This may reference Recommendation ITU-R BS.1116-1, and other current standards****.*
  [Note that this does not define the codecs themselves, only the required audio characteristics.]

7. Summary of Recommendations

(1) This study group recommends that further work be undertaken to ensure that the UHDTV colorimetry employed is signaled on the interface.
(2) This study group recommends that SMPTE undertake further work to study the issues and requirements for color space conversion between UHDTV color space and legacy color space. This study should also consider the requirements to standardize color metadata.
(3) This study group could not come to a consensus whether to include 120/1.001 fps in ST 2036-1 and recommends that further work be undertaken by SMPTE to consider the implications.
(4) This study group recommends that either a modification to SMPTE ST 12-1 to support higher frame rates or a new time labeling method needs to be standardized to support frame rates up to 120 fps.
(5) This study group recommends that further work be undertaken to develop real-time streaming media interface standards in support of UHDTV image formats and payloads up to 120 fps.
(6) This study group recommends that SMPTE undertake work to define specific mezzanine image compression profiles and bit streams that can be mapped to the SDI interface.
(7) This study group recommends that SMPTE continue to work on standardization for the carriage of uncompressed UHDTV image streams over packetized real-time network interfaces.
(8) This study group recommends that SMPTE undertakes work to study extended audio requirements and infrastructure with specific consideration to the following areas:
   - Standardize additional immersive audio formats to be used for UHDTV. Consideration should be given to audio standards created by other organizations, such as the ITU.
   - Standardize a common file format to describe immersive audio to insure interoperability.
   - Standardize the carriage of uncompressed immersive audio over packetized real-time network interfaces, with attention to the technical issues of maintaining the phase relationships between the coincident digital samples in a given sound-field.
   - Standardize audio characteristics for audibly lossless compression. This may reference Recommendation ITU-R BS.1116-1, and other current standards.
     [Note that this does not define the codecs themselves, only the required audio characteristics.]

Annex A UHDTV – Audio Considerations

A.1 Original UHDTV Masters

ITU-R has developed Recommendation ITU-R BS.2051 - Advanced sound system for programme production. An advanced sound system is a kind of hybrid systems employing both channel-based and object-based systems and uses audio data in combination with an appropriate set of metadata to specify a sound scene to be delivered. The specifications include requirements for signaling the properties of advanced sound content and speaker layout to be used in content production for advanced sound systems.

Audio in a UHDTV original master should be uncompressed with a sample rate of 48K or 96K at 24 bit (as specified in ST 2036-2) or higher resolution. IMF (Interoperable Master Format) could be utilized as the mastering format for UHDTV content. The audio characteristics, specifications and audio labeling as defined in IMF documents ST 2067-2 and ST 2067-8 should be followed. It is noted that the carriage of immersive audio in IMF has yet to be defined.

A.2 Carriage And Delivery

In order to achieve high interoperability, standards for the carriage and delivery of immersive audio are critical. While there are various industry efforts underway, including BWF (Broadcast Wave Format), revisions, there is currently no standardized common file format for the carriage and delivery of immersive audio. SMPTE Technology Committee 25CSS is currently engaged in studying this topic for cinema. The use of “metadata/descriptors” to signal the properties of all audio signals is a key component, and may form the basis of a common audio file format for feeding the distribution infrastructure to the home. In addition, hybrid systems may provide greater flexibility for home listeners to adjust portions of the audio (such as voice levels) to assist with hearing issues.

A.3 Audio Compression

For high bandwidth distribution applications, the chosen audio compression ideally should be “mathematically lossless”.

If it is not possible to use mathematically lossless codecs, it is recommended that the chosen compression format be “audibly lossless”. Audibly lossless refers to audio compression that is psycho acoustically transparent and unable to be reliably differentiated by expert listeners when compared with the original uncompressed audio after a number of concatenated encode/decode cycles. Emission codecs at low-to-medium bitrates are typically quite lossy and not considered audibly lossless and therefore are not recommended in high bandwidth distribution applications.

Where lossy codecs are required for consumer delivery of UHDTV, it is recommended that the compression format meet the requirements for emission specified in Annex 2 of Recommendation ITU-R BS.1548-2.
Where lossy codecs are required in an UHDTV broadcast infrastructure, it is recommended that the chosen compression format meet the requirements for contribution/distribution specified in Annex 1 of BS.1548-2.

A.4 Speakers And Sound Reproduction Considerations

While it is unlikely that most home environments will allow for a number of additional speakers to reproduce immersive sound, other methods are available or have been proposed; for example, a Loudspeaker Array Frame attached around the TV screen, the addition of height speakers above the TV screen, or a sound bar system located below and/or above the TV screen.

"Audio Rendering" is a process that utilizes DSP modeling to reproduce a given audio format through multiple types of audio playback systems. The playback systems may utilize technologies such as Wave Field Synthesis (WFS) and binaural audio, among others. Rendering technology is a significant topic being discussed in the MPEG-H 3D audio project. It is possible that the reproduction of immersive audio in the home will depend heavily on audio rendering to be able to deliver the experience to a plethora of different playback systems, including headphones.

The use of a common audio file format combined with fixed or movable audio objects as noted above is key to providing a common input to deliver codecs and to allow audio rendering to be widely usable.

Annex B High Dynamic Range Imaging

In April 2012, the United States Administration made a contribution to ITU-R WP-6C, which proposed a new Electro-Optical Transfer Function (EOTF) to enable the carriage of High Dynamic Range (HDR) content.

The new perceptual EOTF proposed was based not upon the gamma function of a CRT, but directly on the contrast sensitivity ratio of the human eye as described by Barten and referenced in the Report ITU-R 2246-2.

This contribution further proposed that an HDR system should be capable of handling signals with a brightness range from 0 to 10,000nits based on viewer preference testing. The methodology used and the results obtained were also published in the SMPTE Journal May/June 2013 p52-59.

A series of demonstrations during 2013 were made to the content creation industry to demonstrate the capabilities of the combination of HDR imaging with a Wider Color Gamut. (WCG)

SMPTE began work in three key areas relating to HDR and WCG. The following documents are currently work in progress:

- Proposed SMPTE ST 2084 Electro-Optical Transfer Function for High Dynamic Range Reference Displays
- Proposed SMPTE ST 2085 YD_zD_x Color-Difference Encoding for XYZ Signals
- Proposed SMPTE ST 2086 Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images

Annex C Standard Dynamic Range Color Space Conversion

As previously discussed, the UHDTV color space is significantly larger than legacy color spaces. UHDTV workflows and devices that support the UHDTV color space should be able to support an equivalent level of color interoperability and accuracy as HDTV workflows and devices do today. However, it is envisioned that the industry will experience a long transition period when moving to using the full capabilities of the extended UHDTV color space for production and post-production. Color conversion to/from legacy HDTV and SDTV color spaces will be required.

The challenge in color space conversion therefore lies with mixed workflows and devices, where a device somewhere in the distribution chain receives UHDTV color space data and outputs HDTV or SDTV color space data, or maybe vice versa. Unless proper care is taken in color space conversion, material that takes advantage of the UHDTV color gamut may look worse on an HDTV color gamut display than material that was originated in the HDTV color space.

The key observation is that a simplistic color conversion may degrade the image quality to below the quality of a HDTV color space original. Techniques, that are adequate for conversion between HDTV and SDTV color spaces today do not result in optimal results for conversion from UHDTV images.

Gamut mapping is NOT trivial. Currently, there is no known automated method that always gives an acceptable result. Every known automated method works poorly for some images, usually for high-key and low-key scenes. Thus, for good results grading images to the HDTV color space, HDTV is usually a manual scene-by-scene operation; select the mapping that is best for the scene at hand. For example, the Blu-Ray version of a movie is manually color graded scene-by-scene, and gamut mapped differently from the digital cinema movie master. Additionally, a colorist may use “windows” to subjectively optimize parts of the image only, while de-emphasizing other parts, making the mapping a creative element in the story.

C.1 Varying Sensor and Monitor Responses

Different camera sensor technologies and display technologies from different vendors and for different price points offer widely varying color responses and gamuts. Attempts to match a particular color space standard are always an approximation this being true for HDTV and UHDTV. Much of the originating process (cameras and animation) is driven by the artistic choices of the manufacturers, cinematographers and colorists as they adapt their different technologies and content into standardized workflows.

At the time of writing this report, there were no commercially available display devices that supported the full UHDTV color gamut. Therefore the reader should keep in mind that the acquisition devices may capture a wider gamut than can be seen on a current display device.

C.2 Color Space Conversion in UHDTV workflows

As noted earlier in this report the UHDTV color space can contain a much wider color gamut than previous color spaces such as HDTV. Because of this, conversions to and from legacy systems must be taken into account. The sections below contemplate the different color transforms that need to occur.

C.2.1 Typical Color Space Conversion in UHDTV workflows

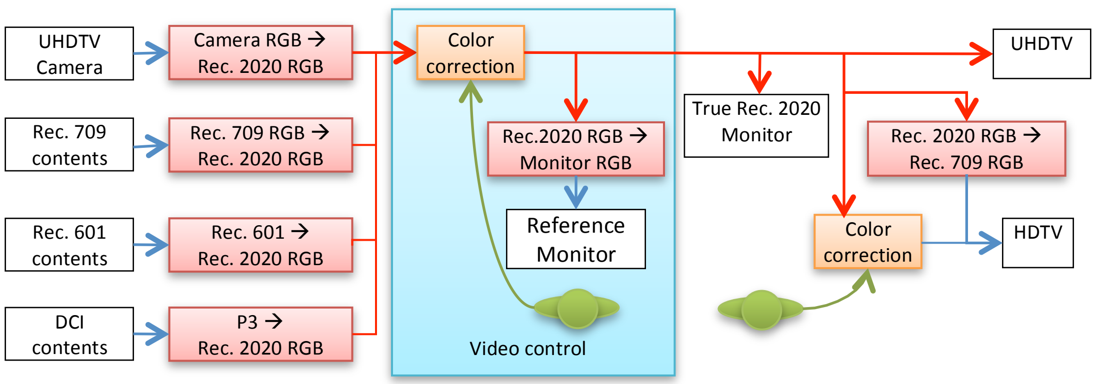

Figure C1 UHDTV Color Space Conversion Workflows

In Broadcast Production UHDTV workflows, there are several types of color space conversions, as shown in Figure 3, and described below:

C.3 Camera to UHDTV Conversion

The output of the sensor is converted from the camera spectral sensitivities via a matrix into UHDTV color space for its output. These matrix transforms are well understood by camera manufacturers.

C.4 UHDTV to HDTV/SDTV Conversion

It is envisioned that the industry will experience a long transition period when moving to Recommendation ITU-R BT.2020 UHDTV color space for production and post-production. Color conversion to the legacy HDTV or SDTV color spaces to comply with legacy workflows will be required.

The conversion from the UHDTV color space to the HDTV or SDTV color space needs to preserve the color details in the saturated UHDTV as much as possible. It is NOT trivial to convert the colors that are outside of the HDTV/SDTV gamut. As stated above, this requires gamut mapping.

Applying the gamut mapping from the UHDTV color space to HDTV/SDTV could be an immediate operation, resulting in images in the HDTV/SDTV color space, or a deferred operation where the gamut mapping operations are carried as colorist metadata in the UHDTV format to be applied where one needs to convert to a HDTV/SDTV format. The industry will may require standardized formats for this colorist metadata.

C.4.1 Further Study on Color Appearance Model Suitable for UHDTV

Gamut mapping algorithms are based on a color appearance model, which contains predictors of at least the relative color appearance attributes of lightness, chroma, and hue. For a gamut mapping from the UHDTV color space to HDTV a simple color appearance model would be sufficient because it is reasonable to assume that the viewing condition, white point of D65, and EOTF for UHDTV are the same as those for HDTV.

C.5 HDTV/SDTV to UHDTV Conversion

Similarly, converting legacy material in HDTV/SDTV color spaces to the much wider UHDTV color space should reverse the process. (See section C.6 below.) However, by merely mapping the legacy image to the limits of the wider gamut, the colors will look oversaturated. If the legacy images are mapped to their legacy equivalent in the UHDTV color space, then they will look about the same as on a legacy workflow, but then the colors in the legacy material will look muted when mixed in with the much more brilliant UHDTV compliant images.

Three methods have been identified:

1) colorimetric conversion to the UHDTV color space - content is mapped using a simple matrix, the HDTV gamut remains the same but is now placed within the UHDTV color space container (reversible if metadata was provided so that the HDTV color space is known)
2) conversion with gamut extension to the UHDTV color space – the content is automatically stretched along the lines of constant hue to increase the brightness and saturation without changing the color (reversible if the stretching algorithm is known and invertible).
3) artistic conversion to the UHDTV color space – the content is modified by a colorist to best match native UHDTV content (reversible only if the tools output metadata which describes the colorist’s actions)

C.5.1 Colorimetric conversion between HDTV and UHDTV

A 3×3 matrix applied to (photometrically non-linear) encoding values is a commonly used process when converting colors between the HDTV and SDTV color spaces. In contrast, to obtain closely matching colors, conversion between HDTV (or SDTV) and UHDTV color spaces will need to be done in a photometrically linear domain such as CIE XYZ. The EOTF defined in Recommendation ITU-R BT.1886 provides the conversion for a photometrically linear domain, and applies equally to both displays with the HDTV color space and displays with the UHDTV color space. The HDTV OETF shall not be used here, as it is an encoding method and does not apply to displays, as it would increase saturation. Thus the steps used for converting RGB in the HDTV color space to RGB in the UHDTV color space may be as follows:

1) Start with encoded RGB 4:4:4 values in the HDTV color space.
2) Apply the BT.1886 EOTF to convert to linear RGB values in the HDTV color space.
3) Apply a 3×3 matrix to convert to linear RGB values in the UHDTV color space.
4) Apply the inverse BT.1886 EOTF to convert to encoded RGB values in the UHDTV color space.

C.6 Concatenated Color Space Conversions (HDTV to UHDTV to HDTV)

Understanding that there will be legacy HDTV display devices with the UHDTV color space in the field for some time, there is a need to consider the results of going back and forth between these color spaces.

As media might get converted back and forth between UHDTV and HDTV, ideally the chosen conversion to the UHDTV color space should be the inverse of the conversion to the HDTV color space. If not, then after multiple generations of conversions back and forth between the two color spaces, the image colors will drift further and further away from the original with each generation, causing saturated colors to change, most likely de-saturation and changed luminance in each cycle.

This is a workflow issue that must be addressed within the industry, including SMPTE and other standards organizations.

Annex D Support for Additional Frame Rates

Research into higher frame rate support for UHDTV systems is in progress principally to ensure that the temporal resolution of UHDTV matches (or remains in proportion to), that of the static resolution.

For example, during camera pans to follow the action at sports events, static portions of the scene change between sharp (when stationary) and smeared (when panning). The implied constraint requiring a reduction of the pan rate is not always practical in live coverage, but in practice compromises such as camera shuttering and deliberate softening of the images (or a reduction in aperture correction) can help reduce the problem. Regardless of this, simple mathematics shows that motion of the camera or of objects within the scene at speeds higher than three pixels per field/frame eliminates all of the additional detail gained by the use of high definition, in the direction of motion. These problems will be compounded by increases in the spatial resolution of UHDTV.

The frame rate of 120 fps initially specified in ST 2036-1 was intended as a single worldwide high frame rate for UHDTV. It implied equal pain in the conversion to and from the commonly used frame/field rates of 50 and 59.94 fps. The implications of this, and its long-term advantages (of simplification and potential cost savings for both standards and equipment) as compared to retaining the present split between the 50 and 59.94 worlds, is an area where further study has now been undertaken[5], particularly in the areas of standards/frame-rate conversion, and lighting flicker.

NHK's work[6] has showed that 80 frames per second (fps) is sufficient to prevent flicker (and sample-and-hold displays in any case prevent flicker), and something over 100 fps is required for the fusion of trackable motion.

Thus higher frame rates should be designed to:

- Exceed the threshold for visibility of flicker on intended screen size and brightness,
- Exceed the threshold for the human visual system's ability to track motion; such as to make a sequence of discrete images appear as a continuously moving entity.

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[5] BBC Research & Development White Paper (In preparation)

[6] Sugawara, M.; 2011; *Psychophysical Requirements for Higher Frame Rates in Future Television.* DCS 2011, SMPTE Conference at NAB Show, Las Vegas, April 2011.

The third requirement considered by NHK was to ensure that movement is not blurred. Dr. Sugawara's work indicated that a shutter opening of 1/320 second was required to adequately freeze motion, independent of image resolution.

There are other aspects relating to image presentation and frame rate that go beyond the above three factors. Firstly, a short shutter (such as 1/320 second) with a higher frame rate (such as 120 fps) has three implications:

- It does not prevent aliasing of repeating structures (the wagon wheels going backwards effect),
- It does not prevent the impression of strobing in non-tracked motion (where there is more than one motion in the composition, where there is rotational motion, or where there is scaling of image components),
- There are implications for noise performance, due to a short shutter opening relative to the frame period.

All of these three factors would be mitigated by a frame rate of 300 fps or higher, although further study is required to quantify the importance of these factors. This frame rate also has the virtue of easy conversion to 50 and 60 fps (but still retains the 1/1.001 issue).

One BBC study[7] has indicated that a frame rate of 140 fps is required to satisfy the eye's requirements for resolution in the case of untracked motion, and as high as 700 fps for tracked motion. This study did not however consider the use of shorter shutters, nor the effect of strobing for untracked motion, but is an indication of how high the frame rate might need to be for a visually lossless television system.

In the light of the above, frame rates considerably higher than 120 fps could have some advantages in the future for capture and post-production, for different shots, or even for different portions of the image within a particular shot. A capture rate sufficiently high that motion is effectively frozen in a single frame with a completely open shutter would enable complete freedom in post-production.

Editing points might be in frame multiples. So edit points for 120 fps might be every 4 frames (i.e. as though editing 60 field/sec video material) or every 5 frames (as 24 fps). On the other hand editors may enjoy the extra freedom of finer granularity of edit points.

Storage clearly increases with higher frame rates, although mezzanine compression may be an important enabling technology.

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[7] Noland, K. C., 2013, *The Human Visual System and High Frame Rate Television*, UHDTV - Voices & Choices Conference, EBU Geneva, 25th November 2013

The increased noise in each frame, as a consequence of a shorter frame exposure time, is a potential challenge for coding techniques, although an increase from 50/60 to 120 fps is not hugely significant in this respect. The visibility of noise to the human visual system presented at higher frame rates reduces with increasing frame rates. Whether this will exactly counteract the increase due to the shorter capture time is not yet understood, and so is a known area for more work.

The extent to which higher frame rates are relatively easily handled within a file-based production flow should be an enabling technology for the practical implementation of what are presently unconventional frame rates. However, given that the main application of higher frame rates is likely sports and event coverage, real-time signal chains must be considered.

Annex E Critical Viewing Environment

For critical viewing, it is generally considered necessary to keep the worst-case viewing angle at less than 45 degrees away from perpendicular to the display. This is independent of display technology. At angles greater than 45 degrees, geometric distortion and light falloff become issues.

In a typical grading suite the colorist is centered on the display, with seating for one creative on either side. The widths of the seats are typically about .67 meters (about 26 inches) for such suites. Seat width turns out to be the controlling factor in selection of the display size.

Looking at the table below, we can see that for a 120" display, the worst-case viewing angle is 41.63 degrees. However, it may not be practical to use this large a display. Based on the numbers, it appears that 90" is the minimum display size if the primary viewer is in line with the horizontal center of the display.

Dimensions in meters unless otherwise specified						
screen diagonal	screen width	screen height	distance to center viewer	width of viewer **w**	side viewer normal to far edge of screen	worst-case viewing angle **a** (degrees)
120"	2.66	1.50	2.25	0.67	2.00	41.63
90"	2.00	1.13	1.69	0.67	1.67	44.70
60"	1.33	0.75	1.13	0.67	1.34	49.88

Table E1 Critical Viewing Distances

Annex F Real-Time Streaming Media Interface (SDI)

UHDTV interfaces, in particular real-time streaming interfaces, require very high transmission bandwidths. Depending on the image format, interface rates in excess of 200 Gbit/sec could be required and to achieve these high bandwidths, multi-link interfaces are needed.

The SMPTE Technology Committee 32NF (TC-32NF) has developed or is in the process of developing single-link and multi-link optical fiber and coaxial cable based SDI interfaces in support of UHDTV SDI. The interfaces are described in the following sections.

F.1 Multi-link 3G SDI

TC-32NF has completed its work of developing standards for 2D image formats with nominal payloads of up to 10Gb/s as illustrated in Table F1.

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	SDI Standard	
			10-bit 4:2:0 10-bit 4:2:2	12-bit 4:2:0 12-bit 4:2:2 12-bit 4:4:4 10-bit 4:4:4:(4)
3840	2160	60	ST 425-5 Quad Link 3G	
3840	2160	50		
3840	2160	30	ST 425-3 Dual-link 3G	ST 425-5 Quad-link 3G
3840	2160	25		
3840	2160	24		

Table F1. 3G multi-link SDI Interface for UHDTV production

Both optical fiber and coaxial cable based 3G SDI interfaces are defined in:

SMPTE ST 424:2012 3Gb/s Signal/Data Serial Interface
SMPTE ST 297:2006 Serial Digital Fiber Transmission System for SMPTE 259M, SMPTE 344M, SMPTE 292 and SMPTE 424M Signals

F.2 Single-link and Multi-link 6G SDI

At the time of writing this report TC-32NF is currently in the process of developing single-link, dual-link and quad-link 6G SDI standards for 2D image formats with nominal payloads of up to 20 Gb/s as illustrated in Table F2.

<table>
<tr><th rowspan="2">Horizontal Pixels</th><th rowspan="2">Vertical Pixels</th><th rowspan="2">Frames per Second (nominal)</th><th colspan="2">Proposed SDI Standard</th></tr>
<tr><th>10-bit 4:2:0
10-bit 4:2:2</th><th>12-bit 4:2:0
12-bit 4:2:2
12-bit 4:4:4
10-bit 4:4:4:(4)</th></tr>
<tr><td>7680</td><td>4320</td><td>30</td><td rowspan="4">ST 2081-12
Quad-link 6G SDI</td><td rowspan="4"></td></tr>
<tr><td>7680</td><td>4320</td><td>25</td></tr>
<tr><td>7680</td><td>4320</td><td>24</td></tr>
<tr><td>3840</td><td>2160</td><td>120</td></tr>
<tr><td>3840</td><td>2160</td><td>60</td><td rowspan="2">ST 2081-11
Dual-link 6G SDI</td><td rowspan="2">ST 2081-12
Quad-link 6G SDI</td></tr>
<tr><td>3840</td><td>2160</td><td>50</td></tr>
<tr><td>3840</td><td>2160</td><td>30</td><td rowspan="3">ST 2081-10
Single-link 6G SDI</td><td rowspan="3">ST 2081-11
Dual-link 6G SDI</td></tr>
<tr><td>3840</td><td>2160</td><td>25</td></tr>
<tr><td>3840</td><td>2160</td><td>24</td></tr>
</table>

Table F2. Proposed ST 2081, 6G multi-link SDI Interface for UHDTV production

Both optical fibre and coaxial cable based 6G SDI interfaces are defined in:

SMPTE ST 2081-1, 6Gb/s Signal/Data Serial Interface – Electrical
SMPTE ST 2081-2, 6Gb/s Signal/Data Serial Interface – Optical

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White Plains, NY 10601 USA
www.smpte.org

F.3 Single-link and Multi-link 12G SDI

At the time of writing this report TC-32NF is currently in the process of developing single-link, dual-link and quad-link 12G SDI standards for 2D image formats with nominal payloads of up to 40 Gb/s as illustrated in Table F3.

<table>
<tr><th rowspan="2">Horizontal Pixels</th><th rowspan="2">Vertical Pixels</th><th rowspan="2">Frames per Second (nominal)</th><th colspan="2">Proposed SDI Standard</th></tr>
<tr><th>10-bit 4:2:0
10-bit 4:2:2</th><th>12-bit 4:2:0
12-bit 4:2:2
12-bit 4:4:4
10-bit 4:4:4:(4)</th></tr>
<tr><td>7680</td><td>4320</td><td>60</td><td rowspan="2">ST 2082-12
Quad-link 12G SDI</td><td rowspan="2"></td></tr>
<tr><td>7680</td><td>4320</td><td>50</td></tr>
<tr><td>7680</td><td>4320</td><td>30</td><td rowspan="4">ST 2082-11 Dual-link 12G SDI</td><td rowspan="4">ST 2082-12
Quad-link 12G SDI</td></tr>
<tr><td>7680</td><td>4320</td><td>25</td></tr>
<tr><td>7680</td><td>4320</td><td>24</td></tr>
<tr><td>3840</td><td>2160</td><td>120</td></tr>
<tr><td>3840</td><td>2160</td><td>60</td><td rowspan="2">ST 2082-10
Single-link 12G SDI</td><td rowspan="2">ST 2082-11
Dual-link 12G SDI</td></tr>
<tr><td>3840</td><td>2160</td><td>50</td></tr>
<tr><td>3840</td><td>2160</td><td>30</td><td rowspan="3"></td><td rowspan="3">ST 2082-10
Single-link 12G SDI</td></tr>
<tr><td>3840</td><td>2160</td><td>25</td></tr>
<tr><td>3840</td><td>2160</td><td>24</td></tr>
</table>

Table F3. Proposed ST 2082, 12G multi-link SDI Interface for UHDTV production

Both optical fiber and coaxial cable based 12G SDI interfaces are defined in:

Proposed SMPTE ST 2082-1, 12Gb/s Signal/Data Serial Interface – Electrical
Proposed SMPTE ST 2082-2, 12Gb/s Signal/Data Serial Interface – Optical

F.4 Single-link and Multi-link 24G SDI

TC-32NF is tasked with developing standards for 2D image formats with nominal payloads up to 144 Gb/s as illustrated in Table F4.

<table>
<tr><th rowspan="2">Horizontal Pixels</th><th rowspan="2">Vertical Pixels</th><th rowspan="2">Frames per Second (nominal)</th><th colspan="2">Proposed SDI Standard</th></tr>
<tr><th>10-bit 4:2:0
10-bit 4:2:2</th><th>12-bit 4:2:0
12-bit 4:2:2
12-bit 4:4:4
10-bit 4:4:4</th></tr>
<tr><td>7680</td><td>4320</td><td>120</td><td>ST 2083-12
Quad-link 24G SDI</td><td>ST 2083-13
Octa-link 24G SDI</td></tr>
<tr><td>7680</td><td>4320</td><td>60</td><td rowspan="2">ST 2083-11
Dual-link 24G SDI</td><td rowspan="2">ST 2083-12
Quad-link 24G SDI</td></tr>
<tr><td>7680</td><td>4320</td><td>50</td></tr>
<tr><td>7680</td><td>4320</td><td>30</td><td rowspan="4">ST 2083-10
Single-link 24G SDI</td><td rowspan="4">ST 2083-11
Dual-link 24G SDI</td></tr>
<tr><td>7680</td><td>4320</td><td>25</td></tr>
<tr><td>7680</td><td>4320</td><td>24</td></tr>
<tr><td>3840</td><td>2160</td><td>120</td></tr>
<tr><td>3840</td><td>2160</td><td>60</td><td rowspan="5"></td><td rowspan="5">ST 2083-10 Single-link 24G SDI</td></tr>
<tr><td>3840</td><td>2160</td><td>50</td></tr>
<tr><td>3840</td><td>2160</td><td>30</td></tr>
<tr><td>3840</td><td>2160</td><td>25</td></tr>
<tr><td>3840</td><td>2160</td><td>24</td></tr>
</table>

Table F4. Proposed ST 2083, 24G multi-link SDI Interface for UHDTV production

Both optical fiber and coaxial cable based 24G SDI interfaces are defined in:

Proposed ST 2083-1, 24Gb/s Signal/Data Serial Interface – Electrical
Proposed ST 2083-2, 24Gb/s Signal/Data Serial Interface – Optical

F.5 SMPTE ST 435, 10.692Gb/s optical SDI interface

TC-32NF has standardized a 10.692Gb/s optical SDI interface as SMPTE ST 435 part 1 though part 3. This multi-part document suite defines the carriage of multiple (up to 8), 1.5Gb/s virtual SDI links on a 10.692Gb/s optical interface.

This standard defines: Basic Stream Derivation in part 1; Basic Stream Data Mapping in part 2 and the 10.629 Gb/s Optical Fiber Interface in part 3.

ST 435 supports 2D image formats with nominal payloads of up to 9 Gb/s as illustrated in Table F5.

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	SDI Standard	
			10-bit 4:2:0 10-bit 4:2:2	12-bit 4:2:0 12-bit 4:2:2 12-bit 4:4:4 10-bit 4:4:4
3840	2160	30	ST435-1 Single-link 10G	
3840	2160	25		
3840	2160	24		

Table F5. SMPTE ST 435, 10G-SDI Interface for UHDTV production

F.6 SMPTE ST 2036-3, Single-link and Multi-link 10.692Gb/s optical SDI interface

SMPTE ST 2036-3 directly leverages the basic stream and mapping concepts of ST 435-1 and -2 and utilizes the 10G optical interface defined in ST 435-3 as the basic building block for the single-link and multi-link DWDM (Dense Wave-length Division Multiplex), optical interface.

SMPTE ST 2036-3 supports 2D image formats with nominal payloads of up to 72 Gb/s as illustrated in Table F6.

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	SDI Standard	
			10-bit 4:2:0 10-bit 4:2:2 10-bit 4:4:4	12-bit 4:2:0 12-bit 4:2:2 12-bit 4:4:4
7680	4320	60	ST 2036-3 Octa-link 10G	
7680	4320	50		
7680	4320	30	ST 2036-3 Quad-link 10G	
7680	4320	25		
7680	4320	24		
3840	2160	60	ST 2036-3 Dual-link 10G	
3840	2160	50		
3840	2160	30	ST 2036-3 Single-link 10G	
3840	2160	25		
3840	2160	24		

Table F6. SMPTE ST 2036-3, 10G SDI interface for UHDTV production

F.7 UHDTV Multi-link 10Gb/s Interface

TC-32NF is currently in the process of further developing the 10.692Gb/s multi-link optical interfaces in support of UHDTV production for 10 bit and 12 bit, 4:2:0, 4:2:2 and 4:4:4, images up to 120 Hz as shown in Table F7.

Proposed SMPTE ST 2036-4 supports 2D image formats with nominal payloads of up to 144 Gb/s as illustrated in Table F7.

<table>
<tr><th rowspan="2">Horizontal Pixels</th><th rowspan="2">Vertical Pixels</th><th rowspan="2">Frames per Second (nominal)</th><th colspan="3">Proposed SDI Standard</th></tr>
<tr><th>10-bit or 12-bit 4:2:0</th><th>10-bit or 12-bit 4:2:2</th><th>10-bit or 12-bit 4:4:4</th></tr>
<tr><td>7680</td><td>4320</td><td>120</td><td>ST 2036-4
12-link 10G</td><td>ST 2036-4
16-link 10G</td><td>ST 2036-4
24-link 10G</td></tr>
<tr><td>7680</td><td>4320</td><td>60</td><td rowspan="2">ST 2036-4
6-link 10G</td><td rowspan="2">ST 2036-4
8-link 10G</td><td rowspan="2">ST 2036-4
12-link 10G</td></tr>
<tr><td>7680</td><td>4320</td><td>50</td></tr>
<tr><td>7680</td><td>4320</td><td>30</td><td colspan="2" rowspan="5">ST 2036-4
4-link 10G</td><td rowspan="5">ST 2036-4
6-link 10G</td></tr>
<tr><td>7680</td><td>4320</td><td>25</td></tr>
<tr><td>7680</td><td>4320</td><td>24</td></tr>
<tr><td>3840</td><td>2160</td><td>120</td></tr>
</table>

Table F7. Proposed ST 2036-4, 10.692Gb/s interface for UHDTV production up to 120 fps

F.8 Proposed SMPTE ST 2062, 25Gb/s optical SDI interface

In addition to the 10G optical SDI interface, TC-32NF is currently working towards publication of a (nominal) 25Gb/s optical SDI interface as Proposed SMPTE ST 2062 part 1 and part 2.

This standard defines: Source Image and Format Mapping in part 1 and defines the 25.79851 Gb/Sec Optical Fiber Interface in part 2.

Proposed SMPTE ST 2062 supports 2D image formats with nominal payloads of up to 18 Gb/s as illustrated in Table F8.

Horizontal Pixels	Vertical Pixels	Frames per Second (nominal)	Total Payload (nominal)	
			10-bit 4:2:0 10-bit 4:2:2 10-bit 4:4:4	12-bit 4:2:0 12-bit 4:2:2 12-bit 4:4:4
3840	2160	60	Proposed ST 2062-1 Single-link 25G	
3840	2160	50		
3840	2160	30		
3840	2160	25		
3840	2160	24		

Table F8. Proposed SMPTE ST 2062, 25Gb/s interface for UHDTV production

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SMPTE ST 377-4:2012, MXF Multichannel Audio Labeling Framework

SMPTE ST 424:2012, 3 Gb/s Signal/Data Serial Interface

SMPTE ST 425-1:2011, Source Image Format and Ancillary Data Mapping for the 3 Gb/s Serial Interface

SMPTE ST 425-2:2012, Source Image Format and Ancillary Data Mapping for Stereoscopic Image Formats on a Single-Link 3 Gb/s Serial Interface

SMPTE ST 425-3:2014, Image Format and Ancillary Data Mapping for the Dual Link 3 Gb/s Serial Interface

SMPTE ST 425-4:2012, Dual 3 Gb/s Serial Digital Interface for Stereoscopic Image Transport

SMPTE ST 425-5:2014, Image Format and Ancillary Data Mapping for the Quad Link 3 Gb/s Serial Interface

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SMPTE ST 435-2:2012, 10 Gb/s Serial Signal/Data Interface — Part 2: 10.6921 Gb/s Stream — Basic Stream Data Mapping

SMPTE ST 435-3:2012, 10 Gb/s Serial Signal/Data Interface — Part 3: 10.6921 Gb/s Optical Fiber Interface

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SMPTE ST 2036-1:2013, Ultra High Definition Television – Image Parameter Values for Program Production

SMPTE ST 2036-2:2012, Ultra High Definition Television — Audio Characteristics and Audio Channel Mapping for Program Production

SMPTE ST 2036-3:2012, Ultra High Definition Television — Mapping into Single-link or Multi-link 10 Gb/s Serial Signal/Data Interface

SMPTE ST 2048-1:2011, 2048 × 1080 and 4096 × 2160 Digital Cinematography Production Image Formats FS/709

SMPTE ST 2048-2:2011, 2048 × 1080 Digital Cinematography Production Image FS/709 Formatting for Serial Digital Interface

SMPTE ST 2048-3:2012, 4096×2160 Digital Cinematography Production Image Formats FS/709 — Mapping into Multi-link 10 Gb/s Serial Signal/Data Interface

SMPTE ST 2063:2012, Stereoscopic 3D Full Resolution Contribution Link Based on MPEG-2 TS

SMPTE ST-2066:2012, Disparity Map Representation for Stereoscopic 3D

SMPTE ST-2068:2013, Stereoscopic 3D Frame Compatible Packing and Signaling for HDTV

The following documents are currently in development within SMPTE and may not be publically available at time of this writing.

Proposed SMPTE ST 2081-1:20xx, 6Gb/s Signal / Data Serial Interface – Electrical

Proposed SMPTE ST 2081-2:20xx, 6Gb/s Signal / Data Serial Interface – Optical

Proposed SMPTE ST 2081-10:20xx, 2160-line and 1080-line Source image format and ancillary data mapping onto a single-link 6Gb/s Signal / Data Serial Interface

Proposed SMPTE ST 2081-11:20xx, 2160-line and 1080-line Source image format and ancillary data mapping onto a dual-link 6Gb/s Signal / Data Serial Interface

Proposed SMPTE ST 2081-12:20xx, 4320-line, and 2160-line Source image format and ancillary data mapping onto a quad-link 6Gb/s Signal / Data Serial Interface

Proposed SMPTE ST 2082-1:20xx, 12Gb/s Signal / Data Serial Interface – Electrical

Proposed SMPTE ST 2082-2:20xx, 12Gb/s Signal / Data Serial Interface – Optical

Proposed SMPTE ST 2082-10:20xx, 2160-line and 1080-line Source image format and ancillary data mapping onto a single-link 12Gb/s SDI Signal / Data Serial Interface

Proposed SMPTE ST 2082-11:20xx, 4320-line and 2160-line Source image format and ancillary data mapping onto a dual-link 12Gb/s Signal / Data Serial Interface

Proposed SMPTE ST 2082-12:20xx, 4320-line and 2160-line Source image format and ancillary data mapping onto a quad-link 12Gb/s Signal / Data Serial Interface

Proposed SMPTE ST 2083-1:20xx, 24Gb/s Signal / Data Serial Interface - Electrical

Proposed SMPTE ST 2083-2:20xx, 24Gb/s Signal / Data Serial Interface – Optical

Proposed SMPTE ST 2083-10:20xx, 4320-line and 2160-line Source image format and ancillary data mapping onto a single-link 24G UHD-SDI Signal / Data Serial Interface

Proposed SMPTE ST 2036-4:20××, Ultra High Definition Television —Multi-link 10 Gb/s Signal/Data Interface using 12-bit width container

Proposed SMPTE ST 2062-1:20××, 25 Gb/s Serial Signal/Data Interface — Part 1: Source Image Format and Data Mapping

Proposed SMPTE ST 2062-2:20××, 25 Gb/s Serial Signal/Data Interface —Part 2: 25.79851 Gb/s Optical Fiber Interface

Proposed SMPTE ST-2076-1:20××, Stereoscopic 3D (S3D) Production Timing and Synchronization - Camera Systems

Proposed SMPTE ST-2076-2:20××, Stereoscopic 3D (S3D) Production Timing and Synchronization – Live Production Systems

Proposed SMPTE ST 2076-3:20××, Stereoscopic 3D (S3D) Production Timing and Synchronization - Physical Layer for Video Transport

Proposed SMPTE EG 2076-4:20××, Stereoscopic 3D (S3D) Production Timing and Synchronization - Physical Layer and System Guidance