Future MPEG standards VVC and EVC: 8K broadcast enabler

T. Biatek, M. Abdoli, T. Guionnet, A. Nasrallah and M. Raulet

ATEME

ABSTRACT

8K-TV momentum has grown these past years, fostered by CE-display manufacturers and perspective of Tokyo's Olympics broadcasting. However, a broad 8K-TV deployment is still uncertain. Although HEVC provides sufficient coding efficiency to enable DTH broadcasting, the transmission cost remains high and the HEVC licensing situation makes deployment complicated, especially for DTT. In that context, the emerging codecs VVC and EVC are both capable of addressing these issues by increasing coding efficiency without repeating HEVC licensing situation. In this paper, we demonstrate how VVC and EVC could be 8K-broadcast enablers in the upcoming years. Based on encoding constraints coming from DVB-T2/S2 and 5G-broadcast transmission scenarios, the relevance of both codecs is assessed based on encoding efficiency and complexity criterions. In addition, we highlight that early 8K-deployment is possible with these codecs since a reduced set of tools is capable of achieving minimal required efficiency. Finally, some preliminary results of ATEME industrial VVC encoding platform are provided to show that early 8K deployment is possible using the latest video coding standards.

INTRODUCTION

4K-UHD is currently the state-of-the-art video format for broadcast, which has been commercially developed these last years, driven by DVB [1] and ATSC [2]. It provides increased Quality of Experience (QoE), thanks to NGA, HDR/WCG and HFR. The excellent coding efficiency of HEVC [3] enabled 148 4K-UHD services to be deployed in the past years over various networks [4]. Despite these deployments, the 4K-UHD adoption is slowed down by unclear HEVC licensing costs which accelerated the development of emerging video coding standards claiming straightforward licensing terms and further increased efficiency. Developed within the MPEG standardization committee, both VVC [5] and EVC [6] are candidates to supersede HEVC in that context.

In the meantime, the 8K format emerged, fostered by CE-display manufacturers and perspective of Tokyo's Olympics in Japan [7]. A previous study [8] shows that to maintain an optimal QoE, 8K HEVC encoding requires up to 50Mbps which remains prohibitive in many transmission scenarios. Although 8K suffers from low content availability, the usage of VVC/EVC combined with latest transmission systems (e.g. DVB-T2/S2, ATSC-3.0 or 5G-Broadcast) offers the perspective of having 8K services deployed in the upcoming years. From a commercial standpoint, 8K is also endorsed by promising shipment forecasts, especially in China, as indicated in a recent market analysis [9].

DTH is currently the only delivery method compatible with 8K HEVC encoding requirements. It was demonstrated that a complete 36MHz transponder can host a single 8K channel [10]. DTT, which offers a lower bandwidth capability, could be used to deliver 8K channels but would require higher coding efficiency since realistic DVB-T2 or ATSC-3.0 configurations enable around 35Mbps [11][12]. In addition, the development of feMBMS [11] during the past years reinforce the fact that 5G-broadcast combined with next generation codec could drive 8K deployments in the future.

The rest of the paper is organized as follows. The potential 8K-broadcast deployment scenarios are first analyzed to extract encoding constraints that need to be addressed by VVC and EVC. Then, an experimental study is conducted to illustrate how EVC and VVC perform on 8K contents for these scenarios. The results are analyzed from both coding efficiency and complexity perspective. The pros and cons of each codec are also discussed in terms of packaging and transport capabilities. In addition, some results from our early industrial VVC encoder are provided in that context. The conclusion discusses remaining 8K technological locks and future outlook.

8K BROADCAST SCENARIOS

1. *8K-broadcast with DTT/DTH*

DTT/DTH is the most efficient way for 8K to reach high penetration in houses because of its wide coverage. While HEVC 8K transmission has been demonstrated on satellite using DVB-S2X, terrestrial HPHT networks using DVB-T2 or ATSC-3.0 do not offer enough bandwidth in a single channel to make 8K delivery possible. Recent development in France, in the context of next-generation DTT platform, show that realistic DVB-T2 profiles enable at most 34.9Mbps, according to the desired coverage versus capacity trade-off [14]. Although ATSC-3.0 achieves similar physical layer performance, it should be noted that it supports file-based delivery mechanism using DASH/MMT unlike DVB broadcast standards that are MPEG-TS centric.

Table 1: DVB-T2 profile under consideration for France next-generation DTT [14], 8MHz channel

Profile	Subcarrier	Constellation	Code rate	Guard interval	Pilot pattern	nxTi/Lf	FEC length	Bitrate (Mbps)
C1	32k(E)	256-QAM	3/5	1/32	PP6	3/58	193	**34,909**

2. *8K broadcast with 4G-feMBMS and 5G*

In 3GPP release-14, feMBMS is introduced to enable SIM-less broadcast services reception over 4G-networks. Currently, 3GPP-SA4 is working on development of such features for 5G release-17 specification. This work includes multicast enhancement for media-streaming [15] and next-generation video codecs for 5G use-cases [16]. The table 2 below provides anticipated feMBMS physical layer configuration giving similar coverage as aforementioned DTT profiles [17]. Although feMBMS performs lower than DTT, it should be noted that we have selected a modulation profile for HPHT networks aligned with DTT; other profiles could lead to higher spectral efficiency. From an encapsulation perspective, mobile broadcast services are expected to use CMAF with low-latency profiles to enable QoE aligned with traditional DTT/DTH services.

Table 2: feMBMS profile using HPHT broadcast infrastructure, near-DTT performance, 10MHz-Channel

Profile	Constellation	FEC	Subcarrier bandwidth	Cyclic prefix	Spectral Efficiency	Bitrate (Mbps)
MCS-26	QAM-64	0.85	1.25 kHz	20%	2.98 bit/s/Hz	**29.800**

3. *VVC and EVC as 8K enabler*

Although the above approaches use different encapsulation schemes, i.e. mostly stream-oriented for DTT/DTH (MPEG-TS) and file-oriented for mobile (CMAF), both aim at delivering the same QoE in terms of latency, service access and audio/video quality. To enable 8K broadcast, it is observed from Table 1 and Table 2 that eligible codecs should be capable of operating high 8K quality video in a 35Mbps bitrate range. In addition, codecs should be encapsulation-agnostic and be compatible with both stream and file-oriented delivery. These constraints automatically rule out HEVC and AV1. HEVC is lacking coding efficiency and AV1 is not compatible with MPEG-TS encapsulation [1][33]. Thus, this study will be focused on emerging VVC and EVC codecs and compare them to HEVC from two points of view: business and technical aspects.

The main business issue with HEVC has been its complex and unclear licensing policy, rather than its cost. As of today, three patent pools (MPEG-LA [18], HEVC-advance [19] and Velos media [20]) license essential patents of HEVC. Moreover, there seem to be several IP holders that have not yet joined any of the pools. As a result, it is not clear for implementors of HEVC neither how much, nor to whom, they should pay. To avoid taking the same licensing path as HEVC, a third-party entity, called Media Coding

Industry Forum (MC-IF) [21], has been initiated to monitor the development of VVC and reduce the risk of similar licensing issues. However, MC-IF has no official power over the standardization process, which is mostly technical. Thus, the main functionality of MC-IF will be creating profiles and levels based upon licensing terms proposed by each IP holder. Unlike VVC, the solution of EVC for licensing-friendliness has been included in the standardization. To this end, two profiles are simultaneously being developed: Main and Baseline. The Baseline profile is royalty free as it uses at least 20 year old tools and has similar performance to AVC, while the main profile is somewhat close to VVC, both in terms of performance and technologies. To prevent EVC from developing licensing issues, EVC proponents committed to publish FRAND licensing terms in the two years following FDIS publication. Both VVC and EVC feature the ability to deactivate a subset of coding tools using high level syntax. Thus, it will be possible to later create new profiles excluding coding tools that eventually will be found to create licensing uncertainty.

The technical aspects of VVC [22] and EVC-main [23] are close, keeping roughly the same structure as that of HEVC, both VVC and EVC improve the existing coding modules with more sophisticated functionalities, in terms of coding efficiency and diversity of format support. A major part of the coding efficiency gains of VVC and EVC against HEVC, in 4K and 8K, is simply due to two improvements in the picture partitioning. First, the largest pixel processing unit in both standards is increased to 128x128 pixels, instead of 64x64 in HEVC. This aspect alone allows a highly content-adaptive picture division that more properly exploits local motion/texture redundancies. The second aspect is a flexible multi-type Coding Unit (CU) splitting, allowing Quad/Ternary/Binary partitioning, while in HEVC only Quad partitioning is allowed. Furthermore, VVC allows non-rectangular partitioning such as triangle or trapezoid for motion isolation. Other than partitioning, several new coding tools have been adopted in VVC and EVC (prediction, residual and transformation, entropy coding, loop filtering etc.). Compared to the new partitioning scheme discussed above, each of these new tools are responsible for a relatively small but significant portion of their codec's gain against HEVC. As both VVC and EVC are being developed in the well-known ISO/ITU framework, liaison is made with the MPEG system group, thus fulfilling the required transport constraints for broadcast and streaming applications.

EXPERIMENTAL STUDY

1. Test-conditions

First, a survey of existing performance evaluation is conducted to estimate VVC/EVC achievable gains on high-resolution content. Second, codecs are tested on some 8K sequences to assess coding gains and confirm that VVC and EVC address the requirements of 8K-broadcast scenarios. The reference test model of each codec is tested, namely HEVC Model (HM), VVC Test Model (VTM) and EVC Test Model (ETM). To guarantee fairness, the codecs settings are selected carefully so that they benefit from their full potentials. Moreover, a common hierarchical GoP structure with a single Intra is used for all codecs. Encoding using commonly used Quantization Parameters (QP) - {22,27,32,37} are conducted for each codec. The performance measurements are carried out in terms of the Bjontegaard delta bitrate (BDR) saving which is interpreted as the amount of bitrate saving in the same level of quality (estimated here with PSNR metric).

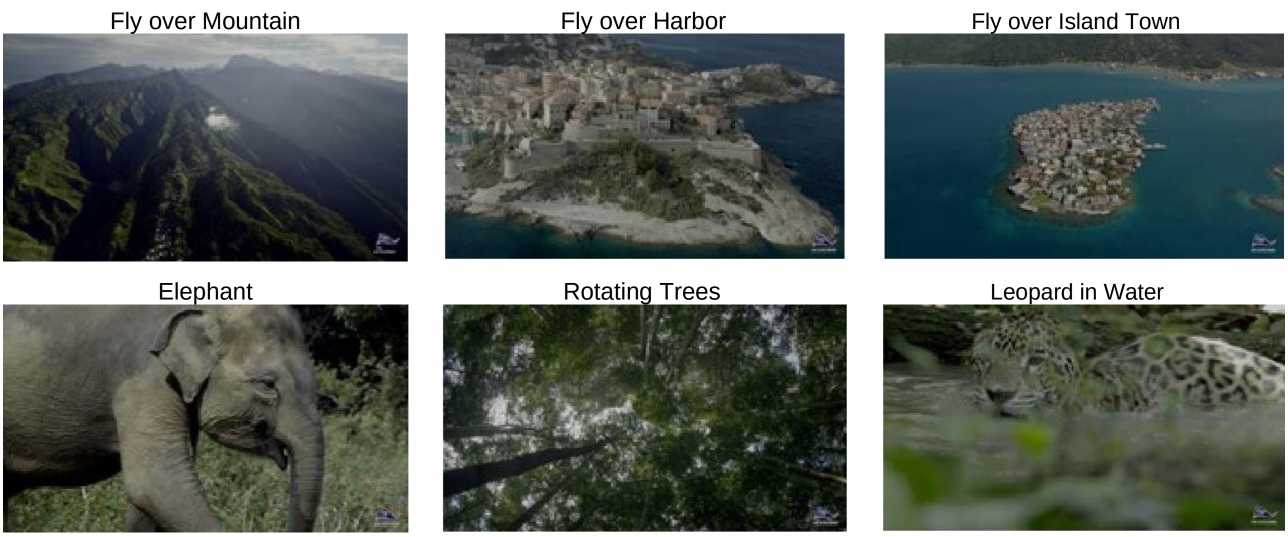

Figure 1: Miniatures of selected 8K sequences

The selected 8K sequences are coming from the well-known professional production *The Explorers*™ [24]. In practice, it is expected to align broadcast Random-Access Points (RAP) with CMAF segment duration to enable a unified headend. The length of the used sequences has been chosen to be 5 seconds which is consistent with average real-world segment duration. The content is HDR PQ-10, using BT-2020 color space shot at 50 frames per second. To give an idea of the selected content, miniatures provided in Figure 1 show various documentary content including fine textures such as water, forest and moving animals.

2. Performance of reference software

Table 3 provides a survey on existing work related to performance evaluation of new codecs against HEVC. For each reference the measured performance and test conditions are summarized and sorted according to software version, resolution and considered quality metric. Bitrate saving is evaluated using BDR using either PSNR, VMAF [32] or Mean Opinion Score (MOS) as quality metric. PSNR and VMAF are both objective metrics while MOS is the commonly used subjective metric for video quality evaluation. MOS consists of computing the arithmetic mean over all individual values on a predefined scale that a subject assigns to his opinion of the performance of a system quality. From this survey, it appears that VVC objective performance compared to HEVC is in the range of -30%, reaching -40% when subjective viewing is conducted. For EVC, objective performance is a bit lower, with -20% for mixed HD/4K content and -30% for 4K only. Regarding complexity, EVC shows lower encoding/decoding runtime increase than VVC which is consistent with bitrate saving analysis. The results presented in the table converge towards the effectiveness of these future codecs for 8K-broadcast scenarios. More specifically, it has been noticed in these tests, that bitrate savings on 8K sequences are even better than on lower resolutions. These preliminary gains applied to the current 50Mbps requirements for 8K-HEVC further reduces the bitrate to 30-35Mbps which is aligned with the aforementioned DTT/feMBMS scenarios.

Table 3: Existing studies on VVC/EVC performance evaluation for high resolution content

Reference	Resolution	Anchor	Tested	Quality metric	Performance		
					Bitrate saving (Y)	Enc runtime	Dec runtime
[26]	4K	HM-16.20	VTM-4.0	PSNR	-29,08	547%	111%
	8K			PSNR	-30,81	498%	106%
[27]	mixed HD/4K	HM-16.18	VTM-5.0	PSNR	-35,70	1274%	160%
			ETM-2.01	PSNR	-20,50	474%	156%
[28]	4K	HM-16.20	VTM-5.0	PSNR	-34,40	N/A	N/A
				MOS	-40,00	N/A	N/A
				VMAF	-40,44	N/A	N/A
[29]	8K	HM-16.20	VTM-6.0	PSNR	-27,5	783%	132%
[30]	4K	HM-16.6	ETM-3.0	PSNR	-30	413%	167%

To confirm the observation and analysis from literature, Table 4 compares the performance of VVC, EVC and HEVC on the selected 8K sequences, using the latest reference implementations. As can be seen, the bitrate savings of VVC over HEVC as well as EVC over HEVC are somewhat consistent.

Table 4: Bitrate saving of VVC and EVC against HEVC (HM-16.20) on selected 8K sequences

Sequence	Bitrate saving (%)	
	VVC (VTM-8.0)	EVC (ETM-5.0)
Fly over Harbor	-32%	-23%
Rotating Tree	-22%	-14%
Elephant	-45%	-35%
Average	**-33%**	**-24%**

As an additional interesting result, the performance of the VTM with limited subsets of its tools is also measured. In the first experiment, all new coding tools, except those related to partitioning, were deactivated. The main purpose of this test is to observe that a very limited effort (i.e. flexible partitioning) on top of HEVC can still significantly improve its performance. As expected, this experiment resulted in -10% to -15% bitrate saving on 4K and 8K content. In addition, tools evaluation conducted inside JVET Ad-hoc group 13 indicates that a subset of some additional tools (e.g. dependent quantization, adaptive loop filter, affine motion and adaptive motion vector resolutions etc.) potentially provides an additional bitrate saving of -10% on top of the first experiment [25].
To support further that idea, we conducted some additional tests showing that VVC with a subset of tools provides sufficient gains to fulfill the bitrate requirements of our broadcast use-cases. As mentioned, a part of the answer is provided by the JVET AHG13 [25], which studies the effect of the deactivation of each tool individually. Our own study is going a step further by considering subsets of tools in combination. Thus, the positive and negative interactions between tools can be captured and the best combination can be derived for any coding performance target. In the table 5 below, three tests launched with the VTM8.0 on Class A1/A2 sequences are presented (UHD). The first one summarizes the best VVC coding performance, that is with all coding tools switched on. The second test on the contrary, is the result of turning off all the switchable tools, thus providing the lowest possible complexity, at the price of a much lower bitrate saving. The third test is the best output found to the challenge imposed: conserve the highest possible proportion of the maximum bitrate gains provided by full VVC (all tools on) while keeping the complexity at its lowest possible level. This example offers an encoder that is 2 times less complex than full VVC, for a bitrate saving only 1.33 times lower. The best tradeoff disables some tools bringing minor gains compared to the introduced complexity, including multiple transform selection (MTS), triangular partitioning (TPM), sub block transform (SBT), matrix intra prediction (MIP) or intra sub partitioning (ISP).

Table 5: VVC measurement of different complexity-vs-efficiency tradeoffs (on UHD content).

Test	Performance	
	Bitrate saving over HEVC	**Encoding runtime over HEVC**
VVC all tools on	-36,07%	1051%
VVC all tools off	-12,05%	162%
Best tradeoff	-27,05%	471%

It is noted that the tradeoffs presented above are measured on UHD test material using the VTM-8.0 reference software. Thus, it is expected that higher gains will be achieved using 8K test material and latest reference software VTM-10.0. We can legitimately conclude that a subset of VVC tools with reasonable complexity makes 8K broadcast deployments possible, achieving 30-35% gains over HEVC with a reasonable complexity increase. Since both VVC and EVC benefit from similar partitioning scheme and tools, one can expect that these new standards using a subset of tools at the encoder side can be used to foster early 8K deployments in the near future.

3. *Performance of ATEME VVC encoder*

Near-live 8K encoding performance is measured using ATEME's live HEVC and VVC codecs. The goal of this experiment is to demonstrate the potentials of adopting new codecs for future live event broadcast. It is noteworthy that since the VVC standardization has not finished yet, this live encoder is rather a demo version than a commercial product. Therefore, to ensure fairness, a comparable level of encoder throughput in terms of frames/second is considered for both codecs. In this test, all six 8K sequences of Figure 1 have been coded. As showed in Table 6, a significant bitrate saving will be achieved for live 8K broadcast by using VVC. Once more, a comparable gain can also be expected from EVC main profile, as it benefits from a similar coding toolset.

Table 6: Performance of ATEME VVC encoder under live conditions on selected 8K sequences

VVC live vs. HEVC live	Fly over mountain	Fly over Harbor	Fly over Island Town	Elephant	Rotating Trees	Leopard in Water
Bitrate saving	-16%	-17%	-21%	-24%	-15%	-28%

4. *Discussion on VVC and EVC*

If both VVC and EVC are suitable for 8K deployment, one may wonder which of the two should be preferred. EVC is expected to have lower licensing costs. On the other hand, in terms of coding efficiency, VVC has a clear advantage. Using verification models, VVC significantly outperforms EVC, at the cost of twice as much encoding complexity. Interestingly, this situation may change in practical applications, especially live. Indeed, live encoders tend to trade some coding efficiency to guarantee real-time performance. VVC being more complex than EVC, its real-time implementation will be more challenging. It is already easy to make VVC comparable to EVC by deactivating a subset of coding tools. It is very likely that early real-time implementations of EVC and VVC will have similar coding performance. Thus, EVC may become the most sensible choice, same performance, less cost. At least at the beginning. With technical evolution, encoders improve continuously. EVC may be the easy choice for early 8K deployments, but VVC is the future-proof choice, as it will benefit from higher coding efficiency in the coming years. Moreover, VVC versatility promises cost reductions, thanks to a single “do-it-all" codec strategy, all along with enhanced user experience.

CONCLUSION

In this paper, the relevance of both VVC and EVC for 8K-broadcast was thoroughly investigated. From existing literature survey and new encoding results, it was demonstrated that VVC/EVC bitrate saving enables us to reach the bandwidth requirements of mobile and terrestrial 8K broadcast use-cases, delivering high quality video around 35Mbps. While VVC outperforms EVC on paper, but at a higher complexity cost, performance of both codecs should converge when real-time gain versus complexity tradeoff is targeted. To confirm this tendency, performance results of ATEME VVC encoder in a live-context shows 24% of coding gains compared to the live HEVC encoder, at an early development stage. It is therefore confirmed that 8K deployment at a reasonable bandwidth cost is possible in the upcoming years using these new codecs.

GLOSSARY

Acronym	Description
3GPP	The 3rd Generation Partnership Project
3GPP-SA4	3GPP SA4 working group deals with the specifications for speech, audio, video, and multimedia codecs
ATSC	The Advanced Television Systems Committee, Inc., is an international, non-profit organization developing voluntary standards for digital television
ATSC-3.0	ATSC 3.0 is the next generation terrestrial broadcast system designed from the ground up to improve the television viewing experience. The ATSC 3.0 standard is defined in a suite of more than 20 Standards and companion Recommended Practices
AVC	Advanced Video Coding, a.k.a H.264
BDR	Bjontegaard delta bitrate, the commonly used method to measure bitrate saving between two rate-distortion curves
CMAF	Common Media Application Format
DASH	Dynamic Adaptive Streaming over HTTP
DTH	Direct to the Home, refers to digital satellite services providing television viewing
DTT	Digital Terrestrial Television

DVB	The Digital Video Broadcasting consortium, is an international, non-profit organization developing voluntary standards for digital television
DVB-S2	Last DVB technology for satellite transmission
DVB-T2	Last DVB technology for terrestrial transmission
ETM	Essential Video Coding Test Model. Reference software for EVC
EVC	Essential Video Coding
FDIS	Final Draft International Standard
feMBMS	Further evolved multimedia broadcast multicast service
FRAND	Fair Reasonable and Non-Discriminatory
HDR	High Dynamic Range imaging.
HEVC	High Efficiency Video Coding, a.k.a. H.265
HFR	High Frame Rate
HPHT	High Power High Tower
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JVET	Joint Video Experts Team, in charge of VVC standardization
MC-IF	The Media Coding Industry Forum, aims at facilitating VVC licensing
MMT	MPEG Media Transport
MOS	Mean Opinion Score
MPEG	Moving Picture Experts Group
MPEG-TS	MPEG Transport Stream, a.k.a. H.222
NGA	Next Generation Audio, refers to MPEG-H 3D Audio and Dolby AC-4
PSNR	Peak Signal to Noise Ratio
RAP	Random Access Point
VMAF	Video Multi-Method Assessment Fusion, an objective video quality metric
VTM	Versatile Video Coding Test Model. Reference software for VVC
VVC	Versatile Video Coding, a.k.a. H.266
WCG	Wide Color Gamut

REFERENCES

[1] Digital Video Broadcasting (DVB), “Specification for the use of Video and Audio Coding in Broadcast and Broadband Applications”, Specification TS-101-154.version 2.6.1, 2019-09.

[2] Advanced Television Systems Committee (ATSC), “ATSC Standard: Video – HEVC”, Specification A/341:2019, 14 February 2019.

[3] Recommendation ITU-T H.265 (11/2019): "High efficiency video coding" | ISO/IEC 23008-2:2020: "High Efficiency Coding and Media Delivery in Heterogeneous Environments - Part 2: High Efficiency Video Coding".

[4] Ultra HD Forum, “UHD Service Tracker B2C”, https://ultrahdforum.org/uhd-service-tracker/

[5] B. Bross, J. Chen, S. Liu, Y.-K. Wang, “ Versatile Video Coding (Draft 8)”, document JVET-Q2001, 17th Meeting: Brussels, BE, 7–17 January 2020.

[6] ISO/IEC DIS 23094-1, “Information Technology – General Video Coding – Part 1: Essential Video Coding”, Document N18774, October 2019, Geneva, Switzerland.

[7] S. Hara, A. Hanada, I. Masuhara, T. Yamashita and K. Mitani, "Celebrating the Launch of 8K/4K UHDTV Satellite Broadcasting and Progress on Full-Featured 8K UHDTV in Japan," in SMPTE Motion Imaging Journal, vol. 127, no. 2, pp. 1-8, March 2018.

[8] 8K association, https://8kassociation.com/wp-content/uploads/2019/04/ATEME-8K-Video-Compression.pdf

[9] HIS Market “4K-TV and UHD: the whole picture”, https://cdn.ihs.com/www/pdf/4ktv-uhd-ebook.pdf

[10] Digital Video Broadcasting (DVB), “Demonstrating S2X capabilities for 8K delivery”, https://dvb.org/news/demonstrating-s2x-capabilities-for-8k-delivery

[11] M. Slimani et al., "Results of the DVB-T2 Field Trial in Germany," in IEEE Transactions on Broadcasting, vol. 61, no. 2, pp. 177-194, June 2015.

[12] S. Jeon et al., "Field Trial Results for ATSC 3.0 TxID Transmission and Detection in Single Frequency Network of Seoul," 2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Valencia, 2018, pp. 1-4.

[13] R. Kaliski, C. Chou and H. Wei, "Further Enhanced Multimedia Broadcast/Multicast Service in LTE-Advanced Pro," in IEEE Communications Standards Magazine, vol. 3, no. 3, pp. 44-51, September 2019.

[14] Conseil Supérieur de l’Audiovisuel (CSA), « Consultation Publique pour la Modernisation de la PlateformeTNT », december 2019, https://www.csa.fr/content/download/255185/747858/version/8/file/CSA-Consultation%20publique%20plateforme%20TNT.pdf

[15] 3GPP TR 26.802: "5G Multimedia Streaming (5GMS); Multicast architecture".

[16] 3GPP TR 26.955: "Video codec characteristics for 5G-based services and applications".

[17] 5G-XCast, “Broadcast and Multicast Communication Enablers for the Fifth-Generation of Wireless Systems”, http://5g-xcast.eu/wp-content/uploads/2019/04/5G-Xcast_D3.1_v1.1_web.pdf

[18] MPEG-LA, https://www.mpegla.com/programs/hevc/

[19] HEVC Advance, https://www.hevcadvance.com

[20] Velos Media, http://velosmedia.com/

[21] Media Coding Industry Forum (MCIF), https://www.mc-if.org/

[22] J. Chen, Y. Ye, S. Kim, “Algorithm description of Versatile Video Coding and Test Model 8 (VTM 8)”, document JVET-Q2002, 17th Meeting: Brussels, BE, 7–17 January 2020.

[23] ISO/IEC JTC 1/SC 29/WG 11, “Test Model of Essential Video Coding (ETM-5.0)”, document MPEG N18985, October 2019, Geneva, Switzerland.

[24] The Explorers, https://theexplorers.com/landing?culture=en

[25] W.-J. Chien, J. Boyce, W. Chen, Y.-W. Chen, R. Chernyak, K. Choi, R. Hashimoto, Y.-W. Huang, H. Jang, R.-L. Liao, S. Liu, “JVET AHG report: Tool procedure and testing (AHG13)”, document JVET-Q0013, 17th Meeting: Brussels, BE, 7–17 January 2020.

[26] ISO/IEC JTC 1/SC 29/WG 11, “[AHG13] Compression performance analysis for 4K and 8K HLG test sequences”, document JVET N0828, March 2019, Geneva, Switzerland.

[27] ISO/IEC JTC 1/SC 29/WG 11, “Extra results to JVET-N605 “Comparative study of video coding solutions VVC, AV1 and EVC versus HEVC” ”, document JVET-O0898, 15th Meeting: Gothenburg, SE, 3–12 July 2019.

[28] N. Sidaty, W. Hamidouche, O. Déforges, P. Philippe and J. Fournier, "Compression Performance of the Versatile Video Coding: HD and UHD Visual Quality Monitoring," 2019 Picture Coding Symposium (PCS), Ningbo, China, 2019, pp. 1-5, doi: 10.1109/PCS48520.2019.8954562.

[29] ISO/IEC JTC 1/SC 29/WG 11, “[AHG13] Compression performance analysis for 8K HLG sequences”, document JVET-P0616, 16th Meeting: Geneva, CH, 1–11 October 2019.

[30] https://www.itu.int/en/ITU-T/Workshops-and-Seminars/20191008/Documents/Ken_McCann_Presentation.pdf

[31] G. Bjontegaard, "Calculation of Average PSNR Differences between RD-curves," in ITU-T video Coding Experts Group document VCEG-M33, 2001.

[32] Z. Li, A. Aaron, I. Katsavounidis, A. Moorthy, and M. Manohara, "Toward a practical perceptual video quality metric," Netflix Technology Blog, Available: https://medium.com/netflix-techblog/toward-a-practicalperceptual-video-quality-metric-653f208b965

[33] ISO/IEC. Information technology -- Generic coding of moving pictures and associated audio information: Systems ITU-T Rec. H.222.0 / ISO/IEC 13818-1:2013. URL: http://www.itu.int/rec/T-REC-H.222.0-201206-I